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Return to the River: Restoration of Salmonid Fishes in the Columbia River Ecosystem

Development of an Alternative Conceptual Foundation
and
Review and Synthesis of Science
underlying the Fish and Wildlife Program
of the Northwest Power Planning Council

by
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10 September 1996

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Table of Contents

List of Tables

List of Figures

Chapter 7 - Hydroelectric Development

Chapter 8 - Habitat, Harvest and Hatcheries

Appendices

EXECUTIVE SUMMARY

BACKGROUND

In the December 1994 amendments to the Columbia River Basin Fish and Wildlife Program (Section 3.2B), the Northwest Power Planning Council called on the Bonneville Power Administration to fund the Independent Scientific Group to conduct a biennial review of the science underlying salmon and steelhead recovery efforts and Columbia River Basin ecosystem health. The Council's objective was to provide the region, to the greatest extent possible, clear and authoritative analysis conducted by impartial experts.

The Council also asked that the independent scientists develop a conceptual foundation for the fish and wildlife program (Section 5.0F), to provide an overall set of scientific principles and assumptions on which the program and fish and wildlife management activities basinwide could be based and against which they could be evaluated.

On September 18, 1996, we delivered to the Council this report, which contains the first biennial review and a proposed conceptual foundation for the Fish and Wildlife Program. This report has been peer reviewed by additional scientists, whose comments, where appropriate, are reflected in this report. Appendix A, contains a history of the Independent Scientific Group and brief biographies of its members.

After an introductory chapter, this report is divided into four main components: Chapter 2 contains the proposed conceptual foundation for the Fish and Wildlife Program; Chapter 3 contains the review of the scientific basis for measures included in the current Fish and Wildlife Program, using the conceptual foundation as a template for this evaluation; Chapters 4 through 10 contain the detailed technical data and documentation on which Chapters 2 and 3 are based; Chapter 11 describes general conclusions from our review.

It must be noted at the outset that we were not asked to carry on original research. Nor were we asked to provide specific recommendations for revising the Council's Fish and Wildlife Program. Our charge was to analyze existing data and measures currently in the program, and draw conclusions based on that analysis. The relevant scientific literature we reviewed and cited in this analysis is listed at the end of each chapter.

In submitting this report, the Independent Scientific Group hopes that it will be a valuable resource for decision-makers. The findings should enable fishery managers to focus future research activities on areas that still are not thoroughly understood. However, the review does not include policy recommendations for recovery and restoration. Nor does it recommend specific measures or strategies or deal with institutional structures. It is not an implementation plan. Instead, the conceptual foundation proposed in this report should provide the scientific foundation for public policy to be developed by the Council and other decision-making bodies. It can be used to guide salmon restoration activities in general, as well as future development of the Columbia River Basin Fish and Wildlife Program.

AN ALTERNATIVE CONCEPTUAL FOUNDATION

Defining a Conceptual Foundation

A conceptual foundation is a set of scientific principles and assumptions that can give direction to management activities, including biological restoration programs. It is the filter through which information is viewed and interpreted. Recovery measures and research findings will take on different meanings when viewed through different filters.

Because ecosystems that have been disrupted over several decades, such as the Columbia River Basin, have scarce evidence left of thriving natural ecologies, scientists must rely on the best available information and remnant populations to assemble as complete a picture as possible. In these instances, the conceptual foundation is designed to be changed over time as new information, about the problems *or* the solutions, becomes available.

Conceptual Foundations in the Current Fish and Wildlife Program

As we began our development of this conceptual foundation, we looked first to the Columbia River Basin Fish and Wildlife Program to determine whether such a foundation already exists in that document. Our answer is yes and no. The Fish and Wildlife Program actually has several implied conceptual foundations. This is likely a result of the process through which it is created, in which recommendations from fish and wildlife managers and others are reviewed and adopted. Each participating agency or individual brings to the process some version of a conceptual foundation on which their recommendations are based. In nearly every instance, these conceptual foundations are not stated outright, but are only implied. In some cases, the foundations that make their way into the program through the adoption of specific measures are in conflict.

In our review of the Fish and Wildlife Program, we analyzed the general assumptions that seem to determine the direction of program activities. The most fundamental assumption appears to be that the natural ecological processes that result in a healthy salmon population can be, to a large degree, circumvented, simplified and controlled by humans. Out of this context, we drew three further assumptions:

1. The number of adult salmon made available to spawn is primarily a direct response to the number of smolts produced. (More young fish will automatically result in more adult spawners.)

2. Salmon production can be increased by actions taken within the river without accounting for conditions in the estuary or ocean.
3. Management actions will not compromise environmental attributes of the ecosystem that supports salmon.

The assumptions above drive management toward actions that are best characterized as technological substitutes for ecological processes. They are often measures that respond to individual problems and they may be credible scientific approaches to those problems if they are viewed in isolation: hatcheries and mechanisms for improving salmon survival at hydroelectric projects, for example, rather than actions that look at the broader context of salmon life history, behavior and habitat. They reflect a good faith effort by the Council and the region's fisheries managers to recover salmon populations. However, the continuing decline of the basin's salmon populations indicates that the conceptual foundations in the current fish and wildlife program and the actions based on those foundations are inadequate.

Our Proposed Conceptual Foundation

The conceptual foundation we propose departs from some of those in the current program. It is not intended to validate existing measures in the program, nor does it derive out of those measures. It is instead designed to form a framework into which recovery measures can be integrated, when they are appropriate. It can provide a template against which recovery actions can be measured and evaluated.

In this proposed conceptual foundation, we treat the Columbia River and its tributaries as both a natural *and* a cultural system. A natural-cultural ecosystem encompasses all the ecological and social processes that link organisms, including humans, with their environments. This approach integrates the habitat of salmon and other wildlife, as well as human habitat, with land use and other cultural developments.

We draw our conceptual foundation from established ecological principles, based on what we understand about the decline of salmon populations and their habitat in the Columbia River Basin.

There are three critical elements of our conceptual foundation:

1. Restoration of Columbia River salmon must address the entire natural and cultural ecosystem, which encompasses the continuum of freshwater, estuarine and ocean habitats where salmon complete their life histories. This consideration includes human developments, as well as natural habitats.
2. Sustained salmon productivity requires a network of complex and interconnected habitats, which are created, altered and maintained by natural physical processes in freshwater, the estuary and the ocean. These diverse and high-quality habitats are crucial for salmon spawning, rearing, migration, maintenance of food webs and predator avoidance.

3. Life history diversity, genetic diversity and metapopulation organization are ways salmon adapt to their complex and connected habitats. This biodiversity and its organization contribute to the ability of salmon to cope with the environmental variation that is typical of freshwater and saltwater environments.

1. The Natural-Cultural Ecosystem

We believe an ecosystem with a mix of natural and cultural features can still sustain a broad diversity of salmon populations in the Columbia River Basin. We call this ecosystem "normative," by which we mean an ecosystem where specific functional norms or standards that are essential to maintain diverse and productive populations are provided. In developing our definition of normative, we looked at what conditions lead to high levels of salmon productivity in less-constrained river systems, as well as in the historic Columbia River Basin.

Key among the conditions we define as normative is the availability of a continuum of high-quality habitat throughout the salmon life cycle, from freshwater streams along the entire migratory path into and back out of the Pacific Ocean. This habitat varies from freshwater to saltwater, from fast-moving, gravel-bottom streams to deep pools and deeper seas. We assume that this habitat is dynamic, responding to daily, seasonal, annual or longer life-cycle changes. We also assume that a diverse array of salmon populations and other occupants of this habitat have adapted over time to the majority of these natural changes. Under some circumstances, salmon in mainstem reaches and adjacent subbasins of the Columbia formed groups of interconnected populations, which we refer to as metapopulations.

Development of the Columbia River for hydropower, irrigation, navigation and other purposes has led to a reduction in both the quantity and quality of salmon habitat, and most critical, a disruption in the continuum of that habitat. Depleted salmon populations cannot rebuild if any habitat that is critical during any of their life stages is seriously compromised.

Consequently, we believe that the most promising way to help salmon populations rebuild is to reduce or remove conditions that limit the restoration of high-quality salmon habitat at each of their life history stages. Our intent in describing a normative ecosystem for salmon is to point out key characteristics that are critical to their survival and productivity. Our description is necessarily general. Specific prescriptions, such as flow regimes, levels of stock diversity, etc., will need to be developed through a process that includes policy development and trade-offs between the natural and cultural elements of the ecosystem. Our normative ecosystem is also dynamic. Conditions in the normative ecosystem will vary, progressing from the current state of the river toward historic conditions, based on the region's decisions and actions.

2. Productivity and the Network of Habitats

The Columbia River is a complex network of habitat types from the headwaters to the estuary. Populations of salmon, as well as other fauna and flora, are distributed throughout this network, thriving wherever there are sufficient resources to sustain their growth and reproduction. Some species are relatively localized, finding adequate resources within a narrow geographic range. These include resident fish. Others, such as anadromous salmon, require vast migrations and specific conditions at each "post" in those migrations, if they are to thrive.

The system of hydropower dams on the Columbia has greatly diminished the diversity of habitat once characteristic of this watershed. The dams severed the continuum of habitat, leaving very little riverine habitat left in the mainstem and isolating other types of habitat. Dams also altered flooding and draining patterns, which further reduced available habitat types and food webs in those habitats. Two key consequences of this loss of habitat diversity have been a reduction in the biodiversity of native salmon stocks and the proliferation of non-native species. Certain species have been able to adapt to conditions created by the dams, while others have not. For example, invertebrates, fish and plants that are not native to the Columbia have proliferated in the impounded river reaches rather than in free-flowing reaches, generally because impounded habitat is more homogeneous.

Normative river conditions are re-expressed at some distance downstream from dams – the further from the dam, the more habitat recovery occurs. This has been demonstrated on the Flathead and Clearwater rivers, for example. However, the mainstem dams on the Columbia and Snake rivers, for the most part, preclude such resetting of habitat conditions because water released from each dam pours directly into the reservoir behind the next downstream dam. The exception is the Hanford Reach on the mid-Columbia, the last free-flowing stretch of the river. The Hanford Reach provides a model of the productivity possible in river reaches that are not fully regulated by dams. It supports a healthy population of fall chinook capable of surviving downstream migration, harvest in the ocean and return upstream to spawn.

Our study has led us to the further conclusion that ocean conditions, which are variable, also are important in determining the overall productivity of salmon populations. Fluctuations in atmospheric and oceanic processes change the physical environment of the ocean, including food webs, water temperatures and other conditions.

Traditionally, fishery managers did not account for ocean conditions in their management decisions. This was largely for two reasons: they assumed the ocean environment and its food webs were substantially in equilibrium, and they recognized that it is impossible to control the climatic patterns and physical factors that influence ocean productivity.

While we agree that the ocean itself is uncontrollable, our management decisions in response to ocean conditions *can* be altered. What we need is a better understanding of and more attention paid to the linkages between freshwater and marine environments and the processes in the ocean that influence production of salmon. For example, conservation programs designed to address one set of ocean conditions may not be appropriate for another set. Furthermore, river-based management programs and dependence on hatcheries for production have led to a significant reduction in salmon diversity, potentially eliminating those salmon that have adapted to the greatest variety of ocean conditions.

3. Life History Diversity and Metapopulation Organization

In a natural river system, the availability of complex and connected habitats is a critical contributor to salmon productivity. These habitats, whether riverine, estuarine or oceanic, are dynamic. They change daily, annually and sometimes over decades. They change in response to cyclic events, such as the annual spring runoff, and to major non-cyclic events, such as volcanic eruptions, droughts or landslides. How effectively salmon populations survive these changes, or fail to survive them, is influenced by their life history characteristics.

Life history characteristics of salmonids include such traits as: age and size at juvenile migration; growth and maturity during migrations; spawning habitat preferences; migration patterns; and age and timing of spawning migration. These are the characteristics that enable salmon to survive and reproduce within the range of their interconnected habitats. But it is the diversity of habitats that is the template for this diversity of life history characteristics. Salmonids evolved over time in response to their diverse and ever-changing environment.

In the salmon ecosystem of the Columbia River Basin, the variety of habitat types was vast. The loss of much of the habitat and degradation of even more, as well as the loss of connectivity, have constrained salmonid production and reduced life history diversity.

In their 1996 review of the status of Pacific salmon, the National Research Council recommended that salmon be viewed as metapopulations rather than as isolated stocks. This application of metapopulation concepts to natural populations is still being debated among scientists, so our inclusion of the metapopulation structure as it applies to salmon should be viewed as a hypothesis that requires further study and confirmation.

Metapopulations are groups of local populations that are linked by individuals that stray among the populations. Metapopulations persist through the mechanism of straying. When local populations become extinct, they can be re-established through colonization by strays from neighboring local populations. We believe that metapopulation structure is likely in salmon because these fish display both a high degree of homing to their natal streams, which establishes the groups of local populations, and a variable level of straying, which provides the dispersal of genetic traits needed to successfully recolonize habitat vacated by lost populations.

Salmonid metapopulations appear to structure themselves into core and satellite groups. The core populations are generally large productive populations that occupy high-quality habitat. Such large, core populations tend to be less susceptible to extinction than are satellite populations, which have fewer numbers and may occupy lower-quality habitat. Core populations appear to be important as sources for re-colonizing habitat following extinction of local populations.

Studies indicate that the most abundant salmon spawning populations likely occurred in river segments with well-developed floodplains and gravel bars, where habitat complexity was high, including areas suitable to spawning, egg incubation and juvenile rearing. We conclude that salmon populations spawning in large alluvial mainstem reaches of the Columbia may have served as core populations and, as such, may have played critical roles in sustaining salmonid populations in the basin.

Loss of prime mainstem spawning habitat for core populations, and further losses from fragmentation, isolation and degradation of habitats in tributary systems, could have significantly reduced the long-term persistence and stability of regional salmon production. For example, most fall chinook that spawned in the mainstem Columbia and Snake rivers are now extinct.

One of the only surviving mainstem populations of fall chinook spawns in the Hanford Reach in the mid-Columbia. This is the largest naturally spawning population of chinook salmon above Bonneville Dam, and it has been stable during the years when salmon in other parts of the basin have undergone severe decline. It is possible that fall chinook in the Hanford Reach now function as a core population, which might serve as a source for colonization of adjacent habitats if normative conditions were restored in those areas.

Isolated populations of salmon are less likely to be recolonized should they be driven toward extinction because they may lack adjacent populations with similar genetic traits. For the same reason, surviving isolated populations also have less likelihood of successfully contributing to efforts to replenish declining populations elsewhere in the basin. As populations become isolated, local extinctions become permanent, and the entire metapopulation moves toward extinction. Therefore, we believe that restoring salmon populations in this basin will require both the restoration of more diverse habitat conditions and the reconnecting of habitats into the continuum necessary to support salmonids at every stage of their life histories. If this continuum can be restored, we believe that metapopulations will re-emerge to help stabilize regional salmon populations against environmental fluctuations.

REVIEW OF THE SCIENCE UNDERLYING THE FISH AND WILDLIFE PROGRAM

Using our proposed conceptual foundation as the template, we examined the scientific assumptions underlying the Council's Fish and Wildlife Program. However, while our conceptual foundation addresses the continuum of salmon habitat from freshwater streams, through the estuary and into the ocean, the Council's program is only required to address salmon habitat within the Columbia River Basin. Furthermore, while we looked at all causes of salmon decline and sought ways to reduce and reverse losses from all causes, the Council is mandated to respond only to hydropower-related losses. Consequently, the Fish and Wildlife Program addresses only a subset of the factors contained in our conceptual foundation, and we believe it is fundamentally limited in its effectiveness by these constraints.

Our approach to reviewing the scientific basis for the fish and wildlife program was to examine general principles and specific assumptions implied by the measures in the program and then assess the validity of those assumptions. We did not evaluate individual measures, but looked instead at the biological rationale for measures or groups of related measures. For example, the large number of program measures that relate to flow augmentation in the mainstem river suggests an assumption that flow rates, altered by the hydroelectric system, contributed to the decline in salmon populations. Once stated, that assumption can be analyzed scientifically, while the individual measures may be more difficult to analyze.

On the other hand, it is possible that individual measures or groups of measures may have solid scientific justification, but combined with other measures or strategies the outcome may be inadequate for recovery or inappropriate. In our analysis, we looked at the program, the process through which it is developed and the validity of assumptions reflected in it, based on existing scientific data.

Development of the Fish and Wildlife Program

The Northwest Power Act requires that the Columbia River Basin Fish and Wildlife Program be assembled from recommendations submitted to the Council by the region's fish and wildlife managers, including Indian tribes from the basin. The recommendations are proposed by these managers and other interested parties, reviewed by members of the public throughout the Northwest and adopted by the Council. The measures that are approved for inclusion in the program do not necessarily spring from or respond to a common understanding of the basin or its fish and wildlife resources. They are not necessarily based on a common conceptual foundation. In fact, as we noted above, there appears to be some conflict among implied conceptual foundations in the program.

We argue in Chapter 3 that there are three major problems with this approach to building a recovery program and incorporating new information as it is learned. First, the program becomes a "list" of measures, with advocates for various measures competing for recognition rather than working together to build the most cohesive and comprehensive effort. Second, measures are not prioritized based on overall goals or objectives. There are no overall schedules, nor is there an integrated means to monitor and evaluate measures. Third, the emphasis on individual measures immerses the Council and implementors in endless details rather than an attention to the broader picture.

Our recommendation is to incorporate an integrated approach with measures based on the conceptual foundation we propose in Chapter 2. Measures could then be evaluated against that framework. They could be judged on how they contribute to the protection, mitigation and enhancement of ecosystem characteristics that are consistent with the biological needs of salmon, while providing for environmentally responsible energy production.

In addition, we suggest that credible, scientific review is needed of projects proposed for funding. We have prepared guidelines for research proposals, for proposal review and for peer review of projects, which can help the Council design a peer review process for the program.

Adaptive Management in the Fish and Wildlife Program

The Council incorporated the concept of adaptive management in the Fish and Wildlife Program in 1987, as a means of moving forward with recovery actions while the region continued to debate questions of biology and hydrology. In our view, adaptive management has since been used to justify a variety of actions on the premise that they may provide new information. We contend that adaptive management is intended as a much more rigorous scientific approach. The term should only be used in reference to explicit management experiments that include hypotheses, test conditions and a detailed experimental design. The concept of adaptive management should not be used as justification for every action about which the outcome is uncertain.

Assessment of the Fish and Wildlife Program

In our review of the scientific basis of the fish and wildlife program, we assigned a qualitative rating that summarized our assessment of the scientific support for various assumptions. Our numeric rating ranked assumptions and principles based on what we deem the “level of proof.” A “level one” would apply to an assumption for which there is solid peer-reviewed empirical evidence. A “level two” would be backed by strong evidence, but not conclusive evidence. “Level three” assumptions have theoretical support with some evidence. “Level four” assumptions are speculative, with little empirical evidence to support them. Finally, “level five” assumptions are contradicted by good evidence to the contrary. Chapters 4 through 10 contain our analysis of the data we reviewed to establish these conclusions.

We first reviewed three general principles that appear in both the Council’s program and in the Northwest Power Act.

1. *The salmon bearing ecosystem in the Pacific Northwest and northeast Pacific Ocean has considerable excess carrying capacity.* Level of proof: four. This assumption leads to the further assumption that there is a simple relationship between the numbers of smolts and increasing overall productivity over the long term. What confounds this assumption is the complexity of both freshwater and marine conditions. Inriver, estuary and ocean environments fluctuate dramatically in response to both human-caused and environmental changes. These fluctuations influence the long-term carrying capacities of the available habitat. The key to resilience in a variable environment is not just the numbers of smolts nor the quantity of habitat. Given the dynamic nature of the environment, we conclude from our analysis that it is the diversity of both habitat and genetic traits that is critical to restoring Columbia Basin salmon, not the quantity alone.
2. *Abundance of salmon and steelhead in the Columbia River Basin has, to a significant degree, declined due to, and is presently limited by, human actions.* Level of proof: one. This assumption is irrefutable. Even accounting for natural variation in the environment, decline of most species has closely paralleled the development of the basin. Damage from early and ongoing development has removed substantial portions of the basin from access by salmon, altered remaining habitat, reduced the abundance of salmon and decreased the ability of surviving salmon populations to cope with natural environmental variations. Focusing only on hydropower impacts severely constrains the region's ability to reverse these trends.
3. *Ecosystem functions lost as a result of development of the Columbia River can be replaced by technological solutions to individual problems.* Level of proof: four. The best evidence against this assumption is the continuing decline of the basin's salmon populations. Despite decades of experiments with technological solutions and the expenditure of billions of dollars in recovery efforts, salmon populations remain depressed. While technology will continue to be a part of any restoration effort in the Columbia River, we recommend that the region move from a strategy of "fixing" ecosystem damage to one that places greater reliance on re-expression of the natural biological and physical processes of the Columbia River salmon-bearing ecosystem.

We also analyzed 29 specific assumptions contained in the Fish and Wildlife Program, assigned a numeric ranking to each, and provide in Chapter 3 a brief overview of the science supporting our ranking. In Chapters 4 through 10, we expand on this evidence.

GENERAL AND SPECIFIC CONCLUSIONS

As we noted above, restoration of Columbia River Basin salmon populations will require a new definition and understanding of the salmon ecosystem. Humans have transformed the Columbia River Basin from a thriving natural environment to a great hydroelectric, irrigation and transportation system, one that drives this region's economy. The human approach to salmon recovery has reflected these impressive technological accomplishments: hatcheries have attempted to replaced natural productivity, flow augmentation has attempted to replace the spring freshet, barge transportation has attempted to replace inriver migration, and so on. To reverse the decline of salmon populations, we believe the region must endorse a conceptual foundation for salmon recovery, such as the one we describe in Chapter 2, and base its efforts on that foundation.

The key to salmon productivity in the future will be the degree to which normative ecosystem conditions are re-introduced into the Columbia River Basin. To accomplish this return to normative conditions, we recommend the following:

1. Recognize explicitly that salmon in the Columbia Basin exist naturally as collections of locally adapted populations organized into aggregates of core and satellite populations known as metapopulations. To increase total productivity, management decisions should nurture life history and population diversity. That diversity will require protection for the remaining core populations, and restoration and reconnection of potential core habitats at strategic areas within the basin. The Hanford Reach, the last free-flowing stretch of the Columbia, could be a model for this management approach.
2. Protect and restore freshwater habitat for all life history stages, with a focus on key Columbia River and tributary reaches and lakes. This approach would include: restoration of the spring freshet to revitalize inriver habitats; stabilization of daily fluctuations in flows to allow food webs to persist in shallow-water habitats that are important juvenile rearing areas; provision of incentives for watershed planning that emphasizes riparian and upland land-use activities to enhance instream and lake habitats; and identification of food web compositions and other key conditions that are critical for migrating juveniles in key habitats. Wherever possible, reconnect restored tributary habitats to restored mainstem habitats, particularly where remnant core populations, such as the Hanford Reach fall chinook, exist.
3. Manage stocks with a more complete understanding of migratory behavior and the limitations that migratory behavior could place on river operations. From our review, we concluded that the Columbia and Snake rivers should not be treated merely as conduits through which young salmon passively migrate to the sea. On the contrary, we learned that the young fish have ecological requirements that must be met during their downstream migration through the

mainstem habitat. Fishery managers need to better understand these needs and manage accordingly.

4. Reduce sources of mortality throughout the salmonid ecosystem, including the ocean and the estuary, as well as the rivers and tributaries of the Columbia River Basin.
5. Current and future salmon recovery measures should correspond to the normative ecosystem concept and be evaluated for their effectiveness in meeting stated objectives. For example, an approach whose goal is a normative ecosystem would highlight restoration of life history diversity, rather than more technological approaches, such as transporting fish in barges or producing them in hatcheries. Hatcheries and transportation should only be used selectively and experimentally, and they should be monitored carefully. To deal with the uncertainties associated with the region's efforts, the FWP as a whole needs an integrated ecosystem monitoring and evaluation program.
6. Recognize that estuary and ocean dynamics are important regulators of the patterns of salmon productivity. While repairing conditions in the ocean is difficult, if not impossible, some management actions can be taken to improve the productivity of salmon in these environments. For example, managers can regulate harvests to maintain viable food chains, they can set sustainable escapement targets so sufficient numbers of spawning pairs are allowed to reach upriver habitats, and they can implement hatchery protocols that allow fish populations to respond to natural fluctuations in ocean productivity. The estuary can be improved and protected through pollution abatement, enhancement of riverine flows and restoration of wetland habitats within the estuary.
7. Re-evaluate the concept of salmon reserves as a means of protecting core populations and potential core population habitat. These core populations could enable reseeding of available healthy habitat, which in turn could rebuild salmon abundance and metapopulation structure throughout the Columbia Basin. The region should consider establishing a salmon reserve in the vicinity of the confluence of the Snake and Columbia rivers, including the Hanford Reach.

IMPLEMENTATION OF NORMATIVE CONDITIONS

We recognize that what we are proposing is an ecosystem recovery that, if we are successful, will be unmatched anywhere in the world. Uncertainties remain, but those uncertainties can be addressed through innovative research and adaptive management. We are convinced that restoring normative conditions at every stage of the salmon life cycle will give this region the opportunity to accomplish the goal of restoring salmon populations in this basin. Salmon are remarkably resilient and productive in healthy habitat. If the focus of our management actions returns to the river, so that natural processes and habitat are restored, the salmon also are likely to return to the river.

CHAPTER 1. INTRODUCTION

Purpose of the review

The Columbia River Basin Fish and Wildlife Program was developed by the Northwest Power Planning Council (hereafter NPPC or Council) as directed by Congress in the Pacific Northwest Electric Power Planning and Conservation Act of 1980. Congress charged the Council to develop a plan to "protect, mitigate and enhance" the fish and wildlife of the Columbia River as affected by development and operation of the Columbia River Basin hydroelectric system. In its latest revision of the Fish and Wildlife Program, FWP (Northwest Power Planning Council, 1994), the Council created the Independent Scientific Group and directed them to 1) develop a conceptual foundation for the Fish and Wildlife Program (section 5.0F), and 2) provide a biennial review of the scientific basis for the Fish and Wildlife Program (section 3.2B). This report responds by providing a conceptual foundation based on current ecological science and by evaluating the assumptions and beliefs embodied in the Fish and Wildlife Program in light of this scientific foundation.

Following this introduction that provides the background for our review, the report is organized into four sections:

1. An explicit, ecologically based conceptual foundation for the FWP (Chapter 2),
2. A review of the scientific basis for the assumptions and beliefs implied by measures in the FWP based on this conceptual foundation (Chapter 3),
3. A technical review and documentation supporting the conceptual foundation and the review of the FWP (Chapters 4-10).
4. Conclusions and implications of the overall review (Chapter 11).

History of the Fish and Wildlife Program

Congress directed the Council as its first act to prepare a fish and wildlife plan to address the loss of fish and wildlife in the Columbia River Basin resulting from the operation and development of the hydroelectric system. The first Fish and Wildlife Program was adopted in November, 1982, following an extensive public process to garner ideas and projects. The Council conducted similar processes to revise the program in 1984, 1987, 1992 (Strategy for Salmon), and most recently December of 1994. Unless otherwise specified, the focus of this review is the Fish and Wildlife Program of December 1994 (Northwest Power Planning Council, 1994). Our report constitutes the first scientific review of the Fish and Wildlife Program.

Each version of the Council's Fish and Wildlife Program (FWP) has described a wide variety of actions to be carried out by the Bonneville Power Administration, other federal agencies and the region's state and tribal fish and wildlife managers. These have focused on in-river returns and production of anadromous salmonids. The Fish and Wildlife Program emphasizes actions to increase survival of salmon and steelhead in the Lower Snake River (i.e., downstream from Hells Canyon Dam), the middle and lower reaches of the mainstem Columbia River (i.e., downstream from Chief Joseph Dam), and their tributaries. Actions implemented so far, include: modification of mainstem dam operations and facilities to improve bypass of adults and juveniles; coordination of river operations to provide enhanced spring flows; reduction of smolt predators; construction and operation of hatcheries, modification of existing artificial production operations, including supplementation of naturally reproducing populations; implementation of "best management practices" for land use activities; and a variety of research and monitoring objectives designed to answer critical questions. Similar measures have been implemented, but at a reduced scale, for resident salmonids and sturgeon in headwater tributaries (Northwest Power Planning Council, 1994). The Fish and Wildlife Program also counsels against new hydropower development on any anadromous fish stream or in stream reaches with a high value to resident fish or wildlife habitat.

Congress included the fish and wildlife provisions in the Act because it recognized the impact of hydroelectric development on salmon and steelhead in the Columbia River. By the time the hydroelectric system was completed in 1975 with the construction of Lower Granite Dam on the Snake River, salmon runs had declined considerably from their previous abundance. As the Act was being debated in Congress, the National Marine Fisheries Service began to analyze the status of Snake River chinook populations to determine if they warranted protection under the Endangered Species Act (ESA; 43 Fed. Reg. 45628 (1978)). Passage of the Act forestalled ESA listing determinations by NMFS for approximately a decade. However, declines resumed in the late 1980's and Snake River sockeye, spring, summer, and fall chinook were listed under the Endangered Species Act in the early 1990's. These listings, and the listing of Kootenai River white sturgeon in 1991, has added another layer of complexity and additional capital cost to the restoration effort in the Columbia River. Development of recovery plans for listed fish populations in the Columbia River are the responsibility of the National Marine Fisheries Service (NMFS). The Fish and Wildlife Program may constitute one of the most ambitious environmental restoration efforts ever undertaken worldwide (Lee and Lawrence, 1986).

As the river basin has been developed over the last 100 years or so, piecemeal technological approaches, such as artificial production, fish bypass, and transportation, among others, have been developed to substitute for losses in salmon production and habitat and to sustain harvest. Despite these efforts, populations of anadromous and resident salmonid species have declined markedly from their historical abundance and distribution. Prior to development in the basin, the Columbia River may have supported over 200 distinct anadromous stocks, which returned several million adult salmon and steelhead to the river annually (Northwest Power Planning Council, 1986; Nehlsen et al., 1991). All five native eastern Pacific salmon species and steelhead historically returned to the Columbia River, although chinook stocks dominated the runs. Today, most chum, pink, and wild coho stocks (with the possible exceptions of Hamilton Creek, Hardy Creek and Grays River chum stocks, and Hood, Clackamas, and Klickitat river coho stocks) are extinct and the other species are at risk of extinction. Nehlsen (1991) identified 69 extinct stocks and 75 others at risk of extinction in some areas of the basin. Only Lewis River (WA) and Hanford Reach (WA) fall chinook, Lake Wenatchee and Lake Osoyoos (WA) sockeye, and five summer steelhead stocks in the John Day River (OR) can be classified as healthy (Mullan et al., 1992; Huntington et al., 1996). Total returns of cultured and wild chinook and sockeye reached an all time low in 1995 (Figure 1.1). Likewise, resident salmonid populations, such as bull trout, also are increasingly isolated by habitat fragmentation and have been eliminated from many river segments. Many remaining populations are reduced in size and vulnerable to extinction. Evaluation of native salmonids in headwater reaches of the Columbia River shows that the distribution of healthy stocks are reduced to 10-30% of their original distribution, depending upon species (Behnke, 1992; Anderson et al., 1996; Lee et al., *In Press*).

Legal Objectives and Constraints

The Act was intended to restore salmon and steelhead as affected by hydroelectric development while ensuring an efficient, adequate, economical, and reliable power system. It placed specific objectives and constraints on development of the Council's Fish and Wildlife Program including:

1. The program should improve the survival of anadromous fish at dams.
2. It should provide adequate flows between dams to improve production, migration, and survival as needed to reach sound biological objectives.
3. Measures must complement the activities of federal and state fish and wildlife agencies, and appropriate Indian tribes.
4. The program should use the best available scientific information.
5. It must be consistent with the legal rights of appropriate treaty Indian tribes.
6. Where equally effective means of achieving the same sound biological objectives are available, the Program must use the least costly alternative.

The Fish and Wildlife Program was not intended to deal comprehensively with salmonid restoration in the basin, but was to address the effects of development and operation of the hydroelectric system. The Act also allowed the Council to seek off-site mitigation to compensate for hydroelectric losses. In other words, mitigation activities need not be confined to dam sites.

The Council is primarily a policy development body; it has no jurisdiction or regulatory authority over harvest, water rights, or land management in the basin. The Bonneville Power Administration (BPA) is obligated to fund actions in a manner consistent with the Council's program. The U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation and the Federal Energy Regulatory Commission must take the program into account "to the fullest extent practicable."

Goals of the Fish and Wildlife Program

The Council evaluated the historical abundance of salmon and steelhead in the basin and inferred the impact of operation and development of the hydroelectric system to derive general goals for the Fish and Wildlife Program (Northwest Power Planning Council, 1987). While the goals have been reworded and modified in subsequent versions, they remain essentially unchanged in the 1994 Fish and Wildlife Program. The goal is to increase (i.e., double) numbers of salmon and steelhead in the Columbia Basin, while preserving genetic and life history (phenotypic) diversity by reducing human-caused mortality at all life stages. We take this to mean that salmon and steelhead should increase without loss of species diversity or decreases in genetic and life history diversity within populations and species. The Fish and Wildlife Program emphasizes production in areas above Bonneville Dam where hydropower development has been most extensive.

Development of the Fish and Wildlife Program

The Act requires the Council to base Fish and Wildlife Program measures (actions) on recommendations submitted by the region's fish and wildlife managers, and Indian Tribes, and other regional parties. Consequently, the Fish and Wildlife Program is a collection of individual measures proposed by a diverse constituency. The measures were discussed in public before they were adopted by the Council. The measures, as a whole, do not necessarily reflect an explicit concept of the system. As a result, the Fish and Wildlife Program does not originate from a single *a priori* framework of assumptions and information about how the physical and biological components interact to form the salmon bearing ecosystem. We think this is a fundamental shortcoming and germane to this review. Sets of measures, however, such as for artificial propagation in hatcheries or for mainstem passage of smolts, do have underlying assumptions and concepts, although they are not clearly stated or integrated. We have attempted to identify these topical assumptions as a basis for our review (see Chapter 3).

Relationship to Other Plans and Reviews

Other insightful scientific syntheses of the salmonid fisheries problems in the Columbia River and adjacent region predate our effort, e.g., (Netboy, 1980; Ebel et al., 1989; Rhodes et al., 1994; Lichatowich et al., 1995). Also, at least six recent reviews (Table 1.1) provide detailed action plans or recommendations to reduce mortality and increase salmonid production, in addition to reviewing the status of the fisheries and the causes and consequences of declines. A main theme in these reviews, and our review, is that the downward trend in numbers (i.e., adult returns in anadromous species and population size in resident species) and stock diversity is due in large part to human actions occurring against a backdrop of natural environmental change (Figure 1.2). Agents of natural environmental changes are cyclic oceanic changes such as El Nino, floods, drought, predation, competition and disease. Examples of human-mediated environmental change is related to habitat degradation and loss, hatchery effects, harvest, and introductions of non-native biota. Effects of human mediated changes may be exacerbated by ineffective transfer of information among research scientists, managers, and policy makers.

Our report follows logically from other recent reviews and recovery plans (Table 1.1). It focuses primarily on the Columbia Basin ecosystem and the Council's Fish and Wildlife Program. Nevertheless, our report emphasizes many of the same factors and reaches many of the same conclusions as the recent NRC report, which examined the decline of Pacific salmon stocks at large. The NRC panel (National Research Council 1996) emphasized the importance of life history and genetic diversity of salmon populations and recommended management efforts be directed at the local population and metapopulation levels. The panel also focused on rehabilitation of the Columbia Basin salmon ecosystem through regeneration of natural processes, rather than through a primary reliance on substitution oriented technological solutions, such as hatcheries, transportation, or modification of stream channels.

Application of RETURN TO THE RIVER to Future Efforts

Throughout our review, RETURN TO THE RIVER, we attempt to identify ecological processes that require restoration, as opposed to identification of technological methods. We stress the need to restore the natural functions of the Columbia River ecosystem that produce salmonid fishes, as opposed to circumventing natural ecological processes. Salmonid populations, and other riverine biota, cannot recover in the absence of quality habitat for each life history stage. Despite decades of effort, the present condition of most populations in the Columbia River Basin demonstrates the failure of technological methods to substitute for lost ecosystem functions.

Normative conditions, which provide critical habitat functions in the natural-cultural landscape, must be restored, not mitigated. By conducting our review in the context of a conceptual foundation that focuses on ecosystem-scale habitat restoration, we hope we have provided a perspective for the salmon recovery effort in general, as well as a logical mechanism for evaluating the scientific efficacy of measures (and the implied assumptions) contained in the Fish and Wildlife Program.

Implementation

The ISG presented its preliminary findings to the Council and to the region's salmon managers on April 23, 1996 and May 9, 1996 respectively and solicited scientific and technical peer reviews of the draft document. Responses to the presentations and comments from some of the peer reviewers revealed a common concern: the need for specific prescriptions to implement the recommendations contained in our review. An implementation program containing specific recommendations would have to incorporate social and economic concerns in addition to a scientific basis for action. This is beyond the scope and role of this group and our charge to evaluate the science underlying the Council’s Fish and Wildlife Program. Although this is not an implementation document and the review is not intended to fill that role, concerns about implementation raise important questions concerning the application of RETURN TO THE RIVER in subsequent regional efforts to develop an ecosystem restoration program. These include:

1. What should the Council do with RETURN TO THE RIVER?

2. What strategic actions would be consistent with the conceptual foundation in RETURN TO THE RIVER?

3. What could the Council and the region expect of a program based on the RETURN TO THE RIVER?

What should the Council do with RETURN TO THE RIVER?

We believe that the conceptual foundation presented in RETURN TO THE RIVER (Chapter 2), is consistent with the objectives of the Northwest Power Act and the broad policies expressed in the Fish and Wildlife Program. Nevertheless, the conceptual foundation described in the next chapter is a departure from the overall approach to restoration that has characterized the region’s efforts to date and is embodied in the assumptions underlying the Council's program (see Chapters 2, 3 and 11).

We believe a failure to adopt an ecologically based conceptual foundation and to change the approach to salmon restoration in the basin will lead to more extinctions of salmon populations and little progress towards the rebuilding goal. Temporary increases in some populations may occur in response to fluctuations in ocean conditions, but the overall downward trend in returns that has occurred throughout this century will likely continue. We recommend that the Council accept Return to the River as a scientific basis for refocusing the region's efforts.

What strategic actions would be consistent with Return to the River?

As stated above, the development of specific prescriptions is beyond the scope of this study. Developing tactical steps to implement the recommendations in Return to the River is a separate project that should be undertaken after appropriate strategic steps are taken. The recommendations contained in Return to the River, in particular the movement towards a more normative river ecosystem involves policy decisions that include tradeoffs between salmon and important regional social and economic factors. As a first strategic step in implementing the recommendations contained in Return to the River, the Council should examine the implications of the normative ecosystem concept; in particular, what steps would move the Columbia River along the continuum from its current state to a more normative state (i. e., the restoration of natural ecological processes consistent with the needs of native fish and wildlife species). Steps ranging from watershed level restoration in subbasins, manipulation of mainstem flows, permanent drawdowns and dam removal should be evaluated in terms of the social and economic costs to the region. The potential social, economic and biological costs and benefits of implementing normative conditions should be determined and become part of the regional debate regarding salmon restoration.

What could the Council and the region expect of a program based on Return to the River ?

The normative river is not a static target; it is a continuum of conditions covering a broad range of values from slightly better than the current state of the river to conditions that closely approximate the pre-development state (Figure 1.3). Because the region lacks experience in the approach to restoration described in Return to the River, we cannot predict the exact relationship between increasingly normative conditions and salmon production. The relationship might be linear with salmon production increasing continuously in proportion to the movement towards normative conditions (Figure 1.3). It may be non-linear (logistic) with little or no increase in production until significant changes accumulate followed by rapid increases in production (Figure 1.3). We believe the more likely relationship will be characterized by a series of thresholds and plateaus (Figure 1.3). As the river moves towards more normative conditions little improvement may be observed until a threshold is reached causing an increase in production to a new level or plateau. The shape of the response of the ecosystem to restoration actions has important implications for scaling the region's expectations and the amount of effort required to elicit identifiable change (Figure 1.3).

The region does have experience with taking very small steps toward the normative conditions and tinkering around the edges of the existing system of natural resource use in the basin (see Box 1.1). Those small steps have produced no discernible progress towards the objectives of the Northwest Power Act, the Council's goals or the condition of populations listed under the Endangered Species Act. Because of this, it is reasonable to question the underlying rationale that has guided these efforts. It is becoming increasingly clear that more substantial changes, based on a scientifically derived rationale, must be taken. At the same time, our knowledge of how to restore key attributes of an ecological system of the scope and complexity of the Columbia River is imperfect and a rigorous program of evaluation, monitoring and research will be required. In the following chapters, we present a scientifically rigorous framework for making those major changes. A fish and wildlife program based on this conceptual foundation is unlikely to be socially painless or inexpensive nor is it likely to provide short-term gratification. Scientific uncertainties abound and unforeseen events will occur. However, we believe that an approach based on the principles described in following pages, combined with an implementation program governed by the principles of adaptive management, offers the best hope for preventing large scale extinction of salmon in the basin and making meaningful progress towards the Council's goals.

Box 1.1. In his review of the 1993 National Marine Fisheries Service Biological Opinion on Columbia River mainstem operations (the Biological Opinion is similar in scope and rationale to the mainstem actions in the Council's program). Judge Marsh concluded: "... the process is seriously, "significantly," flawed because it is too heavily geared towards a status quo that has allowed all forms of river activity to proceed in a deficit situation-- that is, relatively small steps, minor improvements and adjustments-- when the situation literally cries out for a major overhaul." Idaho Department of Fish and Game v. National Marine Fisheries Service, Civil No. 92-973-MA, slip opinion at p. 36 (D. Ore. 1994).

Table 1.1. Recent recovery or enhancement plans and other detailed analyses of scientific information pertaining to the decline of anadromous salmonid fishes of the Columbia River.

NAME	CITATION(S)	NOTES
USA v. OR & WA management plan	see Chapter 7	Federal, court-ordered plan to meet tribal treaty rights; emphasizes escapement and hatchery production
Inter-tribal plan for restoration	(Columbia River Inter-Tribal Fish Commission, 1995)	Evolved from USA v. OR & WA; emphasizes supplementation and habitat restoration
Chapman plan for Snake River chinook and sockeye	(Chapman et al. 1990; Chapman et al. 1991)	Analysis of status and causes of decline; emphasizes habitat restoration and supplementation
Fish and Wildlife Program	(Northwest Power Planning Council 1994)	Mandated by Congress; emphasizes hatchery production, transportation, flow augmentation and mitigation studies by agencies (see Chapter II)
Snake River salmon (NMFS) recovery program	(National Marine Fisheries Service 1995)	Mandated by Congress; emphasizes supplementation, transportation and flow augmentation

Botkin report	(Botkin et al., 1995)	Analysis of regional salmon status and causes for declines; emphasizes habitat degradation and overharvest as problems and provides generalized restoration mechanisms
National Research Council report (Upstream)	(National Research Council 1996)	Analysis of regional salmon decline by National Research Council of National Academy of Science; emphasizes habitat degradation, genetic problems associated with hatchery production, overharvest and institutional constraints as problems and provides generalized restoration mechanisms
East-Side Assessment Broad-Scale Assessment of Aquatic Species And Habitats	(Lee et al., *in press*)	Assessment of aquatic resources within the interior Columbia River basin ecosystem. Concludes that losses and degradation of habitat have severely reduced native fish diversity and abundance. Identifies strategies to manage and rehabilitate habitats and fish populations.

Literature Cited

Anderson, D.A., G. Christofferson, R. Beamesderfer, B. Woodard, M. Rowe and J. Hansen. 1996. StreamNet: Report on the Status of Salmon and Steelhead in the Columbia River Basin - 1995. Portland, Bonneville Power Administration. Oregon**:** 76.

Behnke, R.J. 1992. Native trout of western North America. Bethesda, Maryland, American Fisheries Society.

Ebel, W.J., C.D. Becker, J.W. Mullan and H.L. Raymond. 1989. The Columbia River: Toward a holistic understanding. Proceedings of the International Large River Symposium (LARS). D. P. Dodge, Special Publication of the Canadian Journal of Fisheries and Aquatic Sciences. 106**:** 205-219.

Huntington, C., W. Nehlsen and J. Bowers. 1996. A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California. Fisheries 21(3): 6-14.

Lee, D.C., J. Sedell, R. Thurow and J. Williams. *In Press*. Broadscale assessment of aquatic species and habitats *In* An assessment of ecosystem components in the Interior Columbia River Basin and portions of the Klamath and Great basins. Portland, OR, USDA Forest Service, Pacific NW Research Station.

Lee, K.N. and J. Lawrence. 1986. Adaptive management: learning from the Columbia River Basin fish and wildlife program. Environmental Law 16: 431-460.

Lichatowich, J., L. Mobrand, L. Lestelle and T. Vogel. 1995. An approach to the diagnosis and treatment of depleted Pacific salmon populations in Pacific Northwest watersheds. Fisheries 20(1): 10-18.

Mullan, J.W., A. Rockhold and C.R. Chrisman. 1992. Life histories and precocity of chinook salmon in the Mid-Columbia River. Progressive Fish-Culturist 54(1): 25-28.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Netboy, A. 1980. The Columbia River Salmon and Steelhead Trout: Their Fight for Survival. Seattle, University of Washington Press.

Northwest Power Planning Council. 1986. Council Staff Compilation of Information on Salmon and Steelhead Losses in the Columbia River Basin. Portland, Northwest Power Planning Council. Oregon.

Northwest Power Planning Council. 1987 Columbia River Basin Fish and Wildlife Program. Portland, Northwest Power Planning Council. Oregon**:** 246.

Northwest Power Planning Council. 1994. Columbia River Basin Fish and Wildlife Program. Portland. Oregon.

Rhodes, J.J., D.A. McCullough and J. F. A. Espinosa. 1994. A Coarse Screening Process for Evaluation of the Effects of Land Management Activities on Salmon Spawning and Rearing Habitat in ESA Consultations. Portland, Columbia River Inter-Tribal Fish Commission. Oregon.

CHAPTER 2. A CONCEPTUAL FOUNDATION FOR RESTORATION OF COLUMBIA RIVER SALMONIDS

"Conservation efforts must nurture the whole life history, not focus inordinate attention on elusive "bottlenecks" to production. I believe conservation efforts will fail if primary attention is not directed to providing the habitat opportunities that historically supported the stock in its natural state." (Healey 1994).

The ISG was directed by the Fish and Wildlife Program (Section 5.0F) to develop a conceptual foundation for restoration of Columbia River salmonids. Our approach was to treat the Columbia River as a natural and cultural system (Figure 2.1); that is, a regional ecosystem with boundaries logically defined by the life cycles of native salmonid fishes and including human land use and other cultural activities that characterize the basin. Restoration requires detailed understanding of the interactive, biophysical attributes and processes that control the survival of salmonids (e.g., Figure 2.2) rather than a simple accounting of numbers of fish at various points and times in the ecosystem. This approach is consistent with Council's policy to support native species in native habitats (Section 2.2A of the FWP), but it also identifies problems with the Council's approach to restoration.

In the development of a conceptual foundation, we attempted to be responsive to the directives, explicit or implied, in the FWP; however, we did not try to fashion a conceptual foundation that justified the existing measures of the FWP. Rather, we attempted to build a framework based on established ecological principles that would be consistent with the available data explaining the decline of salmonid fishes and their habitats in the ecosystem. Stanford et al. (*in press*) recently proposed a general protocol for restoration of large rivers regulated by dams and diversions. This paper, which in part grew out of our review, summarizes the influences of dams on river ecosystem processes and biota and is a key supporting document for our conceptual foundation for the restoration of Columbia River salmonids.

What is a Conceptual Foundation?

A conceptual foundation is a set of scientific principles and assumptions that can give direction to management activities, including restoration programs, such as the FWP. A conceptual foundation determines how information is interpreted, determines what problems (e.g., limitations on fish production) are identified, and as a result, establishes the range of appropriate solutions (Lichatowich et al., 1996). Because it influences the interpretation of information, the conceptual foundation can be a powerful scientific element of management and restoration plans and it can determine the success or failure of those plans. Natural resource management carried out with the best intentions and methodological expertise can have disastrous consequences if based on incorrect assumptions (Cronon, 1995). The importance of a conceptual foundation and the problems created by the failure to explicitly define it extends beyond natural resource management. Heilbroner and Milberg (1995) attributed chaos in economic analysis for the last several decades to the lack of a central vision, or in our terminology, a conceptual foundation.

To illustrate the importance of a conceptual foundation, think of it as analogous to the picture that comes with a jigsaw puzzle. Each piece of the puzzle is a small data set containing useable information; but interpreting the relevance of that information is difficult or even impossible without referring to the picture. Salmon managers generate and review many data sets and large volumes of information. They look at many pieces to the puzzle of salmon management and ecosystem restoration. However in fisheries management, watersheds or ecosystems do not come with a picture clearly illustrating the functional ecological processes that lead to production of desirable fishes. Consequently, to interpret the relevance of those data sets, the picture (conceptual foundation) must be developed by scientists and managers from the best available, scientific principles and assumptions. If the conceptual foundation underlying a program such as the Fish and Wildlife program is erroneous, it is equivalent to an attempt to complete a jigsaw puzzle using the wrong picture as a guide. Conceptual foundations should not be static, but should be revised continually as new theory emerges and new empirical information becomes available.

The power of the conceptual foundation to determine how information is interpreted, even to draw the wrong conclusion from otherwise sound data, is illustrated through the following example. Around the turn of the century, biologists working with Pacific salmon were debating the "home stream theory". Some held that adult salmon had the ability to home back to the stream of their birth to spawn. Other biologists, including the eminent ichthyologist David Starr Jordan, rejected the home stream theory (Jordan, 1904). In Jordan's conceptual foundation, the salmon's ecosystem did not extend much beyond the mouth of the natal river. He assumed that juvenile salmon migrated no more than 20 to 40 miles from the mouth of their natal stream. When the salmon reached maturity, they simply swam into the first river they came to, which, because they never migrated far from it in the first place, was almost always their home stream.

In 1896, juvenile salmon from the Clackamas hatchery were fin-clipped for later identification and released into the river. Four years later, some of the tagged fish returned to the Columbia River. Instead of interpreting the recovery of tagged salmon in the Columbia River as evidence of homing, Jordan interpreted it as support for his assumption that the salmon did not migrate far from the mouth of their natal stream. Jordan's conceptual foundation contained at least one erroneous assumption, which caused him to misinterpret otherwise sound information.

The debate over the “home stream theory” was not an academic exercise. Whether or not salmon homed to their natal stream had important implications for salmon management, particularly the transfer of stocks between rivers through the hatchery program. By today's standards, Jordan derived his conceptual foundation from limited ecological data and from a rudimentary body of ecological theory. Nonetheless, his conceptual foundation was insufficient to allow new information to be correctly interpreted. A robust conceptual foundation is derived from thorough analysis of the problem (i.e., breaking the problem into its components and their corollaries) and synthesis of available information (formalizing what is known).

Does the Fish and Wildlife Program have a Conceptual Foundation?

Unfortunately, salmon management and restoration plans rarely contain an explicitly described conceptual foundation. The Fish and Wildlife Program is no exception. However, it would be incorrect to conclude that a conceptual foundation is not implicit in the FWP. In fact, the Fish and Wildlife Program probably has been derived from more than one conceptual foundation. Each agency, institution, or interest group that proposed measures adopted by the Council derived those measures from a conceptual foundation, sometimes from different conceptual foundations. Thus, the existing suite of measures in the Fish and Wildlife Program probably was derived from conceptual foundations some of which may be contradictory or inconsistent with each other and possibly with current knowledge. Because those conceptual foundations were not stated, the Council, scientists, and the public cannot review or evaluate them. The current PATH (Plan for Analyzing and Testing Hypotheses) process is an exception. PATH is an iterative process for defining and testing a logical framework of hypotheses related to the Columbia River anadromous salmon bearing ecosystem (Marmorek and Parnell, 1995). In our view, PATH is attempting to explicitly define the conceptual foundation (logical framework) for several of the models used in the management of the Columbia River. The logical framework being developed by PATH has a narrower scope and purpose than the conceptual foundation described here. PATH and our review have taken very different approaches to the development of a conceptual foundation. PATH focuses on ESA listed stocks of anadromous salmonids, whereas, our review has focused on the total ecosystem and a wider array of species, stocks and life history types.

In our review of the Fish and Wildlife Program, we identified several assumptions that are implied in the program or generally form the basis of salmon management in the basin (see review of FWP in Chapter 3). We have equated those assumptions to the Fish and Wildlife Program’s implied conceptual foundation. Because our assessment of the conceptual foundation in the FWP is derived from implied, rather than stated assumptions, it is necessarily global, rather than specific.

Management of the Columbia River and its salmonid populations has been based on the belief that the natural ecological processes that characterize a healthy salmonid production system to a large degree can be circumvented, or the natural production process simplified and controlled by humans, while maintaining or even enhancing production (Lichatowich et al., 1996).. Within the overall context of a belief in simplification, circumvention, and control, the Independent Scientific Group identified three global assumptions implicit in the Fish and Wildlife Program (Whitney et al., 1993, see Box 1).

Box 1. Global assumptions implicit in the Fish and Wildlife Program. as inferred by the Independent Scientific Group (Whitney et al., 1993).

1. The number of adults recruited is primarily a simple, positive response to the number of smolts produced (i.e., it is assumed that human-induced losses of the natural production capacity can be mitigated by actions to increase the number of smolts, for example through the use of passage technology, barging, and hatcheries.

2. Salmon and steelhead production can be increased by focusing management primarily on in-river components of the Columbia River (estuary and ocean conditions are ignored because they are largely uncontrollable).

3. Management actions will not compromise environmental attributes which form the basis for production of salmonids.

The Independent Scientific Group (Whitney et al., 1993) concluded that these assumptions and the Fish and Wildlife Program’s implied conceptual foundation drive management toward solutions, which attempt to use technologies as substitutes for ecosystem functions. The current approach is exemplified by the use of hatcheries and the passage of juvenile and adult salmonids through the hydroelectric projects. Survival of salmon migrating past dams is an important problem that deserves attention, but passage must be considered in the context of the salmon's entire life history and its ecosystem. Much of the work on passage is focused on achieving marginal improvements in the established technology of passage (reviewed in Chapter 7) for a limited number of life history types, while ignoring the broader context of salmonid life history, behavior, and habitat. Aquaculture technology has been an essential component of salmon recovery, however, its contribution has been minimized because it was not applied within the context of a normative ecosystem. In view of the continuing decline in salmon, it should be obvious that the current conceptual foundation, its implied underlying assumptions, and the implementation of measures derived from the current implied conceptual foundation, have failed to meet the Fish and Wildlife Program goals and lead to the recovery of salmonids throughout the Columbia River. The conceptual foundation that we propose and describe herein contains departures from some of the assumptions that have driven salmon management and restoration in the Columbia River basin for the past several decades, although it retains and extends some fundamentally sound assumptions. In sum, it incorporates fundamental ecological principles and some newly emerging theory.

An Alternative Conceptual Foundation

Synopsis of Fundamental Assumptions and Principles

The critical elements of our conceptual foundation were derived from a synthesis of riverine ecological theory (Stanford et al., *in press*) in the context of habitat diversity (Frissell et al., In press; In press), life history diversity (Thorpe, 1994; Healey and Prince, 1995), and declining trends in abundance of Columbia River salmon (Nehlsen et al., 1991; National Research Council, 1996). The critical elements are given below and described in detail in sections that follow.

Box 2. An alternative conceptual foundation developed by the Independent Scientific Group

1. Restoration of Columbia River salmonids must address the entire natural and cultural ecosystem, which encompasses the continuum of freshwater, estuarine, and ocean habitats where salmonid fishes complete their life histories. This consideration includes human developments, as well as natural habitats.

2. Sustained salmonid productivity requires a network of complex and interconnected habitats, which are created, altered and maintained by natural physical processes in freshwater, the estuary and the ocean. These diverse and high-quality habitats, which have been extensively degraded by human activities, are crucial for salmonid spawning, rearing, migration, maintenance of food webs and predator avoidance. Ocean conditions, which are variable, are important in determining the overall patterns of productivity of salmon populations.

3. Life history diversity, genetic diversity and metapopulation organization are ways salmonids adapt to their complex and connected habitats. These factors contribute to the ability of salmonids to cope with environmental variation that is typical of freshwater and marine environments.

The Conceptual Basis for Restoration

1. Restoration of Columbia River salmonids must address the entire natural and cultural ecosystem, which encompasses the continuum of freshwater, estuarine, and ocean habitats where salmonid fishes complete their life histories. This consideration includes human developments, as well as natural habitats.

A natural-cultural ecosystem encompasses all the ecological and social processes that link organisms, including humans, with their environments (Figure 2.1). The natural-cultural system supporting Columbia River salmonids extends from headwater tributaries into the northeast Pacific Ocean and includes upland regions and riparian corridors, as well as surface and subsurface flow pathways and processes. The salmon bearing ecosystem is characterized by processes that create and maintain a wide array of habitats in which fishes grow and reproduce.

Complex habitats with a high degree of spatial and temporal connectivity permit the development and expression of life history diversity, which is an essential component of salmonid productive capacity. In a life history context, salmonid restoration implies re-establishment of life history diversity, which requires relaxing or removing the constraints on diversity (Figure 2.3). Depleted populations of native salmonids cannot be expected to rebuild if any of the habitats required for successful completion of all life stages are seriously compromised by human activities.

The current approach to restoration in the Fish and Wildlife Program tends to focus on a small subset of habitats or life history types, abstracting them from the whole and ignoring the interaction among elements of the ecosystem and life histories. The search for a simple relation between river flows and survival of salmon is an example. The juvenile salmon are treated as physical objects moving passively with the current rather than as living organisms interacting with their habitat (reviewed in Chapter 6). For example, life history diversity in relation to mainstem migration is ignored and the effects of flow manipulation on the estuary and its capacity to support salmon are not considered.

The Normative Ecosystem

We believe an ecosystem with a mix of natural and cultural features that typifies modern society can still sustain all life stages of a diverse suite of salmonid populations. We call this ecosystem "normative". Normative is the functional norm which ensures that we provide the essential ecological conditions and processes necessary to maintain diverse and productive salmonid populations. We emphasize that our description of the normative ecosystem is necessarily general and focuses on biological and physical processes and conditions characterizing the normative ecosystem. The normative ecosystem is not a static target or a single unique state of the river. It is a continuum of conditions from slightly better than the current state of the river at one end of the continuum to nearly pristine at the other end. The region through its policy representatives will have to decide based on its economic, cultural, and ecological values how far it will move the river along the normative continuum (Figure 2.4). Specific prescriptions, such as flow regimes, levels of stock and life history diversity, etc., will need to be developed to meet the normative ecosystem concept. We recognize that, because we are dealing with an ecosystem that has sustained extensive human development for over 150 years, numerous social and biophysical constraints exist for enhancing normative conditions. The challenge before the region is to reach consensus on the extent to which these constraints can be relaxed or removed to achieve Fish and Wildlife Program goals. Nevertheless, we believe strongly that approaching more normative ecosystem conditions is the only way in which Fish and Wildlife Program goals for recovery of salmonids and other fishes can be met. Progress toward the restoration goal would require moving the system from the current, degraded state toward normative conditions with regard to the most critical attributes for salmonids

The River Continuum

2. Sustained salmonid productivity requires a network of complex and interconnected habitats, which are created, altered and maintained by natural physical processes in freshwater, the estuary and the ocean. These diverse and high-quality habitats, which have been extensively degraded by human activities, are crucial for salmonid spawning, rearing, migration, maintenance of food webs and predator avoidance. Ocean conditions, which are variable, are important in determining the overall patterns of productivity of salmon populations.

The Columbia River, like all large gravel bed rivers is a complex, dynamic gradient of habitat types from the headwaters to the estuary. Salmonids and all other riverine flora and fauna are distributed rather predictably along that gradient according to the requirements of each stage in their life cycle (Vannote et al., 1980). Each species or unique life history type will be present wherever there are enough resources to sustain growth and reproduction and thereby sustain the presence of the population in the river food web at that location (Hall et al., 1992). Some species can be maintained without much movement and suites of organisms appear to occur in zones along the river continuum. Other species must move long distances in search of resources needed for each life stage, sometimes involving migrations into lakes (e.g., adfluvial bull trout and cutthroat trout), the ocean (e.g., chinook salmon, coho salmon, chum salmon, and steelhead trout) or both (e.g., sockeye salmon).

Like all river ecosystems, the Columbia River has three important spatial dimensions (Figure 2.5) (Ward, 1989): 1) Riverine - a longitudinal continuum of runs, riffles and pools of varying geometry from headwaters to mouth; 2) Riparian - a lateral array of habitats from the middle of the main channel through various side and flood channels and wetlands to flood plains and the uplands of the valley wall, including streamside vegetation and associated faunal assemblages; and 3) Hyporheic - a latticework of underground (hypogean) habitats associated with the flow of river water through the alluvium (bed sediments) of the channel and flood plains. These three interconnected habitat dimensions are constantly being reconfigured by physical (e.g., flooding) and biological processes (e.g., salmon digging redds; beavers damming small streams and side channels on flood plains of larger rivers). Critical habitats for the various life stages of salmonids exist in all three dimensions.

Channel morphologies are determined by bedrock geometry and geology and by the legacy of flooding which mediates the process of cut and fill alluviation. Big floods fill channels with inorganic and organic materials eroded laterally and vertically from areas upstream, thereby producing a continuum of instream structures (pools, runs, riffles, gravel bars, avulsion channels, islands, debris jams) and lateral floodplain terraces in many sizes and shapes. Much of the Columbia River and its tributaries within the Columbia Plateau are constrained by ancient basalts (lava rock) and flood plains are not expansive. In other areas of the basin, rivers have deeply bedded and expansive flood plains interspersed between canyon reaches. Channels with a greater sediment supply and frequent overbank flooding are constantly shifting, braiding or meandering on the valley bottom from year to year as the channel fills with material in one place causing the flow pathway to erode new channels into the flood plain.

Flow of river water through interstitial pathways in gravel bars and floodplain alluvium and back to the surface is an especially important habitat forming process that may be overlooked with respect to salmonid ecology (Gibert et al., 1994). Salmonids select upwelling (water flowing upward through the gravel toward the gravel surface) and sometimes downwelling sites for spawning because their eggs are naturally aerated in those places. Nutrients increase along interstitial flow pathways and stimulate production of food for larvae and juvenile salmon in upwelling zones. The river temperatures are moderated by interstitial flow. Relative to surface temperatures, ground water from the hyporheic zone is cool in the summer and warm in the winter. Regional patterns of hyporheic flow appear to be critical to rivers of the high desert of the Columbia Plateau (e.g., Grande Ronde, John Day, Yakima), where late summer instream temperatures may be too high for salmonids (Li et al., 1995; Li et al., 1995). The upwelling zones provide cool refugia for salmonids on hot summer days and enhances winter growth by keeping the water warm and some habitats ice free. Upwelling ground water also mediates establishment of riparian plants. Leaves and wood debris eroded from the riparian zone into the channel energize the riverine food web, provide cover for fishes, and cause localized cut and fill alluviation that provides additional habitat complexity.

The importance of a complex and dynamic continuum of habitats in the Columbia River is a central tenet of our conceptual foundation. We believe that the floodplain reaches and gravel-cobble bedded mainstem segments (e.g., Hanford Reach) are especially important because habitat diversity and complexity is greatest in those locations. Alluvial reaches are arrayed along the stream continuum between canyon segments like beads on a string and appear to function as centers of biophysical organization within the river continuum (Regier et al., 1989). They are likely to be nodes of production and biological diversity that are structurally and functionally linked by the river corridor (Copp, 1989; Gregory et al., 1991; Zwick, 1992; Stanford and Ward, 1993; Ward and Stanford, 1995; Ward and Stanford, 1995). Worldwide, intermountain and piedmont valley floodplains like the Hanford Reach of the Columbia River are characterized by nutrient rich floodplain soils and diverse and productive backwater and mainstem fisheries (Welcomme, 1979; Davies and Walker, 1986; Lowe-McConnell, 1987; Sparks et al., 1990; Junk and Piedade, 1994; Welcomme, 1995). Not surprisingly, these areas are frequently centers of human activities within the watershed (Amoros et al., 1987; Petts et al., 1989; Wissmar et al., 1994).

The River Discontinuum: the Ecology of the Regulated River

At least three fundamental principles emerge from the large literature on the ecology of regulated rivers (Stanford et al. *in press*). These principles are particularly germane to derivation of restoration strategies for Columbia River salmonids.

<u>1. Habitat diversity is substantially reduced as a consequence of regulation</u>

The dams of the Columbia River have inundated many of the piedmont and mountain valley floodplains, thereby severing the river continuum. Mass transport dynamics that create instream and floodplain habitats for riverine biota in remaining free flowing reaches have been drastically altered. Flood peaks have been eliminated, daily discharges are more variable, and temperature seasonality has been altered.

As a consequence of reservoir storage of peak flows for flood control, navigation, irrigation, and hydropower production, base flows have increased substantially and in many places fluctuate so erratically that aquatic biota cannot survive in shallow, near-shore habitats. Persistent shallow or slack water habitats are especially important for survival of early life history stages of fishes that cannot survive in the strong currents of the channel thalweg. Storage of bedload in the reservoir and constant clear-water flushing downstream artificially has depleted gravel and finer sediments in the tailwaters causing armoring of the bed with large cobble and boulder substratum. Channel constrictions and habitat simplification is nearly universal, except in headwater areas. Vegetation has clogged backwaters owing to loss of scouring flood flow. Riparian communities have been altered by deforestation and agricultural activities which interact with effects of regulation to reduce habitat heterogeneity (all of these impacts are reviewed in detail in Chapter 5 of this report).

The general conclusion is that regulation has created a discontinuum of environmental conditions and severed the connectivity of channel, groundwater, floodplain, and upland components of the catchment ecosystem. Habitats for riverine biota have become spatially homogeneous, limited to the permanently wetted portion of the channel thalweg that is dominated by conditions dictated by operations of upstream storage reservoirs. Indeed, serial construction of low-head dams has converted virtually the entire mainstems of the lower Snake and Columbia Rivers into shallow reservoir habitat that is neither truly laucustrine nor riverine.

2. Native biodiversity decreases and non-native species proliferate as a consequence of regulation

Native biodiversity has decreased substantially in the last 120 years (Behnke, 1992; Huntington et al., 1996). Most salmon populations spawning in the mainstem Columbia and Snake Rivers have been extirpated. In the headwaters of tributaries, salmon populations have become increasingly isolated by flow regulation, diversion and habitat degradation especially in the lower reaches. Moreover for anadromous species, mortality resulting from passage through dams and reservoirs in the mainstem may not affect all species and life histories equally, selecting against certain life history types, thereby reducing biodiversity, increasing habitat fragmentation, and increasing the vulnerability of populations to extinction.

Altered temperature patterns and continual export of very fine organic matter and dissolved nutrients, coupled with simplification of the channel, stabilization of bottom substratum, and loss of floodplain inundation, has promoted environmental conditions to which native species are maladapted (see Table 5.1 in Chapter 5 listing native and exotic fish species in the Columbia River Basin). This has created opportunities for nonnative plants and animals to establish robust populations. In some cases, one or a few native species are more abundant than they were before regulation (Poe et al., 1991). Non-native invertebrates, fishes, and plants are consistently more abundant in regulated river reaches compared to unregulated reaches (Li et al., 1987). Reasons for non-native proliferation vary, but in general non-native species are often better competitors in the homogeneous habitats of regulated river reaches. A wide array of non-natives have been introduced into the Columbia River system.

3. Normative conditions are re-expressed predictably in relation to influences of tributaries and as distance downstream from the dam increases

The Serial Discontinuity Concept (SDC) (Ward and Stanford, 1983; Ward and Stanford, 1995) predicts that the conditions described above that are attributable to flow regulation will ameliorate in river reaches downstream of storage reservoirs, as a natural consequence of the biophysical energetics of rivers. The distance downstream of the dam needed to reset normative conditions is related to the limnological attributes (depth, volume, water retention time, trophic state) of the reservoir, the mechanics of water release (surface, bottom or depth-selective), the mode of dam operations, and the influence of tributaries entering downstream from the dam. If the tributaries are large and unregulated, they may substantially accelerate the reset (Stanford and

Hauer, 1992). In any case given enough distance, conditions at some point downstream from the dam will closely approximate original conditions.

Reset towards natural conditions has been demonstrated in Columbia River tributaries downstream of storage reservoirs, e.g., Flathead River (Hauer and Stanford, 1982; Stanford et al., 1988); Kootenai River (Perry, 1986); and Clearwater River (Munn and Brusven, 1991). For the lower Snake and Columbia Rivers, however, little reset of riverine conditions can be expected, because almost no river environments remains due to nearly continuous impoundment. The free flowing Hanford Reach is the single exception in the mainstem.

The Marine Environment

The Pacific Ocean and atmosphere do not move towards a steady state condition but continually shift in response to changes in the global heat budget. Responses on the local scale to remote atmospheric and oceanic disturbances suggest that the Pacific basin is an interconnected oceanic ecosystem. Fluctuations in atmospheric and oceanic processes change the physical environment and the composition of assemblages of marine biota and act in effect to reset ecological conditions on local and regional scales. Local salmon populations may encounter a different set of conditions each year they enter the coastal ocean. The new conditions may be sufficient to qualitatively change the relationship between a species and regularly occurring environmental phenomena, such as coastal upwelling. For example, a reset in the ecological and physical processes might explain why production of coho salmon was positively correlated to upwelling in the 1960s and 1970s and negatively correlated to upwelling during the past decade (see Chapter 10 for a detailed discussion of ocean processes).

Historically, salmon managers treated the ocean as a constant in the development of management and restoration plans, as well as in the population models they used to set escapement and harvest levels. The models and programs assumed that oceanic habitats and biotic communities existed in stable equilibrium. Salmon managers ignored the ocean because it is impossible to control the climatic patterns and physical factors that influence ocean productivity. Although we cannot control oceanic processes, it is possible to control and regulate our behavior and adjust management practices in response to changes in the ocean. In that sense the ocean is not beyond our capacity to act, but appropriate action will require better understanding of the linkages between freshwater and oceanic environments and of the biophysical processes in the ocean that influence marine production of salmon.

Changes in the northeast Pacific ocean that dramatically alter both freshwater and marine conditions for salmon call into question management programs that emphasize constancy of the natural environment. Conservation programs designed under one climatic regime may not be appropriate under another. An ocean that is variable requires life history and genetic diversity in the anadromous species to successfully respond to a wide variety of potential environmental conditions. A highly controlled river and widespread use of artificial propagation has reduced diversity and the flexibility of salmon and steelhead and made them more vulnerable to collapse when ocean conditions change. The performance of salmon in the estuary and ocean is not independent of management programs in freshwater. Management programs that reduce variability in freshwater may unwittingly eliminate behaviors that buffer salmon production in unstable marine environments.

Salmonid Life Histories and Habitat

3. Life history diversity, genetic diversity and metapopulation organization are ways salmonids adapt to their complex and connected habitats. These factors contribute to the ability of salmonid to cope with environmental variation that is typical of freshwater and marine environments.

Availability of complex and connected habitat facilitates the expression of salmonid life history diversity and productivity in a watershed (Figure 2.3). Aquatic habitats are dynamic. They change in response to fluctuations in the environment on daily, annual or decadal cycles and in response to major disturbances such as record floods and droughts, volcanic eruptions, landslides, and other geomorphic processes. Variability is not limited to freshwater habitat. Ocean conditions favorable for salmon growth and survival vary on cycles that are both long (decades or more) and short (El Nino events of one to a few years) in duration. Salmonid populations increase or decrease in response to natural environmental changes, and during extreme changes, when constraints are strongest, individual populations in marginal habitats may be extirpated (Figure 2.3). However, the effects of natural disturbances moderate over time, habitat quantity and quality are gradually restored, and habitats where local extinction has occurred are recolonized by salmonids from neighboring populations

W. F. Thompson (1959) visualized the salmon’s habitat as “a chain of favorable environments connected within a definite season in time and place, in such a way as to provide maximum survival”. Salmonids following some habitat chains exhibit high survival while other chains may lead to extinction from time to time, in response to the natural changes in habitat We interpret Thompson’s chain of interconnected habitats as temporal and spatial “pathways” through the entire ecosystem (freshwater, estuarine and marine). Salmonids following a particular chain of habitats --a particular pathway-- exhibit a unique life history pattern. A life history pattern is the salmonid's solution to problems of survival and reproduction in that chain of habitats.

Life histories are comprised of demographic or phenotypic traits such as age at maturity, mortality schedules, size, and growth (Stearns, 1976). Salmonid life history traits also include: a) the age and size that juveniles migrate within the river system, into lakes or to the sea; b) growth and maturity during riverine and laucustran migrations; c) spawning habitat preferences; d) emigration patterns and; e) age and timing of spawning migration. All of these traits help salmonids survive and reproduce within the spatial and temporal boundaries of a chain of interconnected habitats

The complex, integrated set of phenotypic traits that comprise a salmonid's life history pattern results from interaction of an individual's genotype and its environment (Healey and Prince, 1995). An important element of the environment is the "pathway" of habitats that the individual follows from birth to death. Life history diversity, which is characteristic of salmonids in general (Groot and Margolis, 1991; Rieman and McIntyre, 1993), arises when individuals follow different habitat "pathways" and consequently manifest different sets of phenotypic traits. Healey and Prince (1995) argue that the population and its habitat are the basic unit of conservation. They summarize a fundamental premise of the normative river concept:

> *"Maintaining a rich diversity of Pacific salmon genotypes and phenotypes depends on maintaining habitat diversity and on maintaining the opportunity for the species to take advantage of that diversity."*

Thus, spatial and temporal habitat diversity are critical for expression of life history diversity. Multiple life histories in relation to habitat structure have been observed in several populations of anadromous salmonids (Reimers, 1973; Schluchter and Lichatowich, 1977; Carl and Healey, 1984; Gharrett and Smoker, 1993; Lestelle and Gilbertson, 1993). In the salmon bearing ecosystem of the Columbia River, life history diversity should be substantial owing to the ecosystem's large size, its complex riverine physiography and geomorphology, highly variable flow regime, and complex oceanic circulation pattern. Enhancing normative conditions and increasing salmonid production requires restoration of habitat diversity which will enable reexpression of life history diversity (Figure 2.3).

Salmonids following different chains of interconnected habitats may exhibit variation in important life history traits. For example in chinook salmon, phenotypic diversity is exhibited over a broad geographic scale in the stream and ocean life history types (Healey and Prince, 1995). Stream type chinook salmon migrate to sea in the spring of their second year in freshwater, whereas ocean type chinook migrate to sea in their first year, usually within a few months after emerging from the gravel (Healey, 1991). Stream and ocean type fish also differ in other aspects of their life histories, such as oceanic distribution and timing of adult migration (Healey, 1991).

Stream and ocean life histories are major life history themes, but variation in juvenile migration patterns occurs within each theme. Continual downstream migration through the lower mainstem of rivers by ocean type chinook salmon throughout most of the spring, summer and fall (Rich, 1920; Beauchamp et al., 1983; Nicholas and Hankin, 1988) may represent several discrete migrations of juveniles from different locations in the watershed (Rich, 1920). What appears to be a single continuous migration of ocean type juvenile chinook salmon may be a diverse assemblage of groups of salmon following somewhat different habitat pathways or life histories. Stream type juvenile chinook salmon that migrate to sea in their second year also exhibit variation in their migration pattern. Some stream type chinook salmon remain in headwater areas to rear, while others move into the mainstem to rear in large pools over winter (Healey, 1991). In the Columbia Basin, this pattern has been observed in the Yakima River (Confederated Tribes Yakima Indian Nation (CTYIN) et al., 1990), Grande Ronde River**,** Deschutes River (Ratliff, 1981; Lindsay et al., 1986) and the Lemhi River (Keifer et al., 1993).

Habitat degradation and the loss of connectivity among habitats constrains production and the expression of life history diversity (Watson, 1992; Lichatowich and Mobrand, 1995) (Figure 2.3). Within the Columbia River watershed, the decline of ocean type life history has been an important contributor to the overall decline in production of chinook salmon (Lichatowich and Mobrand, 1995). In sampling conducted in the lower Columbia River from 1914 to 1916, Rich (1920) observed a migration of ocean type chinook salmon throughout most months of the year. He attributed this to the sequential migration of juvenile chinook salmon from tributaries progressively further upstream. Because the occurrence of the ocean type life history pattern is related to areas in the watershed where stream temperatures afford enhanced growth opportunity (Taylor, 1991), the ocean type life history pattern likely would have originated from populations of fall chinook salmon that spawned in the mainstems of the Snake and Columbia Rivers and in the lower and middle reaches of some subbasins. Summer and spring chinook salmon that spawned in the warmer, middle and lower reaches of some subbasins also produced juvenile chinook salmon with the ocean type life history pattern.

Mainstem spawning salmon populations with ocean type life histories were depleted with the construction of the hydroelectric system. The Hanford Reach and small areas in the Snake River support the last remaining populations of that life history type. Loss of habitat connectivity was a major contributor to the loss of the ocean type life history in the subbasins (Lichatowich and Mobrand (1995). Excessive summer temperature in the lower mainstems of subbasins is due to a cumulative effect of watershed-wide habitat degradation, which severs the connectivity of the chain of habitats linking the subbasin to the mainstem (Table 2.1), as happened in the Yakima River. The ocean type life history is characterized by a continuous downstream migration in the subbasins and in the mainstems. The loss of the migration corridor through excessive temperatures or other barriers, (Confederated Tribes of the Umatilla Indian Reservation (CTUIR) and Oregon Department of Fish and Wildlife (ODFW), 1990; Confederated Tribes Yakima Indian Nation (CTYIN) et al., 1990; Oregon Department of Fish and Wildlife (ODFW) et al., 1990; Oregon Department of Fish and Wildlife (ODFW) and Confederated Tribes of the Warm Springs Reservation (CTWSR), 1990; Oregon Dept. of Fish and Wildlife, 1990; Washington Department of Fisheries (WDF) et al., 1990) eliminated those life histories dependent on migration in the summer and fall months. For example, lethal temperatures in the lower mainstem eliminated several life history pathways in spring chinook salmon in the Yakima River (Watson, 1992).

Table 2.1. Habitat suitability for juvenile chinook salmon in the lower reaches of the study subbasins. (Source Lichatowich and Mobrand 1995)

Subbasin	Comments on Habitat	Source
Yakima	Lower river below Prosser (RM 47.1) frequently exceeds 75°F and occasionally reaches 80°F in July and August rendering the lower river uninhabitable by salmonids.	CTYIN et al. 1990
Tucannon	Water temperatures in lower river at or above lethal levels.	WDF et al. 1990
Umatilla	Lower 32 miles subject to irrigation depleted flows and temperatures exceeding upper lethal limits for salmonids.	CTUIR and ODFW 1990
John Day	Juvenile chinook salmon generally not found in the river where temperatures reach 68°F. High stream temperature eliminates juvenile rearing habitat in the lower river.	Lindsay et al. 1981, ODFW et al. 1990
Deschutes	In the mainstem Deschutes River, summer temperatures are adequate for chinook salmon. However, there are temperature problems in the lower reaches of the tributaries where spring chinook salmon spawn. In addition *Ceratomyxa shasta* limit the survival of juvenile chinook salmon in the mainstem through the summer months.	Ratliff 1981, ODFW and CTWSR 1990

The section above describes how complex and interconnected habitats are created and maintained in the Columbia Basin through natural riverine processes and introduces how the availability of these habitats facilitates the expression of life history diversity and production in salmonid populations. The diversity that salmonids exhibit ecologically, behaviorally, and genetically is remarkable and well-recognized (Utter et al., 1974; Stearns, 1976; Stearns, 1977; Groot, 1982; Hutchings and Morris, 1985; Utter et al., 1989; Taylor, 1990; Groot and Margolis, 1991; Taylor, 1991; Behnke, 1992; Stearley, 1992; Hutchings, 1993; Allendorf and Waples, 1996). This diversity arises at the population scale out of an interaction between salmonids (comprised of genetically variable individuals) and the local conditions of their environments (i.e., local adaptation) (Taylor, 1991; Allendorf and Waples, 1996).

There is strong evidence that spawning populations of anadromous salmonids exhibit highly specific local adaptations for a number of traits, such as migrational timing, time of fry emergence from spawning gravels, juvenile migrational timing, etc. (Taylor, 1991; Allendorf and Waples, 1996). Freshwater (i.e., non-anadromous forms) typically show greater amounts of isolation among populations than do anadromous forms, and consequently exhibit greater amounts of divergence (genetic and phenotypic) over smaller geographic scales than do anadromous salmonids.

Because salmonid populations occurred throughout the Columbia Basin across a mosaic of different landscapes, adaptation of individual populations to specific habitats (and life history pathways) created the abundant diversity that characterized salmonid fishes in the Columbia Basin (Taylor, 1991). The diversity observed in salmonids, both life history and genetic, occurs within and among populations and is structured primarily on a the basis of geographic proximity; that is, populations that occur close to one another are likely to be more similar to one another than they will be to geographically distant populations. In turn, aggregates of geographically proximate populations are thought to form metapopulations that act to stabilize regional population structure against environmental fluctuation. Thus, habitat complexity as generated, altered and maintained by natural river processes, acts as the template upon which salmonid diversity, productivity and stability is expressed and upon which it depends.

Salmonid Metapopulations

In their review of the status of Pacific salmon, the National Research Council (1996) recommended that salmon be viewed as metapopulations, rather than isolated stocks. Metapopulations are spatially-structured groups of local populations linked by dispersal of individuals (Hanski, 1991; Hanski and Gilpin, 1991). Metapopulation persistence is determined by the balance of local population extinction and re-establishment of extinct populations through recolonization. Dispersal from neighboring local populations allows recolonization of habitats where local extinction has occurred.

The application of metapopulation concepts to conservation currently is being debated by scientists and managers, e.g., (Harrison, 1994; Mann and Plummer, 1995). Data pertaining to salmonid metapopulation structure and dynamics is limited and many uncertainties remain to be addressed. Thus, the following discussion of salmon metapopulation structure should be viewed as a hypothesis that requires further empirical evaluation.

Metapopulation structure is likely in salmonids (National Research Council, 1996) because they display high fidelity of homing to their natal streams (Helle, 1981), while at the same time exhibiting relatively low, but variable levels of straying (Quinn, 1993). High natal fidelity favors adaptation of specific breeding demes (i.e., local populations) to their environments via natural selection (National Research Council, 1996), which in turn promotes population differentiation at the local level. Low levels of straying between populations will tend to counteract the effects of isolation and facilitate recolonization of habitats where local extinction has occurred.

Recent studies suggest that salmonid metapopulations may maintain core-satellite structures (Rieman and McIntyre, 1993; Li et al., 1995; Schlosser and Angermeier, 1995). Core populations occupy high quality habitat and are generally large, productive populations that are less susceptible to extinction than the smaller satellite populations (Hanski, 1991; Harrison, 1991; Schoener, 1991; Harrison, 1994). Core populations also can serve as important sources of colonists (Harrison, 1991; Schoener, 1991; Rieman and McIntyre, 1993; Harrison, 1994; Schlosser and Angermeier, 1995) to sustain populations whose abundance has been severely depleted, i.e., the "rescue effect" (Brown and Kodric-Brown, 1977; Gotelli, 1991). Thus, core populations can buffer metapopulations against environmental change and contribute to the resiliency of regional salmonid production.

Spawning populations with the highest abundances likely occurred historically in alluvial segments with well-developed flood plains and gravel bars. These areas provide a complex habitat mosaic highly suitable for spawning, egg incubation, and juvenile rearing and may have functioned as centers of habitat stability. Productive populations spawning in large alluvial mainstem reaches may have functioned as critical core populations (Stanford et al., *in press*). The remnant populations observed today may represent a collapsed state of historical core populations and therefore might serve as foci for restoration efforts. An example of metapopulaton organization using chinook salmon in the Columbia Basin is presented in Chapter 4.

Potential Human Impacts on Metapopulation Organization

The extinction rate of local populations of chinook salmon has increased over the last century (Nehlsen et al., 1991; Williams et al., 1992; Frissell, 1993; National Research Council, 1996) and has altered the organization of regional systems of populations in the Columbia basin. Metapopulation theory suggests that fragmentation and destruction of habitat can disrupt regional metapopulation organization leading to the collapse or extirpation of vital core populations and isolation of remaining populations. In turn, this can significantly reduce long-term metapopulation persistence and the stability of regional production (Rieman and McIntyre, 1993; Harrison, 1994; Li et al., 1995; Schlosser and Angermeier, 1995).

Most fall chinook populations spawning in the mainstem reaches of the Columbia and Snake Rivers have been driven extinct. One of the remaining viable mainstem populations is the fall chinook population spawning in the Hanford Reach (Becker, 1985). Escapement to the Hanford Reach, where relatively high quality spawning and rearing habitat is still available, has averaged 40-50 thousand fish since the mid-1960's and peaked at over 200,000 spawners in 1986 (Figure 2.6). This population is the largest naturally spawning population of chinook salmon above Bonneville Dam and has been stable over the years when populations in other parts of the basin have undergone severe decline (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995). Fall chinook in the Hanford Reach may presently function as a critical core population and might function as a source for colonization of adjacent tributaries if normative conditions were restored in them. Apparently fall chinook spawners also were abundant in the section of the mainstem Columbia presently inundated by the John Day Reservoir (Fulton, 1968). This section of river could have formed another critical core area.

Remnant populations of fall chinook also occur in the lower mainstems of most major subbasins, in the Snake River below Hell’s Canyon dam, and in the tailraces of some mainstem dams (Lavier, 1976; Garcia et al., 1995), but their abundance is much lower than in the past. Most summer and spring chinook which spawned in upper mainstem segments of subbasins and lower reaches of tributaries to subbasin mainstems have been extirpated (Lichatowich and Mobrand, 1995). Aside from the Hanford Reach, natural production of chinook salmon is largely confined to relatively small populations of spring and summer chinook in headwater streams where high quality habitat is still available. For example, spring chinook are confined to headwater areas of the Grande Ronde and Imnaha rivers and their tributaries where many of the streams supporting spring chinook originate in wilderness areas (Figure 2.9).

The probability of metapopulation extinction is enhanced if the dynamics of local populations and their individual probabilities of extinction become temporally correlated or synchronized (Harrison and Quinn, 1989; Hanski, 1991). Regional stochasticity refers to the correlated or synchronized dynamics of local populations resulting from the operation of common environmental factors (Hanski, 1991). Human activities have not only increased extinction rates of local salmonid populations (Nehlsen et al., 1991; Williams et al., 1992; Frissell, 1993; National Research Council, 1996), but they also could act to synchronize the dynamics of remaining populations and thus, render regional metapopulations more susceptible to extinction (Rieman and McIntyre, 1993). For example, land use activities can have pervasive, region-wide effects on geographically diverse local populations (see Chapter 5). Synchrony can also be induced in common migratory pathways and the ocean as a result of mortality due to excessive harvest, construction of dams, and degradation or destruction of mainstem habitats. Synchrony may be more likely if migration timing of diverse populations is seasonally restricted. Moreover, during the last century, extinction rates have been elevated by human development of the basin, and local population and metapopulation sizes and dispersal rates have been reduced, possibly making salmon more susceptible to the effects of correlated natural environmental changes (Harrison and Quinn, 1989).

Human impacts may have shifted metapopulation structure from core-satellite to non-equilibrium metapopulations. In non-equilibrium metapopulations, extinction rates are consistently greater than recolonization rates and the metapopulations are undergoing regional decline (Harrison, 1991). Many stabilizing core populations have been driven extinct, recolonization and re-establishment of extinct local populations is limited or does not occur, and only isolated satellite populations remain. Isolated populations have little chance of being refounded after a local extinction compared to a population that is close to other populations. As populations become isolated, local extinctions become permanent and the entire metapopulation moves incrementally toward extinction (Rieman and McIntyre, 1993).

Summary

Habitat conditions for salmonids vary greatly among watersheds within the Columbia River basin as a consequence of geographic variation in physiographic factors such as climate and geology. Even within a watershed, conditions vary from headwater areas to the lower mainstem reaches. As salmonids complete their life cycles, they encounter a wide array of habitat conditions to which they must adapt to successfully survive and reproduce. Biodiversity in salmonid species is manifested as phenotypic, life history, stock, and genetic diversity and, at least in part, it represents adaptation to variation in habitat conditions both in space (i.e., from location to location) and in time. A fundamental premise of the conceptual foundation presented in this chapter is that biodiversity is sustained by complex, high quality habitats with conditions suitable for completion of diverse life cycles.

In general, human actions, including hydroelectric development and habitat degradation, can constrain or reduce the expression of habitat diversity within and among watersheds which , in turn, can constrain the expression of salmonid biodiversity, disrupt the integrity of metapopulations, and lower regional salmonid productivity and stability (Figure 2.3). Other human perturbations such as excessive harvest and introduction of non-native species, can act in concert with habitat loss to reduce salmonid biodiversity. As a consequence of human development of the basin, major spawning populations in the mainstem Columbia and Snake and the lower mainstems of major subbasins have been eliminated and, with the exception of the Hanford Reach fall chinook, salmonid production in the basin largely has become confined to hatcheries and to headwater areas where high quality habitat remains.

In this context, restoration of salmonids involves removing or reducing influences constraining the expression of biodiversity across the landscape. A critical aspect of biodiversity restoration is restoration of the diversity and connectivity of habitats necessary for successful completion of an array of life histories. Full re-expression of diversity may not be possible, either because society may not be willing or able to sufficiently reduce some constraints due for economic and other social reasons, or because some other human activities (e.g., greenhouse effects; regulation of the flow of entire river systems by hydropower operations, non-native species, deforestation) may have fundamentally altered the ability or capacity of the ecosystem to re-express diversity.

Literature Cited

Allendorf, F.W. and R.S. Waples. 1996. Conservation and genetics of salmonid fishes. Conservation genetics: Case histories from nature. J. C. Avise, Chapman Hall**:** 238-280.

Amoros, C., A.L. Roux, J.L. Reygrobellet, J.P. Bravard and G. Pautou. 1987. A method for applied ecological studies of fluvial hydrosystems. Regulated Rivers 1: 17-36.

Beauchamp, D.A., M.F. Shepard and G.B. Pauley. 1983. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest). Chinook Salmon. Seattle, University of Washington, Fishery Research Unit. Washington.

Becker, C.D. 1985. Anadromous Salmonids of the Hanford Reach, Columbia River: 1984 Status. Richland, Pacific Northwest Laboratories. Washington.

Behnke, R.J. 1992. Native trout of western North America. Bethesda, Maryland, American Fisheries Society.

Brown, J.H. and A. Kodric-Brown. 1977. Turnover rates in insular biogeography: effects of immigration on extinction. Ecology 58: 445-449.

Carl, L.M. and M.C. Healey. 1984. Differences in enzyme frequency and body morphology among three juvenile life history types of chinook salmon (*Oncorhynchus tshawytscha*) in the Nanaimo River, British Columbia. Can. J. Fish. Aquat. Sci. 41: 1070-1077.

Confederated Tribes of the Umatilla Indian Reservation (CTUIR) and Oregon Department of Fish and Wildlife (ODFW). 1990. Umatilla River subbasin salmon and steelhead production plan. Portland, OR, Northwest Power Planning Council.

Confederated Tribes Yakima Indian Nation (CTYIN), Washington Department of Fisheries and W.D.o. Wildlife. 1990. Yakima River subbasin salmon and steelhead production plan. Portland, OR, Northwest Power Planning Council.

Copp, G.H. 1989. The habitat diversity and fish reproductive function of floodplain ecosystems. Envir. Biol. Fish. 26: 1-27.

Cronon, W. 1995. With the best of intentions (Forward). Forest dreams, forest nightmares. N. Langston. Seattle, WA, University of Washington Press**:** vii-ix.

Davies, B.R. and K.F. Walker. 1986. River systems as ecological units: an introduction to the ecology of river systems. Ecology of River Systems. B. R. Davies and K. F. Walker. Dordrecht, Dr. W. Junk Publishers. 60**:** 1-8.

Frissell, C.A. 1993. Topology of extinction and endangerment of native fishes in the Pacific northwest and California (U.S.A.). Conservation Biology 7(2): 342-354.

Frissell, C.A., W.J. Liss, R.E. Gresswell, R.K. Nawa and J.L. Ebersole. In press. A resource in crisis: changing the measure of salmon management. Pacific Salmon and Their Ecosystems: Status and Future Options. D. J. Stouder, P. A. Bisson and R. J. Naiman. New York, Chapman and Hall.

Frissell, D.A., W.J. Liss, R.K. Nawa, R.E. Gresswell and J.L. Ebersole. In press. Measuring the failure of salmon management: from rationalizing exploitation to redefining restoration. Pacific Salmon and Their Ecosystems.

Fulton, L.A. 1968. Spawning areas and abundance of chinook salmon (Oncorhynchus tshawytscha) in the Columbia River Basin--past and present., USDI, Fish and Wildl. Serv., Special Sci. Rpt--Fisheries No. 571.

Garcia, A.P., W.P. Connor and R.H. Taylor. 1995. Fall chinook salmon spawning ground surveys in the Snake River. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and K. F. Tiffan. Portland, Bonneville Power Administration. Report No. COE/BP-21708-3**:** 1-21.

Gharrett, A.J. and W.W. Smoker. 1993. Genetic components in life history traits contribute to population structure. Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 197-202.

Gibert, J., D.L. Danielopol and J.A. Stanford. 1994. Groundwater Ecology. San Diego, Academic Press, Inc.

Gotelli, N.J. 1991. Metapopulation models: the rescue effect, the propagule rain, and the core-satellit hypothesis. The American Naturalist 138: 768-776.

Gregory, S.V., F.J. Swanson, W.A. McKee and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience 41(8): 540-551.

Groot, C. 1982. Modifications on a theme - a perspective on migratory behavior of Pacific salmon. Salmon and Trout Migratory Behavior Symposium, Univ. of Washington School of Fisheries.

Groot, C. and L. Margolis, Eds. 1991. Pacific salmon life histories. Vancouver, University of British Columbia.

Hall, C.A.S., J.A. Stanford and F.R. Hauer. 1992. The distribution and abundance of organisms as a consequence of energy balances along multiple environmental gradients. Oikos 65: 377-390.

Hanski, I. 1991. Single species metapopulation dynamics: concepts, models and observations. Biol. Jour. Linnean Soc. 42: 17-38.

Hanski, I. and M. Gilpin. 1991. Metapopulation dynamics: brief history and conceptual domain. Biol. Jour. Linnean Soc. 42: 3-16.

Harrison, S. 1991. Local extinction in a metapopulation context: an empirical evaluation. Biol. Jour. of the Linnean Society 42: 73-88.

Harrison, S. 1994. Metapopulations and conservation. Large-scale Ecology and Conservation Biology. P. J. Edwards, R. M. May and N. R. Webb. Oxford, Blackwell Scientific Publications.

Harrison, S. and J.F. Quinn. 1989. Correlated environments and the persistence of metapopulations. Oikos 56: 293-298.

Hauer, F.R. and J.A. Stanford. 1982. Ecological responses of hydropsychid caddisflies to stream regulation. Can. J. Fish. Aquat. Sci. 39(9): 1235-1242.

Healey, M.C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, UBC Press.

Healey, M.C. and A. Prince. 1995. Scales of variation in life history tactics of Pacific salmon and the conservation of phenotype and genotype. Amer. Fish. Soc. Symp. 17: 176-184.

Healey, M.C. and A. Prince. 1995. Scales of variation in life history tactics of Pacific salmon and the conservation of phenotype and genotype. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 176-184.

Heilbroner, R.a.M., William. 1995. The Crisis of Vision in Modern Economic Thought, Cambridge University Press.

Helle, J.H. 1981. Significance of the stock concept in artificial propagation of salmonids in Alaska. Can. J. Fish. Aquat. Sci. 38: 1665-1671.

Huntington, C., W. Nehlsen and J. Bowers. 1996. A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California. Fisheries 21(3): 6-14.

Hutchings, J.A. 1993. Adaptive life histories effected by age-specific survival and growth rate. Ecology 74(3): 673-684.

Hutchings, J.A. and D.W. Morris. 1985. The influence of phylogeny, size and behavior on patterns of covariation in salmonid life histories. Oikos 45: 118-124.

Jordan, D.S. 1904. The salmon of the Pacific. Pacific Fisherman 2: 1.

Junk, W.J. and M.T.F. Piedade. 1994. Species diversity and distribution of herbaceous plants in the floodplain of the middle Amazon. Verh. Internat. Verein. Limnol. 25: 1862-1865.

Keifer, S., M. Rowe and K. Hatch. 1993. Stock summary reports for Columbia River anadromous salmonids. Volume V: Idaho. Portland, O, Bonneville Power Administration.

Lavier, D.C. 1976. Major Dams on Columbia River and Tributaries. Olympia, Washington Dept. of Game. Washington.

Lestelle, L.C. and L.G. Gilbertson. 1993. Harvest Management and Recovery of Snake River Salmon Stocks. Portland, Bonneville Power Administration. Oregon**:** 75.

Li, H.W., K. Currens, D. Bottom, S. Clarke, J. Dambacher, C. Frissell, P. Harris, R.M. Hughes, D. McCullough, A. McGie, K. Moore and S. Thiele. 1995. Safe havens: refuges and evolutionarily significant units. American Fisheries Society Symposium 17.

Li, H.W., G.A. Lamberti, T.N. Pearsons, C.K. Tait and J.L. Li. 1995. Cumulative impact of riparian disturbances in small streams of the John Day Basin, Oregon. Trans. Amer. Fish. Soc. 123: 627-640.

Li, H.W., C.B. Schreck, C.E. Bond and E. Rexstad. 1987. Factors influencing changes in fish assemblages of Pacific Northwest streams. Community and Evolutionary Ecology of North American Stream Fishes. W. J. Matthews and D. C. Heins. Norman, Univ. of Oklahoma Press**:** 193-202.

Lichatowich, J.A., L. Mobrand and T. Vogel. 1996. A History of Frameworks Used in the Management of Columbia River Chinook Salmon (Draft). Portland, Bonneville Power Administration. Oregon**:** 117.

Lichatowich, J.A. and L.E. Mobrand. 1995. Analysis of chinook salmon in the Columbia River from an ecosystem perspective, Mobrand Biometrics.

Lindsay, R.B., W.J. Knox, M.W. Flesher, B.J. Smith, E.A. Olson and L.S. Lutz. 1986. Study of Wild Spring Chinook Salmon in the John Day River System. Portland, Bonneville Power Administration. Oregon.

Lowe-McConnell, R.H. 1987. Ecological Studies in Tropical Fish Communities. Cambridge, Cambridge Univ. Press.

Mann, C.C. and M.L. Plummer. 1995. Are wildlife corridors the right path? Science 270: 1428-1430.

Marmorek, D. and I. Parnell. 1995. Plan for analyzing and testing hypotheses (PATH): Information package for Workshop 1. Design of retrospective analyses to test key hypotheses of importance to management decisions on endangered and threatened Columbia River salmon stocks. Vancouver, B.C, ESSA Technologies Ltd.

Munn, M. and M.A. Brusven. 1991. Benthic macroinvertebrate communities in nonregulated and regulated waters of the Clearwater River, Idaho. Regulated Rivers 6: 1-11.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Report on the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids for the National Research Council of the National Academy of Sciences. Washington D. C., National Academy Press.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Nicholas, J.W. and D.G. Hankin. 1988. Chinook Salmon Populations in Oregon Coastal River Basins: Description of Life Histories and Assessment of Recent Trends in Run Strengths. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Oregon Department of Fish and Wildlife (ODFW), Confederated Tribes of the Umatilla Indian Reservation (CTUIR) and Confederated Tribes of the Warm Springs Reservation (CTWSR). 1990. John Day River Subbasin: salmon and steelhead production plan. Portland, OR, Northwest Power Planning Council.

Oregon Department of Fish and Wildlife (ODFW) and Confederated Tribes of the Warm Springs Reservation (CTWSR). 1990. Deschutes River Subbasin: salmon and steelhead production plan. Portland, OR, Northwest Power Planning Council.

Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife. 1995. Status Report, Columbia River Fish Runs and Fisheries 1938-94. Portland. Oregon.

Oregon Dept. of Fish and Wildlife, C.T.o.t.U.I.R., Nez Perce Tribe, Washington Dept. of Fisheries, and Washington Dept. of Wildlife. 1990. Grande Ronde River Subbasin, Salmon and Steelhead Production Plan. Portland, Northwest Power Planning Council. Oregon.

Perry, S.A., W. B. Perry and J. A. Stanford. 1986. Effects of stream regulation on density, growth, and emergence of two mayflies (Ephemeroptera: Ephemerellidae) and a caddisfly (Trichoptera: Hydropsychidae) in two Rocky Mountain rivers (U.S.A.)., Can. J. Zool. 64:656-666.

Petts, G.E., H. Moller and A.L. Roux, Eds. 1989. Historical Change of Large Alluvial Rivers: Western Europe. Chichester, John Wiley & Sons.

Poe, T.P., H.C. Hansel, S. Vigg, D.E. Palmer and L.A. Prendergast. 1991. Feeding of predaceous fishes on out-migrating juvenile salmonids in John Day reservoir, Columbia River. Trans. Am. Fish. Soc. 120: 405-420.

Quinn, T.P. 1993. A review of homing and straying of wild and hatchery-produced salmon. Fisheries Research 18: 29-44.

Ratliff, D.E. 1981. *Ceratomyxa shasta*: Epizootiology in chinook salmon of central Oregon. Trans. Am. Fish. Soc. 110: 507-513.

Regier, H.A., R.L. Welcomme, R.J. Stedman and H.F. Henderson. 1989. Rehabilitation of degraded river ecosystems. Proceedings of the International Large River Symposium., Can. Spec. Publ. Fish. Aquat. Sci.

Reimers, P.E. 1973. The length of residence of juvenile fall chinook salmon in Sixes River, Oregon. Research Reports of the Fish Comm. of Oregon 4(2): 3-43.

Rich, W.H. 1920. Early history and seaward migration of chinook salmon in the Columbia and Sacramento Rivers. Bulletin of the US Bureau of Fisheries, Washington, DC 37.

Rieman, B.E. and J.D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. Ogden, US Forest Service, Intermountain Research Station. Utah**:** 38.

Schlosser, I.J. and P.L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Amer. Fish. Soc. Symp. 17: 392-401.

Schluchter, M. and J.A. Lichatowich. 1977. Juvenile Life Histories of Rogue River Spring Chinook Salmon *Oncorhynchus tshawytscha* (Walbaum), as determined from scale analsysis. Corvallis, Oregon Dept. of Fish and Wildlife. Oregon.

Schoener, T.W. 1991. Extinction and the nature of the metapopulation: a case system. Acta Oecologica 12(1): 53-76.

Sparks, R.E., P.B. Bayley, S.L. Kohler and L.L. Osborne. 1990. Disturbance and recovery of large floodplain rivers. Envir. Management 14: 699-709.

Stanford, J.A. and F.R. Hauer. 1992. Mitigating the impacts of stream and lake regulation in the Flathead River Catchment, Montana, USA: An ecosystem perspective. Aquatic Conservation 2: 35-63.

Stanford, J.A., F.R. Hauer and J.V. Ward. 1988. Serial discontinuity in a large river system. Verh. Internat. Verein. Limnol. 23: 1114-1118.

Stanford, J.A. and J.V. Ward. 1993. An ecosystem perspective of alluvial rivers: Connectivity and the hyporheic corridor. J. N. Am. Benthol. Soc. 12(1): 48-60.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant. *in press*. A general protocol for restoration of regulated rivers. Regulated Rivers.

Stearley, R.F. 1992. Historical ecology of Salmoninae, with special reference to *Oncorhynchus*. Systematics, historical ecology, and North American freshwater fishes. R. L. Mayden. Stanford, CA, Stanford University Press**:** 649-658.

Stearns, S.C. 1976. Life-history tactics: A review of the ideas., Q. Rev. Biol. 51(1):3-37. .

Stearns, S.C. 1977. The evolution of life history traits: A critique of the theory and a review of the data., Ann. Rev. Ecol. Syst. 8:145-155.

Taylor, E.B. 1990. Environmental correlates of life-history variation in juvenile chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). J. Fish Biology 37: 1-17.

Taylor, E.B. 1991. A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon. Aquaculture 98(1991): 185-207.

Thompson, W.F. 1959. An approach to population dymanics of the Pacific red salmon. Trans. Am. Fish. Soc. 88(3): 206-209.

Thorpe, J.E. 1994. Salmonid flexibility: responses to environmental extremes. TAFS(123): 606-612.

Utter, F., G. Milner, G. Stahl and D. Teel. 1989. Genetic population structure of chinook salmon, Oncorhynchus tshawytscha, in the Pacific Northwest. Fish. Bull. 87: 239-264.

Utter, F.M., F.W. Allendorf and H.O. Hodgins. 1974. Genetic variability and relationships in Pacific salmon and related trout based on protein variation. Syst. Zool. 22: 257-270.

Vannote, R.L., G.W. Minshall, K. W.Cummins, J.R. Sedell and C.E. Cushing. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37(1): 130-137.

Ward, J.V. 1989. The four-dimensional nature of lotic ecosystems. J. N. Am. Benthol. Soc. 8(1): 2-8.

Ward, J.V. and J.A. Stanford. 1983. The serial discontinuity concept of lotic ecosystems. Dynamics of Lotic Ecosystems. T. D. I. Fontaine and S. M. Bartell. Ann Arbor, Ann Arbor Science Publishers**:** 29-42.

Ward, J.V. and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers 11(1): 105-120.

Ward, J.V. and J.A. Stanford. 1995. The serial discontinuity concept: extending the model to floodplain rivers. Regulated Rivers 10(2-4): 159-168.

Washington Department of Fisheries (WDF), Confederated Tribes of the Umatilla Indian Reservation (CTUIR), Nez Perce Tribe (NPT) of Idaho and Washington Department of Wildlife (WDW). 1990. Tucannon River Subbasin salmon and steelhead production Plan. Portland, OR, Northwest Power Planning Council.

Watson, B. 1992. Using "Patient/Template Analysis" in the design of projects to increase natural production of anadromous salmonidss. Salmon management in the 21st century: recovering stocks in declineProceedings of the Coho / Chinook Workshop, Boise, ID, Northeast Pacific Chinook and Coho Workshop.

Welcomme, R.L. 1979. Fisheries Ecology of Floodplain Rivers. London, Longman.

Welcomme, R.L. 1995. Relationships between fisheries and the integrity of river systems. Regulated Rivers 11(1): 121-136.

Whitney, R.R., L.D. Calvin, C.C. Coutant, J. Michael W. Erho, J.A. Lichatowich, W.J. Liss, W.E. McConnaha, P.R. Mundy, J.A. Stanford and R.N. Williams. 1993. Critical Uncertainties in the Fish and Wildlife Program. Portland, Bonneville Power Administration. Oregon**:** 17.

Williams, J.E., J.A. Lichatowich and W. Nehlsen. 1992. Declining salmon and steelhead populations: New endangered species concerns for the west. Endangered Species Update 9(4): 1-8.

Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, G.H. Reeves and J.R. Sedell. 1994. A history of resource use and disturbance in riverine basins of Eastern Oregon and Washington (early 1800s-1900s). Northwest Science. D. L. Peterson. Seattle. 68**:** 1-35.

Zwick, P. 1992. Stream habitat fragmentation - a threat to biodiversity. Biodiversity and Conservation 1: 80-97.

Chapter 3. Review of the Science Underlying the Council's Fish and Wildlife Program

Validity Of Assumptions And Strategies For Salmonid Restoration In The Columbia River Ecosystem Embodied in the Fish and Wildlife Program

We reviewed the science behind the Council's Fish and Wildlife Program from the perspective of the conceptual foundation described in the preceding chapter. Our conceptual foundation encompasses the salmon bearing ecosystem and provides a framework applicable to salmon restoration at large. The Council's Fish and Wildlife Program, however, was developed to "protect, mitigate and enhance" the fish and wildlife of the Columbia River as affected by development and operation of the Columbia River Basin hydroelectric system. Consequently, the Fish and Wildlife Program deals with a subset of the factors incorporated in our conceptual foundation. These actions can only be evaluated in the context of the overall salmonid ecosystem embraced by the conceptual foundation in Chapter 2. Given that context, our approach to review the science behind the Council's Fish and Wildlife Program was to list global principles (3) and specific assumptions (29) implied by the measures included in the program and then evaluate the validity of those assumptions. These were derived as part of our review based on the measures adopted by the Council and are not explicitly endorsed or contained in the Council's program.

Thus, our review did not evaluate individual program measures, but instead focused on the biological rationale for measures or groups of related measures. For example, the fact that the Program devotes a considerable number of measures to the idea of flow augmentation in the mainstem river presumably reflects a belief that flow rates as modified by operation and development of the hydroelectric system have contributed to the declines in salmonid populations. Once articulated, such a statement is amenable to scientific analysis whereas the individual measures themselves may not be.

However, as we discuss further below, consideration of the scientific basis for individual assumptions may lead us to a situation of focusing on the trees, while missing the forest. It is quite possible for each individual measure or strategy to be based on sound scientific principles, but for these measures collectively to be an inadequate response to the modification of the ecosystem that has occurred during this century. This could be a case of simply doing too little too late, or, as we contend is true of salmon restoration efforts in general, a case where an inadequate and poorly documented conceptual foundation has led to an inappropriate response to the problem.

In the review below, we begin with an examination of the program in general and how it is developed through the Council's process. This is followed by an evaluation of the set of assumptions and beliefs implied by the array of measures in the Fish and Wildlife Program.

Development of the Fish and Wildlife Program.

Strategically, the Fish and Wildlife Program (FWP) is a collection of individual measures proposed by regional parties without reference to an explicit, common scientific framework or conceptual foundation. The measures have been proposed by various interest groups in the Pacific Northwest, discussed in public forums, and adopted by the Council. Thus the FWP represents a political agreement which has not been evaluated with reference to a scientifically based standard for evaluation. Individual measures in the FWP have been grouped logically by topic and secondarily by entity or entities to be responsible for accomplishing each measure. The measures are diverse and span a broad spectrum of often traditional mitigation interests (e.g., hatchery development, habitat restoration, juvenile fish survival through the hydroelectric system). Some measures have been completed since the beginning of the FWP in the early 1980's, thus eliminating these measures from the list. As the program has undergone subsequent revisions, measures have been added. On the whole, revisions have been variations on the initial theme and have consisted of rearrangement of the program to provide an organizational structure, provide monitoring and evaluation, and deal with uncertainty.

A fundamental question is whether this is the best strategy for incorporating scientific knowledge into the restoration effort. We find three overall difficulties with this approach. First, the "list" definition of the FWP encourages a confrontational atmosphere in the proposal and selection of measures. Advocates argue for their suite of measures as most important (scientifically, politically, culturally, geographically, etc.). The list has no logical endpoint -- controversy can be accommodated by simply adding new items. The Council has limited legislated ability to reject measures, evaluate their scientific merit or incorporate them within an overall framework. Even if all parties can agree to a specific list at a specific point in time, new items can be added later. Because the Act mandates that the Council use an amendment process and revise the FWP periodically, the process can become a continuous process of reorganization and the addition of new items to the list. This leaves the Council and other resource managers of the region open to the criticism that they have not really established a comprehensive plan and defined a strategy.

Second, the FWP lacks a structure for selecting or prioritizing measures based on a framework of overall goals and objectives. While the Council has identified general goals and priorities for the FWP, their level of generality is such that they provide little guidance or rationale for subsequent selection or prioritization of measures. Each item (measure) on the list is given equal weight and acted upon before the FWP can be evaluated as a comprehensive solution. While there is some sequencing and scheduling built into the Program, there is little incentive for parties to follow the schedule or accountability if measures are not completed on time or at all. The 1994 program identifies important hypotheses and includes a process for testing and refinement of hypotheses, but sequencing of actions is not tied to this hypothesis testing. Prioritization of measures occurs outside the Council's public process in various forums and outside any logical structure that makes the collection of measures a program. Project ranking appears to depend greatly on the vigor with which proponents pursue their own agendas.

Third, focusing on the individual items encourages interest groups to become immersed in the endless fine details, thus losing sight of the big picture. Instead of focusing on the most biologically effective and socially acceptable means of achieving a specified biological condition, the Council has been diverted by efforts of various groups to protect or promote their own interests. The list structure of the FWP, although not precluding effective progress on specific items, tends to be unstructured and unfocused making evaluation and effective change difficult.

We recommend that the FWP incorporate an integrated approach to ecosystem management that is based on an overall, scientifically credible conceptual foundation such as we proposed in the previous chapter. This would lead to a rational structure of goals and objectives and provide a standard for evaluation of measures based on general properties of the salmon bearing ecosystem. It also would provide the Council with an objective, explicit structure around which to shape a scientifically based program. We suggest that the Council's approach should be to "protect, mitigate, and enhance" ecosystem properties that are consistent with the biological needs of salmon, steelhead and other native fish and wildlife species while providing for environmentally responsible energy production. While it would be naive to think that this would eliminate the traditional controversies that have divided the region's efforts for decades, we feel that this approach would place the FWP on firmer scientific ground and provide a rational structure for the region's efforts.

Additionally, credible scientific review is needed of projects proposed for funding. Projects needs to be reviewed for their scientific rigor and potential contribution to the purposes of salmon recovery. A credible review process would provide a means to assess projects and funding priorities, along with their potential contribution to salmon recovery goals. The Independent Scientific Group has developed guidelines for proposal preparation (ISG Report 90-3; "Guidelines for Research Proposals" and ISG Report 94-2; "Guide to Proposal Review") and has proposed a process for project review (ISG Report 94-1; "Guide to Peer Review of Projects") that could serve as a basis for design of an appropriate peer review process.

The Role of Adaptive Management in the Fish and Wildlife Program

Adaptive management uses management actions as part of an experimental design to refine understanding concerning scientific questions. As a result of these experiments, management should adapt, resulting in improved response to environmental problems (Holling, 1978; Walters, 1986). The appealing common sense of adaptive management belies the practical difficulties in actually implementing an adaptive approach. Although the concept has a rich literature spanning several decades, the number of cases of successful use of adaptive management are quite limited (McAllister and Peterson, 1992; Halbert, 1993; McConnaha and Pacquet, *in press*).

The Council introduced adaptive management to the region in its 1987 revision of the Fish and Wildlife Program. The initial efforts to craft a fish and wildlife program made the Council acutely aware of the deep divisions in the region that often revolved around technical questions of biology or hydrology. Adaptive management offered a way for the Council to take action in the face of significant scientific uncertainties (Lee and Lawrence, 1986).

With the Council's adoption of the concept, adaptive management became part of the standard lexicon of the Columbia Basin. Since its appearance in the FWP, adaptive management has been used to justify a variety of actions on the premise that something might be learned that could lead to improved management. Such a passive approach to learning is at odds with the rigorous application of the scientific method that is at the heart of adaptive management (Walters, 1986; Hilborn and Winton, 1993).

The use of adaptive management in the Council's program has been reviewed by Volkman and McConnaha (1993) and McConnaha and Paquet (*in press*). They noted that the Council's program is one of the first attempts to use adaptive management as part of an ecosystem scale restoration program. Previous applications focused on limited, if often complex, problems such as harvest management (McAllister and Peterson, 1992). Practical difficulties have resulted in only limited success in using adaptive management as part of the Council's Fish and Wildlife Program; there appears to be no instance where adaptive management, in the sense of Holling (1978) and Walters (1986), has been used to address major uncertainties (Volkman and McConnaha, 1993).

In the 1994 FWP, the Council laid out a strategy for using management actions to refine hypotheses concerning transportation and in-river passage (Section 5.0). This provided an explicit set of hypotheses on major scientific uncertainties and proposed a management experiment to address these hypotheses. The experiments were to be timed to coincide with identified regional decisions concerning drawdown, flow augmentation and transportation. However, the Council appears to have had little interest in following through on this experiment. The NMFS Biological Opinion on mainstem operations and the proposed recovery plan for endangered Snake River salmon contained many elements in common with the Council's proposed experiment, although the integration of the hypotheses, experimental actions and evaluation are less clear.

A major thrust of our review has been to provide an explicit conceptual foundation for the Council's efforts. Many features of our conceptual foundation can probably only be tested through experimental manipulation of management actions. Faced with the same need to take action in the face of scientific uncertainty that prompted the Council to originally incorporate adaptive management into the FWP, we find that adaptive management still offers the best solution to refining and testing ecosystem-scale hypotheses. In their review of the scientific basis for ecosystem management, the Ecological Society of America (Christensen et al., 1996) has recognized the key role of adaptive management in dealing with the complexities and dynamic behavior of ecosystems.

However, the weak links in an adaptive approach are a long term commitment to scientific evaluation and the political will for management to change or adapt to new information (Christensen et al., 1996). Adaptive management requires a long-term vision that can support scientific evaluation in the face of fixed or declining budgets. It also calls for a fundamental shift in the relationship between managers and the scientific community. Managers need to treat their actions as experiments, accept failure as part of the learning process and discard cherished paradigms that fail under scientific testing (Lee, 1993; Volkman and McConnaha, 1993). It is not clear that the Council or any other regional management entity is politically equipped to effectively utilize adaptive management.

We recommend that the use of the term adaptive management be confined to explicit management experiments and avoided as a general prescription. The tendency in the region has been for a vast array of actions, very few of which lead to meaningful learning or improved actions, to be justified under the banner of adaptive management. Like any good scientific experiment, management experiments should include description of hypotheses, test conditions (management actions), and an explicit experimental design. A critical feature of a management experiment, and perhaps the most difficult, is a process for coupling the results of the experiment to management decisions.

Assessment of the Fish and Wildlife Program.

Below we describe our assessment of the conceptual foundation implied in the array of measures contained in the FWP and summarize our evaluation of the scientific justification for the critical assumptions and beliefs. This assessment is based on the conceptual foundation described in Chapter 2 supported by the review of scientific information presented in chapters 4 through 10.

For each italicized assumption, we assigned a qualitative rating that summarizes our assessment of the scientific support for the assumption based on the analysis presented in Chapters 4-10 (Box 2.1). The rating system is necessarily subjective, and is intended to convey our judgment of the degree of scientific support available for each italicized assumption based on our review, rather than representing a rigorous quantitative score.

Each assumption is highlighted in italicized print and followed by the appropriate reference to the Council's Fish and Wildlife Program (FWP), by the chapter in this report that supplies documentation for the conclusions presented here (RETURN TO THE RIVER or RTR), and our qualitative assessment of level of proof for supporting evidence. This is followed by explanatory text, which summarizes details and conclusions from the referenced RTR section

Box 3.1. Levels of scientific support for implied assumptions in the Fish and Wildlife Program.

1- Thoroughly established, generally accepted, good peer-reviewed empirical evidence in its favor.
2 - Strong weight of evidence in support but not fully conclusive.
3 - Theoretical support with some evidence from experiments or observations.
4 - Speculative, little empirical support.
5 - Misleading or demonstrably wrong, based on good evidence to the contrary.

General Principles

Both the Northwest Power Act and the Council's program appear to be premised on the following general principles:

1. The salmon bearing ecosystem in the Pacific Northwest and Northeast Pacific Ocean has considerable excess carrying capacity.

Level of Proof: 4

The conceptual foundation in Chapter 2 describes a Columbia River salmon bearing ecosystem that includes the marine areas encompassed by the migrations of salmon and steelhead populations as well as the freshwater habitats. The implied assumption of the FWP, and indeed in most management of Pacific Salmon, is that improvement of the freshwater environment will have a positive impact on overall salmon production by increasing the number of juvenile fish surviving to reach the ocean. Validity of this assumption requires that there is presently excess capacity in the ocean to support the increased numbers of smolts.

However, there is evidence that the abundance and dominance of different marine fish species fluctuates in response to environmental fluctuations, as well as to the removal of dominant species by harvest or other factors. The consequences of this for salmon in the Columbia River is that increases in numbers of juvenile fish due to improvements in the freshwater environment may not result in an immediate, corresponding increase in adult returns. While removal of ecosystem constraints caused by human activities in freshwater is key to restoration of salmon, an appreciation of the dynamic nature of both the freshwater and marine portions of the salmon bearing ecosystem is necessary to avoid unrealistic expectations of simple cause and effect relationships between management actions and fish production. It also emphasized that actions to protect salmon in freshwater become more and more important as survivals of salmon in the marine environment decline (see Chapter 10).

The normative ecosystem concept described in Chapter 2 stresses that pristine or pre-development conditions in the Columbia River are unattainable because species composition and other key features of the ecosystem have irrevocably changed. Similarly, the estuary and ocean ecosystems may have fundamentally changed during this century as a consequence of harvest, other human-caused factors, and natural environmental change. Variation in the ocean environment further confounds the relation between the actions in freshwater and resulting returns. Relative abundance of sardines and anchovies in the Pacific Ocean, for example, has shifted over time, as has the abundance of tule and bright fall chinook in the Columbia River. These, and other species shifts, may reflect long term environmental cycles that can be expected to continue into the future and will affect the outcome of efforts to control negative human impacts in the freshwater environment.

Spatial and temporal variability in the biological and physical aspects of the marine and freshwater phases of the ecosystem are fundamental features that have shaped the evolution of Columbia River salmonids. The biological solution to salmonid survival in a fluctuating environment has been for to develop a corresponding diversity of life histories. However, regional priorities in terms of effort and dollars have, for many years, stressed certain life histories and species over others. Fisheries restoration has focused on a subset of life histories and decreased overall life history diversity. For example, in the Columbia River, actions such as flow augmentation, spill, and smolt transportation have been managed to benefit primarily the central portion of the juvenile downstream migration composed predominantly of hatchery produced fish. This leaves the early and late migrating naturally produced populations unprotected, further driving the region to reliance on a very narrow range of solutions to a highly variable environment.

Restoration of life history diversity through improved management and the restoration of a diverse array of habitats, would increase the probability of achieving FWP goals. Increased life history diversity in fresh water environments should serve to buffer the effects of variability in the estuary and ocean environments.

2. Abundance of salmon and steelhead in the Columbia River Basin has, to a significant degree, declined due to, and is presently limited by, human actions.

Level of proof: 1

That human alteration of the salmon bearing ecosystem in the Columbia River has greatly contributed to the decline in salmon and steelhead in the basin is irrefutable. Even accounting for natural variation in the environment, decline of most species has closely paralleled the development of the basin and the degree of ecosystem alteration. Development and operation of the hydroelectric system has removed substantial portions of the basin from access by salmon and steelhead, altered the remaining mainstem and estuarine habitats, while logging, agriculture and urbanization have greatly changed tributary habitats. These continue to limit the abundance of anadromous and resident fish species and have decreased their ability to cope with natural environmental variation and alteration of the marine environment discussed above.

While the Northwest Power Act and the resulting Fish and Wildlife Program developed by the Council are premised on the importance of the alteration of the river by development and operation of the hydroelectric system, the narrow focus of the region on this single source of ecosystem alteration has hampered salmon restoration. This has also caused the region to focus much of its efforts on a single species and life history (Snake River stream-type spring chinook) thereby losing an appreciation of the diversity and abundance of salmon and steelhead encompassed by the entire basin. Without discounting the important role of alteration of mainstem habitat in the decline of salmonid species in the Columbia River, we feel that the ecosystem perspective of the conceptual foundation in Chapter 2 is key to the development of comprehensive solutions that address human imposed limitations on salmonid abundance throughout the basin at each stage of their lifecycle.

3. Ecosystem functions lost as a result of development of the Columbia River can be replaced by technological solutions to individual problems.

Level of proof: 4

During this century, the Columbia River Basin has been modified to provide for and protect human economic needs. Salmon restoration in response to that development has been based on the assumption that technological innovations could be devised that would substitute for ecosystem functions which would permit the continuation of abundant salmon populations. As dams were constructed, hatcheries were developed to substitute for lost habitat to permit the continuation of high harvest rates. The solution to alteration of mainstem habitat was to develop bypass systems, provide minor augmentation of flow for spring migrants, and to transport juvenile migrants around the developed river in barges and trucks. The extreme extension of this paradigm is evident in proposals to completely separate salmon from their ecosystem by construction of canals or pipelines to transport fish downriver leaving the river completely available to fulfill economic needs.

After decades of implementing these approaches, it is apparent they have failed. Despite innovative engineering and expenditures of billions of dollars over the course of this century, runs have declined inexorably to their present depressed condition (Figure 3.1). Efforts to develop technological solutions to individual human-imposed ecosystem changes have been based on the best of intentions and often on sound, if narrowly focused, science. In the review of the science behind each assumption in the present FWP that follows, it is apparent that, by and large, many individual assumptions are supported by the available scientific information. Yet, the fact remains that salmon have continued to decline despite actions based on these assumptions. It is our belief that this is the result of the guiding premise that for each identified source of mortality there is an individual technological solution. This piecemeal approach to ecosystem restoration presumes that we have sufficient knowledge to identify all direct, indirect, synergistic and cumulative impacts of our actions and that we can devise a technological solution for each impact. The recognized complexity and dynamic nature of ecosystems and the lack of success of this paradigm identifies this as an act of hubris. While technology will continue to be a part of any restoration effort in the Columbia River, we recommend that the region move from a strategy of "fixing" ecosystem damage to one that places greater reliance on re-expression of the natural biological and physical processes of the Columbia River salmon bearing ecosystem.

SPECIFIC ASSUMPTIONS

1. *Operation of the hydroelectric system is a major source of human-induced mortality limiting numbers and diversity of salmonid populations.*

FWP Chapters 1, 5 and 6; RTR Chapter 7. Level of proof: 1

Mortality induced by the development and operation of the hydropower system is well substantiated. Grand Coulee and Hells Canyon dams removed major portions of the basin from anadromous salmonid production, while dams below these produced reservoirs that destroyed most of the remaining mainstem fall chinook habitat. The series of hydroelectric dams induces both direct (such as in turbine passage) and indirect (such as flooding or blocking of spawning sites and increased predation) mortality. Modification of the salmon bearing ecosystem through development of the hydropower system is clearly one of the major factors limiting the numbers and diversity of upriver salmonid populations.

The negative impacts of habitat modification to the mainstem affect all populations above the dams regardless of local habitat conditions. With the exception of the Hanford Reach, the present river lacks many of the attributes of the normative river. Seasonal variation in flow has been reduced, while daily fluctuations have increased. Mainstem spawning and rearing habitat that may have historically supported vital core populations has been eliminated, species composition and diversity have changed, and food chains that formerly supported salmon and steelhead have been modified or eliminated. The magnitude of the mortality inflicted by the hydroelectric system relative to mortalities inflicted by other factors, such as habitat degradation in tributaries or ocean productivity cycles, is less clear. Efforts to minimize detrimental effects to salmon and their ecosystem from specific hydropower-related sources of mortality are desirable for preservation of salmon populations.

2. Operation and development of the hydroelectric system has altered the hydrologic profile of the river, which adversely affects survival of juvenile emigrants.

FWP Chapter 5 and 6; RTR Chapter 6 and 7. Level of proof: 1

The hydrologic profile has been altered by the hydrosystem in many ways that have important ramifications for the salmon bearing ecosystem that can adversely affect survival of juvenile salmonids. The spring flood that formerly assisted the juvenile outmigration have been reduced, increasing the metabolic costs of emigration. Fish that evolved to use water velocity to assist downstream migration must now expend metabolic resources to move downstream and to avoid predators. Salmon may reach the estuary late, exhausted of energy, or both. Flooding has been reduced or eliminated in both riverine reaches and in reservoirs thus reducing the production of aquatic insect food used by migrants and the biological and physical processes that maintain riverine food chains and habitats. Daily fluctuation in flow for power peaking along with rip-rap and other bank stabilization actions has simplified formerly complex habitats and created a barren shoreline zone less capable of supporting juvenile salmonids. Daily fluctuations also strand juvenile salmonids to die in peripheral slack waters or on shorelines. Annual temperature cycles that organisms use as developmental cues and that set rates of development have been altered by water storage and releases timed for hydropower purposes.

The altered seasonal flow pattern has changed the dynamics of the freshwater plume in the estuary and nearshore ocean, thus affecting productivity cycles there. The pattern and nature of sediment and organic matter delivered to the estuary has been altered by changes in flow patterns and the creation of reservoirs that act as settling ponds to trap sediment and organic debris.

These results have been demonstrated in varying levels of detail, but the weight of evidence for an overall major effects is clear. Re-establishment of key riverine aspects of the normative ecosystem is desirable for salmonid production.

3. There is a limited period of time within which yearling juvenile emigrants must reach the estuary to successfully move from the freshwater to the marine phase of the life cycle.

FWP Chapter 5; RTR Chapter 6 and 7. Level of proof: 2-3

This is an assumption with multiple causes, each having a different degree of substantiation. There are two aspects to the assumption: (1) smoltification, which is the sum of physiological and morphological changes in a juvenile salmonid that make it ready to migrate to the sea and be capable of tolerating the change from fresh water to salt water, and (2) estuarine conditions including food availability and predator abundance. This second point is related to the synchrony of timing of smolt entry to the estuary and coastal waters to coincide with seasonal cycles of plant and animal production. Both aspects of this assumption are cued by seasonal aspects of day length, temperature, and river flow, and it is reasonable to assume that salmon are evolutionarily adapted to a limited range of these conditions. Migration that is not successfully coupled to these processes is assumed to be at high risk.

Smoltification is a well substantiated process with timing and attributes that vary with life history type and species (see Chapter 6 on juvenile salmon migration). There is a large scientific literature on the process from physiological and morphological perspectives. The relationships of smoltification to the survival of juvenile emigrants is less certain. Experimental tests of the assumption have been largely based on releases of hatchery fish at different times, in which survival is determined relative to when the fish are deemed “ready” to migrate. The length of time within which fish must reach the estuary to make the transition to the marine environment or how this window is related to stock or environmental variables is relatively unexplored. The conservative approach that entails ensuring outmigration timing that is reasonably close to “natural” in order to match presumed smoltification is founded on theory that needs more substantiation. Maintenance of stock diversity may have depended on the migrants not all passing at a similar time. At the same time, the estuarine environment encountered by juvenile salmonids is highly variable and subject to a complex set of biological and physical factors. Smoltification and its ecological consequences are a suite of processes occurring against a backdrop of a complex and variable estuarine environment and unlikely to be fully understood soon. Because of this, preservation or restoration of normal seasonal cycles of flow, temperature and physical habitat, and maintenance of a diversity of estuarine entry times and patterns is likely to aid the normal expression of smoltification.

4. Yearling chinook emigrants utilize the mainstem Snake and Columbia rivers primarily as an outmigration corridor linking tributary and marine areas.

FWP Chapter 5; RTR Chapter 6 and 7. Level of proof: 2

There is good evidence that yearling chinook salmon are primarily in a migration phase when they occupy the mainstem Snake and Columbia rivers. However, treatment of the mainstem as a simple conveyance for rapid flushing of outmigrant yearlings by high flows is an oversimplification that is not based on the full scope of scientific evidence. Juvenile salmonids use the mainstem Snake and Columbia rivers for rearing and migration to the ocean. The degree of use of the mainstem for either of these activities varies with different life histories. There is likely a continuum of variation in the relative use of the mainstem for rearing and migration ranging over the different chinook life histories. The range is set by the ocean type (subyearling) life history that uses the mainstem for most or all of the pre-smolt rearing in addition to emigration, to the stream type (yearling) life history that rears in tributary areas and uses the mainstem mainly for emigration.

Yearling chinook emigrants need to have flows in the main channel available when necessary to move downstream. Clearly, downstream migration is facilitated by downstream water movement and higher migration rates are associated with higher water velocities. However, this is an incomplete model of the relationship between habitat conditions in the mainstem and yearling chinook survival. Being incomplete, it has led to incomplete solutions to alteration of mainstem habitats that are based around the concept that yearling chinook (and steelhead and other spring migrants) simply need to be moved out of the river as quickly as possible. The relationship between chinook emigrants and their ecosystem is likely to be far more complex than is suggested by the conventional model.

Although yearling migrants pass through the mainstem corridor quickly as compared to subyearlings, a limited amount of scientific data suggests that resting and feeding habitats are needed during pauses in migration, particularly at lower flow levels. Smolts undergo a daily cycle of movement, with the majority of movement occurring at night or during hours of dusk and dawn (although this does not occur for all fish every day and patterns at different locations may vary). Thus, habitat space is needed that is suitable for periodic holding. The use of the term "corridor" implies a simple channel, which neglects the likely (but incompletely tested) relationships between fish movement and velocity structure (turbulence, unsteady flows).

5. *Survival of yearling juvenile emigrants is inversely related to the amount of time they spend in the impounded sections of the mainstem Snake and Columbia rivers.*

FWP Chapter 5; RTR Chapters 6 and 7. Level of proof: 3

The relationship between exposure time of emigrating smolts to mortality factors in the hydroelectric system and the overall survival of smolts is intuitively reasonable, but has not been demonstrated conclusively. Abundance of yearling chinook has clearly declined in concert with the expansion of the hydropower system. One of the effects of the damming of the Snake and Columbia rivers has been an extension of the migration time spent in impounded sections, which has been documented. Reasonable mechanisms have been proposed for relating survival to duration of time in the hydroelectric system, including among other factors, increased exposure time to predators, disease vectors, and the amount of energy needed to complete migration. As temperatures increase, predator activity and metabolic rates climb, increasing the probability of predation. Various disease organisms become pathological with the increased temperatures found in the reservoirs. Thus, other factors interact with time in migration through reservoirs. The relative importance of the interactions of passage time with these factors has not been well defined. The nature of relationship between flow and survival remains to be established.

6. The amount of time spent by yearling juvenile emigrants within the hydroelectric system is inversely related to the prevailing water velocity. Therefore, survival is positively related to the water velocity prevailing during the outmigration.

FWP Chapter 5; RTR Chapter 6. Level of proof: 3

Since juvenile salmon use water currents to move down river, it is both reasonable and well documented that the amount of time spent by yearling juvenile emigrants within the hydroelectric system is inversely proportional to water velocity. To date, water velocities have been analyzed to generally relate them to fish movement on a daily or seasonal basis over large reaches of the river. However, the flow and velocity environment within reservoirs is complex and it is likely that the relationship is a much more localized phenomenon in that fish react to water velocities encountered at particular places and times. However, because it has not been possible to separate the influence of flow from that of other variables on survival, the relation between flow and survival remains obscured.

Water flow and velocity are extremely important physical components of the normative ecosystem which shape the environment and link the series of habitats occupied during the life histories of anadromous salmonids. For juvenile salmon, sufficient water velocity during the down river migration likely reduces energy costs, saves time, and thereby increases the fitness of the emigrants. Survival during emigration depends on a multiplicity of factors which are related to flow and velocity, such as temperature, predation, food availability, and hydroelectric system operations.

A prominent feature of the debate in the region over fisheries restoration has been the shape and parameters of the relationships between flow, velocity, fish travel time, and survival. It seems unlikely that an incremental quantitative relationship between these variables would apply equally to all species and life history types or necessarily be constant over time and space. Hence, we suggest the abandonment of the search for the elusive “correct” or “optimum” flow and instead we advise focusing on the restoration of a riverine velocity structure as close as possible to the pre-impoundment hydrograph.

7. *Water velocity can be enhanced either by augmenting flows from upstream reservoirs or by reducing the elevation of downstream reservoirs.*

FWP Chapter 5; RTR Chapters 6 and 7. Level of proof: 1

Under normal circumstances, augmentation of flows from upstream reservoirs increases volume of flow in rivers (generally raising main-channel water velocities) and reduction of the water surface elevation of downstream (mainstem) reservoirs will increase water velocities in these reservoirs. This has been demonstrated empirically and it has a firm and well understood basis in hydraulic engineering. See Chapter 6 on juvenile migration, especially the portion on fluid dynamics. Each has additional side effects, such as enhancing the Columbia River plume (flow augmentation) and restoration of riverine habitat (reservoir drawdown). Water velocities may be increased locally for benefit of salmonids by other means, however (e.g., baffles), which may be preferable to the larger-scale options.

8. *Subyearling emigrants utilize the mainstem Snake and Columbia rivers for both rearing and outmigration.*

FWP Chapter 5; RTR Chapter 6. Level of proof: 1

This has been clearly established through many years of field studies. As is discussed in point 4, above, chinook with the ocean type (subyearling) life history use the mainstem river for both rearing and emigration. In contrast to the stream (yearling) life history, the demarcation between rearing and emigration phases of the life cycle is less distinct in the ocean type life history. At the present time, despite elimination of most of the historical mainstem habitat, the ocean type life history appears to be favored over the stream type as evidenced by the predominance of fall and summer run fish. While the subyearlings thus have somewhat different habitat requirements than yearlings, they are not mutually exclusive.

9. *Subyearling chinook emigrants are less dependent on flow and water velocities as a physical aid to migration than yearling chinook emigrants, but are affected by high summer water temperatures.*

FWP Chapter 5; RTR Chapter 6. Level of proof: 1

This has been clearly established through many years of field studies. Subyearlings (ocean-type, fall and spring run chinook) spend more time than do yearlings (stream type, spring run chinook) holding in the shallow-water, near-shore habitats where they feed and rear. They use channel velocities mainly at night, but move shorter distances than do yearlings. Their combined rearing and migration is protracted through spring and summer. The shallow habitats they occupy in the daytime are subjected to severe solar warming and temperatures increase above their preferred and physiologically optimum levels in the low-velocity reservoirs. Field studies in Snake River reservoirs have shown that high temperatures force the fish out into the channel where food resources are often insufficient for normal growth

10. Creation of reservoirs has enhanced native and exotic predator populations and increased the vulnerability of juvenile salmonids to predation.

FWP Chapter 5; RTR Chapter 6. Level of proof: 1

Non-indigenous (exotic) predator species of fish have been introduced into the Columbia River system and appear to be well adapted to the present reservoir system. While there is incomplete evidence regarding increased numbers of indigenous (native) predatory fish as a result of the alteration of the mainstem environment, there is ample evidence from the literature regarding changes in fish community structure following impoundment in other river systems to believe that present conditions have resulted in increased numbers of indigenous predators as well. It is also clear that the present reservoir system has produced conditions that increase the vulnerability of juvenile salmonids to both indigenous and non-indigenous fish predators.

Although predation rates are now high as shown by detailed field studies, direct evidence is lacking to compare the current predation rates with rates that prevailed in the unimpounded river. A related uncertainty is whether the predator control program has been effective in increasing smolt survival although it appears to have been effective in reducing the numbers predatory fish. Creation of reservoirs has likely increased vulnerability, even without the presence of additional predators. High temperatures, gas bubble disease, poor food production, and greater energy expenditure required to transit slowly moving reservoirs compared to a swift river, and disorientation in dam passage, are some factors affecting vulnerability of juvenile emigrants.

11. Impacts of alteration of the hydrologic cycle in the Columbia River on salmonid survival is not limited to the impounded section of the river, but extends to the conditions in the estuary and survival outside the impounded section.

FWP Chapter 5; RTR Chapters 6,7, and 10. Level of proof: 3.

This statement is logical, and can be demonstrated for physical habitat, but resulting changes in salmon survival are unsubstantiated. Estuarine ecosystems, including an extensive coastal plume in the case of the Columbia River, depend on the horizontal and vertical mixing dynamics of fresh and saline water for their essential characteristics. There is good evidence that the changes in flows of the Columbia River have altered the seasonal extent and characteristics of the brackish Columbia river estuary and plume. Diking and filling in the estuary have reduced emergent plant production which has reduced the macrodetritus available to shallow water benthic consumers. Creation of dams and reservoirs has blocked downstream movement of organic debris from upriver areas. Because estuarine organisms that utilize organic detritus are prominent prey of juvenile salmonids, it is reasonable to assume there is a linkage between that change in the food web and the status of salmon, although that linkage has not been demonstrated. The food web in the estuary is now composed of deep water, benthic, and pelagic consumers which are favored by fishes such as Pacific herring, smelts, and the non-native American shad. There is some evidence that the fresh or brackish water plume of the river extending into the ocean could protect juvenile life stages from marine predators. The decreased size of the plume during the spring as a result of riverine flow modifications could increase the vulnerability of salmon during their entry into the ocean. The river-estuary interactions can not be ignored.

12. In addition to alteration of the hydrologic cycle and creation of reservoirs, the dams themselves form a second major impact of development and operation of the hydroelectric system.

FWP Chapters 5 and 6; RTR Chapter 7. Level of proof: 1

It has been clearly demonstrated over several decades that the dams themselves are temporary barriers to upstream and downstream migration and a complex source of additional mortality to juveniles that pass through forebays, turbines, and tailwaters. Fish ladders for adults have been reasonably successful; however, even with highly engineered bypasses, juvenile mortalities remain high. Spill of water and fish over spillways has been demonstrated to provide lower mortalities than mechanical bypass systems, but spill can cause gas supersaturation, which can cause mortality to fish.

Fish bypass systems have been developed as afterthoughts to the construction of most hydroelectric dams. The dams were designed primarily to produce electricity, allow navigation and provide flood control, and secondarily to permit safe passage of fish. Existing designs require extraordinary fish behavior such as sounding to pass through turbine intakes and into bypass systems. As a result, juvenile fish are delayed in their migration and made more vulnerable to predation, independent of the success of the bypass system once it is located by the emigrating fish. Examination of fish bypass needs in the context of the normative salmon bearing ecosystem concept might suggest alternative bypass designs based on the natural behavior of downstream migrating fish. Not only might bypass design be approach differently, but the normative ecosystem concept might suggest that schedules and operations of bypass systems be extended to provide protection for less abundant, but potentially biologically important, populations arriving before or after the bulk of the migration.

13. The primary source of mortality at dams occurs as juvenile fish pass through turbine generating units. This mortality occurs within the turbines and immediately downstream of the units.

FWP Chapter 5; RTR Chapter 7. Level of proof: 2-3

This is a generally valid assumption, although it varies among projects, salmon species, and life history types. Until recently, direct measurements of turbine-induced mortality were remarkably rare. The passage of fish through turbines includes delays at the forebay, descent to depths of turbine intakes, passage through the rotating blades, entrainment in the turbulence and pressure changes of the turbine draft tube, and ejection in a disoriented condition into the tailrace. Each step has potential for damage and mortalities. The assumption does not address losses in the forebay (e.g., predation, disease), which are caused mainly because descending to turbine intakes is contrary to the natural behavior of surface-oriented migrants. Because physical structure differs among the various hydropower projects, the relative impact of the many passage steps varies among projects. Although turbine passage is considered the primary source of mortality, it can be less damaging than poorly constructed bypasses or poorly located bypass discharges. Historically, gas supersaturation at dams may have induced more mortalities (latent and in-river) than turbine passage under some conditions.

14. Devices to collect juvenile fish before they pass into the turbines and deposit them downstream of the dam provide a benign means of passing the project.

FWP Chapter 5; RTR Chapter 7. Level of proof: 3

Substantiation of this assumption is mixed, depending on details of the bypass. The Council's goal of 90% FGE for intake screens has been achieved at some projects for steelhead, coho, and yearling chinook, but not for subyearling chinook or sockeye. The Council's goal of 98% survival in bypass systems has been achieved in a few hydropower projects, and is probably achievable in others with properly designed and maintained systems.

Bypasses in dams that use turbine-intake screens force migrants to alter their normal surface orientation, thus increasing delay in the forebay and associated mortality. Screens can also damage juvenile fish. Although bypass piping may be benign, release of fish downstream of the dam can increase predation. Some studies have documented overall bypass mortality in excess of that from turbine passage. Technology improvements to turbine-diversion bypasses have reduced overall mortalities, but the requirement of forcing fish to do something unnatural (dive to deep water and find passageways through gatewells and other dam structures) remains. Much more promising is the surface fish bypass, being tested at several dams, which uses the normal surface orientation of migrants and their tendency to follow surface currents as migration cues. This technology has promise of leading to benign passage. However, technology development is slow (bypasses have been developed over a period of over 30 years) and poorly responsive to rapidly declining fish stocks.

Finally, operation of bypass systems, like the operation of other bypass measures, is based on an implied cost per fish basis. Systems are operated when there are enough fish to justify the expense in the eyes of the operating entity. As is discussed elsewhere in this report, this results in less protection for early or late arriving migrants that may have important benefits to life history diversity. Over time, this could lead to selection of fish within a narrowing window of time and a further lessening of life history diversity.

15. Spill provides the route of hydroelectric project passage with the lowest mortality to juvenile emigrants.

FWP Chapter 5; RTR Chapter 7. Level of proof: 3.

Many uncertainties remain associated with this assumption. Managed spill using existing spillways to divert juvenile emigrants from turbine intakes is clearly less hazardous than turbine passage for those species and life history types for which measurements have been made. As levels of gas supersaturation which accompany spill increase, the benefits of spill may become less because prolonged exposure to gas supersaturated waters is a well substantiated mortality risk. Improperly managed spill or high levels of uncontrollable spill could decrease survival and negate any beneficial effect of spill passage.

Spill is known to disrupt feeding of predators on juvenile salmon in the areas immediately below dams. Hence the low mortalities observed for juvenile salmon passing hydroelectric projects via spill in the past may have depended in part on the effect of spill on rates of predation. Because of the cumulative effect of spill at successive dams, the desirability of spill as a means of maximizing survival of juvenile emigrants within the hydroelectric system as a whole, is less certain than the ability of spill to minimize mortalities of emigrants at individual hydroelectric projects. Field tests of critical assumptions regarding mechanisms and locations of reservoir mortalities, along with reach mortality estimates, are needed before spill can be relied upon as the most desirable means of passing the juvenile emigrants of all species and life history types through the hydroelectric system.

16. Transportation can mitigate, in some fashion, for the biological impact of operation and development of the hydroelectric system for some species and life history types of juvenile salmonids in the mainstem Snake and Columbia rivers, particularly in years of low runoff or other unusually bad conditions.

FWP Chapter 5; RTR Chapter 7. Level of proof: 3.

Transportation benefits are incompletely substantiated and assumptions of benefits are based on surprisingly few complete studies. Transportation involves the overt separation of salmon from their ecosystem and can provide no substitute for normative river conditions across the entire array of salmonid diversity in the river. However, in the absence of normative river conditions within the hydroelectric system, it may be able to delay the process of extinction for some species and life history types such as Snake River spring chinook.

The smolt transportation program in the Columbia River appears to have developed on the basis of the assumption that, because cumulative mortality on juvenile salmon passing through the mainstem rivers is high and occurs from a multitude of sources, a smolt transportation program would eliminate the need for both detailed scientific understanding of the ecological relationships that sustained salmon in the past and for technological solutions to each of the various sources of mortality brought on by development of the river. This logic has been supported by a series of studies that indicate better smolt-to-adult survival to the location where the tagged fish were released relative to the survival of fish migrating through the existing in-river conditions. These survival increases have been measured for only a few life history types and the increases are most substantial in years of very low flow. However, studies to date have not addressed the issue of whether transportation adequately mitigates for operation and development of the hydroelectric system or is simply better than the alternative for some life histories under some conditions. Abundance of most salmon and steelhead populations in the Snake-Columbia basin have plummeted during the period of mass transportation. This suggests that transportation is, by itself, insufficient to restore salmon species.

Under unfavorable migration conditions associated with low flows in the Snake River, transportation appears to offer a survival advantage for the stream type (yearling) chinook life history. The benefits of transportation to other life histories or species have not been tested in the Snake River. However, survivals of ocean type (subyearling) chinook transported from McNary Dam on the Columbia River indicate a positive benefit relative to migration over a broad range of lows under existing hydroelectric system configuration.

Restoration of normative river conditions may make transportation of juveniles unnecessary, if survivals of salmon were sufficiently high. Restoring the link between salmon and their ecosystem is a key feature of our proposed conceptual foundation. Normative conditions in the river would benefit feeding and rearing conditions for yearling and subyearling emigrants. Pending implementation of normative conditions, unfavorable circumstances associated with low flows may require transportation to be used in conjunction with, or in addition to, other mitigative measures.

The inability of transportation to protect all of the life history types of the listed species may require alternative mitigative measures and modification of transportation operations. Transportation is another mainstem juvenile fish passage measure that is conventionally managed to protect primarily the abundant central part of the migration with lesser or no protection for early or late migrants. Focusing on the central part of the migration is likely to contribute to reduced life history diversities and increase vulnerability to adverse fluctuations in natural conditions. Transportation also benefits only those fish susceptible to collection by bypass systems. If transportation is to be used, it should be applied across all dates of a migration, from beginning to end regardless of the number of fish migrating at any time. Because only collected fish can be transported, the benefit of transportation will also depend on the bypass factors discussed in points 12 through 14, above. The lower the fish guidance efficiency (FGE) for a species and life history type, and the greater its dependence on mainstem spawning and rearing habitat, the more important it is to provide conditions favorable within the river.

We conclude 1) that any benefit of transport will not accrue to all migrants but only to those for which we have a high ability to collect for transport and which are less dependent on habitat conditions in the mainstem for spawning and rearing, 2) that existing knowledge of the benefits of transportation across species, life histories, biological and physical condition is limited and based on a small number of studies conducted under a restricted set of conditions, and 3) that the existing knowledge indicates a decrease in benefits of transport as conditions move toward the more normative condition. For these reasons transportation is unlikely to be an adequate response to modification of the mainstem Snake and Columbia rivers, and is inadequate, by itself, to rebuild Columbia River salmonid populations. Transportation should be considered an experimental, interim measure pending restoration of normative conditions sufficient to permit persistence of all types of salmon in the Columbia River ecosystem.

17. Operation and development of the hydroelectric system has been a major source of human-induced mortality to adult migrants, which has limited numbers and diversity of upriver salmonid populations.

FWP Chapter 6; RTR Chapter 7. Level of proof: 2

Inter-dam losses of immigrating adult salmon indicate that not enough has been done to provide in-river passage conditions suitable to fall chinook, as well as for other salmon species and steelhead. Requirements for successful passage are understood, if not satisfactorily implemented at all projects. For example, at some projects restraints to adult passage occur under certain operating conditions and river flows that can lead to failure to achieve escapement goals. Warm temperatures during migrations are a serious cause of concern, particularly for fall chinook, but also for summer chinook and sockeye salmon in the mid-Columbia. Substantial migration delays also occur in the Snake River and its major tributaries due to temperature blocks, which preclude movement of adult fall chinook and steelhead above Ice Harbor Dam until waters have cooled in autumn. Although the technology for adult passage at dams has been mature for several decades, dam operations and temperature regimes have not been carefully studied for their impact on adult survivals. Fall back of adult salmon and steelhead through the turbines occurs at some dam projects and may be a problem.

Interruption of migrations due to the prevalence of high temperatures in the mainstem Snake River in the fall is well established. Upstream impoundments have generally shifted annual temperature cycles toward later dates. Thus, peak summer temperatures that once occurred prior to arrival of fall migrants, now occur during the fall runs. Delayed movements into the Snake River have been documented. Because of well-known physiological responses, delays at elevated temperatures use energy reserves needed for migration and spawning activity, which may result in pre-spawning mortalities even after the fish have cleared the hydroelectric system alive. Studies now in progress need to be carefully evaluated and acted upon.

18. Present harvest rates are a significant factor limiting chinook populations in the Columbia basin.

FWP Chapter 8; RTR Chapter 8. Level of proof: spring chinook, 4; fall chinook, 1.

It is well documented that chinook of all races, including spring chinook, are available to conventional harvest methods in the Strait of Juan de Fuca, the Strait of Georgia, the west coast of Vancouver Island, and points north to Alaska. Tagging information indicates that most of the reported harvest of Columbia River chinook consists of fall chinook and summer chinook for the mid-Columbia area, while landings of spring chinook in ocean fisheries are small.

However, impact of ocean fisheries on spring chinook salmon is uncertain due to an almost complete lack of information on stock composition of undersized chinook or chinook incidentally killed in the Pacific Ocean fisheries. Because ocean fishers are required to release smaller salmon, and because some of these released salmon do not survive, very large numbers of chinook are killed, but not landed in Pacific Ocean hook and line fisheries. Until the very sharp harvest quota reductions implemented in 1995, Pacific Salmon fisheries killed, but did not land the equivalent of several hundred thousand adult chinook from a variety of west coast populations.

Because these incidentally killed chinook were not landed to be sampled, the locations of their spawning habitats are unknown. This does not include ocean trawl net fisheries, which also kill salmon incidentally during fishing operations. It is therefore not inconsistent with available data to postulate that substantial numbers of immature spring chinook salmon of Columbia basin origin could be killed each year in the Pacific Ocean fisheries.

Fisheries operating in the Columbia River impact fall chinook almost exclusively. A commercial harvest of upriver spring chinook has not occurred since 1977 and the last commercial catch of summer chinook took place in 1973. Sockeye have been commercially harvested irregularly and not at all since 1988. Treaty Indian Tribes in the Basin may land up to several thousand spring and summer chinook each year for ceremonial and subsistence use, with the actual numbers landed dependent upon conservation needs of the stocks.

19. Adult return to spawning areas can be limited to some degree by illegal harvest in the Columbia and Snake rivers.

FWP Chapter 8; RTR Chapter 8. Level of proof: 4

Loss of adult fish to illegal catch is, by its nature, usually undocumented. There is no evidence that illegal harvest is a significant, chronic factor contributing to low returns of fish to upriver areas. Law enforcement efforts make it highly unlikely that poaching is a significant factor causing decline, even though some poaching may occur in remote areas.

20. Management of fisheries should be based on the amount of information available to managers regarding stock composition and abundance. Managers should be most restrictive on harvest when information on stock composition and abundance is the most uncertain so that errors do not occur at the cost of biological needs of the populations.

FWP Chapter 8; RTR Chapter 8. Level of proof: 2.

It is a fundamental principle of modern salmon management that information on mortality schedules and stock composition for all stocks of concern needs to be in hand before sanctioning fishing mortalities due to harvest. Nevertheless, such information is difficult to obtain for many stocks. The least amount of information on stock abundance and composition is available for high seas fisheries, while information increases as fish move inshore and into their natal rivers. Where uncertainty or lack of information hampers harvest decisions for specific stocks, a conservative approach is warranted, which minimizes risk to the stock in spite of uncertainty.

The definition of stocks of concern for the purposes of management and the extent to which each stock of concern must be addressed, are policy matters. However, the wisdom of managing harvest conservatively until adequate information is available to determine the allowable impact to different populations is evident if not common.

21. Permanent loss of production capacity in the Columbia Basin as a result of operation and development of the hydroelectric system can be at least partially mitigated by improvements in habitat conditions in tributary areas.

FWP Chapter 7; RTR Chapters 5 and 8. Level of proof: 3.

Construction of Grand Coulee Dam on the Columbia and Hells Canyon Dam on the Snake permanently removed substantial portions of the basin from the production of salmon and steelhead. Dams below these points inundated most of the remaining fall chinook habitat with the exception of the Hanford Reach. Because of capacity limitations, major losses of production of mainstem spawning populations resulting from inundation of spawning habitat cannot be mitigated solely by enhancing tributary habitat. Loss of access to tributaries above impassable dams also cannot be mitigated in remaining tributaries accessible to salmon. Juveniles from tributary stocks still need food production capacity in the mainstem for successful migration. Restoration of tributary populations should consider metapopulation concepts that include the tributary "satellites" in the context of a broader and fluid mainstem "core" population structure. For example for fall chinook, metapopulation concepts suggest that restoration of historic production zones in several mainstem areas, coincident with enhancing normative conditions via habitat restoration in the lower reaches of adjacent major tributaries, would be the most promising way in which both overall and tributary production could be enhanced.

22. The watershed is the appropriate physical unit around which to organize efforts to improve conditions in the tributaries.

FWP Chapter 7; RTR Chapter 5. Level of proof: 1

Rivers form a natural organizing feature of many ecosystems including the Columbia River Basin. For this reason, watersheds or catchments are natural structural elements and are appropriate units for organizing efforts to improve land use practices. However, a system of the extent and complexity of the Columbia River Basin is structured as a nested hierarchy such that efforts in individual subbasins or watersheds only make sense within the context of higher organizational levels such as ecoregions and the Columbia River Basin as a whole. Similarly, behavior of the ecosystem at these higher organizational levels can be understood only as the collective behavior of the lower organizational units. While subbasins or watersheds may be appropriate organizational units for biological, physical and social reasons, watershed planners should avoid undo introspection but instead should incorporate metapopulation structure and regional and basin-wide factors that form the context for their efforts.

23. Artificial production can be used to augment harvest without detrimental effects on naturally spawning populations.

FWP Chapter 7; RTR Chapter 8. Level of proof: 4

There is little empirical support for the proposition that harvest can be augmented by hatchery production without imposing detrimental effects on naturally spawning populations. There is increasing evidence that hatchery practices also have accelerated the decline of wild stocks. Harvest management programs focusing on harvesting hatchery production have chronically applied excessive harvest rates to naturally spawning populations.

Interactions between wild and hatchery fish have not been comprehensively examined, but the weight of evidence points to negative effects.

Because there has been a lack of comprehensive evaluation throughout the 120-year history of the implementation of the hatchery paradigm, it is not clear how to make the hatchery system more productive and more compatible with natural production in the basin.. Artificial propagation should be integrated into subbasin-specific watershed management, with a role and production objectives that are consistent with natural production goals for that subbasin. Artificial production must be viewed as an experiment, and should be implemented within an adaptive management framework. An important new objective of the experiment should be to reestablish metapopulation structure and function in the basin.

24. Natural populations are detrimentally affected by straying of returning hatchery fish.

FWP Chapter 7; RTR Chapter 8. Level of proof: 2.

Hatchery strays that interbreed with wild salmon are necessarily problematic if the hatchery has intentionally or inadvertently exerted selection pressure rendering the artificially propagated stock less fit in the natural habitat than the wild stock. Straying occurs naturally in salmon populations and is an important mechanism permitting recolonization of suitable habitat and the functioning of metapopulations. Salmon released from hatcheries also stray from their home stream into natural spawning areas and may successfully interbreed with wild salmon. The scale of hatchery production is often larger than the scale of natural production in streams, therefore, even if hatchery reared salmon stray at the same rate as wild salmon, the absolute number of hatchery strays can be greater. Consequently, large numbers of straying hatchery salmon can genetically swamp the naturally spawning population.

25. Overall survival of salmon and steelhead is decreased by exceeding the carrying capacity of the river, estuary, and/or ocean because of excessive releases of juvenile fish from production facilities.

FWP Chapter 7; RTR Chapter 6 and 8. Level of proof: 3.

The ecological, behavioral, and energetic interactions of hatchery fish with native species (including wild salmon) and fish assemblages of the Columbia River ecosystem have not been thoroughly studied and evaluated. However, the hydroelectric system has reduced the food production capability of the Columbia and Snake mainstems according to our analysis. An important component of this food base depended on seasonal flooding of riparian areas and rapid colonization and growth of aquatic insects (primarily chironomid midges). Regulated tributaries may have a similar reduction in food production important for rearing of migrants. Riverine food components have been replaced in lower Columbia River reservoirs by estuarine invertebrates that have lower nutritional value for juvenile salmonids. The Snake River mainstem has neither a riverine nor an effective replacement estuarine food base. The dominant reservoir plankton may be insufficient for the nutritional needs of juvenile salmonids. Additionally, it may be located in places that are inaccessible to subyearling migrants. Thus, the food production capability of the mainstem is deficient and may be made worse by infusion of an overabundance of hatchery fish.

26. Artificially reared fish can be used to augment the production of natural fish populations (i.e., in supplementation projects) in a manner that minimizes genetic change or reductions of fitness in the population.

FWP Chapter 7; RTR Chapter 8. Level of proof: 3

It remains to be shown whether natural and artificial production systems can be used in the same system to sustain long-term productivity. The conservation hatchery and captive broodstock technology are new concepts and roles for artificial propagation. Their purpose is to assist in the preservation of threatened or endangered stocks of salmon and to reestablish metapopulation structure. Their successful use is uncertain. Supplementation with a local stock depends on the ability of the habitat to support both naturally spawning and supplemented fish. Supplementation must be viewed as an experiment, and should be implemented within an adaptive management framework, confined to a limited and definite duration, using temporary facilities where possible. An important new objective of experimental supplementation should be to reestablish metapopulation structure and function in the basin.

27. Absence of fish screens or inadequate screens on agricultural and municipal water intakes leads to increased mortality of juvenile salmon and steelhead.

FWP Chapter 7; RTR Chapter 5. Level of proof: 1

Entrainment of juvenile migrants in agricultural and municipal water intakes is a well known source of mortality. Lack of screening may have been a factor in the extirpation of a number of salmonid populations including Snake River basin coho. Screening of water intakes is commonly employed in salmon restoration programs and has been shown to remedy this problem.

28. Productivity of naturally spawning populations is limited by habitat availability and habitat quality.

FWP Chapter 7; RTR Chapter 5. Level of proof: 1

Evidence exists to indicate that food production capability of the present mainstem habitat may be reduced relative to historic levels. A number of studies have documented the loss of pool and spawning habitats in tributaries due to siltation and inundation. Uncertainties about the lack of fertility in lakes, streams and headwater reaches resulting from the loss of nutrients contained in salmon carcasses has likely led to the disruption of the biogeochemical cycles. Disruption of this cycle leaves open the possibility of detrimental changes in food webs throughout the basin. Quantity of mainstem spawning habitat has undeniably been reduced by impoundments. Remaining spawning habitat in dam tail races is often of poor quality. Uncertainties about lack of fertility in headwater reaches remains

29. Biological diversity can be stabilized or increased through habitat conservation.

FWP Chapter 7; RTR Chapter 5. Level of proof: 2

Biological diversity arises as the interaction between the spatial and temporal diversity of the environment and the genetic and biological potential of the species. Diversity within the existing population of salmonids in the Columbia River is almost unquestionably less than occurred prior to development although comparative data are not available. While some diversity has been lost due to outright extirpation of populations, decline in diversity also has occurred in a more subtle manner through the elimination of habitat and the simplification of much remaining habitat. Management practices such as harvest, hatcheries and operation of mitigation measures such as transportation have also served to narrow the distribution of salmonid life histories. Conservation of the natural feature of the remaining habitat is essential to retaining the existing biological diversity, while re-expression of the natural diversity of tributary and mainstem habitats is essential to increasing biological diversity in the future.

Literature Cited

Christensen, N.L., A. Bartuska, J.H. Brown, S. Carpenter, C. D'Antonio, R. Francis, J.F. Franklin, J.A. MacMahon, R.F. Noss, D.J. Parsons, C.H. Peterson, M.G. Turner and R.G. Woodmansee. 1996. The report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. Ecological Applications 6(3): 665-691.

Halbert, C. 1993. How adaptive is adaptive management? Implementing adaptive management in Washington State and British Columbia. Reviews in Fisheries Science 1(3): 261-283.

Hilborn, R. and J. Winton. 1993. Learning to enhance salmon production: lesson from the Salmonid Enhancement Program. Canadian Journal of Fisheries and Aquatic Sciences 50(2043-2056).

Holling, C.S. 1978. Adaptive environmental assessment and management. New York, J. Wiley and Sons.

Lee, K. 1993. Compass and gyroscope: integrating science and politics for the environment. Washington, D.C., Island Press.

Lee, K.N. and J. Lawrence. 1986. Adaptive management: learning from the Columbia River Basin fish and wildlife program. Environmental Law 16: 431-460.

McAllister, M.K. and R.M. Peterson. 1992. Experimental design in the management of fisheries: a review. N. Amer. J. Fish. Mgt. 12(1): 1-18.

McConnaha, W.E. and P.J. Pacquet. *in press*. Adaptive strategies for the management of ecosystems: the Columbia River experience. Multidisciplinary Approaches to Reservoir Fisheries Management. Bethesda, Amer. Fish. Soc.

Volkman, J.M. and W.E. McConnaha. 1993. Through a glass, darkly: Columbia River Salmon, The Endangered Species Act, and adaptive management. Environmental Law 23(4): 1249-1272.

Walters, C.J. 1986. Adaptive Management of Renewable Resources. New York, MacMillan Publishing Company.

CHAPTER 4. DIVERSITY, STRUCTURE AND STATUS OF SALMONID POPULATIONS

"...that from so simple an origin, through the selection of infinitesimal varieties, endless forms most beautiful and most wonderful have been evolved." (Darwin, 1909)

In this chapter, we briefly review the status of the native salmonids of the Columbia River, with an emphasis on the diversity observed within and among populations and species. Salmonids are well-recognized for their diversity of life history strategies, ecological adaptations, and genetic variation. These factors are thought to be linked to salmonid productivity and to long-term persistence. The chapter is organized into two major section. In the first section, we provide background information on the stock concept, metapopulation organization, and the genetic structure of salmonid populations. In the second section, we describe the status of salmonid species in the Columbia Basin.

The Stock Concept

Diversity is an inherent property of salmonids in a normative ecosystem (Groot and Margolis, 1991; Taylor, 1991; Behnke, 1992). Salmonid diversity is expressed as population, life history, and genetic diversity and results in part from the ability of salmonid fishes to adapt to a wide array of habitat conditions (Taylor, 1991; Healey, 1994). Since habitats vary in space (i.e., from location to location) and through time at each location, diversity is likely not constant but changes as conditions in the environment change. Diversity probably contributes to resilience and stability of regional groups of salmonid populations.

From the time of Plato until the 19th century, western scientists viewed species as fixed types, based on an idealized set of characters that described each species (i.e., the Essentialists' view). Individual variation from this fixed type or ideal was viewed as an error attributable to developmental processes. Thus, biological diversity within a species had little positive meaning.

The transition from the concept of species as a fixed type, to species being comprised of many populations, each containing individuals that vary slightly from each other, was a major advancement in biology. It was this shift that gave Charles Darwin the point of view he needed to see the struggle for existence taking place between individuals and not species. Population thinking paved the way for Darwin's work on natural selection and the revolution of biological sciences that followed (Mayr, 1982).

A population, or stock, can be defined as a self-sustaining breeding group within a species that is relatively reproductively isolated from other breeding groups (Ricker, 1972). However, the term population has been used to define other kinds of aggregations of plants and animals. For example, fishery managers often define a stock as all the fishes of a species in a management area whose boundaries are set for administrative or regulatory purposes. Administrative and biological definitions of stock often come into conflict in salmon management. The implications of that conflict are discussed later in this section. The generally accepted definition of a salmon stock comes from Ricker (1972):

> *"fish spawning in a particular lake or stream (or portion of it) at a particular season, which fish to a substantial degree do not interbreed with any group spawning in a different place, or in the same place at a different season".*

Stock concept in fisheries

Population thinking was recognized earlier, and has undergone greater development in fisheries than in any other field of biology (Sinclair, 1988). All species of fish do not have the same level of complexity in their population structure. A comparison of population richness among marine fish species from the north Atlantic (Table 4.1) placed Atlantic salmon at one end of the range (a large number of populations) and the European eel at the other end (single population) (Sinclair and Iles, 1989). Pacific salmon should fall on the left-hand side of Table 4.1 at a level similar to the Atlantic salmon (Ricker, 1972).

Table 4.1. The continuum of population richness in anadromous and marine species in the northern Atlantic. (Source: Sinclair and Iles, 1989).

Atlantic salmon								
	Atlantic shad							
		Atlantic Herring						
			Atlantic cod					
				rainbow smelt				
					haddock			
						Atlantic mackerel		
							Atlantic menhaden	
								European eel

Decreasing population richness → → → →

Stock concept in Pacific Salmon

Not long after Pacific salmon came under commercial harvest, careful observers on the West Coast recognized that salmon from different rivers varied in important life history or morphometric characteristics. R. D. Hume, who operated salmon canneries in California and Oregon and was an early proponent of the artificial propagation of salmon, observed in 1893:

> *"The fact that in rivers which enter the sea within a few miles of each other, as well as the different tributaries of the same river, the fish (salmon) will have local characteristics which enable those who are familiar with the various streams to distinguish to which river or tributary they belong.*
>
> *I firmly believe that like conditions must be had in order to bring about like results, and that to transplant salmon successfully they must be placed in rivers where the natural conditions are similar to that from which they have been taken"* (Hume, 1893).

After reviewing the results of tagging experiments which supported the hypothesis that Pacific salmon homed to their natal stream, Rich (Rich, 1938) concluded that the species of Pacific salmon were divided into local populations:

> *"In the conservation of any natural biological resource it may, I believe, be considered self-evident that the population must be the unit to be treated. By population I mean an effectively isolated, self perpetuating group of organisms of the same species. Given a species that is broken up into a number of such isolated groups or populations, it is obvious that the conservation of the species as a whole resolves into the conservation of every one of the component groups; that the success of efforts to conserve the species will depend, not only upon the results attained with any one population, but upon the fraction of the total number of individuals in the species contained within the populations affected by the conservation measures."*

At least some fish culturists recognized the implications of the stock structure as early as 1939 and realized that the transfer of salmon between rivers was not a desirable management activity (Oregon Fish Commission, 1933). Although conclusive proof was lacking, biologists working in the Columbia Basin began to recognize that the salmon species were composed of populations adapted to their local habitat (Craig, 1935). Management had to take each population into consideration if it was going to be successful.

> *".....knowing further that each race is self-propagating, it becomes perfectly apparent that all parts of the salmon run in the Columbia River must be given adequate protection if the run as a whole is to be maintained. The protection of only one or two portions of the run will not be sufficient, inasmuch as certain races will be left entirely unprotected."* (Oregon Fish Commission, 1931).

Elements of a conceptual foundation that recognized the importance of stocks and local adaptation emerged in the 1930s (Rich, 1938). However, progress in this direction was truncated by the development of the hydroelectric potential of the basin and the plan devised to mitigate for that development, the Lower Columbia River Fishery Development Program (LCRFDP). Although the LCRFDP had six phases, the overall approach was to shift salmon and steelhead production to the lower river below the proposed McNary Dam. The desired level of production would be achieved by a combination of enhanced lower river stocks and the transfer of upper river stocks to the lower river (Laythe, 1948). The belief that such a transfer could be successful seems to contradict the understanding biologists had at the time regarding the importance and management implications of the stock structure of Pacific salmon. It should be noted that the Fraser River restoration program initiated a few years before the LCRFDP did emphasize the importance of individual stocks.

> *"Management of the Fraser River sockeye population by individual genetic races was developed and perfected by the commission (International Pacific Salmon Fisheries Commission). This management philosophy was an important component of the rehabilitation of the runs in combination with the contribution of fishways and commercial fishing closures"* (Roos, 1991).

The importance of stock structure in salmon management received renewed emphasis in the late 1960s and early 1970s (Calaprice, 1969; Paulik, 1969; Ricker, 1972). The Endangered Species Act (ESA) focused attention on the stock structure of Pacific salmon in the Columbia River in the late 1980s up to the present. Recently, stocks of Pacific salmon have been inventoried and their status described (Howell et al., 1985; Washington Department of Fisheries et al., 1993; Washington Deptartment of Fish and Wildlife and Oregon Deptartment of Fish and Wildlife, 1994).

Scientists often refer to local adaptation in salmon populations, although the evidence for it is circumstantial (Taylor, 1991). The term local adaptation can be misleading if adaptation is interpreted to occur only to a specific local environment, such as a spawning area in a tributary stream, rather than to all the habitats in which salmon complete their life cycle. Although salmon exist in populations that typically home to their natal stream and spawn in relative isolation from other salmon populations, they are adapted to the habitats (river, estuary, and ocean) where individuals in a population complete their life cycles, as well as to the variability that occurs in these habitats over both short- and long-term time scales. Such variation encompasses annual and decadal variations in climate, ENSO's (El Nino-Southern Oscillations), and geologic events.

Salmonid Life Histories and Habitat

Adaptation to the locally varied habitat may be expressed through variation in life history traits, although not all variation in traits among populations is adaptive. A trait exhibited by a local population is adaptive if it has a genetic basis and if it enhances survival or reproductive success (Taylor, 1991). Life histories are comprised of demographic traits such as age at maturity, mortality schedules, size, and growth (Stearns, 1995). Salmonid life history traits also include: a) the age and size that juveniles migrate within the river system (resident, riverine), into lakes (resident, adfluvial) or to the sea (anadromous); b) growth and maturity during riverine and laucustran migrations; c) spawning habitat preferences; d) emigration patterns; and e) age and timing of spawning migration. Many of these traits vary in response to environmental variation. For successful completion of the life history, quality habitat must exist for each life stage or mortality ultimately will exceed productivity and that life history type will be extinguished. In tributaries flowing through the shrub and shrub-steppe region of the Columbia river basin, the loss of summer migrating underyearling chinook salmon due to habitat degradation may have been a major cause of decline in spring and summer chinook salmon (Lichatowich and Mobrand, 1995).

Salmon habitat simply may be thought of as seasonally important places where salmon carry out their life histories (Thompson, 1959). The presence of these places is important, but so is the ability to move between them at appropriate times. Complex habitats with a high degree of spatial and temporal connectivity permit the development and expression of life history diversity, which is an essential component of salmonid productive capacity. In a life history context, salmon restoration implies re-establishment of life history diversity.

Stock Conservation

While the conservation of local populations or stocks of Pacific salmon and the preservation of their genetic resources is an important goal (Riggs, 1990; Altukhov and Salmenkova, 1991; Kapuscinski et al., 1991), achieving that goal is not simple or easy. Merely verifying that a local stock has different traits (size, time of spawning, time of juvenile migration, etc.) compared to other nearby stocks is not sufficient, but it is a good start. Documenting that the observed differences between populations is adaptive requires that the trait's genetic basis be documented. Variation in the trait must be related to differences in survival or reproductive success among individuals in a common environment, and the mechanism which maintains the trait in the population must be demonstrated (Taylor, 1991). These are not easy criteria to meet.

One might assume, since the extinction of a stock could represent a substantial loss of genetic diversity, managers would give evidence of local adaptation, even circumstantial evidence, the benefit of the doubt when setting stock boundaries. However, the size of a stock's boundary can have critical impacts on management programs. Narrowly defined boundaries complicate or prohibit harvest management in marine and lower river areas where stocks are mixed, and they restrict the use of hatchery fish in outplanting programs.

The need to conserve biodiversity between and within locally adapted stocks of salmon and the conflict between that goal and traditional management programs has created two strongly held positions characterized by the terms "lumpers or splitters". Lumpers tend to see few large stocks, where as splitters tend to see a large number of small stocks. Driving this debate is the underlying question: How much weight should we give to management strategies, as opposed to biological criteria, when setting stock boundaries? Biologists that manage salmon harvest and hatchery programs often define stocks as aggregates of populations (Thompson, 1965; Wright, 1965). Traditional harvest and hatchery practices based on that approach have contributed to a homogenization of the genetic differences between stocks (Calaprice, 1969; Nelson and Soule, 1987; Reisenbichler and Phelps, 1989), reduced the productivity, and have threatened the existence of populations in smaller, less productive streams (Ricker, 1958; Thompson, 1965; Wright, 1993).

To a large degree, the debate over the size of stock boundaries is driven by the search for the "ideal" stock designation. Managers are looking for stock boundaries that lead to the conservation of biodiversity and at the same time conveniently fit into existing harvest and hatchery management strategies.

However, there is no ideal stock designation. Even the definition used by Ricker (1972) leads to different interpretations because there is so little hard information on reproductive isolation or genotypic or phenotypic descriptions of spawning aggregations of salmon, particularly in the smaller streams. In addition, the species of Pacific salmon are organized in a hierarchical structure (this chapter, below). The biological units in the hierarchy (species, population or stock, subpopulation, individual) and their associated geographical units (region, river, tributary and redd) persist for different time intervals. The objective for most management actions should be to select the most inclusive population/geographic unit for which a management action will not cause the loss of genetic diversity contained in less inclusive groups (Mundy et al., 1995).

The debate over the home stream theory has been settled for several decades, but the stock concept still stimulates debate. Now the debate is over the methods and criteria used to identify stocks (stock boundaries). The Council's Fish and Wildlife Program (1994) calls for a study to identify criteria for setting stock boundaries (7.1c.1). The debate between "lumpers" and "splitters" is likely to intensify with the implementation of that measure.

The biological implications of the stock concept to fisheries management are profound. Disregarding the smaller populations or managing them collectively as we often do in our mixed stock salmon fisheries, can lead to disintegration of the stock system (Altukhov and Salmenkova, 1981). It is important to consider the fate of small subunits of a stock during management of routine harvest, hatcheries, river flows, and habitat protection. It is also critical that they be considered during years of crisis (Thompson, 1965; Paulik, 1969). For example, during periods of sustained drought, focusing management entirely on the larger stocks or stock aggregations will quickly drive the smaller subpopulations to extinction. The small populations that inhabit the marginal habitats within the range of a metapopulation may be an important source of genetic diversity of the species (Mayr, 1970; Scudder, 1989). W. F. Thompson (1965) described the problem thirty years ago:

> *"We regulate our fisheries. But we concentrate them on the best races and one by one these shrink or vanish and we do not even follow their fate because we have not learned to recognize their independent component groups or to separate them one from the other. We continue our unequal demands, knowing only that our total catches diminish, as one by one small populations disappear unnoticed from the greater mixtures which we fish".*

Salmonid Metapopulations

Metapopulations are spatially-structured groups of local populations linked by dispersal of individuals (Hanski, 1991; Hanski and Gilpin, 1991). Metapopulation persistence is determined by the balance of local population extinction and re-establishment of extinct populations through recolonization. Dispersal from neighboring local populations functions in recolonization of habitats where local extinction has occurred.

In their review of the status of Pacific salmon, the National Research Council (1996) recommended that salmon be viewed as metapopulations, rather than isolated stocks. The application of metapopulation concepts to conservation currently is being debated by scientists and managers, e.g., (Harrison, 1994; Mann and Plummer, 1995). Evaluation of the applicability of the concepts for understanding regional dynamics of aggregates of fish populations, including metapopulation structure, the role and rates of dispersal of individuals among local populations, and population extinction rates is in its early stages, e.g., (Rieman and McIntyre, 1993; Gresswell et al., 1994; Li et al., 1995; Mundy et al., 1995; Rieman and McIntyre, 1995; Schlosser and Angermeier, 1995; National Research Council, 1996; Rieman and McIntyre, 1996). Consequently data pertaining to salmonid metapopulation structure and dynamics is limited. Thus, the following discussion of salmonid metapopulation structure should be viewed as a hypothesis that requires further empirical evaluation.

Metapopulation structure is likely in salmonids (Rieman and McIntyre, 1993; Mundy et al., 1995; Schlosser and Angermeier, 1995; National Research Council, 1996) because they display high fidelity of homing to their natal streams (Helle, 1981), while at the same time exhibiting relatively low, but variable levels of straying (Quinn, 1993). High natal fidelity favors adaptation of specific breeding demes, i.e., local populations) to their environments via natural selection (National Research Council, 1996). In turn, this promotes population differentiation at the local level. However, because adjacent local populations are likely to occur in habitats that are similar (due simply to proximity), they may have very similar selection regimes. Therefore, any differences or genetic divergence that accrue among them may be due largely to the effects of isolation and genetic drift. Low levels of straying (i.e., gene flow) between populations will tend to counteract the effects of isolation and gene flow, thus retarding or even preventing genetic divergence among local populations. At the same time, straying among geographically adjacent populations permits recolonization of habitats where local extinction has occurred.

Recent studies suggest that salmonid metapopulations may maintain core-satellite structures (Rieman and McIntyre, 1993; Li et al., 1995; Schlosser and Angermeier, 1995). A metapopulation with a core-satellite structure (Hanski, 1982) tends to have high among-population variation in local population abundance (Harrison, 1991; Schoener, 1991; Harrison, 1994). Core populations are generally large, productive populations occupying high quality habitat. Large core populations tend to be less susceptible to extinction than satellite populations, which generally are less abundant and occupy lower quality habitats (Diamond, 1984; Hanski, 1991; Harrison, 1991; Schoener, 1991; Harrison, 1994). Core populations serve as important sources of colonists (Harrison, 1991; Schoener, 1991; Rieman and McIntyre, 1993; Harrison, 1994; Schlosser and Angermeier, 1995) that could both reestablish satellite populations in habitats where extinction had occurred and sustain populations whose abundance had been severely depleted, i.e., the "rescue effect" (Brown and Kodric-Brown, 1977; Gotelli, 1991). Rescue effects may be particularly important for persistence of smaller populations where environmental variation leads to high variability in demographic parameters (Stacey and Taper, 1992). Thus, core populations can buffer metapopulations against environmental change and contribute to the resiliency of regional salmonid production.

Spatial and temporal variation in habitat shapes metapopulation structure (Frissell et al., 1986; Reeves et al., 1995; Schlosser and Angermeier, 1995). The mosaic of alluvial and constrained reaches within watersheds, as described earlier in this chapter, influences the spatial distribution and proximity of local spawning populations (Schlosser and Angermeier, 1995; Stanford et al., *in press*). Moreover, favorability of connecting habitats influences the ability of dispersing individuals to move successfully among habitats (Rieman and McIntyre, 1993; Li et al., 1995; Rieman and McIntyre, 1995; Schlosser and Angermeier, 1995).

Spawning populations with the highest abundances likely occurred historically in alluvial segments with well-developed floodplains and gravel bars (Stanford et al., *in press*). These areas provide a complex habitat mosaic highly suitable for spawning, egg incubation, and juvenile rearing and may have functioned as centers of habitat stability. Channel morphology and hydraulics suggest that habitat in the lower reaches of streams is more stable than in smaller streams in the upper parts of watersheds (Naiman, 1992). Productive populations spawning in large alluvial mainstem reaches may have functioned as critical core populations (Stanford et al., *in press*). At a larger spatial scale, an entire watershed may function as a core area for neighboring watersheds within a region (Lindsey and McPhail, 1986; McPhail and Lindsey, 1986; Rieman and McIntyre, 1993; Schlosser and Angermeier, 1995).

Geographic Organization of Chinook Salmon

The geographic organization of chinook salmon in the Columbia basin above Bonneville Dam prior to extensive human development likely consisted of a complex mosaic of spring, summer, and fall races of salmon distributed among mainstem and headwater spawning areas (Figure 2.7). Local populations of fall chinook salmon whose juveniles migrated to the ocean as subyearlings spawned in several mainstem areas of the Columbia and Snake rivers and lower mainstem segments of Columbia River tributaries (Fulton, 1968; Howell et al., 1985; Mullan et al., 1992). Spring and summer chinook that migrated as subyearlings reproduced in upper mainstem segments of major subbasins and lower reaches of tributaries to subbasin mainstems (Lichatowich and Mobrand, 1995). Summer chinook probably spawned lower in the subbasin mainstems than spring chinook (French and Wahle, 1959; Fulton, 1968; Mullan et al., 1992; Lichatowich and Mobrand, 1995). Populations of spring chinook with yearling life histories reproduced in headwater streams of subbasin tributaries.

The complex of spatially distributed local spawning populations associated with major subbasins and contiguous areas of the mainstem Columbia or Snake rivers probably formed metapopulations. Fall chinook spawning in mainstem reaches of the Columbia and Snake and the lower reaches of major subbasins could have formed one type of metapopulation, while summer and spring chinook spawning in the upper mainstems of major subbasins and spring chinook spawning in headwater areas could have comprised another type.

Both genetic and life history evidence distinguish spring chinook from fall chinook in the Columbia and Snake basins. Additionally, genetic and tagging data show that Columbia River chinook are well differentiated from Snake River chinook, suggesting significant long-term reproductive isolation between the two groups (Utter et al., 1989; Matthews and Waples, 1991; Waples et al., 1991; Utter et al., 1995). In the Snake River, fall chinook are differentiated from the spring and summer races with respect to life history characteristics such as annual timing of adult migration, geographic distribution of spawning habitat, and genetic attributes (Matthews and Waples, 1991; Waples et al., 1991). French and Wahle (1959) observed summer and spring chinook on the spawning grounds of the Wenatchee and Methow rivers, whereas Mullan et al. (1992) reported mixing of summer and fall fish on the spawning areas of mid-Columbia river tributaries. In the Columbia River, there has been a tendency to group summer chinook and fall chinook because they both migrate downstream as subyearlings.

Historically, chinook population sizes and probabilities of extinction probably varied along a continuum determined in part by habitat size and quality. At one end of the continuum were the large core-type populations spawning in high quality mainstem habitats. Other local populations likely had characteristics similar to satellite populations. Local chinook populations most prone to extinction and probably most variable in abundance may have been those inhabiting smaller streams in arid terrain. In periods of drought, salmon populations inhabiting these streams may have had difficulty in persisting. Chinook populations intermediate in size and sensitivity to extinction may have occupied streams in regions with higher precipitation and streams draining mountainous terrain whose headwaters are in high elevation areas. In these streams, both flows and temperatures may be more suitable for juvenile rearing.

Potential Human Impacts on Metapopulation Organization

The extinction rate of local populations of chinook salmon has increased over the last 100 years (Nehlsen et al., 1991; Williams et al., 1992; Frissell, 1993; National Research Council, 1996) and has altered the organization of regional systems of populations in the Columbia basin (Figure 2.8; see also Figure 2.9). Metapopulation theory suggests that fragmentation and degradation of habitat can disrupt regional metapopulation organization through extirpation of vital core populations and isolation of remaining populations (Rieman and McIntyre, 1993; Harrison, 1994; Schlosser and Angermeier, 1995). In turn, this can significantly reduce long-term metapopulation persistence and the stability of regional production (Rieman and McIntyre, 1993; Harrison, 1994; Li et al., 1995; Schlosser and Angermeier, 1995).

Most fall chinook populations spawning in the mainstem reaches of the Columbia and Snake Rivers have been driven extinct. One of the remaining viable mainstem populations is the fall chinook population spawning in the Hanford Reach (Becker, 1985; Geist, 1995). Escapement to the Hanford Reach, where relatively high quality spawning and rearing habitat is still available, has averaged 40-50 thousand fish since the mid-1960's and peaked at over 200,000 spawners in 1986. This population is the largest naturally spawning population of chinook salmon above Bonneville Dam and has been stable over the years when populations in other parts of the basin have undergone severe decline (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995). Perhaps fall chinook in the Hanford Reach presently function as a critical core population. Recent observations of radio-tagged fall chinook from the Hanford Reach reveal extensive movements throughout an area that includes the confluences of the Snake, Columbia and Yakima rivers (D. Geist and D. Dauble, personal communication to ISG, May 1996). In turn, this suggests that chinook salmon from the Hanford Reach could function as colonists into adjacent habitats if normative conditions were restored in them. Apparently fall chinook spawners also were abundant in the section of the mainstem Columbia presently inundated by the John Day Reservoir (Fulton, 1968). This section of river could have formed another critical core area.

Populations of fall chinook also occur in the lower mainstems of most major subbasins, in the Snake River below Hell's Canyon dam, and in the tailraces of some mainstem dams (Lavier, 1976; Garcia et al., 1995), but their abundance is much lower than in the past. Most summer and spring chinook which spawned in upper mainstem segments of subbasins and lower reaches of tributaries to subbasin mainstems have been extirpated (Lichatowich and Mobrand, 1995). Aside from the Hanford Reach, natural production of chinook salmon is largely confined to relatively small populations of spring and summer chinook in headwater streams where high quality habitat is still available. For example, in northeast Oregon (Figure 2.9), a small population of fall chinook spawn in the lower reaches of both the Grande Ronde and Imnaha, in the free-flowing section of the Snake River below Hell's Canyon dam, and in the tailrace of Lower Granite dam (Garcia et al., 1995). Spring chinook are confined to headwater areas of the Grande Ronde and Imnaha rivers and their tributaries. Many of the streams supporting spring chinook originate in wilderness areas.

Fragmentation of metapopulation organization has caused reduction of local population and life history diversity and has increased isolation of extant populations. Inundation of alluvial habitats in the mainstem Columbia and Snake rivers following construction of dams and degradation of mainstem habitats in major subbasins (see Chapter 5) have virtually eliminated productive mainstem spawning stocks, as well as potentially important rearing areas for juveniles migrating downstream from tributary populations.

Regional Stochasticity

The probability of metapopulation extinction is enhanced if the dynamics of local populations and their individual probabilities of extinction become temporally correlated or synchronized (Harrison and Quinn, 1989; Hanski, 1991). Regional stochasticity refers to the correlated or synchronized dynamics of local populations resulting from the operation of common environmental factors (Hanski, 1991). Asynchronous or relatively independent fluctuations in local population abundance, in which some populations are increasing while others are decreasing, reduces the probability of metapopulation extinction (Boer, 1981; Gilpin, 1987; Goodman, 1987; 1988; Hanski, 1991) and probably stabilizes regional production. An important consequence of human development in watersheds likely is increased synchrony in the dynamics of naturally and artificially produced salmon.

Regional stochasticity can reduce metapopulation persistence time (Gilpin, 1987; Quinn and Hastings, 1987; Gilpin, 1988; Harrison and Quinn, 1989; Hanski, 1991; Rieman and McIntyre, 1993). Regional stochasticity tends to have less impact on metapopulation persistence when metapopulation size is large (the metapopulation is composed of many local populations), local extinction rates are low, and dispersal is high (Hanski, 1989; Harrison and Quinn, 1989; Hanski, 1991).

Adjacent local populations are more likely to respond synchronously to environmental factors, whereas local populations that are more geographically distant are more likely to experience asynchronous dynamics (Harrison and Quinn, 1989; Hanski, 1991; Rieman and McIntyre, 1993). However, the dynamics of geographically diverse populations can become correlated if, at some stage in their life history, individuals from diverse populations share a common environment, such as the ocean or a common migratory pathway (Rieman and McIntyre, 1993).

Salmon likely experience some degree of synchrony in dynamics due to the effects of natural environmental factors acting on regional scales in the ocean and in freshwater. Historically, if natural extinction rates in most local populations of salmon were relatively low, as they appear to be for many vertebrates (Schoener, 1983; Harrison and Quinn, 1989; Schoener, 1991) and metapopulation size was large, theoretically salmon could withstand the impacts of regional stochasticity (Harrison and Quinn, 1989). Synchrony also could be reduced if diverse populations or life history types migrated through mainstem areas at somewhat different times. For example, downstream migration of juveniles through the mainstem Columbia River historically appears to have occurred throughout the year but now it is restricted to specific periods during the late spring and summer (Lichatowich and Mobrand, 1995). Deleterious effects of environmental correlation among habitats also could be moderated if individuals within each local population responded differentially to the same set of environmental conditions, inducing a kind of within-population asynchrony.

Human activities have not only increased extinction rates of local salmonid populations (Nehlsen et al., 1991; Williams et al., 1992; Frissell, 1993; National Research Council, 1996), but they probably also synchronized the dynamics of remaining populations and thus, rendered regional metapopulations more susceptible to extinction (Rieman and McIntyre, 1993). For example, land use activities can have pervasive, region-wide effects on geographically diverse local populations (see Chapter 5). Synchrony can also be induced in common migratory pathways and the ocean as a result of mortality due to excessive harvest, construction of dams, and degradation of mainstem habitats. Synchrony may be more likely if migration timing of diverse populations is seasonally restricted. Moreover, over the last century, extinction rates have been elevated by human development of the basin, and local population and metapopulation sizes and dispersal rates have been reduced, possibly making salmon more susceptible to the effects of correlated natural environmental changes (Harrison and Quinn, 1989).

Redd counts in index areas of the Imnaha and Grande Ronde rivers and their tributaries suggest that some local spring chinook populations have been experiencing synchronous decline since the late 1960's - mid 1970's (Figures 2.10.1 - 2.10.5). Since the habitat where these stocks spawn is of relatively high quality, and considering that the Wenaha River (a tributary of the Grande Ronde River) is nearly entirely within a wilderness area, the synchronizing influence is likely downstream from the spawning areas, either in lower mainstems of the Grande Ronde and Imnaha, in the mainstem Snake or Columbia River, or in the ocean.

Human impacts may have shifted metapopulation structure from core-satellite to non-equilibrium metapopulations. In non-equilibrium metapopulations, extinction rates are consistently greater than recolonization rates and the metapopulations are undergoing regional decline (Harrison, 1991). Many stabilizing core populations have been driven extinct, recolonization and re-establishment of extinct local populations is limited or does not occur, and only isolated satellite populations remain. Isolated populations have little chance of being refounded after a local extinction compared to a population that is close to other populations. As populations become isolated, local extinctions become permanent and the entire metapopulation moves incrementally toward extinction (Rieman and McIntyre, 1993).

Conclusions for Metapopulations

1. The metapopulation concept, a spatially-structured system of local populations connected to some degree by dispersal, offers a different paradigm for understanding salmon life histories, population dynamics, and population persistence. Although largely untested and still developing theoretically, metapopulation structure, is a logical construct derived from the natural life history attributes of salmon, which include high homing fidelity to natal streams and low dispersal between populations, which results in local adaptation and genetic divergence among populations in a watershed.

2. We hypothesize that the large chinook populations that existed historically in the mainstem Columbia and upper Snake Rivers may have formed core populations for regional metapopulations. Core populations are large productive populations with low probabilities of extinction, that may have served to stabilize regional salmon production and probably functioned as source populations for recolonization of less favorable habitats where satellite populations occurred.

3. Human development has altered the organization of salmon populations, and consequently has probably altered metapopulation organization. This has very likely caused losses in resilience, life history diversity and adaptive capacity, and a reduction in regional stability of production.

4. Present restoration efforts have focused primarily on remaining satellite populations, which are smaller and less productive and may have higher probabilities of extinction than core populations.

5. Human development and management actions have increased the potential for synchrony among geographically diverse local populations and may have rendered present metapopulation organization more sensitive to the effects of regional stochasticity by reducing metapopulation size, increasing local population extinction rates, and reducing dispersal between populations.

Genetic Structure of Salmonid Populations

> *"Sustainable increases in salmon and steelhead productivity in the Columbia River Basin can only be achieved if the genetic resources required for all forms of production, present and future, are maintained in perpetuity" (Riggs, 1990).*

Anadromous salmonids occur widely throughout the northern hemisphere in river systems north of approximately 40^{o}N latitude. Native species in the genus *Salmo* occur across the northern arc of the Atlantic basin, while species in *Oncorhynchus* occur throughout the northern arc of the Pacific Basin. Species in *Salvelinus* occur in both Atlantic and Pacific Basin river systems. As a group, the salmonid species exhibit a remarkable range of diversity in life history characteristics, ecological attributes, and molecular genetic variability (Groot and Margulis 1991; Taylor 1991; Quinn and Unwin 1993). Although the exact mechanisms and relationships are poorly understood, genetic diversity is recognized as a major contributor to productivity, fitness, and adaptability (Allendorf and Leary, 1986; Quattro and Vrijenhoek, 1989; Liskauskas and Ferguson, 1991; Beatty, 1992). Therefore, it is important to understand how genetic variation in salmonids is structured within each species and among its populations, in order to preserve existing genetic diversity and to insure the persistence of evolutionarily derived aggregates of populations (Allendorf and Phelps, 1981; Allendorf and Phelps, 1981; Allendorf and Leary, 1988; Allendorf and Waples, 1996). The importance of local adaptation, and the microgeographic scale under which it may occur (Philipp and Clausen, 1995), is only now receiving increasing attention, in spite of its recognition by early fisheries managers (Rich, 1939; Schuck, 1943). Burgeoning recognition is also occurring that a biologically and economically feasible way to increase salmonid production is to utilize the natural productive capacity of existing native stocks that are adapted to their local environments, rather than attempting to rely on hatchery-reared fish that may not be adapted to specific local environments for production boosts.

Significant population genetic research, most of it relying on allelic variation at protein coding loci (i.e., allozymes), has occurred on salmonids in the last twenty years. These studies have described general patterns of genetic variation that are common to both anadromous and resident forms of salmonids. More recent direct analyses of mitochondrial and nuclear DNA, although frequently providing additional resolution beyond that provided by allozyme analysis, have largely revealed the same general principles of genetic structure within and among populations.

General patterns

Due to the commercial value and problems related to harvest, culture, and conservation (Utter, 1991), considerable effort has been directed into large scale genetic studies of Pacific salmonids. The initial purpose of these studies was to identify genetic differences among geographic populations within different species, such that samples from a mixed stock fishery as typically occurs in ocean catches could be examined for contributions by each of the geographic populations (Fournier et al., 1984; Milner et al., 1985; Utter et al., 1987; Shaklee et al., 1990; Utter and Ryman, 1993). An extensive multi-agency program has resulted in the creation of very large datasets that can be used to assess genetic structure within some species over much or all of their natural distributions. For example, geneticists from a number of federal, state, and provincial agencies, as well as universities, have compiled a dataset for chum salmon (*O. keta*) that examines 50-75 gene loci from over 150 populations throughout the Pacific Rim (Washington, British Columbia, Alaska, Russia, and Japan) (Beacham et al., 1985; Kondzela et al., 1994; Phelps et al., 1994; Wilmot et al., 1994; Winans et al., 1994; Phelps et al., 1995). Large genetic datasets also exist for other species of Pacific salmon and Atlantic salmon (*Salmo salar*), as well as for several interior salmonids including cutthroat trout (*O. clarki*), interior rainbow trout (*O. mykiss newberryi*), and bull trout (*Salvelinus confluentus*) (see species summaries below).

Such studies of genetic variation commonly indicate strong patterns of geographic structuring in salmonid species (Allendorf and Utter, 1974; Allendorf and Utter, 1979; Loudenslager and Gall, 1980; Stoneking et al., 1981; Utter et al., 1989; Bartley and Gall, 1990; Gall et al., 1992; Bernatchez and Dodson, 1994; Kondzela et al., 1994; Phelps et al., 1994; Shaklee and Varnavskaya, 1994; Varnavskaya et al., 1994; Wood et al., 1994). Geographically adjacent populations are typically less distinct from one another than from geographically distant populations based on suites of molecular genetic characters. Thus, genetic structuring among most salmonid species is hierarchical in nature, with the first level of differentiation occurring as geographical aggregates of populations (Figure 4.1).

Phylogenetic or evolutionary analysis of such data often reveals that the primary geographic groupings correspond to major evolutionary or ancestral lineages within each species (Utter et al., 1989; Busack and Shaklee, 1995; Utter et al., 1995; Williams et al., *in press*). These lineages reflect clear evolutionary divergence from other lineages within the species. For example, pink salmon (*O. gorbuscha*) can be separated into two major evolutionary lineages, based on even-year and odd-year occurrence (see species summaries below). The two lineages exhibit large genetic differences that are an expected consequence of the rigid two-year life history of pink salmon. This results in the nearly complete reproductive isolation of the even- and odd-year broodlines. Consequently, genetic differences have accumulated over evolutionary time between the two lines.

Below the level of the major evolutionary lines (Note: these are the major ancestral units of Utter et al. (1995) and the major ancestral lineages (MALs) of Busack and Shaklee (1995). See Appendix C for additional description of these categories specific to the Columbia Basin), salmonid species exhibit further genetic structuring that is also typically geographic in nature (Figure 4.1). Such regional differentiation has been observed in chum salmon in Washington (Kondzela et al., 1994), British Columbia (Beacham et al., 1985), Alaska (Phelps et al., 1994; Wilmot et al., 1994), and the western Pacific Basin (Russia and Japan) (Winans et al., 1994), where populations clustered on the basis of major islands, major river systems, and along major contiguous coastlines (see Chapter 4 for descriptions of genetic structure in individual salmonid species).

Typically, the next level of genetic structuring observed in salmonids is that of the individual watershed or subbasin, within which populations are usually closely related to one another (Figure 4.1; Utter et al., 1989). Nevertheless, populations within an individual subbasin may exhibit diverse life history strategies that include differences in run-timing, age and size at maturity, etc. Presently, we do not know the lower limit of genetic structuring within salmon populations; however, recent work by Gharrett and colleagues (Gharrett and Smoker, 1991; Gharrett and Smoker, 1993) on pink salmon in a small creek near Juneau, Alaska, has revealed heretofore unexpected levels of genetic substructuring within a single salmon population. Although salmonids are known for their ecological and behavioral plasticity, results such as these suggest a very strong role for local adaptation (with fitness implications) for many populations.

Genetic structure of Columbia Basin chinook salmon

Genetic structure of individual Columbia Basin salmonid species are presented in Chapter 4; however, it is instructive to briefly review the genetic structure of chinook salmon in the Columbia Basin because they demonstrate the general patterns discussed above, as well as a second pattern that seems to occur only in large river systems. Across their geographic distributions, chinook salmon form a genetically complex network of populations that are structured primarily on the basis of geography into large regional groups (see Figure 4.2; Wilmot et al. 1994), that correspond to the large regional groups identified for many other Pacific salmon species (Utter et al., 1989). Within the large regional groups, chinook also show substantial geographic substructuring, largely on the basis of subbasins or individual watersheds. Time of adult return to the river was not a major factor in establishing relationships of stocks among areas. Instead, populations with different run timings from the same stream were more similar genetically to one another than to populations with similar run-timing from different areas (Utter et al., 1989). Thus, one major conclusion from these observation is that run-timing differences between stocks within subbasins have evolved via life-history diversification from a single founding stock, regardless of the run timing of the founder stock. Therefore, the seasonal races of chinook salmon that occur in many subbasins have evolved many times as independent events. Evidence from introductions of Pacific salmon into exotic locations supports this idea. For example, Kwain and Thomas (1984) observed the development of spring-spawning chinook salmon in the Great

Lakes from introductions of fall-spawning chinook, while Quinn and Unwin (1993) described five different life history strategies in chinook salmon introduced to New Zealand from a single founding source.

In contrast to the general pattern described above, chinook populations in the upper Columbia and Snake Rivers (Matthews and Waples, 1991; Waples et al., 1991; Utter et al., 1995), exhibit substructuring on the basis of run timing, rather than geography (see Figure 4.3). In these instances, populations with similar run-timing were more similar to each other than they were to geographically proximate populations with different run-timing. In the Columbia Basin, these differences result in four distinct evolutionary groupings and are reflected in the ESA designations shown below (Table 4.2; Matthews and Waples, 1991; Waples et al., 1991):

Table 4.2. ESA designations for chinook salmon in the Columbia and Snake rivers.

River system	*Run-timing*	*(ESA designation)*
Upper Columbia River (UCR)	springs	ESU 1 (unlisted)
	summer-falls	ESU 2 (unlisted)
Snake River (SR)	summer-springs	ESU 3 (Endangered)
	falls	ESU 4 (Endangered)

It is interesting to speculate on why run-timing associations among populations, which are not apparent throughout most of the chinook salmon's range, occur in the Columbia and Yukon rivers. It may be related to the very large nature of these river systems that, although variable over space and time, probably supported core habitats that were stable over long periods of time, allowing local adaptation and divergence of populations based on run-timing. Strong heritability is associated with run-timing (Helle, 1981). Therefore, in an undisturbed system, one would predict that divergence between run types would be the evolutionary endpoint, however, turnover time for populations may occur frequently enough to counteract the processes of local adaptation, isolation, and divergence. This process can be looked at much like ecological succession, where there is an endpoint towards which things move if the system is left undisturbed long enough. However, frequent disturbance events continually reset the system back to or back towards its starting point, which for salmonids is the initial colonization of a watershed.

Pacific Salmon Species

Pacific salmon, as well as resident salmonids, have disappeared from much of their historic range, and in many locations once abundant populations have been extirpated or are severely depressed. For overviews of the decline and current status of Columbia River basin stocks see Nehlsen et al. (1991), Huntington et al. (1996), and the NRC report (National Research Council, 1996). Detailed status reviews also are available for mid-Columbia and Snake River salmon and steelhead stocks e.g., (Craig and Hacker, 1940; Chapman et al., 1994; Chapman et al., 1994; Chapman et al., 1995). At the present time, only Lewis River (WA) and Hanford Reach (WA) fall chinook, Wenatchee River (WA) sockeye, and five summer steelhead stocks in the John Day River (OR) can be classified as healthy (Huntington et al., 1996). Indigenous resident salmonids are now restricted to less than 5% of their original range (Trotter, 1987; Behnke, 1992). We also review the status of white and green sturgeon and Pacific lamprey in this chapter. These species are important food web corollaries of anadromous salmonids in freshwaters and recovery actions for the endangered Kootenay river sturgeon seem to be at odds with actions for endangered salmon e.g., (Marotz et al., 1996).

Chinook Salmon (*Oncorhynchus tshawytscha*)

Background

Chinook salmon are distributed in Asia from Hokkaido, Japan, north to the Anadyr River, Russia, and on the Pacific Coast of North America from central California to Kotzebue Sound in Alaska (Healey, 1991). North of the Columbia River, the post glacial radiation of chinook salmon came from two principal refugia: The two thirds of the Columbia River that remained ice free and Beringia, an ice free area in the lower Yukon River and adjacent coastal areas of the Bering Sea (Lindsay et al., 1986; McPhail and Lindsey, 1986). Chinook salmon radiated south from Beringia to about 56^{o}N and chinook salmon from the Columbia River recolonized deglaciated streams north to 56^{o}N.

Chinook salmon may enter rivers of the northwest in any month of the year (Healey, 1991). In the Columbia River, the spawning migration is divided into three distinct races: spring, summer and fall. At the present time, the largest run enters the river in the fall. Historically, the spring and summer runs were much larger than they are today, but they were depleted by over harvest and habitat degradation (Chapman et al., 1991; Chapman et al., 1994; Chapman et al., 1994; Lichatowich and Mobrand, 1995; National Research Council, 1995; Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995).

Gilbert (1912) divided the juvenile life histories of chinook salmon into ocean and stream types. The ocean type migrates to sea in the first year, often within three months after emergence. The stream type migrates to sea in the spring after a year in freshwater (Healey, 1991). The ocean type is the dominant life history in streams south of the Columbia River. Both ocean and stream types occur from the Columbia River north to 56^{o}N with the ocean type predominantly in the coastal areas and the stream type in inland areas. North of 56^{o}N the stream type life history is dominant (Taylor, 1990). After an analysis of the distribution of stream and ocean type life histories, Taylor (1990) concluded that variability in life history is in part a response to growth opportunity (environmental conditions) and selection for size at migration.

Evolutionary History and Genetic Structure of Chinook Salmon.

Neave (1958) argued that the Pacific salmon diverged into seven species entirely within the Pleistocene 500,000 to 1,000,000 years ago. However analysis of mitochondrial DNA suggests the ancestral line that produced chinook salmon is two to three million years old (Thomas and Beckenbach, 1989).

Genetic data exist for chinook salmon populations ranging from California (Utter et al., 1989; Gall et al., 1992) Oregon, Washington, British Columbia (Utter et al., 1989; Matthews and Waples, 1991; Waples et al., 1991; Utter et al., 1995), to Alaska (Gharrett et al., 1987). Chinook salmon form a genetically complex network of populations that are structured primarily on the basis of geography into large regional groups; see Figure 4.2 (Utter et al., 1995), that correspond to the large regional groups identified for many other Pacific salmon species. Within the large regional groups, chinook also show substantial geographic substructuring, largely on the basis of subbasins or individual watersheds. Throughout most of the chinook salmon's range, populations with different run timings from the same stream are more similar genetically to one another than to populations with similar run-timing from different areas (Utter et al., 1989). Thus, time of return is not a major factor in establishing relationships of stocks among areas. One major conclusion from these observation is that run-timing differences between stocks within subbasins have evolved via life-history diversification from a single founding stock, regardless of the run timing of the founder stock. Therefore, the seasonal races of chinook salmon that occur in many subbasins have evolved many times as independent events. For example, Kwain and Thomas (1984) observed the development of spring-spawning chinook salmon in the Great Lakes from introductions of fall-spawning chinook, while Quinn and Unwin (1993) described five different life history strategies in chinook salmon introduced to New Zealand from a single founding source.

Although chinook salmon show hierarchical levels of geographically-based genetic structuring throughout most of their range, chinook populations in the upper Columbia and Snake Rivers (Matthews and Waples, 1991; Waples et al., 1991; Utter et al., 1995), exhibit further substructuring on the basis of run timing, rather than geography (Figure 4.3). In these instances, populations with similar run-timing were more similar to each other than they were to geographically proximate populations with different run-timing.

Research on the genetic structure of chinook salmon in the Columbia Basin has focused on the higher levels in the hierarchy of genetic organization (see Appendix C), i.e., major ancestral lineages (Utter et al., 1995), genetic diversity units (Busack and Shaklee, 1995), Evolutionarily Significant Units (ESU); (Waples, 1991), and stocks. These efforts have been critical to our understanding of genetic structure within species and for the identification of genetic conservation units, such as ESUs. However, little effort has been expended on the genetic infrastructure within populations or stocks. The genetic infrastructure of a stock allows the population to adapt to fluctuating environments and to survive long-term environmental change (Gharrett and Smoker, 1993). One visible indication of variation within a population and an indication of infrastructure is the existence of life history diversity. Studies of chinook salmon have shown considerable variation in life history patterns (Reimers, 1973; Schluchter and Lichatowich, 1977; Carl and Healey, 1984). However, only one of these studies examined both life history and genetic diversity in the same population and that study did demonstrate a relationship between juvenile migration patterns and genetic diversity (Carl and Healey, 1984). In the Columbia Basin, Lichatowich (1995) hypothesized that the observed loss of life history diversity in spring and summer chinook salmon was due to depletion of the runs.

Historic and Present Distribution of Chinook Salmon

The predevelopment abundance of chinook salmon in the Columbia Basin was estimated at 4.7 to 9.2 million fish (Northwest Power Planning Council, 1986). In 1994, 400,000 chinook salmon of both hatchery and wild origin entered the river (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995).

Chinook salmon generally spawn in the mainstem and larger tributaries in the Columbia Basin. Therefore, the construction of mainstem dams has had a major impact on their spawning distribution and production. The spring/summer runs of chinook salmon migrated to and spawned throughout the Columbia and Snake rivers. Summer chinook spawned in the mainstem below the outlet of Windermere Lake in British Columbia, 1,200 miles from the sea (Fulton, 1968). In the Snake River, spring chinook migrated to Rock Creek, a tributary below Augur Falls, 900 miles from the sea (Fulton, 1968). Historically, the Salmon River (a Snake Basin tributary) alone produced 39 to 45 percent of the spring/summer chinook salmon in the Columbia Basin (National Marine Fisheries Service, 1995). Spring/summer chinook salmon are totally blocked in their upstream migration in the Columbia River at Chief Joseph Dam and in the Snake River by

Hells Canyon Dam. Fulton (1968) described the historical spring/summer chinook salmon spawning areas which were eliminated by development in the basin:

> *Major areas of the John Day and Umatilla rivers, parts of the Clearwater and Powder rivers, all of the Payette, Owyhee, Boise, and Bruneau, major portions of the Walla Walla, Yakima and Okanogan rivers, important tributaries above Chief Joseph Dam including the San Poil, Spokane, Kettle, Pend Oreille, and Kootenay rivers.*

The fall run of chinook salmon spawned in the lower tributaries and in the lower and middle mainstem of the Columbia River and in the Snake River up to Augur Falls (Fulton, 1968). Some of the most valuable spawning areas were in the mainstems of the Columbia River, nearly all of which were inundated by construction of dams. The Hanford Reach and the Snake River below the Hells Canyon complex of dams are the only remaining free flowing reaches in the Columbia Basin, however, the only significant remaining mainstem spawning area for fall chinook salmon is the Hanford Reach. Irrigation and habitat degradation eliminated spawning areas in many of the lower reaches of tributaries such as the John Day, Umatilla and Walla Walla rivers. In 1957-1960 the largest group of fall chinook (41,000 fish) spawned in the Snake River and the second largest (34,000 fish) spawned in the mainstem Columbia River in the area now inundated by the John Day Dam.

Life History Diversity in Chinook Salmon

The geographic organization of chinook salmon in the Columbia basin prior to extensive human development likely consisted of a complex mosaic of spring, summer, and fall races of salmon distributed among mainstem and headwater spawning areas (Figure 2.7). Local populations of fall chinook salmon whose juveniles migrated as subyearlings spawned in mainstem areas of the Columbia and Snake rivers and lower mainstem segments of Columbia River tributaries (Fulton, 1968; Howell et al., 1985; Mullan et al., 1992). Spring and summer chinook that migrated as subyearlings reproduced in upper mainstem segments of major subbasins and lower reaches of tributaries to subbasin mainstems (Lichatowich and Mobrand, 1995). Summer chinook probably spawned lower in the subbasin mainstems than spring chinook (French and Wahle, 1959; Fulton, 1968; Lichatowich and Mobrand, 1995). Populations of spring chinook with yearling life histories reproduced in headwater streams of subbasin tributaries.

The complex of spatially distributed local spawning populations associated with major subbasins and contiguous areas of the mainstem Columbia or Snake rivers may have formed metapopulations composed of local populations connected at least to some degree by dispersal. One type of metapopulation was composed of fall chinook spawning in mainstem reaches of the Columbia and Snake rivers and the lower reaches of major subbasins, while summer and spring chinook spawning in the upper mainstems of major subbasins and spring chinook spawning in headwater areas comprised another type of metapopulation.

Present metapopulations organization, which is fragmented as compared to probable historic organization, may result in reduced resilience; but, in theory at least metapopulations have the ability to recover from catastrophic decline. Habitat fragmentation has increased isolation of populations and probably reduced dispersal rates due both to increased distances between populations and the degraded quality of connecting habitats. Most mainstem spawning populations, which may have served as stable sources of colonists, are virtually extinct and viable naturally spawning populations are confined to relatively isolated headwater areas. Thus, dispersal among populations may be restricted making “rescue” of severely depleted populations and recolonization of habitats where extinction has occurred much less likely. Moreover, confining populations to headwater areas may increase their susceptibility to habitat alterations from land use such as grazing and logging (see Chapter 5) unless the populations inhabit areas protected from adverse land use.

Both genetic and life history evidence suggests that spring chinook are distinguished from fall chinook. Fall chinook are differentiated from the spring races with respect to life history characteristics such as annual timing of adult migration, geographic distribution of spawning habitat, and genetic attributes (Waples et al., 1991). Summer chinook in the Upper Columbia River appear to be more closely related to fall chinook, than to spring chinook; whereas, in the Snake River summer chinook are more closely related to spring chinook (Utter et al., 1995). French and Wahle (1959)observed summer and spring chinook on the spawning grounds of the Wenatchee and Methow rivers, whereas Mullan et al. (1992) reported mixing of summer and fall fish on the spawning areas of mid-Columbia river tributaries. There may be tendency to group summer chinook and fall chinook because they both migrate downstream as subyearlings. Conventional wisdom suggests that all spring chinook exhibit yearling juvenile migration even though there is evidence to the contrary.

Redd (salmon nests) counts in index areas of the Imnaha and Grande Ronde rivers and their tributaries suggest that spring chinook populations have been experiencing synchronous decline since the late 1960's - mid 1970's (Figure 2.10.1 - 2.10.5). In 1994 and 1995, no redds were located in the index areas in Bear, Hurricane, Indian, and the N. Fk. and S. Fk. of Catherine Creeks. No redds were recorded in Sheep Creek from 1993-1995. Since the habitat where these stocks spawn is of relatively high quality, and considering that the Wenaha River is nearly entirely within a wilderness area, the synchronizing influence may be downstream from the spawning areas, either in lower mainstems of the Grande Ronde and Imnaha, in the mainstem Snake or Columbia River, or in the ocean.

Harvest Summary of Chinook Salmon

Intensive fisheries did not begin until cannery technology reached the Columbia River in 1866 (Craig and Hacker, 1940). Chinook salmon, and especially the spring or summer run fish, brought the highest price and made the highest quality canned product so the early fishery targeted those runs (Craig and Hacker, 1940). After 1866, the catch of chinook salmon increased rapidly and peaked in 1883 at 19,413 mt (Beiningen, 1976). The harvest of chinook salmon can be divided into four phases (Figure 4.4.):

A. Initial development of the fishery (1866—1888);
B. A period of sustained harvest with an average annual catch of about 25 million pounds (1889—1922);
C. Resource decline with an average annual harvest of 15 million pounds (1923—1958);
D. Maintenance at a depressed level of production of about 5 million pounds (1958 to the present).

Recent declines may indicate the system is slipping to a new, lower level of productivity.

Between 1889 and 1920, the harvest of chinook salmon was relatively stable, however, catch data alone mask a major qualitative shift in the fishery (Figure 4.4). During that period, the spring and summer races of chinook salmon were declining and harvest was maintained by a shift from the spring/summer fish to fall chinook salmon. In 1892, fall chinook made up 5 percent of the harvest and by 1912, it had risen to 25 percent. In 1920, fall chinook salmon made up 50 percent of the catch. The harvest of all chinook salmon underwent a rapid decline after 1923, however, the decline in the spring and summer races started as early as 1911 (Craig and Hacker, 1940). One of the factors contributing to this decline was the development of the off-shore troll fishery which started in 1910 and expanded in the 1920s. Decline in abundance reached the point that two in-river fisheries were closed: 1965 was the last summer chinook season and 1977 was the last spring chinook season (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1993). In 1994, the Young's Bay fishery accounted for 81 percent of the commercial landings below Bonneville Dam (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995).

Propagation Efforts for Chinook Salmon

Chinook salmon were the first fish to be artificially propagated in the Columbia Basin. In 1877, a private company, the Oregon and Washington Propagation Company, constructed the first hatchery on the Clackamas River. The hatchery program grew rapidly and remained an important management activity even though there was little evidence that artificial propagation was in fact enhancing chinook salmon in the basin. After 1960, with the introduction of better feeds and hatchery practices artificially propagated chinook salmon began making significant contributions to the fisheries. The hatchery program for chinook salmon has grown from releasing 61 million juveniles in 1960 to 160 million in 1988. For more detailed discussion of artificial propagation see Chapter 8.

Coho Salmon (*Oncorhynchus kisutch*)

Background

The spawning distribution of coho salmon in the western Pacific extends from as far south as Chongjin on the east coast of North Korea north to the Anadyr River. In the Eastern Pacific, coho salmon are distributed from the San Lorenzo River on Monterey Bay to Point Hope in Alaska (Sandercock, 1991). Coho salmon generally enter the rivers to spawn in late summer or fall although spawning migrations in other seasons have been noted. More than one seasonal spawning migration into a single river is rare (Sandercock, 1991).

Evolutionary History and Genetic Structure of Coho Salmon

Coho salmon spawn in small tributary and headwater streams more frequently than other salmon species (Aro and Shepard, 1967). Coho exhibit low levels of genetic variation as compared to the other Pacific salmon species (Utter et al., 1973; Olin, 1984; Wehrhahn and Powell, 1987), but still show large regional geographic differentiation. Analysis of mitochondrial DNA suggest that three phyletic lines of salmonids diverged more than two million years ago and in one of those lines a subsequent divergence one to one and a half million years ago led to rainbow, coho and chinook salmon (Thomas and Beckenbach, 1989). Weitkamp et al. (1995) identified six potential coho salmon ESUs in California, Oregon and Washington: Central California coast, southern Oregon/northern California coasts, Oregon coast, lower Columbia/southwest Washington coast, Olympic Peninsula, Puget Sound/Strait of Georgia. The lower Columbia/southwestern Washington coast contains the stocks of coho salmon remaining in the Columbia Basin. Unfortunately, most of the native coho stocks in the Columbia River were extinct before an analysis of their genetic structure could be completed.

Historic and Present Distribution of Coho Salmon

The predevelopment run size of coho salmon was estimated at 903,000 to 1,780,000 fish (Northwest Power Planning Council, 1986). In 1994, the minimum number of coho salmon entering the Columbia River was 178,900 fish (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995) nearly all of which were of hatchery origin.

The principal spawning areas for coho salmon were in the tributaries to the lower river, however, Fulton (1970) also identified coho spawning in tributaries above Bonneville Dam including Hood, John Day, Grande Ronde, Spokane, Entiat, Wenatchee, and Methow rivers. All coho stocks above Bonneville Dam with the exception of the Hood River stock were classified extinct by Nehlsen et al. (1991).

At present, production of coho salmon is almost entirely from artificial propagation. The NMFS could not identify any remaining natural populations of coho salmon in the lower Columbia River that warranted protection under the Endangered Species Act (Johnson, 1991). The possible exception is the late run of coho salmon into the Clackamas River. Whether the Clackamas stock is the last remaining wild stock in the Columbia River or a stock similar to the other hatchery stocks in the lower river is uncertain (Weitkamp et al., 1995). Remnant wild populations may also exist in the Hood River and Klickitat River. Habitat degradation and overharvest contributed to the depletion and extinction of the wild coho salmon stocks in the Columbia River. The massive hatchery program was an additional factor in the decline of coho salmon (Flagg et al., 1995).

Harvest Summary of Coho Salmon

Coho salmon were not as abundant as chinook salmon in the Columbia River. Coho salmon were considered inferior by the cannery operators so they were not harvested in the early years of the intensive fishery in the Columbia River (Figure 4.5) (DeLoach, 1939; Craig and Hacker, 1940). The first coho salmon were commercially harvested in 1892 in conjunction with a shift in harvest to fall running fish when the prime spring run of chinook salmon became depleted (Lichatowich and Mobrand, 1995). The fishery for coho salmon intensified after 1920 when chinook salmon went into rapid decline, however, by the mid 1930s coho salmon were also in a steep decline that persisted for 30 years (Figure 4.6). The decline was real, but part of the apparent decline was due to a shift to offshore fishing by the growing troll fleet. After 1930, harvest in the Oregon Production Index (OPI) is a better indication of the pattern of abundance of Columbia River coho salmon. The OPI includes in-river and ocean catch of coho salmon from southwestern Washington to northern California (Figure 4.7).

In the mid 1960s, improved hatchery practices and favorable ocean conditions combined to produce an apparent recovery of coho salmon production which persisted until 1976 (Figure 4.8). The recovery was primarily due to increased survival of hatchery reared fish. The wild component of the OPI harvest remained depressed throughout the 1960s and 1970s (Figure 4.8; data from ODFW 1982; Borgerson 1992; Pacific Fishery Management Council 1992). By 1991, habitat degradation and fisheries on mixed stocks of wild and hatchery coho salmon led to the conclusion that no viable wild stocks of coho salmon existed in the Lower Columbia River (Johnson, 1991).

Propagation Efforts for Coho Salmon

The first plant of artificially propagated coho salmon in the Columbia Basin took place in 1896. Coho salmon have been propagated continuously since 1900 (Cobb, 1930). There are now 16 hatcheries operating in the lower Columbia River (Johnson, 1991) which have released 29 to 54 million juvenile coho salmon in recent years (1984 to 1992). The origin of the coho salmon brood stocks in Oregon's lower Columbia River hatcheries is uncertain. Johnson et al. (1991) described the brood stocks as mixtures of fish from a variety of sources, including coastal populations, Washington stocks, and native stocks. These mixed stocks have been extensively outplanted throughout the basin (Flagg et al., 1995). For additional information on the hatchery program see Chapter 8.

Chum Salmon (*Oncorhynchus keta*)

Evolutionary History and Genetic Structure of Chum Salmon

Chum salmon populations exhibited the kind of geographic and regional differentiation described in Figure 4.1 (Beacham et al., 1985; Kondzela et al., 1994; Phelps et al., 1994; Wilmot et al., 1994; Winans et al., 1994; Phelps et al., 1995), where populations clustered on the basis of major islands, major river systems, and along major contiguous coastlines (see Figure 4.2 showing the genetic distances among chinook salmon populations from northern Alaska and Russia). In some instances, however, chum salmon populations in regional aggregates sorted by run-timing, rather than by subbasin. In other words, as is the case for chinook salmon outside the Columbia River basin, chum salmon populations in several regions including the Yukon River (see Figure 4.2; summarized from Wilmot et al., 1994), Hood Canal, and Puget Sound (Phelps et al., 1995) were more similar to distant populations with similar run-timing than they were to adjacent populations (within the same subbasin) with different run-timing.

Historic and Present Distributions of Chum Salmon

The three remaining spawning areas for chum salmon are in Washington State in tributaries to the lower river below Bonneville Dam (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1993) in Hamilton Creek, Hardy Creek and the Grays River.

Harvest Summary of Chum Salmon

Chum salmon were not as abundant as chinook salmon in the Columbia River and were considered inferior by the cannery operators, so they were not harvested in the early years of the intensive fishery in the Columbia River (Figure 4.4) (DeLoach, 1939; Craig and Hacker, 1940).

Chum salmon entered the fishery in 1894 in conjunction with a shift in harvest to fall running fish as the prime spring run chinook became depleted (Lichatowich and Mobrand, 1995). From the early 1900s through the 1950s, the harvest of chum salmon was more variable but generally followed the trend in harvest of coho salmon (Figures 4.5 - 4.7). Since chum salmon were the lowest grade of canned salmon in the Columbia River, some of the variability in harvest was due to a fluctuating demand for cheap fish (Craig and Hacker, 1940).

Propagation Efforts for Chum Salmon

Chum salmon were not propagated extensively in hatcheries and their abundance did not increase in the 1960s. The collapse of chum salmon in the 1940s and 1950s paralleled the decline of chum salmon in Oregon, Washington and British Columbia suggesting that it was due to a regional climatological or oceanic factor (Oakley, 1996).

Sockeye Salmon (*Oncorhynchus nerka*)

Background

Sockeye salmon are distinguished from other Pacific salmon species by their use of lakes for the freshwater rearing of juveniles. Sockeye are widely distributed in western North America and eastern Asia (Burgner, 1991), however sockeye have been extirpated from most of the localities formerly occupied in the contiguous United States (California, Oregon, Washington and Idaho).

Substantial information exists on reproductive biology, age structure, growth and productivity of Columbia River sockeye. Columbia River sockeye salmon spawn in tributaries and outlets of Lakes Wenatchee and Osoyoos in August and September (Mullan, 1986; 1994; Hatch et al., 1995) and hatch and swim into rearing lakes in the late winter and spring of the following year. Depending on growth, sockeye juveniles will spend one to three winters in the rearing lake and one to three winters in the ocean. Slower growing sockeye take longer to pass through each life history stanza than faster growing sockeye. The typical Columbia River sockeye spends one winter in freshwater and two winters in the ocean to return as an adult in its fourth year of life.

Lake Osoyoos (Okanogan River) sockeye are unique among sockeye populations in occasionally having three-year-old adults as the dominant age class (one winter in freshwater and one in the ocean). Size at age, growth, productivity, and historical zoogeography are reviewed by Fryer (1995). Columbia River sockeye from Lake Osoyoos tend to be large as smolts, greater than 10 cm, and small as adults, less than 45 cm, and less than 2 kg, whereas Wenatchee sockeye tend to be smaller than Osoyoos sockeye as smolts, and larger and older as adults. Differences between the attributes of Wenatchee and Osoyoos sockeye are ascribed to the physical and biological differences in the characteristics of the rearing lakes (Fryer, 1995).

Evolutionary History and Genetic Structure of Sockeye Salmon

Sockeye salmon occur in rivers associated with nursery lakes or in groundwater dominated streams widely along the Pacific coast north of the Columbia River and within a limited distribution in Russia along the Kamchatka Peninsula and the northern coast of the Bering Sea (Varnavskaya et al., 1994). Like coho salmon, sockeye exhibit a low level of genetic variation as compared to pink, chum, or chinook salmon (Varnavskaya et al., 1994; Varnavskaya et al., 1994; Wood et al., 1994). This may be the result of inbreeding related to the greater extent of reproductive isolation between spawning populations, a consequence of well-developed homing behavior in sockeye as demonstrated by tagging experiments and gene flow calculations (Quinn et al., 1987; Altukhov and Salmenkova, 1991).

Nevertheless, the genetic architecture of sockeye salmon shows large scale geographic differentiation, with groups from Kamchatka, western Alaska, southeastern Alaska, northern British Columbia, southern British Columbia, and Washington being well differentiated (Varnavskaya et al., 1994; Wood et al., 1994). Large genetic differences occur between sockeye from some of the different regions, reflecting major ancestral or evolutionary lineages, which appear to have been influenced by recent historical glaciation events. Present distributions and genetic relationships among sockeye populations appear to be related to historical expansion and recolonization from a few ice-free refugia (Wood et al., 1994). Within each of these larger regions, sockeye salmon populations showed additional geographical substructuring; however, populations within regions were well-differentiated from one another, reflecting the relative reproductive isolation of individual sockeye populations from one another.

Historic and Present Distribution of Sockeye Salmon

At least twenty-seven lakes originally supported populations of Columbia River sockeye in Oregon, Washington, and Idaho (Fryer, 1995). Loss of access to spawning areas due to construction of small agricultural storage and diversion dams has reduced the number of lakes open to sockeye, a reduction of 96% in juvenile rearing habitat between settlement during the 1840s and the present (Rich, 1941; Mullan, 1986; Northwest Power Planning Council, 1986; Fryer, 1995). Sockeye occur in the Columbia River basin in three localities: Lake Wenatchee, Washington; Lake Osoyoos, Washington and British Columbia; and Redfish Lake, Idaho. However the Idaho population is a federally listed endangered species as of December, 1991.

Age, growth and stock identification studies and spawning ground surveys are conducted by the Columbia River Inter-Tribal Fish Commission under the auspices of the Pacific Salmon Treaty.

Harvest Summary of Sockeye Salmon

Historical annual abundances in the area of two to three million adults (Chapman, 1986; Northwest Power Planning Council, 1994) supported annual commercial landings which twice exceeded 4.5 million pounds during the 1890's. As measured by commercial catches, adult returns of Columbia River sockeye declined sharply after, 1900. Present levels of returns are in the tens of thousands, with spawning escapements to both Osoyoos and Wenatchee being less than ten thousand adults each, in 1995. The number of adults deemed by the management entities to be sufficient for fully seeding sockeye spawning grounds, i.e., the escapement goal, for the Columbia River basin is presently 75,000 (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995). No commercial fishing has occurred since 1988, and the annual commercial season has often been canceled during the past twenty-five years. A sport fishery occurs on Lake Wenatchee when abundances permit, yielding a catch of 7,000 sockeye as recently as, 1993 (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995). Subsistence and ceremonial harvests by treaty Indian tribes occur above Bonneville Dam, with harvests being in the area of 5,000 adults per year, prior to the limiting of sockeye salmon as a federally endangered species in Idaho.

Propagation Efforts for Sockeye Salmon

Current propagation efforts for sockeye occur on the Lake Wenatchee, Redfish Lake, and a small population in the Lake Osoyoos sockeye populations. Sockeye have proven difficult to culture with standard hatchery methods due to their susceptibility to disease. The alternative that has been developed is to move the fry soon after hatching into net pens in the lake where they are reared for a time and then released into the lake to overwinter before spring outmigration.

Propagation efforts at Lake Wenatchee, funded by the Chelan County P.U.D. as part of a FERC agreement, have added about 15% to the sockeye outmigration from Lake Wenatchee.

The program for the recovery of the endangered Redfish Lake, Idaho sockeye is administered by the National Marine Fisheries Service in cooperation with the Bonneville Power Administration, the State of Idaho and other concerned fisheries agencies, including Indian tribes. The program involves and relies heavily on artificial production using all returning Redfish Lake sockeye, along with genetic input from the resident beach spawning kokanee, which are part of the same ESU.

Considerable propagation efforts have been directed at kokanee, the resident form of sockeye salmon. Stocks have been widely transferred throughout the basin, and kokanee populations in most large lakes or reservoirs are genetic mixtures of multiple stocks (R. Williams and M. Powell, unpublished data). There is interest in the basin in attempting to reestablish anadromous sockeye runs from residualized kokanee populations; however, the probability of that occurring may be decreased as a consequence of the mixed genetic heritage of most kokanee populations.

Pink Salmon (*Oncorhynchus gorbuscha*)

Evolutionary History and Genetic Structure

Pink salmon can be separated into two major evolutionary lineages, based on even-year and odd-year occurrence that exhibit large genetic differences (Gharrett et al., 1988). This is an expected consequence of their rigid two-year life history and results in the nearly complete reproductive isolation of the even- and odd-year broodlines. Within the even- and odd-year broodlines, pink salmon populations show typical hierarchical geographic differentiation as described above (Beacham et al., 1988; Gharrett et al., 1988; Varnavskaya and Beacham, 1992; Shaklee and Varnavskaya, 1994, 1995 #18462).

In spite of the near reproductive isolation of the two broodlines throughout their native distribution, Kwain and Chappel (1978) reported the development of even-year pink salmon runs from a single release of odd-year breeding pink salmon into the Great Lakes.

Historic and Present Distributions of Pink Salmon

Pink salmon occur irregularly along the Oregon and Washington coasts, including the Columbia River, but spawning distributions occur from Puget Sound and the Olympic Peninsula north to Norton Sound in Alaska (Groot and Margolis, 1991; Hard et al., 1996).

Trout and Char:
Rainbow Trout, Cutthroat Trout, and Bull Trout

Background

Rainbow and cutthroat trout exist in both anadromous and resident forms. Distributions and abundance of both species and forms have declined in the last 150 years to fractions of their historic ranges (10-30% depending upon species) (Trotter, 1989; Behnke, 1992; Lee et al., *In Press*). Reasons for declines are similar for all taxa. The declines are reasonably well-documented and concerns over the status of various species, subspecies, or distinct local populations have prompted a series of petitions for review or listing under the Endangered Species Act. These include reviews of the status of steelhead populations coast-wide and sea-run coastal cutthroat trout from the Umpqua River for anadromous forms, as well as reviews of the status of interior rainbow trout (i.e., redband trout) and bull trout (species wide). None of these petitions have resulted in new listings under the ESA. A listing decision on the Umpqua coastal cutthroat is imminent. The bull trout status review resulted in a decision that listing was warranted, but precluded.

Rainbow trout and cutthroat trout have suffered primarily from habitat degradation and competition with introduced non-native salmonids, usually hatchery rainbow trout (Behnke, 1992). In addition to habitat degradation, steelhead distributions and abundance have been impacted by hydroelectric construction, which eliminated access to large spawning areas above Grand Coulee Dam and the Hells Canyon complex of dams, as well as inducing passage mortalities on both adult and juvenile migrants. Bull trout have suffered primarily from habitat degradation, but also from past fisheries management practices and from the introduction of non-native brook trout (Leary et al., 1993; Rieman and McIntyre, 1993)

Introduction of non-native salmonids impacts native salmonids in two major ways. First, introduced salmonids may serve as ecological competitors with native salmonids and reduce their abundance through competition for food or specific microhabitats (Fausch, 1988). Second, non-native salmonids are frequently able to hybridize with native salmonids. This results in the introduction of non-native genes into the native population, which can reduce the reproductive fitness of the progeny. The degree to which the native population is affected depends, among other things, on the degree of outbreeding depression (i.e., reduction in fitness) that occurs after hybridization. For brook trout and bull trout hybrids, genetic and abundance data from Leary et al. (1993) suggests that brook X bull hybrids are strongly selected against. Brook trout appear to be replacing bull trout in several index streams in Montana and Idaho, probably due to earlier sexual maturation by brook trout and aggressive breeding behavior by brook trout males.

Hybridization and genetic introgression have also been documented many times for native rainbow and cutthroat trout populations (Campton and Johnston, 1985; Campton and Utter, 1985; Currens et al., 1990; Williams et al., 1996), however, this work has rarely been extended into an examination of fitness consequences of introgression. Nevertheless, introductions of non-native salmonids is generally recognized as one of the major factors in the decline of native salmonids in the Interior West (see indigenous species lists in Tables 4.3 and 5.1). Most states have taken steps to inventory native trout populations and protect those that are identified as remnant native stocks free of introgression from non-native salmonids.

Table 4.3. Indigenous species of trout and char with coastal and/or interior distributions.

Coastal species are:

- Coastal Cutthroat Trout (*O. clarki clarki*)
- Coastal Rainbow Trout (*O. mykiss*)
- Dolly Varden Char (*Salvelinus malma*)

Interior species are:

- Coastal Cutthroat Trout (*O. clarki clarki*)
- Westslope Cutthroat Trout (*O. c. lewisi*)
- Interior Rainbow Trout ("redband" trout) (*O. mykiss*)
- Bull Trout or Bull Char (*S. confluentus*)

All of these taxa exhibit a range of life history strategies, which include both migratory and resident (i.e., non-migratory) forms. All of the coastal salmonids and interior rainbow trout exhibit anadromy. Other interior salmonids exhibit resident and migratory life history strategies, the latter which may include adfluvial and fluvial forms.

Evolutionary History and Genetic Structure

Genetic structure has been examined in some detail in cutthroat trout (Loudenslager and Gall, 1980; Campton and Johnston, 1985; Martin, 1985; Leary et al., 1987; Allendorf and Leary, 1988; Behnke, 1992) and bull trout (Leary et al., 1993; Kanda, In press; Williams et al., In press), but less so in rainbow trout (Wishard et al., 1984; Campton and Johnston, 1985; Currens et al., 1990; Williams et al., 1996). Nevertheless, all three species show geographic patterns of genetic variation and divergence into major evolutionary lines. Cutthroat trout and bull trout show additional geographic substructuring within major evolutionary lines, however, such patterns are less clear in rainbow trout, probably due to the more recent evolutionary derivation of many of the inland rainbow forms.

Rainbow and Steelhead trout (*Oncorhynchus mykiss*)

Background.

The rainbow trout group, which includes the rainbow trout and allied forms, such as the Mexican golden (*O. chrysogaster*), Gila (*O. gilae gilae*), Apache (*O. g. apache*), California golden (*O. m. aquabonita*), and the redband trout, occurs throughout coastal rivers from northern Mexico to the Kuskokwim River in Alaska. Inland (i.e., east of the Cascade Mountain crest), rainbow trout (e.g., redbands) occur throughout the Columbia River Basin to barrier falls on the Snake, Spokane, Kootenay, and Clark Fork rivers. Steelhead, the anadromous form of rainbow trout, exist in both coastal and interior rivers.

Evolutionary History and Genetic Structure of Rainbow Trout

Rainbow (and steelhead), rainbow-like, and cutthroat trout evolved from a common ancestor that diverged from Pacific salmon approximately 5 million years ago (Behnke, 1988; Behnke, 1992). The rainbow and cutthroat lines diverged from one another about 2 million years ago. Substantial evolutionary divergence has occurred in each species; however, considerable controversy exists among systematists concerning delineation of species and subspecies forms in rainbow trout. Taxa relationships in the rainbow group are less clear than within the cutthroat species, probably due to the more recent evolutionary derivation of many of the inland rainbow forms.

Historical and Present Distributions of Rainbow Trout

Native populations of rainbow trout, including coastal rainbow trout, have been reduced from their historic distributions (Behnke, 1992; Lee et al., *In Press*). Coastal and interior forms of rainbow trout have been dramatically affected by habitat degradation and by widespread introductions of hatchery reared rainbow trout. In many larger river systems in the Interior West, such as the Kootenay and its tributary creeks, hatchery rainbow trout have survived in many instances and interbred with native interior rainbow trout populations (Sage and Leary, 1995; Williams and Jaworski, 1995). In contrast, hatchery rainbow trout stocked into small desert streams in southern Idaho and northern Nevada have had almost no genetic effect on native rainbow trout populations (Williams et al., 1996). Survival of hatchery rainbow trout is probably extremely low in the harsh environmental conditions of these cold desert stream systems.

Propagation Efforts of Rainbow Trout

Rainbow trout have been extensively propagated (Behnke, 1992). The majority of hatchery rainbow trout strains appear to have been developed from coastal rainbow trout, including both resident and anadromous forms, from the northern California area. Hatchery reared rainbow trout have been widely planted throughout the western U. S. and are thought to be one of the major factors, along with habitat degradation, in the decline of interior rainbow (i.e. redband) and cutthroat trout populations.

Cutthroat trout (*Oncorhynchus clarki*)

Background

The cutthroat trout is a polytypic species that occurs over a wide geographic range of coastal and interior waters in the western United States and Canada. Sixteen subspecies have been recognized in the recent literature (Loudenslager and Gall, 1980; Leary et al., 1987; Behnke, 1992). Eight of these have large geographic distributions; while another eight are either undescribed subspecies, native to a very small geographic area, or both. Four subspecies occur within the Columbia River drainage. Three of these (coastal cutthroat, *O. c. clarki*; westslope cutthroat, *O. c. lewisi*; and Yellowstone cutthroat, *O. c. bouvieri*) have large geographic distributions, while the Snake River Finespot, *O. c. spp.*, has a restricted distribution in the upper Snake River and its tributaries in eastern Idaho and western Wyoming. Yellowstone and Snake River Finespot cutthroat trout occur only above Shoshone Falls, near Twin Falls, Idaho, and therefore rarely figure into resident fish concerns in the Columbia River drainage. However, water abstractions from reservoirs upstream of Shoshone Falls (e.g., Pallisades Reservoir) can affect populations of these subspecies (Thurow et al., 1988).

Evolutionary History and Genetic Structure of Cutthroat Trout

Cutthroat and rainbow trout diverged from one another about 2 million years ago (Behnke, 1992). Substantial evolutionary divergence has occurred in cutthroat trout, resulting in great diversity in morphology, phenotypic traits, behavior, genetic attributes and ecological adaptations (Leary et al., 1987; Trotter, 1987; Allendorf and Leary, 1988; Behnke, 1992). Cutthroat trout invaded the Columbia River before rainbow trout and diverged into four major evolutionary lines between 0.5 - 1 million years ago. The evolutionary lines are represented by the present subspecies of coastal, westslope, Yellowstone, and Lahontan (*O. c. henshawi*) cutthroat trout. The Columbia River drainage, including the Snake River above Shoshone Falls, includes populations of the first three of these subspecies, and therefore contains a substantial portion of the genetic diversity and evolutionary heritage of the cutthroat trout species. No other major river system in the western United States or Canada contained such taxonomic diversity with regards to western trout. Our discussion is restricted to coastal and westslope cutthroat only.

Subsequent evolution of the four major lines of cutthroat trout into the approximately 16 subspecies recognized today occurred quite recently; that is, within the last 100,000 years or less. Genetic divergence among the more recently evolved subspecies is low to non-existent (Leary et al., 1987; Shiozawa and Evans, 1995), reflecting their recent evolutionary separation. Patterns of genetic structure within subspecies are not uniform. Some subspecies appear to have little divergence among populations (e.g., Yellowstone, Snake River Finespot, Lahontan, Humboldt), while others appear to have local adaptation and greater divergence among populations (e.g., westslope and coastal) (Loudenslager and Gall, 1980; Leary et al., 1987; Shiozawa and Evans, 1995). Obviously, strategies to conserve genetic diversity would differ for these two groups of subspecies. Where little divergence occurs among populations, preservation of a small number of populations is likely to conserve a large portion of the genetic diversity that exists within that subspecies. In contrast, where substantial divergence occurs among populations within a subspecies, conservation efforts are going to have to be directed at the local population level in order to conserve genetic diversity.

Coastal and westslope cutthroat trout appear to contain substantial amounts of genetic variation that is highly structured as compared to most other inland subspecies of cutthroat trout. Genetic studies of coastal cutthroat trout (Campton and Utter, 1985) revealed genetic differences among groups of populations from different geographic locations, suggesting a lack of gene flow among populations over geographic scales and the likelihood of substantial local adaptation for populations. Genetic variation among westslope cutthroat populations (Leary et al., 1987; Allendorf and Leary, 1988) showed significant differences among populations, but did not reveal any particular geographic structuring to the variation. Nevertheless, for both subspecies, genetic structuring is apparent among local populations. Thus conservation efforts for both subspecies must be directed at least at the local watershed scale, if not at the population level.

Propagation Efforts for Cutthroat Trout

Most of the interior subspecies of cutthroat trout were propagated at one time or another (Behnke, 1992); however, little recognition was given to the uniqueness of each subspecies, so that stocks from different subspecies were frequently mixed or transplanted. For example, because of the ease of collection of spawning adults from tributary streams of Yellowstone Lake, the Yellowstone cutthroat trout has had more propagation effort and been more widely distributed via stocking than other cutthroat trout subspecies (Gresswell, 1979; Gresswell, 1988). In spite of these early, large-scale hatchery and stock transfer programs, genetic assays of present day cutthroat trout populations reveals little incidence of genetic introgression (Shiozawa and Evans, 1995, R. Williams unpublished data). Thus, it appears that most stock transfers of cutthroat trout outside their native distribution, did not result in hybridization with the indigenous trout (Williams, 1991; Williams and Jaworski, 1995).

Coastal Cutthroat (*Oncorhynchus clarki clarki*)

Background.

Coastal cutthroat trout occur from Prince William Sound in Alaska south to the Eel River in California. Their distribution corresponds closely with the Pacific coastal rainforest belt (Trotter et al., 1993). Typically, coastal cutthroat do not occur east of the Cascade Range in Washington and Oregon. Throughout its range, both anadromous and non-migratory resident forms exist. Anadromous forms show little differentiation across the range, whereas, isolated resident forms exhibit considerable divergence in morphological characters. Like many of the other cutthroat trout subspecies, coastal cutthroat exhibit a diversity of life history strategies, even among resident forms (Trotter, 1989; Behnke, 1992). Trotter et al. (1993) identify at minimum three life history strategies among resident populations, in addition to the anadromous form.

Historic and Present Distribution of Coastal Cutthroat Trout

Like all subspecies of cutthroat trout, coastal cutthroat trout distributions and abundance have declined dramatically since historic times. The subspecies probably suffers more from decreases in abundance than decreases in distribution. Nehlsen et al. (1991) considered almost all native populations of sea-run cutthroat in the western U.S. to be at some risk of extinction due largely to pervasive continuing declines in stock size.

Causes of decline are typical for cutthroat trout in general; habitat degradation due to logging, urban development, or mainstem passage, competition or hybridization from non-native and hatchery trout, and overharvest by anglers (Trotter, 1987; Trotter, 1989; Nehlsen et al., 1991). Coastal cutthroat throughout its range and westslope cutthroat in the Columbia drainage, co-evolved with rainbow trout. Although low levels of gene flow probably occur between the two species (Leary et al., 1987), hybridization with non-native rainbow trout has probably had little effect on coastal cutthroat. In contrast, hybridization with non-native rainbow trout is one of the major factors in the decline of other interior cutthroat trout subspecies, which historically had allopatric distributions from rainbow trout. Presently, the National Marine Fisheries Service is reviewing the status of the Umpqua River coastal cutthroat and a review decision is imminent.

Westslope Cutthroat Trout (*Oncorhynchus clarki lewisi*)

Background.

Westslope cutthroat trout are native to the upper Missouri and Columbia drainages. West of the Continental Divide the natural distribution includes the following rivers: upper Kootenay, Clark Fork, Spokane, Coeur d'Alene, St. Joe, Clearwater, and Salmon. Isolated disjunct populations of westslope are also thought to occur in the John Day River and various tributaries of the middle Columbia, including the Lake Chelan drainage, and numerous tributaries of the Methow River. These disjunct populations may be remnants from the late-Pleistocene flooding of Lake Missoula.

Historical and Present Distribution of Westslope Cutthroat Trout

Westslope cutthroat trout have undergone dramatic range reductions. Liknes and Graham (1988) estimated that genetically pure westslope cutthroat trout in Montana currently occur in 2.5% of their historical range. The Salmon, Clearwater, St. Joe, and upper Flathead River all appear to be strongholds for westslope cutthroat trout. In Idaho, their occurrence is strongly correlated with federal land status; i.e., most strong populations of westslope cutthroat occur in designated or proposed wilderness areas.

Causes of decline are typical for inland cutthroat trout in general; habitat degradation, competition or hybridization from non-native and hatchery trout, and overharvest by anglers (Nehlsen et al., 1991; Trotter et al., 1993). Fisheries agencies have realized the greater vulnerability of cutthroat trout to angling harvest than rainbow or brown (*Salmo trutta*) trout, and frequently, westslope cutthroat populations are now protected by special regulations, specifically catch-and-release. These special regulations have helped maintain westslope cutthroat trout populations in the St. Joe River, Kelly Creek in the Clearwater River, and the Middle Fork of the Salmon. All three locations are well-known in the angling world and function as fishing destinations because of the cutthroat trout and the special regulations.

Bull trout (*Salvelinus confluentus*)

Background.

Bull trout, one of five currently recognized species in the genus *Salvelinus* in North America, have been recognized as a "species of special concern" by the American Fisheries Society (Williams et al., 1989) and by many State agencies. Concern for the bull trout's status prompted petitions for review or listing under the Endangered Species Act in October, 1992 and January, 1993. Review by the U.S. Fish and Wildlife Service (USFWS) resulted in a decision that listing was warranted, but precluded. That decision has since been reviewed and upheld by the USFWS.

Evolutionary History and Genetic Structure of Bull Trout

The genus *Salvelinus* includes a number of species complexes that have confounded systematists for some time. As many as 45 different scientific names have been applied to North American char (Bond, 1992); however, most current systematists recognize only five species. The bull trout was formally described by Cavender (1978), after he examined bull trout and Dolly Varden (*S. malma*) specimens from throughout their respective ranges and identified species level diagnostic morphological characters. Cavender (1978) suggested that bull trout originated in the Columbia River and has extended and constricted its range according to climate changes. Its recent historic distribution extends from the McCloud River in northern California through inland western North America to the upper Yukon and MacKenzie drainages in Canada (Bond, 1992).

Genetic studies of bull trout populations throughout the Columbia and Klamath River drainages (Leary et al., 1993; Williams et al., *in press*) show evidence of macrogeographic genetic structure. Both allozyme and mitochondrial DNA analyses differentiated bull trout in the Klamath drainage from bull trout in the Columbia drainage at a level typical of the major subspecies in cutthroat trout. Within the Columbia River drainage, bull trout from the lower Columbia (Deschutes and Lewis rivers) formed an evolutionarily distinct group from bull trout populations in the remainder of the Columbia River (John Day and above (Williams et al., *in press*). Bull trout populations in the Columbia River system above the Deschutes River shared a common mitochondrial DNA pattern that is suggestive of a single founding populations (Williams et al., *in press*). Allozyme data for the same populations (Leary et al., 1993), in spite of showing little overall genetic variation, revealed significant differences among upper Columbia River bull trout populations. Taken together, the mtDNA and allozyme data show that populations were once linked genetically, but have been separated long enough to accrue population specific allozyme profiles. Thus, historic linkages among bull trout populations in the upper Columbia River have been broken. The genetic data do not provide insight into whether fragmentation of the historic metapopulation structure is a result of natural processes (gradual warming and drying of climate in the Intermountain West) or human induced changes in habitat quality.

Riemen and McIntyre (1993) advocate a conservation approach for bull trout protection and restoration that focuses on identifying core areas that contain linked bull trout populations in high quality habitat. The Flathead River system in northwestern Montana above Flathead Lake may represent one such potential core area. Genetic studies of bull trout within the Flathead subbasin (Kanda, In press) suggest intact metapopulation structure within most of the major drainages, but little gene flow among populations from different drainages.

Historical and Present Distribution of Bull Trout

The current distribution of bull trout in the Pacific Northwest and Intermountain West is fragmented. Populations occur primarily in pristine or nearly pristine headwater regions of the Columbia and Klamath drainages (Rieman and McIntyre, 1993). Many populations have undergone significant declines in recent years (Howell and Buchanan, 1992; Thomas, 1992). Because bull trout populations are now restricted to headwater regions and much of the historic metapopulation structure is now fragmented, vulnerability to extinction has increased for individual populations (Rieman and McIntyre, 1993).

Propagation Efforts for Bull Trout

Bull trout have been little used in propagation efforts; however, recently the U.S. Fish and Wildlife Service has initiated some propagation efforts at the Creston National Fish Hatchery in Montana.

Indigenous Species other than Salmonids

Sturgeon

White Sturgeon (*Acipenser transmontanus*)

Green Sturgeon (*Acipenser medirostris)*

Background

Sturgeon are an ancient anadromous fish, which were formerly widely distributed on all continents in the northern hemisphere. Two species of sturgeon occur in the Columbia River basin. During the twentieth century, extensive disruption of freshwater and estuarine habitats coupled with heavy exploitation severely reduced populations of sturgeon throughout their range (ODFW and WDFW, 1994).

Historic and Present Distribution of Sturgeon

Green sturgeon are found in the lower 40 miles of the Columbia River, in its estuary, and in the adjacent marine waters. The green sturgeon has not been reported in the Columbia River above Bonneville Dam, River Mile 145, and it is thought to be concentrated in the lower 40 miles of the main river (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995). Green sturgeon reach lengths of up to seven feet, and females are sexually mature at five to six feet. Information on the spawning period, spawning behavior and other details of the reproductive biology of green sturgeon in the Columbia River is lacking (Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife, 1995).

White sturgeon were once widely distributed among the watersheds of the Columbia River basin, and they still enjoy a higher abundance and wider geographic distribution than the green sturgeon. White sturgeon below Bonneville Dam exhibit the anadromy characteristic of the species; however, sturgeon in the reservoirs above Bonneville Dam may be capable of completing their reproductive cycle within a single reservoir (Parsley et al., 1993; Parsley and Beckman, 1994). Sexual maturity is found in males of four feet and longer and in females six feet and longer. Females have fecundity proportional to length, with one to three hundred thousand eggs per female. However spawning does not occur annually, but at two to four year intervals. Fecundity may be proportional to the length of time between spawnings. Spawning requires fast flowing waters over rocky substrate at temperatures of 48 - 62^{o}F in May and June.

White sturgeon in the lower Columbia River three feet long or less grow at the rate of about 3 inches per year. Sturgeon beyond three feet in length grow at 3 inches per year until sexual maturation, when annual growth slows substantially. Sturgeon are about eight inches long at one year of life and attain the length of six feet at 23 years of age. The time span between the lengths of 3.5 to 5.5 feet in length is about ten years.

Dams constrain the movements of white sturgeon, creating isolated populations in the reservoirs of the Columbia River power system (Beamesderfer and Nigro, 1993; Beamesderfer and Nigro, 1993; Parsley et al., 1993; Parsley and Beckman, 1994). Productivity of the isolated populations is lower than in the unimpounded river system due to impacts of hydroelectric system operation on the reproductive activities. Low flows in May and June inhibit spawning and subsequent recruitment. Appropriate rearing habitats for juvenile and adult sturgeon are provided within the reservoirs. However, severe population reductions have occurred during the early 1980s in the John Day and The Dalles reservoirs as a result of fishing.

Harvest of Sturgeon

Commercial white sturgeon fisheries began in the 1880s reaching a peak of 6 million pounds in 1892, with catches declining sharply by 1899. During this time the average individual in the harvest were seven feet and 150 pounds. With protection of the broodstock afforded by maximum size limits on harvests imposed in 1950, recovery of the populations became possible. Sturgeon stocks appeared to rebound in the 1970s approximately 20 years after the maximum size limit on harvests was imposed. Contemporary fisheries harvest the same number of sturgeon harvested during the 1890s; however, the average size is much lower, so the annual harvest is about one million pounds. Population levels in the John Day and The Dalles pools have declined sharply, probably in response to levels of exploitation. In the upper Columbia river and in the

Snake River sturgeon populations vary from one impounded section to another, with some sections perhaps approximating historic numbers.

Research and Propagation of Sturgeon

Ongoing research programs are conducted by the Columbia River Inter-Tribal fish commission, and the states of Washington, Oregon, Idaho, and the Nez Perce Tribe of Idaho. Research is focused on understanding the harvest, population dynamics, and reproductive biology of white sturgeon, following recommendations made by Beamesderfer and Nigro (1993; 1993). Some hatchery production of sturgeon has occurred in Oregon and Idaho.

Pacific lamprey (*Lampetra tridentata*)

Background, Distribution, and Status

The Pacific lamprey is a jawless anadromous fish which is widely distributed in western North America and eastern Asia. It is one of three species of lamprey in the Columbia River basin along with the anadromous river lamprey (*L. ayresii*) and the resident brook lamprey (*L. richardsoni*). Numerous factors, including loss of freshwater habitat and construction of hydroelectric dams have contributed to its near extirpation in the Snake River portion of the Columbia River basin, and to the reduction in numbers of adults seen at the counting windows on the hydroelectric dams (Close et al., 1995)

During its marine residency, adult lamprey are obligate parasites on adult bony fishes, including salmon (Scott and Crossman, 1973). Because of this, management agencies have either ignored it, or attempted to eradicate it. In any event, specific data on the age growth and productivity of Pacific lamprey in the Columbia river basin is limited (Kan, 1975). In general, adults spawn in small tributaries at an age of about seven years. The young rear in tributaries in the form of early juveniles called ammocoetes, and in the main river as late juveniles, neither of which are parasitic life history stages. As adults in the marine environment, lamprey attach themselves to hosts where they subsist on bodily fluids extracted through a hole bored in the host's side. Lamprey may return to spawn at around age seven.

Lamprey have had difficulty adapting to the hydroelectric dams. Since lamprey utilize much the same freshwater spawning habitat as do the spring chinook salmon, it may be inferred that lamprey have been reproductively disadvantaged to the same extent as have the chinook due to logging, grazing, agriculture, mining and other natural resource extraction activities.

The role of lamprey in the ecosystem as a prey item, and as a force in the biogeochemical cycle, merits consideration. Their role in bringing nutrients into the predominantly oligotrophic Snake River basin may have contributed directly to salmon production in that region.

Research and Propagation of Pacific Lamprey

Native Americans prize the lamprey as a ceremonial food item, and annual subsistence and ceremonial harvests on the order of several thousand “eels” are taken by the tribes. The Council has called for a lamprey research program, and several institutions have developed background information and recommended an approach to monitoring and management (Close et al., 1995)

Conclusions and Implications

Different species and populations of salmonids in the Columbia River and elsewhere exhibit remarkable phenotypic, life history, ecological, behavioral, and genetic diversity. The diversity described in this chapter, which is a hallmark of salmonids in general, arose from differential or local adaptation to the varied and variable environments within the complex landscapes of the Columbia Basin. The diversity has resulted from the plasticity, adaptability, productivity, and long-term persistence of salmonids in the fluctuating geological and environmental landscapes of the Pacific Northwest. Such diversity, which buffers salmonid populations against both short- and long-term scales of environmental variation, has become even more important today as human activities have increased the rate and amplitude of environmental fluctuations over those salmon experienced historically. We believe diversity (phenotypic, life history, genetic, ecological, etc.) within and among salmon populations is critical to the long-term persistence of salmon in the Columbia River ecosystem. We also believe salmon populations in the Columbia River today can form the base for rebuilding salmon abundance and diversity as described previously in Chapter 2.

Conclusions

1. Diversity within and among salmon populations has been substantially reduced in the Columbia River Basin due to the extinction of many local populations, as well as a reduction in population size of most extant populations. (1)

2. Many fisheries management practices (e.g., harvest, dam operation, hatchery operations, transportation, etc.) have the potential to reduce variation in salmonid stocks. (1) Data exist that document losses of diversity associated with harvest and hatchery practices (see detailed discussion in Chapter 8). (1)

3. The use of hatchery stocks, in many instances, has reduced the between-population component of genetic variation in some species (e.g., Lower Columbia River coho, Upper Columbia River chinook). Note: see detailed discussion in Hatchery section, Chapter 8 (1)

4. The importance of local adaptation to salmonid populations and their long-term persistence has been underestimated. This is supported by the general lack of success of salmonid introductions and re-establishments, within the basin, most of which have failed. (2-3)

5. Losses of genetic diversity may have decreased the reproductive and ecological fitness, and therefore, decreased the probability of long-term persistence for many stocks. Habitat fragmentation and degradation have disrupted historic metapopulation structure. Under unconstrained conditions, metapopulation structure would act to stabilize losses of diversity and reproductive fitness, as well as persistence, within individual populations. (3)

6. Re-establishment of metapopulation structure among Columbia River salmon populations, where possible, would function to slow or even stabilize the loss of diversity in presently isolated local populations. As metapopulation linkages become well-developed, phenotypic, genetic and life history diversity should stabilize and increase. (2-3)

IMPLICATIONS

1. We recommend that management include explicit recognition of the importance of stock diversity in all aspects of the restoration effort. The success of the Hanford Reach fall chinook, which exist in the only free flowing stretch of the mainstem Columbia River that is accessible to anadromous stocks, supports our conceptual foundation described in Chapter 2.

2. Wherever possible, management actions should not be stock or life history selective. For example, all life history types should benefit equally from the action. Monitoring and evaluation should be used to verify that certain life history types are not favored by the action and other life history types selected against.

Literature Cited

.Allendorf, F.W. and R.F. Leary. 1986. Heterozygosity and fitness in natural populations of animals. Conservation biology: the science of scarcity and diversity. M. Soule'. Sunderland, Massachusetts, Sinauer Assoc.**:** 57-76.

Allendorf, F.W. and R.F. Leary. 1988. Conservation and distribution of genetic variation in a polytypic species, the cutthroat trout. Conserv. Biol. 2: 170-184.

Allendorf, F.W. and S.R. Phelps. 1981. Isozymes and the preservation of genetic variation in salmonid fishes. Fish gene pools. N. Ryman. Stockholm, Ecological Bulletins. 34**:** 37-52.

Allendorf, F.W. and S.R. Phelps. 1981. Use of allelic frequencies to describe population structure. Can. J. Fish. Aquat. Sci. 38(12): 1507-1514.

Allendorf, F.W. and F.M. Utter. 1974. Biochemical systematics of the genus Salmo. Anim. Blood Groups Biochem. Genet. 5: 1-33.

Allendorf, F.W. and F.M. Utter. 1979. Population genetics. Fish Physiol. 8: 407-454.

Allendorf, F.W. and R.S. Waples. 1996. Conservation and genetics of salmonid fishes. Conservation genetics: Case histories from nature. J. C. Avise, Chapman Hall**:** 238-280.

Altukhov, Y.P. and E.A. Salmenkova. 1991. The genetic structure of salmon populations. Aquaculture 98: 11-40.

Aro, K.V. and M.P. Shepard. 1967. Pacific salmon in Canada. International North Paciific Fishery Commission Bulletin 23: 225-327.

Bartley, D.M. and G.A.E. Gall. 1990. Genetic structure and gene flow in chinook salmon populations of California. Trans. Amer. Fish. Soc. 119: 55-71.

Beacham, T., R. Withler and A. Gould. 1985. Biochemical genetic stock identification of chum salmon (*Oncorhynchus keta*) in southern British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 42: 437-448.

Beacham, T.D., R.E. Withler, C.B. Murray and L.W. Barner. 1988. Variation in body size, morphology, egg size, and biochemical genetics of pink salmon in British Columbia. Trans. Amer. Fish. Soc. 117(2): 109-126.

Beamesderfer, R. and D. Ward. 1993. An updated biological assessment of the Columbia River squawfish management program. Clackamas, Oregon Department of Fish and Wildlife
Research and Development Section. Oregon**:** 29.

Beamesderfer, R.C. and A.A. Nigro. 1993. Status and Habitat Requirements of the White Sturgeon Populations in the Columbia River Downstream from McNary Dam. Portland, Bonneville Power Administration. Oregon**:** 421.

Beamesderfer, R.C. and A.A. Nigro. 1993. Status and Habitat Requirements of the White Sturgeon Populations in the Columbia River Downstream from McNary Dam. Volume I. Portland, Bonneville Power Administration. Oregon.

Beatty, R.E. 1992. Changes in size and age at maturity of Columbia River upriver bright fall chinook salmon (*Oncorhynchus tshawytscha*): Implications for stock fitness, commercial value, and management. Corvallis, Oregon State University. Oregon**:** 270.

Becker, C.D. 1985. Anadromous Salmonids of the Hanford Reach, Columbia River: 1984 Status. Richland, Pacific Northwest Laboratories. Washington.

Behnke, R.J. 1988. Phylogeny and classification of cutthroat trout. Am. Fish. Soc. Symp. 4: 1-7.

Behnke, R.J. 1992. Native trout of western North America. Bethesda, Maryland, American Fisheries Society.

Beiningen, K.T. 1976. Fish Runs, Report E. Investigative Reports of Columbia River Fisheries Project. Portland, Pacific Northwest Regional Commission.

Bernatchez, L. and J.J. Dodson. 1994. Phylogenetic relationships among Palearctic and Nearctic whitefish (*Coregonus sp*.) populations as revealed by mitochondrial DNA variation. Canadian Journal of Fisheries and Aquatic Sciences 51(Supplement No. 1): 240-251.

Boer, P.J.D. 1981. On the survival of populations in a heterogeneous and variable environment., Oecologia (Berl) 50:39-53.

Bond, C.E. 1992. Notes on the nomenclature and distribution of the bull trout and the effects of human activity on the species. Gearhart Mountain Bull Trout Workshop, August, 1992, Gearhart Mountain, Oregon, Oregon Chapter of the American Fisheries Society.

Brown, J.H. and A. Kodric-Brown. 1977. Turnover rates in insular biogeography: effects of immigration on extinction. Ecology 58: 445-449.

Burgner, R.L. 1991. Life history of Sockeye Salmon (*Oncorhynchus nerka*). Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, UBC Press**:** 3-117.

Busack, C. and J.B. Shaklee. 1995. Genetic diversity units and major ancestral lineages of salmonid fishes in Washington, Washington State Department of Fish and Wildlife.

Calaprice, J.R. 1969. Production and genetic factors in managed salmonid populations. Symposium on Salmon and Trout in Stream, Institute of Fisheries, The University of British Columbia, Vancouver.

Campton, D.E. and J.M. Johnston. 1985. Electrophoretic evidence for a genetic admixture of native and nonnative rainbow trout in the Yakima River, Washington. Trans. Amer. Fish. Soc. 114: 782-793.

Campton, D.E. and J.M. Johnston. 1985. Electrophoretic evidence for a genetic admixture of native and non-native trout in the Yakima River, Washington. Tran. Amer. Fish. Soc. 114: 782-793.

Campton, D.E. and F.M. Utter. 1985. Genetic structure of anadromous cutthroat trout (Salmo clarki clarki) populations in the Puget Sound area: evidence for restricted gene flow. Can. J. Fish. Aquat. Sci. 42: 110-119.

Campton, D.E. and F.M. Utter. 1985. Natural hybridization between steelhead trout (*Salmo gairdneri*) and coastal cutthroat (*Salmo clarki clarki*) in two Puget Sound streams. Can. J. Fish. Aquat. Sci. 42: 110-119.

Carl, L.M. and M.C. Healey. 1984. Differences in enzyme frequency and body morphology among three juvenile life history types of chinook salmon (*Oncorhynchus tshawytscha*) in the Nanaimo River, British Columbia. Can. J. Fish. Aquat. Sci. 41: 1070-1077.

Cavender, T.M. 1978. Taxonomy and distribution of the bull trout, Salvelinus confluentus (Suckley), from the American northwest., California Fish and Game 64(3):139-174.

Chapman, D., A. Giorgi, M. Hill, A. Maule, S. McCutcheon, D. Park, W. Platts, K. Pratt, J. Seeb, L. Seeb and F. Utter. 1991. Status of Snake River Chinook Salmon. Boise, Don Chapman Consultants, Inc., 3653 Rickenbacker, Suite 200. Idaho**:** 520.

Chapman, D., A. Giorgi, T. Hillman, D. Deppert, M. Erho, S. Hays, C. Peven, B. Suzumoto and R. Klinge. 1994. Status of Summer/Fall Chinook Salmon in the Mid-Columbia Region. Boise, Don Chapman Consultants Inc. Idaho**:** 411 + app.

Chapman, D., C. Peven, A. Giorgi, T. Hillman and F. Utter. 1995. Status of Spring Chinook Salmon in the Mid-Columbia Region. Boise, Don Chapman Consultants Inc. Idaho**:** 477.

Chapman, D., C. Peven, T. Hillman, A. Giorgi and F. Utter. 1994. Status of Summer Steelhead in the Mid-Columbia River. Boise, Don Chapman Consultants Inc. Idaho**:** 235 + app.

Chapman, D.W. 1986. Salmon and steelhead abundance in the Columbia River in the nineteenth century. Trans. Am. Fish. Soc. 115: 662-670.

Close, D.A., M. Fitzpatrick, H. Li, B. Parker, D. Hatch and G. James. 1995. Status report of the Pacific lamprey (*Lampetra tridentata*) in the Columbia River basin. Portland, OR 97208-3621., U.S. Department of Energy, Bonneville Power Administration, Division of Fish and Wildlife,.

Cobb, J.N. 1930. Pacific Salmon Fisheries. Washington, Bureau of Fisheries. District of Columbia.

Craig, J.A. 1935. The effects of power and irrigation projects on the migratory fish of the Columbia River. Northwest Science IX(1): 19-22.

Craig, J.A. and R.L. Hacker. 1940. The history and development of the fisheries of the Columbia River. U.S. Bureau of Fisheries Bulletin 32: 133-216.

Currens, K.P., C.B. Schreck and H.W. Li. 1990. Allozyme and morphological divergence of rainbow trout (*Oncorhynchus mykiss*) above and below waterfalls in the Deschutes River, Oregon. Copeia 1990: 730-746.

Darwin, C. 1909. Essay of 1844. In Francis Darwin (ed.) The Foundations of the Origin of Species. Two Essays Written in 1842 and 1844 by Charles Darwin. New York, Cambridge: at the University Press, Kraus Reprint Co. (1969),.

DeLoach, D.B. 1939. The salmon canning industry. Oregon State Monographs Economic Studies No. 1.

Diamond, J.M. 1984. "Normal" extinctions of isolated populations. Extinctions. M. N. Nitecki. Chicago, Chicago Press**:** 191-246.

Fausch, K.D. 1988. Tests of competition between native and introduced salmonids in streams: what have we learned. Can. J. Fish. Aquat. Sci. 45(12): 2238-2246.

Flagg, T.A., F.W. Waknitz, D.J. Maynard and C.V.W. Mahnken. 1995. The effect of hatcheries on native coho salmon populations in the lower Columbia River. American Fisheries Society Symposium 15: 366-375.

Flagg, T.A., F.W. Waknitz, D.J. Maynard, G.B. Milner and C.V.W. Mahkhen. 1995. The effect of hatcheries on native coho salmon populations in the lower Columbia River, Symposium 15. Uses and Effects of Cultured Fishes in Aquatic Ecosystems, American Fisheries Society, Bethesda, MD.

Fournier, D.A., T.D. Beacham, B.E. Riddell and C.A. Busack. 1984. Estimating stock composition in mixed stock fisheries using morphometric, meristic, and electrophoretic characteristics. Canadian Jouornal of Fisheries and Aquatic Sciences 41: 400-408.

French, R.R. and R.J. Wahle. 1959. Biology of chinook and blueback salmon and steelhead in the Wenatchee River system, U.S. Fish and Wildlife Service.

Frissell, C.A. 1993. Topology of extinction and endangerment of native fishes in the Pacific northwest and California (U.S.A.). Conservation Biology 7(2): 342-354.

Frissell, C.A., W.J. Liss, C.E. Warren and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management 10(2): 199-214.

Fryer, J.K. 1995. Columbia River Sockeye Salmon. Seattle, University of Washington. Washington.

Fulton, L.A. 1968. Spawning areas and abundance of chinook salmon (*Oncorhynchus tshawytscha)* in the Columbia River Basin--past and present, USDI, Fish and Wildl. Serv.,.

Fulton, L.A. 1968. Spawning areas and abundance of chinook salmon (Oncorhynchus tshawytscha) in the Columbia River Basin--past and present., USDI, Fish and Wildl. Serv., Special Sci. Rpt--Fisheries No. 571.

Fulton, L.A. 1970. Spawning areas and abundance of steelhead trout and coho, sockeye, and chum salmon in the Columbia River Basin--past and present, USDC, NOAA, NMFS.

Gall, G.A.E., D. Bartley, B. Bentley, J. Brodziak, R. Gomulkiewicz and M. Mangel. 1992. Geographic variation in population genetic structure of chinook salmon from California and Oregon. Fishery Bulletin 90: 77-100.

Garcia, A.P., W.P. Connor and R.H. Taylor. 1995. Fall chinook salmon spawning ground surveys in the Snake River. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and K. F. Tiffan. Portland, Bonneville Power Administration. Report No. COE/BP-21708-3**:** 1-21.

Geist, D.R. 1995. The Hanford Reach: what do we stand to lose? Illahee 11(3 & 4): 130-141.

Gharrett, A.J., S.M. Shirley and G.R. Tromble. 1987. Genetic relationships among populations of Alaskan chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 44: 765-774.

Gharrett, A.J. and W.W. Smoker. 1991. Two generations of hybrids between even- and odd-year pink salmon (Oncorhynchus gorbuscha): a test for outbreeding depression? Canadian Jouornal of Fisheries and Aquatic Sciences 48(9): 1744-1749.

Gharrett, A.J. and W.W. Smoker. 1993. Genetic components in life history traits contribute to population structure. Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 197-202.

Gharrett, A.J., C. Smoot, A.J. McGregor and P.B. Holmes. 1988. Genetic relationships of even-year northwestern Alaskan pink salmon. Transactions of the American Fisheries Society 117(6): 536-545.

Gilbert, C.H. 1912. Age at Maturity of the Pacific Coast Salmon of the Genus *Oncorhynchus*. Washington, US Bureau of Fisheries. District of Columbia.

Gilpin, M.E. 1987. Spatial structure and population vulnerability. Viable Populations for Conservation. M. E. Soule, Cambridge University Press**:** 125 - 139.

Gilpin, M.E. 1988. A comment on Quinn and Hastings: Extinction in subdivided habitats. Conservation Biology(2): 290-292.

Goodman, D. 1987. How do any species persist? Lessons for conservation biology. Conservation Biology(1): 59 - 62.

Gotelli, N.J. 1991. Metapopulation models: the rescue effect, the propagule rain, and the core-satellit hypothesis. The American Naturalist 138: 768-776.

Gresswell, R.E. 1979. Yellowstone Lake - A lesson in fishery management. Wild Trout II, Yellowstone National Park, Federation of Fly Fishermen.

Gresswell, R.E., Ed. 1988. Status and Management of Interior Stocks of Cutthroat Trout. American Fisheries Society Symposium 4. Bethesda, American Fisheries Society.

Gresswell, R.E., W.J. Liss and G.L. Larson. 1994. Life-history organization of Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*) in Yellowstone Lake. Canadian Journal of Fisheries and Aquatic Sciences 51(Supplement No. 1): 298-309.

Groot, C. and L. Margolis, Eds. 1991. Pacific salmon life histories. Vancouver, University of British Columbia.

Hanski, I. 1982. Dynamics of regional distribution: the core and satellite species hypothesis. OIKOS 38: 210-221.

Hanski, I. 1989. Metapopulation dynamics: does it help to have more of the same? Trends in Ecology and Evolution 4: 113 - 114.

Hanski, I. 1991. Single species metapopulation dynamics: concepts, models and observations. Biol. Jour. Linnean Soc. 42: 17-38.

Hanski, I. and M. Gilpin. 1991. Metapopulation dynamics: brief history and conceptual domain. Biol. Jour. Linnean Soc. 42: 3-16.

Hard, J.J., R.G. Kope, W.S. Grant, F.W. Waknitz, L.T. Parker and R.S. Waples. 1996. Status review oF pink salmon from Washington, Oregon, and California. Seattle, U. S. Department of Commerce.

Harrison, S. 1991. Local extinction in a metapopulation context: an empirical evaluation. Biol. Jour. of the Linnean Society 42: 73-88.

Harrison, S. 1994. Metapopulations and conservation. Large-scale Ecology and Conservation Biology. P. J. Edwards, R. M. May and N. R. Webb. Oxford, Blackwell Scientific Publications.

Harrison, S. and J.F. Quinn. 1989. Correlated environments and the persistence of metapopulations. Oikos 56: 293-298.

Hatch, D.R., D.R. Pederson, J.K. Fryer and M. Schwartzberg. 1995. Wenatchee River Salmon Escapement Estimates using Video Technology in 1994. Portland, Columbia River Inter-Tribal Fish Commission. Oregon.

Healey, M.C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, UBC Press.

Healey, M.C. 1994. Variation in the life history characteristics of chinook salmon and its relevance to conservation of the Sacramento winter run of chinook salmon. Conservation Biology 8: 876-877.

Helle, J.H. 1981. Significance of the stock concept in artificial propagation of salmonids in Alaska. Can. J. Fish. Aquat. Sci. 38: 1665-1671.

Howell, P., K. Jones, D. Scarnecchi, L. LaVoy, W. Kendra and D. Ortmann. 1985. Stock assessment of Columbia River anadromous salmonids. Volume I: Chinook, coho, chum and sockeye salmon stock summaries, Bonneville Power Administration and Oregon Dept. of Fish and Wildlife.

Howell, P.J. and D.B. Buchanan, Eds. 1992. Proceedings of the Gearhart Mountain Bull Trout Workshop, August, 1992, Gearhart Mountain, Oregon. Corvallis, Oregon Chapter of the American Fisheries Society.

Hume, R.D. 1893. Salmon of the Pacific Coast. San Francisco, Schmidt Label & Lithographic Co.

Huntington, C., W. Nehlsen and J. Bowers. 1996. A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California. Fisheries 21(3): 6-14.

Johnson, O.W. 1991. Status Review for Lower Columbia River Coho Salmon. Seattle, National Marine Fisheries Service, Northwest Fisheries Center. Washington.

Kan, T.T. 1975. Systematics, variation, distribution, and biology of lampreys of the genus Lampetra in Oregon. Corvallis, Oregon, Oregon State University.

Kanda, e.a. In press. Flathead bull trout. Friends of the Bull Trout, Calgary, Alberta, May 12, 1994.

Kapuscinski, A.R., C.R. Steward, M.L. Goodman, C.C. Krueger, J.H. Williamson, E. Bowles and R. Carmichael. 1991. Genetic conservation guidelines for salmon and steelhead supplementation**:** 55.

Kondzela, C.M., C.M. Guthrie, S.L. Hawkins, C.D. Russell, J.H. Helle and A.J. Gharrett. 1994. Genetic relationships among chum salmon populations in southeast Alaska and northern British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 51(Supplement No. 1): 50-64.

Kwain, W. and J.A. Chappel. 1978. First evidence for even-year spawning pink salmon, Oncorhynchus gorbuscha, in Lake Superior. Journal of the Fisheries Research Board of Canada 35: 1373-1376.

Kwain, W. and E. Thomas. 1984. First evidence of spring spawning by chinook salmon in Lake Superior. North American Journal of Fisheries Management 4: 227-228.

Lavier, D.C. 1976. Major Dams on Columbia River and Tributaries. Olympia, Washington Dept. of Game. Washington.

Laythe, L.L. 1948. The fishery development program in the lower Columbia River. American Fisheries Society, Atlantic City, New Jersey, Amer. Fish. Soc.

Leary, R.F., F.W. Allendorf and S.H. Forbes. 1993. Conservation genetics of bull trout in the Columbia and Klamath River drainages. Conservation Biology 7(4): 856-865.

Leary, R.F., F.W. Allendorf, S.R. Phelps and K.L. Knudsen. 1987. Genetic divergence and identification of seven cutthroat trout subspecies and rainbow trout. Tran. Amer. Fish. Soc. 116: 580-587.

Lee, D.C., J. Sedell, R. Thurow and J. Williams. *In Press*. Broadscale assessment of aquatic species and habitats *In* An assessment of ecosystem components in the Interior Columbia River Basin and portions of the Klamath and Great basins. Portland, OR, USDA Forest Service, Pacific NW Research Station.

Li, H.W., K. Currens, D. Bottom, S. Clarke, J. Dambacher, C. Frissell, P. Harris, R.M. Hughes, D. McCullough, A. McGie, K. Moore and S. Thiele. 1995. Safe havens: refuges and evolutionarily significant units. American Fisheries Society Symposium 17.

Lichatowich, J.A. and L.E. Mobrand. 1995. Analysis of chinook salmon in the Columbia River from an ecosystem perspective, Mobrand Biometrics.

Liknes, G.A.a.G., P. J. 1988. Westslope cutthroat trout in Montana: Life history, status, and management. AFS Symposium 4.

Lindsay, R.B., W.J. Knox, M.W. Flesher, B.J. Smith, E.A. Olson and L.S. Lutz. 1986. Study of Wild Spring Chinook Salmon in the John Day River System. Portland, Bonneville Power Administration. Oregon.

Lindsey, C.C. and J.D. McPhail. 1986. Zoogeography of fishes of the Yukon and Mackenzie basins. Zoogeography of North American Freshwater Fishes. C. H. Hocutt and E. O. Wiley. New York, Wiley and Sons**:** 639-674.

Liskauskas, A.P. and M.M. Ferguson. 1991. Genetic variation and fitness: a test in a naturalized population of brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 48: 2152-2162.

Loudenslager, E.J. and G.A.E. Gall. 1980. Geographic patterns of protein variation and subspeciation in cutthroat trout, Salmo clarki. Syst. Zool. 29: 27-42.

Mann, C.C. and M.L. Plummer. 1995. Are wildlife corridors the right path? Science 270: 1428-1430.

Marotz, B.L., C. Althen, B. Lonon and D. Gustafson. 1996. Model Development to Establish Integrated Operational Rule Curves for Hungry Horse and Libby Reservoirs - Montana. Portland, Bonneville Power Administration. Oregon**:** 114.

Martin, R.C., L. A. Mehrhoff, J. E. Chaney and S. Sather-Blair. 1985. Status review of wildlife mitigation at 14 of 27 major hydroelectric projects in Idaho. Final report., BPA 83-478 and DE-AI79-84BP12149. A-N pp.

Matthews, G.M. and R.S. Waples. 1991. Status Review for Snake River Spring and Summer Chinook Salmon. Seattle, National Marine Fisheries Service. Washington**:** 75.

Mayr, E. 1970. Populations, species and evolution. Cambridge, Massachusets, Belknap Press.

Mayr, E. 1982. Toward a New Philosophy of Biology. Cambridge, Harvard University Press.

McPhail, J.D. and C.C. Lindsey. 1986. Zoogeography of the freshwater fishes of Cascadia (the Columbia system and rivers north to the Stikine). Zoogeography of North American Freshwater Fishes. C. H. Hocutt and E. O. Wiley. New York, Wiley and Sons**:** 615-637.

Milner, G.B., D.J. Teel, F.M. Utter and G.A. Winans. 1985. A genetic method of stock identification in mixed populations of Pacific salmon, *Oncorhynchus spp*. Marine Fisheries Review 47: 1-8.

Mullan, J.W. 1986. Determinants of sockeye salmon abundance in the Columbia River, 1880's - 1982: a review and synthesis., U. S. Fish and Wildlife Service**:** 136.

Mullan, J.W., A. Rockhold and C.R. Chrisman. 1992. Life histories and precocity of chinook salmon in the Mid-Columbia River. Progressive Fish-Culturist 54(1): 25-28.

Mullan, J.W., K.R. Williams, G. Rhodus, T.W. Hillman and J.D. McIntyre. 1992. Production and Habitat of Salmonids in Mid-Columbia River Tributary Streams. Washington, US Fish and Wildlife Service. DC.

Mundy, P.R., T.W.H. Backman and J.M. Berkson. 1995. Selelction of conservation units for Pacific salmon: lessons from the Columbia River. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 28-40.

Naiman, R.J., Ed. 1992. Watershed Management: Balancing Sustainability and Environmental Change. New York, Springer-Verlag.

National Marine Fisheries Service. 1995. Proposed Recovery Plan for Snake River Salmon. Washington, US Dept. of Commerce, National Oceanic and Atmospheric Administration. District of Columbia**:** 387.

National Research Council. 1995. Science and the Endangered Species Act. Washington, National Academy Press.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Report on the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids for the National Research Council of the National Academy of Sciences. Washington D. C., National Academy Press.

Neave, F. 1958. The origin and speciation of *Oncorhynchus*. Proc. Trans. R. Soc. Can. Ser. 3 52(5): 25-39.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Nelson, K. and M. Soule. 1987. Genetical conservation of exploited fishes. Population Genetics and Fishery Management. N. Ryman and F. Utter. Seattle, University of Washington Press**:** 345-368.

Northwest Power Planning Council. 1986. Council Staff Compilation of Information on Salmon and Steelhead Losses in the Columbia River Basin. Portland, Northwest Power Planning Council. Oregon.

Northwest Power Planning Council. 1994. 1994 Columbia River Basin Fish and Wildlife Program.

Oakley, A.L. 1996. A summary of information concerning chum salmon in Tillamook Bay. Oregon Fish Commission Research Briefs 12(1): 5-21.

Olin, P.G. 1984. Genetic variability in hatchery and wld populations of coho salmon (*Oncorhynchus kisutch*) in Oregon. Davis, CA, University of California at Davis**:** 73.

Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife. 1993. Status Report: Columbia River Fish Runs and Fisheries, 1938-92. Olympia. Washington.

Oregon Dept. of Fish and Wildlife and Washington Dept. of Fish and Wildlife. 1995. Status Report, Columbia River Fish Runs and Fisheries 1938-94. Portland. Oregon.

Oregon Fish Commission. 1931. Biennial Report of the Fish Commission of the State of Oregon to the Governor and the Thirty-Sixth Legislative Assembly. Salem. Oregon.

Oregon Fish Commission. 1933. Biennial Report of the Fish Commission of the State of Oregon to the Governor and the Thirty-seventh Legislative Assembly, 1933. Salem, State of Oregon. Oregon.

Parsley, M.J. and L.G. Beckman. 1994. White sturgeon spawning and rearing habitat in the lower Columbia River. North Am. J. Fish. Manage. 14(4): 812-827.

Parsley, M.J., L.G. Beckman and J. G. T. McCabe. 1993. Spawning and rearing habitat use by white sturgeons in the Columbia River downstream from McNary Dam. Trans. Amer. Fish. Soc. 122: 217-227.

Paulik, G.J. 1969. Computer simulation models for fisheries research, management, and teaching., Trans. Am. Fish. Soc. 98(3):551-559.

Phelps, S., J. Uehara, D. Hendrick, J. Hymer, A. Blakley and R. Brix. 1995. Genetic diversity units and major ancestral lineages for chum salmon in Washington. Genetic diversity units and major ancestral lineages of salmonid fishes in Washington. C. Busack and J. B. Shaklee. Olympia, Washington, Washington Department of Fish and Wildlife. RAD 95-02**:** C-1 - C-55.

Phelps, S.R., L.L. LeClair, S. Young and H.L. Blankenship. 1994. Genetic diversity patterns of chum salmon in the Pacific Northwest. Can. J. Fish. Aq. Sci. 51(Suppl. 1): 65-83.

Phelps, S.R., L.L. LeClair, S. Young and H.L. Blankenship. 1995. Genetic diversity patterns of chum salmon in the Pacific Northwest. Canadian Journal of Fisheries and Aquatic Sciences 51(1): 65-83.

Philipp, D.P. and J.E. Clausen. 1995. Fitness and performance differences between two stocks of largemouth bass from different river drainages witin Illinois. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 236-243.

Quattro, J.M. and R.C. Vrijenhoek. 1989. Fitness difference among remnant populations of the endangered Sonoran Topminnow. Science 245: 976-978.

Quinn, J.F. and A. Hastings. 1987. Extinction in a subdivided habitat. Conservation Biology(1): 198 - 208.

Quinn, T.P. 1993. A review of homing and straying of wild and hatchery-produced salmon. Fisheries Research 18: 29-44.

Quinn, T.P. and M.J. Unwin. 1993. Variation in life history patterns among New Zealand chinook salmon (*Oncorhynchus tshawytscha*) populations. Can. J. Fish. Aq. Sci. 50: 1414-1421.

Quinn, W.H., V.T. Neal and S.E.A.d. Mayolo. 1987. El Niño occurrences over the past four and a half centuries. J. Geophysical Research 92(C13): 14,449-14,461.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 334-349.

Reimers, P.E. 1973. The length of residence of juvenile fall chinook salmon in Sixes River, Oregon. Research Reports of the Fish Comm. of Oregon 4(2): 3-43.

Reisenbichler, R.R. and S.R. Phelps. 1989. Genetic variation in steelhead (*Salmo gairdneri*) from the north coast of Washington. Can. J. Fish. Aq. Sci. 46: 66-73.

Rich, W.H. 1938. Local Populations and Migration in Relation to the Conservation of Pacific Salmon in the Western States and Alaska, Fish Commission of the State of Oregon. Oregon**:** 6.

Rich, W.H. 1939. Fishery problems raised by the development of water resources. Dams and the Problems of Migratory Fishes, Stanford University, Fish Comm. of State of Oregon.

Rich, W.H. 1941. The present state of the Columbia River salmon resources. Sixth Pacific Science Congress, Berkeley, Fish Comm. of State of Oregon.

Ricker, W.E. 1958. Handbook of Computations for Biological Statistics of Fish Populations. Ottawa, Fisheries Research Board of Canada**:** 300.

Ricker, W.E. 1972. Hereditary and environmental factors affecting certain salmonid populations. The Stock Concept in Pacific Salmon. R. C. Simon and P. A. Larkin. Vancouver, University of British Columbia**:** 19-160.

Rieman, B.E. and J.D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. Ogden, US Forest Service, Intermountain Research Station. Utah**:** 38.

Rieman, B.E. and J.D. McIntyre. 1995. Occurrence of bull trout in naturally fragmented habitat patches of varies size. Trans. Am. Fish. Soc. 124(3): 285-296.

Rieman, B.E. and J.D. McIntyre. 1996. Spatial and temporal variability in bull trout redd counts. North Am. J. Fish. Manage. 16(1): 132-141.

Riggs, L.A. 1990. Principles for Genetic Conservation and Production Quality. Portland, Northwest Power Planning Council. Oregon.

Roos, J.F. 1991. Restoring Fraser River Salmon. Vancouver, Pacific Salmon Commission. British Columbia, Canada.

Sage, G.K. and R.F. Leary. 1995. Electrophoretic Analysis of Fifteen Rainbow Trout Populations from the Kootenai River in Northern Idaho. Spokane, US Fish and Wildlife Service. Washington**:** 8.

Sandercock, F.K. 1991. Life history of coho salmon Oncorhynchus kisutch. Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, UBC Press**:** 397-445.

Schlosser, I.J. and P.L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Amer. Fish. Soc. Symp. 17: 392-401.

Schlosser, I.J. and P.L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 392-401.

Schluchter, M. and J.A. Lichatowich. 1977. Juvenile Life Histories of Rogue River Spring Chinook Salmon *Oncorhynchus tshawytscha* (Walbaum), as determined from scale analsysis. Corvallis, Oregon Dept. of Fish and Wildlife. Oregon.

Schoener, T.W. 1983. Field experiments on interspecific competition. Am. Nat. 122: 240-285.

Schoener, T.W. 1991. Extinction and the nature of the metapopulation: a case system. Acta Oecologica 12(1): 53-76.

Schuck, H.A. 1943. Survival, population density, growth and movement of the wild brown trout in Crystal Creek. Transactions of the American Fisheries Society 73: 209-230.

Scott, W.B. and E.J. Crossman. 1973. Freshwater Fishes of Canada. Ottawa, Fisheries Research Board of Canada.

Scudder, G.G.E. 1989. The adaptive significance of marginal populations: A general perspective. National Workshop on Effects of Habitat Alteration on Salmonid Stocks.

Shaklee, J.B., S.R. Phelps and J. Salini. 1990. Analysis of fish stock structure and mixed-stock fisheries by the electrophoretic characterization of allelic enzymes. Electrophoretic and isoelectric focusing techniques in fisheries management. D. H. Whitmore. Boca Raton-Ann Arbor, CRC Press.

Shaklee, J.B. and N.V. Varnavskaya. 1994. Electrophoretic characterization of odd-year pink salmon (*Oncorhynchus gorbuscha*) populations from the Pacific coast of Russia, and copmparison with selected North American populations. Canadian Journal of Fisheries and Aquatic Sciences 51(Supplement No. 1): 158-171.

Shiozawa, D.K. and R.P. Evans. 1995. The use of DNA to identify geographical isolation in trout stocks. Wild Trout V: Proceedings of a Symposium, Trout Unlimited, Vienna, VA.

Sinclair, M. 1988. Marine Populations: An Essay on Population Regulation and Speciation. Seattle, University of Washington Press.

Sinclair, M. and T.D. Iles. 1989. Population regulation and speciation in the oceans. J. Cons. int. Explor. Mer. 45: 165-175.

Stacey, P.B. and M. Taper. 1992. Environmental variation and the persistence of small populations. Ecological Applications 2(1): 18-29.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant. *in press*. A general protocol for restoration of regulated rivers. Regulated Rivers.

Stearns, S.C. 1995. The Evolution of Life Histories. New York, Oxford University Press.

Stoneking, M., D.J. Wagner and A.C. Hildebrand. 1981. Genetic evidence suggesting subspecific differences between northern and southern populations of brook trout (Salvelinus fontinalis). Copiea 1981(4): 810-819.

Taylor, E.B. 1990. Environmental correlates of life-history variation in juvenile chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). J. Fish Biology 37: 1-17.

Taylor, E.B. 1991. A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon. Aquaculture 98(1991): 185-207.

Thomas, G. 1992. Status report: Bull trout in Montana. Helena, Montana Department of Fish, Wildlife and Parks. Montana**:** 68+.

Thomas, W.K. and A.T. Beckenbach. 1989. Variation in salmonid mithochondrial DNA: evolutionary constraints and mechanisms of substitution. J. Mol. Evol. 29: 233-245.

Thompson, W.F. 1959. An approach to population dymanics of the Pacific red salmon. Trans. Am. Fish. Soc. 88(3): 206-209.

Thompson, W.F. 1965. Fishing treaties and salmon of the North Pacific. Science 150: 1786-1789.

Thurow, R.F., C.E. Corsi and V.K. Moore. 1988. Status, Ecology and Management of Yellowstone Cutthroat Trout in the Upper Snake River Drainage, Idaho. Status and Management of Interior Stocks of Cutthroat Trout, Symposium 4, American Fisheries Society, Bethesda, Maryland.

Trotter, P.C. 1989. Coastal cutthroat trout: a life history compendium. Trans. Amer. Fish. Soc. 118: 463-473.

Trotter, P.C., P.A. Bisson and B. Fransen. 1993. Status and plight of searun cutthroat trout. Genetic Conservation of Salmonid Fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press**:** 203-212.

Trotter, P.G. 1987. Cutthroat: Native Trout of the West. Boulder, Colorado Associated University Press.

Utter, F., G. Milner, G. Stahl and D. Teel. 1989. Genetic population structure of chinook salmon, Oncorhynchus tshawytscha, in the Pacific Northwest. Fish. Bull. 87: 239-264.

Utter, F.M. 1991. Biochemical genetics and fishery management: an historical perspective. Journal of Fish Biology 39 (Supplement A): 1-20.

Utter, F.M., P. Aebersold and G. Winans. 1987. Interpreting genetic variation detected by electrophoresis. Population Genetics and Fishery Management. N. Ryman and F. Utter. Seattle, Washington, University of Washington Press**:** 21-45.

Utter, F.M., F.W. Allendorf and H.O. Hodgins. 1973. Genetic variability and relationships in Pacific salmon and related trout based on protein variations. Systematic Zoology 22: 257-270.

Utter, F.M., D.W. chapman and A.R. Marshall. 1995. Genetic population structure and history of chinook salmon of the upper Columbia River. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 149-168.

Utter, F.M. and N. Ryman. 1993. Genetic markers and mixed stock fisheries. Fisheries 18(8): 11-21.

Varnavskaya, N.V. and T.D. Beacham. 1992. Biochemical genetic variation in odd-year pink salmon (*Oncorhynchus gorbuscha*). Canadian Journal of Zoology 70: 2115-2120.

Varnavskaya, N.V., C.C. Wood and R.J. Everett. 1994. Genetic variation in sockeye salmon (*Oncorhynchus nerka*) populations in Asia and North America. Can. J. Fish. Aquat. Sci. 51(Suppl. 1): 132-146.

Varnavskaya, N.V., C.C. Wood, R.J. Everett, R.L. Wilmot, V.S. Varnasky, V.V. Midanaya and T.P. Quinn. 1994. Genetic differentiation of subpopulations of sockeye salmon (*Oncorhynchus nerka*) within lakes of Alaska, British Columbia, and Kamchatka, Russia. Canadian Journal of Fisheries and Aquatic Sciences 51(Supplement No. 1): 147-157.

Waples, R.S. 1991. Definition of "species" under the endangered species act: Application to pacific salmon. Seattle, National Marine Fisheries Service. Washington**:** 29.

Waples, R.S., J. R. P. Jones, B.R. Beckman and G.A. Swan. 1991. Status Review for Snake River Fall Chinook Salmon. Seattle, National Marine Fisheries Service. Washington**:** 71.

Washington Department of Fisheries, W.D.o. Wildlife and W.W.T.I. Tribes. 1993. 1992 Washington State Salmon and Steelhead Stock Inventory. Olympia, WA Dept. of Fisheries. Washington**:** 212.

Washington Deptartment of Fish and Wildlife and Oregon Deptartment of Fish and Wildlife. 1994. Status Report: Columbia River Fish Runs and Fisheries, 1938-1993. Olympia, Wash. Dept. of Fish & Wildlife. Washington**:** 271.

Wehrhahn, C.F. and R. Powell. 1987. Electrophoretic variation, regional differences, and gene flow in the coho salmon (*Oncorhynchus kisutch*) of southern British Columbia. Can. J. Fish. Aq. Sci. 44: 822-831.

Weitkamp, L.A., T.C. Wainwright, G.J. Bryant, G.B. Milner, D.J. Teel, R.G. Kope and R.S. Waples. 1995. Status review of coho salmon from Washington, Oregon, and California. Seattle, U. S. Department of Commerce.

Williams, J.E., J.E. Johnson, D.A. Hendrickson, S. Contreras-Balderas, J.D. Williams, M. Navarro-Mendoza, D.E. McAllister and J.E. Deacon. 1989. Fishes of North America endangered, threatened, or of special concern: 1989. Fisheries 14(6): 2-20.

Williams, J.E., J.A. Lichatowich and W. Nehlsen. 1992. Declining salmon and steelhead populations: New endangered species concerns for the west. Endangered Species Update 9(4): 1-8.

Williams, R.N. 1991. Genetic analysis and taxomomic status of cutthroat trout from Willow Creek and Whitehorse Creek in southeastern Oregon. Boise, Department of Biology, Boise State University. Idaho**:** 15.

Williams, R.N., R.P. Evans and D.K. Shiozawa. *in press*. Mitochondrial DNA diversity patterns of bull trout in the Upper Columbia River Basin. Friends of the Bull Trout, Calgary, Alberta.

Williams, R.N. and M. Jaworski. 1995. Genetic Analysis of Two Rainbow Trout Populations from the Kootenai River in Northern Idaho. Meridian, Clear Creek Genetics Lab. Idaho**:** 22.

Williams, R.N., D.K. Shiozawa, J.E. Carter and R.F. Leary. 1996. Genetic detection of putative hybridization between native and introduced rainbow trout populations of the Upper Snake River. Transactions of the American Fisheries Society 125: 387-401.

Wilmot, R.L., R.J. Everett, W.J. Spearman, R. Baccus, N.V. Vanaskaya and S.V. Putivkin. 1994. Genetic stock structure of western Alaska chum salmon and a comparison with Russian Far East stocks. Canadian Journal of Fisheries and Aquatic Sciences 51(Supplement No. 1): 84-94.

Winans, G.A., P.B. Aebersold, S. Urawa and N.V. Varnavskaya. 1994. Determining the continent of origin of chum salmon (*Oncorhynchus keta*) using genetic stock identification techniques: status of allozyme baseline in Asia. Canadian Journal of Fisheries and Aquatic Sciences 51(Supplement No. 1): 95-113.

Wishard, L.N., J.E. Seeb, F.M. Utter and D. Stefan. 1984. A genetic investigation of suspected redband trout populations. Copiea 1984(1): 120-132.

Wood, C.C., B.E. Riddell, D.T. Rutherford and R.W. Withler. 1994. Biochemical genetic survey of sockeye salmon (*Oncorhynchus nerka*) in Canada. Can. J. Fish. Aq. Sci. 51(Suppl. 1): 114-131.

Wright, S. 1965. The interpretation of population structure by *F*-statistics with special regard to systems of mating. Evolution 19: 395-420.

Wright, S. 1993. Fishery management of wild Pacific salmon stocks to prevent extinctions. Fisheries 18(5): 3-4.

CHAPTER 5. FRESHWATER HABITATS

"Maintaining a rich diversity of Pacific salmon genotypes and phenotypes depends on maintaining habitat diversity and on maintaining the opportunity for the species to take advantage of that diversity" (Healey and Prince 1995).

PHYSIOGRAPHY OF THE COLUMBIA RIVER

The Columbia River is one of the larger rivers of the world (Table 5.1) and also one of the most developed with ten major hydroelectric dams on the main river within the United States (Table 5.2; Figure 5.1) The catchment basin encompasses many different environments and climates encompassed by the wet coastal, Cascade and Rocky Mountain ranges and the semi-arid Columbia Plateau, which lies in the rainshadow of the Cascades. The extreme environmental diversity of the Basin is underscored by the fact that the Columbia Basin includes parts of 18 of the 43 physiographic provinces or ecoregions identified for the western United States (Omernik, 1987). Runoff (Table 5.1) derives from snowpack in the headwaters and seasonal rainfall in the lower elevations and coastal areas.

The Columbia River system is composed of steep gradient headwater streams that coalesce to form the major tributary rivers of the basin. The tributary rivers flow through mountain valleys where large alluvial flood plains occur between deep canyon reaches. These complex alluvial flood plains occur within the river continuum from headwaters to mainstem confluence like beads on a string. They are important with respect to salmonid ecology because they provide critical habitats (described below) that are much less available within the constrained channels of many of the canyon reaches. On the Columbia Plateau the lower reaches of tributary rivers like the Deschutes and John Day are partially or completely constrained by ancient lava flows and flood plains are less well developed. The same is true for the much of the mainstem Columbia and lower Snake Rivers; the only segments of the mainstem with extensive flood plains occur in the Hanford Reach and near the confluence of the Umatilla, which is drowned by John Day Reservoir. All of the Columbia Gorge is constrained and now impounded. Most of the channel of the Columbia River on its coastal plain below the Gorge is constrained by revetments built since the 1920s and lateral movement of floodwaters occur only on very high flow years.

Prior to extensive regulation by dams, the river was a gravel bed system from headwaters to mouth, although sand sized substratum became progressively more common in a downstream direction. Pre-regulation photos of the mainstem river in the Columbia Gorge show large sand dunes along the river (JAS has the photos if they need to be included here). Gravel and cobble was deposited extensively on the intermontane flood plains during high flows. The constrained reaches slowed the flow of floods allowing sand, gravel and cobble, along with tree boles and rood wads, eroded upstream to be deposited in the alluvial reaches upstream of the constriction. This process of cut and fill alluviation created a wide variety of instream and floodplain features of many sizes and shapes. Gravel bars and associated features also occurred in the constrained reaches, except at rapids created by exposed bedrock.

The bed load of the river is now largely retained in reservoirs. Only the finest sediments associated with spring runoff and other flooding reaches the estuary, owing to retention behind the many dams that have been constructed in the basin (Table 5.2, Figure 5.1). The mainstem retains only one freeflowing segment, the Hanford Reach. Many of the tributaries also are regulated, either by high storage dams used for hydropower production and flood control or by low head diversion dams for irrigation withdrawals. Bypass devices for migrating fishes have been built only on the mainstem and tributaries below Chief Joseph Dam on the Columbia and Hells Canyon Dam on the Snake.

CHARACTERISTICS OF HIGH QUALITY RIVERINE HABITAT

Salmonid fishes of all species require cold, clean water for survival and growth, and clean, stable, and permeable gravel substrate, usually in running-water environments, for reproduction. The specific habitat requirements of various species are discussed in detail elsewhere (Salo, 1987; Groot and Margolis, 1991; Meehan, 1991; Rhodes et al., 1994). Hence, herein we summarize the major habitat requirements of various life stages.

Habitat for reproduction

Incubation of salmonid eggs and fry occurs within the interstitial spaces of alluvial gravels in the beds of cool, clean streams and rivers. Native species of salmon, trout, and whitefish in the Columbia Basin are all lotic (running water) spawners in alluvial reaches of rivers and streams, except for sockeye salmon and kokanee (land-locked sockeye) which historically spawned on shallow, groundwater-effluent shoals or beaches on isolated shorelines of deep, cold lakes (e.g., Redfish (ID), and Wenatchee (WA), Chelan (WA) Okanagan (BC) and Kootenay (BC) Lakes) or similar environments in tributary streams of the lakes e.g., (Evermann, 1895). A few sockeye populations and some kokanee populations that have residualized from stocking in non-native lakes e.g., Pend Oreille, ID (Rieman and Bowler, 1980). Introduced salmonids such as lake trout and brook trout in general are less dependent on high-quality, running-water habitats for reproduction than are salmonids native to the Columbia Basin.

The season of spawning, egg incubation, and fry emergence varies among species of salmonids, with many rivers and streams historically supporting both fall spawning (winter incubating) and spring-spawning (spring and early summer incubating) populations. The relative success of fall- vs. spring-spawning strategies can vary depending on climate and hydrologic regime, catchment stability and sedimentation, water temperature patterns, the relative influence and availability of groundwater efflux zones, and controls exerted by seasonal flow conditions and physical barriers on the ability of adult fish to gain access to spawning sites. In general, spring-spawning species (e.g., steelhead, rainbow and redband trout, and cutthroat trout) concentrate their reproductive activities in smaller, headwater streams and in spring snowmelt-fed streams. Reproduction of fall-spawning species (chum, chinook, and coho salmon and bull trout) occurs most frequently in alluvial reaches of larger streams and rivers where groundwater efflux strongly buffers local interstitial and surface water conditions. Long-term patterns in local variation in the seasonality of flow and sediment transport, the availability of clean, stable substrates, patterns in groundwater-surface water exchange, and thermal regime exert high-magnitude, density-independent effects on the survival and recruitment of salmonids that strongly constrain the abundance of all later life stages, including harvestable adults. Salmonid fish populations display a diversity of local adaptation of life histories and behaviors in concordance with this local environmental complexity. These components of the freshwater environment are highly vulnerable to alteration by most kinds of human activities and natural events.

Juvenile rearing and movements

Once emergence from the gravel is complete, young salmonids are mobile, which increases their individual flexibility to cope with environmental variation by seeking suitable habitat conditions. Mobility is limited, however, particularly for fry, so that suitable habitat and food resources must be available in proximity to spawning areas for successful first-year survival. Moreover, movement may come with high metabolic cost and high risk of mortality, such as through exposure to predators, unless movements are tied closely to patches of predictable, high-quality habitat. These habitats ideally afford low-velocity cover, a steady supply of small food particles, and refuge from larger predatory fishes, birds and mammals. Examples of such habitats include quiet-water areas, backwaters, and small spring-fed channels along stream margins, floodplain ponds and sloughs, and alcoves within structural complexes created by woody debris, bank structures and riparian vegetation or aquatic plants. These critical habitats are most abundant and structurally diverse on aggraded, floodplain reaches where they are created and maintained by cut and fill alluviation. Alluvial floodplains occur like beads on a string from headwaters to river mouth (Stanford and Ward, 1993), although floodplains in the Columbia River Basin are most complex in the middle reaches of tributary rivers owing to the entrenchment of the mainstem river channel. Pink salmon, which were never very common in the Columbia River, move quickly to the ocean after hatching and sockeye salmon move into lakes as small fry. However, these laucustrine-oriented species also require shallow resting habitats with cover from predators, as provided by the complex features of functional flood plains, during fry migration.

Natal (very young fry) salmonids typically feed on invertebrates and small vertebrates and, in high quality alluvial habitats, they can grow rather rapidly. As water temperature increases beyond about 15°C, metabolic costs escalate rapidly and available food resources support progressively lower densities of juvenile salmonids (Li et al., 1995). Summer temperatures in most Columbia River tributaries, particularly the floodplain reaches that have been extensively altered by human activities, typically far exceed this value and in many cases pass the lethal thermal maximum for salmonids (Rhodes et al., 1994, see discussion later in this chaper). Suspended sediments impair the ability of salmonids to see and capture prey, and accelerated deposition or transport of sediments on streambeds can deplete populations of stream invertebrates that are most important for salmonid growth.

Juveniles of some salmonid populations and species are known to successfully move long distances (many tens or even hundreds of kilometers) from their natal habitats, and some, such as pink, chum, some sockeye and fall or ocean-type chinook salmon, virtually are never resident; they move downstream after emergence progressively stopping to feed and grow in lower-velocity habitats created by eddies in constrained (canyon) segments and, in particular, the complex habitats of floodplains. Experimental studies with several salmonid species indicate directed movements or patterned migratory behaviors that are genetically determined, and these movements are closely tied to available habitats of various kinds. For example, juveniles in some populations in larger rivers tend to move downstream in late fall to seek wintering habitat in low-velocity backwaters of large floodplains or deep pools, whereas others tend to move upstream where wintering habitat is available in aggraded headwater areas (e.g., in beaver ponds).

Each local breeding population likely evolved site-and season-specific patterns of early-life-history behavior that allow juveniles to efficiently locate and exploit the locally available patchwork of habitat. For example, sockeye fry resulting from spawning in lake inlets move downstream to rear in the lake, while those spawned in the outlet usually move upstream to rear in the same lake (Brannon and (eds.), 1982). Lack of such a locally-adapted genetic heritage is one likely reason that hatchery-origin fish, including all forms of cultured and translocated fish and their offspring, typically exhibit lower fry to adult survival rates than indigenous fish of the same species, age and size (Ricker, 1972; Riddell and Legget, 1981), although total survival of some hatchery fish may be higher than wild fish (Shreamer 1995). Moreover, destruction or alteration of available habitat mosaics created by natural biophysical processes (e.g., as a consequence of cumulative effects of flow regulation and fine sediment, thermal and chemical pollution, and upland and riparian land misuse) almost always impairs the survival of indigenous fish by compromising their inherited ability to anticipate and "track" high quality habitats (Stanford et al., *in press*).

Long-distance migration of juveniles or sub adults downstream to lakes, rivers, or the ocean for maturation may intuitively seem maladaptive. However, migration can allow increased opportunities for access to concentrated food resources that allow rapid growth, permit escape from localized concentrations of predators or marginal habitats, and mediate longer life span and large body size which confers selective advantage. While some species retain a diversity of rearing strategies that allow them to persist in headwater populations even when opportunities for downstream migration are poor (e.g., steelhead, kokanee salmon), other species are completely dependent on long-distance migration for maturation and survival (other salmon, and to a lesser extent, bull trout). On the other hand some populations do not move much, staying in the same stream reaches or lakes throughout their life cycle e.g., bull trout in Upper Kintla Lake, MT: (Hauer et al., 1980). However, the great historical abundance of migration-dependent species in the Columbia River indicates this system has (until recently) provided habitat favorable for a wide array of anadromous and river-migrant salmonid life histories for many centuries. Owing to the complex physiography of the Columbia River, opportunities for adaptation to particular rivers and even river segments was historically high and, as noted above in Chapters 2 and 4, metapopulations were composed of suites of interactive, but locally-adapted, stocks.

Habitat for adult migration

After growth and maturation, salmonid adults generally return to natal spawning areas for reproduction. The timing of adult entry and movement in rivers and tributary streams, and even the size, shape, and strength of adult fish represent adaptations to the specific physical and biological challenges presented by the upstream pathway to a specific spawning area. For example, waterfalls and similar physical barriers may be passable only at a specific range of flows that typically occurs during one month of the year, and then only by fish that have particular physical capabilities for jumping or "scooting" over the barrier. The entire sequence of migration behavior must be properly timed to meet such windows of opportunity. For fall-spawning fish, prevailing warm water conditions in late summer often present strong thermal barriers to movement, and suitable habitats for resting may be few and far between (Berman and Quinn, 1991). Therefore, again at the adult life stage, population-specific behavioral patterns, closely attuned to the mosaic of habitats that is available for migrant adults, may be critical for survival and successful reproduction.

Faithful homing to natal spawning areas is typical, but straying does occur. Adult fish also exhibit a remarkable ability to locate and select high-quality habitat patches for spawning (i.e., areas of suitably sized gravel and cobble with high rates of interstitial flow to modulate temperatures and oxygenate the nest or redd), and they will actively stray from natal habitats to spawn elsewhere when habitat conditions in their stream or reach of origin no longer are suitable or accessible for spawning, or are overcrowded with high densities of spawners.

Once they enter the vicinity of spawning areas, large adult migrant fish can be highly visible and vulnerable to terrestrial (including human) and avian predators. The availability of deep resting pools, riparian forest canopy, undercut banks, and large woody debris accumulations in the proximity of spawning habitats can be critical for survival and successful reproduction of migratory salmonids, particularly those that venture far upstream and that are required to spend long periods holding in small river and stream environments. Cover elements can be particularly important in providing physical shelter from high flow events, or refuge during particularly low flows in spawning areas.

Influence of woody debris on development of high quality habitat

Much of the historical habitat complexity of streams throughout the Columbia Basin was associated with accumulations of large woody debris. Historically, virtually all Columbia Basin streams, including rivers of the high desert, traversed riparian forest mosaics that usually included stands of large-diameter, older trees (Wissmar et al., 1994). These riparian forests (including downed trees in the channel) were often the most accessible source for high-quality logs during settlement and later proliferation of timber markets, so large woody material was eliminated early on, and have subsequently been suppressed by continued logging and grazing in riparian areas (McIntosh et al., 1994; Wissmar et al., 1994). Clearance of rivers to facilitate log drives and other forms of navigation also contributed to loss of natural debris jams in many rivers (Sedell and Froggatt, 1984; 1991)

Large, downed trees and coarse woody debris in the channel and on floodplain surfaces are absolutely integral to the development of habitat in Columbia Basin streams, particularly in the alluvial reaches where substratum size is smaller and interstitial cover more limited than in the boulder-dominated channels of high gradient streams. In concert with the bank stability and flow resistance conferred by living riparian vegetation, coarse woody debris acts to deflect flows, creating low-velocity flow refugia, scouring deep pools, locally trapping sediments and fine organic material that contributes to aquatic food webs, and providing a diverse and stable habitat mosaic used heavily by many kinds of organisms, including salmonid fishes (Sedell and Froggatt, 1984; Naiman, 1992). Debris accumulations may play a direct role in forcing surface flows into alluvial aquifers and promoting efflux of hyporheic flow and shallow groundwater back into surface waters (Ebersole, 1994). At a larger scale, debris jams cause temporary obstructions to the river course that during peak flows promote local channel switching and floodplain inundation, primary processes that create and rejuvenate the diverse mosaic of main channel, backwater, slough, springbrook, and hyporheic habitats common to natural alluvial rivers (Sedell and Froggatt, 1984; Stanford and Ward, 1993). Such channel movement and floodplain inundation also sustains diversity in floodplain vegetative communities. Debris jams may act to divert or break up ice accumulations during winter, preventing the downstream propagation of ice drives that tend to naturally channelize rivers in colder, interior areas (Smith, 1979).

Wood debris likely was a very important feature of the mainstem river as well. Lewis and Clark (Moulton, 1988) noted large jams of huge tree boles in eddies and side channels. Today little or no large woody recruitment is possible, even in the free flowing Hanford Reach, because wood recruitment in tributary rivers is retained in the reservoirs.

Groundwater upwelling: a key attribute of high quality habitat

Large woody debris accumulations and other structures confer to natural alluvial rivers a high degree of morphological complexity that results in highly connected subsurface and surface flow paths. Deep pools, low-velocity backwaters, and springbrooks isolated from main channel flows are common zones of upwelling and concentration of groundwater in ways that create diverse thermal refugia for fishes and other organisms (Sedell et al., 1990; Stanford and Ward, 1993; Ebersole, 1994). These habitats are cold relative to warm surface waters in summer, warmer than surface waters in winter, and can sometimes be nutrient-rich and highly bioproductive (Stanford and Ward, 1993).

In winter, groundwater-influenced stream habitats (upwelling zones in main channels and backwaters; back bar and wall based channels; low-terrace springbrooks), especially on alluvial flood plains, often remain free of anchor and surface ice, buffering them from the stresses of winter freezing and thawing processes that can be highly disruptive of biota, including wintering fishes. Groundwater-influenced habitats are well known to provide important spawning habitats for fall-spawning salmon and bull trout. Historical data are clear on where the fish spawned , e.g., see the maps of Fulton, (1968; 1970) and it is likely that these were areas of groundwater upwelling. Groundwater-rich pools, beaver ponds, and springbrooks also appear to provide critical winter habitat for juvenile and adult salmonids, which may move long distances to congregate in these areas (Cunjak and Power, 1986; Chisolm et al., 1987; Cunjak and Randall, 1993).

In summer, coolwater refugia maintained by groundwater upwelling are known to be used heavily by adult spring chinook (Berman and Quinn, 1991), resident trout (Li et al., 1995) and virtually all other salmonids that inhabit warmer river reaches. In large portions of the Columbia Basin at lower elevations and in desert areas, it is likely that native salmonids would not persist except for the availability of cool refugia at groundwater upwelling sites.

Upwelling areas on alluvial reaches are hot spots of bioproduction because the plant available nutrients accumulate in groundwater flow pathways (Vervier and Naiman, 1992;

Stanford et al., 1994). These nutrients greatly stimulate primary production and likely increase protein content of emergent hydrophytes and riparian woody vegetation. Hence, riverine habitats influenced by ground water provide a more consistent and abundant food supply for all life stages of salmonid fishes and other food web components. This is in contrast to steep gradient canyon segments, where surface and groundwater interactions are limited due to bedrock controls on channel geomorphology. Salmonid habitats are limited to main channel features such as rapids, runs, pools and eddy complexes associated with rock and woody debris.

Complex interactions between ground water and surface water are key attributes of high quality riverine habitat for salmonid fishes in the Columbia River. Since these habitats are created by the inter-relation between flow and bedload movement (cut and fill alluviation) in relation to the slope of the main river channel, these habitats are not distributed uniformly. They are most well developed on aggraded floodplains. Floodplain segments also are human foci within the river continuum, because these tend to be the most productive nodes for agriculture and water diversion and impoundment in the watershed landscapes of the Columbia Basin. As a consequence maintenance of critical salmonid habitat has been problematic owing to conflict of uses. Moreover, owing to the early development of floodplain reaches, salmonid habitat in these areas was compromised to varying extents many years ago and measures to protect rivers have tended to focus on much less productive canyon and high mountain segments that were not only of less importance to humans but also were less important habitats for salmonids in general.

We realize that protection was accorded to various river reaches, not in relation to use by salmonids, but because these segments had wilderness or other values. However, the restoration of habitat complexity in the alluvial reaches should be emphasized in recovery efforts.

CAUSES AND CONSEQUENCES OF HABITAT DEGRADATION

Conclusions from recent reviews and synoptic studies

Vast quantities of information on habitat conditions in Columbia Basin watersheds and streams have been collected by numerous agencies. Unfortunately, the quality and scientific value of much of this information is questionable or very limited, much is inaccessible and perhaps permanently lost, and very little of the remainder that is potentially useful has been comprehensively analyzed, summarized, or otherwise made available in reports or publications. Fortunately, over the past few years, several important reviews and a few comprehensive research studies of salmonid habitat status, trends, and threats in the Pacific Northwest and Columbia Basin have been published. Hence, comprehensive review herein would be redundant; readers are urged to consult the citations given below for details. Our objective in this section is to underscore the general conclusions from these reviews: considerable degradation of salmonid habitat has occurred in the Columbia River Basin; habitat conservation and restoration has not been a priority for management; and, where habitat restoration has been attempted the results generally have been unsuccessful or counterproductive (General Accounting Office, 1992).

Regional reviews of salmonid population status (Nehlsen et al., 1991; Frissell, 1993; Rieman and McIntyre, 1993; Society, 1993; National Research Council, 1995) strongly implicate habitat degradation as a major contributing cause of population decline. Frissell (1993) and The Wilderness Society (1993) point out that regional patterns in decline of salmonids and other fishes in areas not subject to the impacts of dams and major diversions indicate the pervasive importance of general, catchment-wide habitat degradation as a threat to fish populations. This is not to say that construction and operation of the many dams and reservoirs in the Columbia Basin are not important factors in run declines (they are); but, clearly other kinds of human land use and associated freshwater habitat degradation can and do endanger salmonid populations.

General discussions of some mechanisms of habitat change in response to human activities and its effects on riverine ecosystems can be found in Stanford and Ward (1992), Elmore (1992), and Naiman et al. (1992), and in earlier sections of this document. Salo and Cundy (1987), Meehan (1991), Bisson et al. (1993), and FEMAT (Forest Ecosystem Management Assessment Team) (1993) comprehensively review some of the multifarious pathways by which human land management activities are known to degrade habitat and affect salmonid populations. These processes are no different in the Columbia River Basin than elsewhere in the world.

Lichatowich and Mobrand (1995) and (Wissmar et al., 1994) discuss many early references to habitat degradation and its consequences for salmon runs in the Columbia Basin. Many of the historical sources date from prior to the turn of the century, and it is clear that degradation of freshwater habitat (e.g., through intense exploitation of beaver and early mining activity) was well underway in the basin soon after its colonization by Europeans. Available data indicate that coho salmon in the Columbia River Basin were in serious decline by the 1930's, long before construction of mainstem dams began, in part reflecting the effects of extensive human-caused changes in low-elevation habitats (Pacific Rivers Council et al., 1993).

Theurer et al. (1985) developed a modeling procedure to relate riparian vegetation to thermal regimes of streams, and tied this to relationships between temperature and salmon abundance developed in previous Columbia River research. They applied the models to assess fish habitat in the Tucannon River drainage, estimating losses of salmon production caused by riparian land uses in the drainage, and predicting potential gains in salmon populations that might result from protection and restoration of historic levels of riparian forest cover. Though necessarily based on limited data, this work is notably one of the first credible attempts to understand natural Columbia River salmon production and habitat status in the context of large-scale human alteration of ecosystem pattern and process. The results strongly suggest that salmon recovery in the alluvial reaches of the Tucannon and likely in other mid-Columbia rivers (our conclusion) is directly tied to substantial improvements in habitat condition. More recently, Li et al. (1995) reported the results of extensive observational and experimental studies demonstrating impacts on the aquatic system of human disturbances in riparian zones in the John Day Basin, including thermal alteration shown to be highly adverse to salmonid fishes.

Wissmar et al. (1994) and McIntosh et al. (1995; 1995; 1995; 1995; 1995) demonstrate the pervasive, adverse impacts on fish habitat that human activities have caused in the Columbia Basin. They document damaging changes in channel morphology and stability and progressive and persistent loss of riparian vegetation, pools, large wood, and other biologically important habitat elements in streams whose catchments experienced extensive logging, grazing, mining, and other human extractive development. By contrast, streams in catchments dominated by relatively undisrupted wilderness or roadless areas exhibited little long-term change, or even showed improvement in fish habitat conditions over the study period (the past several decades).

Obviously, natural disturbance processes (floods, droughts, diseases) occur episodically in roadless and natural areas, but in general natural disturbances appear to have much less adverse effect on native fishes than do human disturbances. For example, catchments affected by large-scale wildfire since the 1940's, as long as they were not also affected by extensive human activities, appeared to maintain high-quality habitat or improving trends in habitat conditions (1995; 1995; 1995; McIntosh et al., 1995; 1995)

Based on regional assessment of biological and federal-land resources in the Columbia Basin, Henjum et al. (1994) strongly advocated the protection of roadless and late-successional forest lands to provide watershed-level refugia for fishes and other aquatic species. Rhodes et al. (1994) presented extensive synthesis of previously unexamined or fragmentary data from various agency sources to demonstrate the extreme importance of roadless and little-impacted catchments as *de facto* strongholds for declining Snake River salmon. In an analysis of a large field data set on habitat condition and fish populations in the Clearwater River basin in the Upper Columbia, Huntington (1995) showed that roadless catchments, even those that had intensely burned earlier this century, provided higher quality habitat to more diverse and abundant native fish populations than did nearby, heavily "managed" catchments. Huntington's analysis also indicated that non-native species such as the brook trout (*Salvelinus fontinalis*), which can displace native trout and interbreed with bull trout, flourish in catchments where habitats have been more extensively impacted by man. Henjum et al. (1994) and Li et al. (1995) pointed out that even though remaining relatively undisturbed headwater areas may afford marginal habitats relative to the historical distribution of fish species in Oregon, protection of these areas appears critical for near-term persistence and long-term restoration of native fishes, including salmon. In a multi-species biodiversity assessment of the Swan River Basin in Montana, Frissell et al. (1995) found that tributaries draining roadless areas, especially those that have not been extensively stocked with non-native fishes, appeared to be disproportionately important for native trout and other aquatic and wetland-dependent species.

Independent scientific reviews of BPA-funded habitat improvement projects in the Columbia Basin (Beschta et al., 1991; Frissell and Nawa, 1992; Kauffman et al., 1993; Henjum et al., 1994; National Research Council, 1995) have been highly critical of habitat management which has (unsuccessfully) emphasized the installation of costly artificial structures in lieu of full protection and restoration of natural vegetation and ecological processes that create and maintain fish habitat.

Doppelt et al. (1993) offers a lucid critique of misplaced priorities in past policy and habitat management programs, and provides a road map for a more comprehensive and ecologically credible approach to restoration of salmon ecosystems. Their recommendations and Wissmar et al. (1994) suggest that managers focus on identifying existing high-quality watersheds and downstream "nodal" habitats or "hotspots" that are disproportionately important for protecting existing native species populations and protecting them from proposed or recent human disturbances (e.g., through removal of existing logging roads or removal of livestock from riparian areas). Second priority in terms of urgency of action, but equally necessary for long-term success, is restoring adjacent and selected downstream habitat patches than can increase basin-wide biological connectivity and allow expansion, life history diversification, and demographic and genetic re-connection of existing population fragments.

Similar effects from different causes: a brief summary of some pervasive human activities and their consequences on salmonid habitat

A theme of this report is that many kinds of human activities tend to result in similar changes in aquatic ecosystems, although the magnitude, persistence, interactions, and biological outcome of the effects can vary widely according to local conditions and history. While site-specific prediction of impacts can be difficult and uncertain (e.g., influences of a particular forestry prescription; outcome of fish stocking), catchment-scale trends and spatial patterns in freshwater habitat condition in the mainstem Columbia River and its tributaries are generally well documented, predictable and stereotypical (Salo, 1987; Rhodes et al., 1994; Rhodes, 1995). In this section we provide a very general sketch of the typical effects of various human activities in the Columbia Basin.

Beaver trapping

Perhaps the earliest exploitative land use in the Columbia Basin was large-scale trapping of beaver, which began in the mid-1800's (National Research Council, 1995). Beaver dams were historically very extensive in nearly all alluvial and low-gradient segments of Columbia River tributaries, and were common in branches and backwaters of the larger tributaries and Columbia itself. Alluvial flood plains were sites of heavy beaver activity causing streams to meander and braid, thereby maximizing the mosaic structure of salmonid habitats.

Beaver dams and their foraging activities created storage sites that buffered flows of water and downstream transport of organic matter, nutrients, and sediment. Beaver ponds were important rearing and wintering areas for many species of salmonids, and promoted channel switching and geomorphic complexity that encourages extensive exchange of surface and subsurface waters in alluvial aquifers (Naiman and Fetherston, 1993). Another under-appreciated function of the beaver may be its unique role as an upstream vector of vegetative propagules of willow and other important riparian species, allowing their recolonization following debris flows, severe drought, and other catastrophes that can wipe out riparian plant communities in tributary catchments.

Trapping permanently reduced or extirpated most beaver populations, with resulting widespread loss of structural elements, floodplain processes, and vegetative diversity that had developed as a result of centuries of ongoing beaver activity. Throughout the Columbia Basin beaver-mediated creation of salmonid habitat is nowhere near its zenith in the river system that Europeans discovered, even though beaver have been included in state wildlife management programs for at least the latter half of this century.

Logging

Early settlement in the Columbia River basin was concentrated in alluvial bottomlands along lower-elevation tributary rivers and streams, where arable soils and water were plentiful and transportation was most feasible. Logging in floodplains and bottomlands accompanied the earliest settlement for purposes of land clearance, access to and through stream channels for transport, and for construction materials. A sawmill was operating in Vancouver, WA, as early as 1827 (National Research Council, 1995). As regional and national markets and transport systems developed, timber grew rapidly to become a major commercial component of the Pacific Northwest's economy. Cutting of timber remains a widespread industrial activity in the Columbia Basin today, although most large, valuable stands of old-growth forest are long-gone. As shown by Henjum et al. (1994), timber cutting in the Columbia Basin has in many areas been disproportionately concentrated in low-elevation valleys and riparian areas, where high-value species and older trees were historically most abundant.

Logging of trees from riparian areas directly eliminates the source of large woody debris that is so central to many ecosystem processes and the maintenance of habitat complexity and productivity in streams and rivers. Moreover, it directly reduces shade and alters near-surface microclimatic conditions that protect streams from climatically-driven warming in summer and freezing in winter (Salo, 1987; Maser, 1988; FEMAT (Forest Ecosystem Management Assessment Team), 1993; Naiman and Fetherston, 1993). Removal of standing live trees or downed wood can jeopardize the long-term stability of channel banks, floodplain, and toeslope surfaces. In areas where tree regeneration is dependent on seed sources or specific ecological conditions, logging has resulted in the permanent loss of ecologically valuable tree species such as western red cedar and ponderosa pine. In addition, operation of machinery necessary to cut and remove trees can directly damage soils, vegetation, and channel feature, altering ecological processes in these sensitive areas.

Despite speculation to the contrary, no study has demonstrated that "safe" or "beneficial" levels or methods of logging in riparian and floodplain areas exist from the standpoint of maintaining the many natural ecological functions of forests. This is exacerbated by the massive, regional scale at which previous logging has caused long-term impoverishment or impairment of ecological components and processes in the Columbia Basin. Therefore recent scientific assessments have recommended no removal of trees from these key areas (FEMAT (Forest Ecosystem Management Assessment Team), 1993; Henjum et al., 1994; Rhodes et al., 1994).

Although today the logging of riparian and floodplain forests continues in many areas, most timber harvest volume is produced by more extensive and frequent cutting of smaller, lower-value trees over larger, upland areas, which requires extensive road networks and results in major alteration of forest cover conditions across large catchments. These landscape alterations have different, but equally threatening effects on catchment processes and freshwater habitat.

Although humans build roads for many purposes, the vast majority of roads in the Columbia Basin have been (and continue to be) constructed for purposes of logging transport and access for silvicultural management of commercial forest lands. In the spectrum of natural disturbance processes, road networks have no known natural analogue. Road networks are direct sources of accelerated sediment production and efficient delivery to the stream network (Meehan, 1991; Rhodes et al., 1994). Roads also permanently intercept and re-direct surface and subsurface flow of water, altering hydrologic and thermal regimes in streams (Meehan, 1991; Rhodes et al., 1994). Roads can serve as vectors for forest pathogens and increase the spatial extent of a wide range of human activities, such as legal fishing, poaching, and deliberate or unintentional introduction of non-native species that threaten native biodiversity (Frissell and Adams, 1995; Frissell et al., 1995; Noss and Murphy, 1995).

Logging often results in the removal of forest cover in patterns and at rates far exceeding the scope of natural events that have historically dominated forest landscapes in the Columbia Basin. Moreover, unlike fire, disease, windthrow, and other natural forest disturbances, logging causes the large-scale removal of largest size fractions of woody debris from forests (Maser, 1988). The mechanical means used for cutting and removing large trees can create unnatural soil disturbance and compaction that accelerates surface erosion and alters hydrologic relations Opening the forest canopy, especially if it occurs across a significant portion of a catchment, alters microclimate, snow accumulation and melt and other aspects of precipitation, and can change the routing and slope storage of water, often resulting in downstream changes in streamflow and channel stability that are detrimental to fishes. Such changes typically include increased flashiness of discharge, increased peak flows, and accompanying increases in sediment load due to erosion of channel margins and heads. On steep and unstable terrain, changes in subsurface flows and soil moisture, perhaps together with reduced root strength, can increase the frequency and alter the style of landslide and gully erosion (Salo, 1987; Meehan, 1991; Naiman and Fetherston, 1993; Rhodes et al., 1994). Increased transpiration and reduced moisture-capturing and retaining efficiency of second-growth forests following extensive logging can result in long-term depletion of summer and fall low steam flows, even as winter and spring peak flows increase (Hicks et al., 1991; Rhodes et al., 1994). Despite the vast spatial extent of past and present logging activities in the Columbia Basin, few of these ecosystem changes are satisfactorily explained or accounted for in existing models of cumulative watershed effects employed by land management agencies to assess environmental impacts, and these processes are rarely monitored on a site-specific or watershed basis.

Grazing

Grazing by domestic livestock can change riparian and stream channel characteristics that are detrimental to salmonids. Kauffman and Krueger (1984), Platts (1991), and Rhodes et al. (1994) provide valuable reviews of this subject. While grazing by domestic species began very early in some areas with cultivation of horse herds by Indian tribes (e.g., the Grande Ronde basin), large numbers of sheep and cattle arrived with European settlers during the late 1800's. Even though peak numbers of livestock probably occurred prior to the turn of the century, grazing impacts on aquatic systems since then have continued relatively unabated. More than a century of continuous grazing in many areas has caused progressive deterioration of range and riparian conditions throughout the Columbia Basin (Rhodes et al., 1994; Wissmar et al., 1994; Lichatowich and Mobrand, 1995).

Livestock impacts to streams occur through three major vectors: 1) direct trampling of channels, banks, and soils; 2) removal and alteration of vegetation, particularly in riparian areas;

and 3) direct introduction or overland flow of fecal wastes and urine into surface waters. The direct effects of large, grazing animals include trampling and sloughing of streambanks, loss of overhanging banks, accelerated bank erosion, compaction of soils and increased sediment input to adjacent and downstream reaches. Grazing and trampling of vegetation in riparian areas and floodplains generally reduces vegetative cover and vigor, suppresses or eliminates some vegetation species (especially palatable but ecologically critical woody species such as willows), and reduces canopy cover over the channel. The result is typically widened and open channels, with lower, warmer, more turbid surface flows in summer, more extensive and damaging ice conditions in winter, and flashier, more turbid, flows in winter and spring runoff periods. Fine sediment concentrations increase and channel stability decreases (Meehan, 1991; Rhodes et al., 1994; Li et al., 1995). Eutrophic enrichment from livestock wastes can cause depletion of oxygen required by fishes and their principle food organisms. These changes are adverse to salmonids at virtually all life stages.

Mining

The many effects of mining are discussed in general terms in Nelson et al. (Meehan, 1991, in Chapter 12). Although extensive mining has occurred in many areas of the Columbia River basin, the history and effects of these activities have not been comprehensively compiled and described in any single source. Mining effects, although difficult to sort out from those of many other simultaneous and subsequent disturbances, were no doubt extensive in some major tributaries (e.g., John Day River, Salmon River, Coeur d'Alene River, Upper Clark Fork River) by the late 1800's. It is likely that the historic impacts of mining on salmon and native trout have been given short shrift in recent reviews (National Research Council, 1995) because of the relative paucity of information, and perhaps because mining today is less widespread an activity than logging, grazing, and irrigated and cropland agriculture. However, the old disturbances and their effects remain.

Mining activities of various kind inflict intense soil disturbance and erosion. In addition to very large sediment inputs to downstream reaches, placer mining causes direct, wholesale destruction of natural channels, floodplains, valley floor soils and vegetation, and alluvial aquifers. Natural recovery is inhibited, perhaps permanently. Areas of the Upper Grande Ronde basin (McIntosh et al., 1994) and elsewhere subjected to placer mining, for example, have not recovered to any semblance of natural structure and function in more than a century. Leaching of toxic materials from mining wastes and milling sites can permanently contaminate and impair the productivity of stream and riverine ecosystems many kilometers downstream, as is most evident in the Upper Clark Fork and Coeur d'Alene river basins in the headwaters of the Columbia, where native salmonids have been virtually eliminated from the affected waters for a century or longer.

It appears likely that other mining districts may suffer more subtle, not yet documented depressions in biological productivity from mining waste toxicity.

Irrigation and cropland agriculture

Cropland agriculture affects vast areas of the Columbia River Basin, although this activity is perhaps most concentrated on arid basalt plateaus and Palouse prairie country where surface waters are scarce. No comprehensive review of the effects of cropland agriculture on fish habitat in the Columbia Basin exists, as far as we know. Farming can significantly alter hydrology and increases erosion and sedimentation processes many-fold over natural rates. Where farming impinges on wetlands, floodplains, and riparian areas, it directly destroys riparian vegetation and channel structure. The principal effects of cropland agriculture on fish in the Columbia Basin no doubt stem from flow diversion and withdrawal for irrigation (National Research Council, 1995). Some irrigation also occurs to support grazing of pasture. Irrigated agriculture began with early settlement in the mid-1800's, but rapidly accelerated with the assistance of large, government-subsidized projects starting in the early 1900's and continuing to the present.

Although a widespread problem globally, few good review papers are available that address the scope of activities and effects of irrigation on freshwater habitat and fish populations. There has not been a comprehensive ecological assessment of the consequences of irrigation for fish in the Columbia Basin.

Dams and diversions for to provide water for irrigation can block movements of migratory fishes and divert fish from natural habitats into ditches or onto fields, killing them. Diversions de-water natural habitats, reducing habitat available in streams and sometimes rendering it entirely hostile (e.g., through warming) or a barrier to fish passage (e.g., loss of surface flow through riffle crests). Water in storage ponds typically warms much more than water free-flowing in streams and natural aquifers. Water that is returned to streams from irrigated fields is typically warm and often laden with very high concentrations of sediments, nutrients, and pesticides. Vaccaro (1988) developed a simulation model of the effects of irrigation diversions on surface water temperature in the Yakima River Basin. Vaccaro projected that removing the effects of irrigation diversion could cool summertime temperatures in critical salmon habitats by up to 2°C; this effect was most pronounced at lower elevations where larger, alluvial reaches of the river and its tributaries once supported abundant salmon production (Lichatowich and Mobrand, 1995).

Urban and other sources of excessive nutrients and toxic pollutants

Concentrations of dissolved solids and pollutant loads generally increase from headwaters to oceanic confluence in most of the nation's large rivers, including the Snake and Columbia Rivers (Smith et al., 1987) as a consequence of the cumulative loads of pollutants from all land use activities. A primary source is treated sewage effluents and storm drainage from the urban areas along the river corridors. Oxygen depletions and other indicators of severe organic and nutrient pollution from point sources near and within urban centers were once common in the lower mainstem reaches of the Columbia River and many of the larger tributaries (Stober and Nakatani, 1992). Owing to the Federal Clean Water Act, sewage treatment, including effluents from pulp mills and other industrial sources, have been substantially improved in the last two decades. Creation of many reservoirs within the continuum also contributed to the decline in pollution because they are processed by food webs and retained in reservoir sediments. However, continuing concern exists for loading of plant growth nutrients in the large on-channel lakes and reservoirs and loads are being legally allocated to sources through actions to limit the total maximum daily load to lakes, e.g., Flathead (MT) (Flathead Basin Commission, 1994) and Long (WA) (Sotero et al., 1992) Lakes. Moreover, metals and organic carcinogens are present in fish tissues throughout the Basin (Stober and Nakatani, 1992), even in headwater systems like Flathead Lake (detectable PCB concentrations in fish tissues) (Flathead Basin Commission, 1994) underscoring the need for continued vigilance. Damkaer and Dey (1986) found that fluoride effluent from the aluminum plant upstream from John Day Dam caused delays of as much as 4 days in passage of chinook past John Day Dam.

Nonetheless, water pollutants, other than from fine sediments, increased temperature and metals from mining districts as discussed elsewhere in this report, generally are not considered a major factor in salmonid declines nor particularly problematic for recovery (see discussion of temperature effects below). We are not sure that the available data have been examined well enough to agree with this consensus. Indeed, data on pollution loads, particularly from diffuse (non-point) sources and interactions between maintenance of salmonid critical habitats for all life stages has not been examined extensively in the Columbia River system, at least in the context of salmonid restoration.

<u>Stream regulation: effects of dams, reservoirs and diversions</u>

Flow regulation for purposes of hydropower production and flood control has been the primary issue for salmonid conservation and restoration in the Columbia Basin, since construction of the first small tributary dams for power generation early this century. The effects of dams in the basin were magnified by construction of mainstem projects since 1938 that directly affect virtually all migratory fishes in the middle and upper Columbia Basin.

Mortality of salmonid fishes caused by dam passage (e.g., through turbines and bypass facilities) has dominated discussion and actions for salmonid recovery. Many millions of dollars have been spent on facilities and research to increase bypass efficiency in the absence of accurate mortality estimation. Recent studies on the Snake River suggest far lower mortality associated with reservoir transit and dam bypass by wild fall chinook than previously thought. These issues are discussed in detail elsewhere in this report. We note that recovery efforts also have focused heavily on decreasing the transit time for smolts in the highly regulated mainstem either by use of storage releases to move smolts out of the system or by barging, even though such actions clearly are selective of specific life history types. We conclude that greater attention to habitat related effects of stream regulation is needed.

The ecology of regulated streams has been summarized in several volumes (Ward and Stanford, 1979; Lillehammer and Saltveit, 1984; Lillehammer, 1984; Craig and Kemper, 1987; Petts and Wood, 1988; Petts et al., 1989; Calow and Petts, 1992; Hauer, 1993). Principles from a very diverse and detailed literature (Stanford et al., *in press*) directly apply to the Columbia River. In this section we point out that dams have many important consequences for salmonid habitat and populations, including: 1) destruction of riverine habitat upstream of dams and its conversion to novel, reservoir habitats; and, 2) the creation of highly artificial flow, thermal, and sediment regimes downstream of dams.

Reservoirs represent massive loss of the once-highly-productive riverine habitat that occurred above most dam sites. Optimal dam sites are often located at narrow bedrock constrictions below wide, aggraded valleys, which allow large storage ratios for a given dam size. As described above, these aggraded, alluvial reaches correspond to highly productive riverine habitats for fishes and other native biota, where lateral habitat complexity is high, interaction between groundwater and surface waters is great, and natural riparian vegetation is extensive, heterogeneous, and productive (Stanford and Ward, 1993, Naiman, 1993 #16284). Not only was key habitat lost to inundation, flow regulation has vastly changed riverine habitats downstream. Operation of the dams limits peak flows and increases baseflow causing channels to degrade and disconnect from floodplains and channel substratum to armor with large rocks and cobbles. Even in the relatively constricted mainstem Columbia River alluvial features prevailed in the form of complex island, point and eddy reattachment bars composed of sand, gravel and cobble. Back bar channels and sloughs were common features of the mainstem channels and floodplains. All of the mainstem habitat open to anadromous fishes above Bonneville Dam is now lacustrine (Figure 5.1), except for the Hanford Reach. However, bars in the Hanford Reach are composed of very large cobble, the fines having been sluiced out, and back bar channels and sloughs are largely filled in with riparian vegetation owing to years of rapidly fluctuating base flow and lack of peak flows.

Native salmonids clearly exploited these lost alluvial habitats heavily as spawning, nursery, refuge, and resting areas based on early inventories of salmonid habitat (Fulton, 1968; Fulton, 1970) Migratory salmon that originated all over the upper Columbia passed through these river segments as juveniles and adults, and these fish almost certainly took advantage of such riverine habitats to varying degrees. It is unknown to what extent reservoirs replace the ecological functions of these lost riverine habitats, but the status and trend of many fish populations suggests to a large degree they do not (Lichatowich and Mobrand, 1995).

Reservoir storage and dam operations dramatically alter flow regimes of rivers downstream of the projects as well. Typically, natural seasonal flow peaks are reduced and delayed or eliminated, and low flow periods are continuously or intermittently augmented by controlled releases. These changes in hydrology, coupled with the effects of limnetic processes (e.g., seasonal, vertical stratification of temperature and biotic productivity) that affect reservoir water before its release, substantially alter thermal and nutrient regimes, which are typically highly predictable in natural, free-flowing large rivers of the Columbia Basin (Stanford and Hauer, 1992; Brusven et al., 1995). As a consequence, high quality rearing habitat associated with shallow low-velocity floodplain features become progressively disconnected from the channel. Owing to lack of scour associated with flooding, these key habitats fill with sediments and dense vegetation. In many cases the vegetation is non-native and regulated streams are active corridors for spread of noxious weeds and woody plants. Indeed, an axiom of the ecology of regulated streams is that artificial regulation of flow, temperature and nutrients favors a select few species, often non-native ones, over the majority of native species whose life histories are evolutionarily adapted to the naturally prevailing thermal and hydrologic template. Accompanying these flow alterations are changes in turbidity and sediment transport caused by storage of sediments behind the dam or lack of scour to move fine sediments influent below the dams, which also can stress native fishes and their natural prey base by altering riverine habitat dynamics and reducing habitat diversity. Moreover, short term baseflow fluctuations associated with hydropower peaking operations produce a large zone along each side of the river where aquatic biota cannot live. This so-called varial zone, which includes all of the shallow, low-velocity habitats within the river channel, occurs on all regulated river segments in the Columbia Basin and substantially compromises instream food webs and productivity. Juvenile salmonids cannot feed and rest in fluctuating flows and are washed downstream whether they want to or not (see Chapter 6 below). Moreover, shallow-water food supplies for juveniles is limited or non-existent.

Stanford et al. (*in press*) proposed a protocol for restoring these lost functions to regulated rivers. They proposed that channel-floodplain connectivity and revitalization of instream habitat structures can be accomplished by re-regulation of flows and temperatures (e.g., by selective release structures) to more normative regimes, assuming that temperature (see below) or pollution are not also a problem. Scouring flows are possible in most regulated reaches on at least average to wet years. Reduction of base flow fluctuation to normative conditions can be accomplished by base loading the turbines; to reduce revenue lost from loss of peaking capability, base flows may be higher than historically occurred but they cannot be fluctuated if a productive food web is to develop in the varial zone. In the Columbia River system, revenue lost by base loading some dams perhaps could be offset by peaking other dams that do not have riverine segments downstream (e.g., the mid-Columbia dams could be operated as reregulation systems for Grand Coulee peaking operations). Moreover, peaking flows provide turbulent waves that likely assist movement of juvenile salmonids through reservoir-dominated reaches (see Chapter 6. below). Obviously, reregulating the Columbia River system in a more normative fashion requires careful analysis. This was attempted in the recently completed System Operations Review; however, the analysis itself and none of the alternatives embraced the principles of the ecology of regulated streams in the manner discussed here.

All of these principles apply equally well to the many regulated tributaries of the mainstem Columbia River. Establishment of normative flow and temperature conditions is possible in many tributaries by reregulation of discharge schedules from the storage reservoirs in the headwaters. Rivers such as the Yakama, Walla Walla and Umatilla are heavily impacted by irrigation withdrawals and high temperatures during periods of very low baseflows. These flows are far less than normative. Indeed, some segments are dry part of the time. Salmon and other aquatic biota cannot exist in these key tributaries in any sustainable numbers until baseflows are elevated to a stage that allows productive food webs to persist in channel and shallow floodplain habitats. Higher base flows will also allow effective interstitial flow through gravel bars and floodplains which likely will substantially cool surface waters in upwelling zones during critical late summer hot periods

Watershed as the Management Unit

It is well-established in the scientific literature that the land and aquatic area comprising watershed or catchment basin exerts strong physical and biological controls on the development of stream and lake ecosystems, e.g., (Schumm and Lichty, 1956; Hynes, 1975; Frissell et al., 1986; Sheldon, 1988; Moyle and Sato, 1991; Stanford et al., *in press*). In the past, attempts to protect and restore aquatic habitat and populations have often met with failure because they disregarded the overriding role of catchment conditions and processes in shaping aquatic ecosystems (Platts and Nelson, 1985; Frissell and Nawa, 1992; Doppelt et al., 1993; Rhodes et al., 1994; Sear, 1994).

Non-native fishes

The Columbia River ecosystem is home to many species of native and non-native fishes (Table 5.2). In general native fishes have declined in range and abundance while non-natives have proliferated.

As has been emphasized in previous sections of this report, through homing and natural selection each native salmonid population is closely adapted to the particular array of habitats that is available to it. Non-native fishes have been widely introduced in the Columbia Basin (see Table 5.3), but it is notable that introduced fishes tend to be most successful in streams and rivers where natural habitat has been altered and native fishes depleted. Large-scale human disruption of historic habitat mosaics can create novel ecological niches that native fishes have not evolved to fill, providing a toehold for the invasion and eventual proliferation of introduced species (Balz and Moyle, 1993). For example, Huntington (1995) reported that non-native brook trout were more abundant in streams draining extensively logged areas of the Clearwater National Forest in Idaho than in streams whose catchments were predominantly roadless and unlogged. The presence of the brook trout may have been due to easier access afforded by roading which likely facilitated planting of brook trout as well as increased fishing pressure on the natives. The logging itself may have been only indirectly involved as related to habitat modification associated with increased water and sediment yield.

Direct human alteration of riverine ecosystems in the Columbia Basin has massively promoted the proliferation of non-native fish species. Li et al. (1987) documented fish assemblage structure in major reaches of the mainstem Columbia, and found that all reservoirs were strongly dominated by non-native species such as smallmouth bass, walleye, yellow perch, and channel catfish. Most of these species are voracious predators on other fishes, and many are known to consume young salmon. These species also tend to prefer different thermal conditions than do native salmonids, so that they may be favored by the many human activities that alter thermal regimes.

By contrast while the free-flowing Hanford reach of the Columbia includes small numbers of virtually all the same species, its overall fish numbers and biomass remain dominated by salmonids and other native fish species (Li et al., 1987). This is strong evidence that maintaining (or restoring) a semblance of historical seasonal flow regime can benefit native fishes and select against introduced species that prey on or otherwise adversely interact with salmon and other native species.

Recent evidence suggests that proliferating non-native fishes in mainstem reservoirs could serve as source populations that promote the progressive invasion of tributary streams (J. Ebersole, C. Frissell, and W. Liss, unpublished data, Oregon State University). This could complicate proposals for restoration, if flow augmentation, drawdowns, and other schemes that strongly affect reservoir levels result in displacement or emigration of large numbers of non-native fishes from mainstem habitats into tributary streams. The result could be temporarily if not permanently increased interaction between wild salmonids and non-native fishes in tributary environments that have so far remained mostly free of dominance by non-native fishes. Continued degradation of habitats in tributary streams and possible climate changes also promote the possibility of wider invasion and establishment of non-native, warmwater and coolwater fishes in the basin.

Changed Food Production in the Mainstem

Juvenile salmonids use the mainstems of the Columbia and Snake rivers both as migration corridors and as habitats for feeding. How well we understand feeding (and resulting growth) may be as important as how well we understand migration. The feeding function is especially important for underyearling fall chinook salmon, which grow as they slowly migrate downstream (see Chapter 6). Yearling salmon and steelhead also feed during migration, as documented in Chapter 6, although their transit of the mainstem is more rapid. The Columbia River basin mainstem, however, has changed greatly in recent years and appears to have lost a major portion of its normal, riverine carrying capacity for feeding juvenile salmonids, particularly outmigrants. This review has looked carefully at components of that capacity that must have been present in the early historical river before about the 1930's and compared them with the present altered (dammed and flow-regulated) condition in the template-patient fashion of Lichatowich et al., (1995). Clearly, the food-producing and feeding habitats of the mainstem Snake and Columbia rivers differ considerably today from those that shaped the evolution of anadromous salmonids. Some alternative foods more typical of slower water have replaced the normal riverine food chain, with unresolved questions of the adequacy of that replacement for feeding migrating salmonids. With a feeding habitat greatly changed and probably much depleted, release of large numbers of hatchery fish into it may exacerbate an already tenuous situation for wild stocks.

The Riverine Food Web

Juvenile salmonids in a riverine environment feed primarily on drifting aquatic insects and terrestrial insects that fall into the water. For smaller salmonids, midges (chironomids) are the predominant source; as fish grow, they eat more of the larger aquatic insects such as caddisflies and mayflies. For example, chironomids and other aquatic insects were highlighted by the earliest studies of chinook salmon in the Columbia River (Chapman and Quistorff 1938). Coho salmon fry in British Columbia were shown to eat pupae, adults, and pupal exuviae (shed skins) of chironomids as they drift downstream (Mundie, 1971). Becker (1973) established that newly-emerged adult midges composed more than half of the diet of underyearling chinook salmon in the

Hanford reach of the Columbia River. Dauble et al. (1980) found midge larvae and pupae accounted for 78 percent by number and 59 percent by volume of the total ingested items in the Hanford Reach. Caddisfly adults became more important as food items there in June and July, as did shallow-water cladocerans (*Daphnia*). Loftus and Lenon (1977) found chironomids were the most important food for chinook salmon in an Alaska river and that heavy feeding occurred during downstream migration. In the lower Columbia River below Bonneville Dam, Craddock et al. (1976) found insects, both adult and larvae, to be the dominant food in spring and fall, although zooplankton from upstream reservoirs was important in summer. In New Zealand, Sagar and Glova (1987) found introduced chinook salmon eating drifting chironomid larvae and pupae, and mayflies in spring and more terrestrial insects in summer. Some other studies in small streams have shown young chinook salmon to eat mostly drifting terrestrial insects (Johnson 1981; Sagar and Eldon 1983). Rondorf et al. (1990) found caddis flies to be the main food item for subyearling chinook salmon (64 percent by weight) in the lower Hanford Reach in May to August. There is less information for yearling salmon, but Schreck et al. (1995) found a wide range of aquatic and terrestrial insects in mostly full stomachs of yearling chinook salmon in the free-flowing Willamette River, with diptera (including chironomids) being either the principal or an abundant component. Rondorf et al. (1985) considered migrating smolts to be actively feeding to offset the depletion of energy reserves during seaward migration. Kolok and Rondorf (1987) reported on food components of juvenile spring chinook salmon in John Day Reservoir. Thus, the general food and feeding relationships of young salmonids in rivers seem well established, although more information could be useful for yearlings.

Riverine environments tend to produce aquatic insects adapted to flowing waters while terrestrial insects fall to the water from the riparian zone. The predam mainstem Columbia and Snake Rivers were classic gravel-bed rivers, dominated by gravel and cobble (rounded rock) substratum variously constituted as bars, low islands, runs and pools with backchannels and sloughs. These are the habitats that produce large numbers of aquatic insects. Alluvial gravel reaches alternated with more canyon-like reaches where bedrock was exposed. Riparian vegetation was typically restricted to a narrow shoreline zone in the upper arid region that constitutes much of the migration corridor (Buss and Wing 1966; Hanson and Eberhardt 1971; Lewke and Buss 1977; Fickeisen et al. 1980a, b; Rickard, 1982). Different floral communities colonized shifting sands at the river's edge, alluvial fans at the mouths of tributary canyons, cobble and gravel slopes, outcroppings of basalt and granite, and disturbed areas caused by annual erosion, rock slides, grazing, and flooding that resulted in seral plant stages. In the entire mainstem, these features remain only in the Hanford reach of the mid-Columbia and transition zones of the lower reaches of the Clearwater River and the Snake River below Hells Canyon Dam to the upper reaches of the Lower Granite pool.

The salmonid life cycles were intimately linked to an annual flooding cycle of the mainstem. Although it is widely understood that juvenile migrants use the spring freshet for downstream migration, it is less well recognized that feeding is also aided by flooding. Fall chinook salmon fry emerging from gravels in spring typically began their feeding and rearing phase in shorelines and sloughs as mainstem water levels rose across cobble bars and into riparian vegetation with the melt of winter snowpacks in the tributaries. The most active rearing period for chinook underyearlings in the mainstem often occurred in late spring and early summer when waters were highest and the most riparian vegetation was flooded. The underyearlings moved gradually downstream through the summer, rearing as they went. Yearlings moved downstream relatively quickly during this same spring freshet period, but there is evidence that they, too, paused periodically in backeddies to feed (Schreck et al., 1995).

Submerged riparian vegetation was probably important for young salmon as a substrate for production of invertebrate food, although this has not been shown directly for the mainstem Columbia and Snake rivers. There is ample evidence from other scientific studies that submerged plant material may be related generally to prey abundance and fish growth. Submerged wood is clearly an important habitat in other aquatic systems for growing invertebrates, especially aquatic insects such as chironomids (midges) (Nilsen and Larimore, 1973, Benke, 1984 #542, Stites, 1989 #13326). More abundant submerged surfaces generally translate to more invertebrates, as with submerged stream macrophytes (Gregg and Rose, 1985).

Flooding provides not only surface areas for aquatic insects but also the colonizers. Larval chironomids of all sizes are a common component of stream drift (Mundie, 1971), especially during periods of flooding. Although larvae are not commonly eaten by young salmon, drift of chironomid larvae seems to serve largely to colonize the submerged gravel and plant surfaces, where the larvae feed on periphyton and attached organic silt and grow rapidly (Oliver 1971). Drifting chironomid larvae loosened from the streambed or as newly hatched instars quickly colonize previously exposed cobbles and submerged vegetation when waters rise. They develop within a few weeks to the pupae and emerging adults that are the preferred food for young salmonids (many chironomid species have short generation times and very high annual productivity). Timing was probably important for feeding salmon: chironomids have their normal peak of production in the spring at the time of peak abundance of downstream-migrating juvenile salmon.

The flooded riparian vegetation also provides terrestrial insects (e.g., ants and spiders) used as salmon food. Because young salmon are at the edges of rivers (underyearlings) and in backeddies (yearlings), they are away from most of the drifting benthic (lithic) invertebrates and in a zone where aquatic and terrestrial drift derived from overhanging brush and flooded riparian vegetation would be most valuable to them. The importance of flood pulses in riverine ecosystems in general is becoming more recognized and is described by Power et al. (1988), Welcomme (1988) and Junk et al. (1989).

Historically positive flow-survival relationships for salmon in the Columbia-Snake rivers may relate, at least in part, to the amount of riparian vegetation flooded during high-flow years. More flooding, when it occurred in a high-volume peak that lasted several weeks as in the mid-Columbia in 1965, would make a large amount of riparian substrates available for aquatic insect colonization and production of abundant food. This hypothesis has not been tested, and may be impossible to test because of other flow-related phenomena that occur simultaneously.

Hydrosystem alterations of food webs

The result of mainstem impoundment and flow regulation is a mainstem ecosystem that does not appear capable of producing nearly as much high-quality food for juvenile salmon as did the free-flowing and annually flooding river. The success of fall chinook salmon in the still-riverine Hanford reach compared to the endangered status of this race in the fully dammed lower Snake River is perhaps partly a result of the differences in food production in the rearing-migration corridor. Research has identified physical and biological causes for the decline and change in food availability.

a) Loss of riverine insect production.

Hydroelectric development has transformed riverine reaches into reservoirs with slow currents, silt bottoms, and fairly stable water elevations. River-like conditions exist in dam tailwaters and persist for a few miles into each reservoir, but most riverine habitat has been lost. With loss of flowing-water habitat has gone the hard-substrate community of chironomids, caddisflies, mayflies, and other insects that fed juvenile salmon (the riverine food chain). In its place have come midges characteristic of soft substrates and aquatic worms, with planktonic zooplankton becoming a major replacement food (Bennett et al. 1988, 1993). Slowly moving shoreline waters of reservoirs warm rapidly in summer, forcing juvenile salmon to move out of their normal shoreline habitat and to the cooler channel (Curet, 1993). Fish that relied on shoreline-oriented food production are now obliged to feed on reservoir zooplankton (Muir and Emmett, 1988, Rondorf, 1990 #18399). D. Bennett and his students at the University of Idaho have recently attempted to quantify the changes in bottom fauna.

b) Loss of riparian flooding.

Impoundment and flow regulation by upstream reservoirs have reduced historical flood pulses that previously had inundated vegetated shoreline areas and produced abundant food for salmon. Shorelines once fringed with vegetation are now lined with rock riprap (U.S. Army

Corps of Engineers 1976), which produces little insect life suitable as salmonid food (Janecek and Moog, 1994). Other shorelines are eroding banks. Even where riparian vegetation has developed as reservoir shorelines age, the stability of reservoir surface elevations during salmon outmigration prevents significant flooding and food production.

Current knowledge specific to the Columbia and Snake rivers falls short of quantifying the benefit of flooded riparian vegetation in the normative ecology of juvenile salmon (although research is still possible at Hanford) and its loss through most of the mainstem. Such knowledge would, however, be useful for the contemporary problem of rehabilitating the carrying capacity of salmon rearing habitats. The reasonable, but locally undemonstrated, importance of riparian habitat for invertebrate (especially chironomid) food production could be a working hypothesis for studies of carrying capacity in the Columbia River basin mainstem rivers and lower tributaries. Useful comparisons could be made between Hanford and various reservoir reaches to quantify, as best we can today, the losses through impoundment. If the hypothesized benefits are substantiated and high, then proposals for flow augmentation and reservoir drawdowns could logically take into consideration a restoration of more natural shoreline vegetation and its seasonal flooding.

c) Altered timing of production and consumption.

Hydropower development has apparently altered the match in timing between food production and demand. Whereas much attention has been given to timing of juvenile outmigrations to match food-production cycles in the estuary and ocean, the "window of opportunity" (Walters et al., 1978), little attention has been paid to correlations between timing of fish abundance, flooding of riparian habitats, and alternative food-production cycles in the mainstem. Evidence suggests that the reservoir zooplankton on which salmon now feed develops primarily later in summer. This topic needs more research and analysis.

d) Invasion of reservoirs by estuarine invertebrate species.

Mainstem reservoirs have been colonized by invertebrate species usually associated with estuaries, and one of these species (*Corophium salmonis*) has become a prominent part of the salmonid food chain in lower Columbia River reservoirs. In the lower mainstem, *Corophium* has become the predominant food for downstream migrants (Muir and Emmett, 1988). *Corophium* now occurs to the headwaters of Lower Granite Reservoir, where it was the most prevalent invertebrate species in both numbers and biomass between August 1993 and September 1995 (Nightengale and Bennett 1996). It does not appear to be eaten by juvenile salmonids there, however. Another estuarine species, *Neomysis mercedis,* has also become abundant in the mainstem, but its direct and indirect effects on feeding are not known. *Mysis relicta* introduced to freshwater lakes such as Flathead Lake, Montana, has caused much ecological havoc, including detrimental competition with kokanee for planktonic food (Spencer et al., 1991). An "estuarinization" of the mainstem Columbia and Snake rivers has apparently taken place, which may be related to the current poor strength of salmonid populations.

Estuarine species now in the mainstem Columbia are native to the upper Columbia River estuary. Haertel and Osterberg (1967), in their comprehensive, integrated study of the Columbia River estuary, described the sediment-surface invertebrate community as dominated by the crustacean *Neomysis mercedis* with high numerical abundance of several species of the gammarid amphipod *Corophium*. More recent studies of the estuary by Simenstad and Cordell (1985) and Jones et al. (1990) showed *Corophium salmonis* occurred abundantly in the epibenthos in shallow tidal flat and deeper slope habitats of the upper estuary during the early spring fluctuating-flow season. As the high flow season progressed, *Neomysis* became dominant. *Corophium*, especially, is a major food item for salmonids in Northwest estuaries, Columbia (McCabe et al. 1983), Sacramento-San Joaquin, California (Sasaki 1966), Sixes River, Oregon (Reimers et al. 1978), Grays Harbor, Washington (Herrmann 1971), Duwamish estuary, Washington (Meyer, 1981).

In 1984, *Corophium* dominated the food of juvenile salmonids migrating downstream through Bonneville Dam (Muir and Emmett, 1988). This estuarine species was being eaten in the fully freshwater Bonneville Reservoir. There was heavy use of these amphipods by all species of salmon. During the spring migration, Corophium constituted 99 percent of the diet of steelhead, 87 percent in sockeye salmon, 94 percent in coho, 97 percent in yearling chinook salmon, and 90 percent in subyearling chinook salmon. During summer (July and August), the importance of *Corophium* declined dramatically and was replaced by the freshwater plankter Daphnia and adult chironomids. High availability of Corophium was believed to be the main factor in food selection, as all species ate *Corophium* in the same time period.

Muir and Emmett (1988) discussed why salmonid juveniles with a preference for suspended, moving organisms would feed on a tube-dwelling benthic invertebrate. *Corophium salmonis* undergoes vertical migrations in the estuarine water column, both daily and seasonally, with migrational peaks occurring in the evening hours and during spring months (Davis, 1978), Wilson 1983). These migrations, coupled with higher flows during spring, were thought to keep these amphipods suspended in the water for long enough periods of time for them to be susceptible to predation by salmonids. *Corophium* availability thus seems to peak in spring during the major salmonid outmigration and to coincide with peak feeding times (evening) of juvenile salmonids (Johnson 1981; Rondorf et al 1985). Although this behavior was not substantiated for the Bonneville pool, it is consistent with stomach content observations at Bonneville Dam. Nightengale (personal communication) indicated that the *Corophium* in Lower Granite Reservoir does not appear to undergo this vertical migration and is not a major food item for salmonids there.

Corophium had expanded its distribution upriver into the John Day pool by 1982, as evidenced by its presence in juvenile spring chinook salmon stomachs (Kolok and Rondorf 1987). Although terrestrial insects and chironomids were eaten most at the site at River Kilometer 395, *Corophium* accounted for 0.8 to 11 percent of the stomach contents. *Neomysis* was observed by ISG members in smolt monitoring station holding tanks in the lower Columbia River in 1994, but its presence has not been studied as it has not apparently been eaten by salmonids.

Neomysis presence and effects are little known. They were not in the food of juvenile salmon examined in the lower Columbia River reservoirs (Kolok and Rondorf 1987, Muir, 1988 #16100] or Snake River Reservoirs (Curet, 1993). Although observed by the ISG in smolt monitoring stations in the lower Columbia River in 1994 (and noted as common by station workers), they have not been reported in the literature. Based on experiences in the Northwest and worldwide with *Mysis relicta* introductions to lakes and reservoirs (Lasenby et al., 1986, Spencer, 1991 #7793), these predatory invertebrates compete with salmonids for zooplankton food, and can rapidly deplete the zooplankton food supply. When zooplankton is a major substitute for riverine aquatic insects in the food of juvenile salmon (Curet, 1993), competition for it by *Neomysis* could be important for salmonid feeding and growth. Clearly, more study of *Neomysis s* is needed in the Columbia River mainstem.

How *Corophium* and *Neomysis* became established upstream of tidal influence and how they (at least *Corophium*) colonized all the way to Lower Granite Reservoir is not known. Nightengale (personal communication) hypothesizes that the Snake river colonizers were transported upstream in water from below Bonneville Dam by fish transportation barges. *Corophium*, especially *C. salmonis*, requires fine sandy sediments for benthic habitat, a predominant feature of the reservoirs that now occupy the once flowing rapids of the Columbia River basin mainstem. Once inoculated, the populations must have found highly suitable habitat.

e) Nutritional status of juvenile migrants.

There are indications that the nutritional status of outmigrants is now poor. Curet (1993) found that subyearling fall chinook salmon in Lower Granite and Little Goose reservoirs were feeding at only 27 percent of their maximum ration during April-July. This was only 7 percent greater than the estimated maintenance ration that would provide no growth, and it indicated to Curet that there were food limitations in the habitat. The Smolt Monitoring Program observed outmigrant fall chinook salmon in poor physical condition during the recent drought years. This question of nutritional status deserves more research attention than it has been given. Migrants that exist at just above the starvation level can hardly be expected to have good long-term survival.

Whether the newly established *Corophium* is an adequate food substitute for the more normative riverine foods is an important question. Kolok and Rondorf (1987) showed that the consumption of *Corophium* was associated with reduced caloric densities in stomach contents. That is, the amount of usable energy per volume of food material was less than other foods being consumed. (Muir and Emmett, 1988) noted, however, that the low caloric density might be compensated by ease of availability, meaning less energy had to be expended to capture the prey. De La Noue and Choubert (1985) compared the food values of chironomid larvae, daphnia, and a freshwater gammarid amphipod (similar to Corophium) for rainbow trout and found the amphipod to rate poorly. Total and essential amino acids were lowest in the amphipod. Both daphnia and chironomids met the amino acid requirements for salmonids (NRC 1981), but the amphipod was deficient in arginine and lysine. The digestibility was also poorest, with the highest percentage of consumed material being passed as feces. The authors rated the amphipod as "much inferior" to either daphnia or chironomids (which were generally equally good) as an aquaculture food. Thus, the replacement of riverine chironomids by estuarine *Corophium* may well be having a detrimental effect on the nutrition of downstream migrating juvenile salmonids. This inference from published studies needs to be tested by studies of feeding and nutritional status of Columbia River basin fish. Nutritional status can be evaluated by examination of whole body energy content (cal/g). Whole body lipid or fatty acid content are variables that could be very useful, e.g., (Brett, In press #17280].

Comparison of Mid-Columbia and Snake River stocks

A comparison of mid-Columbia and Snake River stocks of salmonids might be fruitful for evaluating the effects of food and feeding on survival. The Hanford Reach has abundant riverine habitat remaining, although flooding has been reduced. The Snake River mainstem is entirely impounded. Food production undoubtedly differs. The mid-Columbia water tends to be clearer with more macrophytes, which may serve as alternative substrates for development of chironomids. *Corophium* may not have colonized the upper mid-Columbia reservoirs, and would, in any case, not proliferate in the flowing Hanford Reach (which may be a barrier to natural upstream colonization). Fish (or other) barge transportation does not occur upstream of Hanford, so colonization by barge bilge water would not occur. These topics deserve attention.

With sketchy information as a basis, a speculative hypothesis for food-chain differences between Mid-Columbia and Snake River fish can be advanced, as follows, based on three main subdivisions of the mainstem (lower reservoirs below the Snake confluence, the Hanford/mid-

Columbia, and the lower Snake River reservoirs) (Figure 5.1). Effects are more acute in warm, low-flow years than when flows are high and water remains cool.

Lower reservoirs: *Corophium* provides an adequate food base for the larger emigrating juvenile salmonids in the lower Columbia River reservoirs in spring and early summer. Though nutritionally deficient, this abundant source adequately feeds both mid-Columbia and Snake River migrants in the lower river (when supplemented with some terrestrial insects and zooplankton), as it normally did in the freshwater estuary below Bonneville Dam. The earlier-migrating Hanford subyearlings are able to make use of this food source. Later migrating Snake River subyearlings arrive in the lower reservoirs after *Corophium* are no longer available in the water column. *Neomysis* competes with late-arriving young salmon for zooplankton, and is not itself eaten. Young salmon in summer are thus poorly fed.

Hanford/mid-Columbia: A typical riverine food chain of nutritious aquatic insects sustains both Hanford stock and upstream migrants through the reach. Reservoir reaches above Priest Rapids Dam and in upper McNary Reservoir upstream of the Snake River confluence have clear water and macrophytes that grow abundant aquatic insects, even where current is slower. Fish enter the lower reservoirs well fed.

Snake River reservoirs: Riverine aquatic insects have disappeared except in the upstream ends of reservoirs. *Corophium*, though abundant, does not enter the water column and thus does not provide alternative food. Warm shoreline water (especially in low-flow years) reduces suitable feeding habitat for underyearling fall chinook in summer, and forces replacement feeding on open-water zooplankton. *Neomysis,* if also in the Snake River reservoirs (not yet reported), competes with salmon for zooplankton. Turbid Snake River water prevents much macrophyte growth and attached aquatic insects. Survival of poorly fed underyearlings is low. Slow growth and low current velocities cause underyearlings to enter the Columbia River late in the migration season when temperatures are high and *Corophium* is not available as an alternative food source for lost riverine aquatic insects. The same factors affect yearlings, but to a lesser degree because they move through the reach earlier and more rapidly.

Overall assessment of mainstem habitat quality for salmonids

This appraisal emphasizes that feeding and growth of juvenile salmonids (and the habitats that promote them) are just as deserving of our attention as factors that affect mortality in the basin (e.g., turbines, predation, gas bubble disease, etc.). There is enough scientific understanding of foods and feeding of juvenile migrants to suggest a major effect of the hydropower system. Because there has been little integrated study of the food chain and fish nutritional status through the mainstem, the scientific base is not yet adequate to ascribe priority of feeding problems relative to other factors that affect juvenile salmonid survival. The best we can do is to advance hypotheses (based on available literature), which should be tested.

Overall Assessment of Tributary Habitat Quality.

The negative influences of logging, grazing, dams, irrigation withdrawals, urbanization, exotic species introductions and other human activities have been documented in all of the Columbia River tributaries. Many, if not all of the larger tributaries are degraded by streamside uses that fail to recognize the importance of riparian vegetation and local upwelling areas (e.g., springbrooks, ponds and wetlands) on flood plains as essential normative features. Some of these habitat problems can be normalized by reregulation of flows as discussed above and detailed in Stanford et al.(1996). In addition, new incentives for streamside stewardship that conserve and enhance connectivity and productivity of floodplain habitats need to be fostered on tributaries as well as mainstem reaches. Special incentives for protection of land-water interface zones are needed in reaches where streamside conditions are normative now as a consequence of a legacy of limited human influences. Owing to the dramatic escalation of intermountian valley development, in the next decade we could lose remaining productive and connected salmonid habitats (e.g., Stanly Basin on the Salmon River, North and Middle Forks of the Flathead River). For example, cool water refugia exist in the Grand Rhonde (Li et al., 1995) that are critical for salmonids. Such refugia should be accorded special protection before they are purposefully or inadvertently degraded. The Quartz Lake watershed in Glacier National Park is the only example we are aware of in the entire Columbia Basin where an entirely native food web, including the full compliment of native headwater salmonids, remains intact. This and other native fish refuges should be completely protected as native salmonid fishery reserves. Plans for protection of remaining quality habitat and stabilization and normalization of degraded habitats are needed for every tributary in the Columbia Basin. However, it may be prudent to focus actions on those tributaries that have the greatest likelihood of playing a key role in salmonid recovery (e.g., those that are in proximity to currently functional habitats that are producing salmonids such as the Yakama and its potential connectivity to the Hanford Reach of the mainstem Columbia River).

HABITAT CONCLUSIONS (LEVEL OF PROOF)

1. Habitat required for salmonid migration, spawning, incubation and juvenile rearing has been severely degraded in the Columbia Basin by the cumulative effects of flow regulation by dams and diversions, sedimentation from forestry and agricultural activities and massive introduction of non-native biota (fish, invertebrates and riparian plants). (1)
2. Owing to the diverse climates and food web assemblages of the different ecoregions that make up the Columbia River catchment, native salmonids displayed great diversity of life history types (stocks or populations) specifically adapted to the wide array of natural habitats.(1) Diversity has been substantially depleted by habitat loss, fragmentation and degradation. (1)
3. Habitat fragmentation and loss is extensive throughout the Columbia River Basin, except in those few areas where human activities are limited, particularly in roadless and wilderness areas in the upper portions of some sub-basins. (1) Incremental loss of incubation, rearing and spawning sites has reduced or eliminated production of salmonid stocks and disrupted natural metapopulation structure and dynamics. (1)
4. Most alluvial floodplain reaches and associated habitats, historically supporting large, productive spawning populations and providing essential, high-quality rearing habitats for maturing and migrating juveniles, have been destroyed by reservoir inundation, substantially degraded by altered flows associated with hydropower operations or disconnected from the salmon ecosystem by dams that block migratory pathways. (1)
5. Habitat restoration using artificial structures (e.g., weirs, logs cabled into streams, coffer dams, rock gardens) has failed to mitigate the adverse effects of temperature alteration, sedimentation, and simplification of habitat structure and processes caused by upland and riparian land use activities. (2)
6. Presence of non-native fishes is a strong indicator of habitat degradation and is problematic for any restoration effort. (1) Non-native fishes are far less abundant and reproductive in freeflowing segments where native habitats remain in relatively good shape (e.g., Hanford Reach). (2) Native salmonids (and other aquatic vertebrates) remain healthy in less than 5 percent of the headwater streams of the Columbia River tributaries in Idaho, Montana, Oregon and Washington, owing to genetic introgression and displacement by non-native species, which has been mediated by a long history of stocking of cultured brook, rainbow, brown and lake trout in headwater lakes and streams. Adfluvial populations of bull and cutthroat trout have been vastly compromised by food web changes in the big valley bottom lakes (e.g., Pend Oreille, Flathead) as a result of misguided stocking of non-native mysid shrimp and the interactions of these shrimp with non-native fishes. (1)

7. In the Hanford Reach and other alluvial river segments highly productive, flooded riparian zones provided much of the riverine food production (in the form of rapidly colonizing and growing chironomids) for migrants in spring (both underyearlings and yearlings); these critical food web components do not exist in mainstem reservoirs and are substantially reduced or eliminated in riverine segments that are regulated by dams. (1)
8. Typical lake food items (zooplankton) provide an inadequate food source (2) and fish in the Snake River reservoirs are energetically deficient. (2)
9. Food abundance in the mainstem during rearing and migration, which is higher with flooding, may affect salmon survival. (5)
10. Estuarine invertebrates have colonized the lower Columbia River reservoirs and provide a food source that constitutes nearly all in Bonneville Reservoir and about 2 percent in John Day reservoir but are not present in Snake River reservoirs. (2)
11. Estuarine food organisms found in lower Columbia River reservoirs are less nutritional for salmon than riverine food sources but may be adequate if eaten in sufficient numbers. (2)
12. Availability of riverine habitat for producing food and the longitudinal continuity of riverine and estuarine food webs are major differences between successful Hanford stocks (riverine, continuity) and unsuccessful Snake River stocks (reservoirs, discontinuous). (4)
13. Submerged macrophytes in the less turbid Mid-Columbia River without flooding may be a successful alternative substrate for producing riverine, chironomid food for salmon (contributing to success of the Mid-Columbia stocks), whereas submerged macrophytes are less common in the more turbid Snake River. (5)

Uncertainties

1. The exact magnitude and timing of restored flows and temperature regimes need to be empirically determined for specific free-flowing segments and requires a broadly multidisciplinary approach. (However, no uncertainty exists with respect to the need to re-establish flow and temperature seasonality and to stabilize base flow and temperature fluctuations).
2. Although "best management practices" (BMP's) may reduce impacts to habitat compared to unregulated land use, uncertainty about effectiveness of present BMP's must be resolved by scientific evaluation at both site-specific and watershed scales; some results will not be known for decades after implementation. In the face of uncertainty about the sufficiency of current land use practices, designation and protection of a well-distributed network of reserve areas and habitat patches from new land-disturbing activities is necessary to establish experimental natural baselines and to establish a biological hedge against possible failure of BMP's in treated areas.
3. Habitat restoration may be ineffective at restoring native species where introduced non-native species are well-established. Available science suggests that non-natives will be most vulnerable, and many can be effectively suppressed, where habitats are maintained by natural range of flow and temperature variation. However, abrupt changes in reservoir management could temporarily drive existing populations of some non-native fishes into tributary habitats, increasing the risk of their colonization of tributaries. On the other hand, reservoir changes also will likely create new mainstem habitat refugia for native fishes. The risk of dispersal and establishment of non-native fishes will be lowest where tributaries retain relatively natural streamflows, thermal regimes, habitat diversity, and intact native fish assemblages.
4. The mainstem Columbia River may have too many hydropower and irrigation storage reservoirs to ever allow sufficient habitat restoration to allow native salmonid diversity and productivity to substantially recover. However, the surprising resilience and salmon productivity of the Hanford Reach suggests that restoration of critical salmonid habitat is possible without impractical alteration of dam operations.
5. The nutritional state of migrating salmonids requires resolution in relation to stability and productivity of food webs, including importance and effects of colonization of mainstem reservoirs by estuarine species and value of macrophytes for producing food for mid-Columbia salmonids.

Recommendations

1. Free-flowing reaches downstream of hydroelectric dams should be reregulated to re-establish normative flow and temperature regimes and thereby allow the river to naturally restore instream and floodplain habitats and food webs.
2. Restoration of substantial mainstem habitat likely can be accomplished by drawdown of selected reservoirs to expose and restore alluvial reaches (e.g., upper ends of John Day and McNary pools). These options should be quantitatively examined.
3. Habitat restoration should be framed in the context of measured trends in water quality because functional salmonid habitats are characterized by high quality (pure, cool, clear) water and few people will argue with the actions to sustain attributes of high water quality.
4. New timber harvest prescriptions (e.g., selective cutting, attempted fire simulations, salvage logging, road retirement), sustainable agriculture practices, and other land use practices for upland and riparian areas, commonly referred to as best management practices (BMP's), need to be empirically tested and demonstrated as effective in credible short- and long-term studies before they can be considered sufficient for conserving and enhancing water quality and salmonid habitats.
5. If the restoration goal of the FWP and other efforts includes conservation and enhancement of remaining native and naturally reproducing salmonids, all stocking of non-native biota should be stopped in habitats used by or hydrologically connected to habitats required by all life stages of native salmonids (resident and anadromous). Carefully evaluated mechanisms to reduce or eliminate the reproductive capacity or dispersal of non-native species in native salmonid habitats should be implemented if riverine controls (e.g., by restoration of flushing flows) prove ineffective in controlling non-native species.
6. A well-distributed network of reserve watersheds and riverine habitat patches, based on the current distribution of strong subpopulations of native salmonids, should be designated and protected from new land-disturbing activities in order to establish experimental natural baselines for evaluation of effectiveness of management practices and to establish a biological hedge against possible failure of BMP's to conserve and enhance aquatic habitat in treated areas.
7. A study plan should be developed for evaluating the importance of food production to the success of juvenile rearing and outmigration in the Columbia River basin, to include:
    a. Test, through field studies, the nutritional state of migrating Snake River salmonids identified by Curet in relation to that of mid-Columbia stocks, to estimate the importance of food availability to salmon survival;

b. Estimate, through field studies of insect colonization and growth during flooding and spatial analyses of floodplains, the quantity of salmonid food potentially produced by flooded riparian lands in the lower Columbia-Snake basin and lost by river regulation, and relate quantitatively to the food requirements of migrating juvenile salmon;
c. Determine, through field studies, the current extent of colonization of reservoirs by estuarine species;
d. Establish, through laboratory feeding experiments, the suitability of estuarine organisms as food for downstream migrants relative to riverine food organisms;
e. Estimate, through field studies and laboratory feeding experiments, the importance of longitudinal continuity of food for relative survival of Mid-Columbia (Hanford) and Snake River migrants;
f. Estimate, through field studies, the value of macrophytes for producing food for Mid-Columbia salmonids; and
g. Evaluate the nutritional status of juvenile salmonids during transportation from upper river dams to below Bonneville Dam.

8. Provide an integrated assessment of the role of food and feeding on the nutrition of downstream migrants leading to conclusions regarding action options for restoration of riverine food chains (e.g., induced flooding, riparian habitat restoration) and promotion of estuarine food chains (e.g., species stocking).

Analysis Of River Temperature Patterns And Salmon Populations And Habitats

Temperature is a critical habitat variable that is very much influenced by regulation of flow and impoundments. The mainstem reservoirs are relatively shallow and heat up in late summer causing concern for salmon survival. The lower reaches of some key tributaries also are very warm in late summer because they are dewatered by irrigation withdrawals. Due to the extreme importance of temperature regimes to the ecology of salmonids in the basin, temperature information merits special attention as a key habitat descriptor. Therefore, we summarized temperature considerations in the December 1994 Fish and Wildlife Program (FWP or Program) and reviewed our understanding of water temperatures of the Columbia River basin.

Temperature in the Council's Program

Basic assumptions. The Council's Program seems to make the basic assumption that the hydropower system has caused elevated water temperatures, which are detrimental to salmon either directly (introduction to Section 5) or through increased predation (5.7). The Program introduces temperature effects with a figure (Fish and Wildlife Program Figure 1-2) that shows average August-September water temperatures at Bonneville Dam rising since the 1940s. This temperature assumption may not be a valid generalization with respect to maximum temperatures of the main river flows, as indicated in the review summary below. It is a valid concern for a time period of the current peak of adult migration upriver, however.

Maximum temperatures in the mainstem Snake River, where salmon survival is most tenuous, are generally lower in summer than before the series of storage and mainstem reservoirs was installed. This is also true in the mainstem Columbia River. The assumption that temperatures may have increased is correct when applied to temperatures seen in late summer and fall, when the latency of reservoir storage is exhibited. Besides a lowering of maximum summer temperatures, the peak temperatures have been shifted to later in the year. Localized temperature increases have been caused by the hydropower system. In particular, shoreline areas inhabited by underyearling chinook salmon during their summer rearing and outmigration have increased.

The Program also seems to assume that river temperature is linked to volume of flow and water velocity. These are not necessarily linked. Thalweg temperature (the temperature of most of the water volume) and its timing are affected by water storage and release schedules. Localized temperatures and their cumulative effects on thalweg temperatures are affected by reservoir topography more than by river flow rates.

Fall chinook salmon adult migration. During preparation of the 1994 Program, there were recommendations to control (reduce) summer and early fall temperatures to improve survival of adult summer and fall chinook salmon (introduction to Section 5). Temperatures at this time are higher than adults can survive for long periods during late summer and fall migrations. These recommendations are consistent with the seasonal shift in high temperatures caused by increased water storage. A strategy for lowering Snake River temperatures for migrating adults is to retain cold winter water in upstream reservoirs, particularly the Dworshak project (5.1A.2; 6.1D.2; 6.1D.4) and Brownlee Reservoir (5.2A.10; 5.2B.3; 6.1D.4) for release later in the year. Some of this water would be made available through better water management by irrigators (5.2D.2). These actions would be consistent with providing suitably cool temperatures for chinook salmon (see below) , if they are operationally feasible.

Because little of the existing data on temperature requirements of chinook salmon has been obtained for the Snake River stocks, the Program includes studies of baseline temperature effects in its request for baseline life history studies of Snake River fall chinook salmon (7.5B.3). This is a pertinent request, particularly because the Snake river stock that persisted for so long at rather high temperatures may be more thermally tolerant than other strains.

Among localized temperatures, those in fish ladders were of special concern in the Program. The Corps of Engineers is requested to evaluate potential methods for decreasing temperature in mainstem fish ladders and to apply these methods where appropriate (6.1A.1; 6.1B.2). We did not review data on fish ladder temperatures but consider warm water temperatures there in late summer and fall to be consistent with the shift in peak temperatures of mainstem flows to later in the year and withdrawal of fish ladder water from fish exit points near the warm reservoir surface. Use of cooler water from lower strata for fish ladders seems feasible within a mainstem project; control of temperatures of the main river flow is a matter of upstream storage and release timing.

River temperature control. Control of thalweg temperatures in the Columbia River basin requires not only operational actions but the ability to track temperature changes and to predict the effects of possible manipulations. The computer models or river temperature developed by Jaske and Gobel (1967) and Jaske and Synoground (1970) were pioneering efforts in this direction. The Corps of Engineers' COLTEMP model is the version now being used. Several other river temperature models are available in the literature for such use. The Council's Program calls for upgrade of the COLTEMP model based on past temperature control operations and monitoring in the Columbia River basin (6.1D.5). The Program also calls for collection of meteorological, hydrological, and temperature data in the tributaries and mainstem that would affect mainstem temperature (6.1D.6).

Requests for both model improvement and monitoring of data needed as input for the model or its calibration are appropriate. However, the science of thermal modeling is well developed internationally and not a matter of developmental research. Numerous models are available that are adequate to evaluate temperature control options, given sufficient meteorological, hydrological and tributary temperature data for input and sufficient calibration and verification runs of the model.

There are practical limitations to increasing flows in summer and fall to aid adult migrations by lowering temperatures and also doing so in spring to aid smolt outmigration by increasing velocity. Cold "winter water" can be exhausted in upstream reservoirs by spring releases and not be available for late summer and fall cooling (introduction to section 5). Operational constraints raised in the Program are real. The relative benefits of water released in spring and summer/fall have not yet been quantified well in a manner consistent with the best scientific knowledge.

Temperatures in hatcheries. Improved propagation of salmon in hatcheries includes provision of suitable temperatures (7.2D). Although there are no specific measures directed toward temperatures in hatcheries, the specific measures on prevention of diseases, improvement in breeding and husbandry practices, and so forth can logically include the abundant data on temperature effects.

Temperatures in tributaries. The Program recommends that habitat restoration efforts in tributaries maintain temperatures in historically useable spawning and rearing habitat at less than 60F, not to exceed 68F (7.6D). It also directs the Forest Service to monitor temperatures as streams leave federal lands and to strive for the 60F recommendation at these points (7.8A.6). This temperature recommendation is consistent with current knowledge. The Program also calls for investigations of methods for controlling temperatures of releases of dams (Detroit, Cougar, Blue river) in the Willamette River basin, to restore temperatures to near pre-project levels (7.9A). Investigation of temperature effects is also called for in the Grande Ronde River basin (7.9C). These requests seem reasonable, although there are temperature problems in many other locations in the Columbia River basin that were not called out (lower Yakima River, Okanagan River, upper John Day River, lower Grande Ronde and Imnaha rivers, and others).

Temperatures during juvenile outmigration. Little was said in the Program specifically about temperatures during juvenile outmigration. However, it is clear from sections on flow and velocity that the Council believes increased flow will also lower river temperatures. As noted above, these factors are not necessarily linked. The Program called for temperature monitoring during the drawdown of John Day reservoir (5.4C.4).

Current State of Science

Water temperatures. Water temperatures in the Columbia River basin have been altered by development and are, at times, suboptimal or clearly detrimental for salmonids. High temperatures alone can be directly lethal to both juvenile and adult salmonids in the Snake River in summer under recent conditions, based on generally accepted thermal criteria (National Academy of Sciences/National Academy of Engineering 1973) and measured temperatures (Karr, 1992).

Temperatures are generally lowest in January and February and highest in August and September (Ebel et al., 1989). Thermal regimes in tributaries throughout the basin differ widely with location, elevation, and input from rainfall, snowmelt, glaciers and aquifers. In general, cold runoff from mountainous tributaries gradually warms as the water progresses downstream. The principal flow of mainstem rivers is warmest near the Columbia River outlet, where temperatures peak near 21°C (70° F). Clearly, there are exceptions in dry , low flow years. Development of tributaries such as the Yakima, Okanagan, and Umatilla rivers for agriculture and urbanization has resulted in their outlets to the mainstem reaching summer temperatures about 4°C above levels expected otherwise. Historically, average temperatures at the mouth of the Snake River during August and September have always been a few degrees higher than those in the mainstem Columbia (Roebeck et al. 1954; Jaske and Synoground 1970).

Effects of dams have been investigated at several scales. Studies in the 1960s (Jaske and Goebel, 1967) showed that the construction of river-run reservoirs on the mainstem of the Columbia River caused no significant changes in the average annual water temperature. However, storage and release of water from Lake Roosevelt had delayed the timing of peak summer temperatures below Grand Coulee Dam since 1941. This delay was about 30 days at Rock Island Dam and was reflected as far downstream as Bonneville Dam near the river's outlet. Temperature extremes in the mainstem were moderated by the reservoir complex so that river below Grand Coulee is now somewhat cooler in summer and warmer in winter. This trend is particularly evident in tailwaters of major storage reservoirs such as Brownlee, Hells Canyon, and Dworshak where high storage to flow ratios hold cold bottom water in the reservoir for release through deep outlets until well into summer. Mainstem reservoirs in the Snake and Columbia rivers have created shallow, slowly-moving reaches of shorelines where solar heating has raised temperatures of salmon rearing habitat (especially for underyearling fall chinook) above tolerable levels, negating this as usable habitat for much of the summer) (Curet, 1993; Key et al., 1995).

Water temperatures in lower tributaries were generally low enough prior to European settlement to allow summer outmigrations of subyearling smolts. This life history strategy is essentially gone today when we have intolerably high late spring and summer temperatures. Watson (1992) describes characteristics of the lower Yakima River that coincided with a subyearling smolt life history. Much of the lower mainstem Yakima River consisted of intricately braided channels flowing through dense riparian forests. The shading, combined with lack of warm irrigation water now prevalent probably resulted in water temperatures considerably lower than today. Haggett (1928) in (Watson et al., 1992) reported that heavy outmigrations of underyearling smolts began in June, peaked in mid-July, and continued through September. Similar timing is still found in the Rogue River (Schluchter and Lichatowich, 1977). Today, any smolt leaving the Yakima must do so nearly two months earlier (although some forays toward the lower river in summer still occur, perhaps as a way of testing the system for migration opportunities; Lichatowich, personal communication). The original braiding and complex of side channels probably retained cooler water from springtime flows in river gravels so that overall lower river temperature was cooled.

A similar problem occurs in the lower reaches of other tributaries. Largely because of water withdrawals for irrigation and removal of riparian vegetation, water temperatures in summer are higher than those known to be lethal or debilitating to salmonids. Streams known to be so affected include the Umatilla, Grande Ronde, and Okanagan. These high temperatures have prevented juvenile fish from migrating or redistributing downstream or to tributary branches. Adult fish have been prevented from ascending to suitable spawning areas. Unsuitable temperatures have served to fragment the habitat of tributary basins (see metapopulation discussion in Chapter 4).

<u>Salmon temperature requirements</u>. Temperature effects on salmonids have been studied extensively, both in general and in the Columbia River basin. There is a firm scientific basis for temperature requirements and the measures that could be taken in the Fish and Wildlife Program (FWP). It remains unclear whether the specific temperature management measures in the FWP make best use of this information, however.

Tolerance levels of salmonids for elevated temperatures at all life stages are well understood. An Interagency Columbia River Thermal Effects Study in the late 1960s focused on temperature effects on Columbia River basin salmonids (Rulifson 1971). As part of that interagency study, much thermal effects research was conducted in the Hanford Reach (Tempelton and Coutant 1970). There has been considerable literature developed since that time, especially in other basins where chinook salmon have been threatened. Several relevant reviews of the literature have been written recently (Brown, 1976; Groot and Margolis, 1991).

Knowledge about overall habitat requirements and migration mechanisms of salmonids and the relationships to temperatures of these habitats have not, however, been adequately accommodated in management decisions.

Responses to temperature are expected to be somewhat variable within the species (see Beacham and Murray 1990). Chinook salmon occur from Alaska to the Central Valley of California. Stocks have evolved or been selected through both natural selection and hatchery practice to tolerate quite divergent environmental conditions and habitats. The degree to which the data summarized here (largely for hatchery stocks) is representative of the migratory wild populations generally and of the Columbia River basin particularly is undetermined.

Temperature requirements differs by life stage. Most literature reviews categorize thermal requirements by life stage in the following sequence: (1) adult migration, (2) spawning, (3) egg and embryo incubation, (4) juvenile rearing. Types of thermal effects information are grouped within these categories. The summarized information usually consists of the type of observation (e.g., peak spawning temperature), the temperature at which the observation is reported to occur, and the literature reference in which it is reported. Anecdotal evidence is often included as well as rigorous testing.

The ISG concludes from available information that the thermal requirements for chinook salmon are approximately as follows. Optimum generally covers several degrees above and below the stated value; stressful is performance markedly below optimum; lethal is for standard 1-week exposures (higher temperatures may be tolerated for short-duration exposures). Other salmon species are not markedly different.

adult migration and spawning: optimum 50°F (10°C), with a range of about 46.4-55.4°F (8-13°C); stressful >60°F (15.6°C); lethal >70°F (21°C)

incubation: optimum <50°F (<10°C), with a range of about 46.4-53.6°F (8-12°C); stressful >56°F (13.3°C); lethal >60°F (15.6°C)

juvenile rearing: optimum 59°F (15°C) with a range of about 53.6-62.6°F (12-17°C); stressful >65°F (18.3°C); lethal 77°F (25°C)

Documentation of the past temperature control work called for in the present program has been largely in ad hoc reports of limited distribution, e.g., (Karr, 1992), which has restricted productive review of their scientific basis by the ISG. In general, the studies have shown that the cooling effect of planned releases at tributary dams is noticeable in the Snake River but diminishes with distance downstream. The temperature control projects seem nearly devoid of the underlying biological basis for such actions, especially any emphasis on temperatures in the actual habitats used by salmon. A more thorough review of the actions and their basis is needed before it is possible to say whether the management approaches are sound.

TEMPERATURE CONCLUSIONS (And Levels of Proof):

1. The FWP assumes that the hydropower system has generally raised water temperatures and that mainstem river temperature is linked to flow and water velocity. These are oversimplifications based on current knowledge, and inadequate for effective remedial measures.
2. Storage impoundments in the Columbia River basin have shifted annual peak temperatures of the mainstem thalweg (all the way to the ocean) to later in the season, when late summer and fall migrating salmonids encounter them. This has occurred even though annual average temperatures have not changed. Tailwaters of storage reservoirs are colder than normal in summer and warmer in fall and winter, but selective withdrawal systems are being installed to provide more natural thermal regimes. (1)
3. Nearshore reservoir waters of the mainstems used by underyearlings are warmed to levels rarely seen in the unimpounded rivers. (1)
4. There is abundant information in the scientific literature on the thermal requirements of the major salmonid species, based on research in the Columbia River basin and elsewhere, which can be used to evaluate and manage thermal effects on fishes. This information indicates that temperatures can exceed lethal levels and often exceed temperatures suitable for successful growth and development. (1)
5. Temperature models and monitoring have been used to track and manage river temperatures for benefit of fish, but documentation of these efforts is inadequate for peer review. (2)
6. Temperature has been identified as a problem in more circumstances than are addressed in the FWP. (1)

Temperature Global Conclusion:
High temperatures in the late summer and fall are detrimental to both juvenile and adult salmon in the mainstem and tributaries, but recent efforts to model and monitor temperatures and manage temperatures for salmonids are too poorly documented to allow independent peer review.

Critical Uncertainties:
For adequate independent peer review, the major critical uncertainty is the status of documentation of temperature monitoring, modeling, and management programs in the basin.

Recommendations:
1. Develop better documentation of temperature programs for peer review.
2. Consider annual temperature cycling as part of the normative river and continue efforts to provide storage reservoirs with selective withdrawal systems to move toward the normative condition.
3. Consider temperature in tributaries as part of the environmental change that has fragmented salmonid habitat, and develop programs to move temperatures there to a more normative condition.

Table 5.1 Discharge statistics and basin areas of the Columbia River and its major tributaries.

River Station Name and Location	Average Discharge (cfs)	Discharge Extremes (cfs) Maximum	 Minimum	Drainage Area above Station (sq. mi.)	Average Discharge per Sq. Mi. above Station (cfs)	Period of Record
Columbia:	71,300	377,000	8,940	34,000	2.10	1913-1970
Columbia at Birchbank, Br. Col.						
Columbia at The Dalles, Ore.	194,000	1,240,000	12,100 (dam closure)	237,000	0.82	1878-1970
Kootenai:						
Kootenay at Newgate, Br. Col.	10,490	98,200	994	7,660	1.37	1930-1970
Kootenai at Porthill, Idaho	16,030	125,000	1,380	13,700	1.17	1904-1927 1928-1970
Pend Oreille-Clark Fork:						
Clark Fork above Missoula, Mt.	2,930	31,700	340	5,999	0.49	1929-1970
Pend Oreille below Box Canyon, near Ione, Wash.	28,220	125,700	125	24,900	1.13	1952-1970
Snake:						
Snake near Heise, Idaho	6,806	60,000	460	5,752	1.18	1910-1970

Snake below Ice Harbor Dam, Wa.	1966-1970					
	range:	298,000	0 (dam-testing)	108,500	0.36-0.53	1907-1917 1962-1970
Willamette-Middle Fork of Willamette:						
Middle Fork of Willamette near Oakridge, Ore.	765	39,800	209	258	2.96	1958-1970
Willamette at Wilsonville, Ore.	28,350	339,000	3,600	8,400	3.38	1948-1970

Source: Date from the U.S. Geological Survey, 1972-1976 (Patrick, 1995)

Table 5.2. Year in operation, length of reservoir, year in service of juvenile salmon collection facilities, location of PIT tag detectors and deflectors, and year in service and capacities for barges and trucks for hydroelectric dams of the Columbia Basin.

DAM	YEAR OF INITIAL SERVICE	LENGTH OF RESERVOIR
Columbia River		(miles)
Rock Island (RM 453.4)	1933	21
Bonneville (RM 145.5)	1938	46
Grand Coulee (RM 596.6)	1941	151
McNary (RM 292)	1953	61
Collection Facilities	*1979*	
Chief Joseph (RM 545.1)	1955	52
The Dalles (RM 191.5)	1957	24
Priest Rapids (RM 397.1)	1959	18
Rocky Reach (RM 473.7)	1961	42
Wanapum (RM 415.8)	1963	38
Wells (RM 515.1)	1967	29
John Day (215.6)	1968	76
Snake River		
Brownlee (SRM 285)	1958	57
Oxbow (SRM 273)	1961	12
Ice Harbor (SRM 9.7)	1961	32
Hells Canyon (SRM 247)	1967	22
Lower Monumental (SRM 41.6)	1969	29
Collection Facilities	*1992*	
Little Goose (SRM 70.3)	1970	37
Collection Facilities	*1975*	
Lower Granite (SRM 107.5)	1975	39
Collection Facilities	*1976*	

* Barge and Truck Transportation-1976, truck transport began; 1977, barge (2) use began; 1981, barges (3) and trucks (5) expanded; 1982, barges (4) expanded, trucks (5); 1990, new barges (2) added; now at full capacity: 6 barges (296,000 pounds of fish), 5 trucks, 3 mini-tankers.

* Juvenile PIT tag detection system-currently installed at Lower Granite, Little Goose, Lower Monumental, McNary, John Day, and Bonneville Dams. Source: Corps of Engineers (1984), Athearn (1994)

Table 5.3. Fishes of the Columbia River basin.

Common Name	Scientific Name	Anadromous Marine Freshwater	Locality	Native Introduced
Pacific lamprey	*Entosphenus tridentatus* (Gairdner) (or *Lampetra tridentata*?)	A	Widespread in basin	N
River lamprey	*Lampetra ayresi* (Gunther)	A	Widespread in basin. WA, OR, ID	N
Western brook lamprey	*Lampetra richardsoni* (Vladykov and Follett)	F	Coastal, mouth of Columbia	N
Green sturgeon	*Acipenser medirostris* (Ayres)	MF	Lower Columbia and marine	N
White sturgeon	*Acipenser transmontanus* (Richardson)	A	Widespread in basin. WA, OR, ID	N
Arctic grayling	*Thymallus arcticus*		Introduced	
Golden trout	*Salmo aguabonita*		Introduced	
American shad	*Alosa sapidissima* (Wilson)	A	Abundant and increasing	I
Yellowstone cutthroat	*Oncorhynchus bouveri*		Native in Snake Plateau	
Lake whitefish	*Corregonus clupeaformis* (Mitchill)	F	Banks Lake, WA. Occurs ID	I
Chum salmon	*Oncorhynchus keta* (Walbaum)	A	Lower river	N
Coho salmon	*Oncorhynchus kisutch* (Walbaum)	A	Lower river. Upriver runs extirpated.	N
Sockeye salmon (kokanee)	*Oncorhynchus nerka* (Walbaum)	A	Two lakes in WA. One ID. Extirpated 24 others. Introduced various inland waters.	N
Chinook salmon	*Oncorhynchus tshawytscha* (Walbaum)	A	Widespread. Some stocks low.	N
Mountain whitefish	*Prosopium williamsoni* (Girard)	F	Widespread	N
Pygmy whitefish	*Prosopium clarkii*			N
Cutthroat trout	*Oncorhynchus clarki*	F (A)	Widespread. Common in smaller tributaries	N

Rainbow trout (steelhead)	*Oncorhynchus mykiss*	AF	Widespread. Abundant in tributaries	N
Atlantic salmon	*Salmo salar* (Linnaeus)	AF	Rare in Columbia River. Escapees from aquaculture.	?
Brown trout	*Salmo trutta* (Linnaeus)	F	Locally in WA, ID and OR	I
Brook charr	*Salvelinus fontinalis* (Mitchill)	F	Scattered streams and lakes	I
Bull charr	*Salvelinus confluentus*	F	Widely distributed. Abundance varies	N
Lake charr	*Salvelinus namaycush* (Walbaum)	F	Scattered lakes	I
Interior redband	*Oncorhynchus gibbsi*			N
Surf smelt	*Hypomesus pretiosus* (Girard)	M (F)	Mostly marine. Occasionally freshwater. WA, OR	N
Eulachon	*Thaleichthys pacificus* (Richardson)	A	Abundant seasonally in lower river	N
Westslope cutthroat	*Oncorhynchus lewisi*			N
Grass pickerel	*Esox americanus vermiculatus* (LeSueur)	F	Two lakes in eastern basin. WA	I
Northern pike	*Esox lucius* (Linnaeus)	F	Pend Oreille Lake. Coeur d'Alene River. ID	I
Chiselmouth	*Acrocheilus aleutaceus* (Agassiz and Pickering)	F	Widespread and abundant in WA, ID, and OR	N
Goldfish	*Carassius auratus* (Linnaeus)	F	Uncommon in Col. R. Abundant in scattered lakes. WA, OR, ID	I
Lake chub	*Couesius plumbeus* (Agassiz)	F	Restricted. Upper Columbia, WA, ID	N
Carp	*Cyprinus carpio* (Linnaeus)	F	Widespread. Abundant, WA, OR, ID, MT	I
Tui chub	*Gil bicolor* (Girard)	F	Abundant eastern Col. basin, WA, OR, ID	N
Utah chub	*Gila atraria* (Girard)	F	Snake River drainage. ID	I
Leatherside chub	*Gila copei* (Jordan and Gilbert)	F	Snake River drainage. ID	I
Oregon chub	*Hybopsis crameri* (Snyder)	F	Willamette River. OR	N

Fathead minnow	*Pimephales promelas* (Rafinesque)	F	Snake River drainage. ID	I
Peamouth	*Mylocheilus caurinus* (Richardson)	F	Abundant Columbia River, WA, OR, ID	N
Northern squawfish	*Ptychocheilus oregonensis*	F	Widespread and abundant. WA, OR, ID, MT	N
Longnose dace	*Rhinichthys cataractae* (Valenciennes)	F	Widespread. WA, OR, ID	N
Leopard dace	*Rhinichthys falcatus* (Eigenmann and Eigenmann)	F	Common in upper Columbia. WA, OR, ID	N
Speckled dace	*Rhinichthys osculus* (Girard)	F	Widespread and abundant. WA, OR, ID	N
Redside shiner	*Richardsonius balteatus* (Richardson)	F	Widespread. Abundant. WA, OR, ID	N
Tench	*Tinca tinca* (Linnaeus)	F	Rare. Columbia River. Spokane River. WA, OR, ID	I
Utah sucker	*Catostomus ardens* (Jordan and Gilbert)	F	Snake River drainage, ID	N
Longnose sucker	*Catostomus catostomus* (Forster)	F	Widespread. Abundant. WA, ID	N
Bridgelip sucker	*Catostomus columbianus* (Eigenmann)	F	Locally abundant in upper Columbia drainages. WA, OR, ID	N
Bluehead sucker	*Catostomus discobolus* (Cope)	F	Snake River drainage. ID	N
Largescale sucker	*Catostomus machrocheilus* (Girard)	F	Widespread. Abundant. WA, OR, ID, MT	N
Mountain sucker	*Catostomus platyrhinchus* (Cope)	F	Restricted. Upper Columbia drainages. WA, OR, ID	N
Black bullhead	*Ictalurus melas* (Rafinesque)	F	Rare. WA, OR, ID	I
Channel catfish	*Ictalurus punctatus* (Rafinesque)	F	Abundant. Middle reaches. WA, OR, ID	I
Tadpole madtom	*Notorus gyrinus* (Mitchill)	F	Rare. WA, OR, ID	I
Flathead catfish	*Pylodictus oliveris* (Rafinesque)	F	Snake River drainage. ID. Possibly OR	I
Sandroller	*Percopsis transmontanus* (Eigenmann and Eigenmann)	F	Widespread. Common tributaries. WA, OR, ID, MT	N
Burbot	*Lota lota* (Linnaeus)	F	Common in deep lakes. WA, OR, ID, MT	N

Three spine stickleback	*Gasterosteus aculeatus* (Linnaeus)	MF	Widespread and abundant. WA, OR, ID, MT	N
Striped bass	*Morone saxatilis* (Walbaum)	A	Rare at mouth of Columbia. WA, OR	I
Green sunfish	*Lepomis cyanellus* (Rafinesque)	F	Klamath River, OR	I
Pumpkinseed	*Lepomis gibbosus* (Linnaeus)	F	Locally abundant. WA, OR	I
Smallmouth bass	*Micropterus dolomieui* (Lacepede)	F	Common in middle reaches. WA, OR, ID	I
Largemouth bass	*Micropterus salmoides* (Lacepded)	F	Abundant. WA, OR, ID	I
White crappie	*Pomoxis annularis* (Rafinesque)	F	Abundant lower reaches, esp. McNary pool. WA, OR, ID	I
Black crappie	*Pomoxis nigromaculatus* (Lesueur)	F	Potholes. WA	I
Yellow perch	*Perca flavescens* (Mitchill)	F	Abundant in some lakes. Rare in tributaries. WA, OR, ID, MT	I
Walleye	*Stizostedion bitreum* (Mitchill)	F	Common and abundant in river. WA, OR, ID	I
Shiner perch	*Cymatogaster aggregata* (Gibbons)	M	Tidewater. Abundant. WA, OR	N
Starry flounder	*Platichthys stellatus* (Pallas)	M	Occasionally in freshwater. WA, OR	N
Coastrange sculpin	*Cottus aleuticus* (Gilbert)	F	Lower river to Bonneville Dam. WA, OR	N
Shorthead sculpin	*Cottus confusus* (Bailey and Bond)	F	Bonneville Dam. Usually higher altitude tributaries. WA, OR	N
Mottled sculpin	*Cottus bairdi* (Girard)	F	Common. Upper Columbia drainages. WA, OR, ID, MT	N
Piute sculpin	*Cottus beldingi* (Eigenmann and Eigenmann)	F	Common. Upper Columbia drainages. WA, OR, ID	N
Slimy sculpin	*Cottus cognatus* (Richardson)	F	Rare. Tributaries to Lake Chelan. WA	N
Shoshone sculpin	*Cottus greenei* (Gilbert and Culver)	F	Snake River drainage. ID	N
Torrent sculpin	*Cottus rhotheus* (Smith)	F	Common. Widespread. WA, OR, ID	N

Prickly sculpin	*Cottus asper* (Richardson)	FE	Common. Estuary and lower river to Hanford reach. WA, OR	N
Margined sculpin	*Cottus marginatu*s (Bean)	F	Restricted. Umatilla River to Walla Walla River. WA, OR	N
Riffle sculpin	*Cottus gulosus* (Girard)	F	Lower Columbia to Cowlitz and Lewis Rivers. WA, OR	N
Reticulate sculpin	*Cottus perplexus* (Gilbert and Evermann)	F	Overlaps with C. gulosus and may hybridize	N
Pacific staghorn sculpin	*Leptocottus armatus* (Girard)	M(F)	Primarily marine. Occasionally freshwater. WA, OR	N
Spoonhead sculpin	*Cottus ricei*			

Literature Cited

Balz, D.M. and P.B. Moyle. 1993. Invasion resistance to introduced fishes by a native assemblage of California stream fishes. Ecol. Appl. 3: 246-255.

Becker, C.D. 1973. Development of Simulium (Psilozia) vittatum Zett. (Diptera: Simuliidae) from larvae to adults at thermal increments from 17.0 to 27.0 C., Am. Midl. Nat. 89(1):246-251.

Berman, C.H. and T.P. Quinn. 1991. Behavioral thermoregulation and homing by spring chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), in the Yakima River. J. Fish Biol. 39: 301-312.

Beschta, R.L., W.S. Platts and B. Kauffman. 1991. Field review of fish habitat improvement projects in the Grande Ronde and John Day River Basins of eastern Oregon. Portland, Bonneville Power Administration. Oregon.

Bisson, P.A., T.P. Quinn, G.H. Reeves and S.V. Gregory. 1993. Best management practices, cumulative effects, and long-term trends in fish abundance in Pacific Northwest river systems. Watershed Management: Balancing Sustainability and Environmental Change. R. J. Naiman. New York, Springer-Verlag**:** 189-232.

Brannon, E.L. and E.O.S. (eds.), Eds. 1982. Proceedings of the Salmon and Trout Migratory Behavior Symposium. Seattle, University of Washington School of Fisheries.

Brown, H.P. 1976. Aquatic dryopoid beetles (Coleoptera) of the United States. Cincinnati, U.S.E.P.A. Environmental Monitoring and Support Laboratory. Ohio**:** 82.

Brusven, M.A., D.J. Walker, K.M. Painter and R.C. Biggam. 1995. Ecological-economic assessment of a sediment-producing stream behind Lower Granite Dam on the Lower Snake River, USA. Regulated Rivers 10(2-4): 373-388.

Calow, P. and G.E. Petts, Eds. 1992. The Rivers Handbook, Volume 1: Hydrological and Ecological Principles. Oxford, Blackwell Scientific.

Chisolm, I.M., W.A. Hubert and T.A. Wesche. 1987. Winter stream conditions and use of habitat by brook trout in high-elevation Wyoming streams. Trans. Am. Fish. Soc. 116: 176-184.

Craig, J.F. and J.B. Kemper, Eds. 1987. Regulated Streams: Advances in Ecology. New York, Plenum Press.

Cunjak, R.A. and G. Power. 1986. Winter habitat utilization by stream resident brook trout and brown trout. Can. J. Fish. Aquat. Sci. 43: 1970-1981.

Cunjak, R.A. and R.G. Randall. 1993. In-stream movements of young Atlantic salmon (*Salmo salar*) during winter and early spring. Can. J. Fish. Aquat. Sci. Special Publ. 118: 43-51.

Curet, T.S. 1993. Habitat use, food habits, and the influence of predation on subyearling chinook salmon in Lower Granite and Little Goos Reservoirs, Washington. Moscow, University of Idaho. Idaho.

Dauble, D.D., R.H. Gray and T.L. Page. 1980. Importance of insects and zooplankton in the diet of 0-age chinook salmon (*Oncorhynchus tshawytscha*) in the central Columbia River. Northwest Science 54(4): 253-.

Davis, H.T. 1978. Idaho's environment., Environ. Sci. & Technol. 12(3):276-283.

Doppelt, B., M. Scurlock, C. Frissell and J. Karr. 1993. Entering the Watershed: A New Approach to Save America's River Ecosystems. Covelo, CA, Island Press.

Ebel, W.J., C.D. Becker, J.W. Mullan and H.L. Raymond. 1989. The Columbia River: Toward a holistic understanding. Proceedings of the International Large River Symposium (LARS). D. P. Dodge, Special Publication of the Canadian Journal of Fisheries and Aquatic Sciences. 106**:** 205-219.

Ebersole, J.L. 1994. Stream habitat classification and restoration in the Blue Mountains of northeast Oregon. Corvallis, Oregon State University. Oregon.

Elmore, W. 1992. Riparian responses to grazing practices. Watershed Management: Balancing Sustainability and Environmental Change. R. J. Naiman. New York, Springer-Verlag**:** 442-457.

Evermann, B.W. 1895. A preliminary report upon salmon investigations in Idaho in 1894. Bull. U.S. Fisheries Commission 15: 253-284.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest Ecosystem Management: An Ecological, Economic, and Social Assessment. Portland, Interagency Supplemental Envir. Impact Statement Team. Oregon.

Flathead Basin Commission. 1994. 1993-1994 Biennial Report. Kalispell, Flathead Basin Commission. Montana**:** 48.

Frissell, C.A. 1993. A new strategy for watershed restoration and recovery of Pacific salmon in the Pacific Northwest. Eugene, Pacific Rivers Council. Oregon**:** 33.

Frissell, C.A. and S.B. Adams. 1995. Factors affecting distribution and co-occurrence of eastern brook trout and other fishes in the northern Rocky Mountains, USDA Forest Service, Intermountain Research Station.

Frissell, C.A., J. Doskocil, J.T. Gangemi and J.A. Stanford. 1995. Identifying priority areas for protection and restoration of aquatic biodiversity: a case study in the Swan River Basin, Montana, USA. Polson, Flathead Lake Biological Station, The University of Montana. Montana.

Frissell, C.A., W.J. Liss, C.E. Warren and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management 10(2): 199-214.

Frissell, C.A. and R.K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12: 182-197.

Fulton, L.A. 1968. Spawning areas and abundance of chinook salmon (*Oncorhynchus tshawytscha)* in the Columbia River Basin--past and present, USDI, Fish and Wildl. Serv.,.

Fulton, L.A. 1970. Spawning areas and abundance of steelhead trout and coho, sockeye, and chum salmon in the Columbia River Basin--past and present, USDC, NOAA, NMFS.

General Accounting Office. 1992. Endangered Species: past actions taken to assist Columbia River salmon, General Accounting Office.

Gregg, W.W. and F.L. Rose. 1985. Influence of aquatic macrophytes on invertebrate community structure, guild structure, and microdistribution in streams. Hydrobiologia 128: 45-56.

Groot, C. and L. Margolis, Eds. 1991. Pacific salmon life histories. Vancouver, University of British Columbia.

Hauer, F.R. 1993. Artificial streams for the study of macroinvertebrate growth and bioenergetics. J. N. Am. Bentho. Soc. 12(4): 333-337.

Hauer, F.R., E.G. Zimmerman and J.A. Stanford. 1980. Preliminary investigations of distributional relationship of aquatic insects and genetic variation of a fish population in the Kintla Drainage, Glacier National Park, Proc. 2nd Symp. Res. National Parks. Am. Inst. Biol. Sci. 2: 71-84.

Henjum, M.G., J.R. Karr, D.L. Bottom, D.A. Perry, J.C. Bednarz, S.G. Wright, S.A. Beckwitt and E. Beckwitt. 1994. Interim Protection for Late-Successional Forest, Fisheries, and Watersheds: National Forests East of the Cascade Crest, Oregon and Washington. Bethesda, The Wildlife Society.

Hicks, B.J., R.L. Beschta and R.D. Harr. 1991. Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. Water Resources Bulletin 27(2): 217-226.

Huntington, C.W. 1995. Fish Habitat and Salmonid Abundance within Managed and Unroaded Landscapes on the Clearwater National Forest, Idaho. Walla Walla, USFS Eastside Ecosystem Management Project. Washington.

Hynes, H.B.N. 1975. The stream and its valley. Proceedings of the International Association of Theoretical and Applied Limnology.

Janecek, B.F.U. and O. Moog. 1994. Origin and composition of the benthic invertebrate riprap fauna of impounded rivers. Verh. Internat. Verein. Limnol. 25: 1624-1630.

Jaske, R.T. and J.B. Goebel. 1967. Effects of dam construction on temperatures of the Columbia River. J. Amer. Water Works Assoc. 59: 935-942.

Jones, K.K., C.A. Simenstad, D.L. Higley and D.L. Bottom. 1990. Community structure, distribution, and standing stock of benthos, epibenthos, and plankton in the Columbia River estuary. Prog. Oceanog. 25: 211-241.

Junk, W.J., P.B. Bayley and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Proceedings of the International Large River Symposuim. Canadian Special Publication of Fisheries and Aquatic Sciences106. D. P. Dodge**:** 110-127.

Karr, J.R. 1992. Ecological integrity: protecting earth's life support systems. Ecosystem Health. New Goals for Environmental Management. R. Costanza, B. G. Norton and B. D. Haskell. Washington, Island Press**:** 223-238.

Kauffman, J.B., R.L. Beschta and W.S. Platts. 1993. Fish Habitat Improvement Projects in the Fifteenmile Creek and Trout Creek Basins of Central Oregon: Field Review and Management Recommendations. Portland, Bonneville Power Admin., Div. of Fish and Wildlife. Oregon.

Kauffman, J.B. and W.C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications - a review. J. Range Mgmt. 37: 430-438.

Key, L.O., R. Garland and E.E. Kerfoot. 1995. Nearshore habitat use by subyearling chinook salmon in the Columbia and Snake Rivers. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and K. F. Tiffan. Portland, Bonneville Power Administration. Report No. COE/BP-21708-3**:** 74-107.

Lasenby, D.C., T.G. Northcote and M. Furst. . 1986. Theory, practice and effects of *Mysis relicta* introductions to North American and Scandinavian Lakes. Can. J. Fish. Aquat. Sci. 43: 1277-1284.

Li, H.W., K. Currens, D. Bottom, S. Clarke, J. Dambacher, C. Frissell, P. Harris, R.M. Hughes, D. McCullough, A. McGie, K. Moore, R. Nawa and S. Thiele. 1995. Safe havens: refuges and evolutionarily significant units. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 371-380.

Li, H.W., K. Currens, D. Bottom, S. Clarke, J. Dambacher, C. Frissell, P. Harris, R.M. Hughes, D. McCullough, A. McGie, K. Moore and S. Thiele. 1995. Safe havens: refuges and evolutionarily significant units. American Fisheries Society Symposium 17.

Li, H.W., G.A. Lamberti, T.N. Pearsons, C.K. Tait and J.L. Li. 1995. Cumulative impact of riparian disturbances in small streams of the John Day Basin, Oregon. Trans. Amer. Fish. Soc. 123: 627-640.

Li, H.W., C.B. Schreck, C.E. Bond and E. Rexstad. 1987. Factors influencing changes in fish assemblages of Pacific Northwest streams. Community and Evolutionary Ecology of North American Stream Fishes. W. J. Matthews and D. C. Heins. Norman, Univ. of Oklahoma Press**:** 193-202.

Lichatowich, J., L. Mobrand, L. Lestelle and T. Vogel. 1995. An approach to the diagnosis and treatment of depleted Pacific salmon populations in Pacific Northwest watersheds. Fisheries 20(1): 10-18.

Lichatowich, J.A. and L.E. Mobrand. 1995. Analysis of chinook salmon in the Columbia River from an ecosystem perspective, Mobrand Biometrics.

Lillehammer, A. and S.J. Saltveit, Eds. 1984. Regulated Rivers. Oslo, Oslo University Press.

Lillehammer, A.a.S.J.S. 1984. The effect of the regulation on the aquatic macroinvertebrate fauna of the River Suldalslagen, western Norway. IN: Lillehammer, A. and S. J. Saltveit (eds.), Regulated Rivers., Oslo Univ. Press, Oslo, Norway. 540 pp.

Maser, C., R. F. Terrant, J. M Trappe and J. F. Franklin (eds.). 1988. From the Forest to the Sea: A Story of Fallen Trees., USDA Forest Service, Pacific Northwest Research Station, Portland, OR. 153pp.

Mcintosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Clearwater, Salmon, Weiser, and Payette River Basins, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Cowlitz River Basin, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Umatilla, Tucannon, Asotin, and Grande Ronde River Basins, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Willamette River Basin, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Yakima River Basin, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., J.R. Sedell, J.E. Smith, R.C. Wissmar, S.E. Clarke, G.H. Reeves and L.A. Brown. 1994. Historical changes in fish habitat for select river basins of eastern Oregon and Washington. Northwest Science. D. L. Peterson. Seattle. 68**:** 36-53.

Meehan, W.R., Ed. 1991. Influences of Forest and Rangeland Management of Salmonid Fishes and Their Habitats. Bethesda, American Fisheries Society.

Meyer, J.L., G. E. Likens and J. Sloane. 1981. Phosphorus, nitrogen, and organic carbon flux in a headwater stream., Arch. Hydrobiol. 91(1):28-44.

Moulton, G.E., Ed. 1988. The Journals of the Lewis and Clark Expedition July 28-November 1, 1805. The Journals of the Lewis and Clark Expedition. Lincoln, University of Nebraska Press.

Moyle, P.B. and G.M. Sato. 1991. On the design of preserves to protect native fishes. Battle Against Extinction: Native Fish Management in the American West. W. L. Minckley and J. E. Deacon. Tucson, University of Arizona Press**:** 155-169.

Muir, W.D. and R.L. Emmett. 1988. Food habits of migrating salmonid smolts passing Bonneville Dam in the Columbia River, 1984. Reg. Rivers 2: 1-10.

Mundie, J.H. 1971. Sampling benthos and substrate materials, down to 50 microns in size, in shallow streams., J. Fish. Res. Board Can. 28:849-860.

Naiman, R.J., Ed. 1992. Watershed Management: Balancing Sustainability and Environmental Change. New York, Springer-Verlag.

Naiman, R.J. and K. Fetherston. 1993. Restoration of watersheds and naturally-spawning salmon populations in the Pacific Northwest, Testimony before the US House of Representatives Subcommittee on Environment and Natural Resources, Committee on Merchant Marine and Fisheries, Mar. 9, 1993.

National Research Council. 1995. Science and the Endangered Species Act. Washington, National Academy Press.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Nilsen, H.C. and R.W. Larimore. 1973. Establishment of invertebrate communities on log substrates inthe Kaskaskia River, Illinois. Ecology 54: 366-374.

Noss, R.F. and D.D. Murphy. 1995. Endangered species left homeless in Sweet Home. Conservation Biology 9(2): 229-231.

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Annals Assoc. Amer. Geographers 77(1): 118-125.

Pacific Rivers Council et al. 1993. Petition to the National Marine Fisheries Service for a rule to list, for designation of critical habitat, and for a status review of coho salmon (*Oncorhynchus kisutch*) throughout its range in Washington, Oregon, and California under the Endangered Species Act. Eugene, OR.

Patrick, R. 1995. Rivers of the United States. Volume II: Chemical and Physical Characteristics. New York, John Wiley & Sons.

Petts, G.E., H. Moller and A.L. Roux, Eds. 1989. Historical Change of Large Alluvial Rivers: Western Europe. Chichester, John Wiley & Sons.

Petts, G.E. and R. Wood, Eds. 1988. River Regulation in the United Kingdom, John Wiley & Sons.

Platts, W.S. and R.L. Nelson. 1985. Stream habitat and fisheries response to livestock grazing and instream improvement structures, Big Creek, Utah. Journal of Soil and Water Conservation 40: 374 - 379.

Power, M.E., R.J. Stout, C.E. Cushing, P.P. Harper, F.R. Hauer, W.J. Matthews, P.B. Moyle, B. Statzner and I.R. Wais De Badgen. 1988. Biotic and abiotic controls in river and stream communities. J. North Am. Benthol. Soc. 7: 456-479.

Rhodes, J.J. 1995. A Comparison and Evaluation of Existing Land Management Plans Affecting Spawning and Rearing Habitats of Snake River Basin Salmon species Listed Under the Endangered Species Act. Portland, Columbia Inter-Tribal Fish Commission. Oregon.

Rhodes, J.J., D.A. McCullough and J. F. A. Espinosa. 1994. A Coarse Screening Process for Evaluation of the Effects of Land Management Activities on Salmon Spawning and Rearing Habitat in ESA Consultations. Portland, Columbia River Inter-Tribal Fish Commission. Oregon.

Ricker, W.E. 1972. Hereditary and environmental factors affecting certain salmonid populations. The Stock Concept in Pacific Salmon. R. C. Simon and P. A. Larkin. Vancouver, University of British Columbia**:** 19-160.

Riddell, B.E. and W.C. Legget. 1981. Evidence for an adaptive basis variation in body morphology and time of downstream migration juvenile Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 38: 308-320.

Rieman, B.E. and B. Bowler. 1980. Kokanee trophic ecology and limnology in Pend Oreille Lake. Moscow, Forest, Wildlife and Range Exp. Station., University of Idaho. Idaho.

Rieman, B.E. and J.D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. Ogden, US Forest Service, Intermountain Research Station. Utah**:** 38.

Rondorf, D.W., G.A. Gray and R.B. Fairley. 1990. Feeding ecology of subyearling chinook in riverine and resevoir habitats of the Columbia River. Trans. Amer. Fish. Soc. 119(1): 16-24.

Salo, E.O.a.T.W.C.e. 1987. Streamside management: forestry and fishery interactions., Univ. Washington, Seattle, Contribution No. 57, 471 pp.

Schluchter, M. and J.A. Lichatowich. 1977. Juvenile Life Histories of Rogue River Spring Chinook Salmon *Oncorhynchus tshawytscha* (Walbaum), as determined from scale analsysis. Corvallis, Oregon Dept. of Fish and Wildlife. Oregon.

Schreck, C.B., J.C. Snelling, R.E. Ewing, C.S. Bradford, L.E. David and C.H. Slater. 1995. Migratory Characteristics of Juvenile Spring Chinook Salmon in the Willamette River. Portland, Bonneville Power Administration. Oregon.

Schumm, S.A. and R.W. Lichty. 1956. Time, space and causality in geomorphology. American Journal of Science 263: 110-119.

Sear, D.A. 1994. River restoration and geomorphology. Aquatic Conservation: Marine & Freshwater Ecosystems 4: 169-177.

Sedell, J.R. and J.L. Froggatt. 1984. Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verh. Internat. Verein. Limnol. 22: 1828-1834.

Sedell, J.R., F.N. Leone and W.S. Duvall. 1991. Water transportation and storage of logs. Amer. Fish. Soc. Special Publ. 19: 325-367.

Sedell, J.R., G.H. Reeves, F.R. Hauer, J.A. Stanford and C.P. Hawkins. 1990. Role of refugia in recovery from disturbances: Modern fragmented and disconnected river systems. Environ. Manage. 14(5): 711-724.

Sheldon, A.L. 1988. Conservation of stream fishes: patterns of diversity, rarity and risk. Conservation Biology 2(2): 149-156.

Smith, D. 1979. The larval stage of Hydropsyche separata Banks (Trichoptera: Hydropsychidae)., Pan-Pac. Entomol. 55(1):10-20.

Smith, R.A., R.B. Alexander and M.G. Wolman. 1987. Water quality trends in the nation's river. Science 235: 1607-1615.

Society, W. 1993. The Living Landscape: Vol. 2 Pacific Salmon and Federal Lands, The Wilderness Society, Bole Center for Forest Ecosystem Management**:** 88 + app.

Spencer, C.N., B.R. McClelland and J.A. Stanford. 1991. Shrimp stocking, salmon collapse, and eagle displacement: cascading interactions in the food web of a large aquatic ecosystem. BioScience 41(1): 14-21.

Stanford, J.A. and F.R. Hauer. 1992. Mitigating the impacts of stream and lake regulation in the Flathead River Catchment, Montana, USA: An ecosystem perspective. Aquatic Conservation 2: 35-63.

Stanford, J.A. and J.V. Ward. 1992. Management of aquatic resources in large catchments: Recognizing interactions between ecosystem connectivity and environmental disturbance. Watershed Management. R. J. Naiman. New York, Springer-Verlag**:** 91-124.

Stanford, J.A. and J.V. Ward. 1993. An ecosystem perspective of alluvial rivers: Connectivity and the hyporheic corridor. J. N. Am. Benthol. Soc. 12(1): 48-60.

Stanford, J.A., J.V. Ward and B.K. Ellis. 1994. Ecology of the alluvial aquifers of the Flathead River, Montana. Groundwater Ecology. J. Gibert, D. L. Danielopol, J. A. Stanford. San Diego, Academic Press, Inc.**:** 367-390.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant. *in press*. A general protocol for restoration of regulated rivers. Regulated Rivers.

Stober, Q.J. and R.E. Nakatani. 1992. Water quality and biota of the Columbia River system. Water Quality in North American River Systems. C. D. Becker and D. A. Neitzel. Columbus, Battelle Press**:** 51-84.

Theurer, F.D., I. Lines and T. Nelson. 1985. Interaction between riparian vegetation, water temperature and salmonid habitat in the Tucannon River. Water Resour. Bull.(21).

Vaccaro, J.J. 1988. Simulation of Stream Temperatures in the Yakima River Basin, Washington, April-October 1991, US Geological Survey.

Vervier, P. and R.J. Naiman. 1992. Spatial and temporal fluctuations of dissolved organic carbon in subsurface flow of the Stillaguamish River (Washington, USA). Archiv fur Hydrobiologie 123(4): 401-412.

Walters, C.J., R.M. Hilborn, R.M. Peterman and M.J. Staley. 1978. Model for examining early ocean limitation of Pacific salmon production. J. Fish. Res. Board of Canada 35: 1303-1315.

Ward, J.V. and J.A. Stanford, Eds. 1979. The Ecology of Regulated Streams. New York, Plenum Press.

Watson, S., E. McCauley and J.A. Downing. 1992. Sigmoid relationships between phosphorus, algal biomass and algal community structure. Can. J. Fish. Aquat. Sci. 49: 2605-2610.

Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, G.H. Reeves and J.R. Sedell. 1994. A history of resource use and disturbance in riverine basins of Eastern Oregon and Washington (early 1800s-1900s). Northwest Science. D. L. Peterson. Seattle. 68**:** 1-35.

Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, G.H. Reeves and J.R. Sedell. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s-1990s). Northwest Science 68: 1-35.

CHAPTER 6. JUVENILE SALMON MIGRATION BEHAVIOR AND THE EFFICACY OF THE FLOW-SURVIVAL HYPOTHESIS

One suspected overall cause of the decline in anadromous salmonid production is an increase in migration time through the mainstem Snake and Columbia rivers (Raymond, 1968; Park, 1969; Raymond, 1979). Migration is slowed in two ways: slower migration in languid reservoir water, and delay in passing through dams. Longer migration time is believed to increase time available for the action of many sources of mortality. This is especially intuitive when one considers juvenile migration in the context of changes in shallow shoreline habitats and invasions of non-native predators and increases in native predators wrought by reservoir construction (discussed in Chapter 5, above).

Current restoration efforts focus on moving juvenile salmonids from the river system as rapidly as possible by altering mainstem flows through reservoirs in spring with reservoir drawdowns, increased spring flows, or both {Northwest Power Planning Council 1994}, (National Marine Fisheries Service, 1995). This strategy appears to be based on the following premises: (1) survival of juveniles and eventual return of adults to the river is highest when spring-summer flow rates and velocities through the mainstem are greatest, (2) slowed migration through the mainstem reservoirs is more important in leading to mortality than delay in dam forebays, and (3) slack water in reservoirs and diminished spring freshets (by upstream storage) are the causes of slower downstream movement of water and fish through mainstem reservoirs.

The flow-survival relationships have been reviewed recently with different conclusions (Cada et al., 1994; Steward, 1994) {Williams and Matthews 1996; Hilborn 1996}. All agree that relevant data sets are extremely limited. Cada et al. concluded that the general relationship of increasing survival with increasing flow seems reasonable. They found that plots of different expressions of survival versus different expressions of flow have, with few exceptions, been best described by models that show positive flow-survival relationships. Studies with different stocks and using different methods tended to show the same general patterns. However, the other authors have raised doubts about some of the specific data points used in the evaluations, first conducted by Sims and Ossiander (Sims and Ossiander, 1981), and generally failed to confirm the alleged relationships. Objective analysis of a possible flow-survival relationship has been complicated by increasing emphasis on surrogate relationships among flow, velocity, and travel time (Berggren and Filardo, 1993; Petrosky, 1993).

Petrosky (1993) and Petrosky and Schaller (1993) provided an example of what they believed to be a flow-survival relationship. They related the success of spring chinook salmon adult returns to Idaho and Oregon tributaries with flows in the Snake River measured at Lower

Granite Dam during the main emigration period. There was much interannual variability that complicated a clear picture, but a trend was detected, suggesting better smolt-to-adult returns when river flows were high. Interannual variability in survival increased after the hydrosystem was completed in the mid 1970s (interpreted as an indication of instability of the salmon-production system) and it exceeded variability over the same years for yearlings from a downriver stock (Warm Springs River). The upriver-downriver comparison excluded estuary and ocean conditions as the main causes of interannual variability. The authors interpreted these results as indicating that unimpeded movement of smolts from the tributary and lower river system has high survival value.

Our evaluation of these reviews and studies has left us with the conclusion that a clear flow-survival relationship adequate for defining flow requirements in the system has yet to be demonstrated. The historical record generally shows better salmon production in wet years (Anderson et al., 1996). Droughts have been particularly devastating for survival of juvenile salmonids and returns of adults in subsequent years in this and other river basins (e.g., California). But interpretation of these data to support specific flows, velocities, travel times, and other within-year features of discharges in the Columbia and Snake rivers is incomplete and inadequate.

There are many avenues by which volume of river flow could affect salmonid survival in addition to moving them faster through the mainstem reservoirs (Figure 6.1). These avenues are discussed below and elsewhere in this report, and include spill of water at dams during high flows (facilitating passage through dams), flooding of riparian zones (with stimulation of food production), reduced summer temperatures (less high-temperature stress), reduced predator efficiency in high velocities and water volumes (less predation mortality), and the aggregate energy budget of migrating fish (better growth and survival). Thus, the overall flow-survival relationship may be valid, but its simplification to a relationship centering on water velocity and travel times for juveniles in reservoirs is probably inappropriate for a full range of life history types, and it does not take a holistic view of recovery and re-establishment of salmonid populations.

Present debate among fisheries managers centers more on how to accomplish the strategy of moving juvenile salmon through reservoirs in spring and summer than on whether it is the wisest strategy based on the needs of fish. There are multiple tradeoffs among generally costly alternatives. Drawing down mainstem reservoirs during juvenile emigrations would increase water (and fish) velocity through them but disrupt river navigation, irrigation withdrawals, and hydropower. It would likely cause scour of fine sediments in the reservoirs and increase river turbidity. Release of more water from storage in spring would increase velocity in mainstem reservoirs but retain less water for reduction of temperatures in the summer and less for hydropower generation through the whole system in other seasons. It would lower storage reservoir elevations with disruption of irrigation and reservoir-based recreation in the headwaters. Spill of water at dams would avoid passing fish through turbines but reduce hydropower, might lead to greater upstream releases, and could cause gas supersaturation in water and gas bubble disease in fish. With each choice comes the question how much of that remedial measure is needed or desirable. These policy debates have largely preempted a thorough evaluation of the biological aspects of juvenile salmonid use of the mainstem and the environmental features that could be emulated to facilitate successful migration. The nature of the debate reflects the current technological conceptual framework for salmon restoration.

The current Columbia River Basin Fish and Wildlife Program places highest research priority on evaluating the relationship between spring and summer flow and velocity, and their effectiveness to increase overall suvival relative to transportation (Northwest Power Planning Council 1994,§ 5.0F). Because of the simultaneous need for action and better scientific information, the Council believes that the relationships can be best clarified through an adaptive management approach. This approach would involve the simultaneous use of inriver passage and transportation (by truck and barge) as management experiments to address specific hypotheses. The experiments would include a combination of management actions, research, monitoring, and evaluation. The Council wants the adaptive management framework to be developed in an independent, scientifically-credible and open manner. It has charged the Independent Scientific Group to ensure that the framework and the research are scientifically credible. This review addresses this, by a thorough examination of existing information on fish migration behavior in relation to downstream passage.

Our premise is that to rehabilitate fish populations, we need to know what the *fish* need in the context of the river basin ecosystem. A reconstructed understanding of the historical quality of habitats for their match with the diversity of life history traits exhibited by salmon has been proposed as an important step in ecosystem-based restoration planning (Sedell and Luchessa, 1981; Lichatowich et al., 1995). Although comparative statistics on run (population) sizes usually compare historically high abundances with recent low numbers, analyses of abundance usually do not emphasize predevelopment habitat conditions that governed those abundances. If habitats are emphasized at all, fishery scientists have generally stressed the present altered condition rather than development of an understanding of the historical nature of the stream and river conditions. Historical reconstruction creates a scientific template of the healthy habitat and life histories of target fish populations in a patient (present-day)-template comparative analysis (Lichatowich et al., 1995). This analysis helps define the normative condition toward which we should manage the system.

How to accomplish the benefits embedded in high river discharge and thus increase fish survival to the extent possible in the present dam-dominated, water management environment depends on the specific needs of the fish, beyond any recognition of a general pattern of a flow-survival relationship. Flow occurs in the context of a total river environment, one that historically provided a number of diverse habitats for use by different fish species and stocks as they moved downstream as juveniles and upstream as adults. Hydropower has changed these riverine habitats, but not the basic needs of the fish. The high economic cost of various remedial measures would seem to make imperative a sound scientific basis for the direction taken and attention to biological and ecological details of salmon migration and the habitats and conditions the fish need for it.

There are several relevant details of what fish need. We discuss and document below and in Appendix D (1) the different migration types among the salmonids that inhabit the Columbia River basin mainstem, (2) that emigration is not a passive riding of currents straight to the sea, but rather emigration is a spiral of alternating active movement and use of mainstem habitats for resting and feeding, (3) that quality of mainstem habitat for the resting and feeding stage is important (also, see discussions of habitat in Chapter 5), (4) that juvenile salmonids are generally surface oriented when moving, and (5) that they probably use the complex unsteady and turbulent flow of river environments as migration guides and assists rather than relying on either mass water movement or their swimming abilities. Important work, largely under the Council's program, is summarized in some detail by life-history type and species. Finally, we relate these features of juvenile salmonid migration to mitigation measures such as augmented flows, spill, reservoir drawdowns, surface fish bypasses, dam removal, and velocity-enhancing structures for reservoirs that could move the present system toward the normative mainstem ecosystem to which the salmonids evolved. We recognize that there are directed movements of presmolts during rearing in tributaries, e.g. movements to overwintering sites or upstream movements in tributaries to seek cooler temperatures. We focus here however, on migrations in the mainstem.

MAJOR FEATURES OF JUVENILE MIGRATION

Different migration types

There are two major life-history types of salmonids in the basin. The two types are generally distinguished by the relative lengths of freshwater rearing. The most relevant differences for this discussion relate to the developmental stage when the juveniles occupy the mainstem. Rearing (feeding and growing to downstream-migration size) and downstream migration to the sea occur in fresh water, whereas major growth to adulthood occurs during ocean residence. Based on the relative lengths of the rearing/migrating and ocean phases, a distinction is made between "ocean-type" and "stream type" salmon species or stocks (Gilbert, 1912; Groot and Margolis, 1991). Ocean type salmonids exhibit a short freshwater residence for rearing, usually leaving the river ecosystem within six months of emergence from the spawning gravel. Stream-type fish reside in the stream for one year or longer before emigrating for the ocean. Ocean-type stocks are usually mainstem or coastal river spawners with short migration distances to the sea whereas stream-type stocks have generally longer migration routes (Taylor, 1990).

The mainstems of the Columbia and Snake rivers have both types. Presently, ocean-type fish are represented by fall chinook salmon (and summer chinook in the mid-Columbia) that spawn in the mainstem and lower reaches of tributaries and rear in the mainstem as they move in spring and summer toward the sea. Stream-type fish are represented by several species and stocks that generally undergo a year or more of rearing in tributary headwaters and have a brief passage through the mainstem in spring. These include spring chinook salmon (and summer chinook in the Snake River drainage), coho salmon (which often rear for 2 years in tributaries), and steelhead/rainbow trout (which may rear in tributaries for as many as 7 years before migrating to sea but most often for 1 to 2 years; (Peven et al., 1994). Sockeye salmon is a "stream type" in that it rears for a year or more (although in lakes) before migrating to the sea in spring. Thus, the mainstem hosts subyearling ocean-type juvenile salmonids for rearing and migration, and stream-type yearling juveniles that are generally considered to be entirely in a rapid migration phase. Management approaches for the mainstems need to accommodate both life-history types.

Migration is not Just Continual Downstream Movement (Flushing)

Downstream migration of juvenile salmonids is more complex than their being washed downstream by river flows. Our independent review of the literature has shown that once migration is initiated, downstream migration is more aptly characterized as a discontinuous, spiraling movement rather than as the continual linear progression characteristic of a water particle. We call the behavior in which the fish chooses to move with the flow of water, exhibiting positive rheotaxis in a fashion similar to a water particle, “flushing”, to distinguish it from those negatively rheotactic behaviors which the fish may employ to stop its downstream movements (Figure 6.2).

Physiological and behavioral changes in most anadromous juvenile salmonids cue their increased tendency to move downstream. Larger juveniles approach a time when they are ready to move from the system. There is a large but rather inconclusive literature concerning the environmental and biological cues that stimulate migration (Groot and Margolis, 1991),. Several studies have shown a general relationship between increased size of juvenile salmonids and selection of greater water depth and/or current velocity (references in (Dauble et al., 1989), although these studies have generally been made in small streams rather than mainstems of large rivers. Fish in deeper, swifter water of tributary streams would thus be more readily transported downstream passively. When young salmon reach a certain size (or receive other cues, such as day length) they also transform physically (coloration and body shape), physiologically, and behaviorally from the parr stage to the smolt stage that is better adapted to make the transition to saline water, a process referred to as "smoltification" (Hoar, 1976). These transformations include changed swimming behavior and proficiency, lower swimming stamina, and increased buoyancy that also make the fish more likely to be passively transported by currents (Saunders, 1965; Folmar and Dickhoff, 1980; Smith, 1982). In general, smoltification is timed to be completed as fish are near the fresh water-salt water transition. Too long a migration delay after the process begins is believed to cause the fish to miss the "biological window" of optimal physiological condition for the transition (Walters et al., 1978). Nonetheless, the smoltification process is usually identifiable in yearlings from the time they leave their tributary rearing areas.

The concept of migration as mostly passive, taking advantage of downstream displacements by water currents, is initially attractive for fish in the Columbia River Basin. Rutter {1904} was convinced that salmon in the Sacramento River drifted downstream tail first, keeping the head upstream to promote water passing through the gills and for catching food. Hoar {1954} favored the idea of passive migration of sockeye and coho salmon, which he reasoned were carried by currents when their heightened activity at migration time brought them to zones of water movement. Smith (1982) - using experimental observations of coho salmon, supported the idea of fish orienting mostly head-upstream during emigration while drifting seaward. Recent laboratory flume experiments by Nelson et al. (1994) confirmed swimming behavior by chinook salmon underyearlings at about one body length per second (bl/s) heading into the current during downstream displacement. This behavior, in experimental fish taken from migrating populations in McNary pool and McNary and John Day dams throughout the main 4-month migration period, would allow fairly passive displacement. Passive migration has been the predominant view for Atlantic salmon that migrate from Scotland (Thorpe and Morgan 1978; Thorpe et al. 1981) and Maine (Fried et al. 1978; McCleave 1978). Thorpe (1982) reasoned that there should be little biological advantage in a migrant expending scarce energy resources by actively swimming. High water discharge in rivers correlates with downstream movement of juveniles in a variety of fish species (see review by (Jonsson, 1991).

Passive displacement may account for downstream movement, but this scenario seems insufficient for explaining the full migratory behavior of juvenile salmonids. Active downstream movement of sockeye salmon was observed and even attributed to a compass orientation mechanism rather than to simply following currents {Brett and MacKinnon 1955; Groot 1965; Brannon et al. 1981}. Complex behavioral changes both stimulate and maintain behavior (Hoar, 1976). Many migration studies have involved Atlantic salmon, in which response to currents is complex, and a mix of passive and oriented movement {Arnold 1974}. Atlantic salmon studies showed that active swimming is used for a considerable portion of the distance traveled even though it may be a small proportion of the time {Fangstam et al. 1993}. Most studies just cited identified at most 6 to 9 hours of juveniles moving with the current at a speed more or less consistent with current velocity, often at night. There is an active process of transition (spiraling) between daytime feeding and nightime movement. Smith (1982) acknowledged active swimming for only about a third of the time as a possibility in Columbia River salmon smolts. Adams {1995} found that yearling steelhead moved about 50% faster than yearling chinook salmon through Lower Granite Reservoir under the same flow rates, indicating migration mechanisms different from passive drift.

We discuss in more detail below the recent studies of underyearling and yearling salmon migration in the Columbia and Snake rivers that have led us to view migration as more like a spiral than simple linear movement. This view suggests a new ecosystem perspective on migration in relation to salmon restoration, with implications for habitat conditions needed to support resting and feeding as well as active movement.

Diel Migration

There is an abundant literature that supports the conclusion that there is alternating movement and holding by migrating juveniles. The general pattern is for a daily cycle. Northcote (1984), in summarizing research on the mechanisms of fish migration in rivers, states that most downstream movement is not constant but nocturnal except during periods of high turbidity. Jonsson (1991) reviewed the effects of water flow, temperature, and light on fish migration in rivers and noted that many authors have found downstream migrations to occur mainly during darkness (see numerous references cited). When migration is not completed in a single night, as it might be in coastal rivers, the migrants occupy holding areas during daylight (McDonald, 1960; Hartman et al., 1967; Solomon, 1978; Hansen and Jonsson, 1985). These observations have often been confirmed experimentally; see references in (Jonsson, 1991) .

Daily cycles are evident in the Columbia River basin. Mains and Smith (1963) identified diel periodicity in studies of the undammed Snake and Columbia rivers in the 1950s (Figure 6.3). There was a notable diurnal periodicity as all salmonids (chinook yearlings, chinook underyearlings, steelhead, coho, and sockeye) passed John Day Dam in 1986, with most fish caught between sunset and sunrise (Johnsen et al., 1987, Figure 6.4). Although perhaps an artifact of dam passage, the similarity to movement in the undammed reaches studied by Mains and Smith (1982) suggests this is an innate behavior. Laboratory flume studies with fall chinook underyearlings show day-night differences in tendency to be displaced downstream in changing water velocities (Nelson et al., 1994). This was also seen in New Zealand underyearling chinook salmon (Irvine, 1986) indicating a genetic basis for nighttime movement. Also, studies generally have shown that Columbia River basin fish, with the exception of steelhead, migrate over long distances (several days) at a speed significantly slower than the concurrent water travel time (Beeman et al., 1990; Berggren and Filardo, 1993; Buettner and Brimmer, 1993) (Figure 6.5).

Selective drift, in which a fish selects only particular times and water currents (and rests during others) may be important, as it is in tidal waters (Weihs, 1978; Arnold and Cook, 1984; McCleave et al., 1984). Even the supposedly passive migrations of Atlantic salmon cited by Thorpe {1982} do not occur continually throughout 24 h but show cyclic spurts of high activity (Solomon, 1978) and a predominantly nocturnal migration pattern with 87% caught between 2200 and 0200 h (Hesthagen and Garnas, 1986) and several references therein). What happens in the fish's life between times spent drifting or otherwise moving downstream is probably very important to survival.

Surface orientation

Most studies of salmon migration in rivers and reservoirs have indicated a surface orientation during movement. Early studies of passage at dams showed accumulation of fish at the surface in dam forebays and a preference for surface outlets (Andrew and Geen, 1960) {Smith et al. 1968}. The development of fish bypasses in Columbia basin dams was influenced greatly by observations that fish drawn into deep turbine entrances sought to return to the surface through gatewells (Long, 1968; Marquett et al., 1970; Bentley, 1976). Smoltification is accompanied by a transition to more pelagic behavior and surface orientation (Schreck, 1984). Netting of fish in the unimpounded mainstem Snake and Columbia rivers showed a predominantly surface orientation (Mains and Smith, 1963; Dauble et al., 1989) as did studies in Snake river reservoirs (Smith, 1982).

The natural surface orientation of juvenile salmonids, especially at dam forebays, is presumed to be a principal reason why a surface flow bypass at Wells Dam on the mid-Columbia River has been so successful at passing fish (Johnson et al., 1992) (see additional discussion in Chapter 7). The surface bypass is in the vertical window in which the fish normally migrate. It is demonstrably better to design fish guidance that accommodates the normal behavior of fish rather than attempts to subvert it. Attempts are now underway to both better define the reasons why the Wells situation is so successful and to adapt the key features of the Wells bypass to other dams in the basin.

Use of flow dynamics in migration

There is increasing evidence that juvenile salmon make use of certain features of flow hydrodynamics in their migration. For example, accelerating flows appear to foster fish movement. Wild and hatchery yearling chinook salmon and steelhead at the Salmon River and

Snake River traps and steelhead at the Clearwater trap show increases in sample counts during and shortly after flow increases (visual inspection of graphs) (Fish Passage Center, 1994; Buettner and Brimmer, 1995). Similarly, the number of yearling smolts passing Prosser Dam on the Yakima River was positively associated with both flow and change in flow when flows increased (Mundy, In press).

Our examination of the fluid dynamics literature for rivers suggests many features that are probably used by migrating salmonids to assist their migration (Appendix D), although the advanced development of hydrodynamic theories and practices has not been matched by fish behavior studies. These features include surges or stage waves, turbulent bursts, and vortices. The somewhat confusing literature on juvenile salmonid responses to flow (rheotaxis) might be clarified if the focus of attention were to be directed to the fluid dynamic structure of flows as orienting mechanisms. The effectiveness of flow baffles for guiding fish at certain spill sites (e.g., Wells Dam) are likely the result of inducing features of fluid flow that are naturally important for fish migration. Flow structure in reservoirs and dams forebays might be modified in ways that simulates the normative river in order to guide migrants.

SPIRALING AS A MODEL FOR JUVENILE MIGRATION

Two views of the mainstem as juvenile salmon habitat can be distinguished for purposes of clarifying the normative river environment and guiding our attempts to meet fish needs. One is a continual, linear downstream movement with water flow (called *constant flushing*, for simplicity) in which (as in current thinking) the downstream migrating salmon juveniles leave their rearing areas in headwaters and hitch a ride on the high water volumes and velocities during the spring freshet and are rushed out of the basin as if in a pipe. The other is *spiraling*, in which fish intersperse flushing behavior with stops for rest (Figure 6.2). In spiraling behavior the juvenile emigrants positive behavior alternately hitch a ride on the freshet and stay in the river ecosystem using portions of the system other than the fast-flowing main channel for functions important to survival (Figure 6.2). Migratory spiraling is analogous to nutrient spiraling in streams, a concept that has clarified the dynamic "cycles" of nutrient uptake and release by components of stream ecosystems, while the nutrients gradually wash downstream (Newbold et al., 1981; Newbold et al., 1982; Elwood et al., 1983; Newbold et al., 1983; Mulholland et al., 1985) (Figure 6.6). In the schematic views of cycling and spiraling, adapted from Elwood {1983}, Figure 6.6, note the following features; (a) Cycling of a nutrient or material in a closed system, such as an aquarium; (b) cycling in an open system with input and output; (c) spiraling in an open system such as a stream with downstream transport (the dashed vertical lines represent arbitrary operational boundaries of stream reaches); (d) view of a stream showing components of a unit spiral (S) including the longitudinal distance in moving water (the flush phase for a migrating fish; Sw) and the distance of relative immobilization (in particulate material, if a nutrient, or in holding habitats, if a fish; Sp); and (e) fluxes in water (Fw), in the particulate or holding compartment (Fp), and exchange fluxes from water to the holding area (Rw) and from holding area to water (Rp). Because salmon stocks have a multitude of life-history strategies, either innate to the stock or flexible depending on environmental conditions, the contrast between constant flushing and spiraling modes of migration is not absolute.

The concept of migratory spiraling in juvenile salmon is not new, except in name. Juvenile chinook salmon in some rivers were seen as having a slow rearing migration through mainstems rather than distinct rearing and migration periods (Beauchamp et al., 1983). The primitive condition for salmon was believed to be one of an essentially constant flow of juveniles moving downstream with the larger juveniles having a greater tendency than smaller juveniles to move (Nicholas and Hankin, 1989; Lichatowich and Mobrand, 1995). But the recent drastic decline in numbers of fish, especially in populations from the Snake River, indicates that specific evidence and detailed information on migratory behavior is needed for the Columbia and Snake rivers if appropriate mitigation measures are to be adopted.

The tendency to flush or spiral through the mainstem differs between the two main life-history types, ocean and stream (Figure 6.7). Thus, their needs for habitat differ somewhat. Both types begin life in a tight spiral, that is, they spend much time in feeding and resting and little in downstream displacement. Ocean-type fish both feed and rear in the mainstem; stream-type fish carry out these activities it in tributaries. Ocean-type fish gradually lengthen the spiral (i.e., spend less time holding and feeding) as they move down the mainstem, and lengthen it markedly only when they have reached the estuary (or attained a certain size; (Reimers, 1973)). Stream-type fish, however, change quickly from a short to long spiral as spring freshets arrive at their first (usually) anniversary. The particular value of a spiraling model is to recognize that the stream-type juveniles do spiral, require habitat for resting and feeding, and are not just continually being flushed downstream.

The concept of spiraling highlights that there is more than one feature of the normative mainstem river to which salmonid juveniles are dependent. The common focus is on the main channel, or thalweg, in which the young salmon are believed to be transported in some fashion with water currents. The often overlooked features are those needed for the holding phases, such as slack currents of backeddies or flooded riparian zones, each with food resources available. These are generally most prevalent in alluvial reaches, although even constrained reaches (canyons) have usually had backeddies and tributary mouths for shelter. Corridors and transition zones need to be available between appropriate holding areas and the main channel, so that fish can make regular (usually at least twice daily) transitions between them. Thus, there is a need for rearing habitat in the mainstem, not just water flow. Mitigation is best when it accommodates the full range of needs, not just those during downstream displacement.

The spiraling pattern of migration and the appropriate habitats for each life-history type are evident in the scientific literature on juvenile salmon migration. We discuss them by life-history type and species.

Underyearling Chinook Salmon Migrants

At present, the main ocean-type salmon in the mainstem Snake and Columbia rivers is the fall chinook salmon (Healey, 1991), although there may have been other stocks in the past (Lichatowich and Mobrand, 1995). Some downstream-migrating underyearling chinook salmon from the upper Columbia River are derived from the summer chinook runs (Park, 1969). Although there were once populations spawning in mainstem gravel bars throughout the system (Fulton, 1968), the remaining mainstem-spawning populations are now in the mid-Columbia at the undammed Hanford site (most recently documented by (Dauble and Watson, 1990) and in the free-flowing Snake and Clearwater rivers between Lower Granite Reservoir and migration-blocking storage dams (Hells Canyon Dam on the Snake River and Dworshak Dam on the Clearwater River) (documented by Garcia et al. (1995). Before Brownlee and Hells Canyon dams were constructed beginning in the late 1950s, fall chinook salmon spawned in the mainstem Snake River well above the dam sites (Krcma and Raleigh, 1970). Small numbers of fall chinook salmon spawn in the mainstem Columbia River upstream of Hanford and Priest Rapids Dam in the tailraces of Wanapum and Rock Island dams (Horner and Bjornn, 1979; Dauble et al., 1989), other upstream Mid-Columbia dams (M. Erho, personal comm.) and there are small populations in main channels of some lower Columbia River tributaries. It has recently been recognized that there are also small groups that spawn in tailwaters of Snake River dams, particularly below Lower Granite and Little Goose dams (Garcia et al., 1995).

The actual or probable historical distribution of fall chinook subyearlings in space and time during migration can be reconstructed from several sources. Early accounts (Rich, 1920) quantitative observations at unimpounded Hanford and Snake River sites (Mains and Smith, 1963; Dauble et al., 1989), shoreline seining surveys in unimpounded reaches (Becker, 1973; Dauble et al., 1980; Key et al., 1994; Key et al., 1995), and from the estuary below all dams (Dawley, 1986) provide useful information on unimpounded conditions. Spatial and temporal distribution in the impounded Snake River is available from Smith (1974) Curet (1993) and Key et al., (1994; 1995) and in the impounded Columbia River at McNary Reservoir (Key et al., 1994; 1995) and John Day Reservoir (Giorgi et al., 1990).

Migration in rivers

Before dams, subyearling chinook salmon used the lower river throughout the summer for a combination of rearing and seaward migration (Rich, 1920). Even after dams were built, subyearling chinook salmon migrated through the reservoirs at relatively slow migration rates through the summer and into autumn (Raymond et al., 1975; Johnsen et al., 1987) {Miller and Sims 1984; Giorgi et al. 1994). There has been concern over the demonstration that the time of seaward migration has been lengthened by the effects of lower water velocities in reservoirs than found in unimpounded river conditions (Raymond, 1968; Park, 1969; Raymond, 1979). The lengthened migration times coincide with general population declines of Snake River fish. Temporal patterns of counts of fish passing dams has provided most of this information; there has been little investigation of what behavioral changes may have occurred to the fish in the reservoirs during the delay. The importance of this delay for survival is unclear. Giorgi et al. (1990) have attempted to consolidate some of this information for John Day Reservoir.

The Hanford site, where the fall chinook salmon population is successful, is closest to being a normative river of any sites on the mainstem. This site is characterized by broad gravel spawning bars primarily about 5-12 km (3.1-7.5 miles) and 40 km (25 miles) downstream of Priest Rapids Dam that are occupied in October-March by thousands of salmon redds (Dauble and Watson, 1990). Annual spawning surveys were conducted by D. Watson beginning in the 1940s. Bauersfeld (1978) and Chapman et al. (1983) have characterized the effects of gravel size and flow regimes on the most densely occupied spawning area at Vernita Bar. These redds generally lie upriver of a 48-km (30-mile) zone of islands, side channels, backwaters, and sloughs that extends to the city of Richland (especially the White Bluffs, F-Area, and Hanford townsite areas). Because of the great importance of these spawning areas, a long-term (years 1988-2005) Vernita Bar Settlement Agreement was approved by the Federal Energy Regulatory Commission (FERC) in December 1988 for flow regulation to maximize spawning success.

The use of shoreline habitats by juveniles is well demonstrated at Hanford. Chinook salmon fry drift downstream throughout the river cross section in March-May after they emerge from redds (Dauble et al., 1989; Key et al., 1994; 1995) and move to shoreline areas where they begin to rear. Young chinook parr occupy large expanses of shoreline areas of reduced current velocity (Dauble et al., 1989; Key et al., 1995) where they feed primarily on emerging chironomids and terrestrial insects (Becker and Coutant, 1970; Becker, 1973; Dauble et al., 1980). Shoreline or bank aggregations of early chinook salmon juveniles have been observed in other systems, with deeper water used as fish grow, e.g., Big Qualicum River, BC; (Lister and Genoe, 1970). Production of aquatic chironomids and drop of terrestrial insects is probably facilitated in the Columbia River basin by rising waters of the freshet which inundate large areas of gently sloping cobble bars, sandy shores, and vegetated riparian zones of sloughs and high-water channels (see habitat Chapter 5). Because laboratory studies have shown that chinook salmon feeding rates were highest in moderate turbidities and low in clear water (Gregory and Northcote, 1993), the turbidity of freshets was probably also important for rearing.

There is a daily cycle of movement. The chronology of subyearling chinook movement through the nearly 90-km Hanford reach can be deduced from catches in fyke nets suspended at different depths across the river cross section and shoreline seining and electrofishing (Dauble et al., 1989). Fish appear to move downstream gradually in a diurnal cycle, feeding in shallows in the daytime and moving downstream in deeper, swifter water at night (peak fyke-net catches in the channel occur at 2200 to 2400 h with fish distributed throughout the water column, particularly during the later phases of rearing and migration; (Dauble et al., 1989). Fish collections identified an activity pattern that included migration, feeding, and resting periods. Much of the pattern seems to be daily, although an individual fish could spend more than one day in a shoreline area. This rearing-migration spiral both moves the fish downstream (at night) and provides ample food for sustained growth (daytime feeding). Because the Hanford reach is undammed, the pattern of juvenile fall chinook salmon distribution may approximate the historical condition.

Hatchery-released fall chinook salmon smolts may be less oriented to shorelines than are wild fish. They were less abundant in nearshore areas than were wild fish in studies at Hanford (Dauble et al., 1989). These artificially reared fish may be less characterized by a migratory spiral, at least in the initial weeks following release from Priest Rapids hatchery just upstream of the Hanford reach. This behavioral change may be significant in determining relative survival during emigration.

In the unimpounded Snake River above Lewiston, Idaho, chinook salmon spawn in scattered redds at rapids between river kilometer 238.6 (head of Lower Granite Reservoir) and 396.6 (Hells Canyon Cam) and in the tailwaters of at least Lower Monumental Dam (Garcia et al. 1994, Garcia, 1995 #16320]. They also spawn in the lower Clearwater River. There is more suitable spawning area than spawning activity (Connor et al. 1994). Snake River fall chinook salmon emerge from the gravel later than at Hanford, with peaks occurring in late April to late May (Connor et al., 1995; Connor et al., 1995). They rear in nearshore areas from mid -March through mid-July both here and in the Clearwater River, depending on emergence dates, with a mid-May to mid-June peak. Fish appear to concentrate in particular shoreline areas and stay there for some time, based on high percentages of recaptures of tagged fish (Connor et al., 1995) . As water warms and flows begin to decline, rearing fish move downstream. Since 1991, flow augmentation from Hells Canyon Dam has been used to assist these fish in moving past Lower Granite Dam, which is a summer event. Migration past Lower Granite Dam of PIT-tagged fish has sometimes been protracted (into early September) but sometimes truncated by late July. These studies, which are continuing, have not yet sought daily patterns in movement.

A daily pattern of downstream migration of underyearlings was documented in the Snake River before it was impounded. Mains and Smith (1963) observed a pattern that was similar to that at the Hanford reach. Most migration was at night, although there seemed to be some underyearlings moving downstream in the main channel at all times of day during their Snake River study. They did not examine diurnal patterns of horizontal distribution, but noted high overall catches near shore, where shoreline proximity, not velocity, was stated as the main factor. Daily patterns were also evident in catches of fall chinook underyearlings emigrating downstream in the Snake River as it entered Brownlee Reservoir in the 1960s, before this population was extirpated (Krcma and Raleigh, 1970). This stock migrated mostly from sunrise to 10 am and from 3-7 pm. Because this timing contrasts with mostly nighttime migration elsewhere, there once might have been stock differences in diurnal timing.

Migration in the freshwater estuary

The freshwater estuary can also provide information on migration in an unimpounded reach. A pattern of spatial distribution of fall chinook salmon subyearlings somewhat similar to that at Hanford was seen in the tidal freshwater Columbia River estuary below the most downstream dam, where conditions more nearly approximate the pre-dam condition (Dawley, 1986; Ledgerwood et al., 1990). Here, the underyearlings from both upriver sources and lower river tributaries were most abundant May through September, when beach seines were the most effective gear for capturing juveniles (indicating shoreline orientation) (Dawley, 1986). Dawley et al. (1986) obtained most beach seine catches (90%) during daylight hours with peaks during early morning and at dusk. Subyearlings caught in pelagic (open-water) habitats were larger than those collected in intertidal areas, were in the top 3 m of the water column, and had fewer food items in their stomachs, suggesting active emigration (Dawley, 1986). These larger fish tended to be from upriver sources, which suggested they had completed their rearing. Generally, feeding was most intense in the shallow, intertidal areas {McCabe et al. 1986}. Underyearlings in shore areas tended to move gradually downstream as they fed in the daytime (Dawley, 1986). Ledgerwood et al. (1990) also found a clear daily pattern of abundance of subyearlings in beach seine catches, with a peak about 1.5 hr after sunrise followed by steady catches during daylight and a minor peak 1.5 hr before sunset. Night catches along the shoreline were low. Purse seine catches in the river channel peaked just before sunrise and decreased throughout the day. Generally low night catches in the channel suggested that there was no pronounced nighttime movement.

Migration timing in the upper estuary and the sizes of migrants indicates a migration pattern that is not characterized by constant flushing by high flows. The annual pattern of movement of underyearlings seen by Dawley et al. (1986), in which few fish moved through the area as early as June and many moved in August, suggested that these fish were not migrating with high early-summer flows. Marked hatchery releases in the upper estuary summarized by Dawley et al. (1986) showed no relationship between rate of downstream migration and river flows, despite an earlier migration of upriver subyearlings in high water years than in low water years. There was, however, an increased rate of movement with increasing fish size. The evidence supports fish remaining in the river until reaching 7-8 cm length before entering the estuary. The trend toward later timing of migrants in the estuary (Dawley, 1986) might be partially explained by a slower growth rate in the river (because of less abundant preferred food and higher than optimum temperatures) rather than changes in river velocity.

For each of these estuary studies, a spiral model of daytime shoreline feeding and night (or twilight) migration would seem to fit the distribution most accurately (perhaps with less night-time movement in the estuary than in upriver sites, as consistent with longer estuarine residence shown by Reimers (1973) and slower estuarine than riverine movement shown by Dawley et al. (1986). River flow and velocity seem to be little involved.

Migration in Reservoirs

Early studies at dams showed that more underyearling chinook salmon moved through the dams at night than in the day. In research using special bypasses at Bonneville Dam, Gauley et al. (Gauley et al., 1958) found significantly more underyearling chinook moving from 6 pm to 6 am in 4 out of 5 seasons--1946, 1949, 1950, and 1953. Diel movement of migrating underyearling chinook salmon in the turbine intakes at The Dalles Dam in 1960 was shown by Long (1968) where the passage at night was 60-70 percent of the daily total. The clear diurnal pattern for underyearlings was evident at John Day Dam in 1986 in all weeks from mid May to the end of October, although there were always some fish moving in the day (Johnson and Wright, 1987). Movement of most fish at night implies a more stationary state for them in the daytime, and thus a spiraling behavior.

Studies in Snake River impoundments show spiraling behavioral patterns for underyearlings under reservoir conditions. Snake River fall chinook were captured in impounded waters upstream from Lower Monumental Dam during emigration {Smith 1986}. Migrating fish were sampled by gill nets set in relatively shallow (48 feet deep) and deep (96 feet) areas of the reservoir (but there was no sampling along shore). Most chinook (92%) were taken at night in the upper 12 feet of the central, deep portion of the reservoir (80% of these in the upper 6 feet). Few were collected in the reservoir during the day in either the deep or shallow reservoir station, suggesting (not tested by the author) that the chinook salmon were elsewhere, most likely near the unsampled shoreline. These data seem to indicate migration with a daily spiral, with high abundance in upper pelagic waters of the reservoir at night (for active migration) and resting or feeding in the shoreline area not sampled in the daytime. This pattern would be consistent with observations at Hanford.

A shoreline distribution of subyearling juvenile chinook in the impounded Snake River in daytime was confirmed over several years of shoreline seining (agency reports 1986-1993 by D. H. Bennett, Idaho State University) and through three years of shoreline seining and open water trawling of Lower Granite and Little Goose reservoirs by Curet (1993). Slow-velocity, sandy shores were preferred and artificial shorelines of rock rip-rap were strongly avoided. Curet observed that fish became more pelagically oriented during the day once shoreline temperatures exceeded 18-20°C. Thus, diurnal warming of nearshore shallows could cause some change in onshore-offshore movements in reservoirs during the later spring and summer migration times. Curet (1993) linked these high shoreline temperatures to reduced feeding and higher than normal metabolic demands. He concluded that subyearling chinook appear to not just pass quickly through, but to use the shoreline and open water areas of the reservoirs for rearing before migrating farther downriver.

The Snake River and Hanford fish both share the same emigration path in reservoirs of the Columbia River below their confluence. Sims and Miller (1981) concluded that in John Day Reservoir neither the rate of downstream movement nor residence time of subyearling fall chinook salmon was influenced by river velocities. This was corroborated by Miller and Giorgi (1987) and Giorgi et al. (1990) for the early 1980s but not by Berggren and Filardo (1993) (Figure 4), who included later years that have been dominated by especially low flows (<160,000 cfs). At all flows in the longer data set, fish moved downstream much more slowly than did water (factor of two). Rondorf et al. (Beeman et al., 1990) concluded from study of juvenile feeding in the McNary pool (including a riverine section below Hanford, an intermediate section below the Snake River confluence, and the dam forebay) that the river and reservoirs are not used as a conduit for rapid migration, but that there is summer rearing and gradual downstream movement in the reservoir system in much the same way as these juveniles used the free-flowing Columbia River. The relationship between flow and migration travel time in a reservoir reported by Berggren and Filardo (1993) might appear at very low flows when fish have essentially no current to orient to in the nighttime hours of normal downstream displacement.

Subyearling chinook salmon did not exhibit consistent downstream movement indicative of continual, directed seaward migration in studies of John Day Reservoir in the early 1980s (Giorgi et al., 1986) A majority of fish captured by purse seine, marked, and released at transects throughout the reservoir were recaptured at or upstream from the site of release. They were not consistently displaced passively downstream via the current. Although Giorgi et al. felt that their observed upstream movement was not consistent with the tail-first drift model of migration, there could be more consistency than was appreciated. A scenario can be visualized in which nighttime "drift" in the pelagic zone, alternated with shoreline feeding in the day, actually moves the fish upstream as it weakly swims against a non-existent (or very slow) current. With no orientation other than suspended objects nearby, the fish may be behaving quite normally. Flume experiments by Nelson et al. (1994) showed daytime swimming behavior could exceed the test water velocity (especially in August) thus displacing fish upstream.

Key et al. (1994; 1995) found the shoreline orientation of subyearling juvenile chinook salmon in the daytime and low numbers there at night to occur also in a slough habitat of McNary Reservoir, just downstream of the Snake-Columbia confluence. At this point in time and space the fish had transformed to the smolt stage. They concluded that the shoreline orientation was more related to fish behavior than to either fish size or environmental conditions (temperatures were not sufficiently high to force fish away from shallows). Their analysis of fish distribution led them to hypothesize that subyearlings in the reservoir situation now move to the bottom in intermediate depths (rather than to the channel) where they become torpid during the night. This hypothesis has not been tested by field sampling at night.

Experimental research

Experimental results on subyearling swimming behavior by Nelson et al. (1994) were more complex than could be explained by continual, passive or directed movement. Orientation into the current (positive rheotaxis) was the most common observation. As water velocities increased, the number of fish exhibiting positive rheotaxis increased. At slower velocities in the 5 to 50 cm/s range studied, fish swam upstream at rates comparable to the experimental water velocity thus maintaining their position in the flume. As velocities were increased, a threshold velocity of 25 to 40 cm/s was passed at which fish reduced their swimming to speeds of 0.5-1.5 bl/s and they were displaced downstream. This displacement was not "passive", as even during times of displacement experimental fish were never displaced downstream as far as they would have been by drifting with the current. During all trials, fish rarely drifted without locomotor control. These experimental results are consistent with a holding behavior in low flows (typical of the shoreline feeding part of a spiral) and controlled downstream displacement at high flows (consistent with the downstream movement part of a spiral). The experiments also showed that fish tended to swim slower at night, which is the normal time of downstream displacement. This change in threshold for displacement could provide the necessary twice-daily transitions for a spiral migration. The authors cite convincing literature to support a behavioral explanation for these observations rather than one based on fatigue (fish would not have become physiologically fatigued by the velocities and length of time exposed in their tests, based on published studies of salmon fatigue).

There were also hints of other relevant behaviors not yet fully explored in the tests by Nelson et al. (1994). There was one day of directed downstream swimming in late May during the normal peak emigration and a selection of highest velocities in the flume for downstream displacement during dates of most active emigration. The authors propose an increased "disposition to emigrate" during this time that would coincide with a change to lower threshold water velocities for a fish to reduce its swimming speed to the minimum orientation velocity of about 1 bl/s. Perhaps the migratory spiral for underyearlings has a seasonal change in periodicity, with a behavioral basis for a longer spiraling length at the times (daylengths?) of normal peak river flows.

Contrasts in success: Hanford and Snake River stocks

The different population successes of fall chinook salmon in the Snake River and the Columbia River at Hanford provide useful contrasts that may be related to rearing and migration habitats. The Hanford stock flourishes (Dauble and Watson, 1990) whereas the Snake River stock is listed as endangered (National Marine Fisheries Service, 1995) Understanding differences in the habitats and behaviors that promote survivorship of these two stocks may be critical for stemming the decline of Snake River salmon. These stocks share habitat from the confluence to the ocean but differ in their upstream habitats. They may also differ in locations of their ocean residence, which could affect overall population success (A. Giorgi, personal communication).

The relative success of the two stocks of fall chinook seems consistent with availability of suitable mainstem habitats for a spiraling migration. Hanford stocks can spiral daily to shorelines with abundant insect food in the riparian vegetation and flooded cobble beaches. Snake River fish, soon after entering Lower Granite Reservoir, move to reservoir shorelines characterized by eroding soil banks or rock rip-rap, both of which would be poor habitats for producing abundant insect prey (Janecek and Moog, 1994). By late May or early June, shoreline waters in the Snake River reservoirs are often too warm and the feeding portion of a spiral has to occur in pelagic waters where preferred food is scarce. Pelagic Cladocera, not shoreline chironomids, were the dominant food item, even though chironomids provided the greatest caloric value (Rondorf et al., 1990). These authors indicated a shift in diet by subyearlings to smaller, less preferred Daphnia species in embayments of Lake Wallula (behind McNary dam) was the result of their higher densities and ease of capture in the pelagic environment. Curet (1993) demonstrated that juvenile fall chinook in Lower Granite and Little Goose reservoirs were not obtaining sufficient food to account for much more than basal metabolism (7% greater than estimated maintenance ration), which could be a major factor in their lack of population success.

The shoreline-feeding portion of the migration spiral may be most critical for long-term survival in the early stages of rearing and migration of underyearling chinook salmon. It is at this time when the Snake River and Hanford stocks differ most. It could be argued that superior growth and energetic reserves of Hanford fish acquired in the high quality riverine habitat of the free-flowing reach just below the spawning areas is enough to carry them through the poorer food resources of downstream reservoirs whereas the Snake River underyearlings are impoverished nearly from the start by barren shorelines of Lower Granite and Little Goose reservoirs. Even though underyearlings are well fed and have grown rapidly in the reach below Hells Canyon Dam (Rondorf, personal communication), they may not endure the poor migration habitats of the Snake River reservoirs.

As a spiraling migration behavior of underyearling chinook is better understood in relation to smoltification, parts of McNary Reservoir may be found to be as critically important to survival of the Snake River stock as the condition of the lower Snake River impoundments. From the mouth of the Snake River to nearly the Walla Walla River (a distance of about 14.5 km) the Snake River side of the Columbia River is a series of sloughs and wetlands not shared by the opposite shore (Asherin and Claar, 1976). These wetlands are probably the combined result of an ancient Snake River channel (Burbank Slough) and sediments from the present Snake River confluence that have been distributed in two major sets of bars down the Columbia River. Key et al. (1995) conducted diurnal sampling of underyearling chinook salmon in Villard Slough in this complex and much of the remainder of sampling appears to have been carried out in this reach. Already-smolted juveniles from the Snake River appear to be drawn into these long slough areas to feed during the day, but are unable to return to the channel at night to resume downstream drift. One can speculate that this trapping on the Snake River side (but not on the side occupied by flows from the upper Columbia River), in combination with the advanced state of smolt development of Snake River emigrants, could be responsible for a disproportionate loss of Snake River fall chinook at this point compared to the Hanford stock coming down the Columbia channel at the same time.

Snake River fall chinook may have evolved to partially compensate for naturally poor feeding habitat during emigration through the lower Snake River mainstem. Taylor (1990) in his review of 160 chinook salmon populations ranging from California to Alaska, Kamchatka and New Zealand, indicated that increased migration distance selects for larger size at seaward migration, due to increased metabolic demands of migration. Recent research has, indeed, found the Snake River underyearlings in the unimpounded reach between Lower Granite Reservoir and Hells Canyon Dam to be larger than Hanford fish at comparable dates despite emerging later from the gravel and having more distance yet to travel (Key et al., 1994). How much of the dissimilarity between stocks in their emergence timing and early size could be due to temperature differences has not been determined (Hells Canyon Dam discharges are warmer in winter and cooler in spring and summer than temperatures at Hanford). But despite this apparent growth rate and size advantage, the Snake River stock now does poorly.

Smoltification effects

As Giorgi et al. (1990) pointed out, the effects of smoltification on migratory behavior of underyearling chinook salmon is not clear. Smolt development would come into play with advancing time and increasing age of the juveniles as they rear/migrate. Smoltification could be cued by fish size, temperature, photoperiod, or other factors. Zaugg (1982) cited examples that suggested smolt development might be an important process governing migratory behavior in underyearling chinook salmon. Ewing et al. (1980), however, showed that the enzymatic signal of smoltification (ATP-ase) was not consistently found in seaward migrants. The state of smoltification is unclear in underyearlings passing through the mainstem. Fish in the Snake River show signs of smolting and at McNary Reservoir most have smolted (Key et al., 1994); fish at John Day Dam further downstream had not (Miller and Giorgi, 1987), although the years were different. Both smoltification and mortality are occurring simultaneously, and the mortality rates of presmolts and smolts could differ, leaving a skewed population downstream. In principle, a spiral migration behavior might tend toward increasing spiral lengths with time, i.e., more time in downstream displacement and less in feeding, as the fish aged. Smoltification might trigger an abrupt shift to longer spiral lengths in the freshwater mainstem. Observations by Key et al. (1994; 1995) that underyearlings found in a slough of McNary reservoir just downstream of the Snake River confluence (Snake River side) were already smolts but still showed preference for daytime occupancy of shoreline habitats (and did not appear to find the channel at night for migration) may have important implications for their survival.

Risks of a constant flushing model for migration of underyearling migrants

There may be risks for underyearling salmon associated with management actions based on a constant flushing model. Because underyearlings spend a large amount of time in shoreline habitats for feeding, management alternatives for the mainstem that focus on increasing water velocities in the main channel through reservoir drawdowns or flow augmentation need careful evaluation. Lowering of reservoir elevations in the spring freshet season is one of the principal methods proposed for attaining a high water velocities thought to be conducive to constant flushing in the mainstem Snake and Columbia rivers {NPPC 1994} (National Marine Fisheries Service, 1995). The logic is that a smaller volume of water in a reservoir would translate to a more rapid movement of a unit volume of water through it, including contained fish. Temporary reservoir drawdowns to attain the presumed benefits of spring flows for constant flushing behavior in yearling emigrant salmon might diminish needed habitat for underyearling salmon.

Because the critical habitat for underyearling survival most likely is flooded shorelines, complex backchannels, and other vegetated habitats that are productive of invertebrate food, temporary seasonal drawdowns could be counterproductive. As an experimental drawdown of Lower Granite Reservoir in 1992 showed, drawdowns created long expanses of muddy shorelines that would have little or no food available for underyearling salmon during the shoreward portion of their daily migratory spiral. Moderate flooding of a stable, vegetated riparian shoreline is more compatible with the fall chinook salmon's spiraling migration. Permanent drawdown would, however allow riparian vegetation to develop and seasonal flooding to enhance the river's productivity during emigrations.

High levels of flow would appear to reduce food availability for juvenile fall chinook in the present reservoir system. Rondorf et al. (1990) observed a reduction of the present main food item, pelagic cladocerans, in midreservoir and dam forebay stations during June, that coincided with peak seasonal flows. High flows apparently flushed away these planktonic food items, which were the main replacements for the insects (midges and caddisflies) eaten in the riverine section below Hanford.

Spilling water at dams to help emigrants move through the reservoirs and past the dams, thereby avoiding the damaging effects of turbines, can be managed better with an understanding of the spiraling behavior of fall chinook salmon. With most migration occurring at night, spills would have their maximum effectiveness when carried out during those daily migration times (although passage via spill at some dams has occurred throughout the day). Because juvenile salmon migrate near the surface, spill of water near the surface is a more natural migration route. Generation of supersaturated gases by the spills (see below) would be restricted to only part of the day and thus supersaturate the whole river to a lesser extent than would continuous spills.

These are but suggestions of points to be evaluated as management options are considered. We believe the detailed migration behavior is very relevant to selecting the most effective measures. As is shown below, the migration behavior and needed habitats for yearling chinook salmon differ.

Information needs for underyearlings

The spiraling nature of migrations by underyearling fall chinook, with low importance of river velocity for survival, seems established without much question. The following areas need attention:

- The secondary effects of flow differences on nearshore habitat conditions of present-day reservoirs (temperature, flow, food production) need to be measured and evaluated. These factors may be more important to fish survival than the flow (velocity) itself, and may be amenable to other solutions.

- The effects of shoreline modifications along reservoirs (rip-rap, erosion, permanent sloughs) compared to the riverine condition need to be evaluated. Because rip-rap is known to be a poor producer of salmonid food, its predominance along the reservoir system may have a major effect on underyearling survival. Shoreline erosion in other reaches may limit productivity in these areas. Permanent sloughs at the margins of reservoirs may warm the water, harbor predators, and restrict the natural onshore-offshore spiraling migration of underyearlings.

- There is considerable uncertainty about the effects on underyearlings of changes in river flows designed to aid yearling migrants, principally spring chinook salmon and steelhead. Effects of augmented flows and/or reservoir drawdowns on nearshore habitats important to underyearlings need to be analyzed, for aid to yearlings may involve a detriment to underyearlings.

- The effects of augmented flows on rearing fall chinook in unnaturally cold reaches of the Snake and Clearwater rivers in spring needs study. This should include not only rearing (probably delayed) and dispersion (premature emigration) in the reservoir tailwater areas, but in the reaches of lower river to which the fish are dispersed and where they encounter overly warm water in summer.

- Surface orientation and a tendency to follow flows during migration suggest that underyearlings may be naturally susceptible to guidance to spills and surface fish bypasses, which deserve more study at experimental installations through the basin. This work is being accomplished under PUD and Corps of Engineers funding (see Chapter VII and associated appendices).

Yearling Chinook Salmon Migrants

Most spring and summer chinook salmon from the Snake River drainage are considered to be of the stream type, migrating to sea rapidly after one year in freshwater. However, Curet (1993) notes personal observations by Idaho Department of Fish and Game personnel that some subyearlings in the Snake River are of spring chinook origin and Mattson (1962) observed three distinct migrations in Willamette River spring chinook in the 1940s--in their first spring and summer as underyearlings, in fall as a migration of underyearlings at time of heavy fall rains, and in spring as a movement of yearlings. There are suggestions that some stocks of spring chinook now extirpated had primarily underyearling emigrations (Lichatowich, personal communication). Summer chinook salmon in the mid-Columbia above Hanford are allied with the fall runs rather than with the spring runs, as in the Snake River system. Whereas underyearling chinook salmon exhibit a slow downstream migration that we have seen is composed of downstream movement interspersed with shoreline feeding on a daily cycle (spiraling migration with a short spiraling length), the yearlings are commonly thought to have a very different migratory pattern, consisting of a rapid emigration of fish from the river during the spring freshet which is consistent with flushing behavior.

Evidence for flushing.

In the Snake River, there are several tributaries with productive wild spring chinook salmon populations, although populations are in decline and the stock is listed as endangered. One of the most far-removed tributaries from the ocean is the upper Salmon River in Idaho, which is still a major natural salmon production area (Kiefer and Lockhart, 1995). Before construction of Brownlee and Hells Canyon dams beginning in the late 1950s, spring chinook salmon spawned in Eagle Creek and the Weiser River, both upstream tributaries to the Snake River (Krcma and Raleigh, 1970). In the mid-Columbia River, a large number of yearling juveniles come from upper Columbia River hatcheries (Dauble et al., 1989). Spring chinook salmon also occur in the Willamette and Yakima rivers. Yearlings are normally in the process of smoltification as they migrate downstream. This process of physiological change begins 20-30 days after river migration begins (Beeman et al., 1990). Decreased swimming performance (and greater ease of passive movement by currents) during smoltification seems to be a part of their emigration strategy (Smith, 1982).

Wild/natural spring chinook from Idaho move rapidly downstream with spring flow in the unimpounded tributaries. In all years studied (1988-1992) by Kiefer and Lockhart (1995), wild spring chinook salmon smolts from the upper Salmon River were stimulated to migrate in spring by increases in discharge (often storm events) and their peak of arrival at Lower Granite Dam coincided with peaks in flow there. Such results suggest a flushing mechanism. Similar results were obtained for spring salmon smolts tagged in the Middle Fork Salmon River (Matthews et al., 1992). There was also a downstream movement of parr in autumn stimulated by rapid declines in temperature (Kiefer and Lockhart, 1995). Higher percentages of parr emigrated from higher elevations (harsher climate). Natural migration in Snake River tributaries must be somewhat slower than water flow, otherwise smolts stimulated to emigrate at first increase in discharge would not arrive at the first mainstem dam on the Snake River at peak flow (Kiefer and Lockhart, 1995).

Similarly rapid emigration of wild yearling smolts was observed between an outmigrant trap on the Salmon river and either a Snake River trap at Lewiston or Lower Granite Dam in 1993 (Buettner and Brimmer, 1995). A two-fold increase in discharge increased migration rate to Lower Granite Dam by 5.2 times. Hatchery and wild chinook were shown to be capable of traveling between the Salmon River and Snake River traps (164 km) in 24 to 30 hours.

Telemetry studies by Schreck et al. (1995) showed clear periods of flushing and directed downstream swimming. A majority of fish at these times moved at rates faster than measured water velocities, particularly in two years when the radiotelemetry was conducted during prominent high-water freshets. When flows were low or declining, fish usually moved more slowly than the water. Many fish moved uniformly as a group, although the lead fish and the order of the others changed numerous times, suggesting differing lengths of time spent in resting and feeding. Some fish migrated considerably more slowly than the majority, remaining in the upper river for considerable lengths of time following tagging and release.

Migration rates varied with water velocities (Schreck et al., 1995). This occurred along the Willamette River as fish generally moved more rapidly in the upstream zones of more rapid water flow. They also moved more rapidly in times of high flow than in times of lower flow in any one year. During non-freshet spring periods (3 of 5 years studied), fish moved more slowly than the water over 24-h periods. High and rising flows, however, appeared to stimulate a emigration of fish from the river in a manner consistent with flushing behavior. At freshet times, fish appear to have long spiraling lengths, and thus exit from the system quickly.

Evidence for spiraling.

Despite the reputation for rapid downstream movement (and abundant documentation), there is evidence for spiraling. Mains and Smith (1963) found substantial numbers of chinook salmon yearlings migrating at all times of day, but there were more 3 - 6 am and least 6 am until noon. There was a prominent day-night cycle of abundance for year-old chinook salmon smolts collected in both barge-mounted nets and shoreline electroshocking in the Columbia River at Hanford (Dauble et al., 1989, their Figure 10). Most catches were at night, from 2200 to 0400 hours. Fish at these times were concentrated in the deepest part of the main channel. They were also abundant just after sunset in shallow, near-shore areas less than 30 cm deep. Thus, there was a diurnal cycling between deep channel and shore at Hanford that does not support a constant flushing mode of migration, but rather a spiraling one as the natural mode.

Spring chinook salmon yearlings in the Willamette River in the 1940s were collected by beach seine during the day near Oswego (below spawning tributaries and in the migration corridor) by Mattson (1962), indicating occupancy of habitats other than just the main channel. Massey (1967) found diurnal patterns in emigration at Willamette Falls. Although substantial numbers of chinook salmon migrants passed at all hours of the day during the main migration season, there was a peak 6-9 am and a minimum midnight to 3 am. These patterns in the Willamette River would fit the spiraling concept better than a constant flushing one.

Weiser River spring chinook salmon (collected in the Snake River above Brownlee Reservoir) migrated largely between 7 and 11 am and 3 and 7 pm, with lowest numbers 10 pm to 4 am, as they approached the reservoir (Krcma and Raleigh, 1970). A similar diurnal periodicity at this site was reported by Monan et al. (Monan et al., 1969). The well-defined diurnal peaks disappeared during the heaviest migration time. The Eagle Creek population moved mostly at night 6-12 pm, except during high flows and turbid water, when the few fish migrated at all times throughout the day and night. Thus, spiraling was common for much of the migration, even though some flushing behavior was evident during the highest flows. Fish were oriented more toward the surface in the day and toward the bottom at night, although there were fish across the breadth and depth of the unimpounded river (Monan et al., 1969).

Radiotagged spring salmon yearlings in the Willamette River provided valuable information on migration behavior, movement rates, and feeding of stream-type fish (Ward et al., 1994; Schreck et al., 1995). There was clear evidence of a spiraling behavior. The fish used by Schreck et al. were hatchery-derived and the Willamette River is a tributary not directly associated with the Snake and Mid-Columbia river migrations, but the results are probably indicative of a similar behavior in the mainstem migration routes. Ward et al. {1994} studied fish movements over 15.3 km in Portland harbor 1988-1990; Schreck et al. (1995) studied fish for 280 km from Dexter Dam to Willamette Falls 1989-1993. Both studies had varying flow conditions. Downstream migration was characterized by rapid downstream movement (often at 24 h average rates faster than measured water velocities) interspersed with periods of resting and feeding (Schreck et al., 1995). Resting and feeding usually occurred in the afternoon, although there was movement by some fish at different times both day and night). Ward et al. {1994} found three of 14 spring chinook migrants tagged in 1989 stopped for at least 24 h at separate near-shore locations in Portland harbor. They found no significant correlation of fish migration rate with river flow.

The location of feeding and food materials are instructive about the habitats needed during the more stationary phase of the spiral. The feeding fish with radiotags seemed to locate themselves in the upper ends of pools and lower ends of riffles, much as these fish do during the tributary rearing phase. Both tagged and untagged smolts were susceptible to beach seining, suggesting some were resting or feeding in shallow shoreline habitats. A wide range of aquatic insects and some terrestrial insects were eaten. Nearly all freshly caught fish had food in their stomachs, indicating that feeding was a normal behavior for most of the migrating population. Aquatic diptera, commonly produced in large numbers on flooded riparian vegetation, were either the principal or an abundant food material. Ants, also probably fallen from riparian vegetation, were sometimes abundant. Food items more commonly associated with riffles were sometimes abundant. Riffles and shorelines that are productive of drifting invertebrates thus seem essential for migrating yearling spring chinook salmon in the Willamette River.

Radiotelemetry of chinook salmon smolts at dams has also identified "holding" behavior as well as rapid downstream migration (Giorgi et al., 1986; Giorgi et al., 1988; Snelling and Schreck, 1994). Chinook salmon smolts tended to show holding patterns upstream of John Day Dam (average duration 32.8 h) as well as downstream movements (Giorgi et al., 1986). Giorgi et al. (1988) found that some live chinook salmon yearlings took as long as experimentally killed ones to move from a tailwater release area below Lower Granite Dam to downstream transects, whereas others made the journey rapidly. Furthermore, 13% of tagged fish released upstream of the dam failed to be detected passing the dam over the 4-d tag life, suggesting holding above the dam, as well. A third of all smolts released by Snelling and Schreck upstream of The Dalles Dam searched out a place to hold after passing the dam (those released downstream of the dam were placed in the main current that forced them away from two identified holding areas). The holding areas were eddies near islands. These sites contrasted with the migration corridor in the deep channel at 3 to 10 m deep. Fish often held during the day, then moved downstream just after dark. Only 2 of 89 tagged fish held downstream of John Day Dam, in that relatively straight section without islands. The holding area used there was a 7-m deep pool well known to fishing guides.

Factors other than a spiraling migration were identified by the authors as affecting their telemetry results near dams. Giorgi et al. {1988} considered undetected tags from the forebay as a failure to migrate and the observation that some live fish in the tailrace acted like dead ones was an obstacle to their ability to assess survival rates of dam passage. Snelling and Schreck {1994} related the tendency to hold to dam-related stress. These authors considered any fish in a holding pattern to be highly vulnerable to predation, although they did not document any of their tagged fish being eaten. Spill patterns at the dam were adjusted to keep fish from being able to hold. Both studies may reflect a normal spiraling migration pattern, although effects of tagging are not fully ruled out. Giorgi et al. {1988} observed altered buoyancy in smolts with radio tags that may affect the observed holding patterns. Nevertheless, Giorgi et al. (1986) found that radiotagged fish in the forebay of John Day Dam matched purse-seine distribution patterns of non-tagged smolts.

Flow structure as an aid to yearling migration .

Accelerating flows and hydrodynamic features such as waves or surges may greatly assist the migration rate of yearling migrants. Recent analyses of yearling chinook salmon movements (Box 1) in relation to flows in the Yakima River by Mundy et al. (manuscript in preparation) point to flushing behavior during periods of accelerating flow. These observations agree with observations of yearling chinook salmon by Mains and Smith (1963) on the unimpounded Snake River and Schreck et al. (1995) on the Willamette River. Critical to the analysis of Mundy et al. is definition of the "event horizon" of migration, which defines the period of time after the fish have become developmentally ready to move and before most of the fish have passed the point of reference (such as a dam where counts are made). Consideration of flows outside this event horizon for migration introduces flow data that would not be expected to provide any statistical correlations with fish numbers (an effect that Mundy et al. attribute to several studies that have failed to find significant correlations between flow and migration, such as one by McNeil (1993). Within the event horizons at the Chandler trap at Prosser Dam on the Yakima River for 1983-1992, fish were moving downriver during periods of acceleration in flow but not in periods of declining or stable flows in all ten years (statistically significant correlations between daily acceleration of normalized Yakima River flow at Prosser and daily acceleration of 5-d moving average of daily percent spring chinook passage). Similarly, Hesthagen and Garnas (1986) showed that significantly more Norwegian Atlantic salmon migrated when the discharge was increasing (with a drop in temperature) than under the opposite conditions. In the context of a spiraling view of migration, the spiraling length would extended during accelerating flow, resulting in more fish passing a point in a given time.

Box 1. Summary of significant negative and positive correlations between daily water movements, as flows (cfs) and daily change in flows (accelerations), and daily yearling spring chinook abundance, Yakima River, Washington State, March 1 through June 30, 1983 - 1995. Work in progress by P.R. Mundy and B. Watson.

Summary of All Comparisons

	Dates	Segments
Total	2957	145308
Flows	1485	73338
Accel	1472	71970

Summary of Significant Comparisons

	Numbers			Proportions		
	Positive	Negative	Total	Positive	Negative	Total
Total	56381	9414	65795	0.39	0.06	0.45
Flows	33214	7554	40768	0.45	0.10	0.56
Accel	23167	1860	25027	0.32	0.03	0.35

Product moment correlation coefficients were calculated and tested for significance (alpha = 0.05) for daily flow and fish abundance, and for daily change in flow and fish abundance, on all possible time segments ten days and longer. On the 1,485 dates with fish and flow data, 73,338 time segments were examined, and 40,768 of those flow time segments had significant correlations between fish numbers and flow; 33, 214 were positive and 7, 554 were negative. Of the 1,472 dates containing fish abundance and change in flow observations, 71,970 time segments were examined and 23,167 of those were positive and 1,860 were negative. Numbers of yearling spring chinook moving past the collection site were positively correlated with water movement on 45 percent of the time segments tested, and the correlations for both flow and acceleration were predominantly positive. Spring chinook movements may occur independently of the magnitudes and sign of water movements, however yearling spring chinook emigration from the Yakima River is highly likely to be associated with rising flows.

Our analysis of data from the Fish Passage Center (1994) and Buettner and Brimmer (1995) suggest that movement is occurring in the Snake River system with accelerating flow. Wild and hatchery yearling chinook salmon and steelhead at the Salmon River and Snake River traps and steelhead at the Clearwater trap show increases in sample counts during and shortly after flow increases (visual inspection of graphs). The effect seems to be present still at Lower

Granite Dam, but not thereafter at Snake River dams (the wild yearling chinook index was not included in the 1993 report for Columbia River dams). Wild steelhead seem to show the effect in FPC data from McNary, John Day, and Bonneville dams.

Achord et al. (1995) noted a historical pattern of migration on rising water flow in Snake River chinook yearlings, with the pattern still evident in PIT-tag detections at Lower Granite Dam of spring chinook tagged the previous summer as parr. Lower dams did not show the historical pattern; migration coincided with peak flows. For summer chinook yearlings, the main passage of tagged fish was during rising flows at all three dams. The evidence for a flushing mechanism of migration (discussed above) generally includes observations of migration on rising flows, especially freshets.

Some rapid movement may be attributed to surges and waves. With increasing evidence that yearling chinook salmon move downstream on rising flows (see references to migration with freshets cited above and by {Northcote 1982**}**, and similar observations for steelhead), it is tempting to suggest that they may be adapted to catching the stage wave (flood surge) as well as the water mass. Rapid increases in flow or other disturbances in a channel generate a moving surge or stage wave downstream that is recognized in the field of fluid dynamics (Albertson and Simons, 1964). Such surges or waves move ahead of the main water mass and at rates faster than water particle movement (which also accelerates as stage increases). Koski {1974} found that the velocity of the wave in the Snake River in Hells Canyon was 12.9 fps at 7,700 cfs and 11.4 fps at 5,000 cfs, whereas the average velocity of the watermass was 2.3 fps at 7,700 cfs and 1.7 fps at 5,000 cfs.

To students of fluid mechanics in open channels, waves generate "unsteady flow." Equations are available in hydraulics texts that relate water depth, wave height, water velocity, and the downstream speed of the wave (celerity) (Appendix 6.1, Figure A6-3). Wave heights become accentuated when depth becomes shallower (as they do on a beach) so that small waves in a stream can pile up to form a breaking surge or bore. Moreover, at fast enough water velocities any waves generated by disturbances (like a pebble tossed in a lake) cannot move upstream and only propagate downstream.

Smolts adapted to migrating on moving surges would get both a directional cue and an assist that could move them, too, at rates faster than water particle movement. A lucky fish might, by swimming hard at the right time, maintain itself at the crest of a nearly breaking surge in a shallow river. The phenomenon would be much like a surfer catching a wave on the beach. Telemetry studies in the Willamette River (Schreck et al., 1995) showed spring chinook yearlings accelerating to faster than water velocities in swift, shallow reaches (where small waves would be expected to merge into larger surges). Conversely, as depth increases, the wave height decreases and waves have less tendency to pile up as surges or bores. Reservoirs would thus inhibit the formation of surges and continuation of those begun in riverine sections. Waves in slowly moving reservoir waters could easily propagate upstream as well as downstream. A fish could lose both directional cue and assistance in moving downstream.

If catching surges, especially those generated by spring spates, is an important part of downstream migration of yearling chinook salmon (and other yearlings, such as steelhead) , it would offer another reason besides feeding and resting for spiraling migration. Much as a surfer spends part of his or her time waiting to catch the next wave, a fish would ride a wave for a short time (probably until the wave passes it) and then wait for the next one. Thus migration would be a series of swift downstream movements alternating with holding (during which feeding and rest could occur). No reviews of fish migration have mentioned this possible mechanism. No fisheries research could be found on this subject, but the travel times of stage waves and water masses were presented for the Hells Canyon reach of the Snake River in the context of water requirements for salmon (Pacific Northwest River Basins Commission, 1974).]

How catching waves relates to diel periodicity of movement (mostly at night or in dusk or dawn periods) is not evident. Perhaps a fish rushing to catch a surge in daylight is too obvious a target for avian predators such as gulls. Doing so in the dark or dim light could have distinct survival benefits. The advantage may lie in the activity during holding rather than in migration. For example, a visual feeder such as yearling chinook salmon would need to be feeding during the day when drifting prey could be seen. They could, on average, be more free to migrate during the times of poor light.

Alluvial and constrained reaches of the mainstem may have had sufficiently different fluid dynamics that the migration of juveniles (particularly yearlings) through them differed. An alluvial reach with a broad profile and having many islands, gravel bars, and side channels would dissipate surges. On the other hand, a constrained reach would tend to amplify them. The telemetry data of Schreck et al. (1995) showed smolts moving especially rapidly through narrow riffle areas. Further evaluation of migration differences in alluvial and constrained reaches may provide additional insights into the features of a normative river that we should emulate.

Clear establishment of normal migration during accelerating flows, including stage waves or flood surges, would have important implications for flow management. Large volumes of water thought needed to sustain high flows may not be necessary to assist fish movement. Appendix 6.1 further discusses fluid dynamics in relation to fish migration.

Studies in the estuary

Studies of migration in the upper estuary are generally consistent with the riverine studies. A diel pattern of movement in the upper estuary seems to be prevalent, although somewhat different from that in the mainstem river. In the upper Columbia River estuary at Jones Beach

(Rm 46), Dawley et al. (1986) and Ledgerwood et al. (1990) found that the majority of yearling chinook salmon migrated midriver (few were caught in beach seines; more were caught in pelagic purse seines). Their migration rates were about the same in the estuary as in the river. Peak catch was mid- to late morning. After a period of low catches between dusk and midnight, there were larger catches (but still fairly low) during the rest of the night. The authors conclude that because mid-river-oriented yearling fish do not appear in shoreline areas during low migration rates of darkness, they probably hold near the bottom in deep areas of low current velocity. The yearlings were feeding, as evidenced by stomach contents. From release to recapture, groups of yearlings analyzed by Dawley et al. (1986) did not show movement rates that were well correlated with river flows (in data that spanned very high to very low flow years). Despite differences in timing between the river and estuary, there is evidence of a spiraling, rather than a constant flushing, character to the migration.

Studies in reservoirs

Yearlings in reservoirs also emigrate rapidly and generally more rapidly at higher flows. Buettner and Brimmer (1995) chronicled travel time and migration rate of PIT-tagged wild chinook salmon through Lower Granite Reservoir. They calculated that a two-fold increase in discharge increased migration rate by 4.1 times. This change occurred while flows were accelerating from about 60 to 160 thousand cfs. However, as flows decelerated later in the season, travel rate slowed markedly in a pattern that did not conform to the flow-migration rate relationship seen during accelerating flows. Thus, a pattern of migrating largely on accelerating flows may persist in reservoirs as well as rivers. Because discharge is not easily related to water velocities experienced by the fish, it is difficult to infer swimming behavior. These data need to be integrated with those of Achord et al. (1995) discussed above for the same reaches. The Fish Passage Center summarized median travel times over six years for yearlings passing through Snake River and mid-Columbia River reservoirs that show fairly clearly that fish move faster at higher flows during the migration period, especially evident at lower flow ranges {FPC 1993}. Complicating these relationships is the tendency for later-migrating fish to move faster.

As for underyearlings, early studies at dams identified a clear diurnal periodicity in passage. Gauley et al. (1958) found significantly more yearlings migrating through a Bonneville Dam bypass in four out of five years in the 1940s and 1950s during nighttime hours than during daytime hours. Long (1968) found about 94 % of yearling chinook salmon passed The Dalles Dam in nighttime hours in 1960. Yearling chinook salmon passed John Day Dam mostly at night, with prominent peak movement between sunset and midnight in all weeks between early April and mid June 1986 (Johnsen et al., 1987). Radiotelemetry of individual chinook salmon smolts has shown a diel periodicity of movement. For fish tagged and released upstream of John Day Dam, both arrival at the dam and passage through it occurred on a diel cycle, with peaks near dusk (Giorgi et al., 1986). A spiraling pattern of alternating movement and rest appears to be well established for reservoirs close to these dams.

The otherwise consistent diel pattern was not borne out in studies of PIT-tagged spring and summer chinook yearlings at two Snake River dams and McNary Dam in 1992 or 1993. Achord et al. (1995) found diel patterns in the fish bypass systems to be weak, inconsistent between dams, and often the reverse of the normal pattern--peaks often occurred in the daytime. The anomaly, although not well understood, could signal a breakdown or a variation of the usual diel spiraling migration in these reservoirs.

Radiotagged smolts released at John Day Dam traversed the Celilo (The Dalles) pool at speeds of about 2.0 m/h and usually did not stop in the reservoir before arriving at The Dalles Dam forebay (Snelling and Schreck, 1994). After passing the dam volitionally (through the ice-and-trash sluiceway or through spillways), nearly one-third held in downstream areas.

Smith's (Smith, 1982) postulation that smolts swim weakly upstream and thereby move downstream tail-first at a velocity less than that of water movement, has been used to explain the difference between water particle travel time and smolt travel time (Berggren and Filardo, 1993). Although perhaps partially true, this explanation fails to acknowledge the observed diurnal periodicity of migration with hours of little or no migration. A general relationship of travel time and flow velocity would still hold, based on just the hours of nighttime migration.

The progressive increase in smoltification of chinook salmon yearlings with time in the migration season appears to correlate with depth of travel and thus changes in fish guidance efficiency at dams (Giorgi et al., 1988). More thoroughly smolted fish were caught in the tops of fyke net screens over turbine intakes, whereas less thoroughly smolted ones were nearer the bottom in three of four test dates. Decreases in swimming performance observed during smoltification of coho salmon (Glova and McInerney, 1977; Flagg and Smith, 1982), also are consistent with the results of these collections. These tests suggest an increased tendency of more developed fish to flush, at least during the movement period. The results also are consistent with studies of Atlantic salmon, which increase their buoyancy by filling the swim bladder in an apparent effort to aid the transition from bottom dwelling to pelagic existence during migration (Giorgi et al., 1988).

Degree of smoltification clearly affected travel times of yearling chinook through Lower Granite pool and responses of travel times to changes in flow (Beeman et al., 1990; Giorgi, 1993, see Figure 8). Whereas fish with low levels of ATPase (beginning of smoltification) traveled the reservoir length slowly and showed a marked increase in travel times at lower flows, the more smolted fish with high ATPase levels had a nearly uniformly rapid rate of movement over all flows. Slowing was seen only at the lowest flows. Cramer and Martin {1978}, as reported in

(Giorgi, 1993) observed larger Rogue River chinook salmon migrated fastest. Viewing migration as a spiraling event suggests that the less smolted fish could stop to rest more often (shorter spiraling length) or for longer durations than the more smolted fish, which may move more continuously (rather than just at a faster speed). These alternatives could be tested with radiotelemetry.

If the speculative relationship between yearling chinook salmon migration and surges or stage waves in the normal river is valid, then a major effect of reservoirs on migration could lie in the altered fluid dynamics of such waves. Upper reservoir reaches may be sufficiently river-like to sustain a wave. A reservoir that broadens and deepens markedly may dissipate the wave. In any event, the wave would be stopped at the dam. These speculations regarding relations between features of the fluid dynamics and the flushing behavioral responses of fish need attention. There is some evidence that yearling spring chinook salmon in reservoirs respond to pulses in flow at the dam (Giorgi, 1993), in a pattern that seems quite similar to correlations of fish movement with accelerating flows seen by Mundy et al. (unpublished) on the Yakima River. Salmon River spring chinook salmon passed through Lower Granite Dam collection facilities in peaks that often corresponded to rising river flow. Operational changes at the turbines at these times make it difficult to separate biological responses of the fish from water flow changes in the forebay and possible changes in fish guidance efficiency of the intake screens.

Population contrasts: Snake and Willamette Rivers

As with underyearlings, it is useful to look for well-studied populations that differ in their success and compare their migratory behavior and habitats. A contrast as clear as between Hanford and upper Snake River underyearling fall chinook salmon populations is not available for yearlings. It seems reasonable, though, to compare the successful Willamette River spring chinook salmon (a population that does not pass mainstem dams) with the endangered Snake River spring/summer chinook that pass dams on both the Snake and Columbia rivers. Some comparable study techniques (telemetry) have been used, although data are sparse. In 1992, when downstream migration flows in the Snake-Columbia were especially poor, few jacks returned to the Snake River whereas Willamette River jacks returned in numbers above the historic average (Fish Passage Center, 1994).

Spiraling was evident in the Willamette River spring chinook tracked in their downstream migration through most of the undammed river from Dexter Dam upstream of Eugene to Willamette Falls near Portland (Schreck et al., 1995). Fish fed well, predominantly on immature insects characteristic of drift. In contrast, yearlings from the Snake or upper Columbia swam the length of The Dalles pool without stopping (Schreck and Snelling, 1994). Migration was interrupted at the dam forebay, but fish maintained an active searching behavior rather than a holding (resting/feeding) one. Only one route of passage at the dam allowed fish to find and use holding areas near islands. Examination of the Snake River reservoirs shows few, if any, habitats that would qualify as normal holding areas, based on the limited data on habitat suitability from the Willamette River and The Dalles tailwater. Although lack of a flow appropriate to support constant flushing behavior in the Snake River has been viewed as the critical missing habitat factor for its unsuccessful salmon populations, it may be that the lack of both high, accelerating velocities and suitable habitats for resting and feeding are equally important. Further data collection and analysis of the situation with these two populations may lead to results useful for management in the Snake River.

Needed information for yearling chinook salmon

Yearling chinook salmon are more oriented to center channel movement with current during high river flows than are the underyearlings, although a diel periodicity of migration with holding and feeding episodes is apparent. The following critical points need study and evaluation:

- Durations and intervals of movement and holding, presumably for resting and feeding, need to be better defined for yearlings in both riverine and reservoir reaches. The common view of these fish as being flushed nearly continuously to the ocean from tributary rearing areas may be insufficient for effective management.

- The role of hydrodynamic features other than thalweg velocity in fish emigration needs to be explored, for a proven link to such features as stage waves and turbulent bursts may offer opportunities for water management that could be more effective in moving fish with less water than would current proposals.

Sockeye Salmon

Juvenile sockeye salmon emigrate as one-year-olds from the upper Columbia River, principally from lakes on the Okanagan and Wenatchee rivers (Fryer, 1995). Historically, sockeye salmon existed in all moraine lakes in the Stanley Basin of Idaho (Salmon River drainage) (Evermann, 1895). The Snake River stock from lakes in the Stanley Basin of Idaho, now restricted to Redfish Lake, are on the endangered species list and virtually extinct.

Hanford netting found most mid-Columbia sockeye at night (2200 to 0400 hours) in the deepest part of the channel, along with yearling chinook (Dauble et al., 1989). Where these fish were located in daylight hours was unexplained. The meager evidence of a daily cycle is more supportive of a spiraling migration than of a constant flush.

Sockeye smolts at John Day Dam migrated with a distinct diurnal cycle in studies in 1986 by Johnson et al. (1987). There were daily peaks shortly after sunrise. Passage rates during much of the night were similar to daytime rates early in the migration (late April-early May) but much higher in all weeks thereafter until mid June. Earlier dam passage studies (Gauley et al., 1958; Long, 1968) did not tally sockeye. Giorgi (1993) indicated that the current low level of the Snake River stock, despite some PIT-tagging of Redfish Lake juveniles, meant that it is unlikely that there would be sufficient data to investigate effects of flow on migration times and survival for many years.

Much of what we know about sockeye salmon migration has come from extensive research on the species in British Columbia. Sockeye smolt migration in British Columbia has been shown to peak at dusk and dawn {Groot 1965} (Hartman et al., 1967). Speed of migration in British Columbia sockeye smolts changed with time of day and the net displacement of fish increased as the season progressed (Johnson and Groot, 1963). Downstream migrating fish tend to rise to the surface of a river or lake {Groot 1965, 1967; McCart 1967}. Smolts entering a river from a lake swim actively with the currents (Groot, 1982). Groot (1982) considered sockeye salmon migration to be a number of "hops" during which fish rise to the surface during peak times of activity and return to greater depths during periods of lower activity (a view supportive of spiraling).

Steelhead

Steelhead populations have been crossbred and transferred extensively throughout the streams of both Oregon and Washington (Royal, 1972). They spawn widely throughout the Columbia River basin tributaries. Thus, the ability to distinguish stock-specific migratory behaviors is probably lost. Generalized species' responses are the most germane. Steelhead has the reputation for being a fast migrator and a species that would be aided by flows appropriate to support constant flushing behavior. Nevertheless, even in this species, a detailed examination of the data has found support for a spiraling mode of migration.

Yearling or age 2 steelhead migrate downstream in the mid-Columbia River from spawning streams and upstream plantings from hatcheries (Dauble et al., 1989). As for spring chinook and sockeye salmon, steelhead were found at night (2400 to 0400 hours) in the deep part of the Hanford main channel (Dauble et al., 1989). Some were electroshocked in shoreline areas, but not enough to establish a diurnal pattern. Diurnal variation in appearance in the deep main channel suggests that there must be a cyclic (spiraling) pattern of migration.

Massey (1967) observed diurnal periodicity in steelhead emigration at Willamette Falls, Oregon, based on sampling of industrial shoreline water intakes. Peak movement was noon to 3 pm, with a minimum from midnight to 3 am. The majority of these fish moved downstream near the center of the river. Andrews (1958) noted that wild steelhead smolts in the Alsea River, Oregon moved both day and night, but the most rapid movement was just after sunset and just before sunrise.

Northcote (1962) observed the downstream movement of rainbow trout in streams with infra-red light, and concluded that the majority were heading downstream, many were at or near the water surface, and that they swam at a speed greater than the surrounding water. This agrees with travel time data for Snake River steelhead presented by Berggren and Filardo (1993) that showed movement faster than water travel time. Rainbow/steelhead thus appear to be adapted to the flush, and to improve upon it by active swimming, at least for part of the day. As suggested above for yearling chinook salmon, the downstream migrants may be adapted to catching the stage wave as well as the moving water mass (Pacific Northwest River Basins Commission, 1974).

In the upper Salmon River, which is a major production area for natural summer steelhead, smolts behaved similarly to spring chinook (Kiefer and Lockhart, 1995). They began to emigrate in spring with the first rising flows and arrived at Lower Granite Dam with the peak flows. There was also an autumn downstream displacement of age 2 fish from higher elevations that seemed stimulated by falling temperatures.

Wild steelhead moved rapidly downstream in the upper Snake River system, and increased their migration rate about proportionately to changes in flow, in PIT-tag studies by Buettner and Brimmer (1995). A two-fold increase in discharge increased migration rate by two times between the Clearwater trap and Lower Granite Dam and 2.1 times between the Salmon River trap and the dam. Both river and reservoir passage were included in these estimates.

Migrating steelhead smolts feed on their way to the ocean. Messersmith (1958), cited in (Royal, 1972), found most migrating steelhead in the Alsea River, Oregon, both wild and hatchery, had food in their stomachs. Aquatic insects were the main food items. This feeding strongly supports a spiraling migration in that coastal river.

As for chinook salmon smolts, radiotelemetry of steelhead has identified "holding" behavior as well as rapid downstream migration. Ward et al. (1994) observed holding behavior in some steelhead smolts even though most migrated through the 15.3-km Portland harbor in 1-2 d. Snelling and Schreck (1994) found that smolts released upstream and downstream of The Dalles Dam searched out a place to hold in the riverine sections just downstream. The holding areas were eddies near islands, the same places used by yearling chinook. These sites contrasted with the migration corridor in the deep channel. The authors related holding to stress, but it may reflect a normal spiraling pattern.

In the estuary, Dawley et al. (1986) observed that steelhead traveled 50% faster in the estuary than they did in the river. This observation is especially interesting in light of riverine migrations being more rapid than water travel (Berggren and Filardo, 1993). These fish may use tidal flows to their advantage, as has been seen in other species.

In Lower Granite Reservoir, Buettner and Brimmer (1995) found the rate of migration of wild steelhead also to be flow dependent. Statistical analysis of five years of data showed that a two-fold increase in flow increased migration rate by 2.5 times. Such data have been interpreted as support for a constant flushing mode of migration. As for chinook salmon yearlings, however, detailed analysis of the data for 1993 shows a slowing of migration on deceleration of flows that does not conform to the flow-rate relationship during accelerating flows.

In the impounded Snake River, Smith found most steelhead migrating in the upper 36 feet (Smith, 1974). About three-quarters of those caught were taken at night (between dusk and dawn). There was no indication of where these fish were in the daytime.

Yearling steelhead were identified in early studies at dams as having a diurnal pattern of migration with most passing at night. Studies at a Bonneville Dam bypass by Gauley et al. (1958) showed this pattern in four out of five seasons in the 1940s and 1950s. Long's studies of turbine passage at The Dalles Dam showed 80 to 90 % of yearling steelhead passed in the night. The steelhead pattern of passage at John Day Dam from early April to mid June 1986 showed most fish traveling at night with prominent peak migration times shortly before midnight (Johnsen et al., 1987). These consistent patterns strongly suggest a spiraling migration behavior in which habitat other than main channel flow is also important.

Coho Salmon

Coho salmon migrations have been little studied in the Columbia-Snake rivers. Most fish recently originated from hatchery stocks in the lower and mid-Columbia River (mid-Columbia hatchery rearing of coho was terminated in the early 1990s). They migrate as yearlings.

In the Columbia River estuary at Jones Beach, Dawley et al. (1986) and Ledgerwood et al. (1990) found coho salmon in both beach seine and channel purse seine catches. There were erratic changes in numbers in beach seine catches through the day and generally low catches at night. Most fish were caught in beach seines between 0830 and 1430 h, with peak catches in mid-day. Channel samples showed little day-night differences except for sharp peak just after sunrise. The data suggest schools of fish moving in both areas, but nearshore in the daytime. Marked releases of coho showed travel in the estuary at rates about 40% faster than in the river, suggesting some use of tidal currents to aid migration. Movement rate was not correlated with river flow.

As with other species of salmon, coho showed a diurnal passage pattern at dams. Studies at John Day Dam in 1986 revealed almost all coho moving at night with peak passage shortly before midnight (Johnsen et al., 1987). Considerable passage occurred through the night until shortly after sunrise.

Thus, the little data available for coho salmon suggests a spiraling pattern of migration. Shorelines appear to be used in a manner more similar to underyearling chinook salmon than to yearling chinook salmon. There is much uncertainty regarding this species, but its minor status in the Columbia River mainstem and complete hatchery dependence makes study and management less important than for other species.

Migration Rates as Evidence of Spiraling

Migration rates between points on the river should, in principle, provide evidence for migration behaviors and thus allow inferences about necessary habitats. For example, a fish swimming toward the ocean 24-h/d in the center of an open channel (flush) would move somewhat faster than the general water mass (which includes slower-moving water at sides and bottom). In contrast, a fish that rests or feeds for half of the day (and needs shoreline or other habitat for that purpose) and drifts passively for half a day near the center channel (spiral) could migrate at about half the water speed.

There has been considerable effort devoted to the collection of data on migration rates of downstream-migrating salmonids and the statistical relationships to environmental variables (e.g., (Buettner and Brimmer, 1995). There has been less effort expended in conceptual thinking about migration speed, including consideration of the fundamental principles of animal and water movement and relationships of these principles to the observed migratory timing. Fluid dynamics of surges or stage waves, turbidity bursts in an unimpounded river, and hydrodynamics of river flows as they enter low-velocity areas of reservoirs are examples. Even less attention has been given to whether and how different migration rates affect salmon survival (i.e., relationships between timing of movement and the innate behavioral patterns and ecological needs of the species and life stage). The exception to survival linkage has been attempted connections between initiation and rate of movement and the physiological processes of smoltification (Wedemeyer et al., 1980).

There is notable disagreement over what the empirical evidence about the rate of migration timing and river discharge tells us. McNeil (1992) found no positive relationship between flow and passage time, however, the preponderance of thought clearly supports the links between flow and migration rate, with presumed benefits for survival (Raymond, 1968; Berggren and Filardo, 1993; Giorgi, 1993; Cada et al., 1994). This view is reflected in proposed salmon restoration plans (NPPC, 1994; National Marine Fisheries Service, 1995). Some of the disagreement relates to the time periods selected for statistical analyses, in which inclusion of dates outside the actual migration period can severely affect the results. Attempts to sort out the scientific basis for disagreement may not be possible until we better understand and consider the natural, inherent mechanisms of migration in each species (or stock). Disagreements attributed to the "science" may, in fact, be true differences that reflect life history diversity among the fish. We can use that understanding to clarify the implications for both existing river impoundments (the source of our current data) and proposed flow and reservoir elevation manipulations.

Migration timing depends upon the fish's orientation and behavior in the water as well as whether downstream migrating salmonids flush or spiral. There has been much debate over whether downstream migrations, in general, are active or passive; see literature reviewed by (Jonsson, 1991). Downstream swimming in the direction of water flow would generate quite rapid downstream movement, with travel times shorter than those for water during periods of active migration. This behavior, as observed in rainbow trout by Northcote (1962), especially when it might be coupled with accelerating flows as in a flood surge, could be very effective in moving fish rapidly. Orientation upstream at a stabilizing swimming velocity, as suggested by Rutter {1904}, Smith (1982), and Williams et al. (1994), would generate a downstream drift at rates less than water movement. Totally passive migration, is also possible, in which undirected (or no) fish movements result in net displacement at the rate of the water mass. Coupled with a possible spiraling migratory behavior having alternating times of displacement and resting or feeding, these orientation alternatives could give considerably different migration rates over distances of kilometers. Should these orientations differ temporally, such as in a daily cycle (perhaps related to spiraling) or between early and late migrants in a cohort or whether or not a stage wave is passing, the resulting travel times could be expected to differ in ways that would confound conventional statistical approaches.

It is quite possible that both passive and active migrations occur, even for the same species at different times. As Jonsson (1991) noted, fish must actively initiate emigration. Clearly, fish that are holding during a diel cycle, either at the bottom or in shoreline backwaters, must actively swim to get themselves oriented into the main current for what might later be passive movement. Both avoiding obstacles during downstream movement (e.g., being swept into backeddies) and ending the movement phase of spiraling would require an active component. All of these complicate a simple interpretation of migration rates between widely separated points.

To clarify alternative migration mechanisms for purposes of making quantitative evaluations (by species, time of year, at different flows, etc.), it can be useful to compare the evidence for six basic migration types: (1) continuous, passive drift (Type I), (2) continuous, downstream swimming (Type II), (3) continuous downstream drifting (with slow, stabilizing swimming upstream) (Type III), (4) passive drift alternating with periods of resting/feeding (spiraling) (Type IV), (5) downstream swimming, perhaps with hydraulic assists, alternating (spiraling) with resting/feeding (Type V), and (6) downstream drifting (upstream orientation) alternating (spiraling) with resting/feeding (Type VI). These types are tabulated (Table 6.1), with the characterizing fish behavior, implications of that behavior for the unimpounded river, implications for a reservoir, and projected effects of increased water velocity attained by flow augmentation or reservoir drawdown.

This exercise in classification of migration behaviors can have two uses. One is to compare the different implications for rivers and reservoirs with the results of field studies of fish passage to see which implications (and thus behaviors) are supported by the evidence. It has already led us to consideration of stage waves or surges in migration (not proposed to date in any discussion of migration mechanisms, but recognized by the field of fluid dynamics). However, the effectiveness of surge pulsing remains to be demonstrated in impoundments. Another use is to test different fish behaviors with river management alternatives in hydrodynamic models of river and reservoirs to develop computer simulations of fish passage timing. The simulations under different combinations of behaviors and water flow regimes can be compared to the field data. Additional scenarios can be examined, more than is possible with the actual historical record of flows, migration times, and other factors. For example, the effects on passage rates of different lengths of time spent in displacement and stationary resting/feeding under the spiraling hypothesis can be examined for a range of flows even though there are few field studies of diurnal behavior. The objective of such analyses would be to indicate the possible habitat requirements of each species/stock and their projected gain (or loss) from velocity increases from managed reservoir drawdown or augmented flows.

Field evidence can be compared with migration behaviors using data compiled by Berggren and Filardo (1993). They provided both water and fish travel times over a range of river discharges for Snake River yearling chinook salmon, John Day Pool subyearling chinook salmon, Mid-Columbia River steelhead and Snake River steelhead (Figure 6.5). Their objective was to determine if there was a statistically significant relationship between travel times of water and fish. Subyearling chinook traveled much slower than water at all flows (by a factor of 3 at high flows and 2.5 at low flows). This is consistent with a spiraling migration behavior and the observations of daytime residence in shoreline areas. Migration in May and June with about 16 hours of light and 8 hours of darkness is consistent with the model of nighttime movement with swimming against the current. Thus slow-water habitats are necessary that can sustain these fish during 2/3 of the diurnal cycle.

Yearlings in the Snake River moved, on average, at a rate slightly slower than water at high flows (1.5 times as long to move the same distance) but essentially the same as water movement at low flows (Berggren and Filardo, 1993). However, the data were widely scattered and some groups maintained the 1.5 ratio across the range of flows whereas other groups (8 of 24) moved slightly faster than water (0.6 times as long to move the same distance). These results are consistent with spiraling at high flows (and are consistent with observations of diurnal migration) but show an increased tendency to shift behavior (and habitat requirements?) at low flows. The inconsistency among groups suggests that the migration behavior of this class of salmon needs additional special study.

Snake River steelhead were unique in moving almost exclusively at a rate faster than water movement in the Snake River. The difference appeared to be greatest at high flows and nil at low flows. One interpretation of these travel times could be that the fish use directed downstream migration with no spiraling. Steelhead would thus not need shoreline or other resting habitats and would be aided by a continuous faster water flow. Mid-Columbia steelhead, however, behaved quite differently. These fish took about 1.5 the time of water to cover a distance, which is more consistent with spiraling or at least swimming against the current. Speculation about use of surges and stage waves would suggest another answer: Snake River fish, with more riverine distance traveled in the studies, still use freshet surges to allow travel at a more rapid rate than water whereas the mid-Columbia fish have mostly reservoirs without surge flows. More work along these lines on all species and stocks may prove valuable.

SPIRALING AND LIFE-HISTORY DIVERSITY OF SPECIES AND STOCKS

The Columbia-Snake river basin, at the time Europeans arrived, was characterized by an assemblage of Pacific salmon species and stocks with highly divergent life-history strategies (see Chapters 3 and 4). This diversity developed as the Wisconsin glaciation retreated and the exposed landscape was recolonized by stream-type salmon from northern refugia and ocean-type fish from southern refugia (Lindsey and McPhail, 1986; McPhail and Lindsey, 1986). Differentiation probably occurred within stocks as they adapted to the peculiarities of specific tributary systems and the migration corridors to and from them. It is believed that migration distance and growth opportunity in the vicinity of spawning (a combination of water temperature and day length) were major factors in this differentiation (Taylor, 1990). Northcote {1982} observed that the "more closely we look at the detailed aspects of migratory behavior in riverine fish populations, the more evidence we uncover for marked local variation of a highly adaptive nature" (and he cited several references).

Overall stock diversity was probably reflected in diversity of migration behaviors related to constant flushing or spiraling, as well. It follows logically from the diversity of tributary habitats and flows that salmon as a group would diversify to make full use of different migratory corridors, as Rich (1920) observed. The differences in diurnal migratory behavior of the now extirpated Snake River stocks of spring chinook salmon studied by Krcma and Raleigh (1970) and other stocks is just one example. The primal river had spring freshets of varying magnitudes and durations that afforded quick passage, open channels for quick flush, backwaters for lingering, eddies and deep pools for resting, riparian habitats that afforded stragglers with abundant food and shelter, and so forth. Each habitat niche was probably occupied by a species or stock (often overlapping). Because each salmon species in the Columbia-Snake system has a multi-year life cycle and attainment of maturity can vary across several ages, each population was buffered from unfavorable conditions in any one or few years as the riverine environment varied from year to year. Good years for one species' or stock's migration strategy (habitat use) may have been bad for another one's strategy. Because the relative benefit could switch from year to year, the diversity of stocks would persist.

Any strategy that manages river flows consistently is likely to favor fish stocks with one migratory behavior or habitat use to the detriment of others. Some stocks will, therefore, be pushed to extinction or very low levels while others are protected and fostered. For example, consistently high flows in the Snake River in May coupled with reservoir drawdown may create a fast-flushing, bare channel highly suited for moving yearling spring chinook downstream rapidly (begging the question of any daytime resting requirements), but at the same time be inconsistent with the requirements of underyearling fall chinook salmon for slow-water areas with riparian vegetation for their characteristically slow downstream movement. It can be hypothesized that the Snake River fall run fish are in their present sad state because of the poor riparian habitat of the present Snake River (in contrast to the riparian vegetation-rich Hanford reach).

The most favorable flow strategy for a diverse assemblage of salmonids would be one that varies, favoring some stocks at one time and other stocks another time. In the normative river concept, this variability should mimic natural variability, although replacing a climate-driven variability with a planned one (assuming the reservoirs are not permanently drawn down to natural riverbed). Although not easy, one could envision flow management in which reservoirs are drawn down temporarily in different ways in successive years: one year in three for maximal support of constant flushing behavior, and another in which floods are created to overtop riparian zones to create maximal shoreline habitat. The third year could be maintained stable. These flow strategies would be coupled with non-flow measures for salmon such as replacement of shoreline rock rip-rap with vegetation. The occasional exceptionally dry year (that restricts planned flooding) or wet year (that floods no matter what the plan) would add a certain primal variability.

SPIRALING AND SERIAL DISCONTINUITY

Disruption of normal spiraling migration behavior by juvenile salmon can be viewed as a break in the serial continuity of the mainstem river. More than a decade ago, Ward and Stanford (1983) developed the serial discontinuity concept as a theoretical construct that views impoundments as major disruptions of longitudinal gradients along rivers (see Chapter 2). Dams break continuity of longitudinal gradients and reset biotic and abiotic patterns to different longitudinal states. Thus, the continuum (in the sense of the river continuum concept of (Vannote et al., 1980) is broken into discrete and often repeating fragments. One aspect of the continuum (and discontinuity) not adequately considered initially was the interaction between river and floodplain (see Chapter 5). Juvenile salmon tend to migrate during flood phases when the shoreline resting-holding-feeding areas are actually food-rich flooded shorelines.

The migratory spiral of juvenile salmon can be viewed in the light of both a continuum and imposed discontinuity. Juvenile fall chinook salmon in the Columbia/Snake system can be viewed as once having had a long, continuous spiral from spawning area to the ocean. Spiraling lengths were short in the immediate rearing area (long shoreline feeding periods in the flooded riparian zone compared to short times drifting in currents, over the first month or two) and then lengthened (relatively more time moving) as the fish moved downriver gradually. The spiral length remained quite short, however, and shoreline habitats were consistently used heavily until the fish reached a size for rapid migration through the lower river and estuary. Dams and reservoirs disrupt the continuity of this spiral. Slowing current means less assisted movement when fish purposely move toward the channel from shoreline areas. Warm reservoir shorelines break the feeding part of the spiral through high temperature avoidance. Passage through the dam may reset the spiral in more riverine reaches of reservoirs, but the behavior pattern can be soon thwarted by lack of currents further downstream in the next reservoir. Destruction and resetting of a basic behavioral pattern repeatedly as several reservoirs are traversed could, at least theoretically, be very disruptive to survival.

Yearling salmon migrants probably experience the serial discontinuity in different ways. For them, the migratory spiral is very tight in their first year of rearing (there is little downstream displacement, although this is stream-dependent and longer spiral lengths occur in upper reaches in autumn as fish move to lower wintering areas). Spiraling lengths increase dramatically as spring freshets arrive with more water (and perhaps with significant assists from waves and turbulent flows). Besides less downstream displacement in impoundments during movement phases of the spiral, the normal holding areas (e.g., backeddies) are changed markedly. A new movement and holding behavior probably needs to be initiated in the slower downstream ends of reservoirs. With passage through a dam, the long spiraling length may resume only to be thwarted time and again.

High river flows might have some of their effect on improving survival by acting to reduce the serial discontinuity of spiraling migration. Higher flows generally mean that a higher current is maintained further downstream in a reservoir. Certain flows may be sufficient to maintain a functioning "river" for salmon migration behavior (that is, maintaining normal spiraling) throughout the length of reservoirs. Higher volumes of water relative to reservoir volume in the mid-Columbia River may result in less serial discontinuity of behavior and explain the relatively good survival of mid-Columbia stocks relative to those in the Snake. Although speculative, these theoretical relationships may warrant investigation.

FISH MIGRATION BOTTOM LINES

CONCLUSIONS:

1. Current views of the fish-migration literature are inadequate for application to the Columbia-Snake watershed and a new interpretation is needed (2);
2. Migration of juvenile salmonids can be viewed as a spiral, with periods of moving and holding (not just constant downstream moving) (2);
3. Short spiral lengths characterize "rearing" periods (first year stream type & ocean type) whereas long spirals characterize "migrating" periods (yearling stream type and ocean type close to ocean), although the durations of, and between, stops is not well understood. (4).
4. Movement has been measured in several places in the unimpounded river and at dams with somewhat different results, but on the whole, movement appears to be diel, with most at night or at dusk or dawn (2);
5. Moving fish are surface and thalweg oriented during movement but shoreline (underyearlings) or bottom oriented (yearlings) during holding (1);
6. Migrants use water velocity to assist migration, thereby saving energy (1);
7. Migrants use several types of behavior to minimize energy expenditure through use of turbulence and unsteady flows (4);
8. Velocity structure (unsteady flows) is important as well as bulk flow velocity, and this riverine flow structure has been lost in reservoirs (4);
9. Holding periods are important primarily for feeding, which is done in daytime (sight feeders, proper habitat needed) (2); see additional conclusions on feeding.
10. Management alternatives for aiding juvenile salmon migration probably can be selected that are consistent with the normative river concept.

CONCLUSIONS

The current approach to managing flows and habitats in the mainstem Columbia and Snake rivers to aid salmon migration is based on an inadequate conceptual foundation that does not recognize the complex behavioral and ecological components of migrations.

CRITICAL UNCERTAINTIES

1. The amount of usable unsteady flow that would be generated by additional flow volume, reservoir drawdown, physical structures or managed water releases including spill, is not known.
2. Characteristics of the migratory spiral are not well quantified, especially the relative distances and durations of migration and holding in different parts and at different times of a fish's migration.
3. Use of unsteady flows (velocity structure) by juvenile salmon to assist migrations needs to be verified by experiments or observations, including quantifification of the characteristics of unsteady flows that aid salmon migration.

RECOMMENDATIONS FOR RESEARCH

1. Conduct field research to better characterize the gross migratory behavior of juvenile salmonids, including spiraling lengths and time durations spent in migrating and holding, in order to better define the habitats needed by migrating fish;
2. If initial results from #1 are promising, conduct laboratory and field scoping studies to test the hypothesis of the use of several types of unsteady flows by migrating salmonids, so that this understanding may be used to increase migratory assists;
3. If the hypothesis in #2 is substantiated, conduct assessments and field experiments to estimate the amount of usable unsteady flow that would be generated by several action options, including additional flow volume, reservoir drawdown, physical structures or managed water releases including spill.
4. Conduct an integrated assessment of fish migratory behavior and bioenergetics in relation to natural and engineered flow characteristics to address the efficacy of the action options. This is not easy and will take many years.
5. Alternative management actions should be reviewed carefully in light of present scientific understanding for their effects on, and ability to enhance, juvenile salmonid downstream migration.

DISSECTION OF THE COUNCIL'S FLOW-SURVIVAL HYPOTHESIS

The Council's FWP gives high priority to testing the flow-survival hypothesis, i.e., that there is a positive relationship between river flow (discharge) and survival of anadromous salmonids that migrate in the river basin at corresponding times. Our independent review has shown that this hypothesis encompasses many intermediate steps and alternative pathways of causality (Figure 6.1). Flow is clearly essential for anadromous fish to complete their life cycles. However, we will improve our abilities to determine whether the flow-survival hypothesis for the mainstem is supported by existing data, to obtain more relevant data, and to develop remedial management measures if we dissect the broad hypothesis into component parts. This dissection is easier to understand following our review of the literature on salmonid migrations in the basin and development of the ideas of spiraling migration and the normative river in this and preceding chapters. Many of the component parts of a presumed flow-survival relationship are readily observed, and such data are part of the existing record. Other components remain to be measured and evaluated. When the intermediate steps in the hypothesized relationship are left obscure, the resulting statistical correlation analyses may have little power and may, in fact, lead to inappropriate tests of the hypothesis. It should be accepted that anadromous salmonids rely upon flows in a normative ecosystem. The target of investigations should be to determine how and to what extent they use flows, including the relationship of velocity and survival.

There are several different chains of factors that are subsumed into the flow-survival hypothesis (Figure 6.1). Most occur concurrently. Some link the independent variable (discharge) and the dependent effect (survival, as measured in several ways) tightly through mostly physical attributes. Some of these attributes involve the river-reservoir system whereas others relate primarily to operational capabilities of the hydrosystem. Other chains link intermediate relationships (often biological) that are possible components of the flow-survival hypothesis. Direct physical relationships are the ones most often sought in statistical analyses (e.g., discharge during emigration related to number of adults of the year-class returning). This is, in part, because these physical factors have been measured. Biotic relationships are often cited as the underlying reasons for the more apparent direct relationships (e.g., discharge relationships to predation or temperature effects), but the biotic factors are less often quantified. The distinction between the various chains of relationships is useful both for systematizing the problem and for clarifying what kinds of data can be important.

Dissection of the chain(s) of causality can reveal that the oft-measured features of the system are not the most helpful in relating flow to survival. For example, how useful are data on daily average discharges at a dam if migration of juveniles depends on flow rate only between certain hours of the day? If accelerating stream discharges are the real cues to initiating and sustaining active downstream swimming, of what use are flow data that include times of flow decrease? What are we to make of flow peaks that occur before fish are physiologically ready to migrate and those peaks that occur after most of the available fish have already moved past the measuring point? Clearly, we need a better understanding of these impediments to testing statistical flow-survival relationships.

If salmon populations in the Columbia River basin are to be restored, simply adding more flow (water volume) may not attain the desired result and could be wasteful of water resources. Assumption that water velocity is the main operative biological component of flow (as in the current Fish and Wildlife Program) may not be sufficient, either. When we ask whether the science behind the FWP is sufficient to justify the actions proposed, we need to delve further into the relationships. It is quite possible that relationships other than river discharge or reservoir pool level can be found that could be managed to greater benefit.

Here we dissect the flow-survival relationship into representative component parts and comment on importance of each component, how well we understand each component and what information is needed so that each component will aid and not bias the flow-survival evaluation. There are undoubtedly important relationships we have not listed.

Physical Relationships Between Flow (Discharge) and Fish Survival

A. River-reservoir.

1. Flow : water velocity.

Discharge translates to water velocity in complex ways that depend on the topography of the river-reservoir system. This is particularly true when the relevant velocities are those seen by particular fish stocks rather than velocities across some summary physical description of the water body (because fish occupy portions of the waterbody, often changing on a diurnal cycle). Fish respond behaviorally to velocity at a fine scale, although these behavioral responses can have aggregate effects at larger scales (e.g., in passage between major points on the system such as dams). Few studies have attempted to relate discharge to local water velocities in the large system of the mainstem Snake-Columbia rivers, although instream flow methods have been developed to do so for smaller streams. Velocities measured near where fish are migrating are needed, even though this is difficult to accomplish.

2. Flow : water travel time.

Water travel time is often used casually as if synonymous with water velocity. The hydrodynamics of water travel time through a river-reservoir system are complex and involve longitudinal mixing, lateral spreading, wave effects, and particularly the detailed morphology of the river-reservoir conduit. Water travel time estimates used for comparison with fish travel times, e.g., (Berggren and Filardo, 1993) have been highly simplified and lead to opportunities for obscuring relationships. Better estimates of water travel times are needed.

3. Water velocity (or water travel time) : fish travel time.

The most appropriate water velocity or travel time statistic(s) for comparison with fish travel times has not been established. Because species (and perhaps stocks) vary in behavior, the appropriate statistic(s) are likely not consistent for salmonids in general. For any one stock or life history pattern, the relationship may vary by location and time. Fish may respond to change in water velocity (e.g., acceleration) rather than fixed levels. The region is developing much data on fish travel times between major points (dams or trapping sites) through PIT tagging. How these data will be used with the water discharge and movement data is not clear. Much work is needed to fully understand the relationships between either water velocity of water travel time and rates of fish movement.

4. Fish travel time : survival.

Appropriate measures of fish travel times can perhaps be related to survival in useful ways. Few studies have used survival to the adult as the measure. This relationship although complex (see Figure 6.1), can be dissected usefully into reach survival, emigration survival, survival to the ocean fishery (a measure of sub-adult survival), and survival of adults to the lower river, and survival of adults to the spawning ground. Transportation studies involve the ultimate in speeded travel time within the hydroelectric system. A better understanding of travel times and adult returns is needed. Value of rapid travel time should be considered in light of data that show larger fish are more fit for survival on entry to the ocean. Especially for life-history types that must rear in the mainstem during migration, the relative energetics of rapid transit and slow rearing must be considered.

B. Operational Relationships of the Hydrosystem

1. Flow : spill.

Spill can be necessary when flows exceed the capacity of turbines or discretionary (or mandated) when planned to aid fish migration. Both have been seen in recent system operations. Turbine-generators can be operationally unavailable because of repairs. Sufficient flow must be available to support discretionary or agency-mandated spill programs (mandated programs may require reduction in hydropower output). The physical operation of the hydrosystem and regulatory requirements ought to be well enough understood to allow very accurate calculation of the relationship between flow and spill. One would expect that spill would be coordinated with available flows. (Also see Chapter 7 for discussion of this and subsequent operational relationships)

2. Spill : turbine passage mortality.

Water spilled does not pass through turbines. Fish in the spilled water circumvent mortality due to turbine passage. Spill does have a low rate of mortality associated with it, however. Both factors probably are somewhat unique to each dam and operating scheme (e.g., which bays are used to spill and which turbines are put out of service or reduced in efficiency thereby). Quantifying these relationships seems important, although it has not been done for any mainstem dam.

3. Spill : gas supersaturation.

Spill is known to induce elevated gas saturation in downstream waters, to a degree that is dependent on the design of the dam (e.g., whether flip lips were installed) and amount of spill relative to turbine flow. Depending on exposure conditions (water depth, temperature, duration) fish can exhibit gas bubble trauma that can lead to poor performance or death. Gas saturation monitoring is conducted below each dam but there has been insufficient correlation with dam operations. Also, little is known of the in-river dynamics of gas saturations below spillways and turbine discharges and at all depths. High-saturation plumes downstream of dams should be correlated with fish location in three dimensions.

4. Gas saturation : fish survival. (see E below).

Biotic Relationships

A. Through the Riparian Food Chain (tributaries, historical mainstem, Hanford, below Hells Canyon Dam)

1. Flow : flooding.

We know that increases in flow (discharge) can induce flooding of riparian zones of tributaries and the mainstem. For each tributary and reach, however, we lack a good discharge : water elevation relationship. Dams have reduced flooding and riparian habitat in ways that need to be quantified beyond simple riparian maps such as those prepared by the Corps of Engineers. It is not clear at present how detailed the riparian flooding quantification needs to be to develop relationships relevant to fish survival. Any restoration of a normative cycle of flooding will probably be beneficial for food production. Restoration of riparian zones may be needed.

2. Flooding : food production.

Flooding increases food resources for juvenile salmonids, although it has not been quantified in the Columbia or Snake rivers. This is true for under-yearlings migrating and rearing in the mainstem and for parr rearing in tributaries before major migration. It is likely true, also, for yearlings during migration. The quantitative relationships need to be demonstrated.

3. Food production : growth.

We assume more food production in riparian zones means better growth rates and bigger fish (more robust) at migration. This assumption should be evaluated. High temperatures in shallows of reservoirs may limit use of a food-rich habitat, however.

4. Growth : juvenile survival.

Although intuitive, there are few data clearly testing the assumption that bigger, more robust fish survive better during migration. Turbine-induced mortality has been demonstrated to be greater for larger fish, so large size may be a detriment in a system where fish must pass through turbines. There seems to be an incompatibility of selective forces at work--the ecosystem may be selecting for better survival of larger fish while the hydrosystem is selecting for smaller fish.

5. Juvenile growth (size at entry to estuary/ocean) : survival to adult.

This seems well established as a generalization. How species specific it is remains unclear. Conditions of the estuary and ocean may strongly influence the relationship between juvenile growth and survival to the adult.

B. Through Reservoir Plankton Food Chain (current mainstem).

In addition to the relationships between flow, water velocity, and water travel times and between feeding, growth and survival (see above) there are additional relationships related to plankton production.

1. Flow : water replacement times in reservoirs.

Somewhat different from water travel times is the water replacement times in reservoirs. Higher velocities and shorter water travel times translate to more rapid replacement of water in reservoirs and less time for biological activity in the watermass, especially generation of planktonic biomass suitable as food for juvenile salmon. This needs study and evaluation for mainstem reservoirs.

2. Water replacement times : zooplankton production.

This depends on the generation times of zooplankton species and the phytoplankton available, nutrient supplies, and species interactions. This needs analysis and field study.

3. Zooplankton abundance : salmon feeding and growth.

How well salmon migrants feed on zooplankton is unclear since they had an insect-based food supply in their evolutionary history. Juveniles enter reservoirs from streams or unimpounded reaches where this is still their main food. There are data on under-yearlings using plankton but less information is available for yearlings. Whether plankton feeding by salmon is equivalent from a bioenergetics perspective to their traditional food is unclear.

4. Estuarine organisms in reservoirs : salmon feeding and growth.

We have only recently recognized the significance of invasions of the Columbia and Snake reservoirs by organisms (amphipods and mysids) normally associated with the freshwater estuary. Benthic amphipods apparently find suitable habitat in the fine sediments of reservoirs and are found to the headwaters of Lower Granite Dam. They are available as food for juvenile salmonids primarily when in the water column during spring vertical migrations (planktonic). Their composition makes them a poor food source relative to normal riverine foods (aquatic and terrestrial insects).

C. Through Predation Mortality

1. Flow : velocity. (see direct relationships)

There is a need to evaluate velocities where predators are, especially where predators and salmon are likely found together. Analysis should include areas of flooding and velocities in flooded areas.

2. Velocity : predator feeding behavior.

Do predators eat as much salmon at all velocities? Squawfish seem to reduce feeding at higher velocities.

3. Velocity-dependent feeding : number of salmon consumed.

Water velocity at feeding locations will affect the number of fish passing a point on the river/reservoir that are consumed. Cumulative effects from spawning area to the river mouth should be determined.

D. Through Temperature Effects on Fish

In addition to the relationship of flow to retention time (above), retention time affects heating and temperature. As noted above, growth can affect survival.

1. Retention time : heating.

The longer water is retained in a slowly moving or static state, the more opportunity it has to be warmed by solar radiation. This is particularly true in shallow areas of overbank reservoirs. Thermal models should be able to calculate this. It is not clear how much the one-dimensional thermal modeling of the river basin considers this feature.

2. Heating : river temperature.

Rate of heating will influence both local and thalweg river temperatures. Thalweg temperature is represented in on-dimensional thermal models. Models that consider temperatures where fish reside for feeding and growth are needed.

3. Temperature : fish survival.

Most likely there are not acutely lethal high-temperature conditions in the Snake and Columbia, but this needs to be monitored. Curet (1993) showed clear avoidance of warm shoreline areas in summer by migrating adult chinook salmon. A thorough analysis of water temperatures in habitats occupied by juvenile salmon does not seem to have been done.

4. Temperature : fish growth.

This is a likely effect, probably mediated by behavior (avoidance of high temperatures in feeding areas). Temperature is very important to the bioenergetic balance in growing juvenile fishes. This is especially important for the underlings that both rear and migrate through the summer. Growth is essential to survival. Under-yearlings must grow through their mainstem migration period in order to be at the appropriate size when they reach the estuary. Small fish have lowered survival in the ocean compared to larger fish. Small fish are more vulnerable to predation. No good analysis of salmon juvenile growth during emigration seems to have been done. Analyses of this relationship are needed.

E. Through gas bubble trauma

Flow influences spill, which in turn affects gas supersaturation (above).

1. Gas supersaturation : tissue trauma.

Although laboratory experiments have clearly established that gas bubble trauma in fish tissues occurs, the specific biotic and abiotic factors that cause survival-reducing debilitation in the river remain unclear. Water quality standards of 110% of saturation as an upper allowable limit have been questioned in the tradeoff against assumed high turbine-induced mortalities if there is no spill. Although bypassed fish at dams are examined for signs of external gas bubble trauma, in-river evaluation of fish behavior and development of clinical signs of trauma has not been adequate.

2. Tissue trauma : lowered survivorship.

Direct death may occur although the more likely route of loss of survivorship is sublethal debilitation. Fish that are internally damaged are unlikely to swim as effectively in migration, feed as effectively during holding periods, grow as well, and avoid predators as well. As with development of tissue trauma in the field, the amount that causes reduced survivorship has not been established.

A Synthetic Approach to Migration, Flow and Survival

The dissection exercise above demonstrates the complexity of the relationships between flow and survival of juvenile salmonids during their migration through the mainstem Columbia and Snake rivers. One can legitimately ask whether “science” could possibly sort out and quantify each and all possible sub-hypotheses. It is reasonably clear that it cannot, especially in the time-frame needed by managers for salmon restoration. However, synthesis of available science can, and has, identified broad topics of likely causality that need priority attention from researchers and managers. Recognition of these important topics has shown that overly simplistic statistical analyses that seek correlations may be inappropriate or misleading when the underlying mechanisms are not considered.

An alternative to an ever-finer, mechanistic breakdown of the flow-survival hypothesis is the normative river concept. The many, interrelated features of a river system that lead to high salmonid production occur normally in a river basin unaffected by human alterations. Science is gradually defining which of those features are key elements for salmon. Without quantifying all of them in detail, a more synthetic approach is possible. By restoring key features of the system such as seasonal high flows and recognizing key migration attributes of juvenile salmon (such as surface orientation, need for feeding habitats and appropriate food, and tendency to follow flows), aspects of the river basin can be managed or reengineered to accommodate the key functional features. We can align our water management policies and engineer our physical structures to more closely approximate the key functions of a normative river.

Science still has many issues to resolve, but movement to a more normative salmon bearing ecosystem need not wait. For example, research needs to evaluate the food web implications of having estuarine organisms colonize nearly the entire reservoir system. We need to establish the importance and possible benefits of unsteady flows for fish migration, such as pulsing of dam discharges during seasonal high water periods. The normative river framework allows the myriad of potential research projects (as suggested by the hypothesis dissection above) to be prioritized and focused under a firm conceptual foundation. In the meantime, accommodation of well understood normative features by management agencies can begin.

FLOW-SURVIVAL BOTTOM LINES

CONCLUSIONS

1. Numerous chains of causality can link river flow with juvenile salmonid survival, including passage routes used, food production and availability, predator feeding efficiency, and water temperature. (1)
2. A clear flow-survival relationship adequate for defining flow requirements in the system has yet to be demonstrated (see Figure 6.1). (1)
3. No chain of causality has been studied sufficiently to be confident of its role over a range of river flows. (1)
4. Different chains of causality probably dominate in different flow ranges, and thus in different years. (3)
5. Water velocity (water travel time) is one part of one chain of causality that may link flow and survival, and it is insufficient as the only basis for managing river flows for out-migrating salmonids. (1)
6. Simultaneous testing of multiple hypotheses for the relationships between flow and survival are impractical without prioritization and focusing with a conceptual foundation, whereas the normative river concept provides that foundation and suggests immediate management options that will be of value to juvenile salmonid migrations.

GENERAL CONCLUSION:

A simple, direct relationship between flow and survival, and its common surrogate of a flow-velocity relationship, are insufficient as a conceptual basis for managing river flows during juvenile salmonid emigration, whereas the normative river concept embraces multiple sub-hypotheses embedded in a complex relationship.

IMPLICATIONS:

1. The many components of a flow-survival relationship should be viewed in a broad normative river context for selection of management options.
2. The roles of potentially key causative relationships between flow and survival should be studied through field research and analysis of available data, as prioritized and focused by the normative river concept, so that the most effective management actions can be taken.

MANAGEMENT IMPLICATIONS

The key attributes of migration behavior of juvenile salmonids discussed in this chapter have potential management implications for salmon restoration. In general, management can and should be aware of fish behavior in a normative river ecosystem and move toward compatible ecosystem attributes. As a general rule, it is better to do what the fish are adapted to do normally rather than force an unfamiliar behavior. What follows are examples of management options that derive logically from the normative river ecosystem concept (with some examples of what is not logical, and should be discarded). The examples are not specific ISG proposals or recommendations at this stage, although some could be implemented quickly. Others need further study and evaluation.

Migration strategies

Underyearling and yearling migrants have different rearing and migration strategies. With two different migration types using the mainstem, management to improve the fate of one type may disadvantage the other. Lowering of reservoirs in spring to provide transporting flows for migrants will primarily benefit yearlings and be of little use to underyearling movements and may further remove needed shoreline rearing habitat. More normative spring flows (“augmented”, compared to recent practice) can both increase water velocities in the channel and provide shoreline flooding for underyearlings. Better understanding of how the river normally accommodated these differing requirements will aid in its future management. Permanent drawdown of a selected reservoir (or reservoir reach, such as the upper John Day Reservoir) would accommodate both migration types.

Spiraling

Recognition that most juvenile salmonids, with the possible exception of steelhead, migrate in a spiraling fashion, that is, they have alternating periods of movement and holding (for resting and feeding), indicates that there are important mainstem habitats beyond that of a flowing channel. This array of normative habitats needs to be managed as part of the hydrosystem (Figure 6.8). In particular, coves and backeddies are needed near the channel that have bottom substrate and riparian vegetation capable of producing invertebrate food materials. Annual flooding of riparian vegetation in May and June, with high water levels maintained for several weeks, is needed to produce abundant aquatic midges and terrestrial insect fall. Although probably not necessary every year, creation of abundant food for juveniles through planned flooding should be a regular occurrence within the normal lifespan of the salmon species (e.g., something like one year in three or four).

Resting and feeding areas too far removed from the main channel may be detrimental for juvenile salmon survival and restriction of their access to these areas may be desirable (Figure 6.9). This would need to be done after careful study and evaluation of survival in these locations.

Daily cycles

Migration generally occurs in daily cycles. Because movement occurs at certain times of day, management strategies can include changes through a 24-hour day that could aid both fish migration and conservation of water for other uses. An example is the timing of managed spill, which may be most effective at night (although subject to site-specific considerations).

Surface orientation, following flow

The surface orientation of juvenile salmon during migration with river flow indicates that bypasses at dams should cater to this behavior rather than oppose it (see also Section VII). Currently, adult passage at dams is more consistent with fish behavior in the normative river than is juvenile passage (Figure 6.10). Fish ladders mimic the normative river situation, and passage is usually successful. Adults generally swim against the current, orient to shorelines, and are structure oriented. Thus, adult fish ladders are designed along shorelines with attraction flows to entice fish to the ladders, and a ladder itself is a sequence of structures and flows that are similar to what fish would encounter in the normative river situation. Juvenile bypasses, in contrast, operate counter to adapted behavior. The bypasses force the surface-oriented juveniles to dive deeply to enter turbine intakes, thus causing fish to delay in forebays where predators abound. The bypasses counteract the fish's natural tendency to follow water flow in turbine intakes by inserting massive screens in the fish's path. Only the fish's rise in the water column of a gatewell makes use of natural behavior.

Understanding of fish behavior and review of empirical results suggest that there are several management options for bypassing juveniles that are better than turbine-intake screens. Juvenile bypasses can simulate the key features of behavior in the normative river (Figure 6.11). Only recently have the advantages of surface bypasses been taken seriously, even though the success of surface spill and surface ice/trash collectors for passing juveniles was established decades ago (see Bypass section in Chapter 7). Return to the historical river at dam sites is not necessary for successfully passing juveniles when surface spill, surface collectors, and selective use of ice and trash sluiceways are management options that use natural fish behavior.

Turbulent Flows

Use of fluid dynamics of rivers (turbulence and unsteady flows) by juvenile salmonids in assisting their migration (Appendix D), although still theoretical and in need of empirical evaluation, suggests several management options to move toward a more normative river. The first set of options is to use reservoir elevation and volume of river flow, separately or together, to increase the length of turbulent, river-like reaches in reservoirs (Figures 6.12, 6.13, and 6.14). The upstream reaches of reservoirs (often tailwaters of upstream dams) are shallow and river-like. These reaches respond to flow changes in much the same way as the unimpounded river (Figure 6.12). This is especially true in constrained reaches such as much of the lower Snake and Columbia rivers. Increases in river flow raise water levels in these reaches and extend the influence of turbulent conditions downstream. A similar response can be obtained by lowering a reservoir elevation without changing flows (Figures 6.13, 6.14). In each case, more of the length of a reservoir is near the normative, turbulent state. This state provides behavioral cues and physical assists to the downstream movement of juveniles. It, coincidentally, moves particles of water faster and also any fish that migrate passively. Flow augmentation and reservoir drawdowns during the migration season are recognized as options for aiding juvenile emigration in the current FWP, although the technical justifications may not be fully complete.

Another option is to induce turbulent flow in reservoirs by addition of structural modifications. In reservoirs with small flow velocities, strategic placement of pylons, vanes, or bottom materials could induce vortices and bursts that would both guide migrants and speed their movement (or minimize energetic costs) as they attach to the downstream-moving portions of the vortices. Vertical structures (e.g., pilings) might be added to create horizontal vortices. Bottom roughness might be created to induce vertical bursts (see figures in Appendix VI-1). This approach has not been tested for efficacy in aiding fish migration in reservoirs, but appears viable, in principle. Structures that induce flow changes (baffles) are commonly used as fish guidance mechanisms at dam bypasses (Taft, 1986; Johnson et al., 1992, see Chapter 7). Induction of turbulence with vanes has been used effectively to allow the current of a river to clear channels of sediment (Figure 6.15).

Waves and surges

Waves and surges are another aspect of unsteady flow that may have management utility for assisting emigrants during periods of migration. The spring freshet used by emigrants was probably characterized by changes in flow that were reflected in waves and surges, unlike base flow conditions of autumn and winter that were more stable (Appendix D). It is likely, although not proven, that migrating fish would use the velocity assists of surges and waves to speed their migration or to lessen their energetic cost. These features of unsteady flow can be induced at dams by abruptly varying the output of turbines or spill, which would mimic the unsteady normative river condition during the freshet. Used selectively during emigration periods, flow pulses could be of considerable benefit to migrants that attach to waves.

Diversity

Because the full assemblage of salmonids in the Columbia River basin probably used many migration strategies, a diversity of management schemes should be used to assist migration. Without diversity of management, there is likely to be further stock selection rather than a return to stock diversity as envisioned in our conceptual foundation (Figure 6.16). Please refer to Figure 6.16 during the following discussion. In the normative river (left) migrants (top) consisted of many stocks, with some more abundant than others. This composition was fostered by environmental conditions (bottom) that, over long periods of time, showed a pattern of wide variation (lighter bars). When environmental conditions in one year (bottom, dark bars) were quite different from the long-term norm, less abundant stocks (upper) were favored. Other stocks would be favored in a subsequent year when the environment was different. Individual stock abundance fluctuated over time, but the metapopulation as a whole remained fairly stable. Current conditions (right) have reduced the diversity of stocks (top) and increased the likelihood that most remaining stocks would be disadvantaged by environmental conditions in any one year (bottom). Management of the mainstem migration corridor to increase stock diversity (by providing suitable habitats and flows throughout the migration season) will increase the ability of the overall metapopulation to be maintained. Although some inadvertent stock selection is inevitable, an understanding of different migration behaviors among species and stocks can help managers design broadly compatible features of the multi-purpose river system.

Research

Clearly, more study is required for these management options to become realities. Studies in both basic fish behavior and evaluation of management options are needed. Although there are tantalizing hints in the literature on behavioral biology of fishes, true quantitative understanding of the range of migratory behaviors of salmonids useful for designing normative-river structures is mostly lacking. Our long drawn out history of bypass developments for juveniles strongly indicates that future effort needs to be directed first at basic biological studies of behavior and ecology before investing in additional technolgical solutions and hardware.

Each of the general management options we suggest as being compatible with a redirection toward normative river conditions needs thorough evaluation. The framework of moving toward a normative river ecosystem should provide guidance to those studies, not dictates or more “pet projects.” For example, creation of more turbulent flows in the upstream reaches of Snake River reservoirs to benefit juvenile migrations requires detailed examination of the river lengths affected by drawdowns to specific elevations (e.g., spillway crest). A useful example is the research and analysis that went into the 1983 settlement agreement for Columbia River flows downstream of Priest Rapids Dam to establish what we would call “normative” base-flow conditions for protection of fall chinook spawning and incubation on Vernita Bar and the rest of the Hanford Reach.

Literature Cited

Citations contained in curly brackets { } are not presently in the literature cited.

Achord, S., D.J. Kamikawa, B.P. Sandford and G.M. Matthews. 1995. Monitoring the Migrations of Wild Snake River Spring and Summer Chinook Salmon Smolts, 1993. Portland, Bonneville Power Administration. Oregon.

Albertson, M.L. and D.B. Simons. 1964. Fluid mechanics. Handbook of Applied Hydrology. V. T. Chow. New York, McGraw Hill Book Co.**:** 7-1 - 7-49.

Anderson, D.A., G. Christofferson, R. Beamesderfer, B. Woodard, M. Rowe and J. Hansen. 1996. StreamNet: Report on the Status of Salmon and Steelhead in the Columbia River Basin - 1995. Portland, Bonneville Power Administration. Oregon**:** 76.

Andrew, F.J. and G.H. Geen. 1960. Sockeye and Pink Salmon Production in Relation to Proposed Dams in the Fraser River System, International Pacific Salmon Fisheries Commission**:** 259.

Andrews, R.E. 1958. Factors influencing the seward migration of smolt steelhead trout in the Alsea River, Oregon. Corvallis, Oregon State University. Oregon.

Arnold, G.P. and P.H. Cook. 1984. Fish migration by selective tidal stream transport. Mechanisms of Migration in Fishes. J. D. McCleave, G. P. Arnold, J. J. Dodson and W. H. Neill. New York, Plenum Press**:** 227-261.

Asherin, D.A. and J.J. Claar. 1976. Inventory of Riparian Habitats and Associated Wildlife along the Columbia and Snake Rivers. Walla Walla, US Army Corps of Engineers. Washington.

Bauersfeld, K. 1978. The Effect of Daily Flow Fluctuations on Spawning Fall Chinook in the Columbia River, Washington Dept. of Fisheries. Washington.

Beauchamp, D.A., M.F. Shepard and G.B. Pauley. 1983. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest). Chinook Salmon. Seattle, University of Washington, Fishery Research Unit. Washington.

Becker, C.D. 1973. Columbia River thermal effects study: reactor effluent problems., J. Water Pollut. Control Fed. 45(5):850-869.

Becker, C.D. and C.C. Coutant. 1970. Experimental Drifts of Juvenile Chinook Salmon through Effluent at Hanford in 1968. Richland, Battelle-Northwest. Washington.

Beeman, J.W., D.W. Rondorf, J.C. Faler, M.E. Free and P.V. Haner. 1990. Assessment of Smolt Condition for Travel Time Analysis. Portland, Bonneville Power Administration. Oregon.

Bentley, W.W.a.H.L.R. 1976. Delayed migrations of yearling chinook salmon since completion of Lower Monomental and Little Goose Dams on the Snake River., Trans. Am. Fish. Soc. 105(3):422-424.

Berggren, T.J. and M.J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. North. Am. J. Fish. Manage. 13: 48-63.

Buettner, E.W. and A.F. Brimmer. 1993. Smolt Monitoring at the Head of Lower Granite Reservoir and Lower Granite Dam: Annual Report 1992. Boise, Bonneville Power Administration. Idaho**:** 64.

Buettner, E.W. and A.F. Brimmer. 1995. Smolt Monitoring at the Head of Lower Granite Reservoir and Lower Granite Dam. Annual Report for 1993 Operations. Portland, Bonneville Power Administration. Oregon.

Cada, G., M.D. Deacon, S.V. Mitz and M.S. Bevelhimer. 1994. Review of information pertaining to the effects of water velocity on the survival of juvenile salmon and steelhead in the Columbia River Basin., Northwest Power Planning Council**:** 70.

Cada, G.F., M.D. Deacon, S.V. Mitz and M.S. Bevelhimer. 1994. Review of Information Pertaining to the Effect of Water Velocity on the Survival of Juvenile Salmon and Steelhead in the Columbia River Basin. Oak Ridge, Oak Ridge National Laboratory. Tennessee.

Chapman, D.W., D.E. Weitkamp, T.L. Welsh and T.H. Schadt. 1983. Effects of Minimum Flow Regimes on Fall Chinook Spawning at Vernita Bar 1978-82. Boise, Don Chapman Consultants, Inc. Idaho.

Connor, W.P., H.L. Burge, D. Steele, C. Eaton and R. Bowen. 1995. Rearing and emigration of naturally produced Snake River fall chinook salmon juveniles. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and K. F. Tiffan. Portland, Bonneville Power Administration. Report No. DOE/BP-21708-3**:** 41-73.

Connor, W.P., A.P. Garcia, A.H. Connor, R.H. Taylor, C. Eaton, D. Steele, R. Bowen and R.D. Nelle. 1995. Fall chinook salmon spawning habitat availability in the free-flowing reach of the Snake Rier. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and K. F. Tiffan. Portland, Bonneville Power Administration. Report No. DOE/BP-21708-3**:** 22-40.

Curet, T.S. 1993. Habitat use, food habits, and the influence of predation on subyearling chinook salmon in Lower Granite and Little Goos Reservoirs, Washington. Moscow, University of Idaho. Idaho.

Dauble, D.D., R.H. Gray and T.L. Page. 1980. Importance of insects and zooplankton in the diet of 0-age chinook salmon (*Oncorhynchus tshawytscha*) in the central Columbia River. Northwest Science 54(4): 253-.

Dauble, D.D., T.L. Page and J. R. W. Hanf. 1989. Spatial distribution of juvenile salmonids in the Hanford Reach, Columbia River. Fishery Bulletin 87: 775-790.

Dauble, D.D. and D.G. Watson. 1990. Spawning and abundance of fall chinook salmon (Oncorhynchus tshawytscha) in the Hanford Reach of the Columbia River, 1948-1988. Richland, U. S. Department of Energy
Pacific Northwest Laboratory. Washington.

Dawley, E.M.e.a. 1986. Migrational Characteristics, Biological Observations, and Relative Survival of Juvenile Salmonids Entering the Columbia River Estuary, 1966-1983. Portland, Bonneville Power Administration. Oregon.

Elwood, J.W., J.D. Newbold, R.V. O'Neill and W.V. Winkle. 1983. Resource spiraling: an operational paradigm for analyzing lotic ecosystems. Dynamics of Lotic Ecosystems. T. D. Fontaine, III and S. M. Bartell. Ann Arbor, Ann Arbor Science**:** 3-27.

Evermann, B.W. 1895. A preliminary report upon salmon investigations in Idaho in 1894. Bull. U.S. Fisheries Commission 15: 253-284.

Ewing, R.D., C.A. Fustish, S.L. Johnson and H.J. Pribble. 1980. Seaward migration of juvenile chinook salmon without elevated gill (Na+K)-ATPase activities. Trans. Amer. Fish. Soc. 109: 349-356.

Fish Passage Center. 1994. Fish Passage Center Annual Report 1993. Portland, Bonneville Power Administration. Oregon.

Flagg, T.A. and L.S. Smith. 1982. Changes in swimming behavior and stamina during smolting in coho salmon. Salmon and Trout Migratory Behavior Symposium, Univ. of Washington School of Fisheries.

Folmar, L.C. and W.W. Dickhoff. 1980. The parr-smolt transformation (smoltification) and seawater adaptation in salmonids. A review of selected literature. Aquaculture 21: 1-37.

Fryer, J.K. 1995. Columbia River Sockeye Salmon. Seattle, University of Washington. Washington.

Fulton, L.A. 1968. Spawning areas and abundance of chinook salmon (*Oncorhynchus tshawytscha)* in the Columbia River Basin--past and present, USDI, Fish and Wildl. Serv.,.

Garcia, A.P., W.P. Connor and R.H. Taylor. 1995. Fall chinook salmon spawning ground surveys in the Snake River. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and K. F. Tiffan. Portland, Bonneville Power Administration. Report No. COE/BP-21708-3**:** 1-21.

Gauley, J.E., R.E. Anas and L.C. Schlotterbeck. 1958. Downstream Movement of Salmonids at Bonneville Dam, US Fish and Wildlife Service.

Gilbert, C.H. 1912. Age at Maturity of the Pacific Coast Salmon of the Genus *Oncorhynchus*. Washington, US Bureau of Fisheries. District of Columbia.

Giorgi, A.E. 1993. Flow Augmentation and Reservoir Drawdown: Strategies for Recovery of Threatened and Endangered Stocks of Salmon in the Snake River Basin. Portland, Bonneville Power Administration. Oregon.

Giorgi, A.E., D.R. Miller and B.P. Sanford. 1990. Migratory Behavior and Adult Contribution of Summer Outmigrating Subyearling Chinook Salmon in John Day Reservoir, 1981 - 1983. Portland, Bonneville Power Administration. Oregon**:** 68.

Giorgi, A.E. and L. Stuehrenberg. 1988. Lower granite pool and turbine survival study, 1987. Portland, Bonneville Power Administration. Oregon**:** 30.

Giorgi, A.E., L.C. Stuehrenberg, D.R. Miller and C.W. Sims. 1986. Smolt Passage Behavior and Flow-Net Relationship in the Forebay of John Day Dam. Portland, Bonneville Power Administration. Oregon.

Giorgi, A.E., G.A. Swan, W.S. Zaugg, T. Coley and T.Y. Berila. 1988. Susceptibility of chinook salmon smolts to bypass systems at hydroelectric dams. N. Amer. J. Fish. Mgmt. 8: 25-29.

Glova, G.J. and J.E. McInerney. 1977. Critical swimming speeds of coho salmon (*Onchorhynchus kisutch*) fry to smolt stages in relation to salinity and temperatures. J. Fish. Res. Board Canada 34: 151-154.

Gregory, R.S. and T.G. Northcote. 1993. Surface, planktonic, and benthic foraging by juvenile chinook salmon (*Oncorhynchus tshawytscha*) in turbid laboratory conditions. Can. J. Fish. Aquat. Sci. 50: 233-240.

Groot, C. 1982. Modifications on a theme - a perspective on migratory behavior of Pacific salmon. Salmon and Trout Migratory Behavior Symposium, Univ. of Washington School of Fisheries.

Groot, C. and L. Margolis, Eds. 1991. Pacific salmon life histories. Vancouver, University of British Columbia.

Hansen, L.P. and B. Jonsson. 1985. Downstream migration of hatchery-reared smolts of Atlantic salmon (*Salmo salar*) in the River Imsa, Norway. Aquaculture 45: 237-248.

Hartman, W.L., W.R. Heard and B. Drucker. 1967. Migratory behaviour of sockeye salmon fry and smolts. J. Fish. Res. Board Canada 24: 2069-2099.

Healey, M.C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, UBC Press.

Hesthagen, T. and E. Garnas. 1986. Migration of Atlantic salmon smolts in River Orkla of central Norway in relation to management of a hydroelectric station. N. Amer. J. Fish. Mgmt. 6: 376-382.

Hoar, W.S. 1976. Smolt transformation: evolution behavior and physiology. J. Fish. Res. Board. Can. 33: 1233-1252.

Horner, N. and T.C. Bjornn. 1979. Status of Upper Columbia River Fall Chinook Salmon. Boise, US Fish and Wildlife Service. Idaho**:** 45.

Irvine, J.R. 1986. Effects of varying discharge on the downstream movement of salmon fry, *Oncorhynchus tshawytscha* Walbaum. J. Fish Biol. 28: 17-28.

Janecek, B.F.U. and O. Moog. 1994. Origin and composition of the benthic invertebrate riprap fauna of impounded rivers. Verh. Internat. Verein. Limnol. 25: 1624-1630.

Johnsen, R.C., L.A. Wood and W.W. Smith. 1987. Monitoring of Downstream Salmon and Steelhead at Federal Hydroelectric Facilities - 1986. Portland, Bonneville Power Administration. Oregon.

Johnson, G.E., C.M. Sullivan and J. M. W. Erho. 1992. Hydroacoustic studies for developing a smolt bypass system at Wells Dam. Fisheries Research 14.

Johnson, L. and R. Wright. 1987. Hydroacoustic Evaluation of the Spill Program for Fish Passage at John Day Dam in 1987, Associated Fish Biologists, Inc.**:** 77 pp. + app.

Johnson, W.E. and C. Groot. 1963. Observations on the migration of young sockeye salmon, *Oncorhynchus nerka*, through a large complex lake system. J. Fish. Res. Board Canada 20: 919-938.

Jonsson, N. 1991. Influence of water flow, water temperature and light on fish migration in rivers. Nordic Journal of Freshwater Research 66: 20-35.

Key, L.O., R. Garland and E.E. Kerfoot. 1995. Nearshore habitat use by subyearling chinook salmon in the Columbia and Snake Rivers. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and K. F. Tiffan. Portland, Bonneville Power Administration. Report No. COE/BP-21708-3**:** 74-107.

Key, L.O., J.A. Jackson, C.R. Sprague and E.E. Kerfoot. 1994. Nearshore habitat use by subyearling chinook salmon in the Columbia and Snake Rivers. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. D. W. Rondorf and W. H. Miller. Portland, Bonneville Power Administration. Report No. DOE/BP-21708-3**:** 120-150.

Kiefer, R.B. and J.N. Lockhart. 1995. Intensive Evaluation and Monitoring of Chinook Salmon and Steelhead Trout Production, Crooked River and Upper Salmon River Sites. Portland, Bonneville Power Administration. Oregon.

Krcma, R.F. and R.F. Raleigh. 1970. Migration of juvenile salmon and trout into Brownlee Reservoir, 1962-65. Fishery Bulletin 68: 203-217.

Ledgerwood, R.D., F.P. Thrower and E.M. Dawley. 1990. Diel sampling of migratory juvenile salmonids in the Columbia River estuary. U.S. Fishery Bulletin 89: 69-78.

Lichatowich, J., L. Mobrand, L. Lestelle and T. Vogel. 1995. An approach to the diagnosis and treatment of depleted Pacific salmon populations in Pacific Northwest watersheds. Fisheries 20(1): 10-18.

Lichatowich, J.A. and L.E. Mobrand. 1995. Analysis of chinook salmon in the Columbia River from an ecosystem perspective, Mobrand Biometrics.

Lindsey, C.C. and J.D. McPhail. 1986. Zoogeography of fishes of the Yukon and Mackenzie basins. Zoogeography of North American Freshwater Fishes. C. H. Hocutt and E. O. Wiley. New York, Wiley and Sons**:** 639-674.

Lister, D.B. and H.S. Genoe. 1970. Stream habitat utilization by cohabiting underyearlings of chinook (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon in the Big Qualicum River, British Columbia. J. Fish. Res. Board Canada 27: 1215-1224.

Long, C.W. 1968. Diel movement and vertical distribution of juvenile anadromous fish in turbine intakes. U. S. Fishery Bulletin 66: 599-609.

Long, C.W. 1968. Research on Fingerling Mortality in Kaplan Turbines, NMFS/NOAA Northwest Fisheries Science Center.

Mains, E.M. and J.M. Smith. 1963. The distribution, size, time and current preferences of seaward migrant chinook salmon in the Columbia and Snake Rivers. Washington Dept. of Fish. Res. Paper 2(3): 5-43.

Marquett, W., F.J. Ossiander, R. Duncan and C.W. Long. 1970. Research on the Gatewell-Sluice Method of Bypassing Downstream Migrant Fish around Low Head Dams, NMFS/NOAA Northwest Fisheries Science Center**:** 32.

Massey, J.B. 1967. The Downstream Migration of Juvenile Anadromous Fish at Willamette Falls, Oregon. Portland, Oregon State Game Commission, Fishery Division. Oregon**:** 17 + app.

Matthews, G.M., S. Achord, J.R. Harmon, O.W. Johnson, D.M. Marsh, B.P. Sandford, N.N. Paasch, K.W. McIntyre and K.L. Thomas. 1992. Evaluation of Transportation of Juvenile Salmonids and Related Research on the Columbia and Snake Rivers, 1990, U.S. Army Corps of Engineers.

Mattson, C.R. 1962. Early Life History of Willamette River Spring Chinook Salmon. Portland, Fish Commission of Oregon. Oregon**:** 50.

McCleave, J.D., F.R.H. Jones, W.C. Leggett and T.C. Northcote. 1984. Fish migration studies: future directions. Mechanisms of Migration in Fishes. J. D. McCleave, G. P. Arnold, J. J. Dodson and W. H. Neill. New York, Plenum Press**:** 545-554.

McDonald, J. 1960. The behavior of Pacific salmon fry during their downstream migration to freshwater and saltwater nursery areas. J. Fish. Res. Board Canada 17: 655-676.

McNeil, W.J. 1992. Timing of passage of juvenile salmon at Columbia River dams**:** 60.

McNeil, W.J. 1993. Stream Discharge and Seaward Migration of Stream-Type Chinook Salmon in the Yakima River (Includes reports of April 25, 1992, May 12, 1992, and March 15, 1993).

McPhail, J.D. and C.C. Lindsey. 1986. Zoogeography of the freshwater fishes of Cascadia (the Columbia system and rivers north to the Stikine). Zoogeography of North American Freshwater Fishes. C. H. Hocutt and E. O. Wiley. New York, Wiley and Sons**:** 615-637.

Miller, D.R. and A.E. Giorgi. 1987. Effects of Flow on the Migratory Behavior and Survival of Juvenile Fall ans Summer Chinook Salmon in John Day Reservoir. Portland, Bonneville Power Administration. Oregon**:** 35.

Monan, G.E., R.J. McConnell, J.R. Pugh and J.R. Smith. 1969. Distribution of debris and downstream-migrating salmon in the Snake River above Brownlee Reservoir. Trans. Amer. Fish. Soc. 98: 239-244.

Mulholland, P.J., J.D. Newbold, J.W. Elwood, L.A. Ferren and J.R. Webster. 1985. Phosphorus spiralling in a woodland stream: seasonal variations. Ecology 66: 1012-1023.

Mundy, P.R.e.a. In press. The historical relation between stream discharge and seaward migration of juvenile spring chinook salmon in the Yakima River. .

National Marine Fisheries Service. 1995. Proposed Recovery Plan for Snake River Salmon. Washington, US Dept. of Commerce, National Oceanic and Atmospheric Administration. District of Columbia**:** 387.

Nelson, W.R., L.K. Freidenburg and D.W. Rondorf. 1994. Swimming performance of subyearling chinook salmon. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. Annual Report for 1992. D. W. Rondorf and W. H. Miller. Portland, Bonneville Power Administration. Report No. DOE/BP-21708-2**:** 39-62.

Newbold, J.D., J.W. Elwood, R.V. O'Neill and A.L. Sheldon. 1983. Phosphorus dynamics in a woodland stream ecosystem: a study of nutrient spiralling. Ecology 64: 1249-1265.

Newbold, J.D., J.W. Elwood, R.V. O'Neill and W.V. Winkle. 1981. Measuring nutrient spiralling in streams. Can. J. Fish. Aquat. Sci. 38(7): 860-863.

Newbold, J.D., P.J. Mulholland, J.W. Elwood and R.V. O'Neill. 1982. Organic carbon spiralling in stream ecosystems. Oikos 38: 266-272.

Nicholas, J.W. and D.G. Hankin. 1989. Chinook Salmon Populations in Oregon Coastal River Basins. Corvallis, Oregon Dept. of Fish and Wildlife, Res. and Devt. Section.

Northcote, T.G. 1962. Migratory behaviour of juvenile rainbow trout, *Salmo gairdnerii*, in outlet and inlet streams of Loon Lake, British Columbia. J. Fish. Res. Board Canada 19: 201-270.

Northcote, T.G. 1984. Mechanisms of fish migration in rivers. Mechanisms of Migration in Fishes. J. D. McCleave, G. P. Arnold, J. J. Dodson and W. H. Neill. New York, Plenum**:** 317-355.

NPPC. 1994. Harvest Management, Northwest Power Planning Council.

Pacific Northwest River Basins Commission. 1974. Anatomy of a River. Vancouver, Pacific Northwest River Basins Commission.

Park, D.L. 1969. Seasonal changes in downstream migration of age-group 0 chinook salmon in the upper Columbia River. Trans. Amer. Fish. Soc. 98: 315-317.

Petrosky, C.E. 1993. Analysis of flow and velocity effects on smolt survival and adult returns of wild spring and summer chinook salmon. Passage and Survival of Juvenile Chinook Salmon Migrating from the Snake River Basin, University of Idaho at Boise, University of Idaho.

Petrosky, C.E. and H.A. Schaller. 1993. A comparison of productivities for Snake River and lower Columbia River spring and summer chinook stocks. 1992 Northeast Pacific Chinook and Coho Workshop, Boise, Idaho.

Peven, C.M., R.R. Whitney and K.R. Williams. 1994. Age and length of steelhead smolts from the mid-Columbia basin, Washington. North Am. J. Fish Mgmt. 14: 77-86.

Raymond, H.L. 1968. Migration rates of yearling chinook salmon in relation to flows and impoundments in the Columbia and Snake Rivers. Trans. of the Amer. Fisheries Soc. 97: 356-359.

Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975. 108(6): 505-529.

Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975., Trans. Am. Fish. Soc. 108(6):505-529.

Raymond, H.L., C.W. Sims, R.C. Johnsen and W.W. Bently. 1975. Effects of Power Peaking Operations on Juvenile Salmon and Steelhead Trout Migrations, 1974, Northwest Fisheries Science Center, National Marine Fisheries Service.

Reimers, P.E. 1973. The length of residence of juvenile fall chinook salmon in Sixes River, Oregon. Research Reports of the Fish Comm. of Oregon 4(2): 3-43.

Rich, W.H. 1920. Early history and seaward migration of chinook salmon in the Columbia and Sacramento Rivers. Bulletin of the US Bureau of Fisheries, Washington, DC 37.

Rondorf, D.W., G.A. Gray and R.B. Fairley. 1990. Feeding ecology of subyearling chinook in riverine and resevoir habitats of the Columbia River. Trans. Amer. Fish. Soc. 119(1): 16-24.

Royal, L.A. 1972. An Examination of the Anadromous Trout Program of the Washington State Game Department. Olympia, Washington State Department of Game. Washington**:** 176 + app.

Saunders, R.L. 1965. Adjustment of buoyancy in young Atlantic salmon and brook trout by changes in swim bladder volume. J. Fish. Res. Board Canada 22: 335-352.

Schreck, C.B. and J.C. Snelling. 1994. Migratory Characteristics of Juvenile Spring Chinook Salmon in the Willamette River (draft). Corvallis, Oregon Cooperative Fishery Research Unit, Dept. of Fish. and Wildlife. Oregon**:** 47 + tables.

Schreck, C.B., J.C. Snelling, R.E. Ewing, C.S. Bradford, L.E. David and C.H. Slater. 1995. Migratory Characteristics of Juvenile Spring Chinook Salmon in the Willamette River. Portland, Bonneville Power Administration. Oregon.

Schreck, C.B.a.H.W.L. 1984. Columbia River salmonid outmigration: McNary Dam passage and enhanced smolt quality., BPA, Project 82-16. 117 pp.

Sedell, J.R. and K.J. Luchessa. 1981. Using the historical record as an aid to salmonid habitat enhancement. Acquisition and utilization of aquatic habitat inventory information. N. B. Armantrout. Bethesda, American Fisheries Society**:** 210-223.

Sims, C. and F. Ossiander. 1981. Migrations of Juvenile Chinook Salmon and Steelhead in the Snake River, from 1973 to 1979, a Research Summary. Seattle, National Marine Fisheries Service. Washington.

Smith, J.R. 1974. Distribution of seaward-migrating chinook salmon and steelhead trout in the Snake River above Lower Monumental Dam. Marine Fisheries Review 36(8): 42-45.

Smith, L.S. 1982. Decreased swimming performance as a necessary component of the smolt migration in salmon in the Columbia River. Aquaculture 28: 153-161.

Snelling, J.C. and C.B. Schreck. 1994. Movement, Distribution, and Behavior of Juvenile Salmonids Passing through Columbia and Snake River Dams (draft). Portland, Bonneville Power Administration. Oregon.

Solomon, D.J. 1978. Some observations on salmon smolt migration in a chalkstream. J. Fish Biology 12: 571-574.

Steward, C.R. 1994. Assessment of the Flow-Survival Relationship Obtained by Sims and Ossiander (1981) for Snake River Spring/Summer Chinook Salmon Smolts. Portland, Bonneville Power Administration. Oregon**:** 82.

Taft, E.P. 1986. Assessment of Downstream Migrant Fish Protection Technologies for Hydroelectric Application. Palo Alto, Electric Power Research Institute. California.

Taylor, E.B. 1990. Environmental correlates of life-history variation in juvenile chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). J. Fish Biology 37: 1-17.

Vannote, R.L., G.W. Minshall, K. W.Cummins, J.R. Sedell and C.E. Cushing. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37(1): 130-137.

Walters, C.J., R.M. Hilborn, R.M. Peterman and M.J. Staley. 1978. Model for examining early ocean limitation of Pacific salmon production. J. Fish. Res. Board of Canada 35: 1303-1315.

Ward, D.L., A.A. Nigro, R.A. Farr and C.J. Knutsen. 1994. Influence of waterway development on migrational characteristics of juvenile salmonids in the lower Willamette River, Oregon. North Am. J. Fish. Mgmt. 14: 362-371.

Ward, J.V. and J.A. Stanford. 1983. The serial discontinuity concept of lotic ecosystems. Dynamics of Lotic Ecosystems. T. D. I. Fontaine and S. M. Bartell. Ann Arbor, Ann Arbor Science Publishers**:** 29-42.

Wedemeyer, G.A., R.L. Saunders and W.C. Clarke. 1980. Environmental factors affecting smoltification and early marine survival of anadromous salmonids. Marine Fishing Review 42: 1-14.

Weihs, D. 1978. Tidal stream transport as an efficient method for migration. J. du conseil International pour l'Exploration de la Mer 38: 92-99.

Williams, J.G. and G.M. Mathews. 1994. A review of flow/survival relationships for juvenile salmonids in the Columbia River Basin. Fishery Bulletin 93: 732-740.

Zaugg, W.S. 1982. Relationships between smolt indices and migration in controlled and natural environments. Salmon and Trout Migratory Behavior Symposium, Seattle.

CHAPTER 7. HYDROELECTRIC DEVELOPMENT

SOURCES OF MORTALITY AND EFFECTIVENESS OF MITIGATION ACTIVITIES

Introduction

The development of the hydroelectric system, dating to the late nineteenth century, has had profound effects on the ecosystems of the Columbia River basin, and it has been especially adverse to the existence of the anadromous salmonids. In this section, we examine what is known about the fate of the anadromous salmonids in the hydroelectric system, including the outcomes of the attempts which have been made to improve the survival of the migrants within the hydroelectric system. Although each dam is different from all others, the reader is first offered an explanation of how fish move through a typical big river hydrolectric dam, as background to the information presented in this section.

The typical large river hydroelectric dam presents challenges to the migrations of both juveniles and adults (Figure 7.1) Juvenile emigrants, moving down the river in the direction from left to right in Figure 7.1, may pass the project by one of three basic routes; the spillway (Point A; blown-up in inset B), the powerhouse (Right of Point A) or the powerhouse bypass system, if present (Enter powerhouse at right of Point A, exit vicinity of Point D). As seen in a cross section of the powerhouse (inset Circle, Figure 7.1), on following the flow of the water onto the upstream face of the powerhouse, the juveniles are forced to dive in order to follow the water flow (Arrows below Point F in the inset) into the entrance to the turbine gallery. If the project has a bypass, the juvenile may encounter a screen which sends it up into the body of the powerhouse, (Up Arrow, below Point F) and on into a series of passages that will bring it out of the powerhouse it below the dam in the vicinity of Area D (Figure 7.1) If it misses the screen, the juvenile will continue on through the turbine, exiting near the downstream side of the powerhouse in the vicinity of point D. Note that point D describes the same basic area in both the circular inset and the main drawing. Adult immigrants moving up the river from right to left in Figure 7.1 may enter the adult powerhouse bypass along the bank to the right of the powerhouse(enter near downstream Point E, exit upstream of powerhouse, Figure 7.1). Adults may also enter the navigational lock to the left of the spillway, exiting at the left-most point E)

A. WATER BUDGETING AND FLOW AUGMENTATION

A primary mitigative activity in the mainstem is the use of water stored in upstream reservoirs to decrease the travel time of juveniles through the mainstem. Water budgeting to flush juveniles is a complex process involving monitoring of fish passage from one dam to the next and selective releases and/or bypass spills of water from the dams. An equally complex consultation process for forecasting runoff and planning annual water budgets has eventuated and is authorized in the Council's FWP (Northwest Power Planning Council, 1994).

Also, potentially lethal high temperatures associated with low flows in late summer in the mid and lower reaches of the Snake and Columbia Rivers and some of the arid land tributaries have been documented. Hence, recovery efforts recently have focused on elevated flows in late summer drawn from headwater storage reservoirs (National Marine Fisheries Service, 1995).

We noted above (Chapter 6) that an incremental, empirical relation between flow and survival has not been demonstrated, even though it is likely that survival is higher on high runoff (wet) years. We also suggested (Chapter 6) that using non-seasonal flow augmentation to force underyearlings out of the Snake and Columbia Rivers (smolt flushing flows) may do more harm than good because they may not have accumulated necessary growth and energy reserves for successful emigration. Underscoring these substantial uncertainties in flow augmentation rationale is the fact that summer drawdowns in upstream storage reservoirs, for example at Hungry Horse Reservoir in Montana, to accomplish summer smolt flushing flows in the lower Columbia River has direct and potentially negative implications for nutrient mass balance and food web productivity in Flathead Lake, located downstream from Hungry Horse. Indeed, integrated rule curves (IRCs) developed for regulating releases from Hungry Horse and Libby Reservoirs in Montana to minimize impacts on reservoir food webs apparently are compromised by flow augmentation during late summer in the lower Columbia River (Marotz et al., 1996). Owing to uncertainties associated with water budgeting and flow augmentation, considerable debate and at least one Congressional hearing has ensued (Senate Subcomittee on Science, Technology and Space, June 18, 1996), with upriver interests noting lack of a flow survival relation associated with flow augmentation in the lower river and lower river interests citing need for elevated flows to improve late summer travel time and potentially reduce high temperatures.

We concur with Stanford et al. (1992) that nonseasonal flow augmentation in the lower Columbia will have food web effects in headwater reservoirs and regulated lakes, like Flathead, although research to clarify influences of mass fluxes of water and nutrients, as influenced by natural and regulated flow dynamics, specifically on growth, behavior and populations dynamics of resident salmonids is needed. We also note that the IRCs developed for Libby and Hungry Horse Reservoirs (Marotz et al., 1996) provide seasonality of flow in downstream reaches as called for under our normative river concept. Loss of the spawning cue associated with the spring freshet is a primary problem for recovery of endangered species of sturgeon downstream from Libby Dam (Marotz et al., 1996). Reregulation to produce freshet flows in the spring for creation spawning habitat and stabilized daily fluctuations in flows to provide shallow water habitat for larval recruits likely will be beneficial to all native fishes in headwater rivers like the Flathead, Kootenai, Clearwater, Clark Fork, Pend Orielle, Upper Columbia, Owyhee, Boise, Deschutes, Willamette and others that are regulated by large storage reservoirs.

Occurrence of high temperatures in the lower Columbia and Snake Rivers will remain problematic under either a normative river or flow augmentation strategy. Heat storage in the mainstem reservoirs will occur, especially on dry, hot years. Release of deep, cold water from headwater storage reservoirs will not ameliorate high temperatures because the reservoirs are too far upstream. However, restoration and enhancement of interstitial flow pathways and discharge of ground water into channel and floodplain habitats of the alluvial reaches (Figure 2.5) likely will cool temperatures in the Hanford Reach and middle and lower reaches of the arid land tributaries. Hiram Li and colleagues at Oregon State University (personal communication) have recently shown that salmon and steelhead move into discrete cold water zones associated with upwelling ground water during hot, low flow periods in the lower John Day River. Similar situations likely occurred on all tributaries draining the arid lands of the Columbia Plateau prior to regulation of these rivers. Today flow abstraction for irrigation has dewatered the alluvial flood plains of the middle and lower reaches of these rivers. For example the middle reach of the Yakima River has been completely dewatered for significant periods during dry years and over 50% depleted on average flow years; summer base flows increase downstream as a consequence of irrigation return flows mainly from shallow, often turbid drainage canals. On the Yakima and other tributaries on the arid Columbia Plateau, loss of baseflow very likely has significantly reduced the natural buffering effect on high summer temperatures formerly mediated by complex interstitial flow pathways of the expansive flood plains. Loss of riparian vegetation due to dewatering and grazing by cattle likely adds to the thermal loading of what water does flow through the impaired reaches. In such cases the solution would be to increase and stabilize late summer flows to increase interstitial flow and decrease propensity for temperature increases. Limiting grazing in the riparian zone of key reaches also seems logical. We believe that restoring function to the alluvial reaches could have significant buffering effect on mainstem temperatures or at least provide thermal refuges. Note here that we explicitly distinguish reregulation to elevate base flows of abstracted reaches of tributaries from flow augmentation to flush smolts through mainstem reaches. These are two very different concepts. The former is based on documented ecological processes (Stanford et al., *in press*); whereas the latter is purely technological and largely unsubstantiated.

Conclusions (level of proof)

1. Establishment of normative river condtions will make the process of designing a water budget specifically to move fish unecessary, as the new hydrograph will more closely match historic hydrographs to which the fish were adapted. (1)

2. Development and application of integrated rule curves for reservior operations throughout the basin may be a mechanism for achieving a rereguallted hydrograph that is consistent with our normative ecosystem concept. (2)

3. Restoration of ecologically functional flood plains in the arid land (Columbia Plateau) tributaries likely will moderate high summer temperatures, as well as other habitat problems in the arid land tributaries and may moderate mainstem temperatures in late summer. (3)

Uncertainties

1. Human mediated changes in mass fluxes of water and nutrients may not significantly influence salmonid and other top consumers in food webs in headwater reserviors and regulated lakes (e.g., oligotrophic Flathead and Pend Orielle Lakes), because population dynamics are controlled more by physical habitat variables, harvest and non-native predators. For example, cascading food web effects associated with nutrient supply (bottom-up effects) are moderated by continual, extreme nutrient limitation thereby accelerating effects of overharvest, non-native predator invasions and other cascading effects that occur at higher trophic levels (top-down effects).

2. Food webs and hence food supply for juvenile salmonids in the laucustrine reaches of the lower Snake River and Columbia River downstream from Grand Coulee Dam may be very unstable owing to high rates of mass flux related to low storage capacity and loss of riverine habitat characteristics.

3. The interaction between normative flows and flood plain function may be insufficent to moderate high summer temperatures in the mainstem river, especially on dry years.

Recommendations

1. Implement food web research in relation to water and nutrient mass flux throughout the basin.
2. Develop integrated rule curves for all reserviors to help facilitate implementation of normative flows and integrate implications for flow management derived from food web research.

B. EFFICACY OF MAINSTEM RESERVOIR DRAWDOWN

Seasonal drawdown of lower Snake and Columbia River reservoirs has been examined as a mitigation tool. Rationale for temporary drawdown focuses primarily on the potential to increase travel time for emigrants. However, this has not been clearly demonstrated. Also, we point out in Chapter 6 that concentration of salmonid juveniles with predators and loss of shallow water habitats are potential problems with drawdown scenarios.

However, permanent drawdown to expose and revitalize drowned alluvial reaches to create riverine habitat for salmonids similar to the Hanford Reach likely is warranted in view of our normative river concept. The Hanford Reach is the only mainstem area that consistently continues to produce salmonids and it is one of only a few river reaches in the entire Columbia River system that provides riverine habitat for a "healthy" salmon stock. However, the Hanford fall chinook spawn only in the upper two thirds of the reach, probably because interstitial flow pathways are nonfunctional in the lower third of the reach due to the elevated water table created by virtual continual maintenance of the full pool elevation of McNary Reservoir. Lowering the McNary pool likely would lower the water table in the alluvial reaches upstream, significantly increasing the size of the river reach at Hanford containing both surface and ground water habitat components. Similarly, the flood plain functions of the Yakima River delta might also be significantly restored.

Restoration of a historically productive and complex riverine segment might also occur through drawdown of John Day pool to spillway crest (Figure 7.2). The upper portion of John Day pool, which lies immediately below the confluence of the Snake and Columbia Rivers, contains what was formerly a large alluvial reach that served as a highly productive area for mainstem spawning chinook populations. Populations in this area, may have functioned as a metapopulation, and served as a core to stabilize chinook salmon production in the region. Restoration and revitalization of the upper John Day pool as a free-flowing river segment might assist in the reestablishment of chinook salmon production and metapopulation structure through straying and dispersal from the adjacent Hanford Reach chinook.

It is logical to note that if normative conditions can be enhanced through drawdown of selected reservoirs to spillway crest, then the “natural river option”, which requires breaching or bypassing dams would be likely to yield normative conditions beyond that achieved by drawdown. These options to increase normative conditions and salmon production in the Basin need to be discussed in an open forum and evaluated with respect to their biological, as well as social and cultural, benefits and costs.

Conclusion (level of proof)

1. Drawdown of mainstem Snake and Columbia Reservoirs to restore drowned alluvial river reaches that were historic salmon producing areas is consistant with our normative ecosystem concept. (1)

Uncertainties

1. Fine sediments stored on the bottom of mainstem reserviors may be problematic for restoration of drowned flood plains owing to extreme turbidity resulting from flushing of fines downstream after drawdown.

2. Fluvial geomorphic responses of dewatered flood plains are difficult to predict and relate to normative flow recommendations for restoration.

Recommendation/ Implications

1. Discuss permanent drawdown and natural river options in an open forum that evaluates their biological, as well as social and cultural, benefits and costs.

2. Identify one or more reservoirs in the Columbia or Snake River where biological and social/cultural considerations suggest that drawdown or natural river options can enhance normative conditions and salmon production.

3. Develop protocols to implement drawdown or natural river options, including the necessary monitoring and evalution to assess increases in normative conditions and responses by salmon populations.

C. BYPASS: Mortality Of Salmonid Smolts At Dams And Development Of Bypass Systems In The Columbia Basin

The emphasis in this section is on studies and development of bypass within the Columbia Basin. However, we wish to stress that these did not occur in isolation from studies and developments that have occurred elsewhere in the world.

As the nearest large river to the north, the Fraser River stands as an example where experience with salmon is useful for comparison with experience in the Columbia. We discuss this in some detail in another section of our report, but the application of the example merits some attention in this section. At the behest of the International Pacific Salmon Fisheries Commission, Andrew and Geen in 1960 undertook an analysis of the probable effects of hydroelectric development in the Fraser River, British Columbia on salmon production in the Fraser system. The proposed development would have involved construction of 18 dams on the mainstem and 44 on tributaries. They concluded that,

> *"Dam construction presents a serious threat to the continued expansion - and indeed the very existence - of the commercial and recreational value of the Fraser River fisheries resource.....Although the fish-dam problem has existed for centuries in many countries, no practical solutions have yet been found that afford complete protection for anadromous fish in rivers obstructed and altered by large dams."* (Andrew and Geen, 1960).

Largely on the basis of their conclusions, the Fraser River mainstem remains undammed to this date. Although their study was completed in 1960, their conclusion that no practical solution to the fish-dam problem has yet been found, still applies, as borne out by experience in the Columbia River which is summarized below.

INTRODUCTION

The need for development of bypass systems for salmonid smolts in the United States has its origin in 1906 with Public law 262, which gave the Secretary of Commerce responsibility for fish passage facilities at federally licensed projects (Office of Technology Assessment, 1995). Later the Federal Power Act of 1920 (U.S.C. § 791a, § 811), provided that the Secretary of Interior may require fishways at all federally licensed projects.[1]

[1] With the transfer in 1970 of the Bureau of Commercial Fisheries, now NMFS/NOAA into the Department of Commerce, leaving the Fish and Wildlife Service in the Department of Interior, the authority is now shared by those departments.

Accordingly, passage for adult salmon was provided at the FERC licensed dams in the Columbia Basin. In addition, when Congress authorized the non-federally licensed projects, i.e. the U.S. Army Corps of Engineers and U.S. Bureau of Reclamation projects, they required fishways at all except Grand Coulee Dam and Chief Joseph Dam.[2] Hells Canyon Dam, constructed by Idaho Power Company on the Snake River included fishways that were not successful, (Petersen, 1995). By the time even the earliest of these projects were constructed, Rock Island Dam in 1933, Bonneville Dam in 1938, and Grand Coulee Dam in 1941, studies of salmon

Box 1. Success of fish ladders. The need to provide for fish passage at dams is a worldwide problem that has been studied since before the turn of the century, (Andrew and Geen, 1960; Bell, 1991) {Clay, 1995}. Andrew and Geen note that the earliest known record of the need to provide for free passage of fish in rivers dates from the Magna Carta in the year 1215. The constitution of the State of Oregon, which entered the union in 1859 included a requirement for fish passage at all dams on Oregon rivers. Criteria for the earliest ladders at the Columbia River projects were largely derived from experience elsewhere on smaller rivers. Initial problems with adult passage at Rock Island Dam, the first dam on the mainstem, were soon overcome. Criteria for design and operation have been developed (Bell, 1991; Bates, 1992). Milo Bell, as engineer, and Harlan Homes, as biologist were involved in the design of fish ladders at Bonneville Dam, the next to be built on the mainstem (Mighetto and Ebel, 1994). Refinements in design and operation of fish ladders resulted from the work of Collins and Elling at a laboratory constructed in 1955 by the COE at Bonneville Dam (Mighetto and Ebel, 1994). While in general adult passage facilities are effective in design and operation (Mighetto and Ebel, 1995), questions remain about possible delays in movement of adults approaching and passing through the ladders. And declines in counts at succeeding dams have been explained as losses of fish in transit due to their inability to locate entrances or similar causes. However, part of the explanation is due to turnoff into tributaries, harvest, and mainstem spawning, as well as to fall back of adults that are thus counted twice, and other factors. A recent review of the available information led Chapman et al (1994) to conclude that the best estimate is a 5% loss of adult chinook between dams, resulting from all of the factors listed above. Recent advancements in the technology of following radio tagged adults has made it possible to closely track individual adult salmon as they make their approach to the dams and fishways, and as they transit {Steuhrenberg, 1994, Bjornn, 1993, 1994} This tool has moved the science of adult passage to the point where it is possible to identify locations virtually anywhere in the river where fish may encounter delays or difficulties finding their way past the projects, and to design corrective measures, where they may be called for. Those studies are still_under way, or in process of interpretation.

[2] Since 1888, the Secretary of the Army has had the authority from Congress to "... in his discretion direct and cause to be constructed practical and sufficient fishways, to be paid for out of the general appropriations for the streams on which such fishways may be constructed." (33 U.S.C. 608).

behavior in laboratory settings and observations in the field had developed criteria for design of fish ladders that were generally successful in passing adults uptream {Clay 1995} (Andrew and Geen, 1960; Bell, 1991; Mighetto and Ebel, 1995).

MORTALITY OF JUVENILE SALMON IN TURBINES

On the other hand, while the need for adult passage was obvious, the need to provide downstream passage for juvenile salmon, although it was suspected by many, (Mighetto and Ebel, 1995), was denied by others (Office of Technology Assessment, 1995; Petersen, 1995), and was not clearly documented until Harlan Holmes conducted a set of experiments at Bonneville Dam from 1938 to 1948 that showed a loss of 11% to 14% of juveniles in passing through turbines {Bell, et al 1967}.

Box 2. Andrew and Geen (1960) and Bell et al, {1967} state that downstream migrant bypass facilities were provided at Bonneville Dam when it was built in 1938. There were four such facilities at Bonneville. Although no description is given, they were apparently surface collection devices placed at the north end of the spillway and south end of the powerhouse (Mighetto and Ebel, 1995), in conjunction with screened water intakes, where it was hoped they would attract juvenile migrants away from the turbines or spillway. They were found to be inneffective for that purpose, as they were sampled by the COE biologist, Ivan Donaldson; and by the 1950's were being used primarily to obtain samples of fish moving past the project (Anas and Gauley, 1956), but their presence demonstrates that biologists were aware of the potential need for juvenile bypass prior to the construction of Bonneville Dam.

Holmes' experiment followed a procedure suggested by Rich (1940), as noted by (Schoeneman et al., 1961). It involved the release of several sets of marked fish, each set consisting of two groups of juvenile chinook salmon, a control group released in the tailrace and a second group released so they would pass through the turbines. He then allowed his marked fish free access to the river. His conclusions were then based on the recovery of marked adults as they returned in subsequent years. Holmes never published the results of his study, though they were known by those working in the field. They continue to be cited as a memorandum in his files, e.g.

(Schoeneman et al., 1961) {Bell et al, 1967}[3]. Bell and Holmes worked closely together for years, for example in the design of the fish ladders at Bonneville Dam (Mighetto and Ebel, 1995).

Box 3. Recently, it was brought to light that Holmes was prevented from publishing his results by his employing agency, the U.S. Bureau of Fisheries (later named the U.S. Fish and Wildlife Service), (Mighetto and Ebel, 1995). Upper level officials ordered that the report be kept confidential. They were concerned about the potential use or misuse of such information in a pending lawsuit brought by the Yakima Indian Nation, in which the Yakimas had asked for compensation for damage to their fishery caused by Bonneville Dam. Furthermore, COE officials remained skeptical of the results of the study **(Petersen, 1995**, p. 110).

Along with the work of Holmes, other studies attempted to measure losses by releasing fish upstream of the turbines and recovering them in the tailrace with a net equipped with a live box at the cod end where the fish would have sanctuary {Bell et al., 1967}. Initially, there were differences of opinion within the scientific community as to the validity of these studies. They were criticized on the basis that mortality and injury induced by capture in the net itself could not be separated from effects of turbine passage. Once Holmes had established a reference point that was acceptable, it was then possible to proceed with methods using recovery nets in the tailrace that did not require waiting years for the adults to return. Verification by other investigators soon followed, {Schoeneman and Junge 1954, 1959; Schoeneman, 1956} (Schoeneman et al., 1961). Bell et al (1981) summarized the mainstem Columbia and Snake River studies up to 1967. They showed a range of loss from 6% to 20% of juveniles as they passed through the turbines. Iwamoto and Williams (1993) summarized studies conducted since then. A generally accepted figure now is 15%, (Northwest Power Planning Council, 1987) although it is recognized that turbine mortality varies depending on a number of factors, which will be discussed below.

[3] Mighetto and Ebel (1995) note that Holmes' papers are available at the University of Washington Library, Seattle, WA.

Box 4. Estimated mortality of juvenile salmon and steelhead associated with passage through turbines at hydroelectric projects in the Columbia River

(Sources: {Bell et al, 1967}; (DeHart, 1987): Others, more recent, are named in the table.

Dam	**Mortality**	**Year / Author**	**Species**
Bonneville I	11% to 15%	1938-1948 /Holmes {1952}, (Mighetto and Ebel, 1995)	Chinook Subyearlings
	4%	1954 / Weber {1954}, See (Iwamoto and Williams, 1993)	Chinook Subyearlings
Bonneville II	2.3% or 9.5%*	1988-90/ Gilbreath et al {1993}	Chinook Subyearlings
John Day	13%	1980/ Raymond and Sims (1980)	Chinook Yearlings
McNary	11% **	1955; 1956/ Schoeneman et al (1961)	Chinook Subyearlings
Ice Harbor	10% to 19%	1968/ Long {1968}	Coho "Fingerlings"
Lower Monumental	16%	1975/ Long et al (1975)	Coho (20-22/ lb)
	(20% in turbine without perforated plate in gatewell. Not current standard.)		
	3.5%	1994/ Muir et al {1995a}	Chinook Yearlings
Lower Granite	16.9% ***	1987/ Giorgi and Stuehrenberg, {1988}	Chinook Yearlings
Little Goose	8%	1993/ Iwamoto et al (1994)	Chinook Yearlings
Wells	16%	1981/ Weitkamp et al {1981}	Steelhead
Rock Island No. 2 (Bulb Turbines)			
	5.7% or 13%****	1979/ Olson and Kaczynski (1980)	Coho and Steelhead
Big Cliff (North Santiam R. ; Tributary to the Willamette River)			
	11% **	1957/ Schoeneman et al (1961)	Chinook Yearlings and Subyearlings
	13.5%	1957/ Oligher and Donaldson {1965}	Chinook Yearlings
	11.8%	1964/ Oligher and Donaldson {1966}	Chinook Yearlings
	8.6%	1966/ Oligher and Donaldson {1966}	Chinook Yearlings

*Gilbreath et al {1993} provide data that produce a weighted average estimate of 2.3% mortality over three years of study, if fish released in the tailrace are used as reference controls. If fish released near the Hamilton Island Boat Launch downstream are used as the reference controls, the estimate is 9.5%. Their data show that, in the two years for which there are comparisons, fish released in the tailrace experienced an additional 6.8% mortality relative to the downstream release. In 1989, fish were released in the spillway. They survived at a higher rate than the fish released in the tailrace and at the same rate as the fish released donwstream. Therefore, the difference between the two estimtes of mortality in turbines can be explained by the fact that the hgher estimate includes an element of mortality in the tailrace. Fish passing through the spillway were not exposed to this source of mortality. It appears that in the tailrace at Bonneville Dam there are peculiar back eddies or shore areas where there may be concentrations of predators (Ledgerwood et al., 1994).

**Schoeneman et al (1961) found no significant difference between the 1955 estimate of 13% and the 1956 estimate of 8% mortality at McNary Dam, and combined them to get the 11% estimate. Similarly, they combined estimates at Big Cliff for yearlings and sub-yearlings.

***Giorgi and Stuehrenberg (1988) felt that their estimate was on the high side due to failure of test and control fish to mix at recovery sites, as required by the experimental protocol. However, their estimate agrees with the later one of Iwamoto et al (1994).

****There was a dispute over the results of this study at Rock Island. The point estimate was 5.7% mortality, but an ad hoc committee appointed to review the study found that there was no significant difference between that estimate and the estimates at Big Cliff and McNary dams, (Chapman and McKenzie, 1980). Nevertheless, the Administrative Law Judge for FERC found in favor of the 5.7% estimate, but ordered development of a bypass system, (Rock Island Project, 34 FERC 63,044 at 665, 167.)

Estimates using HI-Z Turb'n Tag {Heisey et al, 1992}

Rocky Reach Dam			
Variable blades	7%	1994/RMC Env. Serv. and Skalski {1994}	Chinook Yearlings
Fixed blades	3.9%	1994/RMC Env. Serv. and Skalski {1994}	Chinook Yearlings
Lower Granite Dam	5.2%	1995 /RMC Env. Serv., mid-Col. Consulting, and Skalski {1995}	Chinook Yearlings

MORTALITY OF JUVENILE SALMON IN RIVER REACHES

It was recognized that the design of some of the turbine mortality studies left open the possibility that the estimates may have included mortality due to other factors, or may have omitted some causes indirectly associated with turbine passage. In addition to losses of smolts in direct turbine passage, losses have been identified in intake and discharge structures, the tailrace or reservoir, and losses due to predation as an incidental effect of turbine passage, or other losses not directly assignable to turbine effects, (Long et al., 1975). The HI-Z Turb'n Tag {Heisey et al, 1992} makes it possible to recover test fish in the tailrace immediately after they have passed through the turbines or after they have been released in the tailrace as controls, thereby more effectively isolating estimates of mortality directly due to passage through the turbines. The resulting studies have produced estimates in the range of 3.9 to 7%, compared to estimates from other methods that range from 8 to 32%. It must be noted that there is considerable variability from one project to another, and with the exception of recent studies at Lower Granite Dam, that the new technology has not yet been employed at a project where estimates from another method have been obtained.

As another approach to estimating mortality associated with the dams, there have been studies designed to measure total mortality in passing through particular segments of the river, as distinguished from those intended to focus on mortality in turbines. A set of studies conducted over three different years in the mid-Columbia Reach, found an average of about 15% to 16% mortality per project, including mortality in the turbines and reservoirs, for chinook salmon smolts passing the five projects in the mid-Columbia reach (Chapman and McKenzie, 1980; McKenzie et al., 1982; McKenzie et al., 1983)[4]. Similar system-wide mortality estimates of 20 to 25% per project were derived for the Snake River and lower Columbia, (Raymond, 1979; Sims et al., 1984). However, the latter estimates are no doubt higher than in todays system with improved bypasses in place at all of the dams (Steward, 1994; Williams and Mathews, 1994; National Marine Fisheries Service, 1995; National Research Council, 1996).

[4] The 1980 study produced a higher estimate (20%), but there were difficulties in execution of the study design, which called for release groups to arrive at downstream recovery sites at near the same time, which they did not do Chapman, D.W. and D. McKenzie. 1980. Mid-Columbia River System Mortality Study. East Wenatchee, Douglas County Public Utility District No. 1. Washington: 23..

Box 5. Estimated Mortality of Smolts in Passing Through Reaches of River (Sources: Originals as cited, and **Bevan et al, 1994)**

River Reaches	*Mortalities*	*Years / Author*
For Hatchery Chinook		
Mid-Columbia	15%-16% per project (five proj.)	1980/Chapman and McKenzie (1980)
		1982/McKenzie et al (1982)
		1983/McKenzie et al (1983)
Through Lower Granite Reservoir from Asotin		
	18%	1988/Giorgi and Stuehrenberg {1978}
		(Probably an overestimate per the authors)
Lower Granite Reservoir from Asotin to Various Downstream Locations		
To tailrace at Lower Granite	10%	1993/Iwamoto, et al (1994) *
From Lower Granite to		
tailrace Little Goose	14%	1993/Iwamoto et al (1994) *
To tailrace at Lower Granite	8%	1994/Muir et al {1995}
From Lower Granite to		
tailrace Little Goose	21%	1994/Muir et al {1995}
From L. Goose to tailrace L. Monu.	11%	1994/Muir et al {1995}
For Hatchery Steelhead		
Lower Granite Reservoir from Asotin to various downstream locations		

To tailrace at Lower Granite	10%	1994/Muir et al {1995}
From Lower Granite to tailrace Little Goose	22%	1994/ Muir et al {1995}
From L. Goose to tailrace L. Monu.	17%	1994/Muir et al {1995}

For Naturally Produced Chinook

From Lower Granite Reservoir to Lower Monumental tailrace	27%	1994/Muir et al, {1995}

For Naturally Produced and Hatchery Chinook.

(The following figures are taken from the Draft Snake River Salmon Recovery Plan (National Marine Fisheries Service, 1995). They have been criticized by Steward (1994), and Williams and Mathews (1994), who concluded that system and average project mortalities were overestimated (National Research Council, 1995, p. 201). For the purposes of the Recovery Plan and our purposes here, they should be viewed as relative values that provide a comparison of survival before and after Little Goose and Lower Monumental dams were added to the system. In any case they are not relevant to the system as it now exists, as explained in the text below.)

From Salmon River to Ice Harbor Dam: Before and after Little Goose and Lower Monumental Dams Were Built.

Before 1970	11%	Before 1970/Raymond {1979}
After 1970	67%	1970-1978/Raymond {1979}

From Lower Granite to The Dalles Before and After Little Goose, Lower Monumental and Ice Harbor Were Built

Before	37%	Before 1970/Raymond {1979}
After	80%	1970-1978/Raymond {1979}; Sims et al (1994)

This study was designed to test the method and associated assumptions, not to produce survival estimates. Nevertheless, the resulting estimates are close to those in the later study.

According to the Proposed Recovery Plan for Snake River Salmon, conditions have improved considerably since the Snake River studies of Raymond were conducted, (National Marine Fisheries Service, 1995). These improvements have resulted from construction and modification of bypass facilities at some of the dams (construction at Lower Granite and Ice Harbor dams, and modifications at Little Goose and Lower Monumental dams), removal of debris from collection systems, installation of flip-lips in spillways to reduce gas supersaturation, changes in turbine operations, and implementation of the water budget. Their conclusion is supported by the studies of Iwamoto et al (1993) and Muir et al (1995). Although the proposed explanation for the differences in survival rates between those of Raymond and those of Iwamoto et al and Muir et al seems reasonable to some, the new estimates of survival have not achieved universal acceptance. The "PIT Tag" (Prentice, 1990) is a new technology that has made possible studies such as these that can provide estimates of survivals through given "reaches" or segments of the river, where detectors are located at both ends. The proposed procedure for developing such estimates in the Columbia Basin, based on a concept referred to as the Cormack-Jolly-Seber concept (Burnham et al., 1987), was first outlined in a document prepared by Skalski and Giorgi, (1992). This resulted in the Snake River studies by NMFS and the University of Washington in 1993 and 1994, (Iwamoto et al., 1994; Muir et al., 1995). The estimation method employed by Iwamoto et al and Muir et al had been questioned, but at the request of the Council, the ISG supervised a review (Independent Scientific Group, 1996). The ISG issued a report, concluding that the procedure was the best method available for estimating the survival rate in reaches, but methods for determining the variance of the estimates could be improved.

Conditions in the mid-Columbia reach have also improved since the studies of Chapman and McKenzie (1980) and McKenzie et al (1982; 1983) were conducted. Wells Dam has a fully functioning bypass system, as well as new turbines with higher efficiency ratings, and the other projects have added spill amounts as bypass routes for smolts (see Findings of the mid-Columbia Coordinating Committee 1984 to 1993). These factors are discussed in more detail below.

The new estimates of mortality in turbines, along with the estimates of survival in reaches of the river have brought into focus the need to be able to separate turbine induced mortality from mortality from other sources, because the solutions will differ. There have been a few attempts to separate mortality estimates into components for the reservoir and tailrace. Iwamoto et al (1994) produced an estimate of zero mortality for yearling chinook in the reservoir above Lower Granite Dam in 1993, based on a reach survival estimate applying from a point above Lower Granite Dam to the tailrace at little Goose Dam, and an estimate of survival in turbines at Little Goose Dam. Muir et al., (1995) developed an estimate of steelhead smolt mortality from the forebay at Lower Monumental Dam to the tailrace, amounting to 42%. Unfortunately, there seems to be no estimate of mortality of steelhead in turbines for Lower Monumental Dam. However, even assuming the worst, say 20% mortality in the turbines, the result indicates a high loss of smolts in the forebay. At Bonneville Dam, mortality of subyearling chinook in the tailrace downstream to the Hamilton Island Boat Launch was estimated to be 10.5% (Dawley et al., 1989). The data of Johnsen and Dawley (1974) can be used to estimate a 54.5% loss of smolts from the tailrace at Bonneville Dam to Rainier Beach Oregon.

The discussion on bypass systems that follows, focuses on measures that may be taken at the dams to divert salmonid smolts away from the turbine intakes, such as spill, turbine intake screens, surface collectors, conduits to carry diverted smolts for release into the tailrace, and similar measures. While transportation of smolts by barge or truck may be viewed as a type of conduit that depends for its source of fish upon intake screens or surface collectors, we view the focus of transportation as being toward amelioration of mortality in river reaches. In any case, it merits fuller discussion than would be appropriate here, and is discussed at greater length in another section.

SOURCES OF MORTALITY IN TURBINES

The early findings stimulated engineering studies designed to identify factors responsible for the mortalities in turbines and to seek engineering solutions. Existing models of turbine facilities were used in studies designed to explore the factors responsible for the smolt mortality, such as those of Cramer, (1965), Cramer and Oligher (1960; Cramer and Oligher, 1961). Further extensive, pertinent literature on the subject is summarized by Bell et al (1981), Turbak et al (1981), Lucas (1981) and Bell (1991).

Bell et al. (1981) and (Bell, 1991) summarized the findings as follows: Fish survival is related to the efficiency curve of propellor type turbines, highest survival occurring at highest efficiency. All of the Columbia River and Snake River Powerhouses on the portion of the river passable by salmon are equipped with propellor type turbines. Turbines with negative pressure within the draft tube have a higher kill rate than those with positive pressure, pointing to the importance of maintaining an optimum tailwater elevation; in the prototype dimensions it was not possible to establish an effect due to clearances between the runners and wicket gates (as they state - or clearances at other points, such as the hub or the draft tube), though this was suspected to be a potential source of mortality, since larger fish suffered greater mortalities.

They also stimulated studies of behavior of salmonids, as biologists sought to find a clue that might lead to directing juveniles away from the intakes, summarized by (Andrew and Geen, 1960): Examples are (Brett and MacKinnon, 1953; Brett, 1957; Brett and Alderdice, 1958;

Collins and Elling, 1964). They investigated batteries of lights, bubble curtains, electric fields, and sound, among other things. None of these methods was found to be sufficiently effective in directing fish movements to justify full-scale or prototype testing in the field, for application at large hydroelectric projects, (Ebel, 1981); Mighetto, 1994 #16682; Office of Technology Assessment, 1995 #16818]. More information on these is provided in a later section.

Remedies to the turbine passage problem were sought through the decades of the 1960's and 1970's (Mighetto and Ebel, 1995). Best turbine operating criteria were defined - operate at the upper end of the turbine efficiency curve: And design characteristics were analyzed - minimize negative pressures in the draft tube, and avoid clearances around runner blades that could impact fish (Bell, 1967). At the same time, efforts were continued to develop methods for diverting fish away from the turbine intakes.

SPILL AS A MEANS OF BYPASS FOR SMOLTS

NORMAL SPILL

Depending upon the hydraulic capacity of the individual projects and the river flow in the particular year, there will normally be spill during the spring freshet when the largest number of salmonid smolts are moving downstream. Spill provides an avenue by means of which smolts may avoid turbine intakes. Studies of passage through spill are in agreement that mortality of smolts through this route is low or negligible, generally in the range of 0% to 2% in spill, with a potential for added mortality from predation below.[5] Spillway design affects the rate of injury and survival, with freefall being the least injurious {Bell and DeLacy, 1972; Stone and Webster, 1986}. Backroll may be created with certain designs and spill levels, which can trap fish in turbulence, adding to the potential for predation and other causes of mortality {Stone and Webster, 1986}.

[5] Some references state that mortality of smolts in spill ranges from 0% to 4% (Fish Passage Center, 1994), or 0% to 3% (NMFS/NOAA Proposed Recovery Plan, 1995). However, close scrutiny of the studies upon which these numbers are based leads us to conclude that 0% to 2% is the more likely range for standard spill bays, but that local conditions, such as back eddies or other situations that may favor the presence of predators may lead to higher numbers (e.g. such as those Muir et al (1995) suggested may have occurred below Little Goose Dam in 1994.)

Box 6. Estimates of Mortality in spill.

Mortality	*Species*	*Location*	*Reference*
2%	chinook	McNary Dam	Schoeneman et al (1961)
2.2%	steelhead	Lower Monumental Dam	Long et al (1975) (For spill bays with deflectors)
27.5%*	steelhead	Lower Monumental Dam	Long et al (1975) (For spill bays without deflectors)
4%**	chinook	Lower Monumental Dam	Muir et al (1995) (For combined bays)
1.5%	chinook	Lower Monumental Dam	Muir et al (1995) (For spill bay without deflector.)
7%	chinook	Lower Monumental Dam	Muir et al (1995) (For spill bay with deflector.)
0%	steelhead	Wells Dam	Weitkamp et al. (1980) (Confidence interval included 0)
		(See Findings of the mid-Columbia Coordinating Committee for the Period 1979-84)	
1%	coho	Rocky Reach Dam	Heinle and Olson {1981}
0%	chinook	Bonneville Dam	Ledgerwood et al (1990)
0%	chinook	Bonneville Dam	Johnsen and Dawley (1974) (For spill bay with deflector)
0%	chinook	Bonneville Dam	Johnsen and Dawley (1974) (For spill bay without deflector)
1%	chinook	John Day Dam	Raymond and Sims (1980) (point estimate did not differ from 0)
0%	chinook	Little Goose Dam	Iwamoto et al (1994)

- This unusually high estimate at Lower Granite Dam was probably associated either with high predation by sqauwfish or other adverse conditions below the dam, such as were described for Little Goose Dam in 1994 (Muir et al., 1995). See footnote below.

- +* Muir et al (Muir et al., 1995) found no statistically significant difference between the survival estimates for spill bays with and without deflectors, in spite of what the point estimates might suggest

- While the relationship of survival of smolts with flow reported by Sims and Ossiander, (Sims and Ossiander, 1981) now appears to have been an artifact, (Steward, 1994) {Williams and Mathews, 1995} it should not be overlooked that they reported that spill increases survival more than flow. Their analysis suggested that the first 10% of spill increased survival by 28%, while the first 10% increase in flow only added 13%survival.. On the other hand, safe passage may not guarantee survival downstream. (See footnote 5.)

By 1976, the Columbia River was "fully developed" for hydroelectric power generation, as a result of the provision of storage capacity in the upper basin, through construction of Duncan, Keenleyside, and Mica dams in Canada, and Libby and Hungry Horse dams in Montana, {Bonneville Power Administration 1980}. Flood control was an additional benefit identified by the U. S. Army Corps of Engineers and the Bureau of Reclamation (Logie, 1993). The implications for smolt passage were that high river flows previously experienced in the spring during the peak of smolt emigration were reduced such that there was less spill and a higher percentage of the fish had to pass through the turbines.

One early result of reduced flow in the spring from this development was reflected by a complaint filed before the FERC in 1976 by the State of Washington Department of Fisheries, later joined by the Oregon Department of Fish and Wildlife, certain Columbia River Treaty Tribes, and the United States National Marine Fisheries Service against the three mid-Columbia Public Utility Districts, requesting provision of minimum flows for fish at the five projects operated by the PUD's in the mid-Columbia reach, (FERC mid-Columbia Proceeding, Docket # E-9569).

While the primary objective of this petition was to stabilize flows for spawning fall chinook in the Hanford Reach below Priest Rapids Dam, and especially to establish minimum flows to prevent exposure of their redds, the result was a Settlement Agreement, reached among the parties in 1979, that among other things provided for studies over a five-year period to find ways to measure the effects of the projects on the downstream migration of juvenile salmonids in the mid-Columbia reach, to find ways of improving production of salmonids, and as an interim measure provided for spill of 10% of the river flow at each of the projects during the period in the spring when the middle 80% of the migrating smolts were determined to be present. This spill program, which began in the spring of 1980, was the first formal application of spill as a bypass measure for smolts in the Columbia Basin.

In 1989, in response to a measure in the NPPC's FWP, the fishery agencies and tribes, and BPA reached a Memorandum of Agreement on spill to be used as an interim measure at COE projects pending the installation of bypass systems {FPC, 1990}. More information on this subject appears in Parts II and III of this review found in the Appendix.

EFFECTIVENESS OF SPILL

Negotiators felt that a small amount of spill would probably attract and pass a high percentage of the smolts. Subsequent studies using hydroacoustic technology at each of the mid-Columbia projects, revealed that the relationship between the percentage of smolts passed in spill and the spill volume relative to total river flow is complex and varies from project to project. For each of the mid-Columbia projects, studies were conducted to define the relationships between spill volume relative to river flow and the resulting percentages of juvenile fish passed in spill, {Raemhild et al 1984}

(Biosonics, 1983; Biosonics, 1983; Biosonics, 1984). For the studies, spill volume was varied in the range of 20% to 85% spill relative to total river flow. Curves were developed that describe the relationship between spill volume and the percentage of fish passed in spill for each of the projects.

Box 7. As an example of the non-linear relationship often found, at Wanapum Dam in the spring of 1983, night-time spill of 20% of the instantaneous flow passed, on the average about 45% of the fish, while spill of 50% passed 60% of the fish {Biosonics, 1983 d}. On the other hand, at Rocky Reach Dam during the spring of 1983, night time spill amounting to 20% of the instantaneous river flow was estimated to pass about 16% of the fish, spill of 50% passed about 30% of the fish, and spill of 80% passed about 55% of the fish (Biosonics, 1984).

Experience in 1995 at Priest Rapids and Wanapum Dams showed that maintaining spill over a 24 hour period as compared to spill for 12 hours at night doubled the effectiveness of spill in terms of the percentage of fish passed in a given volume of water spilled (see Box 8).

Box 8. In fact, as an example, at Priest Rapids in 1995 using 17% spill for 24 hours a day for 60 days during the summer achieved 62% fish passage, whereas in 1994 spill of 40% for 12 hours per night for 34 nights in the summer only achieved an estimated 33% fish passage **{Hammond, 1995}**.

As for the COE projects, in the late 1970's NMFS/NOAA investigators were seeking ways to increase the smolt passage rate over the spillways (Giorgi and Stevenson, 1995). Spill effectiveness has been intensively studied, using hydroacoustic technology at John Day Dam annually since 1983 (Kuehl and 1986, 1986; Johnson and Wright, 1987; Magne et al., 1987; Ouellette, 1988; McFadden and Hedgepeth, 1990); all as summarized by Giorgi and Stevenson (1995). Magne et al (1987) produced a data set from 1983 that shows a relationship between the percentage of fish passage and percentage of spill in the range from 37% to about 66% spill. The authors focused on developing an overall ratio of percentage fish passage to percentage spill for the whole range of spill values, for the spring and summer seasons, arriving thus at spill effectiveness ratios of 1.3 in 1987, 1.4 in 1989, and 1.1 in summer, 1988. Giorgi and Stevenson concluded that visual inspection of the scattergram of data from the 1983 study showed a ratio that was close to 1.0.

Giorgi and Stevenson combined the data for spring and summer, which seems reasonable in the absence of an expectation of a seasonal difference. When they are plotted separately it becomes apparent that analysis of the spring observations is hampered by a paucity of observations at spill levels other than around 50%. In the spring there were only three observations below 45% spill (four counting the intercept), which leads to caution in drawing inferences. Although our analysis suggests there is a difference between spring and summer, we believe it best to combine the data for spring and summer that are in hand, until a wider range of spill values may be available from the spring period. If the two are combined, the relationship falls short of 1.0. The combined data would estimate 50% fish passage in 60% spill. (Obviously, spill effectiveness must improve at some spill level beyond the observations, since 100% spill must include 100% of the fish.)

The approach used by the authors, using a ratio over the season, assumes a linear relationship between fish passed and relative spill volume, and it must connect that point to the origin (i.e. with zero spill there must be zero fish in spill). That simple model is susceptable to large error at low or high spill levels. It does not fit the experience in the mid-Columbia, as described above. Whether the relationship is linear or curvilinear within the range of the observations (logic would suggest a curvilinear relationship), a regression equation would provide a means for describing a confidence interval about the line.

A study of sluiceway efficiency at The Dalles produced an estimate of spill effectiveness in the process (Willis and Hendricks, 1992). Willis used marked coho that were released in the reservoir above the dam, and released marked coho within the ice and trash sluiceway, then was able, using recovery rates in a trap in the sluiceway, to estimate sluiceway effectiveness at various levels of spill from about 10% to about 60%. The result is a sharply rising curve, showing high spill effectiveness at low spill levels. This result is not surprising, considering the configuration of The Dalles where the spillway is at right angles to the natural course of the river and the powerhouse is nearly parallel to the natural course of the river.

Box 9. Willis developed an equation to describe the relationship between fish passage in the sluiceway and the percentage of river flow that was spilled. He projected the resulting curve through the origin to estimate sluiceway effectiveness at zero spill, arriving at an estimate of 40%. Then, assuming that this 40% estimate of the percentage of fish at the powerhouse would apply for all levels of abundance of fish at the powerhouse (which seems reasonable), he was able to calculate the percentage of fish that must pass through spill at the given flow levels at The Dalles. The equation estimates spill effectiveness of about 30% fish passage at 10% spill, and 75% fish passage at 40% spill. (Willis, 1982). Further details are provided in the appendix.

SURFACE SPILL

On the basis of a study at John Day Dam, Raymond and Sims (Raymond and Sims, 1980) suggested that surface spill would be more effective than standard spill. The standard spill gates in the Columbia River projects are designed to open from the bottom of the spillbay, typically at depths near 50 feet; (47-58 feet below normal operating pool at John Day Dam, for example, according to Giorgi and Stevenson (1995). Raymond and Sims (1980) placed stop logs in the spillbay to create surface spill. They found that smolts passing through the bays with surface spill were as likely to pass in the day time as at night, whereas samples of smolts from the turbine intakes, the ceilings of which were located at about the same depth as the bottoms of the unlogged spill bays, showed a strong peak at night, suggesting that smolts approaching the dam delayed sounding to the intakes until after dark, and that they were more readily passed through surface spill.

Box 10. Giorgi and Stevenson (1995) observed that surface spill remains to be adequately evaluated at COE projects. The COE has begun studies on effectiveness of surface spill. This is discussed further in the Appendix C, Parts 2 and 3.

Some projects are fitted with sluiceway spill gates that open from the top. Wanapum and Priest Rapids dams are each equipped with one such gate that is located closest to the powerhouse in the array of spill gates, (Figure 7.3). They are smaller spill bays, being designed for passage of debris rather than control of water elevation in the forebay. It was thought that spill at these sluiceways might be especially effective in passing smolts because of their proximity to the powerhouse, where flow is normally concentrated. Hydroacoustic evaluations confirmed this hypothesis {Ransom and Malone, 1990; Ransom 1995} (McFadden et al., 1992).

The spillway at Rock Island Dam is equipped with several gates that open from below, but at a depth of about 35 feet, as compared to another set of gates that opens from a depth of about 55 feet. Hydroacoustic studies also found the shallower gates to be more effective in passing fish, per unit volume of water used, than the deeper gates (Ransom et al., 1988).

Box 11. Sluiceway (Surface Spill) Effectiveness in Passing Fish.

Project	*Season*	*Percentage of Fish Passed*	*Percentage of River Flow Spilled*	*Duration of Spill*
Priest Rapids Dam				
	Spring	3.0%	1.3%	12h (night)
		1.6%	0.3%	24h
	Summer	4%	2%	12h (night)
		2.1%	0.6%	24h

Spill in the sluiceway was judged to be twice as effective as spill in the spillway.

Project	*Season*	*Percentage of Fish Passed*	*Percentage of River Flow Spilled*	*Duration of Spill*
Wanapum Dam				
	Spring	4%	0.5%	24h

At Rock island Dam, when spill was split 50:50 between deep and shallow spill gates, the shallow spill gates passed 87% of the fish passing in spill (Ransom et al., 1988).

EFFECTIVENESS OF SURFACE SPILL

Current thinking is that these sluiceways at Wanapum and Priest Rapids dams are more effective than the standard spill gates, not simply because they are located closest to the powerhouse, but because they operate in the upper portion of the water column where the fish prefer to be (see Box 19.) It is now thought that in cases where spill is necessary to accomplish safe passage of a given percentage of smolts, surface spill will be more effective, requiring less water to achieve the objective. Grant County P.U.D. modified a standard spill gate at Wanapum Dam in 1996 to evaluate surface spill. Tests will be conducted in 1996 at The Dalles, and Lower Granite dams to determine whether an overflow weir improves passage at the spillway and to determine at what location and under what conditions an overflow weir will operate most efficiently at those projects. (Source of information - Bill Hevlin, NMFS/NOAA.)

Gas supersaturation, brought about by large volumes of spill remains a problem, which will be discussed in more detail below and in another section. Another complication is that under some powerhouse and spill operations at certain projects, eddies may be created that favor predators and lead to reduced survival below the spillway, as suggested by Muir et al (1995) for Little Goose Dam. They estimated a 7% higher mortality rate of chinook smolts in 1994 compared to 1993, which they thought was brought about by this eddy and the resulting predation by squawfish (see Box 6).

MECHANICAL BYPASS SYSTEMS

INTRODUCTION

A review of development of bypass systems for juvenile salmonids necessarily will include summaries of methods that were tried that failed. The following section briefly reviews the failures and successes. As with all such efforts, the failures ought to shed some light on the path to success.

IMPROVED TURBINE EFFICIENCY

As a result of studies summarized above, showing higher survival of fish in passing through turbines when turbine efficiency is higher, and because damage to the machinery is least at high efficiencies, both factors are incentives to operate the machines in the region of their highest efficiency. Furthermore, improvements have been made in the design of turbines to increase their efficiency, and these have been fitted at a number of projects as replacement occurs. One example is Wells Dam where installation began in 1987 and was completed in 1990, (personal communication Ken Pflueger, Douglas County P.U.D.) At Rocky Reach Dam, planning for installation of such improved turbines began in 1993, and is underway in 1995 with a schedule for completion in the year 2001, (personal communication Bill Christman, Chelan County P.U.D.). At Rocky Reach the schedule for installation of new runners was expedited, and improvements incorporated designs suggested by turbine mortality studies indicating that improvements in fish survival (1.7%) might be obtained thereby {RMC Environmental Services and Skalski 1993}. Ledgerwood et al, (Ledgerwood et al., 1994) suggest that their estimates of smolt mortality in passing through turbines at Bonneville's second powerhouse that are lower than most estimates elsewhere {2.3% or 9.5%, Ledgerwood et al, 1993} were due to higher efficiency of the turbines at that project and a deeper submergence of the blades. (Another explanation has to do with whether fish released in the tailrace are the proper control group to compare as the reference or whether fish released downstream are the proper group. If downstream, the estimate is 9.5% rather than 2.3% mortality. The COE is working to develop an advanced turbine design aimed at improving efficiency and reducing smolt mortality (Office of Technolgy Asessment, 1995)).

TURBINE INTAKE AS A PASSAGE ROUTE

Slotted bulkheads were installed by the COE in 27 of the empty turbine bays in the lower Snake River projects to provide a passage for juvenile fish in 1971 (Mighetto and Ebel, 1995). They induced high mortality on the fish as a result of high water velocities that were created against the bulkheads and they were abandoned.

Free wheeling, or locking of the runners of turbines was investigated at Rocky Reach Dam as a possible means of passing juvenile fish without harm, {Stone and Webster, 1982}. It was concluded that it would not be possible in this way to avoid problems of pressure changes in the scroll case, which would lead to cavitation, and it was not likely to reduce injuries caused by fish strikes in transit.

FLIP-LIP SPILLWAYS

A problem encountered with high spill amounts is gas supersaturation, leading to a condition in fish similar to the divers “bends”, in which gas bubbles appear in the blood stream and other tissues, which can lead to death (Ebel, 1969; Collins et al., 1975; Bouck, 1980). The condition of supersaturation is brought about by the plunging of water from the spillway, carrying air with it and putting it under pressure in the pool below. As the pressure is removed, the bubbles appear. A remedy that has been adopted is a spill deflector (“flip lip”) design for the spillway, which directs the spill in a horizontal direction, rather than vertical {Smith 1974}.

Box 12. Effectiveness of Spill Deflectors. These spill deflectors at Little Goose Dam were shown to reduce gas saturation levels down stream by about 10%, relative to levels before the deflectors were installed, at flows of 123 to 169 kcfs (128% saturation with spill of 46% to 59% of flow), (Park et al., 1977). At Lower Monumental and Lower Granite dams, also equipped with spill deflectors, they found gas saturation levels to be 2% to 8% lower than at Little Goose, under the same flow conditions, probably due to the greater depth of the stilling basin below Little Goose Dam and smaller deflectors there, 8 feet in length compared to 12 feet at the others. At McNary Dam they found gas saturation was lower by 16% to 20% with the spill deflectors in place than it had been before, (op. cit.). In a more thorough analysis, Johnsen and Dawley (1974) developed curves showing the relationship of gas saturation levels below the spillway with forebay gas levels, spill discharges, water temperatures, tailwater elevations and effects of deflectors at Bonneville Dam. With forebay gas levels of 110% and tailrace elevations of 24 feet, the deflectors generally reduced gas saturation levels by about 10% (130% compared to 120%). But at higher discharge rates (thus tailrace elevations) the difference lessened, to the extent that it appeared the deflectors might be disadvantageous at spill discharges above 14 kcfs per bay.

Flip lip spillways have been installed at five of the eight COE projects in the Snake River and lower Columbia River, and are being planned at Ice Harbor and John Day dams in 1997 and 1998 respectively {NMFS/NOAA, 1995; Fishery Agencies and Tribes, 1993} (Bruce, 1995). However, only Lower Granite Dam is fully equipped across the spillway, (See Appendix C, Part 2.)

DIVERSION BARRIERS UPSTREAM OF THE POWERHOUSE

Prior to the construction of Hells Canyon Dam in 1967, and following construction of Brownlee Dam in 1958 it was found that smolts experienced great difficulty in passing through the reservoir above Brownlee Dam, (Graban, 1964; Haas, 1965). As a consequence of the high storage volume relative to inflow and outflow, water velocities were judged to be too low to stimulate movement of the smolts. An additional difficulty was the fact that the turbine intakes were located at depths of over 200 feet, too deep for surface oriented smolts to readily use for passage. This difficulty was well documented elsewhere, as noted by Eicher, (1988). In the reservoir above Brownlee Dam, a barrier net was placed that extended completely across the river at a point 4800 feet upstream of the dam and reached to a depth of 120 feet. The barrier was equipped with a walkway to provide access to three inclined-plane fish traps located at the surface along its length. In addition, in order to attract fish, each of the traps was equipped with a pump to provide appropriate flow to attract smolts. (See "gulpers" described below.) It was found to be difficult to keep the equipment in place under adverse weather conditions and as a result of general accumulation of debris. Furthermore, efficiency of the net in guiding fish was poor as fish passed through or under it (Mighetto and Ebel, 1995).

At Wanapum Dam, a barrier net 12,000 feet long and 40 feet deep, was tested. The net extended laterally from a point on the left bank upstream of the powerhouse across the powerhouse to a point 800 feet west of the powerhouse, leading toward the spillway. In this case, the intention was to lead fish away from the turbine intakes toward the spillway (Tyler and Pock, 1989). Problems that had to be overcome were strong currents that required heavy anchoring systems, accumulation of debris that required deployment of the net with its cork line below the surface, accumulation of periphyton requiring regular cleaning, and the fact that the net only briefly affected migration of smolts that encountered it. After three years, further testing was abandoned when it was concluded the net was not effective at diverting smolts away from the power house.

In 1989, a “forebay wedge screen” was tested at Priest Rapids Dam {Ramsom and Malone 1989}. It consisted of a wedge wire barrier mounted on a framework in the forebay in front of turbine unit 9. Unacceptable head loss occurred due to periphyton growth.

If availability of funds had permitted, the COE planned to test a floating guidance curtain in the forebay of Ice Harbor Dam in 1996. However, this test has been postponed. The intention was to place the curtain so as to divert the downstream migrants away from the powerhouse and toward the spillway. The design was for a net 60 feet in depth. It would leave an opening near the south shore for upstream passage of adult salmon. Evaluation would be by hydroacoustics and by radiotelemetry of juveniles as well as adults to determine their response to the curtain.

FISH “GULPERS”

While the barrier net concept has used nets stretched across the migration path, a related concept has been employed, built around the idea that migrating fish could be attracted or directed to a collection device without completely blocking their path. In some of these, pumps were used to create attraction flows for emigrants, bringing them into an enclosure of some kind (e.g. “Merwin” Trap). Such devices were tested at Pelton Dam on the Deschutes River, Mud Mountain Dam, and Merwin Dam on the Lewis River, (Stockley, 1959; DeHart, 1987). A device with much higher attraction flows was used with some success at Green Peter Dam on the Middle Fork Santiam River, OR, where the device is built into the upstream face of the dam (Wagner and Ingram, 1973). At Baker Lake, WA, a surface collection device of this type was found to be effective at collecting sockeye smolts for transportation below the powerhouse, (Wayne, 1961; Quistorff, 1966). It became a viable solution to the problem of collecting smolts in the reservoir when a lead net was added to the “gulper”, (Cary Feldmann, Puget Sound Power and Light, personal communication).

The NMFS Recovery Plan, (National Marine Fisheries Service, 1995) calls for the IPC to evaluate the efficacy of reintroducing Snake River fall chinook into habitat above the Hells Canyon complex, i.e. Hells Canyon, Brownlee, and Oxbow Dams, as suggested by Armour, (1990). Evaluating the efficacy of that measure would require addressing adult passage over the 300 foot high Hells Canyon Dam, as well as addressing juvenile passage through the slow moving water in the reservoir, and the reluctance of juveniles to sound to the depths where turbine intakes are located. Some of the experience with gulpers suggests possibilities.

GATEWELL SALVAGE

It was early observed that smolts accumulate in turbine intake gatewell slots, a reflection of their tendency to pass through the intakes near the ceiling, This was first observed by C.W. Long, and G. Schneider, according to (Mighetto and Ebel, 1995). Bentley and Raymond, {1969} describe the salvage of juvenile salmonids from gatewells at dams in the Columbia River. A dip basket was developed for use in removing smolts from the gatewells.

A fish salvage operation was undertaken at John Day Dam in 1977, in anticipation of low flows that were expected to lead to accumulation of fish in the gatewells (Johnsen, 1978). The numbers removed from the gatewells were disappointingly low, about 21,000 juvenile salmonids, mostly chinook yearlings.

On the other hand, marked juveniles that were released in the Wanapum reservoir were recovered in the gatewells at Priest Rapids Dam at the rate of 5% for coho, 2.1% for chinook yearlings and 3.6% for steelhead, {CH2M Hill and Wash. Dept. Fish., 1980}. During the initial five years of the mid-Columbia Settlement Agreement, the gatewells at Wanapum and Priest Rapids dams were emptied regularly and enumerated to obtain an index of fish passage. Following the Stipulation of 1985, Grant County P.U.D. has salvaged fish from the gatewells at Wanapum and Priest Rapids dams on a daily basis, weather permitting. Specially designed nets deployed by mobile cranes from the deck of the powerhouse are used to remove fish that have accumulated in the gatewells. Captured fish are placed into tank trucks and transported to below the dam where they are released into the tailrace. In the neighborhood of 200,000 fish are salvaged at each of the two projects each year.

Box 13. As an example of the numbers of fish involved, in 1991, during the spring emigration, there were 142,019 smolts collected from the gatewells at Wanapum Dam that were released in the tailrace below, and 173,273 smolts from the gatewells at Priest Rapids Dam. During the summer emigration there were 31, 218 smolts collected from the gatewells at Wanapum Dam and 46,423 from Priest Rapids Dam. (Personal communication, Stuart Hammond, Grant County P.U.D. No. 2)

AIRLIFT

A gatewell airlift system was tested at McNary Dam in 1981 as part of the study of a proposed intake screen configuration at John Day Dam. While the airlift did not affect the guidance of fish, the turbulence it created in the gatewell made it difficult for the fish to exit through the orifices, leading to unacceptably low orifice passage efficiency {Swan et al, 1982} (Krcma et al., 1983). An airlift installed at John Day Dam is used to sample fish diverted into the gatewell by intake screens [Brege, 1990 #16587; (Wood, 1993).

At Rocky Reach Dam, in 1980, an airlift was investigated as a means of drawing fish out of the gatewells. It was concluded that the airlift was not effective in drawing a significant number of fish up the gatewell, although it could be used to remove some fish from the gatewell (Hill, 1982).

GATEWELL CONDUIT

When the second powerhouse at Rock Island Dam went into service in 1979 it included provision for orifices between the gatewells and a conduit leading from there to the tailrace. It also included a feature allowing for diversion of a portion of the fish thus collected, into a bypass sampler

(Olson, 1981). The effectiveness of the system in diverting fish from the turbine intakes varies among species and from year to year depending upon levels of spill relative to river flow, and ranges around 5 to 15%, being higher in years with low spill.

Box 14. In a 1981 test at Rock Island Dam, average recovery rate of six test lots of coho released in the forebay was 15%. In 1982 four lots each of chinook, steelhead and coho were released in the forebay and brought average recovery rates of 4.1%, 2.2%, and 9.8% respectively. Olson concluded that the difference in recovery rate between the two years was probably due to differences in relative volumes of spill in the two years, more fish passing in spill in 1982, lowering the recovery rate in the gatewells. He felt that many fish sounded out of the gatewells, and that efficiency could be improved by providing a screen (possibly a VBS?) to encourage upward movement of the fish toward the orifices.

OTHER

The Office of Technology Assessment refers to all other devices as “Alternative Behavioral Guidance Devices” (Office of Technology Assessment 1995). They concluded that for the most part, these devices have not been accepted by the resource agencies because they have not been shown to divert a high enough percentage of the fish, (Office of Technology Assessment 1995, p. 87). Stone and Webster {1987} concluded that, up to the time of their review for EPRI, such devices had not offered much promise of meeting agency goals.

Nevertheless, from time to time, there is a revival of interest in these methods, as investigators either have a new perspective on the method, {e.g. Carlson, 1995} or are unaware that it has been tried. Some of these methods have met with varying degrees of success for other species in different applications elsewhere, such as at pump intake diversions or irrigation diversions, (Office of Technology Assessment 1995).

As mentioned previously, in the 1950s and 1960s the Fish Passage Program of the then Bureau of Commercial Fisheries (BCF, now NMFS/NOAA), under the direction of Gerald B. Collins investigated a number of potential methods for their efficacy in directing movements of fish, such as banks of lights, bubble curtains, sound, and electric fields, none of which proved to be practical for application in the field, (Mighetto and Ebel, 1995). Andrew and Geen (1960) reviewed the studies beyond those of BCF and came to the same conclusion. Some other pertinent studies are summarized below.

Electric Fields

Effectiveness of electrical barriers at power plant intakes has been generally poor {Stone and Webster, 1987}. Collins and his colleagues found that successful application of this technology would be limited to situations where velocity of flow was less than one fps (summarized by (Mighetto and Ebel, 1995). This would represent a serious limitation at the turbine intakes in the Columbia Basin. For example, Odgaard et al (Odgaard et al., 1990) determined that the approach velocity measured immediately upstream from the intake screen at Wanapum and Priest Rapids dams was on the order of 1.1-1.2 m/s. (3.6-3.9 fps). There are other serious drawbacks with the application of electricity. Electric fields are potentially dangerous to other fish that may be present. Susceptibility to dangerous shock is a function of fish size, making adult fish more vulnerable than juveniles (Office of Technology Assessment 1995).

Sound

Recently, Carlson, (Carlson, 1994) reviewed the extensive literature base, regarding studies that have been conducted to direct fish by means of sound. He concluded that sound deterrence for salmonids is possible only at short ranges using very low frequencies. Significant challenges remain in the possible application of sound to address problems of systems intended to modify fish behavior. Dolat et al (1995) reported success in using sound to divert from the intake, a portion of the smolts approaching the irrigation diversion at Dryden Dam on the Wenatchee River. Although a clear effect of sound was established, it was not as effective as the screen that is in place (Mueller et al., 1995).

Light

Mighetto and Ebel, (1995) report that Paul Fields was able, using lights, to divert smolts away from the turbine intakes and toward the spillway, but was unable to sustain that response over a 24 hour period. Fields {e.g., 1966**}** developed a large body of information on the effects of light on migration of salmonids, most of which fits the summary in the previous sentence.

In 1986, strobe lights, mounted on the trash racks in the turbine intakes were investigated at Rocky Reach Dam as a possible means of guiding fish away from the intakes, (Hays and Truscott, 1986). Although the lights affected the vertical distribution of smolts entering the gatewell, it was concluded that there was no way to use them effectively to assist fish in avoiding the intake. Mercury vapor lights attached to the frame of a guidance device at Bonneville Dam in tests over several years did not significantly increase guidance or decrease descaling of subyearling chinook (Gessel et al., 1990).

Louvers

Angled louvers have been used effectively at pump intakes and irrigation diversions to divert smolts into alternate channels {Stone and Webster, 1986} (Office of Technology Assessment 1995). They are considered to be standard technologies for turbine intakes in the Northeast but not in the Northwest (Office of Technology Assessment 1995). The difference is apparently due to the high water volumes and velocities present in Northwest river applications. Louvers have been widely applied in the Sacramento River system as fish protection devices {Stone and Webster, 1986}. In the Columbia Basin the primary application has been at irrigation diversions in conjunction with screens. Collins' group found that louvers would only be effective in diverting a high enough percentage of smolts in situations where flows were carefully regulated at low levels and floating debris was sparse (summarized in (Mighetto and Ebel, 1995). However, at Sullivan Dam on the Willamette River, louvers, consisting of modified trash racks guide fish from intakes at units 1 through 12 into the intake for unit 13 where an inclined screen diverts them away from the turbines {Stone and Webster, 1986}. Best estimates of effectiveness ranged from about 40% for subyearling chinook to 80% for yearling chinook approaching the project (Clark and Cramer, 1977, as cited in Stone and Webster, 1986).

Vertical louvers were located behind each screen panel at the Dryden Reclamation District Canal on the Wenatchee River, for the purpose of balancing the flow across the set of screen panels, and were placed to facilitate the working of the screens, but were not completely successful in balancing the flow (Mueller et al., 1995).

TURBINE INTAKE SCREENS

Submerged Traveling Screens (STS)

In the early 1960's, studies by Bureau of Commercial Fisheries investigators showed that smolts tended to be concentrated near the ceiling of the turbine intakes, and a portion of them were drawn into the gatewells above (Long, 1968). This led to the idea that fish might be screened or deflected from the upper portion of the intake, with minimal effect on the generating capacity of the unit. The concept was first tested at model facilities at Washington State University, where initial studies, conducted under the aegis of BCF, also identified optimum screen porosities and deflection angles to mimimize impingement of fish on the screen. The model studies led to predictions of a unit head loss of less than 10% resulting from placement of the screen at the intake, which seemed acceptable. A cleaning mechanism was recommended in order to avoid violation of the operating criteria (Mueller and Osborn, 1969). The first test of a prototype device in the field took place in 1970 at projects on the lower Snake River (Long et al., 1970). The first design incorporated a traveling screen as a self-cleaning feature, leading to the name submerged traveling screen (STS) for the device. Mighetto and Ebel (1995) summarized the decades of work by BCF (later NMFS/NOAA) and the COE to develop a satisfactory intake screen, Figure 7.4.

Criteria for success of intake screens are high fish guidance efficiency (FGE), low impingement, and low injury rates to guided fish. Using these criteria, numerous improvements in the design and deployment of intake screens have been made over the years. An evaluation of screen effectiveness is provided later in the text. Because improvements in designs have been made over the years, the early evaluations of effectiveness are mainly of historic interest, while the most recent estimates are the ones that should be applied in estiating diversion rates at the projects. More information on this subject follows below.

Box 15. The first screen tested in prototype was approximately 24 feet in length, which corresponded with dimensions in the model, and could be deployed at angles of 45 to 60 degrees, (Marquett et al., 1970). It was tested at Ice Harbor Dam in 1969 and 1970, where it was found that by using the screen, the relative number of smolts in the gatewell could be increased by a factor of three. Over the next several years, devices were also tested at Little Goose and Lower Granite dams, and improvements were made in the design. Details are to be found in Ebel, et al (1974), and Park et al (1977). Addition of a porosity plate behind the screen reduced impingement of fish to acceptable levels. Perforated steel panels, referred to as a vertical barrier screen (VBS) split the gatewell, distributing the flow upward, and discouraging fish from sounding out of the gatewell and back into the intake.

Fixed Bar Screens

In the mid-1970's planning for addition of a second powerhouse at Bonneville Dam led to testing of an intake screen at that project (Ruehle et al., 1978). Experience with the traveling screens had shown them to be costly to build and maintain. These Bonneville tests used a fixed screen concept that would be less complex and less costly. It was five feet wide and extended across the full width of one intake slot. Results were promising, leading to testing of a full-scale device at McNary Dam in 1978 that had somewhat different features (Krcma et al., 1978). Rather than flat steel bars used in the test at Bonneville, the McNary test used extremely smooth steel bars, triangular in cross section (wedge wire). Cleaning could be accomplished by periodically raising the angle of the screen to create a backflush through the mesh. Results were favorable (Ruehle et al., 1978); (Krcma et al., 1980). Tests of a bar screen design in prototype at Priest Rapids and Wanapum dams later confirmed the favorable results of the NMFS/NOAA test of the bar screen design at Bonneville and McNary dams {mid-Columbia Coordinating Committee, 1988}. On the other hand, problems with accumulation of trash in tests of bar screens at the Bonneville second powerhouse, led to a recommendation to proceed with traveling screens there and at other COE projects (Gessel et al., 1991).

Extended-length Screens

Initial tests in 1983 of an STS at Bonneville Dam's second powerhouse showed surprisingly poor effectiveness in guiding fish, with FGE less than 25% for chinook and coho. Therefore efforts were directed at improving fish guidance {Gessel, et al, 1992}. In 1994, a frame with bar screen was attached to the trashrack in a position where it would simulate an extension of the STS - an extended screen. The FGE improved sufficiently to justify further tests.

Similarly, at Lower Granite Dam, initial tests in 1982 of the STS indicated poor effectiveness (about 50%) in guiding yearling chinook. From 1984 to 1989 NMFS investigators sought ways to increase FGE (Swan et al., 1992). A fixed bar screen was tested in conjunction with a standard STS in a configuration that simulated an extended screen, forty feet in length compared to the standard screen of 24 feet. Increases of about 15% in guidance efficiency were measured. Descaling of guided fish was estimated to be 1.7%. Impingment that had ranged from 0.04% to 3% was reduced to less than 1% by design changes in 1990 (Wik and Barila, 1990).

Encouraging results at Lower Granite Dam, led to the design of two types of prototype extended-length screens, a bar screen and an STS that were tested at McNary Dam in 1991 to 1994. The results of the simulated extended screen tests were not directly transferable to the design of the new units due to differences in hydraulic characteristics as shown by model studies, and appropriate modifications were made (Swan et al., 1990), Appendix B). Tests of full extended screens were also initiated at The Dalles and Little Goose Dams in 1993 {Gessel, et al, 1994}. At McNary Dam extended length screens, either bar screens or STS's have produced estimates of FGE of over 80% for yearling chinook (81% for the extended bar screen and 88% for the extended STS), {McComas et al, 1993}. No significant increase in descaling of guided fish was observed with the extended screen. For sub yearling chinook FGE of 67% was measured with the extended STS and 52% with the extended bar screen, while descaling was not significantly higher for either of the extended screens than for a standard STS used as a control.

At Little Goose Dam, tests of the full prototype in 1993 and 1994 brought FGE's of greater than 80% and 77% respectively, for yearling chinook (Gessel et al., 1995). For steelhead, FGE averaged 90% in the best configuration. No significant increases in descaling were observed in comparisons with a standard STS.

Plans for installation of extended length screens at COE projects are discussed in the Appendix, Parts 2 and 3 of this report.

Summary

Success with tests of prototype screens has led either to their installation or to schedules for installation at most of the projects in the mid-Columbia, Snake and lower Columbia rivers. Projects not yet equipped with turbine intake screens (not including Wells Dam, which has a different type of bypass, as explained elsewhere) are The Dalles, Priest Rapids, Wanapum, Rock Island, and Rocky Reach dams. This will be discussed further in the Appendix C, Parts 2 and 3. Prototypes have been tested with success at The Dalles, Priest Rapids and Wanapum dams, and schedules for installation are shown in the Appendix C, Part 3. At Rocky Reach Dam, prototype tests of intake screens have not yet produced satisfactory results. At Rock Island Dam, the idea of screening powerhouse number 2 has been abandoned, based on poor performance of prototypes tested, while at powerhouse number 1, test have shown some promise and are continuing.

Although it is not associated with a dam, the hydroelectric facility at Hanford (Hanford Generating Plant) should be mentioned here, as it has a cooling water intake with six bays, each equipped with a traveling screen designed to protect juvenile fish {Stone and Webster, 1987}. Average survival of chinook yearlings encountering the screen was found to be 97.9% {Page et al, 1975}.

SURFACE COLLECTION DEVICES

Ice and Trash Sluiceways

Being located at the surface, directly above the turbine intakes, the ice and trash sluiceways, that were included at the time of construction at some projects, are in good position to attract fish that are approaching the powerhouse. Smolts were observed in the sluiceways at Bonneville and The Dalles, leading to initial testing of the concept, (Michimoto and Korn, 1969). It was found that the efficiency of the sluiceways in diverting smolts from the turbine intakes was generally in the neighborhood of 20% to 40%, (Nichols et al., 1978; Willis and Hendricks, 1992) and {Willis, 1982, 1983}. However, Giorgi and Stevenson (1995) point out that because major modifications were made to the bypass system at the Bonneville Dam first powerhouse in the early 1980’s, it is doubtful that those estimates would apply under current condtions. In 1987, at the Bonneville Dam second powerhouse, the ice and trash sluiceway was shown to pass an estimated 81% of smolts passing the powerhouse in the daytime and 30% at night (Magne et al., 1987).

At The Dalles Dam, as previously discussed under the subject of spill effectiveness, a study using marked fish provided an estimate of 40% sluiceway passage efficiency at zero spill {Willis, 1982}. Willis provided equations describing the relationships for spill effectiveness and sluiceway effectiveness. Confirming Willis’ results at The Dalles Dam, hydroacoustic studies showed fish were more concentrated in the volume of water entering the ice and trash sluiceway than in water entering the turbines, (Nichols and Ransom, 1980; Nichols and Ransom, 1981; Steig and Johnson, 1986). At Ice Harbor Dam, the sluiceway was estimated to pass 48% of the migrants in the daytime in 4% of the water, and pass 21% of the migrants at night in 6% of the water (Ransom and Ouellette, 1991)

Box 16. Raymond and Sims (1980) found that smolts passing through the gates with surface spill were as likely to pass in the day time as at night, whereas samples of smolts from the turbine intakes, the ceilings of which were located at about the same depth as the bottoms of the unlogged spill bays showed a strong peak at night, suggesting that smolts approaching the dam delayed sounding to the intakes until after dark, and that they more readily passed through surface spill. The number of smolts in the ice and trash sluiceway at The Dalles Dam, peaked around mid-day {Nichols, 1979} (Nichols and Ransom, 1980; Nichols and Ransom, 1981; Steig and Johnson, 1986; Johnson and Wright, 1987); and at Bonneville Dam in 1981, the number also peaked at mid-day (Willis and Uremovich, 1981); all as summarized by (Giorgi and Stevenson, 1995). This is in contrast to turbine intakes where the number of smolts reaches a peak at night (Giorgi and Stevenson, 1995) summarize (Long, 1968; Steig and Johnson, 1986; Johnson and Wright, 1987).

There is much current interest in surface collection devices, including ice and trash sluiceways for passing smolts, Investigations that are underway, will be described in a later section.

Wells Dam

The unique design of the hydrocombine at Wells Dam, in which the spillway is located directly above the turbine intakes, provided a situation in which it was thought that juvenile salmonids, observed to enter the turbines near the ceiling, might be diverted into the spillbays above. The FERC Stipulation of 1985 called for spill to bypass 50% of the juvenile salmonids approaching the project.

Two-dimensional model studies were undertaken that were designed to determine the feasibility of altering the approach flow to direct the juvenile salmonids away from the turbine intakes, see (Sverdrup and Parcel and Associates, 1982; Johnson et al., 1992). The design included placement of solid covers on the turbine intake emergency gate slots, opening the flap gate in the top leaf of the spillway gate (surface spill), and installing solid panels in front of the spillway to a point 30 to 40 feet below the surface, (Figure 7.5). Testing of a prototype began in 1983 {Biosonics 1983}. The results were encouraging from the outset. Alternative dimensions and configurations of openings in the intake baffles were tested in prototype in the next several years during which it was found that a vertical slot configuration in the center one of three spillbay baffles was most effective at diverting fish (Sullivan and Johnson, 1986). Following successful tests in 1987 of an enlarged set of diversion baffles encompassing most of the intakes, the mid-Columbia Coordinating Committee agreed that the bypass was expected to perform satisfactorily, so no additional evaluations were undertaken until the system was fully installed in 1989. A sufficient array was in place across the powerhouse by 1987 that it was operated as though it were complete, and spill beyond the amount necessary to operate the bypass has not been required since then {Kudera and Sullivan, 1993}. The volume of water required for operation varies somewhat depending on river flow and the powerhouse load. In 1995 it ranged between 1.2 and 7.5% of the daily average river flow.

In January, 1991, a long-term Settlement Agreement among the parties to the mid-Columbia Proceeding, with respect to issues at Wells Dam was approved by FERC. It calls for operation of the juvenile fish bypass during the spring and summer emigrations, at times to be determined by representatives of the parties. Among other things, that agreement called for a three-year study to measure the effectiveness of the bypass. It established a criterion of at least 80% bypass for the spring period and at least 70% for the summer. From the resulting studies, the three year average bypass during both the spring and summer emigrations was estimated to be 89% (Skalski, 1993). It is currently the most effective bypass system in the basin, and the only one that can meet the standards for fish passage set by FERC, the NPPC, or NMFS/NOAA, without adding spill. (The NMFS standard does not apply in the mid-Columbia.)

Rocky Reach Dam

The success at Wells Dam has stimulated studies of the possibility of applications elsewhere. The FERC Stipulation for Rocky Reach Dam in 1993 called for evaluation of a possible sluiceway for passage of juveniles. The technology used at Wells Dam is not directly transferable to any other mainstem or Snake River project in the basin because Wells Dam is a hydrocombine, with the spillway located directly above the turbine intakes, unlike any of the others.[6] The failure of conventional intake screens that had been tested to that time at Rocky Reach Dam was a factor in the decision to study a surface attraction device. A prototype surface collection device was prepared for testing at Rocky Reach Dam in 1995 (Peven et al., 1995). It consisted of a housing with a 15 foot wide and 56 foot deep opening located downstream of the unit 1 intakes in the corner of the cul-de-sac that is present where the powerhouse meets the forebay wall at nearly a 90 degree angle. Guidewalls extended from the opening upstream to the lower end of the unit 2 intake and downstream to the forebay wall.

A further difficulty arising from the surface collection concept is that it requires a different method of evaluation than the approach used to measure FGE with the turbine intake screens. With the intake screens, an array of fyke nets in place below the screen in the intake is used to capture fish not guided by the screens. Guided fish are removed from the gatewell and counted, thereby providing

[6] The Cowlitz Falls Project on the Cowlitz River is a hydrocombine design where the Wells concept is being tested (Solonsky et al, 1995).

an estimate of fish guidance efficiency. With a surface collection device in prototype, investigators are faced with the practical problem of not being able to directly associate a fyke net catch in an intake with an assignable number of guided fish that may be drawn from a wide area across the powerhouse. At Wells Dam, hydroacoustic estimates of relative fish passage were developed, in the beginning for a set of spillbays and the associated turbine intakes directly below them, and later across the entire hydrocombine. The hydroacoustic method has been employed in general for evaluation of surface collectors.

The method is also being investigated for possible use in evaluating intake screens because of present concerns about the impact of sampling with fyke nets where Snake River stocks are present, and a question whether the presence of the fyke net array may itself affect measurement of FGE through influence on water movement, e.g., (Magne et al., 1989; Thorne and Kuehl, 1989; Stansell et al., 1990; Thorne and Kuehl, 1990; Stansell et al., 1991).

At Rocky Reach Dam, it was estimated that over 725,000 juvenile salmon and steelhead passed through the prototype device during the spring emigration, April 26-June 15, 1995 (Peven et al., 1995). Future development of the concept in 1996 involves installation of a “floor” to assist in guiding fish into the opening. Radio-tagged and other marked fish will be released in the forebay to make possible an estimate of guidance efficiency (Peven, 1996). Surface attraction is also being investigated for juvenile fish bypass at Rock Island Dam.

Wanapum Dam

A parallel effort to develop a surface oriented juvenile bypass system began at Wanapum Dam in 1995 {Ransom et al, 1995}. The physical conditions at Wanapum Dam are much different from conditions at either Rocky Reach or Wells dams. At Wanapum Dam, the spillway portion of the dam is downstream of the powerhouse, and the reservoir is much wider. The prototype tested consisted of a 12 foot wide by 60 foot deep channel attached to the upstream face of the dam in front of units 7 to 10. A single entrance 15 feet wide by 60 feet deep, centered over unit 8, provided access for juvenile migrants. Hydroacoustic evaluation brought estimates of fish passage efficiency in relation to unit 8, of 12.2% to 68.8% and averaged 35% for the spring migration season. Grant County P.U.D. plans to enlarge the prototype for testing in 1996. (Personal communication Stuart Hammond, Grant County P.U.D.)

Ice Harbor and other Corps of Engineers Projects

NMFS/NOAA Proposed Recovery Plan (1994) refer to the success at Wells Dam and call upon the COE to investigate potential applications at COE projects. Accordingly, in 1995 the COE conducted several studies of prototype surface collection configurations at Ice Harbor Dam. Three types of surface collectors were installed: vertical slots in front of two turbine intake slots (in conjunction with the ice and trash sluiceway), a sluiceway surface skimming gate, and stop logs that allowed surface spill at two spillbays {Swan et al, 1995}. The effectiveness was evaluated by radiotelemetry of juveniles and by hydroacoustics. The hydroacoustic study showed that the density of smolts was greatest in the sluiceway, although more total fish passed in spill because of the high volume of spill (Biosonics, 1995). Further tests are scheduled for 1996 at Lower Granite and The Dalles dams, as discussed further below.

EFFECTIVENESS OF MECHANICAL BYPASS SYSTEMS

Fish Guidance Efficiency

The primary criterion in evaluating the effectiveness of mechanical bypass systems is their fish guidance efficiency (FGE), the percentage of fish approaching the powerhouse that are diverted unharmed from the turbine intakes into the system. In the case of turbine intake screens, impingement and injury of diverted fish are problems that have had to be addressed by manipulations of screen openings, angle of deployment of the screen, velocity at the screen and other factors. In one early set of NMFS studies at Bonneville Dam (first powerhouse), FGE for chinook, steelhead and sockeye ranged from 70% to a little over 80% (Krcma et al., 1982). These were judged to be acceptable levels at the time, and installation at a number of COE projects proceeded on that basis.

It has been found that estimates of FGE are variable from one test to another. They differ from project to project, differ among fish species, differ according to the degree of smoltification of the fish, differ with the design and configuration of the apparatus, differ according to time of day (particularly day versus night), and differ as the season progresses (Swan et al., 1985; Hays and Truscott, 1986; 1986; 1987; 1987; Giorgi et al., 1988; Peven and Keesee, 1992).

Box 17. Measurements of FGE at the Bonneville Dam first powerhouse in 1981 brought estimates of 76% for yearling chinook and 72% for subyearling chinook (Krcma et al., 1982). Following installation of an approach channel for a new navigation lock that involved removal of part of Bradford Island (Gessel et al., 1991), FGE was measured again and found to be substantially reduced - to 21% for yearling chinook and 24% for subyearling chinook {Krcma et al. 1984}. Modifications to the screen and its deployment brought FGE up to 26-44% for yearlings and 20-32% for subyearlings {Krcma et al. 1984}. Fish guidance efficiency at Bonneville's second powerhouse was poor at the outset, 19% for yearling chinook and 24% for subyearling chinook {Williams et al. 1988}. Modifications of the apparatus, and eventually extensions of the turbine intakes into the forebay brought improvements by 1986 to around 60% for chinook yearlings, 55% for subyearlings, and 46% for steelhead (Gessel et al., 1991). Further tests were conducted each year through 1989. Best observed FGE was 78% for chinook yearlings and coho, 69% for steelhead, and 25% for subyearling chinook (Gessel et al., 1991). On the basis of these studies, a configuration was recommended for full installation across the second power house. {Gessel et al, 1992}.

More information on FGE measurements is provided in Table 7.1 and later in the Appendix in Part II, the section on requirements for fish passage by FERC, the NPPC, and NMFS/NOAA.

Information on FGE is shown in Table 7.1. In most cases the FGE measured applies to a prototype tested at the project. Usually, these estimates are projections for the particular project based on samples. Ordinarily, the sample is taken from one of three intake slots at a sample turbine, where fyke nets in the intake behind the screen capture, fish that are not guided, while guided fish rise in the gatewell where they are removed and counted. Since 1995, with the ESA listing of Snake River stocks, hydroacoustic methods have been employed for measurement at the Snake River and lower Columbia River dams. In many instances the sample came from one slot, where the adjacent slots were not equipped with screens. Studies at Wanapum Dam verified the fact that although flow patterns were affected by screens in the adjacent slots, the resulting measurements of FGE showed little or no effect {mid-Columbia Coordinating Committee, 1995}.

With extended screens significant increases in FGE have been measured, for example at Lower Granite Dam, 66% for yearling chinook with the extended screen compared to 57% with the standard STS, and 83% for steelhead with the extended screen compared to 77% with a standard STS (Swan et al., 1990)..

At Wells Dam, the final measurement of 89% fish passage effectiveness was made in a three year study after the project was fully equipped with the bypass. Hydroacoustic technology was used at sample locations across the hydrocombine that were subsampled on a timed schedule (Biosonics, 1983; Skalski, 1993) {Kudera et al, 1990}.

Survival at the Screen

Another factor in evaluating the effectiveness of intake screens is mortality of fish caused by striking the screen. A percentage of the approaching fish may strike the screen in passing and lose some scales, while others, particularly the small sub-yearling chinook, may become impinged on the screen (Wik and Barila, 1990). Impingement rate on extended-length screens at Lower Granite Dam was reduced to less than 1% by design changes. Impingement rates of yearling chinook are negligible in properly tuned systems, but of subyearling chinook may be “high” e.g. (Peven, 1993).

Descaling occurs as a result of fish striking the screen or other objects in the bypass system. Standards defining descaling have been developed, and set a threshold level of a percentage of missing scales to meet the criteria of the definition (Koski et al., 1986). Implications of descaling are not clear, since no direct relationship with survival has yet been established. Descaling of 1.7% of all species, representing 2.4% of chinook, and 1.4% of steelhead was observed in the bypass sampler at Lower Granite Dam in 1988, which was an improvement over 1987, when the total was 3.3% (Koski and al., 1989). As a result of improvements in the system and its operation, descaling rates declined to those levels after 1981 and 1982 when descaling had been recorded as 15.5% for chinook and 16.8% for steelhead in 1981, and 8.8% and 10.1% respectively in 1982 {Koski et al, 198}). At Little Goose Dam the combined rate in 1988 was 3.4%. At McNary Dam the figure was 10.4%. Muir et al (1995)estimated addition of 2.8% to the rate of descaling of river-run steelhead as a result of passage through the bypass conduit at Lower Granite Dam. They felt that the 7% descaling rate of hatchery origin steelhead observed after passing through the bypass was not excessive.

Concerns have been expressed about levels of stress induced on the juveniles as they encounter the screens and associated bypass systems (Schreck et al., 1984). Bjornn (1992) found no difference in survival rates of marked chinook that were subjected to high stress prior to release as smolts, compared to those that were not stressed.

Conduit to the Tailrace

As the tests of intake screens proceeded with promising results, appropriate means were sought for encouraging movement of the fish upward in the gatewells, for removing the guided fish from the gatewells on a mass scale, and providing an exit for them to the tailrace below the dam (Mighetto and Ebel, 1995). At Bonneville Dam, at the first powerhouse, orifices were cut from the gatewells to the ice and trash sluiceway to provide an exit for fish. A vertical barrier screen (VBS) was installed in the gatewell to create an upward flow to encourage movement of the fish toward the orifices near the surface.

Box 18. Orifice Passage Efficiency (OPE) is a measure of the percentage of fish that leave the gatewell during a specified time period, normally 24 hours. OPE of 70% is considered satisfactory, (National Research Council, 1995), p. 191). At Wanapum Dam, two baffle systems in the gatewell were tested for their effects on OPE. The best system produced an OPE of near 90% (mid-Columbia Coordinating Committee, 1993).

A dewatering system was provided at the end of the sluiceway, where water was pumped back into the forebay in order to reduce the volume of water that entered a 20 inch conduit leading to the tailrace. At McNary Dam a separate bypass flume was constructed within the ice and trash sluiceway. Evaluations of effectiveness of the systems led to improvements in designs, (Krcma et al., 1982; 1983; 1984; 1985; 1986; Swan et al., 1986).

Effectiveness of Bypass Systems

Performance of the part of the bypass system downstream of the screen itself has come under study. Dead fish are observed in the sampling systems in the bypasses. These deaths may have occurred at any location within the bypass facility, from the screen to the sampler. At Little Goose Dam in the years from 1981 to 1993, average annual smolt mortality observed in the facility amounted to from 0.9% to 6.2%, for chinook, 0.1% to 0.8% for steelhead and 0.6% to 6.3% for sockeye; and at Lower Granite Dam from 0.3% to 1.2% for chinook, and 0.1% to 0.4% for steelhead (Koski and al., 1989) {FTOT, 1994}.

At McNary Dam in 1983 mortality of marked yearling chinook in passing from the gatewells to the bypass sampler ranged from 2% to 4%, depending upon the location of the gatewell (Park et al., 1984). In the years 1989 to 1993, annual facility mortality at McNary ranged from 0.4% to 1.9% for chinook yearlings, from 1.2% to 5.0% for chinook sub-yearlings, from 0.2% to 1.5% for steelhead, and from 0.5% to 4.1% for sockeye {FTOT, 1994}.

Gilbreath et al., {1992} state that in the first years of evaluation in the 1980s, the bypass facilities at both power houses at Bonneville Dam had a number of internal mechanical problems, which the COE subsequently corrected, so that the resulting systems, internally, now have a minimum impact on fish. For example, in 1983, excessive delay and exhaustion of fish was documented at the Bonneville second powerhouse bypass system (Krcma et al., 1984). Now, at Bonneville Dam, juvenile mortality within the bypass system, as measured at the bypass sampler, generally ranges from less than 1% to 4% (Ceballos et al., 1993). Survival rate in bypass systems is given by the COE as 97-98% {COE Salmon Passage Notes, 1992}.

An additional source of mortality to guided fish is the conduit leading from the dewatering screens at the sampler to the tailrace. Marked fish released out of the north shore outfall at McNary

Dam were recovered at half the rate of other release groups, suggesting that predation in the vicinity of the outfall was responsible for added mortality (Sims and Johnson, 1977).

At Lower Granite Dam, studies of delayed mortality due to effects of passage through the entire bypass produced estimated losses of 7.6% , 4.4% and 5.1% in 1984, 1985 and 1986 (Mathews et al., 1987), as summarized by (Chapman et al., 1991).

Results of studies at Bonneville Dam have been surprising {Ferguson 1993; Gilbreath et al, 1993} (Ledgerwood et al., 1990; Ledgerwood et al., 1991; Dawley et al., 1992). During 1987 and 1988, the first two years of the study at Bonneville's second powerhouse, reported by Ledgerwood et al (1991), rates of recovery in the estuary of marked subyearling chinook that had transitted the bypass were significantly lower than fish that had passed through the turbines, indicating higher mortality of smolts in the bypass than in the turbines. In the following two years there was no significant difference in recovery rates, suggesting that the bypass was not accomplishing any reduction in mortality compared to the turbines {Ferguson, 1993}. It was found that the conduit itself contributed an estimated 3% mortality to smolts diverted by the intake screens (Dawley et al., 1992). Dawley et al (1992) and Gilbreath et al, {1993} therefore concluded that the primary source of mortality was outside of the bypass itself. The location of the outfall, in a place where predators could congregate, was identified as the most likely source of the high smolt mortality associated with the bypass that was measured by Ledgerwood et al (1991).

Ledgerwood et al (1994) have begun a similar study of survival in the bypass and turbines at Bonneville's first powerhouse. Results of the first year of study indicated, as with the bypass at the second powerhouse, that survival of smolts that passed through the bypass was lower than for smolts that passed through the turbines. Again, predation at the outfall was thought to be the principal source of mortality. They reported that Tom Poe of the U.S. Fish and Wildlife Service communicated to them the information that a higher proportion of marked smolts released into the bypass were consumed by northern squawfish in the tailrace than were other groups of smolts released at the same time.

Ferguson {1993} observed that bypass evaluations at other mainstem hydroelectric projects have been limited to assessing survival at a collection point within the system, and not below the tailrace. Chapman et al, (1991) recommended further research to evaluate mortality associated with bypass.

Summary

Following studies by NMFS/NOAA and others, a set of criteria for successful bypass systems has been developed. These establish maximum velocities, advise open conduit rather than closed, in order to avoid pressurization, set appropriate angles for curves and changes in elevation, set standards for dewatering, and other factors in the design (Bates, 1992; Rainey, 1995) {NMFS/NOAA, 1990}.

These are being used in the design of bypass systems at Rocky Reach, Wanapum and Priest Rapids dams, and in the improvement of systems at the COE projects. NMFS has adopted a policy statement that provides for development and evaluation of new technology under controlled conditions (Office of Technology Assessment, Appendix B.).

SUMMARY OF BYPASS FINDINGS

Whether it be through spill, intake screens or surface collection, the most successful bypass systems, have taken advantage of a surface orientation of smolts as they move downstream.

Box 19. The preponderance of evidence accumulated in these and other studies demonstrates that smolts migrating downstream are oriented to the upper portion of the water column. Giorgi and Stevenson, (Giorgi and Stevenson, 1995) reviewed much of the evidence at COE projects. Johnson, (1995) reviewed the evidence from salmon literature world-wide. When they encounter a dam, smolts prefer surface outlets when they are available and are reluctant to sound. Further evidence of their surface orientation comes from the fact that smolts are observed to accumulate in gatewells of unscreened turbine intakes, as first noted in the early 1960's by Cliff Long and George Snyder (Mighetto and Ebel, 1995); that they generally do not sound to significant depths unless no alternative is presented, (Wagner and Ingram, 1973; Dunn, 1978). Numerous hydroacoustic studies that were undertaken at each of the five mid-Columbia projects showed that smolts were concentrated in the upper portion of the water column, generally in the upper one-third. (Biosonics, numerous - see references. e.g. Ransom et al (Ransom et al., 1988) found that fish approaching Rock Island Dam were surface oriented.) Smolts have been sampled in the Wells forebay with purse seines, a fishing method that operates at the surface {Findings of the mid-Columbia Coordinating Committee, 1989}. In the forebay at lower Granite Dam, 92% of the smolts were found to be in the upper 36 feet of the water column {Smith, 1976}. The turbine intake screen technology depends upon the fact that smolts are concentrated near the ceiling of the intake as they pass through. Numerous examples exist, e.g. Long, (1968); fyke net sampling at each of the mid-Columbia projects showed that 75-80% of the smolts were in the upper portion of the intakes, (Hays, 1984), etc. Eicher, (Eicher, 1988) reviewed studies of passage efficiency at deep intakes. The studies of Regenthal and Rees, {1957} were particularly informative. They showed 55% of chinook would exit the reservoir when the only route was 118 feet deep or less, 48% when it was at 146 feet, and 8% when it was 160 feet (as summarized in (Eicher, 1988). Eicher concluded that "it has been accepted that fish (Salmonids et al.,) sound to great depths as a last resort, and if an alternative, such as an artificial outlet, is available, they will use it preferentially and can be collected in that way." (op. cit.).

Spill is effective as an interim measure, or a supplement to mechanical bypasses, that has been shown to offer high survival of fish up to the point where supersaturation of atmospheric gas becomes a problem. Further studies in the open river are needed in order to establish the appropriate upper limit for gas saturation that can be tolerated by salmon in the natural situation. The most effective spill is surface spill. Spill spread over 24 hours a day was more than twice as effective per unit volume of water used than night-time spill for 12 hours at Priest Rapids Dam. Effectiveness of spill differs among the projects. More information is needed at most of the COE projects. In addition, effectiveness of surface spill needs to be defined at each project, along with determination of the effects of spilling for different time intervals, such as spilling for 24 hours per day versus 12 hours.

Effectiveness of turbine intake screens seems to have reached an upper limit that is less than the surface collector at Wells Dam. Intake screens are unlikely to prove 100% effective in diverting salmon smolts (Office of Technology Assessment, p.127). Although some measurements of screen effectiveness have shown values as high as 90% for steelhead, and near that for chinook yearlings, none of the screens tested to date approach that value for subyearling chinook or sockeye, both of which are in the neighborhood of 50%, Table 7.1. Although extended screens have demonstrated improvements over standard length screens, their FGE's for subyearlings, ranging from 4% to 63.7%, are still below criteria set for fish passage by the NPPC or NMFS in the Snake River Salmon Recovery Plan. This presents a particularly difficult problem in the Snake River, where these fish are listed as threatened or endangered, and in the lower Columbia River through which these fish pass. Therefore, the Council's goal of 90% FGE can not be achieved universally with present technology. Further discussion of this problem is presented in Appendix C, Parts 2 and 3.

The NPPC criterion of 98% smolt survival within bypass and collection systems from the screen to the end of the outfall that is specified in the 1994 FWP, appears to be attainable. However, losses due to predation at the outfalls and in the tailraces can be substantial in some situations.

Surface collectors are the most promising devices for attaining the fish passage goals established by the council in the FWP or NMFS/NOAA in the Snake River Salmon Recovery Plan.

Current developments are moving toward surface spill and surface collection, as opposed to turbine intake screens. The attractiveness of surface spill and surface collection over standard spill comes from the possibility of passing a high percentage of the smolts in a smaller volume of water by taking advantage of the natural behavior of the fish (Office of Technology Assessment., p. 130). Modification of ice and trash sluiceways offers a potentially effective means of providing a surface exit for smolts.

Table 7.1. Fish guidance efficiency measured at Columbia basin projects. Most recent data.*

- The Fish and Wildlife Program of the Northwest Power Planning Council sets a Standard of 90% FGE for Turbine Intake Bypass Systems. Sources: NPPC (1994) {COE Salmon Passage Notes 1992; FERC orders and agreements of the parties; Progress Reports mid-Columbia Studies. Data for Rocky Reach and Rock Island dams, personal communication C. Peven, Chelan County P.U.D.}

PROJECT	FGE	NOTES
Mid-Columbia Projects.		
Wells (Fully equipped)	89%	Skalski, (1993). Spring and Summer. Surface attraction device. Hydroacoustic estimate provides no species separation.
Rocky Reach	30.8% 38.9%;	Combined species. Highest achieved for yearling chinook for subyearling chinook 21.9%; for steelhead 40.2%; and sockeye 24.1%. None of the prototype screens tested 1985-1992 and 1994 met criteria. Surface collector device being evaluated, 1995.
Rock Island		
Second Powerhouse	-	Prototype screens tested at Powerhouse No. 2 determined to be unfeasible.
First Powerhouse (1994)	85.7%	Yearling chinook
	29.6%	Subyearling chinook during the spring emigration
	63.7%	Subyearling Chinook during the summer
	60.9%	Steelhead
	64.4%	Sockeye

Table 7.1 (continued). Fish guidance efficiency measured at Columbia basin projects. Most recent data.*

PROJECT	FGE	NOTES
Wanapum	75%	Yearling chinook in 1992
	50%	Subyearling chinook in 1992
	26%	Sockeye, Hammond (1991)
Priest Rapids	84%	Average for chinook yearlings
	52%	Average for sockeye,
	76-90%	Range for steelhead, Hammond (1991).
SNAKE RIVER PROJECTS		
Lower Granite		
(Standard STS)	57.3%	Yearling chinook (Swan et al., 1990)**
	77.3%	Steelhead (Swan et al., 1990)
(Extended Screen - Simulated)		
	66%	Yearling chinook (Swan et al., 1990)
	82.4%	Steelhead (Swan et al., 1990)
Little Goose		
(Standard STS)	73%	Yearling chinook - with raised gate (Swan et al., 1986)
(Extended Screen)	77.3%	Yearling chinook (Gessel et al., 1995)
	89.6%	Steelhead (Gessel et al., 1995)

Table 7.1 (continued). Fish guidance efficiency measured at Columbia basin projects. Most recent data.*

PROJECT	FGE	NOTES
Lower Monumental	69%	Yearling chinook (Gessel et al., 1993)
	85.3%	Steelhead (Gessel et al., 1993)
	35.2%	Subyearling chinook (Ledgerwood et al., 1987)
Ice Harbor	78%	Yearling chinook (Brege et al., 1988)
	92%	Steelhead (Brege et al., 1988)
LOWER COLUMBIA RIVER PROJECTS		
McNary		
(Standard STS)	83%	Yearling chinook (Krcma et al., 1982)
	76%	Steelhead (Krcma et al., 1982)
	34-46%	Sub yearling chinook {Swan et al, 1984}
(Extended STS)		
	88%	Yearling chinook (McComas et al., 1994)
	67%	Sub yearling chinook (McComas et al., 1994)
	93%	Steelhead (McComas et al., 1994)
	73%	Sockeye (McComas et al., 1994)
	98%	Coho (McComas et al., 1994)

Table 7.1 (continued). Fish guidance efficiency measured at Columbia basin projects. Most recent data.*

PROJECT	FGE	NOTES
John Day	75%	Yearling chinook {Swan et al, 1982}
(Tests of John Day configuration conducted at McNary Dam)		
	79%	Steelhead {Swan et al, 1982}. (Tests at McNary Dam)
	88%	Yearling chinook (Krcma et al., 1983). (Tests at McNary)
	87%	Steelhead (Krcma et al., 1983) (Tests at McNary Dam)
	72%	Yearling chinook (Krcma et al., 1985; Brege et al., 1992) Test at John Day Dam)
	20%	Subyearling chinook (Krcma et al., 1985; Krcma et al., 1986) (Test at John Day Dam)
	35%	Subyearling chinook (Brege et al., 1987; Brege et al., 1988)
	41%	Sockeye (Krcma et al., 1986; Brege et al., 1992)
	86%	Steelhead (Krcma et al., 1986)
The Dalles		
Standard STS	44-56%	Yearling chinook (Krcma, 1985)
	71-80%	Steelhead (Krcma, 1985)
	40-60%	Sockeye (Monk et al., 1987)
(Extended-length screens)		
	69%	Yearling chinook (Absolon et al., 1995)
	54%	Subyearling chinook (Absolon et al, 1995)
	83%	Steelhead (Brege et al., 1994)

Table 7.1 (continued). Fish guidance efficiency measured at Columbia basin projects. Most recent data.*

PROJECT	FGE	NOTES
The Dalles continued		
	53%	Sockeye (Brege et al., 1994)
	93%	Coho (Brege et al., 1994)
	Scheduled for installation in 1998	
Bonneville		
Powerhouse number 1 (1981)		
	76%	Yearling chinook (Krcma et al., 1982)
	72%	Subyearling chinook (Krcma et al., 1982)
		Measurements following modification of navigation channel
	21%	Yearling chinook (Krcma et al., 1984)
	24%	Subyearling chinook (Krcma et al., 1984)
	14%	Sockeye (Krcma et al., 1984)
	34%	Steelhead (Krcma et al., 1984)
	26-44%	Yearling chinook (Krcma and al., 1984)
	20-32%	Subyearling chinook (Krcma and al., 1984)
Powerhouse number 2		
	32-46%	Yearling chinook (Monk et al., 1992)
	11%	Subyearling chinook (Gessel et al., 1989)
	4%	Subyearling chinook (Gessel et al., 1990).
	Measurements following full installation of turbine intake extensions	
	36-57%	Yearling chinook (Monk et al., 1995)
	23-42	Subyearling chinook {Monk et al, 1994}

Table 7.1 (continued). Fish guidance efficiency measured at Columbia basin projects. Most recent data.*

Bonneville Dam is below criteria. NPPC calls for shutdown of second powerhouse and provision of spill during smolt migration.

- Because over the years improvements have been made in configurations of screens at the projects, early measurements in most cases are mostly of historic interest and do not apply to the existing bypass systems. Some historic information from Bonneville Dam is provided as an example, showing improvement in FGE as turbine intake extensions were provided and flows around the screen were modified in other ways.

- ** Park et al, (1978) measured FGE (actually recovery rate) at Lower Granite Dam by releasing marked fish at the mouth and near the top of the turbine intake in front of the screen, then measured the rate of recovery in the gatewell. While adequate for the purpose of that study, to evaluate relative effectiveness of various screen configurations and deployment angles, the estimates are probably not representative of fish freely migrating downstream. In 12 tests, recovery rates of the marked chinook "fingerlings" ranged from 48 to 90%, depending upon screen angle and porosity of the perforated plate in the intake bulkead slot, and the angle at which the screen was deployed. Similar tests in 1977 had shown lower recovery rates (46% to 87%), as experience was being gained with screen angles and various perforated plates, (Park et al., 1977).

D. Gas Bubble Trauma

Spilling water at dams is a way to improve survival of migrating juvenile salmon as they pass, compared to turbine passage or passage through conventional fish bypasses (see Chapter 7 above on fish bypass). Spill is a route of passage at dams that most closely resembles the natural migration route (a spillway can be viewed as analogous to a natural waterfall). Survival of spilled fish has been measured at 98-100% compared to about 85% for turbine passage. Thus, use of spill has been recommended by state fisheries agencies, the Tribes, the Federal Energy Regulatory Commission, and the Council's Program. A spill management program for benefit of juvenile salmon has been in effect at non-federal dams in the mid-Columbia since the mid 1980s and in 1994-95 in the federal hydropower system in the Snake and lower Columbia rivers. A drawback to spill, however, is that it can increase total dissolved gas levels in the river downstream of the dams. High gas levels can cause serious injury and mortality to the very salmon the spill is intended to protect. Salmonid recovery efforts using spill, therefore, have been constrained by gas saturation levels in the rivers and the best understanding of their biological effects.

Spill and gas supersaturation are addressed specifically in the 1994 Fish and Wildlife Program. The introduction to Chapter 6, Juvenile Salmon Migration, refers to actions to (a) improve fish bypass at mainstem dams through spill that does not exceed state-defined levels of nitrogen gas supersaturation and (b) reduce dissolved gas levels (page 5-4). There are measures for spill (5.6C1), in which the Corps of Engineers, Bonneville Power Administration, and other parties are directed to (a) provide spill with 80% passage efficiency within total dissolved gas guidelines established by federal and state water quality agencies (b) manage spill in close cooperation with the National Marine Fisheries Service and fish managers to respond to monitoring information on gas bubble trauma, and (c) recommend exceptions to the state standards for total dissolved gas saturation by showing that the risk of fish mortality from exposure to higher levels of dissolved gas is less than the risk of failure to provide the spill regime that may result in such levels. BPA and the NMFS are directed to fund a study of dissolved gas saturation and its effects on salmon and steelhead (5.6E.1).

Supersaturation of atmospheric gases in waters of the Columbia and Snake rivers occurs when water is discharged through spillways in dams into deep plunge pools, (Ebel, 1969; Ebel et al., 1971) and {Boyer 1974}. Water released through gates from near the tops of the dams falls into pools where water pressure at depth forces entrained air bubbles into solution. The water can be supersaturated to near 140%, relative to atmospheric pressures at the water surface. This supersaturation tends to equilibrate with the atmosphere by gas exchange at the water surface and by formation of small bubbles that rise to the surface and burst. Supersaturation to levels of 110-115% also occurs naturally by warming of air-saturated water and high rates of photosynthesis by aquatic plants (both usually in shoreline shallows).

Bubble formation occurs in fish tissues as well as in environmental water. These bubbles (similar to the "bends" in human divers) can disrupt blood flow in capillary nets such as gills and fins and fill connective tissue spaces with large and physically disruptive bubbles that affect function (such as causing "popeye" blindness) {Dawley et al. 1975; Dawley and Ebel 1975; Fickeisen and Schneider 1975; Fidler and Miller 1994} (Bouck, 1980; Weitkamp and Katz, 1980). Gas bubble trauma can be directly lethal if there is sufficient tissue disruption or blood vessel blockage. National water quality criteria indicate that continuous levels of supersaturation above 110% can cause eventual direct mortality {NAS-NAE 1973; USEPA 1986}. There are additional concerns that sublethal exposures (either to gas saturation levels below 110% or to higher saturation values for periods of time less than would be directly lethal) can induce debilitation sufficient to cause "ecological death" through increased susceptibility to predation because of performance or behavior changes, increased susceptibility to microbial infections through tissue trauma, loss of stamina and orientation needed for migrations, and reduced growth rates through both impaired feeding and reduced physiological performance. Supersaturation at atmospheric pressure near the water surface can be counteracted when a fish descends to depths where water pressure is sufficient to prevent bubble formation, although many fish functions (feeding, migration) that normally occur near the water surface may be impaired by change in location. Because the Columbia and Snake rivers are migratory corridors for salmon and steelhead (both of which are showing marked population declines and sockeye and chinook salmon in the Snake River are listed as threatened or endangered) there is special concern for the well-being of these migratory stocks. Natural sources of supersaturation are rarely a problem for fish, although occasional fish kills have been reported elsewhere {Weitkamp and Katz 1980}.

Spill and gas supersaturation have occurred for different reasons over the past 35 years. In the 1960s and 1970s, they occurred most often in spring when snowmelt swelled rivers beyond the capacity of upstream reservoirs to store water and when downstream reservoirs were not fully equipped with hydropower turbines that pass water in a way that does not supersaturate it. Large numbers of fish were believed killed in the river system during these high-spill years {Ebel et al. 1971}. Subsequent completion of hydropower projects and addition of more upstream storage reservoirs reduced the incidence of uncontrolled spills. Concern for gas bubble effects then subsided. Concern has revived recently, however, as spill has gained favor as a management tool for passing downstream-migrating juvenile salmonids past dams without going through turbines, which physically damage and kill fish (see Section 7C above, on dam passage). Because spill itself inflicts <2% mortality to downstream migrants at a dam compared to 10-15% mortality during turbine passage, spill has seemed to be a relatively benign route of dam passage {Fish Passage Center 1995}. An unknown amount of gas bubble trauma caused by spill and its potentially damaging in-river effects can potentially shift the overall survival balance between dam-passage routes, however.

To achieve the survival benefits of spill during dam passage with minimal in-river damage from gas bubble disease, a physical and biological monitoring program has been in place, which includes both physical and biological criteria for cessation of spill. The U. S. Army Corps of Engineers has monitored levels of total dissolved gas saturation at near-surface monitoring stations downstream of dams for many years (Engineers, 1993) {Ruffing et al. 1995} and the Smolt Monitoring Program and the National Biological Service have monitored downstream migrants for biological signs of gas bubble trauma at smolt monitoring stations in dam bypasses since 1994 {**S**molt Monitoring Program 1995; McCann 1995}. An expert panel convened by the National Marine Fisheries Service has given advice on gas bubble disease and monitoring of clinical signs {Coutant et al. 1994, 1995, 1996 draft}. A limited program of in-river monitoring for gas-bubble signs has been undertaken recently by the National Marine Fisheries Service {Schrank and Dawley 1996} and the Columbia River Inter-Tribal Fish Commission {Backman et al. 1996}. Although the Expert Panel recommended that monitoring for signs be augmented by estimates of in-river survival ("reach survival estimates," now possible with PIT-tag technology; Coutant et al. 1994), field research to obtain such estimates is still being developed (Muir et al., 1995). There have been few attempts to decipher changed survival due to gas-bubble effects from PIT-tag data {Cramer 1996}.

The monitoring results have been controversial. Physical monitoring has shown that spill increases gas saturation, both when controlled by the management program and when uncontrolled during major runoff events or unavailability of turbines. Values at short distances (usually one mile or less) downstream of dams range to about 115-120% saturation during controlled spill (the maximum physical criteria) but up to about 140% during uncontrolled spill (such as below Ice Harbor Dam in 1995). Even during uncontrolled spill, however, biological monitoring of bubbles in fish at dam bypasses has shown low incidence and severity, much below the biological criterion of 15% incidence in juveniles that would trigger cessation of spill. On the basis of these monitoring results, risk analyses favoring spill have been prepared by the Fish Passage Center (1995) . However, the biological monitoring results seem inconsistent with the biological effects that would be expected on the basis of the published literature. The monitoring program has been peer reviewed by a special panel {Montgomery Watson, Inc. 1994}. Based on this review, an interagency (U. S. Environmental Protection Agency and National Marine Fisheries Service) technical work group evaluated the gas bubble monitoring at dam bypasses and found seven critical assumptions for validity of the monitoring that were apparently not met and which they recommended be the focus of immediate research {BMIT 1995}. The Expert Panel concurred with the BMIT's critical assumptions and advised that 1996 research focus on testing the assumptions of monitoring at dam bypasses and on better relating signs to mortality {Coutant et al. 1996}. It also recommended that increased effort be placed on in-river monitoring of signs and development of reach survival estimates.

STATUS OF SCIENCE FOR GAS BUBBLE DISEASE

The following bullets outline our level of understanding, the usefulness of the information, and a judgment of what science on this topic (both existing and reasonably attainable) can contribute to the restoration effort.

Gas bubble disease in laboratory fish

- Much is known about mortality of fish exposed to supersaturated water in captivity in shallow tanks, for certain gas levels, physiological conditions, and selected species; reviews by (Bouck, 1980; Weitkamp and Katz, 1980) {Fidler and Miller 1993}.

- Debilitating trauma has been related to gas levels and gas composition (largely for mortality and a few other selected indices of trauma). Physiological research and theoretical analyses have helped define that gas bubbles can begin to form in some tissues from as low as 105% saturation, but that debilitating trauma does not usually appear until about 110%. The biophysics of bubble formation and coalescence (the essence of gas bubble disease induction) is understood in principle {Fidler and Miller 1993}, but not enough is known about its variability between species, under different conditions, such as changing temperatures {Coutant and Genoway 1968} and in systems other than the controlled laboratory.

- Responses of adult and juvenile salmon to gas supersaturation are similar, but relative sensitivities, detailed differences in responses, and their significance must be quantified differently because fish function differently at different ages and sizes. Less work has been done on adults than juveniles to evaluate relationships among exposures, signs, and mortality.

- Laboratory studies have not adequately simulated exposures of fish under riverine conditions, which entail fish migrating in varying depths (Chapter 6), saturation levels {Ruffing et al. 1996}, and temperatures (Chapter 5). There is little consensus among biologists about how much laboratory-based dose-response information is needed to establish protective levels for in-river fish. Further research to relate gas exposure to mortality (and secondary effects such as increased predation) will increase the knowledge base but probably not quickly improve consensus.

Gas bubble disease in river fish

- How information from controlled experiments relates to fish in the river is unclear. Much less is known about how gas bubble disease develops in the river system than in the laboratory or artificial field enclosures. Free-swimming fish may avoid supersaturation by swimming in deeper levels where water pressure compensates for high gas concentrations. If so, then data on their normal behavior without supersaturation may not be relevant to estimating exposures.

Alternatively, life-stage-specific behavioral patterns (such as feeding by subyearlings in shallow waters on a daily cycle during emigration) may ensure some exposure to elevated gas saturations. Recent data on the spatial variability of total dissolved gas levels downstream of dams {Ruffing et al. 1996} suggests that migrating salmonids must receive fluctuating exposures. Whether and how these fluctuating exposures accumulate to a debilitating level are not known. More field research is needed to understand what happens in the real world, but it may be long-term. A fully definitive set of experimental information that mimics conditions in the field may not be attainable.

- We know little about sublethal and behavioral effects of exposures to gas supersaturation both in the laboratory and the river system, although there are suggestive observations of both the occurrence and importance of these effects for fish survival in their ecological context (such as increased susceptibility of sublethally exposed juveniles to predation; National Biological Service, Cook, Washington, unpublished). Not enough attention has been given to the ecological context of debilitating exposures; this avenue deserves further research and analysis if we are to relate gas saturation exposures to survival.

Monitoring for gas bubble disease

- Standard methods for measuring and quantifying bubble signs in fish that are clearly related to mortality (or other debilitation) should be useful for routine monitoring. Because a monitoring program for juvenile migrants has been in place at dams for several years (Fish Passage Center, Portland, Oregon, annual reports), the agencies decided to use these facilities for routine monitoring. Although certain measures have been implemented in laboratory testing and field monitoring (bubbles in the lateral line, fins, buccal cavity, and gill lamellae) the link to changes in survival is still unclear. We can not reliably relate severity of damage or probability of death (survivability) to the presence or absence of specific signs used in monitoring today across a full range of possible effects. This deficiency has led some observers to view the use of signs as unproductive and possibly misleading. More perspective is needed linking identifiable signs and survival of fish in the river **{Coutant et al. 1996}**.

- Monitoring of juvenile salmonids for gas bubble disease signs in the bypasses of dams is based upon assumptions that have not been substantiated and thus the results may be skewed toward underestimation of effects {BMIT 1995; Coutant et al. 1996}. The most critical assumptions are that :

(a) signs are not altered in passage through the fish bypass, consisting of a sequence of holding in dam forebay, descent to the turbine intake, screening, ascent in the gatewell, passage through pipes or troughs, separation from water flows in the Smolt Monitoring Program's separator, and holding before examination, evidence from simulator tests suggests that it does; {Montgomery and Watson 1995};

(b) fish at the dam bypasses are representative of fish in the river-reservoir system. Sampling at McNary Dam appears to under sample juveniles of Snake River origin (Coutant et al. 1996);

(c) there is no significant mortality between sample sites (i.e., the dam-sampled fish do not just represent the survivors after direct mortality, predation, etc.);

(d) the relationship between monitored signs and survival is known; and

(e) the dam bypasses represent adequately the highest risk reaches where the most damage may occur.

- The level of accuracy needed in biological monitoring of gas bubble disease signs as an index of survival depends, in part, on the amount of survival benefit derived from using spill rather than turbines for passing fish at dams (Coutant et al. 1996). If the survival benefit from using spill is small, say 5-7% system wide, as suggested by the National Marine Fisheries Service's analyses of transportation (this chapter), then a high level of monitoring accuracy is needed to ensure that in-river mortalities from gas bubble disease do not exceed this value. If, however, the survival benefit from spill is large, then there is more margin for error in the estimates of gas bubble disease effects on survival. Because the benefit of spill is still uncertain, so is the needed accuracy in biological monitoring of indices of survival from gas bubble disease.

- There may be early-detection methods for identifying the development of bubbles in fish that could be used to signal a potential problem in the river, but these have not yet been developed. Optical (reflectance or transmission of light) and acoustic (passing sound waves through fish) methods are examples of "high tech" approaches that might be fruitful for the monitoring program {Coutant et al. 1995}. Such techniques could avoid mortalities from excessive handling or dissection of fish. It may take considerable research to develop these techniques.

- Sampling of fish from the river (through nets, traps, etc.) may provide a more representative sample of riverine fish, and can be directed toward high-risk sites, but collecting fish in a large river-reservoir system is arduous, examinations on a boat are difficult, and there are untested sampling assumptions such as there being no gear selectivity for debilitated fish. Gear selection for debilitated fish could skew the results toward high incidence of signs.

- Biological monitoring of signs in fish as a means for managing spills requires an agreed-upon criterion for action (e.g., cessation of spill when the incidence of signs becomes too high). The relationship between signs and survival is inadequately known to substantiate the current 15% incidence criterion for juveniles and 0% incidence criterion for adults, or any alternative criteria.

- Monitoring of fish from the dams or river for signs of gas bubble disease as a means to regulate concurrent spills is fraught with so many uncertainties that using established physical-chemical criteria may be the better way. This is the historical approach to water quality management. Although simplifying in some respects, such a decision shifts the argument to the level of supersaturation selected. Uncertainties about actual exposures in the river and their relationships to mortality (noted above) make selection of an allowable level difficult. Unless some conservative saturation value for biological effects is agreed upon as a matter of principle, this approach is equally uncertain. Preliminary analyses of 1994-95 PIT-tag survival data by NMFS and the Fish Passage Center (presentation to Council, January 10, 1996) suggested that managed spill yielding gas saturation values generally under 115% did not lower survival.

- Because high in-river survival of fish is the recovery goal, direct measurement of survival under varying conditions of gas supersaturation would appear to be the most useful source of information for managing total dissolved gas saturation and spill. Methods for obtaining reach survival estimates being developed by Muir et al (1995). Analysis techniques initiated by Cramer {1996} call for further examination.

- A research program has been proposed by the National Marine Fisheries Service that tests the critical assumptions of the monitoring program, tests in-river survival of juveniles under controlled conditions of enclosures augmented with capture of in-river migrants, and study of alternative methods for monitoring gas bubble signs. The Expert Panel recommended that this program be pursued while the conventional monitoring program is continued for comparison }Coutant et al. 1996}.

Risk management

- Gas bubble disease is but one consideration among many for management of flow and fish passage in the Columbia and Snake rivers to minimize mortality. Risk management among the many sources of biological damage is important and it depends on having reasonably complete understanding of each source of mortality, including gas bubble disease. A recent risk analysis concluded that the risk of fish loss from gas supersaturation caused by managed spills was less than that expected from turbine passage and other damages (Center, 1995). This analysis, although extensive, has been criticized as not being sufficiently comprehensive.

Reduction in total dissolved gas saturation

- Realizing that the debate over adequacy of relevant biological knowledge from research or monitoring is unlikely to end soon, and entail extensive and expensive research and monitoring, which may not be feasible, an alternative course would be to search for mechanisms to lower levels of total dissolved gas during fish emigration. Carefully evaluated, innovative engineering and water management projects might be identified and implemented to limit the springtime increases in gas saturation while providing adequate fish passage.

- Modification of spillways with "flip lips" was an active program by the Corps of Engineers in the 1970s, but was largely abandoned when spill became less common. Provision of these modifications on the basis of current scientific knowledge about both the probable biological need and engineering feasibility might be more fruitful than further attempts to eliminate all uncertainties in biological monitoring.

- Overall reduction in risk may require water managers to consider plans that spread the effects of high, uncontrolled flows (in flood years) over longer time periods in order to minimize exceptionally high spill (and gas supersaturation) during the peak fish migration season.

CONCLUSIONS (AND LEVEL OF PROOF) FOR GAS BUBBLE DISEASE

1. Salmonids in water supersaturated with atmospheric gases in laboratory experiments (usually shallow tanks) can develop bubbles in tissues at levels as low as 105% saturation although debilitating trauma does not usually occur until about 110% saturation, the USEPA-recommended water quality standard. The severity of debilitating trauma is greater the higher the saturation. Mortalities within 24 hours are common at saturation values of 130% or more. The relationships between development of bubbles and associated mortalities differs between long exposures to low saturation values and short exposures to high values. The relationships between signs and mortality for different exposures and species are not fully described, but work is underway. (1)

2. The cause and persistence of supersaturation in waters of the Columbia River basin are known to be the spilling of water at dams with deep plunge pools followed by slow equilibration with air in downstream rivers or reservoirs. There is complex in-river mixing of supersaturated water from spill and water from turbines and tributaries not enriched with gases that is not fully described, but research is underway. (1)

3. The relationship between in-river gas supersaturation levels and salmonid in-river survival is not well understood because (a) the supersaturation-exposure histories of in-river fish are not well understood (e.g., fish can descend in the water to compensate with water pressure, supersaturation values differ across and down the river as fish migrate) and these variable exposures are not easily related to laboratory dose-response experiments (which have generally not sought to mimic field exposure histories), and (b) sublethally debilitated fish can be lost through predation, disease, or other ecological factors not well quantified. (1)

4. Monitoring of gas bubble disease signs at the bypasses of dams as part of the Smolt Monitoring Program as an index of the incidence and severity of gas bubble trauma in river fish may be inadequate (usually underestimate effects) because of changes in signs in bypasses, loss of debilitated fish in reservoirs between dams, and other untested critical assumptions. (2)

5. Managed spill, used as a means of passing fish at dams with low mortality, can induce supersaturation, as can uncontrolled spill caused by excess runoff. The relative benefits of managed spill when counteracted by any in-river mortalities from gas bubble disease are not well established. Uncontrolled spill at levels of the 1970s is well demonstrated to cause high risk of fish mortalities. Managed spill resulting in levels generally below 115% did not appear to cause mortalities. (2-3)

6. Spill, unless supplanted by surface fish bypasses (this chapter), is the passage route that most closely approximates juvenile passage in the normative river, and thus should be the closest match to the normal behavior patterns of migrants. (1)

7. Given the unresolved scientific aspects of estimating the risks from gas bubble disease relative to the benefits of spill for passing fish at dams, it seems more fruitful to modify dam spillways to allow spill with minimal supersaturation of gases. Solution of the gas saturation problem at the source would solve gas bubble disease problems of both managed and uncontrolled spill. (1)

GENERAL CONCLUSION FOR GAS BUBBLE DISEASE

Gas bubble disease from supersaturation of water with atmospheric gases is a poorly defined but highly plausible (based on much science) risk to in-river fish, a risk that would need to be better defined to quantitatively establish the net value of spill as a mechanism to reduce mortalities during dam passage. This definition would require a large amount of research and monitoring to achieve desired levels of confidence, and may not be feasible.

CRITICAL UNCERTAINTIES FOR GAS BUBBLE DISEASE

1. Relationships of signs of gas bubble trauma to fish mortality.
2. Exposure histories of in-river fish to supersaturated conditions in a river-reservoir environment of varying total dissolved gas supersaturation, depth of migration, and temperature.
3. Unsubstantiated assumptions behind the monitoring of signs at dam bypass monitoring stations.
4. Ability to monitor in-river fish for signs or survival.
5. Relative risks and benefits of spill compared to other means of dam passage.

RECOMMENDATIONS FOR GAS BUBBLE DISEASE

The ISG recommends that dams be modified structurally to avoid or minimize gas supersaturation under conditions of both managed and uncontrolled spill rather than expanding gas-bubble disease research to adequately define the risk of gas bubble disease in river fish. Unless data can be collected inexpensively in conjuction with an integrated program of mainstem monitoring, much research would be necessary, likely beyond our capacity. Spill has a demonstrated lower level of fish mortality at dams than turbine passage and it more closely approximates the normative river system to which migrant behavior has evolved than either passage through turbines or gatewell fish bypasses. In-river monitoring, whether for trauma signs or for reach-specific survival, is being developed and needs further use to establish a more reliable estimate of survival of migrants under differing levels of gas supersaturation than is provided by monitoring at dam bypasses.

E. EFFICACY OF TRANSPORTATION

Transportation of juvenile salmon down river in barges and trucks is one of the techniques employed in the attempt to protect salmon from the harmful effects of the federal Columbia River hydroelectric system. A portion of the juvenile salmon emigrants is removed from the reservoirs when they arrive at the federally owned and operated hydroelectric dams of the Snake and Columbia Rivers during their annual migration down the river (Point F, Figure 7.1). Fish are collected out of the turbine intake bypass system (Figure 7.4). Screens at the intake divert fish into collection channels (bypass flume, Figure 7.4) that take the fish through the dams. At some of the projects there are facilities where fish can either be removed for transportation or allowed to continue down the river. Effectiveness in collecting fish for transportation therefore depends on the fish guidance efficiency of the intake screens (FGE), which varies among projects according to flow, species and life history type, among other factors. In general FGE is higher for life history types with large juvenile emigrants, such as spring chinook, and lower for life history types with small juvenile emigrants, such as sockeye and fall chinook (see preceding sections of this chapter). In any event,without considering any other factors, the efficacy of transport depends heavily on the FGE and the FGE varies on a dam by dam basis with respect to state of maturity within a life history type, and with respect to life history type

The captured fish are placed into water-filled barges or tank trucks, and transported down river to be released into the unimpounded portion of the Columbia River below Bonneville Dam (Figure 2.6). As noted above, methods of collection do not permit all of the juveniles to be collected at any one dam, however collections are made at several dams, so that only a fraction of the migrants is expected to transit the full federal hydroelectric system of eight reservoirs and dams. Not all species and life history types are equally easy to collect, so that the proportion remaining in the river will vary by species and life history type within species.

Determination of effectiveness of transportation

The general experimental approach is to collect actively migrating juveniles at one or more upstream dams, divide a portion of the fish collected into transported and untransported (control) groups, mark fish in each group with distinctive freeze brands and coded wire tags, and then either transport the fish around the remaining dams or return them to the river to continue their downstream journey. The experimental fish rejoin the unmarked population and spend one to four years in the ocean before returning to freshwater to spawn. The number of adults bearing treatment and control marks is recorded in samples obtained from commercial and recreational catches, adults passing mainstem dams, and fish returning to upriver hatcheries and spawning grounds. Evaluation of the transport program is based on comparative rates of return of transported and untransported adults under the assumption that the probability of recapture is the same for all marked fish.

For each transport-control group, the rate of return (R_T or R_C, the subscript denoting the experimental treatment) is defined as the observed number of marked adults (n_T, n_C) in a sample divided by the number of juveniles originally marked and released (N_T, N_C). A Transport/Control (T/C) ratio (or the equivalent Transport Benefit Ratio (TBR) is calculated as R_T /R_C. T/C ratios are determined either for a paired Transport/Control subsample (i.e., a within-season replicate) or, more commonly, for all Transport/Control fish marked at a given site over one season. An "annual" T/C ratio is obtained by combining (not averaging) mark/recapture data across all within-season replicates. Reported values are typically based on the number of adults observed (not estimated) to return to the point of origin rather than to all recovery sites.

Transportation appears to have increased the survival of fish to the point of release in about half of the experiments conducted during 1968-1990 (Table 7.2).

Problems in estimating reduced mortality of transported versus untransported fish

The central thesis of transportation is that transportation removes the mortality that would otherwise have been inflicted by the hydroelectric system. According to this thesis, the maximum expected benefit resulting from transportation would be removal of the mortality experienced in the hydroelectric system by untransported juveniles. But, estimates of hydroelectric system survival for untransported juveniles were not made, nor were estimates of survival to release for transported juveniles made. However, by assuming that mortalities are equal for both groups after exit from the hydroelectric system and transportation until they return as adults, the difference in the release to recapture survivals of the two groups may be attributed to the effects of the hydroelectric system and transportation.

Park's {1985} statement of the fundamental thesis with respect to effectiveness of transportation focuses on an objective to increase smolt survival. However, the impracticality of recapturing sufficient numbers of treatment smolts below the point of release of transported fish (Ebel et al., 1973), led to the necessity of measuring effectiveness in terms of differences in return rates of adults. With the advent of new tagging technology, PIT's (passive integrated transponders), experiments are now well under way at the National Marine Fisheries Service's Coastal Zone and Estuarine Studies Division Seattle, Washington. Such results should permit revisiting the question of measuring the effects of transportation at different points in the life cycle, as well as for routes of passage other than the turbine intake bypass

The question of fixing the lower bound on the effects of transportation on mortalities of juvenile salmonids is most challenging, and no small part of the challenge derives from multiple definitions of the effects. Since much of the research by NMFS has been focused on the ability of transportation to increase the rate of return of adults to the point of release[i] that were transported as juveniles, compared to the rate of return to the point of release of adults not transported as juveniles, the NMFS defines the effect of transportation as a change in the relative rate of adult return to the point of release between transported and untransported juveniles. Hence the null hypothesis is that there is no difference in rate of adult return to the point of release (see footnote 1) between transported and untransported juveniles.

In 1993, in response to new considerations, such as the Endangered Species Act and the recent federal court ruling on the shortcomings of the Biological Opinion on the hydroelectric system (see footnote, Chapter 1 of this report), the interest in effectiveness of transportation was enlarged from a question of whether transportation can improve the survival of downstream migrating smolts, which is the question addressed by the NMFS research, to a question relating to the effectiveness of transportation in increasing adult returns of individual populations or stocks to particular points of natal origin (Ad Hoc Transportation Review Group, 1992). These questions have led to other questions about the basic assumptions needed for future use in transportation work {FWS Technical Staff 1993}, such as the ability of transported fish to find their way back to their natal spawning grounds.

National Marine Fisheries Service investigators have addressed questions regarding the survivals and homing behaviors of juvenile salmon from the inception of their studies. For example, Ebel et al. (Ebel et al., 1973) reported results of a study designed to determine whether transportation affected homing of Snake River chinook and steelhead, concluding that homing ability was not affected, based on the opinion that returns of transported juvenile salmon at Ice Harbor Dam and at the Rapid River hatchery on the Snake River were virtually the same. Slatick et al. (1975, 1988) focused on the question of whether transportation affects homing, and if so, how might the effects be overcome. Park (1985) observed that transported fish tended to spend more time than untransported fish in the lower river as adults.

Since the publications of Ebel (1973); 1980) and Slatick et al. (1975, 1988), questions concerning the degree to which homing abilities may be impaired, the degree to which the act of transportation inflicts mortality on the transported fish, the degree to which the act of gathering the fish for transportation inflicts mortality, and the degree to which the treatment effects of transportation may be measured and understood have become more and more prominent {FWS Technical Staff 1993}. Although the degree to which collection for transportation inflicts injuries and mortalities should not affect the perception of the relative rates of return of transported and untransported adults, collection mortality is a factor which prevents comparison of rates of return of transported fish to rates of return of fish that passed by spill and turbines. The need to evaluate alternative mitigative measures such as spill is pressing (Northwest Power Planning Council, 1992) {DFOP 1993}.

Does transportation reduce mortality and result in greater returns?

Snake Basin spring/summer chinook have shown a response to transportation that is best explained in terms of conditions within the hydroelectric system at the time of transportation. Clearly adverse conditions associated with low flows in the hydroelectric system, such as those of 1973, have shown clearly positive relative rates of adult returns for transported spring/summer chinook to the point of transportation, with extremely low overall survival of both transported and untransported salmon. In another low flow year, 1977, the effects of transportation could not be measured because nearly all of the juvenile salmon marked for the experiment, both transport and control, died before returning as adults. However, under passage conditions associated with higher river flows than those of 1973 and 1977, the responses of relative survivals of spring/summer chinook to transportation may be equivocal, and sometimes negative, in conjunction with overall higher survivals for both transported and untransported salmon. In order to understand the effects of transportation it is essential to have information on survival by route of passage. There is presently no standard for hydroelectric project (dam plus reservoir) and system (the sum of dams and reservoirs) survival for listed species that is based upon the rebuilding schedule for the species.

Juvenile salmon die at rates related to physical conditions existing during the time of emigration in the river, including the hydroelectric system, despite the transportation effort. Given the apparent dependence of the survivals of both transported and untransported juvenile salmon on conditions in the hydroelectric system, transportation alone, as presently conceived and implemented, is unlikely to halt or prevent the continued decline and extirpation of listed species of salmon in the Snake River Basin. While transportation appears to improve the relative survivals of certain kinds of salmon from the Snake River Basin under certain combinations of dam operations and river flow conditions, it removes only part of the mortalities attendant to passage through the hydroelectric system.

Available evidence is not sufficient to identify transportation as either a primary or supporting method of choice for salmon recovery in the Snake River Basin. While juvenile salmon transportation may not be discounted as a recovery measure, the factual basis is insufficient to determine the relative efficacy of transportation as a mitigative measure for recovery of salmon populations listed as threatened and endangered in the Snake River Basin. Hence, even if all juvenile salmon could be collected for transportation, there is not enough evidence from previous research to suggest that even the minimum survival rates necessary for maintenance of population levels could be achieved, let alone those survival rates necessary for rebuilding of salmon populations.

Research results to date are not conclusive regarding the ability of transportation to improve returns to the spawning grounds due to problems associated with experimental design and lack of wild fish. In the Snake River, relative survivals have been measured by returns of adults back to the point of transportation, so the research conclusions do not apply in terms of actual returns to upriver locations such as the spawning grounds.

Stock specific information on the effects of transportation is not at hand. The number of experimental fish does not permit evaluation of the effects of transportation for particular stocks of salmon originating from individual hatcheries and watersheds.

The kinds of Snake River salmon for which transportation is likely to act to improve relative survival to the point of transportation are the steelhead and to a lesser degree the yearling-migrant stream type chinook salmon designated as "spring/summer chinook" by the National Marine Fisheries Service. With respect to Snake Basin fall (subyearling emigrant, ocean type) chinook, the time sequenced progression of fish quality and state of maturation may not be conducive to transportation from a locality such as Lower Granite Dam. Facts are not in evidence to permit the assessment of the utility of transportation from Snake River Dams for the sockeye salmon. Steelhead appear to have the best relative survivals under transportation, as measured at the hydroelectric project from which they are transported. However, the facts regarding the role of transportation in returning steelhead to the spawning grounds are limited.

Since information collected on fall chinook and sockeye salmon in places outside the Snake River Basin may not be applicable inside that basin, there is insufficient information to determine how transportation may affect the survivals of these two federally listed species.

Conclusions

1. Evidence exists that for certain life history types of certain species that transportation can provide increases in survival measured in terms of adult returns to the point where tagged smolts were released.

2. Transportation alone does not appear sufficient to overcome the current negative effects of habitat loss, hydropower operations and other sources of mortality.

3. Transportation is stock (life history) selective and may be unnecessary under normative river conditions where all life history types and species would benefit, rather than just those with biological characteristics which lend themselves to transport.

4. In specific instances where normative river conditions cannot be restored, transporation may have a role in smolt migration.

Table 7.2. Percentage of yearling chinook returning as adults after having been either transported or released as controls from dams on the Snake River as yearling juvenile salmon during the emigration seasons of 1968 - 1990, and the ratio of transport to control, T/C. Data and commentary provided by Dr. John Williams, Coastal Zone and Estuarine Studies Division, NMFS, January 6, 1995.

Species	Dam	Year	Percent return Trans	Contr	T/C	NMFS comments
Yr. Chin	IHR	1968	0.30	0.15	2.1*	
Yr. Chin	IHR	1968	0.16	0.15	1.1	A.
Yr. Chin	IHR	1969	0.24	0.19	1.3*	
Yr. Chin	IHR	1969	0.13	0.19	0.7	A.
Yr. Chin	IHR	1970	0.29	0.20	1.5*	
Yr. Chin	IHR	1970	0.07	0.20	0.4	A.
Yr. Chin	LGO	1971	0.38	0.25	1.6*	
Yr. Chin	LGO	1971	0.42	0.25	1.7*	B.
Yr. Chin	LGO	1972	0.08	0.08	1.1	
Yr. Chin	LGO	1972	0.09	0.08	1.1	B.
Yr. Chin	LGO	1973	0.31	0.02	13.8*	
Yr. Chin	LGO	1973	0.42	0.02	18.4*	B.
Yr. Chin	LGO	1976	0.04	0.02	1.8	C.
Yr. Chin	LGO	1976	0.03	0.02	1.2	C.; D.
Yr. Chin	LGO	1976	0.02	0.03	0.9	E.; D.
Yr. Chin	LGO	1976	0.03	0.01	3.9	D.; F.
Yr. Chin	LGO	1976	0.03	0.03	1.0	E.
Yr. Chin	LGO	1976	0.05	0.01	6.1	F.
Yr. Chin	LGO	1978	0.01	0.01	0.7	
Yr. Chin	LGO	1978	0.00	0.01	0.2	
Yr. Chin	LGR	1975	0.64	0.31	2.0*	
Yr. Chin	LGR	1976	0.02	0.04	0.6	C.
Yr. Chin	LGR	1976	0.04	0.04	1.0	C.; D.
Yr. Chin	LGR	1976	0.03	0.04	0.8	E.; D.
Yr. Chin	LGR	1976	0.08	0.04	2.1	D.; F.
Yr. Chin	LGR	1976	0.02	0.04	0.4	E.

Table 7.2. continued.

Species	Dam	Year	Percent return Trans	Contr	T/C	NMFS comments
Yr. Chin	LGR	1976	0.04	0.04	1.0	F.
Yr. Chin	LGR	1977	13 total returns to all recovery sites from transported fish --- no controls recovered			
Yr. Chin	LGR	1978	0.12	0.01	8.5*	Barge
Yr. Chin	LGR	1978	0.07	0.01	5.3*	Truck
Yr. Chin	LGR	1979	0.04	0.01	3.4*	Barge
Yr. Chin	LGR	1980	none	none	---	
Yr. Chin	LGR	1980	0.00	none	---	
Yr. Chin	LGR	1983	0.28	no controls released		
Yr. Chin	LGR	1984	0.16	no controls released		
Yr. Chin	LGR	1985	0.22	no controls released		
Yr. Chin	LGR	1986	0.16	0.10	1.6*	
Yr. Chin	LGR	1987	0.18	no controls released		
Yr. Chin	LGR	1989	0.06	0.02	2.4*	
Yr. Chin	LGR	1990	0.37	no controls released		

* Statistically significant difference between adult return rates of transported versus inriver migrants.

IHR is Ice Harbor Dam; LGO is Little Goose Dam; and LGR is Lower Granite Dam.

A. Released transported fish at John Day Dam. These fish had much lower return rates than transported fish released below Bonneville Dam. It is highly unlikely that the difference was due to mortalities between John Day Dam and Bonneville Dam as control fish which transited the same area had overall return rates equal to the transported fish.

B. Fish released at Dalton Point rather than the normal release site into the tailrace of Bonneville Dam downstream from the frontroll.

C. These numbers represent data that was combine from releases made at the Washington shore boat launch in April with releases at the normal Bonneville Dam tailrace release site in May and June.

D. These fish were hauled in a 10ppt salt-water solution. The solution was made by adding normal table salt to the water in the tank truck. This is not a procedure in use at this time.

E. Releases were made at the Washington shore boat launch in April. Because of wave action and the location of the ramp, the release hose did not go very far into the tailrace. Fish were washed up on the shore as they were released. (The same thing occurred with the 1987 releases for the Bonneville II survival studies.)

F. These were releases from fish marked in May and June only.

F. PREDATORS AND PREDATOR CONTROL

Predation by other fish species and birds, especially gulls on the mainstem, is a well documented source of mortality for emigrant juvenile salmon in the Columbia River Basin {Ruggerone and Mathews 1984}. Direct observations of rates of consumption, and conclusions derived from simulation models, established fish predation as a factor capable of removing a substantial fraction of the annual juvenile emigration {Willis and Ward 1993}. It was therefore logical for the framers of the Northwest Power Planning Council's Fish and Wildlife Program to consider means of altering predation in ways beneficial to salmon survival.

The application of predator control to increase survivals of emigrants which is now underway in the Columbia River Basin was extensively discussed over a two year period by biologists employed by the fisheries agencies and tribes, the Northwest Power Planning Council and the hydroelectric industries prior to implementation. These scientists constituted a Technical Working Group (TWG). The discussions were conducted in the Reservoir Mortality and Water Budget Effectiveness Technical Working Group under the auspices of the Northwest Power Planning Council in 1988 and 1989 with written reports being presented to the NPPC. One of the primary agents of mortality in reservoirs of the Columbia River was postulated by the Working Group to be predation by piscivorous fishes. The extent to which predation is a documented agent of mortality in juvenile salmonids in the Columbia River system was established by an intensive program of research on predation on juvenile salmon conducted in John Day reservoir; see Poe and Rieman {1988}**;** (Collis et al., 1995)), as well as by prior research, i.e., Thompson and Moran {1959} which formed the basis for the John Day investigations. With a good deal of difficulty owing to the perceived failures of many past predator control programs elsewhere in fish and wildlife management, the Working Group identified predator control as one of the few measures within the Fish and Wildlife Program which might immediately reduce mortalities of emigrant and resident juvenile salmonids.

Northern Squawfish *Ptychocheilus oregonensis* (hereafter NSF) was chosen to be the object of control as one of the best known predators on juvenile salmonids. NSF was the target of the program not only because research indicated it to be responsible for the majority of predation on juvenile salmonids in the reservoir behind John Day Dam {Poe and Rieman 1988}, but also because other predators were the objects of sports harvesting effort, while NSF were not. Exotic predators such as the members of the sunfish family, Smallmouth bass *Micropterus dolomieu*, bluegill and related species *Lepomis macrochirus* and other *Lepomis* spp., and the crappies *Pomoxis* spp. were obvious targets of opportunity, which were spared due to the concerns of the sports fisheries management agencies. The protection was also extended to other introduced predators such as walleye *Stizostedion vitreum* and channel catfish *Ictalurus punctatus* as the object of sports fisheries. As was the case with the decision to consider predator control as a mitigation tool, the decision to discuss limiting that tool to a predator species native to the ecosystem, while sparing exotic species of predators, was very difficult for the Working Group. The decision was made somewhat easier for the Working Group by the concept that the presence and operation of the hydroelectric dams had given the NSF advantages in reproduction and opportunities for predation on juvenile salmonids which did not exist prior to impoundment.

Due to the controversial nature of the predator control measures from the beginning, predator control was envisioned in its broad sense to include non-lethal means of reducing access of NSF to juvenile salmon in the hydroelectric system, as well as more traditional means of removal by fishing and other lethal means {see Poe et al. 1988**}**. Modeling studies indicated that annual exploitation of NSF of approximately 15% could reduce the losses of juvenile salmonids by as much as half {Rieman and Beamesderfer 1988}. The control program was also seen by the Working Group not as a short term effort to eradicate NSF, but as a long term, perhaps continuous, attempt to alter the age composition of the population in favor of the younger, smaller age classes which do not consume juvenile salmonids. Altering the age composition was seen as preferable to eradication efforts, because the NSF age structure might be altered without substantially diminishing the reproductive capacity of the population. With sustained NSF reproduction, other species of predators, which normally target juvenile NSF, would not be forced to switch to juvenile salmonids by declining availability of NSF juveniles.

The Working Group also discussed the need to reduce populations of NSF in the immediate vicinity of the hydroelectric dams. Very large NSF individuals congregate in the forebays and tailraces of the dams. The waters near the dams are also known as the boat restricted zone (BRZ), because the general public is prohibited from the area. Angling from the dams and operational procedures such as turbine operating sequences and spill were also identified as possible ways to disrupt intense predation at the dams.

The control program was implemented by the fisheries agencies and tribes starting with pilot studies in 1990 {see Young 1996}. The pilot approaches to reduction of NSF predator populations to date have been: 1) paying bounty to members of the public for NSF of predaceous size (sport reward fishery); 2) employing net fishers to target NSF in the reservoirs; 3) employing professional hook and line anglers to fish in waters adjacent to dams from which the general public is excluded; and 4) fishing with nets near a hatchery outfall. All approaches but the reservoir net fishing were initially highly productive. The sport reward and hatchery outfall fisheries have continued to be highly productive as of the 1995 season {Young 1996}. The dam angling projects have seen a sharp drop in catches of NSF as of 1995. Angling by all means is estimated to have reduced predaceous populations of NSF to levels which should provide a 36% reduction in potential predation on juvenile salmonids by NSF in 1996, as measured relative to the time period prior to 1990. Reductions in NSF populations are not uniformly geographically distributed, with some areas showing decreases, while others do not.

Northern Squawfish greater than eleven inches in length are known to be predators on juvenile emigrant salmon. The predator control program has demonstrated a sharp decline in the numbers of Northern Squawfish available to angling in the vicinity of Snake and lower Columbia River dams, and it has demonstrated a shift toward younger, smaller individuals available to private anglers outside the areas of dam influence. Annual catches and catch per unit effort by technicians angling below Snake and Columbia River dams have declined by about 80% during the four years of the program ending in 1995, however there has been no appreciable change in the average size of the individuals caught at dams. Annual catches of private anglers, who are paid for each squawfish over eleven inches long, have not declined during this period, however the average size of the individual fish in these catches has declined. Average size of the individuals caught by private anglers appears to be influenced by recruitment from strong year classes in unimpounded areas below Bonneville Dam, and below Priest Rapids Dam. Since fewer squawfish are now experiencing the higher feeding rates available at the dams, it is possible that the program has been instrumental in lowering the rate of NSF predation, which would have otherwise been experienced by the juvenile salmon. The extent to which the predator control program may have changed the total annual rate of predation by all piscivorous species in the hydroelectric system is not known.

CONCLUSIONS FOR PREDATORS AND PREDATOR CONTROL

1. Individuals of Northern Squawfish (NSF) greater than eleven inches in length are known to eat juvenile salmon in the Columbia River basin. Columbia River basin NSF populations are capable of consuming on the order of several million juvenile salmon each year. (1)

2. Rates of predation by NSF on juvenile salmon are known to be higher in the boat free zones of dams than in the reservoirs of the hydroelectric system. Boat free zones include the tailraces below, and the forebays above, where it not safe to operate recreational boats. (1)

3. Since 1990, total annual catches, and catch per unit effort of NSF from professionals angling in the boat free zones of the Snake and lower Columbia River dams (dam angling) have shown a sharp decline, although the average size of the fish in the catches has not declined during this period (1)

4. Since 1991, total annual catch per unit effort from public angling outside the boat free zones above and below the Snake and lower Columbia River dams (i.e., non-sport reward fishing areas) has shown no apparent trend, although the average size of the fish in the catches has declined significantly during this period. (1)

5. Predaceous sized NSF are attracted by hatchery releases of juvenile salmon as demonstrated by site specific net fisheries conducted at hatchery release localities. (1)

6. Since there are now fewer squawfish of predaceous size in the vicinities of the dams where the higher feeding rates are experienced. The overall rate of predation of squawfish on juvenile salmon has been lowered since 1990. (3)

7. The use of spill as a juvenile salmon passage measure has also been in effect between 1990-1995. Spill may be a factor in determining the effects of attempts to control NSF and other predators, since spill appears to reduce the total amount of habitat suitable for piscivorous Northern Squawfish below dams to an extent which depends on the design of the dam (2).

8. When juvenile salmon pass the hydroelectric projects by the spillway, all predators, including NSF, encounter lower prey densities of juvenile salmon in those areas where rates of predation are otherwise the highest, i.e. in the turbine tailraces, bypass outfalls and other areas immediately below the dam. (3)

GENERAL CONCLUSIONS FOR PREDATORS AND PREDATOR CONTROL

As a consequence of the predator control program, the information is available to indicate that the overall rate of predation of squawfish on juvenile salmon has been lowered since 1990. The extent to which any single factor such as spill, or the predator control program, may have been a factor in lowering the rate of predation of Northern squawfish on juvenile salmon is uncertain. Spill is a factor which in some cases might lower the rate of predation by all fish predators in the vicinity of the dams. The change in the size composition of the catches in the sport reward fishery promises a reduced total rate of predation by NSF on juvenile salmon.

Literature Cited

Citations in curly brackets { } are not presently in the literature cited.

Absolon, R.F., D.W. Brege, B.P. Sandford and D.D. Dey. 1995. Studies to Evaluate the Effectiveness of Extended-length Screens at The Dalles Dam, 1994, NSFS/NOAA Northwest Fisheries Science Center**:** 69.

Ad Hoc Transportation Review Group. 1992. Review of salmon and steelhead transportation studies in the Columbia and Snake Rivers, 1984 to 1989, Columbia Basin Fish and Wildlife Authority**:** 40.

Anas, R.E. and J.R. Gauley. 1956. Blueback Salmon, *Oncorhynchus nerka*, Age and Length at Seaward Migration past Bonneville Dam, US Fish and Wildlife Service**:** 46.

Andrew, F.J. and G.H. Geen. 1960. Sockeye and Pink Salmon Production in Relation to Proposed Dams in the Fraser River System, International Pacific Salmon Fisheries Commission**:** 259.

Armour, C.L. 1990. Options for reintroducing Salmon and Steelhead above Mid-Snake River Dams. Fort Collins, US Fish and Wildlife Service, National Ecology Research Center, 4512 McMurray Ave. Colorado 80525**:** 14 pp. + app.

Bates, K.M. 1992. Fishway Design Guidelines for Pacific Salmon. Olympia, WA Department of Fish and Wildlife. Washington.

Bell, C.R. 1967. Plant Variation and Classification. Belmont, Wadsworth Publishing.

Bell, M.C. 1991. Fisheries Handbook of Engineering Requirements and Biological Criteria. Portland, US Army Corps of Engineers, North Pacific Division, Fish Passage and Evaluation Program.

Bell, M.C., A.C. Delacy and G.J. Paulik. 1981. A compendium on the success of passage of small fish through turbines. Updated Compendium on the Success of Passage of Small Fish Through Turbines. M. C. Bell, US Army Corps of Engineers. Contract No. D-35-026-CIVENG-66-C16 and Contract No. DACW-68-76-C-0254**:** Section I: 1-201.

Biosonics, I. 1983. Hydroacoustic Assessment of Downstream Migrating Salmon and Steelhead at Rock Island Dam in 1983. Wenatchee, Public Utility District No. 1 of Chelan County. Washington**:** 99.

Biosonics, I. 1983. Hydroacoustic Monitoring and Distribution of Downstream Migrant Salmonids and Evaluation of the Prototype Bypass System at Wells Dam in Spring, 1983. East Wenatchee, Public Utility District No. 1 of Douglas County. Washington**:** 37 pp. + app.

Biosonics, I. 1984. Hydroacoustic Assessment of Downstream Migrating Salmon and Steelhead at Rocky Reach Dam in 1983. Wenatchee, Public Utility District No. 1 of Chelan County. Washington**:** 52 pp. + app.

Biosonics, I. 1995. Hydroacoustic evaluation of vertical slots, sluiceway and spill at Ice Harbor Dam. Corps of Engineers Meeting, September, Walla Walla, Washington.

Bjornn, T.C. 1992. Survival of Chinook Salmon Smolts as Related to Stress at Dams and Smolt Quality. Moscow, US Fish and Wildlife Service, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho. Idaho.

Bouck, G.R. 1980. Etiology of gas bubble disease. Tran. Amer. Fish. Soc. 109: 703-707.

Brege, D.A., R.F. Absolon, B.P. Sandford and D.D. Dey. 1994. Studies to Evaluate the Effectiveness of Extended-Length Screens at The Dalles Dam, 1993, NMFS/NOAA Northwest Fisheries Science Center**:** 72.

Brege, D.A., R.F. Krcma, R.D. Ledgerwood and D.R. Miller. 1992. Summary report on evaluation of the rehabilitated juvenile fish collection and passage system at John Day Dam - 1985 and 1986. Seventh Progress Report: Fish Passage and Evaluation Program 1984-1990, US Army Corps of Engineers, North Pacific Division, Environmental Resources Division**:** 151-157.

Brege, D.A., D.R. Miller and R.D. Ledgerwood. 1987. Evaluation of the Rehabilitated Juvenile Salmonid Collection and Passage System at John Day Dam - 1986. Portland, NMFS/NOAA Northwest Fisheries Center. Oregon.

Brege, D.A., W.T. Norman, G.A. Swan and J.G. Williams. 1988. Research at McNary Dam to Improve Fish Guiding Efficiency of Yearling Chinook Salmon, 1987. Portland, NMFS/NOAA Northwest Fisheries Center. Oregon**:** 34.

Brege, D.A., G.A. Swan and J.G. Williams. 1988. Fish Guiding Efficiency Studies at Ice Harbor Dam, 1987, NMFS/NOAA Northwest Fisheries Science Center**:** 20.

Brett, J.R. 1957. Salmon Research and Hydroelectric Power Development, Fisheries Research Board of Canada.

Brett, J.R. and D.F. Alderdice. 1958. Research on Guiding Young Salmon at Two British Columbia Field Stations, Fisheries Research Board of Canada**:** 75.

Brett, J.R. and D. MacKinnon. 1953. Preliminary experiments using lights and bubbles to deflect migrating young spring salmon. J. Fish. Res. Board Can. 10(8): 548-559.

Bruce, S. 1995. 1995 migration exceeds expectations. Salmon Passage Notes, Snake and Columbia River Fish Programs September.

Burnham, K.P., D.R. Anderson, G.C. White, C. Brownie and K.H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. Am. Fish. Soc. Monogr.(Monograph 5).

Carlson, T.J. 1994. Use of Sound for Fish Protection at Power Facilities: A Historical Perspective of the State of the Art. Phase I, Bonneville Power Administration**:** 58 pp. + app.

Ceballos, J., S. Petit, J. McKern, R. Boyce and D. Hurson. 1993. Fish Transportation Oversight Team Annual Report - FY 1992. Transportation Operations on the Snake and Columbia Rivers, NMFS/NOAA: 75 pp. + app.

Center, F.P. 1995. Summary of the 1995 Spring and Summer Juvenile Passage Season. Portland, Fish Passage Center. Oregon: 32.

Chapman, D., A. Giorgi, M. Hill, A. Maule, S. McCutcheon, D. Park, W. Platts, K. Pratt, J. Seeb, L. Seeb and F. Utter. 1991. Status of Snake River Chinook Salmon. Boise, Don Chapman Consultants, Inc., 3653 Rickenbacker, Suite 200. Idaho: 520.

Chapman, D., A. Giorgi, T. Hillman, D. Deppert, M. Erho, S. Hays, C. Peven, B. Suzumoto and R. Klinge. 1994. Status of Summer/Fall Chinook Salmon in the Mid-Columbia Region. Boise, Don Chapman Consultants Inc. Idaho: 411 + app.

Chapman, D.W. and D. McKenzie. 1980. Mid-Columbia River System Mortality Study. East Wenatchee, Douglas County Public Utility District No. 1. Washington: 23.

Collins, G.B., W.J. Ebel, G.E. Monan, H.L. Raymond and G.K. Tonanaka. 1975. The Snake River Salmon and Steelhead Crisis. Seattle, Bureau of Commercial Fisheries, Northwest and Alaska Fisheries Center. Washington: 30.

Collins, G.B. and C.H. Elling. 1964. Summary of Progress in Fish Passage Research. Seattle, US Bureau of Commercial Fisheries, Northwest and Alaska Fisheries Center. Washington: 17.

Collis, K., R.E. Beaty and B.R. Crain. 1995. Changes in catch rate and diet of northern squawfish associated with the release of hatchery-reared juvenile salmonids in a Columbia River reservoir. North Am. J. Fish. Manage. 15(2): 346-357.

Cramer, F.K. 1965. Fish Passage through Hydroelectric Turbines. Walla Walla, US Army Corps of Engineers, Walla Walla District. Washington.

Cramer, F.K. and R.C. Oligher. 1960. Fish Passage through Turbines, Tests at Cushman No. 2 Hydroelectric Plant. Walla Walla, US Army Corps of Engineers, Walla Walla District. Washington.

Cramer, F.K. and R.C. Oligher. 1961. Fish Passage through Turbines, Further Tests at Cushman No. 2 Hydroelectric Plant. Walla Walla, US Army Corps of Engineers, Walla Walla District. Washington.

Dawley, E.M., L.G. Gilbreath, R.D. Ledgerwood, P.J. Bentley, B.P. Dandford and M.H. Schiewe. 1989. Survival of Subyearling Chinook Salmon Which have Passed through the Turbines, Bypass Sytem, and Tailrace Basin of Bonneville Dam Second Powerhouse, NMFS/NOAA Northwest Fisheries Science Center: 80.

Dawley, E.M., R.D. Ledgerwood, L.G. Gilbreath, B.P. Sandford, P.J. Bentley, M.H. Schiewe and S.J. Grabowski. 1992. Survival of Juvenile Salmon Passing through Bonneville Dam and Tailrace. Seattle, NMFS/NOAA, Northwest Fisheries Center. Washington.

DeHart, D.A. 1987. Downstream migrant juvenile salmonid protection systems for low to medium head hydroelectric dams. Seattle, School of Fisheries, University of Washington. Washington**:** 152 pp. + app.

Dolat, S.W., S. Hays, R. Nason and J.R. Skalski. 1995. A Study Using Sonalysts, Inc. FishStartle Technology. Waterford, Sonalysts, Inc. Connecticut**:** 28 pp. + app.

Dunn, C.A. 1978. Evaluation of Downstream Fish Passage through Multi-level Outlet Pipes at Wynoochee Dam. Olympia, Washington Dept. of Fisheries. Washington**:** 96.

Ebel, W.J. 1969. Supersaturation of nitrogen in the Columbia River and its effects on salmon and steelhead trout. US Fish. Wild. Serv. Fish. Bull. 68: 1-11.

Ebel, W.J. 1981. Effects of environmental degradation on the freshwater stage of anadromous fish. 50 Years of Cooperation and Commitment (1931-1981). NMFS/NOAA Technical Memo, Northwest Fisheries Science Center**:** 147-180.

Ebel, W.J., E.M. Dawley and B.H. Monk. 1971. Thermal tolerance of juvenile Pacific salmon and steelhead trout in relation to supersaturation of nitrogen gas. U.S. Fish Wildlife Service Fisheries Bulletin 69: 833-843.

Ebel, W.J., R.F. Krcma, D.L. Park, H.L. Raymond, E.M. Slatci, E.M. Dawley and G.A. Swan. 1974. Evaluation of Fish Protection Facilities at Little Goose Dam, NMFS/NOAA Northwest Fisheries Science Center.

Ebel, W.J., R.F. Krcma and H. Raymond. 1973. Evaluation of Fish Protection Facilities at Little Goose and Lower Granite Dams and Review of Other Studies Relating to Protection of Juvenile Salmonids in the Columbia and Snake Rivers, National Marine Fisheries Service.

Eicher, G.E. 1988. Fish collection, transportation and release in relation to protection at power plants. Proceedings: Fish Protection at Steam and Hydroelectric Power Plants. W. C. Micheletti. EPRI CS/EA/AP-5663-SR**:** I-13-23.

Engineers, U.S.A.C.o. 1993. Fish Passage Development and Evaluation Program 1984-1990. Portland, U. S. Army Corps of Engineers
North Pacific Division. Oregon**:** 403.

Gessel, M.H., B. Monk, D. Brege and J. Williams. 1990. Continued Studies to Evaluate the Juvenile Bypass Systems at Bonneville Dam, NMFS/NOAA Northwest Fisheries Center**:** 34 pp. + app.

Gessel, M.H., B.H. Monk, D.A. Brege and J.G. Williams. 1989. Fish Guidance Efficiency Studies at Bonneville Dam First and Second Powerhouses - 1988, NMFS/NOAA Northwest Fisheries Center.

Gessel, M.H., W.D. Muir, B.P. Sanford and D.B. Dey. 1993. Evaluation of the New Juvenile Salmonid Bypass System at Lower Monumental Dam, 1992, NMFS/NOAA Northwest Fisheries Science Center**:** 23.

Gessel, M.H., B.P. Sanford and D.B. Dey. 1995. Studies to Evaluate the Effectiveness of Extended-Length Screens at Little Goose Dam, 1994, NMFS/NOAA Northwest Fisheries Science Center**:** 33.

Gessel, M.H., J.G. Williams, D.A. Brege, R.A. Krcma and D.R. Chambers. 1991. Juvenile salmonid guidance at the Bonneville Dam Second Powerhouse, Columbia River, 1983-1989. North Amer. J. Fish. Mgmt. 11: 400-412.

Giorgi, A.E. and J.R. Stevenson. 1995. A Review of Biological Investigations Describing Smolt Passage Behavior at Portland District Corps of Engineers Projects: Implications to Surface Collection Systems, Don Chapman Consultants**:** 33.

Giorgi, A.E. and L. Stuehrenberg. 1988. Lower granite pool and turbine survival study, 1987. Portland, Bonneville Power Administration. Oregon**:** 30.

Giorgi, A.E., G.A. Swan, W.S. Zaugg, T. Coley and T.Y. Berila. 1988. Susceptibility of chinook salmon smolts to bypass systems at hydroelectric dams. N. Amer. J. Fish. Mgmt. 8: 25-29.

Graban, J.R. 1964. Evaluation of the Fish Facilities at Brownlee and Oxbow Dams. Boise, Idaho Fish and Game Dept. Idaho**:** 60.

Haas, J.B. 1965. Fishery Problems Associated with Brownlee, Oxbow, and Hells Canyon Dams on the Middle Snake River. Portland, Fish Commission of Oregon. Oregon**:** 95.

Hammond, S.L. 1991. Wanapum Prototype Fish Diversion Screen, 1991 Test Plan. Ephrata, Public Utility District No. 2 of Grant county. Washington**:** 4.

Hays, S.G. 1984. Determination of the Depth Distribution of Juvenile Salmonids in the Turbine Intakes at Rocky Reach and Rock Island Dams. Wenatchee, Chelan County Public Utility District No. 1. Washington**:** 67 pp. + app.

Hays, S.G. and K.B. Truscott. 1986. Rocky Reach Prototype Fish Guidance System - 1986 Developmental Testing. Wenatchee, Public Utility District of Chelan County. Washington**:** 50 pp. + app.

Hill, C.M. 1982. Airlift Evaluation Rocky Reach. Wenatchee, Public Utility District No. 1 of Chelan County. Washington**:** 41.

Independent Scientific Group. 1996. Summary of Statistical Reviews of the NMFS/UW Survival Studies.

Iwamoto, R.N., W. Muir, B. Sandford, K. McIntyre, D. Frost, J. Williams, S. Smith and J. Skalski. 1993. Survival Estimates for the Passage of Juvenile Chinook Through Snake River Dams and Reservoirs, NMFS/NOAA Northwest Fisheries Science Center: 140 pp. + app.

Iwamoto, R.N., W.D. Muir, B.P. Sandford, K.W. McIntyre, D.A. Frost, J.G. Williams, S.G. Smith and J.R. Skalski. 1994. Survival Estimates for the Passage of Juvenile Salmonids through Snake River Dams and Reservoirs, 1994. Portland, Bonneville Power Administration. Oregon.

Iwamoto, R.N. and J.G. Williams. 1993. Juvenile Salmonid Passage and Survival Through Turbines, NMFS/NOAA Northwest Fisheries Science Center, jointly with US Army Corps of Engineers, Portland District: 27.

Johnsen, R.C. 1978. Salvage Operation for Juvenile Salmonids at John Day Dam - 1977, NMFS/NOAA Northwest Fisheries Science Center: 4.

Johnsen, R.C. and E.M. Dawley. 1974. The Effect of Spillway Flow Deflectors at Bonneville Dam on Total Gas Supersaturation and Survival of Juvenile Salmon, NMFS/NOAA: 19.

Johnson, G.E., C.M. Sullivan and J. M. W. Erho. 1992. Hydroacoustic studies for developing a smolt bypass system at Wells Dam. Fisheries Research 14.

Johnson, L. and R. Wright. 1987. Hydroacoustic Evaluation of the Spill Program for Fish Passage at John Day Dam in 1987, Associated Fish Biologists, Inc.: 77 pp. + app.

Koski, C.H. and e. al. 1989. Fish Transportation Oversight Technical Team Annual Report - FY 1988, NOAA.

Koski, C.H., S.W. Petit, J.B. Athearn and A.L. Heindl. 1986. Fish Transportation Oversight Technical Team Annual Report - FY 1985. Transport Operations on the Snake and Columbia Rivers, NOAA: 70 pp. + app.

Krcma, R.F. 1985. Preliminary Results of Fish Guiding Efficiency of Traveling Screens at The Dalles Dam, NMFS/NOAA Northwest Fisheries Center.

Krcma, R.F., D.A. Brege and R.D. Ledgerwood. 1986. Evaluation of the Rehabilitated Fish Collection and Passage System at John Day Dam - 1985, NMFS/NOAA Northwest Fisheries Science Center: 25 pp. + app.

Krcma, R.F., D. DeHart, M. Gessel, C.Long and C.W. Sims. 1982. Evaluation of Submersible Traveling Screens, Passage of Juvenile Salmonids through the Ice-Trash Sluiceway, and Cycling of Gatewell Orifice Operations at the Bonneville First Powerhouse, 1981. Seattle, NMFS/NOAA Northwest Fisheries Center. Washington.

Krcma, R.F., W.E. Farr and C.W. Long. 1980. Research to Develop Bar Screens for Guiding Juvenile Salmonids Out of Turbine Intakes at Low Head Dams on the Columbia and Snake Rivers, 1977-1979, NMFS/NOAA Northwest Fisheries Science Center: 28.

Krcma, R.F., C.W. Long and C.S. Thompson. 1978. Research and Development of a Fingerling Protection System for Low Head Dams - 1977, NMFS/NOAA Northwest Fisheries Science Center**:** 32.

Krcma, R.F., G.A. Swan and F.J. Ossiander. 1985. Fish Guiding and Orifice Passage Efficiency Tests with Subyearling Chinook Salmon, McNary Dam, 1984, NMFS/NOAA Northwest Fisheries Center**:** 19 pp. + app.

Krcma, R.W. and e. al. 1984. Evaluation of the Juvenile Collection and Bypass Systems at Bonneville Dam - 1984, NMFS/NOAA Northwest Fisheries Center.

Krcma, R.W., M.H. Gessel, W.D. Muir, C.S. McCutcheon, L.G. Gilbreath and B.H. Monk. 1984. Evaluation of the Juvenile Collection and Bypass System at Bonneville Dam - 1983, NMFS/NOAA Northwest Fisheries Science Center**:** 68.

Krcma, R.W., M.H. Gessel and F.J. Ossiander. 1983. Research at McNary Dam to Develop and Implement a Fingerling Protection System for John Day Dam, NMFS/NOAA Northwest Fisheries Center**:** 32.

Kuehl, S. and 1986. 1986. Hydroacoustic Evaluation of Juvenile Salmonid Fish Passage at John Day Dam in Summer, 1986, Biosonics, Inc.**:** 61 pp. + app.

Ledgerwood, R.D., E.M. Dawley, L.G. Gilbreath, B.J. Bentley, B.P. Sandford and M.W. Schiewe. 1991. Relative Survival of Subyearling Chinook Salmon that have Passed through the Turbines or Bypass System of Bonneville Dam Second Powerhouse, 1990, NMFA/NOAA Northwest Fisheries Science Center**:** 90.

Ledgerwood, R.D., E.M. Dawley, L.G. Gilbreath, P.J. Bentley, B.P. Sandford and M.H. Schiewe. 1990. Relative survival of subyearling chinook salmon which have passed Bonneville Dam via the spillway or the second powerhouse turbines or bypass system in 1989. Seattle, National Marine Fisheries Service. Washington**:** 64 + app.

Ledgerwood, R.D., E.M. Dawley, L.G. Gilbreath, L.T. Parker, B.P. Sandford and S.J. Grabowski. 1994. Relative survival of subyearling chinook salmon at Bonneville Dam, 1992. Seattle, National Marine Fisheries Service. Washington**:** 83.

Ledgerwood, R.D., G.A. Swan and R.F. Krcma. 1987. Fish Guiding Efficiency of Submersible Traveling Screens at Lower Monumental Dam - 1986, NMFS/NOAA Northwest Fisheries Science Center**:** 32.

Logie, P. 1993. Power System Coordination. A Guide to the Pacific Northwest Coordination Agreement. Columbia River System Operation Review, Joint Project of US Dept. of Energy, Bonneville Power Administration; US Dept. of the Army, Corps of Engineers, North Pacific Division; and US Dept. of Interior, Bureau of Reclamation, Pacific Northwest Region**:** 46.

Long, C.W. 1968. Diel movement and vertical distribution of juvenile anadromous fish in turbine intakes. U. S. Fishery Bulletin 66: 599-609.

Long, C.W., R.F. Krcma, W. Marquett and R. Duncan. 1970. Further Research on a Fingerling Bypass for Low Head Dams, NMFS/NOAA Northwest Fisheries Science Center**:** 10.

Long, C.W., F.J. Ossiander, T.E. Ruehle and G.M. Mathews. 1975. Survival of Coho Salmon Fingerlings Passing through Operating Turbines with and without Perforated Bulkheads and of Steelhead Trout Fingerlings Passing through Spillways with and without a Flow Detector, NMFS/NOAA Northwest Fisheries Science Center**:** 8.

Lucas, C.W. 1981. The mortality to fish passing through turbines as related to conditions and performance characteristics, pressure change, negative pressure, and other factors. Cavitation and Hydraulic Machinery, IAHR Symposium, Sendai, Japan.

Magne, R.A., D.R. Bryson and W.T. Nagy. 1987. Hydroacoustic Monitoring of Downstream Migrant Juvenile Salmonid Passage at John Day Dam in 1984-1985. Portland, US Army Corps of Engineers. Oregon**:** 29 pp. + app.

Magne, R.A., W.T. Nagy and W.C. Maslen. 1987. Hydroacoustic Monitoring of Downstream Migrant Juvenile Salmonids at John Day Dam in 1983. Portland, US Army Corps of Engineers. Oregon**:** 35 pp. + app.

Magne, R.A., R.J. Stansell and W.T. Nagy. 1989. Hydroacoustic monitoring of downstream migrant juvenile salmonids at Bonneville Dam, 1988. Seventh Progress Report: Fish Passage Development and Evaluation Program 1984-1990, US Army Corps of Engineers, North Pacific Division, Environmental Resource Division**:** 257-270.

Marotz, B.L., C. Althen, B. Lonon and D. Gustafson. 1996. Model Development to Establish Integrated Operational Rule Curves for Hungry Horse and Libby Reservoirs - Montana. Portland, Bonneville Power Administration. Oregon**:** 114.

Marquett, W., F.J. Ossiander, R. Duncan and C.W. Long. 1970. Research on the Gatewell-Sluice Method of Bypassing Downstream Migrant Fish around Low Head Dams, NMFS/NOAA Northwest Fisheries Science Center**:** 32.

Mathews, G.M., D.L. Park, J.R. harmon, C.S. McCutcheon and A.J. Novotny. 1987. Evaluation of Transportation of Juvenile Salmonids and Related Research on the Columbia and Snake Rivers - 1986, NMFS/NOAA Northwest Fisheries Science Center.

McComas, R.L., B.P. Sandford and D.B. Dey. 1994. Studies to Evaluate the Effectiveness of Extended-Length Screens at McNary Dam, 1993, NMFS/NOAA Northwest Fisheries Science Center**:** 109.

McFadden, B.D. and J. Hedgepeth. 1990. Hydroacoustic Evaluation of Juvenile Salmonid Fish Passage at John Day Dam in Summer, 1989, NMFS/NOAA Northwest Fisheries Science Center**:** 107 pp. + app.

McFadden, B.D., B.H. Ransom and B. Schnebly. 1992. Hydroacoustic Evaluation of the Effectiveness of the Sluiceway at Priest Rapids Dam in Passing Juvenile Salmon and Steelhead Trout during Spring and Summer 1992. Ephrata, Public Utility District No. 2 of Grant County. Washington**:** 77 pp. + app.

McKenzie, D., D. Carlile and D. Weitkamp. 1983. 1983 System Mortality Study. Report to Mid-Columbia Coordinating Committee. East Wenatchee, Douglas County Public Utility District No. 1. Washington**:** 25 pp. + app.

McKenzie, D., D. Weitkamp, T. Schadt, D. Carlile and D. Chapman. 1982. 1982 System Mortality Study. Report to Mid-Columbia Coordinating Committee. East Wenatchee, Douglas County Public Utility District No. 1. Washington**:** 37 pp. + app.

Michimoto, R.T. and L. Korn. 1969. A Study of the Value of Using the Ice and Trash Sluiceway for Passing Downstream Migrant Salmonids at Bonneville Dam. Portland, Fish Commission of Oregon. Oregon**:** 28.

Mighetto, L. and W.J. Ebel. 1994. Saving the Salmon: A History of the US Army Corps of Engineers. Efforts to Protect Anadromous Fish on the Columbia and Snake Rivers. Seattle, Historical Research Associates.

Mighetto, L.M. and W.J. Ebel. 1995. Saving the Salmon: A History of the US Army Corps of Engineers' Role in the Protection of Anadromous Fish on the Columbia and Snake Rivers. Report to the US Army Crops of Engineers, North Pacific Division. Seattle, Historical Research Associates.

Monk, B.F., W.D. Muir and M.H. Gessel. 1987. Studies to Evaluate Alternative Methods of Bypassing Juvenile Fish at The Dalles Dam - 1986, NMFS/NOAA Northwest Fisheries Science Center**:** 16.

Monk, B.F., B.P. Sandford and D.D. Dey. 1995. Evaluation of Fish Guidance Efficiency of Submersible Traveling Screens and Other Modifications at Bonneville Dam Second Powerhouse, 1995, NMFS/NOAA Northwest Fisheries Science Center**:** 25.

Monk, B.H., B.P. Sandford and J.G. Williams. 1992. Evaluation of the Juvenile Fish Collection, Transportation, and Bypass Facility at Little Goose Dam, 1990. Seattle, National Marine Fisheries Service, Northwest Fisheries Science Center. Washington.

Mueller, R.P., C.S. Abernethy and D.A. Neitzel. 1995. A Fisheries Evaluation of the Dryden Fish Screening Facility. Annual Report, 1994. Portland, Bonneville Power Administration. Oregon.

Mueller, R.P. and J.F. Osborn. 1969. Hydraulic Model Studies of a Fish Guidance Screen. Pullman, Albrook Hydraulic Laboratory, Washington State University. Washington**:** 34.

Muir, W.D., R.N. Iwamoto, C.P. Paisley, B.P. Sandford, P.A. Ocker and T.E. Ruehle. 1995. Relative Survival of Juvenile Chinook Salmon after Passage through Spillbays and the Tailrace at Lower Monumental Dam, 1994, NMFS/NOAA Northwest Fisheries Science Center.

Muir, W.D., S.G. Smith, R.N. Iwamoto, D.J. Kamikawa, K.W. McIntyre, E.E. Hockersmith, B.P. Sandford, P.A. Ocker, T.E. Ruehle and J.G. Williams. 1995. Survival Estimates for the Passage of Juvenile Salmonids through Snake River Dams and Reservoirs, 1994. Portland, Bonneville Power Administration. Oregon**:** 187.

National Marine Fisheries Service. 1995. Draft Biological Opinion on Reinitiation of Consultation on 1994-1998 Operation of the Federal Columbia River Power System and Juvenile Transportation Program in 1994-1998, U. S. Army Corps of Engineers, Bonneville Power Administration, Bureau of Reclamation, and National Marine Fisheries Service**:** 146 + app.

National Marine Fisheries Service. 1995. Proposed Recovery Plan for Snake River Salmon. Washington, US Dept. of Commerce, National Oceanic and Atmospheric Administration. District of Columbia**:** 387.

National Research Council. 1995. Science and the Endangered Species Act. Washington, National Academy Press.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Report on the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids for the National Research Council of the National Academy of Sciences. Washington D. C., National Academy Press.

Nichols, D.W. and B.H. Ransom. 1980. Development of The Dalles Dam Trash Sluiceway as a Downstream Migrant Bypass System for Juvenile Salmonids, Oregon Dept. of Fish and Wildlife. Oregon**:** 36 pp. + app.

Nichols, D.W. and B.H. Ransom. 1981. Development of The Dalles Dam Trash Sluiceway as a Downstream Migrant Bypass System, 1981, Oregon Dept. of Fish and Wildlife**:** 34 pp. + app.

Nichols, D.W., F.R. Young and C.O. Junge. 1978. Evaluation of The Dalles Dam Ice-Trash Sluiceway as a Downstream Migrant Bypass System during 1977, Oregon Dept. of Fish and Wildlife. Oregon**:** 10 pp. + app.

Northwest Power Planning Council. 1987. 1987 Columbia River Basin Fish and Wildlife Program. Portland, Northwest Power Planning Council. Oregon**:** 246.

Northwest Power Planning Council. 1992. Columbia River Basin Fish and Wildlife Program. Portland. Oregon.

Northwest Power Planning Council. 1994. 1994 Columbia River Basin Fish and Wildlife Program.

Odgaard, J.A., R.A. Elder and D. Weitkamp. 1990. Turbine-intake fish-diversion system. J. Hydraulic Engineering 116(11): 1301-1316.

Office of Technology Assessment. 1995. Fish Passage Technologies: Protection at Hydropower Facilities. Washington, US Govt. Printing Office. DC**:** 167.

Olson, F.W. 1981. Rock Island Fingerling Bypass Evaluation, CH2M Hill. Available from Public Utility District No. 1 of Chelan County, Wenatchee, WA**:** 31.

Olson, F.W. and V.N. Kaczynski. 1980. Survival of Downstream Migrant Coho Salmon and Steelhead through Bulb Turbines, CH2M Hill. Available from Public Utility District No. 1 of Chelan County, Wenatchee, WA**:** 45.

Ouellette, D.A. 1988. Hydroacoustic Evaluation of Juvenile Fish Passage at John Day Dam in summer, 1988, Biosonics, Inc.**:** 64 pp. + app.

Park, D.L., G.M. Mathews, J.R. Smith, T.E. Ruehle, J.R. Harmon and S. Achord. 1984. Evaluation of Transportation of Juvenile Salmonids and Related Research on the Columbia and Snake Rivers, 1983, NMFS/NOAA Northwest Fisheries Science Center**:** 39 pp. + app.

Park, D.L., J.R. Smith, E. Slatick, G.M. Mathews, L.R. Basham and G.A. Swan. 1978. Evaluation of Fish Protective Facilities at Little Goose and Lower Granite Dams, and Review of Mass Transportation Activities, 1977, NMFS/NOAA Northwest Fisheries Science Center**:** 60.

Park, D.L., J.R. Smith, E. Slatick, G.A. Swan, E.M. Dawley and G.M. Mathews. 1977. Evaluation of Fish Protective Facilities at Little Goose and Lower Granite Dams, and Review of Nitrogen Studies Relating to Protection of Juvenile Salmonids in the Columbia and Snake Rivers, 1976, NMFS/NOAA Northwest Fisheries Science Center**:** 48 pp. + app.

Petersen, K.C. 1995. River of Life, Channel of Death. Lewiston, Confluence Press.

Peven, C.M. 1993. Fish Guidance System Developmental Testing at Rock Island Dam Powerhouse No. 1, Spring and Summer - 1993. Wenatchee, Chelan County Public Utility District. Washington**:** 27 pp. + app.

Peven, C.M. 1996. Study Plan for Testing of Surface Collector at Rocky Reach in 1996. Wenatchee, Chelan County Public Utility District. Washington.

Peven, C.M., A.M. Abbott and B. Bickford. 1995. Biological Evaluation of the Rocky Reach Surface Collector. Wenatchee, Chelan County Public Utility District. Washington**:** 38 pp. + app.

Peven, C.M. and B.G. Keesee. 1992. Rocky Reach Fish Guidance System Developmental Testing. Wenatchee, Public Utility District No. 1 of Chelan County. Washington**:** 20.

Prentice, E.F. 1990. PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. American Fish. Soc. Symposium 7: 323-334.

Quistorff, E. 1966. Floating salmonid smolt collectors at Baker River dams. Fishery Research Papers 2(4): 39-52.

Rainey, W.S. 1995. Considerations in the design of juvenile bypass systems. Symposium on Small Hydropower and Fisheries, Aurora.

Ransom, B.H. and D.A. Ouellette. 1991. Hydroacoustic evaluation of juvenile fish passage at Ice Harbor Dam in Spring, 1987, Biosonics, Inc.

Ransom, B.H., G.A. Raemhild and T.W. Steig. 1988. Hydroacoustic evaluation of deep and shallow spill as a bypass mechanism for downstream migrating salmon and steelhead at Rock Island Dam. Fish Protection at Steam and Hydroelectric Power Plants.

Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975., Trans. Am. Fish. Soc. 108(6):505-529.

Raymond, H.L. and C.W. Sims. 1980. Assessment of Smolt Migration and Passage Enhancement Studies for 1979. Seattle, NMFS/NOAA Northwest Fisheries Science Center. Washington**:** 48.

Rich, W.H. 1940. The future of the Columbia River salmon fisheries. Stanford Ichthyological Bulletin 2(2): 37-47.

Ruehle, T.E., C.W. Long and M.H. Gessel. 1978. Laboratory Studies of a Non-Traveling Bar Screen for Guiding Juvenile Salmonids Out of Turbine Intakes, NMFS/NOAA Northwest Fisheries Science Center**:** 14.

Salmonids, C.o.P.a.M.o.P.N.A., B.o.E.S.a. Toxicology and C.o.L. Sciences. 1995. Upstream: Salmon and Society in the Pacific Northwest. Washington, National Academy Press.

Schoeneman, D.E., R.T. Pressey and C.O. Junge. 1961. Mortalities of downstream migrating salmon at McNary Dam. Trans. Am. Fish. Soc. 90(1): 58-72.

Schreck, C.B., H.W. Li, A.G. Maule, S. Bradford, B. Barton and L. Sigismondi. 1984. Columbia River Salmonid Smolt Outmigration: McNary Dam passage and Enhanced Smolt Quality. Corvallis, US Fish and Wildlife Service, Oregon Cooperative Fisheries Research Unit, Oregon State University. Oregon.

Sims, C. and F. Ossiander. 1981. Migrations of Juvenile Chinook Salmon and Steelhead in the Snake River, from 1973 to 1979, a Research Summary. Seattle, National Marine Fisheries Service. Washington.

Sims, C.W., A.E. Giorgi, R.C. Johnsen and D.A. Brege. 1984. Migrational characteristics of juvenile salmon and steelhead in the Columbia River basin 1983, U.S. Army Corps of Engineers and National Marine Fisheries Services**:** 31 + appendix.

Sims, C.W. and R. Johnson. 1977. Evaluation of the Fingerling Bypass System at John Day Dam and Fingerling Bypass Outfall at McNary Dam, NMFS/NOAA Northwest and Alaska Fishery Center**:** 15 pp. + app.

Skalski, J.R. 1993. Summary of 3-Year Bypass Efficiency Study at Wells Dam. East Wenatchee, Public Utility District No. 1 of Douglas County. Washington**:** 5.

Skalski, J.R. and A. Giorgi. 1992. Juvenile passage proposal: Estimating smolt travel time and survival in the Snake and Columbia Rivers, Center for Quantitative Science, Univ. of Washington, Seattle, WA, and Don Chapman Consultants, Inc., Redmond, WA**:** 55.

Stanford, J.A., B.K. Ellis, D.W. Chess, J.A. Craft and G.C. Poole. 1992. Monitoring water quality in Flathead Lake, Montana. 1992 Progress Report. Polson, Flathead Lake Biological Station, The University of Montana. Montana**:** 31.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant. *in press*. A general protocol for restoration of regulated rivers. Regulated Rivers.

Stansell, R.J., L.M. Beck, W.T. Nagy and R.A. Magne. 1991. Hydroacoustic Evaluation of Juvenile Fish Passage at The Dalles Dam Fish Attraction Water Units in 1990, (Summary: pp. 315-328 IN: US Army Corps of Engineers, North Pacific Division, Environmental Resources Division. 1993. Seventh Progress Report: Fish Passage Development and Evaluation Program 1984-1990).

Stansell, R.J., R.A. Magne, W.T. Nagy and L.M. Beck. 1990. Hydroacoustic Monitoring of Downstream Migrant Juvenile Salmonids at Bonneville Dam, 1989, (Summary: pp. 285-298 IN: US Army Corps of Engineers, North Pacific Division, Environmental Resource Division. 1993. Seventh Progress Report: Fish Passage Development and Evaluation Program 1984-1990).

Steig, T.W. and W.R. Johnson. 1986. Hydroacoustic Assessment of Downstream Migrating Salmonids at The Dalles Dam in Spring and Summer, 1985, Bonneville Power Administration**:** 56 pp. + app.

Steward, C.R. 1994. Assessment of the Flow-Survival Relationship Obtained by Sims and Ossiander (1981) for Snake River Spring/Summer Chinook Salmon Smolts. Portland, Bonneville Power Administration. Oregon**:** 82.

Stockley, C. 1959. Merwin Dam Downstream Migrant Bypass Trap Experiments for 1957. Olympia, Washington Dept. of Fisheries. Washington.

Sullivan, C.M. and G.E. Johnson. 1986. Hydroacoustic Evaluation of the Smolt Bypass System at Wells Dam in 1986. East Wenatchee, Public Utility District No. 1 of Douglas County. Washington**:** 26 pp. + app.

Sverdrup and Parcel and Associates, I. 1982. Wells Hydroelectric Project, Juvenile Salmon Bypass Study. East Wenatchee, Public Utility District No. 1 of Douglas County. Washington**:** 4 pp. + figures.

Swan, G.A., A.E. Giorgi, T. Coley and W.T. Norman. 1987. Testing Fish Guiding Efficiency of Submersible Traveling Screens at Little Goose Dam; Is It Affected by Smoltification Levels in Yearling Chinook Salmon?, NMFS/NOAA Northwest Fisheries Science Center**:** 72.

Swan, G.A., R.F. Krcma and F.J. Osiander. 1985. Development of an Improved Fingerling Protection System for Lower Granite Dam, 1984, NMFS/NOAA Report to US Army Corps of Engineers.

Swan, G.A., R.F. Krcma and F.J. Osiander. 1986. Continuing Studies to Improve and Evaluate Juvenile Fish Collection at Lower Granite Dam, 1985, NMFS/NOAA Northwest Fisheries Center**:** 31 pp. + app.

Swan, G.A., R.D. Ledgerwood, B.H. Monk, W.T. Norman, R.F. Krcma and J.G. Williams. 1992. Summary report on fish guidance efficiency studies at Lower Granite Dam - 1984, 1985, 1987, and 1989. Seventh Progress Report: Fish Passage Development and Evaluation Program 1984-1990. N. P. D. US Army Corps of Engineers, Environ. Resources Division. July, 1993**:** 137-143.

Swan, G.A., B.H. Monk, J.G. Williams and B.P. Sandford. 1990. Fish Guidance Efficiency of Subermersible Traveling Screens at Lower Granite Dam - 1989, NMFS/NOAA Northwest Fisheries Science Center**:** 31 pp. + app.

Swan, G.A. and W.T. Norman. 1987. Research to Improve Subyearling Chinook Fish Guiding Efficiency at McNary Dam - 1986, NMFS/NOAA Northwest Fisheries Science Center**:** 34.

Thorne, R.E. and E.S. Kuehl. 1989. Evaluation of Hydroacoustic Techniques for Assessment of Juvenile Fish Passage at Bonneville Powerhouse I, Biosonics, Inc.

Thorne, R.E. and E.S. Kuehl. 1990. Hydroacoustic Evaluation of Fish Behavioral Response to Fixed Bar Screens at Lower Granite Dam in 1989, (Summary: pp. 299-313 IN: US Army Corps of Engineers, North Pacific Division, Environmental Resources Division. 1993. Seventh Progress Report: Fish Passage Development and Evaluation Program 1984-1990).

Turbak, S.C., R. Reichle and C.R. Schriner. 1981. Analysis of Environmental Issues Related to Small-Scale Hydroelectric Development IV: Fish Mortality Resulting from Turbine Passage. Oak Ridge, Oak Ridge National Laboratory. Tennessee**:** 112.

Tyler, R.W. and J.D. Pock. 1989. Development and Testing of a Long Lead Net to Divert Salmon and Steelhead Smolts at Wanapum Dam**:** 106.

Wagner, E. and P. Ingram. 1973. Evaluation of Fish Facilities and Passage at Foster and Green Peter Dams on the South Santiam River Drainage in Oregon. Portland, Fish Commission of Oregon. Oregon**:** 11.

Wayne, W.W. 1961. Fish handling facilities for Baker River Project. J. of the Power Division, Proceedings of the ASCE 87: 23-54.

Weitkamp, D.E. and M. Katz. 1980. A review of dissolved gas supersaturation literature. Trans. Am. Fish. Soc. 109: 659-702.

Weitkamp, D.E., D. McKenzie and T. Schadt. 1980. Survival of Steelhead Smolts - Wells Dam Turbines and Spillway, 1980. East Wenatchee, Public Utility District No. 1 of Douglas County. Washington**:** 39.

Wik, S.J. and T.Y. Barila. 1990. Evaluation of extended-length screening concept Lower Granite Dam, 1990. Seventh Progress Report: Fish Passage Development and Evaluation Program 1984-1990, US Army Corps of Engineer, North Pacific Division, Environmental Resources Division**:** 329-337.

Williams, J.G. and G.M. Mathews. 1994. A review of flow/survival relationships for juvenile salmonids in the Columbia River Basin. Fishery Bulletin 93: 732-740.

Willis, C.F. and B.L. Uremovich. 1981. Evaluation of the Ice and Trash Sluiceway at Bonneville Dam as a Bypass System for Juvenile Salmonids, 1981, Oregon Dept. of Fish and Wildlife**:** 34 pp. + app.

Willis, L.D. and A.C. Hendricks. 1992. Life history, growth, survivorship, and production of *Hydropsyche slossonae* in Mill Creek, Virginia. J. North Am. Benthol. Soc. 11: 290-303.

Wood, C.A. 1993. Implementation and evaluation of the water budget. Fisheries 18(11): 6-17.

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[i] Unlike steelhead, *Oncorhynchus mykiss*, and spring chinook, *O. tshawytscha,* approximately half of the fall chinook salmon, *O. tshawytscha*, are harvested before they have the opportunity to return to the point of release. In the case of fall chinook, the effects are measured as the relative rates of tag recoveries from transported and untransported juveniles. Fall chinook are transported almost entirely from McNary Dam, having originated from the area below Priest Rapids Dam.

CHAPTER 8. HABITAT, HARVEST, AND HATCHERIES

SOURCES OF MORTALITY AND EFFECTIVENESS OF MITIGATION ACTIVITIES

A. TRIBUTARY AND MAINSTEM HABITAT RESTORATION

In our review of habitat (Chapter 5) problems in the basin we documented that quality habitat for each life history stage is essential to conservation and enhancement of Columbia Basin salmonids. Despite extensive expenditures under the Fish and Wildlife Program and other state and federal programs, it appears there is little evidence that habitat restoration has actually improved the productive capacity of streams and rivers for salmonids (Rhodes et al., 1994).

Apparently, habitat restoration has lagged as a mitigation priority for lack of a clear understanding of the specific biophysical conditions that exemplify quality habitat. We have often heard the argument that large amounts of pristine habitat remain in the headwater reaches of the river system, especially in designated wilderness areas (see Table 8.1). However, headwater reaches are predominantly high gradient within constrained channels and are generally unproductive owing to low concentrations of plant growth nutrients. Food web fertility derived from decaying carcasses of spent adult spawners may have been an essential feature that is now missing from these reaches (Bilby et al., 1996). In some areas of the basin, habitat degradation of headwater reaches is pervasive from mining, logging and road building (see Chapter 5).

Table 8.1. Chinook salmon habitat in the Columbia River basin as length of spawning and rearing habitat accessible in kilometers. Source NPPC (1986).

Type	*Original*	*1975*	*Percent of Original*
Spring	17088	8718	49
Summer	8002	3650	54
Fall	3961	2749	31
Average			45

It is generally assumed that recent use of best management practices (e.g., selective timber harvest prescriptions, larger riparian buffer strips, better road construction and maintenance guidelines) and use of audits to enforce them has improved instream habitats in managed landscapes. However, empirical demonstrations of real influences of best management practices on habitat variables (e.g., sedimentation, temperature, riparian vegetation, woody debris) are rare in the basin (Rhodes et al., 1994). Moreover, habitat enhancement traditionally is viewed mechanistically, consisting of construction or emplacement of instream structures such as rock gardens, step weirs and log piles (Hunter, 1991). Such structures often are not effective and may wash out in floods (Frissell and Nawa, 1992).

Because of the vast spatial scale of human activities that have caused degradation of habitats in tributary streams (especially including grazing, cropland and irrigated agriculture, and logging), it is unlikely that site-specific interventions can successfully offset the adverse ecological effects of land use activities. Instead, significant modification of land use patterns and practices, which if correctly implemented could result in the re-establishment of key natural biophysical processes over large areas, will be necessary for restoration at appropriate ecological scales (Doppelt et al., 1993; Frissell, 1993; 1993; Rhodes et al., 1994). This has been termed "passive restoration" in recent discussion of ecosystem restoration (Kauffman et al., 1995). The first principle of tributary restoration is to identify and fully protect from future human disturbance existing areas where high ecological integrity and largely natural ecosystem processes persist (Reeves and Sedell, 1992; Doppelt et al., 1993; Frissell, 1993; 1993). Such areas might include intact headwater tributary catchments, as well as downstream alluvial reaches where human activities have been relatively limited in their scope and ecological effects (Doppelt et al., 1993; Frissell, 1993; 1993). The most urgent priority for active intervention is to implement selected restoration measures necessary to prevent further ecological damage in these relatively intact areas. Such interventions do not include projects intended to re-create habitat that has been destroyed, but rather to de-fuse processes of impact that discourage the natural re-development of habitat diversity (Doppelt et al., 1993; Frissell, 1993; 1993). Examples of such interventions include obliteration or hydrologic de-commissioning of existing road networks, removal and exclosure of domestic livestock from key areas, modification of irrigation practices (see Table 8.2), removal or modification of selected dams diversion structures and re-establishment of instream flows in key reaches, and perhaps re-introduction of locally-adapted propagules of native riparian plant species (e.g., willows) that have been extirpated from certain tributary drainages. Comprehensive ecological assessment is necessary to successfully identify and establish priorities (among sites and activities) for such interventions, and such assessments must be a principle objective in watershed analysis projects of state and federal agencies (Frissell and Bayles, 1996, critique of).

Table 8.2. Acres under irrigation, and acre-feet of water delivered to agricultural enterprises by the Bureau of Reclamation, Columbia River Basin (Northwest Power Planning Council 1986).

Year	*Acres*	*Acre-ft*	*Source*
1889	400000		App. D. p. 178
1900	500000		App. D. p. 178
1910	2300000		App. D. p. 178
1925	2900000		App. D. p. 178
1947	---------	2639000	App. D. p. 181
1966	6600000		App. D. p. 178
1967	---------	8385500	App. D. p. 181
1979	---------	11653000	App. D. p. 181
1980	7600000		App. D. p. 178
1981	---------	10723200	App. D. p. 181

Our normative ecosystem concept (Chapter 2) emphasizes the importance of channel to floodplain connectivity and seasonality of flooding to create and maintain habitat (Figure 8.1). Restoration and enhancement of habitat forming processes on the large flood plains that are accessible to salmonids through reregulation of flows produce flood peaks and to stabilize baseflows, elimination of pollution loads (sediments, toxic compounds) and protection of riparian vegetation from logging and grazing are key elements of the normative river (Stanford et al., *in press*). These actions contrast with current habitat projects in the FWP and are more inclusive of the processes that the fish, especially juveniles require.

In the mainstem Snake and Columbia Rivers, restoring normative habitat conditions may be more problematic than for the riverine flood plains primarily because so many reservoirs are present that riverine characteristics are largely replaced by laucustrine conditions throughout the mainstems. Freshet flows will not produce habitat within the laucustrine reaches, although high flows associated with spring runoff may be beneficial to juvenile emigration via spill over the dams. In reviewing migration behavior and mortalities (Chapters 6 - 8), the importance of pulsed releases from the dams to simulate naturalized flow dynamics and stimulate emigration after runoff has tapered off was noted along with surface attraction coupled with spill for most effective juvenile bypass of the mainstem dams became apparent. Pulsed releases may be feasible because within the laucustrine reaches of the Columbia River shallow water habitats are limited and less influenced by volume fluctuations than riverine reaches. And, available data strongly suggests that juvenile chinook and sockeye are more likely to move donwstream in association with pulsing flows. However, uncertainty about the quality and accessibility of food webs in sustaining growth and vitality of juveniles within these mainstem reservoirs also was noted (Chapter 6), even though recent measures of mortality suggest lower values than expected for wild fall chinook passing through lower Snake River reservoirs (Muir, 1996). Additional food web research in relation to monitoring of juvenile mortalities is required to resolve normative habitat conditions in the mainstems.

Conclusions (level of proof) and recommendations

1. Habitat restoration in the normative river context has not been emphasized to date in the FWP as a primary mitigation need and it should be. (1)
2. Research to clarify habitat conditions in all of the mainstem reservoirs is needed.(1)

B. Harvest

Salmon are harvested by many different activities in the Columbia River basin. Intentional, or directed, harvest of adults and immature salmon for commercial, subsistence, ceremonial and recreational purposes has occurred since time immemorial, and records of intensive commercial harvest dating to 1865 are readily available (Craig and Hacker, 1940; Chapman et al., 1991; Chapman et al., 1994; National Marine Fisheries Service, 1995; National Research Council, 1996). Unintentional, or incidental harvest of salmon occurs in those activities which are not intended to capture the salmon species or life history stage which is taken. Incidental harvest of Columbia River salmon occurs in marine and freshwater fisheries for other species of fish, during salmon fisheries targeted on older life history stages of salmon, and in the production of electricity at hydroelectric dams, during and after logging operations, during and after irrigation withdrawals, during land development operations such as road and real estate building, and during and after some types of mining operations.

DIRECTED HARVEST

For the past several human generations, the number of salmon harvested in directed salmon fisheries has often been counted or estimated in an attempt to determine whether or not the productive capacity of the populations was being exceeded (Ricker, 1954; Beverton and Holt, 1957) and for other purposes, such as taxation. The directed harvest estimates were made because in theory, and in practice, it is possible to harvest at a rate high enough to diminish a salmon population's spawning potential and to cause it to be extirpated (Cushing, 1983). It was also assumed that the principal source of human induced mortality on salmon were the directed harvests, hence it was assumed that the health of the salmon populations could be assured through appropriate limitations on directed harvests (Mundy, 1985).

INTERACTIVE EFFECTS

In the Columbia River basin it is clear that directed harvest is only one of many sources of mortality, and it follows that all sources of mortality should be accounted for in order to permit the persistence of the salmon. In practice, all human induced mortalities are measured to the extent possible, with all remaining sources, such as predation by marine mammals, being attributed to natural mortality. Clearly traditional harvest management, which seeks only to control directed sources of fishing mortality (Ricker, 1975), is not sufficient to provide for the sustainable production of the Columbia River basin's salmon. However the principles of sustainable harvest management (Beverton and Holt, 1957; Cushing, 1983) need to be carried forward in framing a harvest management paradigm which is appropriate to the persistence of the full diversity of species and life history types of the basin's salmon. Ricker (1958) examined the effects of a fluctuating environment (variable mortalities induced at early life stages) on the productive capabilities of fish stocks.

Ideals from traditional harvest management which need to be retained relate to protecting all identifiable populations, and accounting for all sources of fishing mortality. Specifically, the ideal of limiting fishing mortality to a level which permits persistence of the smallest identifiable stock, also called a deme or population (National Research Council, 1996), a spawning aggregate of a life history type of a species, needs to be retained. In practice, fisheries management agencies have defined stocks as some identifiable aggregate of local spawning populations. The number of populations in the pragmatic stock definitions might be more a function of logistic considerations and the amount of funding available for monitoring than of biological considerations. It is now essential that the definition of a stock consider the biological criteria engendered by Endangered Species Act definitions of stock, such as the Evolutionarily Significant Unit (ESU) (Waples, 1991; Mundy et al., 1995; National Research Council, 1996). The practice of monitoring the populations, which includes counting or estimating the harvests by each of the "fisheries," needs to be retained. The concept of “fishery” should be extended to cover both the incidental and directed removals of salmon at all life history stages.

In addition to applying the principles of traditional harvest management, understanding the interactions and dependencies between harvest, the health of habitat, and the productivities of salmon populations (Ricker, 1954) is essential to improving our abilities to identify and implement salmon restoration efforts. In examining the Columbia River Basin, habitat loss and degradation, and unlimited fishing emerge as parallel companions of the initial decline in population numbers of the principal commercial salmon species (see Chapter 5 on freshwater habitat). The evolution of harvest management protection for naturally spawning Columbia River basin salmon was restrained by increases in hatchery production during the 1960’s . The large numbers of hatchery salmon drove the public policy process to sanction intensive fisheries on mixtures of hatchery and natural salmon which obscured the downward trends in production of the natural salmon populations. In the present, continuing habitat losses combine with ineffective harvest regulation as probable causes for the continuing failure of Columbia River chinook salmon. Therefore, an effective harvest management paradigm cannot be developed outside of an ecosystem context.

OVERFISHING AND INTERACTIONS WITH HABITAT LOSS

Harvests impact salmon productivities directly by reducing the numbers in the spawning populations, and indirectly by reducing the diversity of phenotypes in the population, which impacts factors important to basic productivity, such as average number of eggs per female (Miller, 1957; Ricker, 1981; Cushing, 1983, citing Russell 1931; Beaty, 1992). Overfishing occurs when fishing removes enough spawners from a population to cause it to decline. Overfishing reduces the production of salmon by reducing or eliminating the populations which have adapted to the habitat types and environmental conditions of the basin (Ricker, 1972; Riddell and Legget, 1981; Thorpe, 1995). As it has developed from the experience of the last three generations of fisheries scientists, and as harvest regulations increasingly reflect, management of salmon ought to protect the productive capacity of salmon runs by pursuing the reasonable and essential objective of protecting the genetic diversity of Pacific salmon populations on which production ultimately depends (Paulik, 1969; Lande and Barrowclough, 1987).

Prior to 1941, excessive harvest exploitation and widespread habitat degradation (see discussion in Chapter 5) acted synergistically to reduce abundance of Columbia River Basin salmon stocks. As early as the 1870's, there are observations consistent with overfishing of the salmon runs by the commercial fishery of the lower Columbia River, when Native American harvesters, who fished up river from the commercial fisheries, found they could no longer meet their basic subsistence needs for salmon (Simms, 1877). Seventeen years later, biologists were looking to the lower river fisheries to explain sharp declines in salmon (particularly spring chinook and sockeye) returns to the Yakima River in Washington State (McDonald 1894). Information collected from the commercial fisheries of the lower Columbia River which would have permitted a quantitative assessment of its impacts on the salmon populations of individual tributaries was not available during the time of Simms and McDonald. Putting numerical values on the roles of overfishing and habitat degradation in the decline of salmon productivity remains difficult. To do so requires estimating the mortalities in each life history stage throughout the life of the salmon cohort. Unfortunately, even now we have the capability to do this for only a relatively few life history types of only a few species, such as fall chinook.

As late as 1936, salmon fisheries were an important part of the economy of the region, employing 3,820 harvesters, and generating $10 million annually for the regional economy (Craig, 1899). Although Craig and Hacker (1940) recognized that preventing overfishing was important, the authors emphasized that maintaining suitable spawning and nursery grounds was of paramount importance to the success of salmon fishing in achieving conservation. Craig and Hacker discuss in detail human population growth, logging, mining, hydroelectric power, and flood control and navigation as causes for the decline in salmon resources during the nineteenth and early twentieth centuries.

With regard to factors contributing to the first major Columbia River chinook salmon harvest declines from 1884 to 1889, Craig and Hacker cite the reduction of late spring and early summer chinook by fishing, and reductions in fishing effort as a result of falling demand for the relatively highly priced Columbia River salmon. They also note that species identification of the early landings was not particularly accurate, which opens the possibility that the largest reported landing of Columbia chinook in 1883 could have included species other than chinook.

A contemporary of Craig and Hacker, Willis Rich (1941), linked habitat declines to fishing pressure as a source of decline,

> *"The way in which the Chinook salmon runs have held up under the excessive exploitation and a constant reduction in the available spawning area is remarkable."* (p. 429).

In the same paper Rich issued a prophetic warning to fishermen, laymen and administrators about the futility of trying to replace lost salmon spawning and rearing habitats with hatcheries.

Other contemporaries of Craig and Hacker also recognized the interaction between habitat loss and the effects of fishing in determining salmon population size. Johnson et al. (1948) stated with regard to Columbia River blueback (sockeye) salmon,

> *"The blueback is ... in an advanced stage of depletion. ... A very intense fishery, coupled with elimination of the majority of the important spawning grounds, has reduced the populations to a fraction of their former abundance."* (p. 16).

Johnson et al. (1948) did not express concern about trends in escapement of chinook as of 1935. Such concerns emerged in the literature during the 1950s, especially with respect to spring chinook (Thompson, 1951).

Since the time of Craig and Hacker (1940), a number of authorities have concluded that overfishing was a factor in the decline of Columbia River chinook. William Francis Thompson documented declines in nominal landings per unit effort of spring and summer chinook between 1876 and 1919 that were clearly associated with declines in actual chinook population size (Thompson, 1951). In a comprehensive review of the historical evidence for overfishing of Columbia River salmon, Chapman (1986) joined Thompson in concluding that overfishing was a factor in the decline of chinook.

Historian Anthony Netboy (1974) reported that the chinook salmon runs of the Columbia River were overfished, and in radical decline, after 1885 (pp. 282-283). In addition, Netboy recognized the role of habitat loses in salmon declines by citing the U.S. Army Corps of Engineers "308 Report" of 1948 which documented the existence of over 300 dams of all types in the Columbia River basin at that time (p. 285).

After 1941, the negative impact of fishing on Columbia River chinook salmon appears to be well grounded in observation. For example, Van Hyning (1973) documented the increase of ocean fishing as the main contributor to the decline of Columbia River fall chinook, 1938 - 1959. By this time, fall chinook were the dominant race of chinook in the Columbia River drainages, runs of spring and summer chinook having been reduced in abundance over the preceding 70+ years. The ocean fishery clearly had a negative effect on run sizes during the period of Van

Hyning's data base. It is noteworthy that Van Hyning's analysis included indirect measures of the effects of habitat degradation, in addition to measures of landings and fishing effort.

In order to summarize the history of the rise and fall of Columbia River basin chinook salmon fishery, the five year moving average of the annual landings is used to remove the short term noise in order to make the trends easy to see (Figure 8.2). There are five eras with starting years of 1866, 1884, 1921, 1932 and 1953. From its inception to about 1883, the fishery was reaping the benefits of harvesting relatively lightly exploited populations of chinook salmon. Although Craig and Hacker (1940) estimated annual aboriginal harvest at 18.2 million pounds of chinook (about 900,000 individuals), and while other sources have estimated higher levels of aboriginal salmon harvests (Schalk, 1986), many of the aboriginal peoples had perished in epidemics prior to the growth of the commercial fisheries.

As an apparent response to exploitation, the decline of the populations to lower levels during the second era starting about 1884 appears also to have also coincided with declining salmon markets, reduced fishing effort, and substantial loss and degradation of spawning and rearing habitat. Annual landings during the last five years of this era were on the order of 1.5 - 2 million chinook, using a nominal average weight of 9.1 kg (20 lbs) per chinook . Note that Chapman (1986) used 10.45 kg for spring/summer chinook. Since the historical landings are reported in pounds, 9.1 kg per chinook was chosen for convenience in converting number of pounds to number of individuals. From 1884 until the end of the second era in 1920, the fishery was working at an apparent annual equilibrium landings level on the order of 1.25 million chinook. Although the total chinook landings oscillated about 1.25 million individuals, the stock composition of the landings was changing, with availability of spring and summer runs declining, and exploitation of fall chinook increasing to make up the difference (W.F. Thompson in Chapman 1986).

The economics of World War I set in motion the events that closed out the second era with an increase in fishing effort both in the river, in the mouth of the river, and on the ocean (Craig and Hacker 1940). Increased demand for salmon products resulted in the final peak of the fishery. The year 1921, as fixed by the point where the five-year moving average of chinook landings last dropped below an annual harvest of 30 million pounds (1.5 million chinook, estimated), clearly marked the point where the Columbia River basin chinook populations started the slide toward extirpation, because it was at this point that the sum of the effects of accelerating habitat loss and degradation and ineffective harvest management regimes had converged to drive salmon population numbers below the critical point where they would have been able to replace their numbers from one generation to the next. Trends in marine productivity may have also been a factor exacerbating the effects of habitat loss and overfishing (Ware and Thompson, 1991).

For the next three eras, from 1921 through the present, it is likely that overfishing joined forces with rapidly accelerating habitat degradation to cause lasting reductions in chinook population levels (Craig and Hacker 1940; Rich 1941; Van Hyning 1973). During the third era, 1921 - 1931, Columbia River chinook landings experienced a decline as sharp as that marking the beginning of the second era in 1884. The decline in landings in the third era is apparently related to decreased productive capacity of the populations, since there also appears to have been an increase in fishing effort during this time period (Craig and Hacker 1940). The five-year moving average of landings crossed the 20 million pound (1 million chinook, estimated) level at the beginning of the fourth era in 1932, a year which also witnessed the beginning of development of large hydroelectric dams in the main Columbia River. The first surge of big river dam building on the Columbia during this era brought operations at Rock Island in 1933, Bonneville in 1938, and Grand Coulee in 1941. Given the evidence of fishing being a primary factor in the decline of fall chinook salmon runs beginning in 1938 (Van Hyning 1973), the combination of big river hydroelectric development and fishing pressure led to the third collapse of chinook landings starting about 1941 (Figure 8.2).

In the year when McNary Dam went into operation on the Columbia River, 1953, at the start of the current, and fifth era, the five-year moving average chinook landings crossed the ten million pound mark (500,000 chinook, estimated), not to return to date. Although the Columbia River harvest of chinook in 1988 was 10.54 million pounds (489,000 chinook, actual), the five-year moving average was held down by the lower landing figures before and after 1988. The current era has seen most of the big river dam construction, with 15 dams being built on the Columbia and Snake Rivers from 1953 - 1975, a 500 percent numerical increase over the preceding era. Chinook salmon production during the current era would have probably fallen even more precipitously if salmon produced in hatcheries had not increased sharply after World War II, when a large number of federal and non-federal mitigative programs came into being.

WHY HARVEST CONTROLS HAVE FAILED TO REVERSE DECLINES IN SALMON RUNS

Harvest management of Columbia River chinook populations remains ineffective because the two principal harvest control entities do not provide harvest regulations which explicitly provide for salmon spawning escapements to individual tributaries, i.e. they do not manage according to the productive capacities of the individual stocks (Paulik, 1969). Salmon harvest regulations under the Columbia River Fisheries Management Plan (United States Federal District Court, Portland, Oregon), as implemented by state and tribal fisheries managers, and as coordinated by the Pacific Fishery Management Council (PFMC, Portland, Oregon; PFMC 1996) PFMC, Review of 1995 Ocean Salmon Fisheries Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, Oregon and Pacific Salmon Commission (Jensen, 1986, also

CTC 1993) provide for aggregated spawning escapements to large river counting sites , such as hydroelectric dams, not to tributary spawning grounds (PFMC 1996). The harvest management of Columbia River chinook salmon under the coordinating entities, the PFMC and the PSC, has two fundamental shortcomings relative to salmon recovery efforts. One, with the exception of one natural spawning population, the impacts of PSC and PFMC harvests on naturally spawning Columbia River basin salmon stocks are not directly measured, and two, PSC harvest regulations are based on statistics derived from the number of salmon landed, and not on the numbers actually caught, so the magnitude of ocean fishery impacts on salmon stocks of concern remains obscure. Note that the comments on PSC fisheries offered here do not apply to those salmon fisheries under the jurisdiction of the Fraser River Panel, which is a distinctly different management regime.

Many salmon hatchery stocks, and the naturally spawning Columbia River Hanford Reach fall chinook, are tagged as juveniles with coded wire and fin clipped so that they can be identified in samples of fishery landings. Although hatchery stocks may be appropriate biological entities from which to infer the impacts of PSC fisheries on some naturally spawning populations, it seems unlikely that hatchery salmon stocks can be valid proxies for each and every natural salmon population of concern. For example, annual variations in oceanic distribution and migratory timings of life history stages are but two attributes for which differences between hatchery and natural populations could render any indices of fishing mortality, which are based on hatchery populations, invalid for naturally spawning populations. Further, even for a population which is tagged, if the life cycle is such that the landings of the individuals of legal size are out of proportion to the actual catches of the population, then the indices of fishing mortality will also be invalid.

The second shortcoming, the disparity between catch and landings in the PSC salmon fisheries and PFMC non-PSC salmon and groundfish fisheries, (Table 8.3), is relevant to the Columbia River salmon recovery because catch and bycatch of Columbia River chinook salmon populations in PSC and PFMC fisheries is not being estimated. Catch is a measure of the number of salmon actually killed, whereas landings measure the number of salmon actually kept on the vessel. Landings is a fraction of the number of fish killed in any fishery, and the difference between catch and landings is called bycatch, or incidental mortality. In the PSC hook and line fisheries, a regulation requires the release of fish under a minimum size limit (shakers), and in some hook and line and net fisheries, no chinook salmon of any size are allowed to be retained (chinook non-retention, legal sized and sublegal sized; Table 8.3). Not all of the fish so released are expected to live, so the reported number of salmon landed is necessarily an underestimate of the number of salmon actually killed.

Table 8.3. Annual estimates of total landings, incidental catch by fishery category; shaker, legal, sublegal, total catch, total incidental catch, total incidental catch per total landing, I/L, and percent of incidental catch in the total catch, of number of chinook salmon in adult equivalents, for all Pacific Salmon Commission fisheries, 1979 - 1992.

	Type of Fishery							
	Retention		Non-Retention			Incidental Mortality		
Year	Landed	Shaker	Legal	Sublegal	Catch	Incident	Index I/L	Percent
1979	2365600	301995	0	0	2667595	301995	0.127661	11.32
1980	2251730	294866	0	0	2546596	294866	0.130951	11.58
1981	2189445	303828	4076	3032	2500381	310936	0.142016	12.44
1982	2287289	368901	23770	18315	2698275	410986	0.179683	15.23
1983	2205210	352261	29489	22839	2609799	404589	0.183470	15.50
1984	2186297	337119	31160	23640	2578216	391919	0.179262	15.20
1985	1851845	233542	41140	57518	2184045	332200	0.179389	15.21
1986	1926438	276115	27723	35470	2265746	339308	0.176132	14.98
1987	2050465	304586	57044	62858	2474953	424488	0.207020	17.15
1988	2114972	291768	34880	66431	2508051	393079	0.185855	15.67
1989	1741698	274492	42939	50345	2109474	367776	0.211159	17.43
1990	1740361	300181	36512	52113	2129167	388806	0.223405	18.26
1991	1584825	314182	49235	61889	2010131	425306	0.268361	21.16
1992	1583080	358163	62216	70382	2073841	490761	0.310004	23.66

Source: Computed from data on pages K-1 through K-14 of the Pacific Salmon Commission Joint Chinook Technical Committee 1992 Annual Report. Report TCCHINOOK (93)-2, Pacific Salmon Commission, Vancouver, Canada.

To appreciate the magnitude of the potential impacts of ocean fisheries on salmon stocks of concern, and the disparities between catch and landings, some estimates are available from the 1992 report of the PSC Joint Chinook Technical Committee are useful. For example, in 1992 it is estimated that the PSC sports fishery in the Strait of Georgia caught the equivalent of 233,509 adult chinook salmon, however the number reported landed for this fishery, also in adult equivalents, was 126,922 (CTC 1993). Also in 1992, the PSC chinook troll fishery in Southeast

Alaska reported landing the equivalent of 142,076 adult chinook, however the total catch in this fishery was estimated to be the equivalent of 276,310 adult chinook (CTC 1993). Note that the disparity between annual catch and landings figures will vary by fishery due to changes in the number of small salmon available to be caught. In the aggregate, annual incidental harvests of chinook in PSC chinook salmon fisheries in 1979 - 1992 ran from 294,866 to 490,761 which represented incidental harvests of 11 to 24 percent of total catch, with ratios of landings to incidental harvest ranging from approximately 9:1 to 3:1, as measured in adult equivalents. The 1979 - 1992 time trend in percent incidentally harvested chinook in PSC fisheries is decidedly positive.

Although Columbia River stream type chinook (spring chinook and Snake River summer chinook) are only a very small proportion of PSC chinook landings based on recoveries of coded wire tags applied to hatchery populations, the proportion of these populations represented in the PSC chinook catch is unknown, as a matter of fact, as is also the case for non-PSC fisheries under the PFMC. Measurements of the stock composition by fishery of the PSC and PFMC chinook catches have not been taken. Juvenile chinook salmon, including spring chinook salmon originating in the Columbia River basin, are known from tagging studies to be available for harvest in the areas of some of the present PSC fisheries. Given that the combined Canadian and United States PSC fisheries caught, but did not land, the equivalent of at least 294,866 to as many as 490,761 adult chinook between 1979 and 1992 (Table 8.3), if the Columbia River stream type chinook constitute even 0.5 percent of these incidental harvests, the annual loss in adult equivalents to the Columbia River basin would be 1,500 to 3,000. Any such estimate of actual impacts of PSC fisheries on Columbia River stream type adult returns is necessarily speculative, due to the lack of stock composition data, and the impact of each fishery could be expected to vary substantially. The salmon bycatch in PFMC fisheries beyond the jurisdiction of the PSC for salmon and groundfish would add to the potential impacts of ocean fisheries on Columbia River which are not presently being addressed by assessment programs. However, given only the estimated magnitude of PSC incidental chinook harvests, the lack of stock composition information is a matter of serious concern to recovery of these types of salmon in the Columbia River basin .

CONCLUSIONS FOR HARVEST

Based on the preponderance of evidence and experience of the past one hundred years, the key points relevant to understanding the relationship among harvest, habitat, and salmon productivity are as follows.

1. Harvest management played a role in the decline and extirpation of Pacific salmon populations. Unlimited exploitation of salmon contributed to reductions in the production of salmon in the Columbia River Basin.

2. Traditional harvest management, through imposition of limits on exploitation in directed salmon fisheries, has not been sufficient to allow salmon populations of the Columbia River to persist.

3. Traditional harvest management actions will not compensate for losses due to human activities other than directed harvest because estimates of salmon production from habitats which are constantly declining in productivity will always be too high. Overfishing results when estimates of harvestable surplus are too high. A new harvest management paradigm is needed which will take habitat productivity into account.

A PACIFIC SALMON HARVEST MANAGEMENT PARADIGM

The limits on salmon exploitation rates appropriate to conservation are ultimately dependent on the productive capacity of the habitat from which the populations originate, and on objectives for the magnitude and geographic distribution of spawners. Hence, salmon harvest managers need to look at the effects of degradation of the habitat on which spawners and juveniles depend for survival. The long-term persistence of all species of salmon throughout their ranges is dependent on the implementation of a salmon harvest management paradigm which applies exploitation rates consistent with the status of the salmon bearing ecosystems (i.e., production capability).

When combined with explicit recognition of the role of habitat in determining salmon productivity, the basic approaches to harvest regimes of the salmon fisheries of the Fraser River, Canada (Roos, 1991) and Bristol Bay, Alaska (Mundy and Mathisen, 1981; Eggers, 1992) serve as the entry point to the paradigm. The effective harvest management paradigm for Pacific salmon may be defined in terms of its objectives and the information necessary to attain those objectives. Effective harvest management in an ecosystem context needs to retain some of the same objectives of traditional single species harvest management, such as conservation of population size, public safety, and product quality (Mundy, 1985). In addition, the measure of performance for conservation needs to be extended beyond traditional measures of success, such as sustainable yield for a population of a single species, to include measures of ecological diversity (Pielou, 1969) and of ecological processes (Mathisen, 1972; Kyle et al., 1988).

The minimum information necessary to achieve these objectives under effective Pacific salmon harvest management (Fried and Yuen, 1987; Hilborn, 1987; Walters and Collie, 1988; Eggers, 1992; McAllister and Peterson, 1992) go well beyond the information required to achieve these objectives under the old single species management. Information requirements are more intensive because the assumptions permitted by productive, stable habitat are no longer valid, because the sources of mortality are numerous, and because harvests are often not identified as such. In this paradigm, the inadvertent taking of salmon by humans is recognized as incidental harvest. Salmon are inadvertently taken by other human activities during the course of the salmon's life cycle, by activities such as logging, road building, agricultural cultivation and irrigation, many kinds of pollution, hydroelectric power generation, fishing for other species, and by directed fishing for the same, and for other life cycle stages of salmon.

The concept of stock-recruitment which holds that future spawning stock size is to some extent dependent on present spawning stock size (Ricker, 1954; Cushing, 1983; Walters, 1986; Hilborn and Walters, 1992) needs to be enlarged to include other indicators of the status of the ecosystem (Ricker, 1958). Although the relation between present and future spawning stock size can be highly variable for healthy salmon populations, the understanding physical limits on future population growth posed by the number of eggs per female becomes extremely critical at the low population sizes common to salmon in the contiguous United States. Enlarging this concept will require new models to be developed which explicitly incorporate the role of habitat in determining salmon productivity. It is essential for harvest managers to find ways to establish salmon spawning escapements objectives for a watershed based on analyses of watershed attributes in addition to historical time series of the numbers of salmon spawning in the watershed. The parameters of a stock-recruitment function appropriate to effective harvest management in an ecosystem context should include information on habitat quality and quantity. Quantitative data on riparian vegetation and stream bed condition in relation to surveys of spawning adults and rearing juveniles are generally lacking.. Such information can be drawn from functions of the density and species composition of riparian vegetation, the percent of fine sediment in the spawning substrate, the abundance of critical life history stages of at least one prey, and one predator, species, and the abundance of one species utilized as an alternative by the salmon's predators. If it is possible to explicitly include one, or more, of the preceding habitat variables in the salmon stock-recruitment function, it would remind harvest managers of salmon originating from areas of high human population density of the ephemeral nature of the productive capacity of the environment.

Effective harvest management must be transboundary in scope in order to sustain Pacific salmon and their ecosystems indefinitely. Columbia River chinook salmon, along with most other Pacific salmon populations, migrate through a range of harvest management regimes of differing capabilities in the course of their life cycles. Obviously having effective harvest management regimes in only those areas close to the spawning grounds is only likely to prevent extirpation in those cases where the spawning and rearing areas, as well as the migratory corridors, remain relatively pristine. In those cases where stocks from damaged freshwater habitats interact extensively with ineffective harvest management regimes, extirpation seems likely. The Pacific Salmon Treaty (Jensen, 1986), and its predecessor, the International Pacific Salmon Fisheries Commission (Roos 1991), embody the principles, if not always the practice, of international cooperation in management for salmon conservation.

Effective harvest management requires interdisciplinary staffing beyond the disciplines of the biology of fishes and mathematics ordinarily found in the old single species harvest management. It is essential to develop, *" ... a framework for integrating predictable and observable features of flowing water systems with the physical-geomorphologic environment."* (Vannote et al., 1980, p. 135). The hydrology and geomorphology of the watersheds, as well as the consequences of riparian vegetation for salmon production, needs to be a part of Pacific salmon harvest management for salmon originating in all types of habitats. It is especially important for conservation of stocks originating from damaged habitat. As Willis Rich (1941), Joseph Craig, and Robert Hacker (1940) wrote more than half a century ago, understanding habitat is essential to sustainable salmon production.

EFFECTIVE HARVEST MANAGEMENT

The quantitative attributes of effective harvest management are escapement goals, geographic gradients in fishing mortalities, and zero-sum mortality allocation. Where there are effective management strategies, they are designed to provide adequate spawning escapements to all spawning grounds, and to accurately measure the attainment of these goals on an annual basis. Without monitoring, there is no effective harvest management of salmon, because salmon harvest management depends upon information (Walters, 1986). Escapement goals under effective harvest management are quantifiable objectives, by locality and life history type, for spawning numbers, habitat, and associated species. Escapement goals must be accompanied by monitoring programs in order to be meaningful.

The concept that fishing mortalities need to decrease (be more conservative) as distance from the spawning grounds increases is essential to reduce the risk of extirpation for salmon populations originating in damaged habitat. The farther that harvest occurs from the spawning grounds, the less likely accurate stock identification becomes, and the lower the likelihood that effective harvest management can be achieved. Put another way, ineffectively managed fisheries should be low impact fisheries. The concept that the magnitude of salmon fishing mortality should be inversely proportional to the distance of harvest from the spawning grounds is an especially critical concept at places where distant mixed stock fisheries harvest populations from damaged habitat.

The concept of zero-sum mortality allocation holds that when one source of mortality increases, some other source of mortality must decrease in order to keep the population size from decreasing. Implementation of the zero-sum principle requires that survival be measured at each stage of the life history, that survivals be held to the standard in each life history stanza, and that controls be implemented on those sources of mortality that are controllable. A basic law of biology which is determined by the number of eggs per female among other physical and biological constraints , is that each Pacific salmon population can bear only a certain average total mortality before it starts to decline (e.g. Ricker 1954). As a conservative approximation, if the five year average total annual mortality from egg to spawner for a chinook salmon population reaches the level where one female chinook cannot be expected to produce two spawners in the next generation, the population will necessarily decline. When a population is in decline, the probability of extinction is 100 percent if the decline does not stop (Rieman and McIntyre, 1993). For populations at critically low levels, such as those on the threatened or endangered species lists, when natural mortalities increase, anthropogenic mortalities need to decrease, and if they do not, the population will be extirpated.

Finally, harvest management cannot be effective unless there are consequences for the humans involved in salmon-consuming activities when survival standards and escapement goals for salmon are not met. Both Bristol Bay, Alaska, and the Fraser River, Canada, support thriving sockeye salmon populations today, because, since implementation of effective harvest management regimes, whenever spawning populations have reached critically low levels, fishing has been reduced, or stopped. For example, harvesters and processors in Bristol Bay lost an entire year's income in 1973 when biologists allocated nearly all of the adult return of 2.3 million sockeye to the spawning escapements. The sacrifice of the harvesters in 1973 led to large returns in the form of the sockeye migrations in the next generation in 1978.

In the Columbia River basin by contrast, when the El Nino phenomenon reduces ocean productivity and drought reduces freshwater survival, it is business as usual for the hydroelectric system, the commercial barge transportation system, the irrigation systems, the timber industry, and for other sectors of the economy that cause mortalities to salmon as they operate. Until there are direct consequences to sectors of the economy in addition to harvesters when salmon populations dwindle, it is unlikely that the wide scale geographic effort necessary to prevent salmon from being extirpated can be mounted.

MIXED STOCK FISHERIES

In the face of mounting losses of Pacific salmon populations (Nehlsen et al., 1991; FEMAT (Forest Ecosystem Management Assessment Team), 1993), fisheries for mixtures of salmon stocks could be curtailed or eliminated in an attempt to protect damaged salmon populations, including federally threatened or endangered species (see PFMC 1996). Widespread losses of fishing opportunities might be necessary, if it is possible to identify and define successful concepts and approaches to sustainable salmon harvest management of mixed stocks salmon fisheries. Such concepts and approaches are termed effective harvest management. The effective harvest management paradigm is distinctly different from the historical practice of salmon harvest management, yet it retains some familiar tenets. Scientific evidence and analysis support both the old and the effective paradigms, and both effective and historical approaches are based on the concept of sustainable yield. The effective paradigm differs sharply from the old in its criteria of success, in its objectives, and in the level of detail required in the scientific evidence and analysis on which its harvest actions are based.

Sustainable yield, or catch, is the idea that properly managed salmon populations can provide a harvest benefit to humans in perpetuity (Petersen 1894, Baranov 1918, Lotka 1925, Russell 1931, Ricker 1954, Beverton and Holt 1956, Garrod 1967, Cushing 1981, Roedel 1975). The meaning of "properly managed" is at the heart of the differences between the old and the effective salmon harvest management paradigms. In the effective paradigm, proper salmon harvest management means carefully defining yield to include, as harvest, all sources of human removals of salmon, wherever, and whenever, such harvests may occur. Under effective salmon harvest management, accounting for the actual yield from each stock would require not only counting the numbers caught in all directed, or intentional, salmon harvests from a population, as was often the case in the old salmon harvest management, but it also requires an accounting of incidental, or unintentional, harvest of the population. While most salmon harvest management regimes attempt to do such an accounting, few have achieved success at the level of resolution required for protection of damaged salmon populations. For example, although hydroelectric system mortalities of Columbia River chinook are accounted for in management models along with the effects of many other factors, in the past these effects were lumped into a single value called "natural mortality." Without explicit measurement and recognition of the relative magnitudes of controllable anthropogenic mortalities, management is unable to distinguish controllable effects from the effects of uncontrollable agents of mortality which are truly natural, such as El Nino. Note that such accounting for harvests in effective salmon management practice need not require an exact count, or even a very precise estimate, of removals, in order to be useful to salmon harvest management decisions. For example, in responding to a conservation emergency, simply being able to identify sources of mortality which may be under human control is very useful information, even when precise estimates of the magnitudes of these may be lacking or difficult and expensive to obtain (*see* (National Research Council, 1996)).

Approaches to management of mixed stock fisheries differ sharply between the old and the modern salmon harvest management. Since the "where" and "when" of salmon harvests could potentially span the thousands of miles of fresh and salt waters encompassed by the salmon's migrations, the modern concepts of how to achieve sustainability in salmon conflict sharply with the historical practice of uninformed mixed stock fishing. Mixed stock fishing occurs in areas where mixtures of fish populations, known as stocks, are harvested at the same time. Under uninformed mixed stock salmon fishing, the consequences of harvest to the sustainability of yield are unknown, and harvest management for sustained yield cannot properly be said to be occurring (Mundy 1985). Only when the annual yield, or catch, can be added to the spawning escapements, and the ages of the salmon estimated, can effective salmon harvest management attempt to achieve conservation objectives for salmon stocks. Without stock-specific catch, escapement, and age data, the salmon manager has no idea of the effect of the fishery on sustainability of the salmon populations in the fishery.

Nearly all directed salmon fisheries occur in areas where stocks are mixed to some degree, because harvest or capture takes place before the salmon reach their spawning grounds. Only on the spawning grounds are all the salmon populations clearly separated, consequently both the old and effective salmon harvest management must deal with mixed stock fisheries issues.

The effective approach to implementing modern sustained yield salmon management is informed mixed stock fishing. Informed mixed stock fishing uses information about migratory pathways, migratory timing of different populations, and other differences among salmon populations to determine the impact of fishing on the individual stocks. In an informed mixed stock fishery, catches taken in mixed stock areas can be assigned to their stock of origin in a process known as stock separation. Ideally, stock separation is quantitative with proportions of each stock in the harvest being estimated. In cases when only presence or absence of a stock in the harvest of a locality can be determined reliably, stock identification can still serve a useful purpose by determining whether fishing at that locality needs to be prohibited in the interest of protecting the stock whose presence has been ascertained.

Stock identification of catches has long been recognized by salmon managers as essential to determining impacts of salmon fisheries on stocks. As developed under conventional concepts of sustainable yield, it is assumed, as an ideal, that a fish population can be kept at a level of escapement through controlled harvests which, on average, produce the best long-term average production by the population. This is the theory as it applies for a single identifiable stock, which is essentially a Mendelian population, or a deme (National Research Council, 1996). However, in mixed harvest situations, the question of sustainable yield becomes more complex because stock identification is needed to distinguish among salmon stocks of differing productive capacities of in the mixed stock harvest.

The importance of informed mixed stock harvest to both long term productivity and genetic diversity of salmon has long been established in the scientific literature. In addressing the consequences to long-term conservation of mixed stock salmon fisheries, Paulik et al. (1969) wrote;

> *It is also apparent that different management strategies which result in similar sustained yields may have markedly different effects on the relative abundance of the individual stocks making up the total run of the fishery. Under such circumstances the desirability of preserving a broad genetic level of response to environmental change within a salmon run might mitigate against the application of those strategies which over-exploit small stocks to the level of extinction.* (pp. 2535-2536).

Consequently, when a mixture of stocks is harvested at a common rate which permits them all to survive indefinitely, the sustainable yield is always lower, sometimes much lower, than the sum of the individual sustainable yields of the stocks, if harvested separately at rates appropriate to their individual productivities (Ricker, 1954; Paulik, 1969; Ricker, 1973). Correspondingly, the actual spawning population level, or escapement goal, which provides the greatest sustainable yield from a mixture of stocks is not the escapement goal which gives the theoretical maximum sustained yield from each stock from the mixture. This is because, in salmon management, yield, or catch, when subtracted from the total number of salmon transiting the harvest area equals escapement (Mundy 1985). Constraining harvest by the exploitation rate which permits each stock in the mixture to survive and produce could result in rates of escapement for the most productive stock that are higher than would be considered appropriate to maximize its yield.

When the preceding general principles of population biology are applied to salmon harvest management, it becomes very clear why informed mixed stock harvest is an essential part of the effective management paradigm. In mixed stock salmon fisheries, each identifiable collection of spawners from a watershed, called a stock, may have a different level of maximum sustained yield, due to differences in biological factors such as the number of eggs per female, the average size of the eggs produced, and the critical qualities of the spawning, rearing and migratory environments.

Within species of salmon there are differences in MSY for stocks, even if all the biological factors which determine productivity for each stock are the same. For example, sockeye salmon stocks coming from two lakes identical in every way, except that one is smaller than the other, will have different MSY harvest levels. This is true because the population level at which the number of successful offspring per female is the highest is about one-half the carrying capacity of the environment. Populations of sockeye from lakes will have larger values of MSY than will smaller lakes of the same productivity. In general, big environment means big MSY, and conversely, all other factors being equal.

All existing salmon escapement goals are likely to be based on data collected from mixtures of stocks (see PFMC 1996), so the escapement goal and the corresponding levels of allowable harvest depend on which stocks have been considered to be part of the mixture. For most salmon management agencies, the most economically prominent group of fish stocks were the stocks most often included in the mixture that subsequently defined MSY and escapement goals. Disaggregation of escapement goals to something approaching the watershed level may be necessary to support efforts to increase productivities of salmon populations, to enhance salmon life history diversity, and to broaden the geographic distribution of salmon in the Columbia River basin.

Informed Mix Stock Fishing

The scientific principles which form the basis for the concept of informed mixed stock harvest has been developing in the fisheries literature for more than a century, although its specific application to salmon is somewhat younger (see Roos 1991). This literature makes it clear that accounting for sources of removals, or mortalities, is absolutely essential to effective fisheries management (Petersen 1894, Baranov 1918, Lotka 1925, Russell 1931, Ricker 1954, Beverton and Holt 1956, Garrod 1967, Cushing 1981, Hilborn and Walters 1992). Without an accounting of all sources of mortality potentially under human control, the managers do not have a full range of options available to them when trying to implement conservation measures.

Accounting for all sources of mortality, in addition to directed harvest, is an extremely important part of informed mixed stock harvest. For example, not all fish caught (the catches) are necessarily landed and reported (the landings). Consequently, landings may be only a fraction of the number of salmon actually killed in a fishery. Informed mixed stock fishing requires stock composition information on catch, as well as on landings.

Informed mixed stock harvest has long been accepted in salmon management (see Roos 1991). Accordingly, the history of exploitation of salmon fisheries has been one of seeking increasingly detailed stock composition information on all species of salmon through a variety of means including visible tags (Gilbert and Rich 1925, Aro et al. 1971, Aro 1972, Gray et al. 1978, Meyer 1983, Brannian 1984, Robertson 1984, Lynch and Edginton 1986, Eggers et al. 1991), coded-wire tags (Clark et al. 1985, Shaul et al. 1986), scale patterns analysis, (Wright 1965, Krasnowski and Bethe 1978, McGregor and Marshall 1982, Marshall et al. 1987), and genetic characteristics (Seeb et al. 1986, Seeb et al. 1995). The many thousands of hours, and millions of dollars spent on stock identification in North American salmon fisheries attests to the importance attached to stock composition information by scientists concerned with management.

The best example of how stock identification functions with appropriate monitoring to provide the information necessary to manage sustainable yields from salmon populations is found in the current management of the sockeye salmon fishery in Bristol Bay, Alaska (Fried and Yuen 1987). When accompanied with adult spawning escapement enumeration, stock identification of the catches makes it possible to annually determine the status of individual salmon stocks. Knowing the annual status of each stock makes it possible to formulate fishing regulations which protect the diversity and productivity of each stock. For example, as annual landings records attest, the sockeye salmon of Bristol Bay, Alaska, have been intensively commercially harvested since the third quarter of the 19th century (Mundy, in press). Under virtually unrestricted fishing from 1884 to 1927, annual Bristol Bay sockeye catches rose rapidly to average 15 million adults per year . Annual catches fluctuated greatly, occasionally exceeding 20 million, but otherwise steadily declining under a limited federal management regime, until the fishery was put under a management-by-escapement-objective program in 1954. Under the new regime, stock identification was accomplished by limiting the harvesters to “terminal areas” in the marine waters near the mouths of the major rivers where returning spawners were thought to have separated. Nonetheless, the declines in catches of Bristol Bay sockeye in the terminal areas continued down to a level of only 2.3 million in 1973 in the face of indiscriminate and uncontrolled harvests of the sockeye on the high seas by Japanese fishing vessels (Fried and Yuen 1987). After the Japanese government agreed to cease catching returning adult salmon in 1974, annual sockeye catches rose steadily to routinely exceed 20 million during the 1980’s, with a catch in excess of 40 million sockeye being recorded in 1995. Since 1985, the five year moving average of annual catches of Bristol Bay sockeye has exceeded the largest single annual catch recorded prior to 1927 during the era of uncontrolled fishing . Bristol Bay is the largest of a substantial number of salmon fisheries which are successfully sustainably managed using stock identification information. For example, the management of sockeye salmon under the Fraser River Panel of the Pacific Salmon Commission (Roos 1991) is exemplary.

CONCLUSIONS FOR HARVEST AND HARVEST MANAGEMENT

1. Directed (intentional) and incidental (unintentional) harvest of CRB salmon has occurred in the absence of knowledge of harvest impacts on the abundances and viabilities of the majority of the individual native spawning populations. Viability means having a reasonable probability of survival within an arbitrary time horizon. (1)

2. Harvest rates on native spawning populations of CRB salmon from incidental and direct sources have increased since development of the Columbia River basin by western civilization in the early nineteenth century. (3)

3. Both directed and incidental harvests exert levels of mortality on salmon spawning populations which are large enough to influence their annual abundances and viabilities. (2)

4. Harvest, both incidental and intentional, has contributed to the decline in abundance of CRB salmon and it is a factor limiting their recovery but harvest restrictions in absence of habitat restoration is not sufficient. (2)

5. Interactions between mortality associated with habitat degradation (incidental harvest) and directed harvests by fisheries have lead to the extirpation of many CRB salmon populations. (3)

6. All Columbia River stocks, with the possible exception of Hanford fall chinook, are at such low levels that harvest in the ocean will have to be very low or non-existent to allow the habitat restoration proposed herein to have a reasonable chance to succeed.

GENERAL CONCLUSIONS FOR HARVEST AND HARVEST MANAGEMENT

1. Harvest regulation is a sufficient means of protecting and increasing salmon production only in the presence of reasonably pristine habitat.

2. Harvest management has failed to consider the relation of salmon abundance to other components of the ecosystem which are connected by the life cycle of the salmon.

RECOMMENDATIONS FOR HARVEST AND HARVEST MANAGEMENT

1. Harvest management needs to recognize the relation of salmon abundance to other components of the ecosystem which are connected by the life cycle of the salmon.

2. Sustained yield management of a salmon population, or *deme (see NRC 1995)*, needs to be based on numerical spawning escapement goals which represent both the productive capacities of the habitats for the salmon population and all related salmon populations, geographic gradients in fishing mortality appropriate to the nature of the stock composition information for each fishery, and a zero-sum mortality allocation across all fisheries.

C. HATCHERIES AND EFFECTS OF FISH CULTURE ON NATIVE SALMONIDS

Artificial propagation is an important tool used by salmon managers in the Columbia River for the past 120 years. It was the first management activity undertaken in the basin and it has consumed a major portion of the fisheries budget over the intervening years (General Accounting Office, 1992). In the early years of its development, artificial propagation of salmon was carried out at a small scale in low cost facilities and required little effort. However by as early as 1898, 26 million salmon fry were being released from hatcheries into the Columbia Basin each year. These early attempts at large scale propagation were largely ineffective (Columbia Basin Fish and Wildlife Authority, 1990), thus early hatcheries may not have had a significant effect on the number of adult salmon returning to the river. Nevertheless, the program did have a lasting and major influence on fisheries management philosophy and approach. Consequently, understanding the growth and evolution of the hatchery program is an important starting point for anyone attempting to understand the current status of salmon in the Columbia River basin.

Hatcheries are still a major part of the restoration program and they make a significant contribution to the remnant runs of salmon into the river. Today, about 80 percent of the adult salmon and steelhead entering the Columbia River were hatched and reared in a hatchery (Northwest Power Planning Council, 1992). Between 1981 and 1991, hatcheries consumed 40 percent of the $1.3 billion spent on salmon restoration in the basin. Furthermore, about 50 percent of the increase in salmon production predicted to result from the Council's program is expected to come from artificially propagated fish (Northwest Power Planning Council, 1994, RASP 1992) and much of this through supplementation projects. Hatcheries have had a strong influence on the past attempts to rehabilitate depleted salmon stocks in the Columbia Basin, and the salmon management institutions continue to expect major contributions from hatcheries in the future. However, the National Fish Hatchery Review Panel (Putz and Chairs), 1994), solicited by the U.S. Fish and Wildlife Service to provide outside objective evaluation of the federal fish hatchery program) and the National Research Council (NRC) have recently called for significant changes in the approach, operation and expectations from artificial propagation (Putz and Chairs), 1994; National Research Council, 1995). The Putz et al. report (1994) provides detailed recommendations that would integrate the federal hatchery system into a support role for ecosystem management, including restoration of ESA stocks.

Whether the region's management institutions are willing or able to act on those recommendations is a major uncertainty. Because of the dominant role hatcheries have, and may still play, the review of science in the current fish and wildlife program requires an understanding of the positive and negative contribution of artificial propagation to the status of Pacific salmon in the basin. The purpose of this report is to provide a part of that understanding.

In the section below, we first describe the history and development of the hatchery program and second describe the impacts of hatcheries on salmon in the Columbia Basin. It is generally recognized that the early hatcheries made little or no contribution to salmon production in the basin, so prior to 1930, we emphasize the way hatcheries influenced management policy. After 1930, with the help of a strong emphasis on science, hatcheries slowly improved and began making significant contributions to the fisheries especially after 1960. We describe hatchery evaluations carried out after 1930 and the emergence of new objectives for the use of artificially propagated fish. The final section describes the positive and negative of hatcheries on Pacific salmon in the Columbia River.

Hatcheries In The Columbia Basin Before 1930

In 1877, in response to a perceived decline of the spring run of chinook salmon, and to avoid proposed restrictions in the fishery, Livingston Stone was sent to the Columbia River to help the Oregon and Washington Fish Propagating Company (OWFPC) build and operate a hatchery (Stone, 1879; Hayden, 1930). A site on the Clackamas River was selected and the hatchery buildings and a rack across the river were constructed. OWFPC closed the hatchery five years later in 1882. In 1888, it was reopened and taken over by the state of Oregon (Cobb, 1930). After 1888, there would never be another year in which the reproduction of salmon in the Columbia Basin was entirely natural. By 1928, 15 hatcheries were operating in the basin and a total of 2 billion artificially propagated fry and fingerlings had been released into the river (Figure 8.3).

Because chinook salmon, especially the spring and summer races, made the highest quality canned product and brought the highest prices, fishermen targeted that species in the early fishery (Craig and Hacker, 1940). The early hatchery program also focused exclusively on the chinook salmon (Figure 8.4); however, when the abundance and harvest of chinook salmon began to decline, the fishery switched to other species and the hatcheries followed. Coho salmon and steelhead were propagated in hatcheries beginning about 1900; chum and sockeye salmon were taken into the hatchery program about a decade later (Cobb 1930).

<u>Objectives</u> - The objectives of early fish culture efforts were entirely utilitarian: i.e., to gain control over the production of salmon (Goode, 1884) and maintain a supply of fish for the salmon industry in the face of intensive harvest (e.g., OSBFC 1887, (Commissioners, 1888)). The salmon industry supported hatcheries as an alternative to other forms of conservation such as a restriction in the harvest (DeLoach, 1939). Additionally, the policies governing the early hatchery program reflect overly optimistic expectations of mangers and their belief that artificial propagation was more efficient than natural production.

Assumptions - Salmon managers believed natural reproduction was inherently inefficient and wasteful. It was subject to major, uncontrolled sources of mortality, which could be reduced or eliminated through artificial spawning and incubation in a protected environment (Foerster, 1936; Hedgepeth, 1941). These assumptions are reflected in the hatchery policy of the U. S. Fish Commission, which was to make:

> *". . . fish so abundant that they can be caught without restriction, and serve as cheap food for the people at large, rather than to expend a much larger amount in preventing the people from catching the few that still remain after generations of improvidence."* (Goode 1884, p. 1157)

The belief that protection of incubating eggs in hatcheries would make salmon so abundant that regulations would be unnecessary suggests that carrying capacity or density dependent limits to production were not considered. However, by 1894, after 22 years experience with artificial propagation and few tangible results, the U. S. Fish Commission reduced its expectations for artificial propagation. Marshall McDonald, who succeeded Spencer Baird stated,

> *". . . we have relied too exclusively upon artificial propagation as a sole and adequate means for maintenance of our fisheries. The artificial impregnation and hatching of fish ova and the planting of fry have been conducted on a stupendous scale. We have been disposed to measure results by quantity rather than quality, to estimate our triumphs by volume rather than potentiality. We have paid too little attention to the necessary conditions to be fulfilled in order to give the largest return for a given expenditure of effort and money."* (McDonald, 1894, p. 15).

McDonald raised several questions regarding the use of hatcheries including three important points that are still valid today:

1) a warning regarding an over dependence on hatchery production as a substitute for stewardship;
2) a criticism of evaluations based on the quantity of juveniles released rather than the quality of the adult populations; and
3) a recommendation for the need to evaluate the quality of the receiving waters in watersheds to be stocked with hatchery fish.

However, McDonald's reservations did not diminish the enthusiasm for artificial propagation.

The first hatcheries in the Columbia Basin were built less than 20 years after Darwin (1859) published his evolutionary theories. Concepts such as reproductive isolation, natural selection and local adaptation had not yet become a part of science. Salmon from different rivers were believed to be genetically similar (Ricker, 1972) and interchangeable, consequently mass transfers of fish among streams were common. For example, when Bonneville Hatchery was constructed in 1909, one of its chief purposes was to serve as a central clearing house for the distribution of salmon eggs throughout the region (Figure 8.5). Eggs were brought into Bonneville Hatchery from distant rivers and hatcheries, held to the eyed-stage, then either the fry were released from Bonneville Hatchery into the Columbia River or the eyed eggs were shipped to hatcheries on other rivers. The source stream and the ultimate destination of a group of eggs was rarely the same.

Evaluations - During their first 80 years that hatcheries were operated in the Columbia River, scientifically-based evaluations did not exist. Claims of success for the hatchery program were based on short-term correlations; evidence that was weak at best, or on no evidence at all. The early history of the hatchery program is marked by extravagant and undocumented claims of hatchery effectiveness. For example, in 1883, George Brown Goode of the U.S. Fish Commission told the International Fisheries Exhibition in London, England that the Pacific salmon fisheries in the Sacramento and Columbia rivers were under the complete control of fish culture (Maitland, 1884). When Goode made that claim, the only hatchery on the Columbia River had been closed for two years (Cobb 1930).

Early experiments, based on returns of fin-clipped hatchery fish, were poorly designed and executed and did little more than confirm that some of the fish reared at hatcheries returned as adults (Game, 1904). Declining or fluctuating catches in spite of an increasing number of fry released from hatcheries (Figure 8.3), discouraged fishery managers (Oregon Department of Fisheries 1908) and led in 1911, to an experimental change in the hatchery program. The common practice at the time was to release the salmon shortly after hatching and before they started to feed. In the experiment, hatcheries reared small lots of juvenile salmon for several months and released them at larger sizes. The catch increased in 1914, the year managers expected the first returns from their experiment. After five successive years of improved catches in the Columbia River, the Oregon Fish and Game Commission announced the success of their experiments:

> *"...this new method has now passed the experimental stage, and ...the Columbia River as a salmon producer has 'come back.' By following the present system, and adding to the capacity of our hatcheries, thereby increasing the output of young fish, there is no reason to doubt but that the annual pack can in time be built up to greater numbers than ever before known in the history of the industry..."* (Comm., 1919).

At the same time, the State of Washington claimed that the increase in harvest in 1914 was due to an increase in production from their hatcheries (WDFG 1917). Subsequent review indicated that the claims of hatchery success were premature and the increased catch was not caused by the new methodology (Johnson, 1984) and probably had little to do with artificial propagation in Oregon or Washington. Instead, the increase in harvest from 1914 to 1920 was consistent with the pattern of variation in harvest for the previous 20 years (Figure 8.6) and probably resulted from favorable environmental conditions. For example, the 1914 chinook salmon run into the Umatilla River, which had no hatchery, also increased dramatically (Van Cleve and Ting, 1960), supporting the suggestion that the increase in harvest was a response to natural climatic fluctuations.

In 1914, Willis Rich initiated studies of the life history of chinook salmon which had two practical purposes: 1) to determine the value of hatchery work; and 2) to understand the differences in early life history between spring and fall chinook (Rich, 1920). The latter was important because the spring chinook were more valuable commercially and their increase through artificial propagation was an important objective of the industry. Rich (1920) initiated several marking experiments at hatcheries in the basin to test the efficiency of hatchery practices and to test the homing ability of chinook salmon. He also examined scale patterns from collections of juvenile wild salmon captured throughout the lower Columbia River. The marking experiments also allowed him to verify his interpretation of scale patterns on unmarked salmon (Rich and Holmes, 1929). Rich's marking experiments were a major improvement over earlier "evaluations", but they did not come close to the standards of experimental design used in later evaluations, e.g. (Wahle et al., 1974; 1978). At the time of Rich's experiments, the institutional infrastructure needed to coordinate coastwide recovery of marked salmon did not exist.

Based on his observations on the timing of the migration of juvenile chinook salmon, Rich (1920) concluded that the release of sack fry should be terminated. He recommended that fry be held in the hatchery and released during the natural migration. He also recommended that juveniles be allowed to migrate out of the hatchery ponds on their own volition. One of the more important contributions from Rich’s studies was the acquisition of data, which later contributed to his synthesis paper on the importance of stocks or local breeding groups to the maintenance of productive salmon fisheries (Rich, 1939).

None of the early studies attempted to evaluate the relative contribution of artificially and naturally propagated salmon; i.e., to answer the question: Are hatcheries making a significant contribution to the adult returns to the river?

Nationally, by the 1920s, biologists were beginning to question the efficacy of fish culture during its first 50 years and as a result hatchery programs came under increasing criticism (Wood, 1953). The first scientific evaluations of hatchery programs reinforced the growing skepticism. Studies involving yellow-pike perch in lakes Huron and Michigan (Hile, 1936), whitefish in Lake Erie (Van Oosten, 1942), and Atlantic salmon in the Penobscot River, Maine from 1872 to 1939

(Rounsefell, 1947) concluded that artificial propagation was not significantly more efficient than natural production and in the case of the Atlantic Salmon, that hatcheries were not able to prevent a decline in abundance. The lack of rigorous, scientific evaluation of the hatchery programs for Pacific salmon led Cobb (1930) to conclude that artificial propagation was a threat to the continued existence of the Pacific salmon fishery. Cobb was not opposed to artificial propagation, but he believed that managers had to put aside their optimism and stop relying on hatcheries alone to increase or maintain the fishery.

Results - With all the clarity of hindsight, it is now generally recognized that the early hatchery programs had little positive impact on the abundance of salmon in the Columbia River (Columbia Basin Fish and Wildlife Authority, 1990). Nevertheless, it is impossible to estimate the impacts of massive stock transfers, stream racking, and the overall mining of eggs from productive, wild populations of salmon, although they may have been considerable.

Perhaps the greatest impact of the early hatchery program was its influence on fisheries management philosophy and direction. As suggested in the U. S. Fish Commission's hatchery policy, fish culture was viewed as an alternative to other forms of management, such as harvest regulation or habitat conservation. In addition, hatcheries were also viewed as a means of compensating for production lost through habitat degradation (Lichatowich and Nicholas, In press). If hatcheries could compensate for lost and degraded habitat, managers could afford to give habitat protection and restoration a lower priority, which they did. By 1932, 50 percent of the best spawning and rearing habitat in the Columbia Basin had been lost or severely degraded (Oregon Fish Commission, 1933). This loss and the loss of habitat that continued after 1930 is in part, the legacy of over optimism regarding the effectiveness of artificial propagation.

That this philosophy has continued to the present is clearly shown in the distribution of expenditures for salmon protection in the Columbia River prior to 1980. Less the 1 percent of the funds were spent on habitat, whereas 43 percent of the expenditures went to the hatchery program (General Accounting Office, 1992). In recent years, the situation has improved, but expenditures on habitat are still only 6 percent of the total; hatchery expenditures are 40 percent of total (Office, 1993).

Artificial propagation not only influenced attitudes towards habitat protection, but the overly optimistic expectations and a tradition of inadequate evaluation has extended to the present. After 120 years in which hatcheries have been a primary management tool in the basin, there has never been a comprehensive evaluation of the program.

Hatcheries In The Columbia Basin After 1930

Declining harvests and the failure of the hatchery programs to prevent depletion eventually convinced salmon managers that artificial propagation needed a scientific approach. However, such an approach required the assistance of biologists, basic research, and stream survey information. But in the early decades of this century, state fish commissions, which had been dominated by fish culturists, often did not trust or hire biologists (Moore, 1925). The growing criticism of the hatchery programs and the call for the development of a scientific approach to propagation, e.g., (Culler, 1932; Huntsman, 1937; Needham, 1939) eventually led the Fish Culture Division of the American Fisheries Society (AFS), to question the ability of hatcheries to perform the tasks that had been assigned to them (Gottschalk, 1942). It was becoming clear that artificial propagation had to be based on science, rather than blind optimism.

Objectives - Nevertheless, the objectives of the hatchery program after 1930 remained utilitarian: i.e., to augment declining natural production of salmon and steelhead and maintain a supply of salmon for the fishing industry in the face of intensive harvest. Managers remained overly optimistic about their expectations and predictions for the success of hatcheries and those in the U. S. did little to rigorously evaluate the efficacy of hatcheries themselves or of the overall hatchery program.

Assumptions - Scientific management emphasized the principle of supply and demand, which is best exemplified in the catchable trout program (Bottom, In Press). Catchable sized trout are delivered to the stream in the right quantity to meet the demand. The catchable trout program counted on little or no long-term survival of the planted fish. Therefore, the stream, its habitat, carrying capacity and food gradients were not important considerations (Wood, 1953). The shift to smolt releases in anadromous salmonids can be considered the equivalent to the catchable trout program. As hatchery programs shifted to smolt releases, it diminished the importance of the stream as an integrated ecosystem. The rivers became merely channels to transport smolts to sea (Ortmann et al., 1976).

Salmon managers generally remained convinced that artificial propagation could compensate for the basinwide destruction of habitat in the Columbia River watershed (Schwiebert, 1977). Managers predicted that genetic selection in the hatchery program would produce strains of steelhead suited to the changing environment of the Columbia River (Ayerst, 1977). Through a combination of hatcheries and other technology such as transportation and spillway deflectors salmon and steelhead populations would be restored in a few years and ultimately; in the Snake River, would return in numbers greater than existed before (Ebel, 1977).

Eighteen years later, chinook and sockeye salmon from the Snake River are on the Endangered Species List. Several environmental groups are considering petitions to list Snake River steelhead; because their numbers appear to be declining and following the same downward trajectory as the Snake River chinook races. The National Fish Hatchery Review Panel and the National Research Council (NRC) concluded a major revision in the role and objectives of artificial propagation is necessary (Putz and Chairs), 1994; National Research Council, 1996). In general, the reviews recommended that hatchery programs become integrated into comprehensive ecosystem restoration plans and work toward conservation objectives, rather than focusing on the production of fish for harvest (Flagg et al., 1995).

Evaluation - In 1922, the British Columbia Fisheries Commission was concerned about the lack of any positive results from its hatchery program for sockeye salmon, so it recommended an evaluation be carried out. The Commission stipulated that the study be carried out under competent scientific supervision and R. E. Forester was assigned the task. The question to be addressed by the study was also a departure from the norm. The study was designed to not only evaluate the number of juveniles released from the hatchery and the number of adults returned; it would evaluate the benefits of artificial propagation by comparing the difference in contribution from natural and artificial propagation in a controlled system where both could be monitored (Foerster, 1936). The study was carried out at the Cultus Lake sockeye salmon hatchery in the Fraser River.

The study monitored the contribution of natural and artificial propagation for 10 years. No significant difference in the efficiency of natural and artificial propagation was found. Because the hatchery could incubate only a small fraction of the eggs in the spawning population, the small incremental increase in adult returns produced by artificial propagation was not worth the expense of the hatchery. Based on this study, British Columbia closed all its sockeye salmon hatcheries (Foerster 1936). Foerster not only conducted one of the earliest scientific evaluations of a hatchery program for Pacific salmon, but he tested the fundamental assumption underlying all salmon hatcheries (artificial propagation was more efficient than natural reproduction) and found it to be false at least as far as sockeye salmon was concerned. However, Foerster's study only evaluated the difference in survival between natural and artificial propagation of sockeye salmon when the hatchery fish were planted into Cultus Lake or its tributaries as fry or eyed eggs (Foerster 1936).

In 1934, shortly before Foerster completed his study, Salo and Bayliff (1958) started an evaluation of natural and artificial propagation in Minter Creek, a small stream in Puget Sound. They compared the relative survival and contribution of wild and artificially propagated coho salmon which were reared for extended periods before release, rather than the fry that Foerster used in the Cultus Lake study. At the time Salo and Bayliff's study was initiated, most hatcheries released fry with little or no feeding, conditions that were similar to those evaluated in Foerster's study. However, hatcheries were gradually shifting from fry releases to extended rearing on the assumption that larger, older fish would survive better after release from the hatchery. Like Foerster's study, the Minter Creek evaluation was carried out for several years. The findings, however, differed from Foerster's.

Salo and Bayliff (1958) reported that coho salmon reared in the hatchery for extended periods of 6 to 12 months produced greater adult returns than coho juveniles from an equivalent number of wild spawners. The Minter Creek study showed that under the right hatchery practices, artificial propagation could be more efficient than natural production and artificially propagated salmon could significantly increase adult production in small populations. However, in the 1940s and 1950s, extended rearing presented hatchery managers with a new set of problems for which they had no clear solutions. Extended rearing required improved disease prevention and treatment and the development of nutritious feeds.

By the 1940s, individual hatcheries were fin-clipping juvenile salmon in order to evaluate returns to the hatchery from routine production or to evaluate experimental hatchery practices. Often the experiments had too few recoveries to be conclusive. The results of many of those studies are summarized by Wallis (1964).

Extended rearing in the hatcheries prompted research into the nutritional requirements of juvenile salmon and the prevention and treatment of diseases. By the mid-1960s, the development of new feeds, better prevention and treatment of diseases, and improved hatchery practices such as the optimal size and time of release started to produce tangible results (Lichatowich and Nicholas, In press). Artificially propagated salmon began making significant contributions to the fishery, however, that success created another set of ecological, genetic and management problems which are discussed later in this report.

Beginning in the 1960s, the National Marine Fisheries Service (NMFS) conducted a series of large scale evaluations of the contribution of chinook and coho salmon from Columbia River hatcheries to various fisheries in the Northeast Pacific. The 1961 through 1964 broods of juvenile fall chinook from 13 hatcheries in the Columbia Basin were given special marks (fin clips) before release so their contribution to the sport and commercial fisheries could be estimated. The evaluation was stimulated by a moratorium on new hatchery production until it could be demonstrated that such construction was economically justified (Whale and Vreeland 1978). Results of the evaluation were positive. The benefit cost ratio for all hatcheries combined for each of the brood years was 1961, 3.7:1; 1962, 2.0:1; 1963 7.2:1; and 1964, 3.8:1. The potential catch per 1,000 fish released was 1961, 6.7; 1962, 3.1; 1963, 10.0; and 1964, 6.5. Average survival for all hatcheries combined was 0.7 percent. Overall, an estimated 14 percent of the fall chinook salmon caught in the sport and commercial fisheries from southeast Alaska to northern California originated from the Columbia River hatcheries (Wahle and Vreeland, 1978).

The NMFS repeated the fall chinook evaluation with the 1978 to the 1982 broods. Total survival for all four brood years and all facilities was 0.33 percent or about half the survival of the earlier study, however the benefit-cost ratio was still positive at 5.7:1. The overall contribution to the fishery was 1.9 adults for each 1,000 juveniles released (Vreeland 1989). The NMFS used a similar approach to evaluate the contribution made to the west coast fisheries by the 1965 and 1966 broods of coho salmon. Juvenile coho salmon from 20 hatcheries in the Columbia Basin were marked for the study. Recoveries were monitored from British Columbia to California. Coho salmon from Columbia River Hatcheries made up about 16 percent of the total catch in the sampling area. The catch from both brood years combined was 55 adults for each 1,000 smolts released for a benefit cost ratio of 7.0:1 (Wahle et al., 1974).

Results - A complete evaluation of a hatchery or group of salmon hatcheries should address three questions:

1) Do the salmon and steelhead of hatchery origin contribute to the fisheries and/or escapement and is the economic value of that contribution greater than the cost to produce it?
2) Is the level of contribution consistent with its purpose or objective of the hatchery? For example, if a hatchery is intended to replace natural production lost due to habitat degradation, this question asks did the hatchery, in fact, replace the lost production?
3) Do artificially propagated fish add to existing natural production or do they replace it, i.e., Does the hatchery operation generate a cost to natural production through mixed stock fisheries, domestication and genetic introgression?

The NMFS evaluations were well designed and executed, but they only addressed the first question. That was a serious omission. From a historical perspective, it is clear that artificial propagation has failed to replace natural production lost due to habitat degradation. In addition, hatcheries have caused direct and indirect costs to the existing natural production, e.g., (Flagg et al., 1995; Utter et al., 1995).

Coho smolts released from Columbia River hatcheries achieved high levels of survival in the late 1960s and early 1970s, and although some biologists recognized that favorable ocean conditions contributed to improved production, managers largely credited hatcheries for the improved harvests which "...while most encouraging, was not unplanned nor unexpected" (Oregon Fish Commission 1964).

Columbia River coho salmon are a major contributor to the Oregon Production Index (OPI), which is a measure of the abundance of coho salmon south of Illwaco, Washington

(Oregon Deptartment of Fish and Wildlife 1982). The hatchery and wild stocks of coho salmon from the Columbia River are managed as part of the (OPI). The history of ocean harvest of coho salmon in the OPI illustrates the need for more comprehensive evaluations of hatchery programs. It's now understood that the pattern of production with lows from the 1930s to the 1950s, followed by a period of high production in the 1960s and 1970s and another trough in the 1980s and 1990s (Figure 8.7), reflects the response to changing ocean conditions and climate patterns, rather than only to the release of hatchery reared coho (Nickelson 1986; Lichatowich in press).

Prior to 1960, most of the coho salmon harvested in the OPI were naturally produced (Oregon Deptartment of Fish and Wildlife 1982). After 1960, artificially propagated salmon made up an increasing proportion of the catch. Unfortunately, the contribution of hatchery and wild coho salmon to the OPI ocean harvest was monitored in only eleven of the years between 1960 and 1992 (Figure 8.8). What appears to be a recovery in the 1960s and 1970s (Figure 8.8) was dominated by artificially propagated coho salmon. Wild fish showed little sign of recovery. Harvest targeted on the dominant hatchery component of the OPI had significant impact on the natural production of Oregon's coastal and lower Columbia River coho stocks. The mixed stock (hatchery - wild) fishery in the OPI has consistently over-harvested the wild coastal stocks of coho salmon. Of 55 coastal stocks of coho identified by ODFW, 41 were classified as depressed (Nickelson et al. 1992) and between 1981 and 1991, escapement goals were met in only 3 of the 11 years (Pacific Fishery Management Council 1992).

Wild coho salmon from the lower Columbia River, which were also part of the OPI, are largely extinct, although remnant populations may still exist in the Clackamas, Hood, and Klickitat rivers. High harvest rates on the mixed hatchery and wild stocks, which often exceeded 90 percent, were exacerbated by hatchery practices. Flagg et al. (1995) identified the following hatchery practices that contributed to the decline and extirpation of coho salmon in the lower Columbia River:

1) Selection for early spawners,
2) Fry stocking that exceeded carrying capacity, and
3) Planting fry that were larger than their wild counterparts.
4) Inter-hatchery stock transfers.

Influence on management of Columbia River salmonids

In 1930, John Cobb, Dean of the College of Fisheries at the University of Washington, listed artificial propagation as one of the threats to the fishing industry for Pacific salmon.

"*In some sections an almost idolatrous faith in the efficacy of artificial culture of fish for replenishing the ravages of man and animals is manifested, and nothing*

> *has done more harm than the prevalence of such an idea. While it is an exceedingly difficult thing to prove, the consensus of opinion is that artificial culture does considerable good, yet the very fact that this can not be conclusively proved ought to be a warning to all concerned not to put blind faith in it alone*." (Cobb 1930, p 493).

Artificial propagation of salmon was established in the Columbia Basin before state management institutions were created or before the U. S. Fish Commission established a permanent presence in the Pacific Northwest. In the decades after the management institutions were created, their mission was primarily to build and operate hatcheries. The way in which institutional budgets were expended confirms the priority and emphasis that was given to artificial propagation. In 1922, 76 percent of the Oregon Fish Commission's budget was expended on artificial propagation (Shoemaker and Clanton, 1923). In the Columbia River, since the development of the hydroelectric system, artificial propagation has consumed the largest share of the budget (Figure 8.9). Prior to 1980 habitat received less than one percent of the funding; after 1981 habitat received about 6 percent. These figures reflect a national trend. From 1989 to 1993, the average expenditures of Federal Aid in Sportfish Restoration Program funds in 36 states included 42 percent to hatchery-related projects while only one percent of the funds went to habitat-related projects (McGurrin et al., 1995).

Perhaps the most important legacy of the hatchery program throughout its 120 history has been its influence on management, rather than any direct contribution to the various fisheries. Belief in the success of artificial propagation, which was largely unsubstantiated prior to 1960, made compromise leading to habitat destruction and over-harvest easier to accept (Hilborn, 1992; Lichatowich and Nicholas, In press). Salmon populations throughout the northwest, similar to the one that persists in the Hanford reach, were destroyed in part by faith that hatchery technology would maintain production. Hatcheries have influenced management in two important ways: First, in the late 1800's and through to the 1970's, management institutions were willing to trade habitat for hatchery programs. The result was a massive shrinkage in the natural production base and a dependence on a large, expensive hatchery program which could only maintain salmon and steelhead at a fraction of their historical abundance. Second, management agencies are now forced to provide major emphasis and allocate resources to the restoration of those degraded habitats in an attempt to enhance the depleted base of natural production.

For the past two decades, salmon management has been changing. From a program almost entirely devoted to hatchery production and harvest regulation, management is shifting to a greater concern for natural production. In recent years, the states of Oregon and Washington have conducted extensive surveys of the status of naturally reproducing stocks of salmon and steelhead (Wash. Dept. of Fisheries, 1993; Kostow, 1995). Hatchery programs are being designed to minimize their impact on natural production and new programs are subject to extensive monitoring (Bowles and Leitzinger, 1991; Messmer et al., 1992). Harvests are severely restricted to protect weak natural stocks and biologists are recommending that hatchery programs be revised to include conservation objectives, instead of merely supplying fish for harvest (Flagg et al.1995). Which direction an emerging new role for artificial propagation will take is hard to predict, however biologist Gary Meffe has outlined one approach that has merit:

> *"... a management strategy that has as a centerpiece artificial propagation and restocking of a species that has declined as the result of environmental degradation and over exploitation, without correcting the causes for the decline, is not facing biological reality. Salmonid management based largely on hatchery production, with no overt and large scale ecosystem-level recovery program is doomed to failure. Not only does it fail to address the real causes of salmonid decline, but it may actually exacerbate the problem and accelerate the extinction process."* (Meffe, 1992, p 351).

Biological Effects of Hatcheries

In spite of over a century of reliance on hatchery production to bolster or mitigate natural production, and unheeded cautions about the effects and efficacy of hatchery mitigation (Rich, 1939; Schuck, 1943; Reisenbichler and McIntyre, 1977; Reisenbichler and McIntyre, 1986) , only recently have fisheries managers begun to seriously investigate the effects that cultured fish can have on natural populations of salmonids (Hindar et al., 1991; Krueger and May, 1991; Washington and Koziol, 1993; Busack and Currens, 1995; Campton, 1995; Leary et al., 1995). In part, this effort is fueled by a growing recognition that local salmonid populations (or aggregates of populations; i.e., a metapopulation) are frequently distinct from other conspecific populations (or aggregates) (Allendorf and Utter, 1979; Ryman and Utter, 1987; Gharrett and Smoker, 1993). Past stocking efforts, particularly where non-indigenous stocks were used, have resulted in unanticipated detrimental effects on natural fish populations, rather than bolstering natural production as hoped (Washington and Koziol, 1993; Schramm and Mudrak, 1994; Utter et al., 1995).

Interactions between hatchery and wild fish can occur directly through interbreeding or indirectly through ecological and behavioral interactions (Waples et al., 1991) and can alter the genetic architecture of a species (and natural populations) by changing the distribution of genetic variation within and among populations (Allendorf and Leary, 1988; Allendorf, 1991; Utter et al., 1995). Genetic changes also can occur in hatchery stocks themselves, increasing the likelihood that detrimental consequences will occur when natural stocks experience contact with hatchery stocks (Reisenbichler, 1995). Hindar et al. (1991) reviewed and summarized the genetic effects (both direct and indirect) of cultured salmonids on natural salmonid populations and concluded that where genetic effects have been documented, they always appear to be negative in comparison with the unaffected native populations The one-sidedness of the empirical observations in favor of the greater fitness of local populations resulted from a lack of observations in the opposite direction, rather than from a bias in selecting references.

Campton (1995) presented another perspective on the genetic effects of hatchery fish on wild Pacific salmon populations, in which he notes the genetic effects on wild fish can be attributed to either the direct biological effects of hatcheries and hatchery fish or the indirect -- and biologically independent -- effects of stock transfers, mixed-stock fisheries on hatchery and wild fish, and other human factors related to management. The latter set of factors relate to hatchery management philosophy and practices; whereas the direct biological effects describes the genetic effects of hatcheries and artificial propagation on hatchery fish, as well as the genetic consequences of hatchery fish interbreeding with wild fish.

Direct Genetic Effects - Direct genetic effects are those that result from hybridization of cultured fish with wild fish. The effects of such interactions are generally negative and usually result in reduced fitness in the wild population, due to the breakup of various coadapted gene complexes that are linked to local adaptation, performance, and fitness in the local population. Progeny of such matings usually suffer increased mortality and lowered reproductive success as compared to progeny of native wild fish (Leary et al., 1995). Numerous studies exist that document losses of within- or among-population genetic variability as a result of genetic interactions between hatchery and wild fish (Allendorf and Ryman, 1987; Currens et al., 1990; Hindar et al., 1991; Leary et al., 1995; Williams et al., 1996).

Within-Population Variability. Loss of within-population variation is usually linked to small effective population size (N_e), where allelic diversity can be lost through drift or sampling error. Generally, wild populations are not effected by this process, unless their numbers reach very low levels (like many of the current Idaho salmon stocks); however, considerable data exist documenting the debilitating effect of small N_e on hatchery populations.

In those few instances where hatchery and wild fish populations are similar genetically and slightly inbred, heterosis, or F_1 hybrid vigor may occur. However, as genetic differences between the hatchery and wild stocks increase (usually measured by genetic distance), the more likely it is that outbreeding depression will occur and lead to reduced fitness in the F_1 hybrids.

Recombination in the F_2, and subsequent generations, is likely to reduce fitness even further (Emlen, 1991; Waples, 1991).

Among-Population Variability. Reductions in among-population genetic variances can occur where a single broodstock is used over a wide geographic area (Reisenbichler and Phelps 1989), such as has occurred with the Carson spring chinook stock and the Skamania steelhead stock, or where substantial numbers of cultured fish have strayed into natural populations, as has occurred in Norwegian rivers due to net pen escapees (Hindar et al., 1991; Gausen, 1993; Heggberget et al., 1993). Reductions in reproductive fitness are the most likely result of genetic interactions between hatchery and wild fish (Hindar et al., 1991; Waples, 1991). Such reductions in fitness are due to outbreeding depression (Figure 8.10), where two genetically dissimilar individuals (or stocks) interbreed.

<u>Indirect Genetic Effects</u> - Indirect genetic effects refers to the ecological and behavioral interactions between wild and hatchery fish that occur without direct genetic exchange. However, the interactions have genetic, and therefore fitness, consequences (Waples, 1991). Any factor that causes a reduction in population size can have an indirect effect on the genetic structure of wild fish populations, as well as increasing the risk of local extinction of that population through stochastic environmental perturbations (Soule, 1987; Lande, 1988). Factors that can adversely effect population size include: competition; hatchery stocking densities that exceed carrying capacity; increased physiological stress associated with agonistic encounters; predation; disease; harvest of hatchery target (underharvest - increases opportunities for hatchery fish to stray or to breed with wild fish; overharvest - also harvests wild stock and reduces its population size); and altered selection regimes. There is a substantial body of literature, which is not reviewed here, that documents interactions between wild and hatchery fish for these factors, e.g., (Fausch, 1988, presents a review of competitive interactions between introduced and native fishes in stream systems). Some of these factors can have profound effects on genetic variability and population viability. An extreme example that illustrates the some of the negative consequences that can result from large scale interactions of hatchery raised fish and wild fish occurred in Norwegian Atlantic salmon populations. Heggberget et al. (Heggberget et al., 1993) note that disease transfer from farmed fish into native fish, after a catastrophic release of net pen fish, led to the complete extirpation of more than 30 native populations. Many of these factors alter the selection regimes faced by populations, which can shift the population's genetic and phenotypic attributes, as well as numerical abundance.

Directional Selection. Character values are typically distributed in normal frequency distributions (Figure 8.10.1) that are bell-shaped. Directional selection happens when selection occurs for a character value other than the mean (Figure 8.10.2). A typical example of this type of selection is the effect that fishing pressure (and various types of nets and gear) have in selectively harvesting larger fish, causing the mean size of fish in the run to decrease.

Stabilizing Selection. Stabilizing or truncating selection happens when selection occurs specifically for the mean character, which will act to reduce overall variation, i.e., diversity (Figure 8.10.3). Management actions that focus on mean values may promote selection of this type. An example of this would be the reduction observed by fish passage personnel at John Day Dam over the last 10-15 years in the number of wild smolt emigrants during the September 1 - November 30 time period. These observations suggest that smolts that emigrate in mid-April to mid-June are favored by some set of circumstances related to human development, while those outmigrating in the early spring or the fall months appear to have been eliminated.

<u>Genetic Changes to Hatchery Stocks</u> - Genetic changes, and the potential for such changes, have been well documented for hatchery stocks. Reductions in overall levels of genetic variability, usually due to small effective breeding population size associated with hatchery practices, and concomitant reduced fitness attributed to inbreeding depression have been reported in some hatchery stocks (Allendorf and Phelps, 1980; Leary et al., 1985; Allendorf and Ryman, 1987; Waples and Smouse, 1990), but not all hatchery stocks (Utter et al., 1989). Genetic changes in hatchery stocks can also be attributed to artificial selection or domestication selection.

Artificial Selection. Artificial selection is directed or inadvertent selection that can occur in the hatchery environment (Waples 1991; Reisenbichler 1995). A well-known example of this is the common advancement of time of spawning in hatchery strains rainbow trout and timing of spawning migrations of Pacific salmon and steelhead trout that occurs from a greater than representative contribution to spawning populations from early maturing fish.

Domestication Selection. Domestication selection is natural selection occurring within the hatchery environment, whereby fish that perform better in the hatchery environment have a selective advantage (Reisenbichler and McIntyre 1977). In general, domestication selection results in increased fitness in the hatchery environment, but decreased fitness under wild conditions (Campton 1995).

<u>Genetic Changes to Wild Stocks</u> - Numerous studies have documented direct genetic interactions between wild and hatchery fish (Campton and Johnston, 1985; Campton and Utter, 1985; Bartley et al., 1990; Currens et al., 1990; Forbes and Allendorf, 1991; Eriksson and Eriksson, 1993; Leary et al., 1995; Utter et al., 1995; Williams et al., 1996). Despite a large body of evidence documenting genetic interactions between hatchery and wild salmonids, and correlative observations of declines in abundance of natural salmonids, little empirical evidence

exists documenting reductions in fitness in wild populations as a result of genetic interactions with hatchery reared fish, but see Gharrett and Smoker (1991) (1991) and Philipp and Clausen (1995). Data on fitness have proven notoriously difficult to collect, nevertheless, there is a substantial body of established theory that is supported widely by emperical observation from other vertebrate species and supported to some extent by observation on salmonids indicating that interbreeding between strains of hatchery fish and wild fish can result in offspring with reduced fitness.

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Recent Uses of Hatcheries

Mitigation for Hydropower Development

Grand Coulee Fish Maintenance Project - The first major program designed to compensate for hydroelectric development in the Columbia basin was the Grand Coulee Fish Maintenance Project. With a height of 500 ft, Grand Coulee Dam was too high to successfully pass salmon via a ladder or elevator. Salmon managers considered the construction of a hatchery immediately below the dam, but engineering problems caused the biologists to look for an alternative. The plan eventually implemented had three key elements: 1) adult salmon and steelhead were trapped in the ladders of Rock Island Dam from 1939 to 1943 and the fish taken to holding areas; 2) some adults were released into rivers selected for the transplanted runs and allowed to spawn naturally; and 3) the remaining fish were held for artificial propagation at Leavenworth hatchery. The streams which received the transplanted fish were Wenatchee, Entiat, Methow and Okanogan rivers and Lake Osoyoos (Fish and Hanavan, 1948) .

The results of the fish maintenance program were evaluated by comparing the contribution of relocated stocks to the Columbia River escapement above Bonneville Dam before the Grand Coulee cut off salmon migration (1938-1942). Counts at Rock Island Dam were used as estimates of the escapement of relocated stocks. Based on this analysis, Fish and Hanavan (1948) regarded the Grand Coulee Salmon Salvage Program a success. However, twenty four years later Ricker (Ricker 1972) gave a more pessimistic appraisal of the program and concluded that it salvaged nothing. Mullan et al. (Mullan et al., 1992) concluded that the fish maintenance program conserved the genetic diversity of the salmon stocks in the area, however, the large-scale capture, mixing and relocation of chinook salmon stocks above Rock Island Dam permanently altered the population structure and was the genesis of the present stock structure of salmon in the mid-Columbia (Utter et al. 1995).

Lower Columbia River Fishery Development Program - The current restoration program for Columbia River salmon and steelhead has its roots in the Lower Columbia River Fishery Development Program (LCRFDP), which was strongly influenced by the concepts and design of the Grand Coulee Fish Maintenance Project. Originally, LCRFDP had an implementation life of 10 years, however, the program, with some modifications has continued to the present. As the title suggests, the program's initial objective was to concentrate salmon production in the lower Columbia River below McNary Dam. At the time it was believed that the construction of McNary Dam and the other proposed dams in the upper Columbia and Snake rivers would eventually eliminate salmon in the upper basin. In 1956, congress changed the purpose of the LCRFDP by adding fishery restoration above McNary Dam and the word “Lower” was dropped from the program title (Delarm et al., 1989) .

The LCRFDP had six principal parts:

1) Remove migratory obstructions in the tributaries to the lower Columbia River. This part of the program included the stream clearance work that removed large woody debris and reduced habitat quality in some streams;
2) Clean up pollution in major tributaries like the Willamette River;
3) Screen water diversions to prevent the loss of juveniles in irrigation ditches, and construct fishways over impassable barriers in the tributaries of the lower Columbia River;
4) Transplant salmon stocks from above McNary Dam to the lower river;
5) Expand the hatchery program by rebuilding existing hatcheries or new facilities; and
6) Create salmon refuges by setting aside the lower river tributaries exclusively for the maintenance of salmon and steelhead runs (Laythe, 1948) .

Stream clearance was consistent with management understandings and attitudes at the time, e.g., (Fisheries 1953, p. 17), but it is no longer practiced unless the obstruction presents a complete unnatural block to migration. The transfer of stocks to the lower river ignored the stock concept and the adaptive relationship between the stock and its habitat. The hatchery program was one of six parts of the program, but within a few years it was the dominant part. By 1951, hatcheries consumed 49 percent and habitat work 5 percent of the budget (unpublished budget information obtained from the National Archives PNW Center, record group 22).

Mid-Columbia Mitigation - Mitigation programs in the mid-Columbia evolved in three phases. The first phase was the Grand Coulee Fish Maintenance Project described above. From 1961 to 1967, four hatcheries and a satellite facility were constructed to mitigate for mainstem habitat inundated by five PUD projects. This second phase, originally consisted of three spawning channels (Priest Rapids, Turtle Rock and Wells) and two conventional hatcheries (Rocky Reach and Chelan). The spawning channels were later converted to conventional hatcheries. The third phase has been implemented since 1989 and is composed of the Methow hatchery and two satellite ponds, the Eastbank Hatchery with five satellites, and Cassimer Bar Hatchery. This phase is intended to mitigate for juveniles produced in the tributaries which are lost in passage past Wells and Rock Island Dams. Monitoring and evaluation of the mid-Columbia mitigation is underway.

Lower Snake Compensation Plan - The Lower Snake River Compensation Plan (LSRCP) was developed to mitigate for the loss of fish and wildlife resources resulting from the construction of Ice Harbor, Lower Monumental, Little Goose and Lower Granite dams. The dams were completed between 1961 and 1969 (Lavier, 1976) . Planning for the compensation program started in 1966 and was approved by the U. S. Congress in 1976. The McCall Hatchery was the first facility constructed (completed in 1979), followed over the next eight years by several other hatcheries and satellite facilities. Presently, there are twelve hatcheries and eleven satellites employed in the LSRCP (Mighetto and Ebel, 1994).

Steelhead have increased in abundance as a result of the releases from LSRCP hatcheries and the program is considered successful in terms of their original objectives of the LSRCP (Mighetto and Ebel 1994), although, in 1994 the summer steelhead run was the lowest since 1982 (Wildlife 1995). Chinook salmon returns have been well below target levels. The LSRCP hatcheries were originally designed as conventional hatcheries, however in some cases, conventional hatchery operations have evolved into supplementation programs, e.g., (Messmer et al. 1992). The programs and the supplementation technology are too new to determine if they will be successful (RASP 1992; Bowles 1995).

The objective of the Lower Snake River Compensation Program did not include Snake River coho salmon or Snake River sockeye salmon, which were relatively abundant at the time LSRCP was being planned. Relatively few resources were devoted to Snake River fall chinook, with only one of twelve hatcheries being devoted to this life history type. It is worth noting that coho salmon are presently extirpated from the Snake River Basin, sockeye salmon are nearly extinct, and fall chinook are listed as endangered under the Endangered Species Act.

Summary results on uses of hatcheries

After 120 years of salmon management based largely on the assumption that artificial propagation could replace natural production in the Columbia Basin and the development of a massive system of hatcheries, its instructive to note that the most productive stock in the basin is the fall chinook population that spawns naturally in the free flowing Hanford Reach of the mainstem Columbia. In the context of the entire history of the hatchery program, and the history of salmon management in the basin, the hatchery program has failed to meet its objectives. In 1994, the smallest number of salmon and steelhead entered the Columbia River since counts began in 1938, and by 1939, salmon production was already far below historical levels. Artificial propagation of salmon did not maintain salmon production. The early optimism that predicted hatcheries would make up for overharvest and habitat degradation has given way to the reality of depletion, closed fisheries, and a fragmented ecosystem in which natural production is severely restricted. Today the dominance of hatcheries in management programs is being questioned (Hilborn and Walters 1992; Washington and Koziol 1993; NRC 1996). New roles for hatcheries and guidelines for their operation are being developed or proposed (Putz and Chairs), 1994) (White et al., 1995), however, in the past, the hatchery program has been slow to adopt change. For example, by 1939, fish culturists recognized that the stock concept in Pacific salmon meant interhatchery transfers were detrimental (OFC 1939), however, 56 years later, Flagg et al. (1995) were still recommending that hatcheries restrict that practice.

Since 1960, the total release of hatchery reared salmonids has grown from 79 million to about 200 million (Figure 8.11) -- in recent years (1987 to 1992), the range was 179 to 221 million fish. Since 1960, the number of adult salmon and steelhead entering the Columbia River has not shown an increasing trend (Figure 8.11). although those data do not include the number of salmon harvested in interception fisheries outside the basin, which can be substantial (Lestelle and Gilbertson 1993). Prior to 1960, most of the adult salmon and steelhead entering the Columbia Basin were naturally produced (Authority 1990), however, over the past three decades the proportion of hatchery reared fish in the adult population has grown to about 80% (Northwest Power Planning Council, 1992). From a cursory examination of the overall numbers, it could be argued that in recent decades the hatchery program has accomplished its objective -- hatchery production has replaced natural production lost through habitat degradation, i.e., the increasing proportion of hatchery fish might indicate successful mitigation for habitat loss. However, reality is more complicated. The hatchery program since 1960 contains some successes, in some cases hatcheries have failed to reach mitigation goals, and hatchery practices have been directly linked to depleted natural populations.

The hatchery program for coho salmon contributed to the depletion of wild coho populations in tributaries below Bonneville Dam. Flagg et al. (1995) identified factors related to the hatchery program that contributed to the decline in natural production of coho salmon in the lower Columbia River: Excessive harvest in the fisheries targeting mixed hatchery and wild stocks; selection for early spawning broodstock; fry stocking in densities greater than the carrying capacity of the receiving stream; planting hatchery fry that were larger than the naturally produced fish; and interhatchery transfers.

In the upper Salmon River, hatchery mitigation has not replaced or maintained natural production lost due to smolt mortality, especially at the lower Snake River Dams, however, it has slowed the decline of total production (Bowles, 1993). In the South Fork of the Salmon River, hatchery mitigation has increased total production (Bowles 1993).

In the upper Snake and Columbia rivers, the present geographic distributions and genetic population structures of fall-run chinook salmon reflect stock transfers and hatchery confinements carried out between 1939-1943 under the Grand Coulee Fish Maintenance Project (GCFMP). The GCFMP intercepted upstream migratory salmonids at Rock Island Dam near Wenatchee from 1939 through 1943 for relocation in tributaries downstream of Grand Coulee Dam. In this 5-year period, almost all adult spring-run and summer-fall-run chinook, regardless of original destination, were either confined to restricted areas for natural reproduction or used in hatchery operations (Utter et al. 1995). This large-scale program, of interceptions, stock transfers, and stock mixing, permanently altered the salmon populations in the Upper Columbia River and provided the foundation for their present population structures.

Warm Springs National Fish Hatchery has successfully increased production in that river without adversely affecting wild stock production (Olson et al., 1995). This program appears to be an example of the effective use of adaptive management.

These examples suggest that the results of artificial propagation in the Columbia River since 1930 and especially after 1960 have been mixed. Unfortunately, the lack of a meaningful comprehensive evaluation doses not permit a determination and detailed description of the net effects artificial propagation. Given the current state of the salmon and steelhead in the basin it would be appropriate to conclude that in its 120 year history, the net effect of hatcheries has been negative.

Future Directions for Hatcheries

Recent reviews of the efficacy of hatcheries toward fisheries management goals, and of the impact of hatchery fish and hatchery practices on wild fish populations, all appear to lead to the same general conclusion and recommendations. In the Columbia River Basin, in spite of large-scale hatchery efforts and massive outplantings of hatchery-reared fish, the hatchery program has failed to replace or mitigate for lost natural reproduction of anadromous salmonids. New directions and visions for the hatchery program are clearly needed, and several recent reviews (National Fish Hatchery Review Panel 1995; National Research Council 1995; Campton 1995; White et al. 1995) provide them, suggesting that a new role be defined for hatcheries in general, and in the Columbia River Basin in specific. The reviews are concordant in suggesting that hatcheries should have a much smaller role in salmon production and restoration than they have had in the past. Additionally, their roles and objectives (identified individually for each hatchery) need to be coordinated into an integrated recovery and management plan for each appropriately scaled management unit (watershed or subbasin). Hatcheries need to be used cautiously, as tools, that are integrated into rehabilitation or restoration strategies that focus on habitat restoration, reduction of human-induced mortality agents, and conservation of existing genetic and life history diversity in natural populations (Allendorf and Waples, 1996). The National Fish Hatchery Review Panel (1995) and White et al. (1995) provide detailed recommendations and suggestions for changes in the hatchery system.

Clearly there is a role for hatcheries in the management and restoration of Pacific Northwest anadromous salmonids. For example, in the case of dwindling upriver stocks, hatcheries may provide temporary, but key refuges, in which various populations might be sustained while downstream causes of mortality are removed or modified (Cuenco et al., 1993; Bowles, 1995). Similarly, hatcheries may have a temporary role in rebuilding depressed populations (e.g., through supplementation activities as described in RASP 1992). It remains to be seen, however, if there is a role for large-scale production hatcheries that is compatible with conservation and long-term management of many of our imperiled stocks (Philipp et al., 1993).

Supplementation

One of the new roles for hatcheries and artificial production in the Columbia River Basin is supplementation, where carefully selected stocks of hatchery-produced fish are used to enhance or “reseed” streams where native populations have been depressed or extirpated. Ideally, supplementation is viewed as a small scale and temporary strategy to boost naturalized production in wild stocks (Steward and Bjornn, 1990; Cuenco et al., 1993; Bowles, 1995). Supplementation is important to consider because it is currently expected to be the major tool that will be used to rebuild depressed stocks in the upper Snake Basin. Supplementation has been proposed as one important means for achieving the Council’s goal of doubling adult salmon returns. Thus, much hope is being placed in a concept that remains to be tested and proven each time it is applied (Cuenco et al., 1993; Lichatowich and Watson, 1993, RASP 1992).

Supplementation envisions the use of the protected hatchery environment to obtain a survival advantage through the incubation of eggs and the early rearing stages of juvenile salmon. Those juveniles are then planted back into streams to complete their rearing under natural conditions, in the hope that they will return as adults to spawn naturally, and successfully and thereby augment natural production in the stocked watershed. In the early years of artificial propagation, the speculation that high natural egg mortality occurred was used to justify supplementation with artificially propagated salmon. Today, underseeding of tributary streams and the extremely high total mortality rates for wild salmon stocks provide the rationales for this strategy (Northwest Power Planning Council, 1992).

In the late 19th century, the crude technology of artificial propagation and poor understanding of the salmon's biology limited the chance of success. Today, the technology of fish culture in the hatchery has improved, although, the information needed to integrate artificial and natural production systems is still not well developed (Lichatowich and McIntyre, 1987; Allendorf and Waples, 1996). Unfortunately, the rearing habitats in which juvenile salmon must live after planting have been considerably degraded. Our understanding of the ecology and genetics of Pacific salmon has improved and that understanding has placed new constraints on supplementation. The definition of supplementation adopted by RASP (Regional Assessment of Supplementation Program) (1992) underscores those constraints:

> *Supplementation is the use of artificial propagation in the attempt to maintain or increase natural production while maintaining the long term fitness of the target population, and keeping the ecological and genetic impacts on nontarget populations within specified limits* (RASP 1992, P. 6).

The constraints contained in the RASP definition are new to artificial propagation, and because they are new, there is little experience that can be used to resolve uncertainties. RASP (1992) describes some supplementation uncertainties which are given a thorough review by Steward and Bjornn (1990). The Council has stipulated (7.3B of the FWP) that fishery managers will use the RASP guidelines to plan new supplementation projects. This step is critical and managers must be held accountable for adequate planning of their supplementation projects, including adequate monitoring and procedures for adaptive management. Project plans must receive peer review from fisheries scientists and geneticists.

One of the reasons why supplementation needs critical review and evaluation is the confusion over the interpretation of what constitutes supplementation. Supplementation is generally defined as the use of artificially produced fish to augment natural production without eroding long-term fitness of target and non-target natural populations (Bowles and Leitzinger, 1991; Cuenco et al., 1993; Northwest Power Planning Council, 1994; Bowles, 1995). However, outside the published definition, common usage of the term supplementation has taken on much broader meanings. Because the term supplementation has such broad meaning, there is little practical agreement on a definition. In its broadest sense, supplementation includes various fisheries management activities including: restoration; introduction; rearing augmentation; and harvest augmentation (Miller et al., 1990; Steward and Bjornn, 1990; Sterne, 1995). Differing definitions in current use confound objectives, obscure the mechanisms for accomplishing those objectives, and circumscribe criteria used for evaluating success of supplementation programs.

Confusion over what is meant by supplementation has also hampered efforts to evaluate the effectiveness of supplementation as a tool to rebuild depressed salmon populations. This is a serious shortcoming because as much as 50 percent of the increase in salmon production projected from the systems planning model is expected to result from supplementation projects (RASP 1992). Reviews of supplementation (Miller et al., 1990; Steward and Bjornn, 1990; Hilborn and Winton, 1993; Winton and Hilborn, 1994; Bowles, 1995) indicate that in those few instances where supplementation projects were conducted in a rigorous enough manner to permit evaluation, supplementation was rarely successful in increasing natural production, and often significant risks were incured (Reisenbichler and McIntyre, 1977; Nickelson et al., 1986; Reisenbichler and McIntyre, 1986; Waples and Do, 1995; Allendorf and Waples, 1996). In contrast, success has been verified in programs that introduce fish into vacant habitat, either new areas or areas from which they had been previously extirpated (Cuenco et al., 1993), although these successes are more typical for resident, than anadromous forms of salmonids (Allendorf and Waples, 1996). Unfortunately, some have considered these programs as supplementation, and their success has been transferred or extrapolated into predictions of similar success for the more difficult task of rebuilding depressed populations in the extensively damaged habitats of the Columbia River basin.

The recent NRC report (1996) expressed similar concerns about the use of supplementation. The NRC panel recommended the term "supplementation" be abandoned as a goal of hatcheries. They also concluded that hatcheries were not a proven technology for achieving sustained increases in adult salmon production and their use has had adverse effects on natural salmon populations. Moreover, supplementation, which has multiple and often incompatible definitions in the literature, has generated confusion and uncertainty about appropriate roles for hatcheries. An emerging consensus (Putz and Chairs), 1994; White et al., 1995; National Research Council, 1996) calls for new roles for hatcheries which are tied to rehabilitation or restoration goals of the specific watershed where the hatchery is located. The new roles for hatcheries should be based on and consistent with the conceptual foundation described in our Review of Science.

The NRC (1996) further recommended that hatcheries should be considered an experimental treatment in an integrated regional rebuilding program and should be evaluated accordingly. This is concordant with our review as well. Supplementation will need to be monitored and evaluated on a case-by-case basis for its applicability as a means to accelerate recovery of depressed wild salmonid populations with respect to their abundance and life history diversities. Supplementation may be useful over the short-term to aid in rehabilitating natural populations within the context of an integrated and comprehensive watershed-based restoration approach, that includes an evaluation of the relative risks to the wild population of using versus failing to use supplementation (Hard et al., 1992; Allendorf and Waples, 1996). The proposed chinook salmon supplementation projects in central Idaho appear to follow these guidelines and may be useful as a model for other supplementation projects (Bowles and Leitzinger, 1991).

In implementing the FWP, we advise the Council to resist attempts to implement supplementation on a large scale without adequate planning and review and without adequate monitoring and evaluation in place. Proponents of artificial propagation are often willing to forgoe adequate monitoring and evaluation and assume success. For example, when mitigation for hydro development in the basin began with implementation of the Lower Columbia River Fisheries Development Program, it was promoted as an action program that could be implemented without delay and research was not needed (Committee 1950). Since then the region has found the need to expend millions of dollars in research on conventional fish culture. Supplementation may prove to be a useful tool in the Columbia Basin for rebuilding depressed stocks in some localities, which in turn could lead to rebuilding of salmon metapopulation structure, but this will only occur if supplementation is approached cautiously in an experimental framework that relies on careful design, rigorous evaluation, and incorporates adaptive management. Within the context of our conceptual foundation, supplementation activities are necessarily temporary, until populations rebuild themselves through natural reproduction. Measurable criteria for the success of the supplementation effort need to be rigorously defined *a priori*, and we advise managers to resist the temptation to increase the scale of goals, designs, and hatchery involvement, if success occurs. If the original goals are biologically sound and realistic, then escalating the goals and hatchery involvement at a later date would be inconsistent with the original supplementation design and may pose significant genetic and demographic risks to the target stock.

Artificial propagation has a 120 year history in the Columbia Basin and an important lesson from that experience should be that the success of new technology applied to fish culture cannot be taken for granted. Each set of local biota, physical conditions and salmon life history type to which supplementation is applied represents the development of new form of aquaculture technology. Each application will be clouded by multiple uncertainties which require careful risk assessment before implementation. Adequate monitoring and evaluation are essential if a supplementation project is implemented. The seriously depleted condition of the resource today calls for quick action, yet the depleted salmon populations in the basin cannot afford to be subjected to new technology without adequate evaluation.

Conclusions (level of proof)

1. Artificial propagation has failed to achieve the objective of replacing natural production lost because of habitat degradation in the basin (1);
2. Belief in the efficacy of artificial propagation led to disproportionate budgets for habitat protection and restoration (3);
3. In the 120 year history of the artificial propagation in the Columbia Basin, the program has never been subjected to a comprehensive evaluation (1);
4. The ecological, behavioral, and energetic interactions of hatchery fish with native species (including wild salmon) and fish assemblages of the Columbia River ecosystem have not been evaluated. In the operation of hatcheries, those interactions are generally assumed to be inconsequential or benign (3);
5. The extent to which the artificial propagation program has implemented relevant research, particularly where the interaction between natural and artificially propagated fish is concerned, has been slow (3);
6. Hatchery operations including broodstock selection, interbasin transfers and release practices have contributed to the decline of natural production and loss of locally adapted stocks in the basin (2);
7 .Management of fisheries on mixed hatchery and wild stocks have contributed to the decline of natural production in the Columbia Basin (2);
8. Because of the declining natural production in the Columbia Basin, those fisheries that still harvest Columbia River salmon are largely supported by the hatchery program (1);
9. Hatchery practices are one of the factors that have altered the genetic structure of stocks in the basin (1).
10. In instances where hatchery broodstock have been derived from local wild stocks that are presently severely depressed, the hatchery stock may contain a significant portion of the genetic diversity of the indigenous stock,. If so, and these populations need to be evaluated to address these concerns, the hatchery population may be an essential element for rebuilding abundance and natural production in the depressed indigenous stock (4).

Uncertainties

1. A major uncertainty stems from the question, can we integrate natural and artificial production systems in the same basin to achieve sustainable long term productivity?
2. The conservation hatchery and captive brood technology are new concepts and roles for artificial propagation. Their use to restore depleted salmon populations should be approached with extreme caution and must be accompanied with a well designed and adequately funded M&E program.
3. A major uncertainty associated with the use of supplementation is the condition of the habitat that will receive the juvenile salmon. Is the habitat capable of supporting salmon at levels of survival that will bring about restoration?

Recommendations

1. Use of artificial propagation to restore depleted salmon populations should be preceded by an assessment of the risks, and supplementation applications must be accompanied with a well designed and adequately funded M&E program.
2. There are three questions that need to be answered in evaluating the hatchery program: Do the artificially propagated fish contribute to the fishery and/or escapement and is the economic benefit of that contribution greater than its cost? Has the program achieved its objective; i. e., has it replaced lost natural production if it is a mitigation hatchery? Has the operation of the hatchery incurred costs to natural production? The first and the third questions are related in that a meaningful cost-benefit analysis should include ecological costs.

   Most evaluations of hatchery programs, when they have been carried out, attempted to answer the first question. Information needed to answer the second and third questions has in most cases not collected or has been of poor quality. The FWP should require evaluation which adequately answers all three questions for all funded hatcheries.
3. The FWP should include a valid comprehensive evaluation of the role of artificial propagation in the Columbia Basin. The evaluation should cover the entire 120-year history of the program and include direct and indirect, positive and negative effects. For example, the evaluation should include a discussion of the role that heavy reliance on hatcheries has had on habitat degradation in the tributaries and mainstems and the contribution of hatcheries to the extinction and depletion of naturally producing stocks in the basin. The comprehensive evaluation should also include an assessment of the adequacy of existing monitoring to answer ecological questions.

4. The FWP should include as a separate measure a comprehensive evaluation of the mitigation hatcheries in the basin. What were their objectives, did they achieve their objectives, and if not, why not?
5. The region needs to develop an interim policy regarding the operation and harvest management of production from each hatchery where monitoring has been inadequate to complete a comprehensive evaluation. The interim policy should be designed to minimize the ecological costs of the hatchery until the evaluation can be carried out.
6. The objectives of each hatchery need to be evaluated and redefined if necessary. The objectives should be established within the contexts of the subbasin where the hatchery operates, and our conceptual foundation with particular reference to rebuilding of populations and metapopulations. The hatchery's objectives need to be integrated and defined by the rebuilding objectives of the subbasin. The objectives should consider nontarget species and the existence of metapopulation structure of the target species.
7. Artificial propagation must be treated as an experiment, with hypotheses related to uncertainties, experimental design, analysis, and integration of results with available knowledge consistent with the adaptive management provisions of the FWP.
8. The decision about when and where to use supplementation programs should take into account the principles of the metapopulation concept.
9. Existing hatchery populations may prove to be valuable genetic resources in the future and may prove useful in programs that attempt to rebuild salmon populations and metapopulation structure in the basin.
10. Hatchery populations should be evaluated for evidence of selection, and changes in fitness or genetic diversity associated with residence in the hatchery environment.

D. Infectious Diseases

In 1991, as the Scientific Review Group, we conducted a review for BPA and CBFWA of the Fish Disease Work Plan developed by the Technical Working Group on Fish Disease. We were assisted in the review by Dr. John Schachte, who had been chairman of the Fish Health Section of the American Fisheries Society. Our review was undertaken from the standpoint of how fish disease might affect the council's doubling goal, and provided comments about the Work Plan and associated research priorities (SRG Report 91-4, August, 1991). The following comments are drawn from that review.

The Fish Disease Work Plan and the Fish Disease Technical Working Group did a good job of identifying problem pathogens of salmon in the Columbia Basin, and of focusing research efforts toward understanding and control of those pathogens. The Fish Disease Work Plan and the Fish Disease Technical Working Group appeared to follow groundwork laid down by the Pacific Northwest Fish Health Committee, which by 1984 had developed policy statements on fish disease and was acting as a coordinating entity for research and information exchange on fish disease within the region. In our review, we were particularly complimentary of the Fish Disease Work Plan with respect to three features that were apparent: 1) the sharply focused research objectives stated in the Work Plan; 2) the prioritization process used by the Fish Disease Technical Working Group to rank the research priorities; and 3) the implementation of an annual peer review process to assess progress and modify research objectives, where appropriate. We pointed to the need for periodic updating of the Work Plan to refocus research efforts and priorities as new information is gained.

In setting priorities, the TWG made an assessment of the relative importance of each pathogen in terms of its effects on survival of salmon in hatcheries. However, there is no way of evaluating the efficacy of research on fish disease in terms of its potential to produce more returning adults, unless policy makers are willing to make some broad assumptions that have little or no foundation in experience or documentation. This problem is not unique to the fish disease arena, but is common to the measures in the FWP. Nevertheless, it ought to be possible to assess to some degree what gains in hatchery production might be expected from development of control measures for each pathogen. A beginning was made with BPA's Fish Health Monitoring Program, which extended over five years and gathered information on mortalities of salmon within hatcheries and assigned a cause.

One critical uncertainty in this area is the lack of virtually any information on the impact on wild fish of release of pathogen-infected fish from hatcheries. Policies established by the Pacific Northwest Fish Health Committee are designed to prevent the spread of pathogens that might result from release of seriously infected hatchery fish. The policy calls for destruction of fish infected with such serious pathogens as IHN, for example. Realistically, it is impossible to rear fish in a hatchery and release them with assurance that they are 100% free of pathogens. We were informed that all of the diseases diagnosed in hatchery settings had also been observed in the wild, but with lower frequencies, as a general rule.

Our review pointed to the fact that fish disease research in the basin has focused on microbiological and immunological characteristics of the disease agents. These approaches are intended to lead to development of specific treatments once an agent is determined to be present. We observed that it would be desirable, in addition to that approach, to consider development of preventive measures, by which we meant to consider the effects of the environment on the incidence of disease. By environment, we meant all of the physical characteristics of the hatcheries and of the natural waters themselves, such as loading densities of fish in the raceways, water quality in the hatcheries and streams, and other factors. There needs to be better coordination between groups investigating hatchery effectiveness, whose responsibility encompasses the environmental factors, and those investigating fish disease. Stress produced by unfavorable environment can lead to susceptibility to disease. Furthermore, certain environmental conditions can favor the pathogens.

Outside of the hatchery, disease-induced mortality may be increased by stressful activities associated with transportation, bypass, altered thermal regimes, and fish marking and recapture procedures. The communicability of Bacterial Kidney Disease has been established (Pascho et al., 1993). This has given rise to concern that crowding of fish in the transportation barges my facilitate the transfer of pathogens among fish within the barges.

NPPC Provisions on Fish Disease

The 1984 FWP included measures 704(h)(2)(D) and 704(h)(2)(E), which referred to the policy statement of the PNFHPC and called upon BPA to fund development of programs to prevent the introduction of fish diseases into the Columbia Basin, prevent the spread of existing diseases, improve fish culture, minimize the impact of fish diseases on wild and cultured stocks, and improve the detection, diagnosis and control of fish diseases and parasites. These provisions are repeated in Section 703(e)(4) of the 1987 FWP. The 1994 FWP includes a fish health policy at Section 7.2A.6, which calls for hatchery practices and operations that will preclude the introduction and/or spread of any fish disease within the Columbia Basin, and maximize the health of fish released from hatcheries.

Fish Disease Impacts

The Fish Disease Technical Working Group established a set of criteria to be used in setting priorities for research on fish disease. The highest priority was given to diseases for which no control (below the threshold of management significance) had been established, ability of the disease to cause morbidity and mortality, significance of the fish affected by the disease, and significance of fishery management constraints caused by the disease. Using these criteria, eight diseases were identified as the most important. They were:

1) Bacterial kidney disease (BKD),
2) Infectious hematopoietic necrosis (IHN),
3) Erythrocytic inclusion body syndrome (EIBS),
4) Fungal disease of adult salmon and their eggs,
5) Ceratomyxosis caused by *Ceratomyxa shasta*,
6) Whirling disease caused by *Myxobolus cerebralis*,
7) Bacterial coldwater disease (BCWD), and
8) *Ichtyoptherius* and *Ichtyobodo* gill and skin parasites.

The following information was taken from the Fish Disease Work Plan developed by the Fish Disease Technical Working Group in 1987.

1) Bacterial Kidney Disease. Spring chinook are extremely vulnerable to BKD. Losses as high as 80% can occur in hatcheries. The disease can be spread from parent to progeny, and disinfection of eggs has little effect. BKD can be spread from wild fish to hatchery fish through water intakes. Reuse of hatchery water, crowding, handling and marking, and transportation all can spread infections. The antibiotic erythromycin can slow losses to BKD, but it seldom cures the outbreak. Permits for use of erythromycin must be renewed annually. Attempts are being made to develop a vaccine.

2) Infectious Hematopoietic Necrosis (IHN). Losses among steelhead and rainbow trout from IHN may range from 30 to 95%. Severe culling procedures are used to limit its spread. A primary concern is that the disease may be adapting from steelhead and rainbow trout to become a threat to spring or summer chinook. To date, few chinook have died from IHN, but millions of eggs have been destroyed to eliminate the possibility of transmission. Attempts are being made to develop a vaccine.

3) Erythrocytic Necrosis Inclusion Body Syndrome (EIBS). This disease leads to severe anemia among chinook. Little is known about this disease, other than that it is caused by a virus. No treatment is available. Much remains to be learned about transmission, sources of infection, pathogenicity and diagnostic methods.

4) Fungus. The further upstream that chinook are observed, the more heavily they are infested with fungus. This is a particular problem in hatchery ponds where adults are held before they are ripe and ready for spawning. Left untreated in the holding ponds, fungus can kill 50 to 80% of spring chinook adults prior to spawning. Malachite green was formerly the treatment of choice, however, its use was not permitted after 1989, due to its implication in causing cancer in laboratory animals.

5) Ceratomyxosis. The causative agent of this disease, *Ceratomyxa shasta*, is most abundant in the lower Columbia, the Deschutes, and Willamette rivers. *Ceratomyxa* is seldom a cause of losses in hatcheries, but outmigrating wild and hatchery smolts are thought to encounter losses as they pass through the lower river that may range as high as 15%, depending on migration timing and environmental conditions. No treatments are available.

6) Whirling Disease. This disease, caused by a protozoan parasite, *Myxobolus cerebralis*, was not known to occur in the Columbia Basin until 1986. At the time of its first discovery in the basin, the NPFHPC listed it as an emergency pathogen. It was first recorded in domestic rainbow trout and wild steelhead and chinook in several streams in northeastern Oregon. It has subsequently (1995) been reported from Montana and Colorado, where it has been implicated in sudden sharp declines in native trout numbers. Basic information is urgently needed on the relationship between the pathogen and its hosts.

7) Bacterial Coldwater Disease (BCWD). BCWD has many of the same characteristics as BKD. Its greatest impact is on sac fry and young fingerlings, just beginning to feed. Effective therapeutic agents are being sought for this internal infection.

8) *Ichthyoptherius* and *Ichthyobodo*. *Ichthyoptherius* is perhaps the most common cause of losses of young salmon in their incubators or raceways. *Ichthyobodo* infects the gills of juveniles. When numerous on the gills of smolts, saltwater adaptation of the fish can be difficult or impossible. Treatment formerly consisted of formalin or malachite green. New treatments were being sought in 1991.

Literature Cited

Allendorf, F.W. 1991. Ecological and genetic effects of fish introductions: synthesis and recommendations. Canadian Journal of Fsheries and Aquatic Sciences 48, Supplemental 1: 178-181.

Allendorf, F.W. and R.F. Leary. 1988. Conservation and distribution of genetic variation in a polytypic species, the cutthroat trout. Conserv. Biol. 2: 170-184.

Allendorf, F.W. and S.R. Phelps. 1980. Loss of genetic variation in a hatchery stock of cutthroat trout. Transactions of the American Fisheries Society 109: 537-543.

Allendorf, F.W. and N. Ryman. 1987. Genetic management of hatchery stocks. Population genetics and fishery management. N. Ryman and F. Utter. Seattle, Washington, University of Washington Press**:** 141-160.

Allendorf, F.W. and F.M. Utter. 1979. Population genetics. Fish Physiol. 8: 407-454.

Allendorf, F.W. and R.S. Waples. 1996. Conservation and genetics of salmonid fishes. Conservation genetics: Case histories from nature. J. C. Avise, Chapman Hall**:** 238-280.

Ayerst, J.D. 1977. The role of hatcheries in rebuilding steelhead runs of the Columbia River system. Columbia River Salmon and Steelhead, March 5-6, 1976, American Fish. Soc., Washington, DC.

Bartley, D.M., G.A.E. Gall and B. Bentley. 1990. Biochemical genetic detection of natural and artifical hybridization of chinook and coho salmon in northern California. Trans. Amer. Fish. Soc. 119: 431-437.

Beaty, R.E. 1992. Changes in size and age at maturity of Columbia River upriver bright fall chinook salmon (*Oncorhynchus tshawytscha*): Implications for stock fitness, commercial value, and management. Corvallis, Oregon State University. Oregon**:** 270.

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations, Minist. Mar. Fish. and Minist. Agric. Fish Food (G.B.).

Bilby, R.E., B.R. Fransen and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon in the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53: 164-173.

Bottom, D.J. In Press. To till the water: A history of ideas in fisheries conservation. Pacific Salmon and Their Ecosystems. D. J. Stouder, P. A. Bisson and R. J. Naiman. New York, Chapman and Hall.

Bowles, E. 1993. Operation of Compensation Hatcheries within a Conservation Framework. Boise, Idaho Dept. of Fish and Wildlife. Idaho.

Bowles, E. and E. Leitzinger. 1991. Salmon supplementation studies in Idaho Rivers (Idaho supplementation studies), Experimental design. Portland, USDOE, Bonneville Power Administration. Oregon**:** 132+.

Bowles, E.C. 1995. Supplementation: panacea or curse for recovery of declining fish stocks. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 277-283.

Busack, C.A. and K.P. Currens. 1995. Genetic risks and hazards in hatchery operations: fundamental concepts and issues. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 71-80.

Campton, D.E. 1995. Genetic effects of hatchery fish on wild populations of Pacific salmon and steelhead: What do we really know? American Fisheries Society Symposium 15: 337-353.

Campton, D.E. and J.M. Johnston. 1985. Electrophoretic evidence for a genetic admixture of native and nonnative rainbow trout in the Yakima River, Washington. Trans. Amer. Fish. Soc. 114: 782-793.

Campton, D.E. and F.M. Utter. 1985. Natural hybridization between steelhead trout (Salmo gairdneri) and coastal cutthroat trout (Salmo clarki clarki) in two Puget Sound streams. Can. J. Fish. Aquat. Sci. 42(1): 110-119.

Chapman, D., A. Giorgi, M. Hill, A. Maule, S. McCutcheon, D. Park, W. Platts, K. Pratt, J. Seeb, L. Seeb and F. Utter. 1991. Status of Snake River Chinook Salmon. Boise, Don Chapman Consultants, Inc., 3653 Rickenbacker, Suite 200. Idaho**:** 520.

Chapman, D., A. Giorgi, T. Hillman, D. Deppert, M. Erho, S. Hays, C. Peven, B. Suzumoto and R. Klinge. 1994. Status of Summer/Fall Chinook Salmon in the Mid-Columbia Region. Boise, Don Chapman Consultants Inc. Idaho**:** 411 + app.

Chapman, D.W. 1986. Salmon and steelhead abundance in the Columbia River in the nineteenth century. Trans. Am. Fish. Soc. 115: 662-670.

Cobb, J.N. 1930. Pacific Salmon Fisheries. Washington, Bureau of Fisheries. District of Columbia.

Columbia Basin Fish and Wildlife Authority. 1990. Review of the history, development, and management of anadromous fish production facilities in the Columbia River Basin. Portland, Columbia Basin Fish and Wildlife Authority and U.S. Fish & Wildlife Service. Oregon**:** 52.

Comm., O.F.a.G. 1919. Biennial Report of the Fish and Game Commission of the State of Oregon to the Governor and the Thirtieth Legislative Assembly, 1919. Salem, State of Oregon. Oregon.

Commissioners, O.B.o.F. 1888. First Report of the State Board of Fish Commissioners to the Governor of Oregon. Salem. Oregon.

Craig, J.A. and R.L. Hacker. 1940. The history and development of the fisheries of the Columbia River. U.S. Bureau of Fisheries Bulletin 32: 133-216.

Craig, O.J. 1899. University of Montana Summer School of Science and First Summer Opening of the Montana Biological Station., University of Montana, Missoula.

Cuenco, M.L., T.W.H. Backman and P.R. Mundy. 1993. The use of supplementation to aid in natural stock restoration. Genetic Conservation of Salmonid Fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press**:** 269-293.

Culler, C.F. 1932. Progress in fish culture. Trans. Amer. Fish. Soc.: 114-118.

Currens, K.P., C.B. Schreck and H.W. Li. 1990. Allozyme and morphological divergence of rainbow trout (*Oncorhynchus mykiss*) above and below waterfalls in the Deschutes River, Oregon. Copeia 1990: 730-746.

Cushing, D.H. 1983. Key Papers on Fish Populations. Washington, IRL Press Limited.

Darwin, C. 1859. The Origin of Species by Means of Natural Selection. New York, The Modern Library.

Delarm, M.R., E. Wold and R.Z. Smith. 1989. Columbia River Fisheries Development Program Fishways and Stream Improvement Projects. Seattle, NMFS/NOAA. Washington.

DeLoach, D.B. 1939. The salmon canning industry. Oregon State Monographs Economic Studies No. 1.

Doppelt, B., M. Scurlock, C. Frissell and J. Karr. 1993. Entering the Watershed: A New Approach to Save America's River Ecosystems. Covelo, CA, Island Press.

Ebel, W.J. 1977. Panel 2: Fish passage problems and solutions, major passage problems. Columbia River Salmon and Steelhead, March 5-6, 1976, American Fisheries Soc., Washington, DC.

Eggers, D.M. 1992. The costs and benefits of the management program for natural sockeye salmon stocks in Bristol Bay, Alaska. Fisheries Research 14: 159-177.

Emlen, J.M. 1991. Heterosis and outbreeding depression: a multi-locus modle and an application to salmon production. Fisheries Research 12: 187-212.

Eriksson, T. and L.-O. Eriksson. 1993. The status of wild and hatchery propagated Swedish salmon stocks after 40 years of hatchery releases in the Baltic rivers. Fisheries Research 18(1993): 147-159.

Fausch, K.D. 1988. Tests of competition between native and introduced salmonids in streams: what have we learned. Can. J. Fish. Aquat. Sci. 45(12): 2238-2246.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest Ecosystem Management: An Ecological, Economic, and Social Assessment. Portland, Interagency Supplemental Envir. Impact Statement Team. Oregon.

Fish, F.F. and M.G. Hanavan. 1948. A Report upon the Grand Coulee Fish-Maintenance Project 1939-1947. Washington, US Fish and Wildlife Service. District of Columbia.

Flagg, T.A., C.V.W. Mahnken and K.A. Johnson. 1995. Captive broodstocks for the recovery of Snake River sockeye salmon. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 81-90.

Flagg, T.A., F.W. Waknitz, D.J. Maynard, G.B. Milner and C.V.W. Mahkhen. 1995. The effect of hatcheries on native coho salmon populations in the lower Columbia River, Symposium 15. Uses and Effects of Cultured Fishes in Aquatic Ecosystems, American Fisheries Society, Bethesda, MD.

Foerster, R.E. 1936. Sockeye salmon propagation in British Columbia. Ottawa, Biological Board of Canada. Ontario, Canada.

Forbes, S.H. and F.W. Allendorf. 1991. Associations between mitochondrial and nuclear genotypes in cutthroat trout hybrid swarms. Evolution 45(6): 1332-1349.

Fried, S.M. and H.J. Yuen. 1987. Forecasting sockeye salmon (*Oncorhynchus nerk*a) returns to Bristol Bay, Alaska: a review and critique of methods. Sockeye Salmon (*Oncorhynchus nerka*) Population Biology and Future Management, Canadian Special Publication in Fisheries and Aquatic Sciences. H. D. Smith, L. Margolis and C. Wood. 96**:** 273-279.

Frissell, C.A. 1993. Topology of extinction and endangerment of native fishes in the Pacific northwest and California (U.S.A.). Conservation Biology 7(2): 342-354.

Frissell, C.A. and D. Bayles. 1996. Ecosystem management and the conservation of aquatic biodiversity and ecological integrity. J. Amer. Water Res. Assoc. 32(2): 229-240.

Frissell, C.A., W.J. Liss and D. Bayles. 1993. An integrated, biophysical strategy for ecological restoration of large watersheds. Proceedings of the Symposium on Changing Roles in Water Resources Management and Policy. N. E. Spangenborg and D. E. e. Potts. Bethesda, American Water Resources Association**:** 449-456.

Frissell, C.A. and R.K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12: 182-197.

Game, W.D.o.F.a. 1904. Fourteenth and Fifteenth Annual Report of the State Fish Commissioner to the Governor of the State of Washington. Seattle. Washington.

Gausen, D. 1993. The Norwegian gene bank programme for Atlantic Salmon (*Salmo salar*). Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 181-188.

General Accounting Office. 1992. Endangered Species: Past Actions Taken to Assist Columbia River Salmon. Washington. District of Columbia.

Gharrett, A.J. and W.W. Smoker. 1991. Two generations of hybrids between even- and odd-year pink salmon (Oncorhynchus gorbuscha): a test for outbreeding depression? Canadian Jouornal of Fisheries and Aquatic Sciences 48(9): 1744-1749.

Gharrett, A.J. and W.W. Smoker. 1993. Genetic components in life history traits contribute to population structure. Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 197-202.

Goode, G.B. 1884. The Status of the US Fish Commission in 1984. Part XLI in Part XII. Washington, US Commission of Fish and Fisheries. DC.

Gottschalk, J. 1942. Report of the division of fish culture. Trans. Amer. Fish. Soc., Seventy-first Annual Meeting, August 25-26, 1941.

Hard, J.J., R.P. Joness, M.R. Delarm and R.S. Waples. 1992. Pacific salmon and aritificial propagation under the Endangered Species Act, U. S. Dept. Commer.,.

Hayden, M.V. 1930. History of the Salmon Industry of Oregon. Eugene, University of Oregon. Oregon.

Hedgepeth, J.W. 1941. Livingston Stone and fish culture in California. California Fish and Game 27(3): 126.

Heggberget, T.G., B.O. Johnsen, K. Hindar, B. Jonsson, L.P. Hansen, N.A. Hvidsten and A.J. Jensen. 1993. Interactions between wild and cultured Atlantic salmon: a review of the Norwegian experience. Fisheries Research 18: 123-146.

Hilborn, R. 1987. Living with uncertainty in resource management. North American Journal of Fisheries Management 7: 1-5.

Hilborn, R. 1992. Hatcheries and the future of salmon in the Northwest. Fisheries 17(1): 5.

Hilborn, R. and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. New York, Chapman & Hall.

Hilborn, R. and J. Winton. 1993. Learning to enhance salmon production: lesson from the Salmonid Enhancement Program. Can. J. Fish. Aquat. Sci. 50.

Hile, R. 1936. The increase in the abundance of the yellow pike-perch, (*Stizostedion vitreum* (Mitchill)), in lakes Huron and Michigan, in relation to the artificial propagation of the species. The Collected Papers of Ralphe Hile, 1928-73. Washington, US Dept. of Interior, Fish and Wildlife Service**:** 143-159.

Hindar, K., N. Ryman and F. Utter. 1991. Genetic effects of cultured fish on natural fish populations. Canadian Journal of Fisheries and Aquatic Sciences 48(Supplement 1): 945-957.

Hunter, C.J. 1991. Better Trout Habitat: A Guide to Stream Restoration and Management. Washington, Island Press.

Huntsman, A.G. 1937. Races and homing of salmon. Science 85: 477-478.

Jensen, T.C. 1986. The United States-Canada Pacific salmon interception treaty: an historical and legal overview. Environmental Law 16(3): 363-422.

Johnson, D.R., W.M. Chapman and R.W. Schoning. 1948. The Effects on Salmon Populations of the Partial Elimination of Fixed Fishing Gear on the Columbia River in 1935. Portland, Oregon Fish Commission. Oregon.

Johnson, S.L. 1984. Freshwater Environmental Problems and Coho Production in Oregon. Corvallis, Oregon Dept. of Fish and Wildlife. Oregon.

Kauffman, J.B., R.L. Case, D. Lytjen, N. Otting and D. Cummings. 1995. Ecological approaches to riparian restoration in northeast Oregon. Restoration and Management Notes 13: 12-15.

Kostow, K. 1995. Biennial Report of the Status of Wild Fish in Oregon. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Krueger, C.C. and B. May. 1991. Ecological and genetic effects of salmonid introductions in North America. Canadian Journal of Fisheries and Aquatic Sciences 48(Supplement 1): 66-77.

Kyle, G.B., J.P. Koenings and B.M. Barrett. 1988. Density-dependent, trophic level responses to an introduced run of sockeye salmon (*Oncorhynchus nerka*) at Frazer Lake, Kodiak Island, Alaska. Can. J. Fish. Aquat. Sci. 45: 856-867.

Lande, R. 1988. Genetics anad demography in biological conservation. Science 241: 1455-1460.

Lande, R. and G.F. Barrowclough. 1987. Effective population size, genetic variation, and their use in population management. Viable Populations for Conservation. M. E. Soule. New York, Cambridge University Press**:** 87-124.

Lavier, D.C. 1976. Major Dams on Columbia River and Tributaries. Olympia, Washington Dept. of Game. Washington.

Laythe, L.L. 1948. The fishery development program in the lower Columbia River. American Fisheries Society, Atlantic City, New Jersey, Amer. Fish. Soc.

Leary, R.F., F.W. Allendorf and K.L. Knudsen. 1985. Developmental instability as an indicator of related genetic variation in hatchery trout. Trans. Amer. Fish. Soc. 114: 230-235.

Leary, R.F., F.W. Allendorf and G.K. Sage. 1995. Hybridization and introgression between introduced and native fish. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 91-101.

Lichatowich, J. and J.D. McIntyre. 1987. Use of hatcheries in the management of anadromous salmonids. American Fisheries Society Symposium 1: 131-136.

Lichatowich, J. and B. Watson. 1993. Use of Artificial Propagation and Supplementation for Rebuilding Salmon Stocks Listed Under the Endangered Species Act. Portland, Bonneville Power Administration. Oregon**:** 103.

Lichatowich, J.A. and J. Nicholas. In press. Oregon's first century of hatchery intervention in salmon production: Evolution of the hatchery program, legacy of a utilitarian philowophy and management recommendations. International Symposium on Biological Interactions of Enhanced and Wild Salmonids, June 17-20, 1991, Nanaimo, British Columbia.

Maitland, J.R.G. 1884. The culture of salmonidae and the acclimatization of fish. The Fisheries Exhibition Literature, International Fisheries Exhibition, London, 1883. London, William Clowes and Sons, Limited.

Mathisen, O.A. 1972. Biogenic enrichment of sockeye salmon and stock productivity. Verh. Int. Ver. Limnol. 18: 1089-1095.

McAllister, M.K. and R.M. Peterson. 1992. Experimental design in the management of fisheries: a review. N. Amer. J. Fish. Mgt. 12(1): 1-18.

McDonald, M. 1894. The salmon fisheries of the Columbia River basin. Report of the Commissioner of Fish and Fisheries Investigations in the Columbia River Basin in Regard to the Salmon Fisheries. Senate Miscellaneous Document No. 200, 53rd Congress 2d Session, and House Miscellaneous Document No. 86, 53d Congress, 3d Session: 3-18.

McGurrin, J., D. Ubert and D. Duff. 1995. Use of cultured salmonids in the federal aid in sport fish restoration program. Amer. Fish. Soc. Symp. 15: 12-15.

Meffe, G.K. 1992. Techno-arrogance and halfway technologies: salmon hatcheries on the Pacific coast of North America. Conservation Biology 6(3): 350-354.

Messmer, R.T., R.W. Carmichael, M.W. Flesher and T.A. Whitesel. 1992. Evaluation of Lower Snake River Compensation Plan Facilities in Oregon. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Mighetto, L. and W.J. Ebel. 1994. Saving the Salmon: A History of the US Army Corps of Engineers. Efforts to Protect Anadromous Fish on the Columbia and Snake Rivers. Seattle, Historical Research Associates.

Miller, R.B. 1957. Have the genetic patterns of fishes been altered by introductions or selective fishing? Journal of the Fisheries Research Board of Canada 14: 797-806.

Miller, W., C. Steward and T. Bjornn. 1990. Analysis of Salmon and Steelhead Supplementation, Parts 1-3. Portland, Bonneville Power Administration. Oregon.

Moore, E. 1925. Report of the Vice President Division of Fish Culture, New York State Conservation Commission. Trans. of the Amer. Fish. Soc. Fifty-fifth Annual Meeting, American Fisheries Society, Denver.

Muir, W.D.a.t.c. 1996. Survival Estimates for the Passage of Yearling Chinook Salmon and Steelhead through Snake River Dams and Reservoirs, 1995 (draft). Seattle, Northwest Fisheries Science Center, National Marine Fisheries Service. Washington.

Mullan, J.W., A. Rockhold and C.R. Chrisman. 1992. Life histories and precocity of chinook salmon in the Mid-Columbia River. Progressive Fish-Culturist 54(1): 25-28.

Mundy, P.R. 1985. Harvest control systems for commercial marine fisheries management; theory and practice. Fisheries Dynamics, Harvest Management and Sampling, Washington Sea Grant Technical Report 85-1. P. R. Mundy, a. T. J. Quinn and R. B. Deriso. Seattle, University of Washington.

Mundy, P.R. in press. The role of harvest management in determining the status and future of Pacific salmon populations: Shaping human behavior to enable the persistence of salmon.

Pacific Salmon and Their Ecosystems: Status and Future Options. R. J. N. a. D. Stouder. New York, USA, Chapman Hall.

Mundy, P.R., T.W.H. Backman and J. Berkson. 1995. Experiences from the Columbia River. Defining Conservation Units for Endangered Species. J. M. Nielsen. Bethesda, American Fisheries Society.

Mundy, P.R. and O.A. Mathisen. 1981. Abundance estimation in a feedback control system applied to the management of a commercial salmon fishery. Applied Operations Research in Fishing. K. B. Haley. New York, Plenum Publishing Corp.**:** 81-98.

National Marine Fisheries Service. 1995. Proposed Recovery Plan for Snake River Salmon. Washington, US Dept. of Commerce, National Oceanic and Atmospheric Administration. District of Columbia**:** 387.

National Research Council. 1995. Science and the Endangered Species Act. Washington, National Academy Press.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Report on the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids for the National Research Council of the National Academy of Sciences. Washington D. C., National Academy Press.

Needham, P.R. 1939. Natural propagation versus artificial propagation in relation to angling. Fourth North American Wildlife Conference, February 13-15, American Wildlife Institute, Washington.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Netboy, A. 1974. The Salmon Their Fight for Survival. Boston, Houghton Mifflin Co.

Nickelson, T.E., M.F. Solazzi and S.L. Johnson. 1986. Use of hatchery coho salmon (Oncorhynchus kisutch) presmolts to rebuild wild populations in Oregon coastal streams. Can. J. Fish. Aquat. Sci. 43(12): 2443-2449.

Northwest Power Planning Council. 1992. Columbia River Basin Fish and Wildlife Program. Portland. Oregon.

Northwest Power Planning Council. 1992. Strategy for Salmon, Vol. 1. Portland, Northwest Power Planning Council. Oregon**:** 43.

Northwest Power Planning Council. 1992. Strategy for Salmon, Vol. 2. Portland, Northwest Power Planning Council. Oregon**:** 98.

Northwest Power Planning Council. 1994. 1994 Columbia River Basin Fish and Wildlife Program. Portland, Northwest Power Planning Council. Oregon.

Northwest Power Planning Council. 1994. Columbia River Basin Fish and Wildlife Program. Portland. Oregon.

Office, G.A. 1993. Endangered species: potential economic costs of further protection for Columbia River salmon. Washington, U. S. General Accounting Office. DC**:** 34.

Olson, D.E., B.C. Cates and D.H. Diggs. 1995. Use of a national fish hatchery to complement wild salmon and steelhead production in an Oregon stream. Amer. Fish. Soc. Symp. 15: 317-328.

Oregon Fish Commission. 1933. Biennial Report of the Fish Commission of the State of Oregon to the Governor and the Thirty-seventh Legislative Assembly, 1933. Salem, State of Oregon. Oregon.

Ortmann, D.W., F. Cleaver and K.R. Higgs. 1976. Artificial Propagation. Portland, Pacific Northwest Regional Commission.

Pascho, R.J., D.G. Elliott and S. Achord. 1993. Monitoring of the in-river migration of smolts from two groups of spring chinook salmon, *Oncorhynchus tshawytshca* (Walbaum), with different profiles of *Renibacterium salmoninarum* infection. Aquaculture and Fisheries Management 24: 163-169.

Paulik, G.J. 1969. Computer simulation models for fisheries research, management, and teaching., Trans. Am. Fish. Soc. 98(3):551-559.

Philipp, D.P. and J.E. Clausen. 1995. Fitness and performance differences between two stocks of largemouth bass from different river drainages witin Illinois. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Sooceity Symposium. 15**:** 236-243.

Philipp, D.P., J.M. Epifanio and M.J. Jennings. 1993. Point/Counterpoint: conservation genetics and current stocking practices — are they compatible? Fisheries 18(12): 14-16.

Pielou, E.C. 1969. An introduction to mathematical ecology. New York, John Wiley & Sons.

Putz, B. and F.M.P. Chairs). 1994. U. S. Fish and Wildlife Service National Fish Hatchery Review. Arlington VA, The Conservation Fund, The National Fish and Wildlife Foundation.

Reeves, G.H. and J.R. Sedell. 1992. An ecosystem approach to the conservation and management of freshwater habitat for anadromous salmonids in the Pacific Northwest. Trans. 57th Wildlife and Natural Resources Conference., Washington.

Reisenbichler, R.R. 1995. Questions and partial answers about supplementation -- genetic differences between hatchery fish and wild fish. Columbia River Anadromous Salmonid Rehabilitation Symposium, Richland, Washington.

Reisenbichler, R.R. and J.D. McIntyre. 1977. Genetic differences in growth and survival of juvenile hatchery and wild steelhead trout, *Salmo gairdneri*. Journal of the Fisheries Research Board of Canada 34: 123-128.

Reisenbichler, R.R. and J.D. McIntyre. 1986. Requirements for integrating natural and artificial production of anadromous salmonids in the Pacific Northwest. Fish Culture in Fisheries Management, March 31 - April 3, 1985, Lake Ozark, Missouri.

Reisenbichler, R.R. and J.d. McIntyre. 1986. Requirements for integrating natural and artificial production of anadromous salmonids in the Pacific Northwest. Fish culture in fisheries management. R. H. Stroud. Bethesda, American Fisheries Society**:** 365-374.

Rhodes, J.J., D.A. McCullough and J. F. A. Espinosa. 1994. A Coarse Screening Process for Evaluation of the Effects of Land Management Activities on Salmon Spawning and Rearing Habitat in ESA Consultations. Portland, Columbia River Inter-Tribal Fish Commission. Oregon.

Rich, W.H. 1920. Early history and seaward migration of chinook salmon in the Columbia and Sacramento Rivers. Bulletin of the US Bureau of Fisheries, Washington, DC 37.

Rich, W.H. 1939. Fishery problems raised by the development of water resources. Dams and the Problems of Migratory Fishes, Stanford University, Fish Comm. of State of Oregon.

Rich, W.H. 1941. The present state of the Columbia River salmon resources. Sixth Pacific Science Congress, Berkeley, Fish Comm. of State of Oregon.

Rich, W.H. and H.B. Holmes. 1929. Experiments in marking young chinook salmon on the Columbia River, 1916 to 1927. Bulletin of the Bureau of Fisheries, Washington, DC Document No. 1047.

Ricker, W.E. 1954. Nomenclatorial notes on Plecoptera., Proc. Entomol. Soc. British Columbia 51:37-39.

Ricker, W.E. 1954. Stock and recruitment. J. Fish. Res. Board. Can. 11: 559-623.

Ricker, W.E. 1958. Handbook of Computations for Biological Statistics of Fish Populations. Ottawa, Fisheries Research Board of Canada**:** 300.

Ricker, W.E. 1972. Hereditary and environmental factors affecting certain salmonid populations. The Stock Concept in Pacific Salmon. R. C. Simon and P. A. Larkin. Vancouver, University of British Columbia**:** 19-160.

Ricker, W.E. 1973. Linear regressions in fishery research. J. Fish. Res. Board Can. 30: 409-434.

Ricker, W.E. 1981. Changes in the average size and age of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 38: 1636-1656.

Ricker, W.E.a.H.D.S. 1975. A revised interpretation of the history of the Skeena River sockeye salmon Oncorhynchus nerka)., J. Fish. Res. Board Can. 32(8):1369-1381.

Riddell, B.E. and W.C. Legget. 1981. Evidence for an adaptive basis variation in body morphology and time of downstream migration juvenile Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 38: 308-320.

Rieman, B.E. and J.D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. Ogden, US Forest Service, Intermountain Research Station. Utah**:** 38.

Roos, J.F. 1991. Restoring Fraser River Salmon. Vancouver, Pacific Salmon Commission. British Columbia, Canada.

Rounsefell, G.A. 1947. The effect of natural and artificial propagation in maintaining a run of Atlantic salmon in the Penobscot River. Trans. Amer. Fish. Soc. 74: 188-208.

Ryman, N. and F. Utter. 1987. Population genetics and fishery management. Seattle, WA, University of Washington Press.

Salo, E.O. and W.H. Bayliff. 1958. Artificial and Natural Production of Silver Salmon, *Oncorhynchus kisutch*, at Minter Creek, Washington. Olympia, Washington Dept. of Fisheries. Washington.

Schalk, R.F. 1986. Estimating salmon and steelhead usage in the Columbia Basin before 1850: the anthropological perspective. Northwest Envir. Journal 2(2): 1-29.

Schramm, H.L. and V. Mudrak. 1994. Essay: beneficial aspects of put-and-take trout stocking. Fisheries 19(8): 6-7.

Schuck, H.A. 1943. Survival, population density, growth and movement of the wild brown trout in Crystal Creek. Transactions of the American Fisheries Society 73: 209-230.

Schwiebert, E. 1977. Some notes on the symposium. Columbia River Salmon and Steelhead, March 5-6, 1976, American Fisheries Society, Washington, DC.

Shoemaker, C.D. and R.E. Clanton. 1923. Biennial Report of the Fish Commission of the State of Oregon to the Governor and the Thirty-second Legislative Assembly, 1923. Salem, State of Oregon. Oregon.

Simms, J. 1877. Letter to the Commissioner of Indian Affairs from J. Simms, U.S. Indian Agent, Colville Agency.

Soule, M.E., Ed. 1987. Viable Populations for Conservation. New York, Cambridge University Press.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant. *in press*. A general protocol for restoration of regulated rivers. Regulated Rivers.

Sterne, J.K. 1995. Supplementation of wild salmon stocks: a cure for the hatchery problem or more hatchery problems? Coastal Management 23: 123-152.

Steward, C.R. and T.C. Bjornn. 1990. Supplementation of salmon and steelehad stocks with hatchery fish: a synthesis of published literature. Analysis of Salmon and Steelhead Supplementation, Parts 1-3. W. H. Miller. Portland, Bonneville Power Administration. Project 88-100.

Stone, L. 1879. Report of operations at the salmon-hatching station on the Clackamas River, Oregon, in 1877. Report of the Commissioner for 1877. Washington, US Commission of Fish and Fisheries**:** Part 11 in Part 5.

Thompson, W.F. 1951. An Outline for Salmon Research in Alaska. Seattle, Fisheries Research Institute, University of Washington. Washington.

Thorpe, J.E. 1995. Impacts of fishing on genetic structure of salmonid populations. Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 67-80.

Utter, F.M., D.W. chapman and A.R. Marshall. 1995. Genetic population structure and history of chinook salmon of the upper Columbia River. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 149-168.

Van Cleve, R. and R. Ting. 1960. The Condition of Salmon Stocks in the John Day, Umatilla, Walla Walla, Grande Ronde, and Imnaha Rivers as Reported by Various Fisheries Agencies. Seattle, Dept. of Oceanography, University of Washington. Washington.

Van Hyning, J.M. 1973. Factors affecting the abundance of fall chinook salmon in the Columbia River. Research Reports of the Fish Commission of Oregon 4(1).

Van Oosten, J. 1942. Relationship between the plantings of fry and production of whitefish in Lake Erie. American Fisheries Society 71st Annual Meeting, St. Louis, MO.

Vannote, R.L., G.W. Minshall, K. W.Cummins, J.R. Sedell and C.E. Cushing. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37(1): 130-137.

Wahle, R.J. and R.R. Vreeland. 1978. Bioeconomic contribution of Columbia River hatchery fall chinook salmon, 1961 through 1964 broods, to the Pacific salmon fisheries. Fisheries Bulletin 76(1): 179-208.

Wahle, R.J., R.R. Vreeland and R.H. Lander. 1974. Bioeconomic contribution of Columbia River hatchery coho salmon, 1965 and 1966 broods, to the Pacific salmon fisheries. Fisheries Bulletin 72(1): 139-169.

Wallis, J. 1964. An Evaluation of the Bonneville Salmon Hatchery. Clackamas, Oregon Fish Commission Research Laboratory. Oregon.

Walters, C.J. 1986. Adaptive Management of Renewable Resources. New York, MacMillan Publishing Company.

Walters, C.J. and J.S. Collie. 1988. Is research on environmental factors useful to fisheries management? Canadian Journal of Fisheries and Aquatic Sciences 45: 1848-1954.

Waples, R.S. 1991. Definition of "species" under the endangered species act: Application to pacific salmon. Seattle, National Marine Fisheries Service. Washington**:** 29.

Waples, R.S. 1991. Genetic interactions between hatchery and wild salmonids: lessons from the Pacific Northwest. Can. J. Fish. Aquat. Sci. 48(Suppl. 1): 124-133.

Waples, R.S. and C. Do. 1995. Genetic risk associated with supplementation of Pacific salmonids: captive broodstock programs. Canadian Journal of Fisheries and Aquatic Sciences 51(1): 310-329.

Waples, R.S. and P.E. Smouse. 1990. Gametic disequilibrium analysis as a means of idenitfying mixtures of salmon populations. American Fisheries Society Symposium 7: 439-458.

Waples, R.S., D.J. Teel and P.B. Aebersold. 1991. A genetic evaluation and monitoring program for supplemented populations of salmon and steelhead in the Snake River Basin, National Marine Fisheries Service.

Ware, D.M. and R.E. Thompson. 1991. Link between long-term variability in upwelling and fish production in the northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 48(12): 2296-2306.

Wash. Dept. of Fisheries, W.D.o.W., and Western Wash. Treaty Indian Tribes. 1993. 1992 Washington State Salmon and Steelhead Stock Inventory. Olympia. Washington.

Washington, P.M. and A.M. Koziol. 1993. Overview of the interactions and environmental impacts of hatchery practices on natural and artificial stocks of salmonids. Fisheries Research 18: 105-122.

White, R.J., J.R. Karr and W. Nehlsen. 1995. Better roles for fish stocking in aquatic resource management. Uses and effects of cultured fishes in aquatic ecosystems.

Williams, R.N., D.K. Shiozawa, J.E. Carter and R.F. Leary. 1996. Genetic detection of putative hybridization between native and introduced rainbow trout populations of the Upper Snake River. Transactions of the American Fisheries Society 125: 387-401.

Winton, J. and R. Hilborn. 1994. Lessons from the supplementation of chinook salmon in British Columbia. N. Amer. J. Fish. Mgmt. 14: 12.

Wood, E.M. 1953. A century of American fish culture, 1853-1953. The Progressive Fish Culturist 15(4): 147-160.

CHAPTER 9. MONITORING AND EVALUATION

Our conceptual foundation for the Fish and Wildlife Program necessitates revisiting the program's monitoring and evaluation functions. New metrics more appropriate to this view of the system need to be found or forged from existing activities.

Monitoring and Evaluation in the Program

The Council is committed to monitoring and evaluation to promote sound investments in salmon and steelhead projects (1994 Program sections 1.3A; 1.4; 3.2E.1). Although implied from the earliest planning under the Northwest Power Act, a monitoring and evaluation role was made explicit in the 1987 amended program with inclusion of a System Monitoring and Evaluation Program to track progress of the Fish and Wildlife Progam in achieving the Council's goals of doubling the runs of salmon and steelhead in the basin. The 1994 Fish and Wildlife Progam states that there will be an evaluation path as well as an implementation path (Northwest Power Planning Council, 1994). This path will "monitor overall program implementation, evaluate the effectiveness of actions taken, and judge their scientific merits." The key is ensuring feedback so that the Fish and Wildlife Progam can be modified as needed to reach goals. Learning from implementation is the essence of "adaptive management," which has been adopted as a guiding philosophy for the program. In essence, adaptive management recognizes that many actions related to fish management must occur continually (e.g., river flows), whether ideal or not. Appropriate data gathering during these events should lead to recognition of their value and to refinement of any subsequent actions. The Program also states that base-line information is needed, which will improve management and conservation of wild and naturally spawning populations (§ 7.1C).

Monitoring and evaluation activities have been assessed periodically. Everson et al. (Everson et al., 1989) summarized the history of habitat monitoring and evaluation in the Program up to 1986. Monitoring and Evaluation has been the subject of a NPPC staff issue paper (Northwest Power Planning Council, 1988) and recommendations have been obtained from a peer group established by the Council (Monitoring and Evaluation Group of the Northwest Power Planning Council, 1988). Monitoring and evaluation elements of the Fish and Wildlife Progam are periodically reviewed as part of the Council's System Planning Process (an effort under the lead of the fish agencies and tribes to plan fisheries actions in 31 subbasins related to production objectives, constraints and opportunities). A Coordinated Information System has been developed for collection and dissemination of information produced as part of the Fish and Wildlife Progam. BPA has tried to include decision science in its efforts to use the value of information as a means to focus and prioritize potential monitoring activities (letter of May 24 from G. Drais to R. Whitney).

There has been a significant change in the monitoring and evaluation aspects with the 1994 program, reflecting these assessments. Specifically, more emphasis has been placed on the use of indicator stocks tied to rebuilding schedules which are, in turn, tied to program goals (framework). High priority populations are to be identified as indicator stocks (§ 4.3C) and long-term monitoring strategies developed for them. Rebuilding targets and performance standards are to be established wherever possible as explicit means for measuring progress (Section 4). If progress toward standards and targets falls significantly short, the Council will revisit all aspects of the Program (3.1B). Effects on resident fish and wildlife are to be monitored to avoid indiscriminate shifting of environmental problems from salmon to these species as a result of using upstream reservoirs to supply water for downstream migrants (1.4). Periodic assessment of the ecological health of the Columbia River Basin is called for (introduction to Section 2). Measures of ecosystem health are to be selected to simplify this evaluation (2.1A.1). The annual emigration of smolts is to be monitored by the Smolt Monitoring Program of the Fish Passage Center (5.1B).

One way the Council has moved to ensure monitoring and evaluation is to structure projects so that they test quantitative hypotheses wherever possible (3.2; 5.0). These quantitative hypotheses are to be prioritized according to key uncertainties identified by the Independent Scientific Group (3.2). To narrow the focus of monitoring to a manageable level, the Program calls for identification of index stocks (indicator populations) and their monitoring needs (3.2A.1; 4.3C). Analytical tools for monitoring and evaluation are in need of development (3.2F; 4.3C.1) to link program actions to survival targets, rebuilding schedules, and rebuilding targets. The tools are to reflect the span of legitimate scientific differences and approaches. Computer models and their uses is given special attention. The Program suggests a regional center for biological analysis (3.2F.1). Effective compilation of data and their availability are essential to monitoring and evaluation, and the Program assigns these tasks to the Coordinated Information System (3.3; 4.3C.1). The most explicit foray by the Program into a specific monitoring and evaluation exercise is the mainstem passage experimental program, which requires extensive monitoring and evaluation (Section 5). This experiment will be an evaluation project to test the relative benefits of two modes of fish passage--in-river and transportation (barging and trucking).

Despite good intentions, the 1994 Program recognizes that there has been unsatisfactory progress in coupling actions (taken with the best available information) and evaluation to allow learning from implementation (2.2H). The Program now couples an annual implementation work plan, an annual monitoring report on meeting targets and standards (by the Coordinated Information System), and a biennial evaluation of the Program on its scientific merits (by the Independent Scientific Group)(3.1B; 3.2A.2; 3.2B.1; 3.3A.2). Reflecting the need for the Program actions to be implemented and monitored in a coherent, well-organized, and carefully disciplined manner, the Council has requested a management consultant's analysis of the management of the Program (3.1E.1). This analysis would include development of measurable benchmarks and workable mechanisms for measuring progress. The Program also calls for attention to the endangered species consultation process to ensure consideration of monitoring and evaluation (3.2D.1). Coordination of monitoring and evaluation is to be fostered by publication of summaries of results of all studies funded by the Program and incorporation of them into the electronic database of a the Coordinated Information System, as well as oral presentation of project reports at symposia (3.2G).

The Fish and Wildlife Progam recently included 58 projects categorized by BPA as "monitoring and evaluation" (Lohn, 1995). The Fiscal Year 1995 planned cost for these projects was $22,471,432. Many of these projects involve data collection whereas others are mainly consultative (the funding for the Independent Scientific Group is one such project). The management agencies also conduct extensive monitoring of their resources within the general umbrella of the Fish and Wildlife Progam. For example, the U. S. Army Corps of Engineers monitors the passage of adult fish past each of its projects, while the mid-Columbia public utility districts do so at most of their projects. States have had monitoring programs underway with a different impetus, such as the Lower Snake River Compensation Plan (Corps of Engineers, 1975).

Perspectives on Monitoring and Evaluation

There are two perspectives on "monitoring and evaluation" in the Fish and Wildlife Progam, biological inventory and program evaluation. The two are often inadequately distinguished. Biological inventories are the counting of salmon, steelhead, resident fishes, and wildlife within migrations or water bodies and from year to year (e.g., §s 4.3C and 7.1C) to establish a numerical basis for evaluating trends in population sizes and needs for (and results of) water and habitat management and improvement. The programmatic perspective is the monitoring of the success of specific projects and programs within the Fish and Wildlife Progam (in both social and biological terms) as a basis for evaluating whether to continue them as part of the Fish and Wildlife Progam or to develop alternatives through adaptive management (e.g., § 3.1B). Programmatic monitoring and evaluation are highly dependent on the biological monitoring for measures of success (or failure) of the Fish and Wildlife Progam in terms of salmonid population sizes.

This distinction is not universally applied, and there is often confusion about what is meant by "monitoring and evaluation" (terms that are usually given inseparably). Monitoring is often reserved for the environmental measurements (biological and physical-chemical) whereas evaluation is thought of as programmatic. Monitoring and evaluation, both environmental and programmatic, are separate processes, sometimes occurring together but often not. Linkage of the two terms and failure to differentiate the perspectives behind their use have contributed to numerous false starts at both environmental and programmatic efforts. Monitoring of selected environmental features is essential if we are to keep track of overall progress towards Fish and Wildlife Progam goals. Whether we have environmental monitoring or not, the Fish and Wildlife Progam needs evaluation of all projects and programs. We believe that there should be a clearer distinction between the two terms in the conduct of the Fish and Wildlife Progam.

This section of the review of science focuses on biological-environmental monitoring rather than programmatic monitoring. Monitoring and evaluation of the biological successes of implementation actions are usually built into specific project plans. Some programmatic approaches for monitoring and evaluation the Fish and Wildlife Progam were provided by Coutant and Cada (1985). We previously provided additional guidelines for programmatic monitoring and evaluation.

Issues in Monitoring and Evaluation

Numerous issues have concerned those planning monitoring and evaluation. Many have been procedural (i.e., What is the "flow chart" of information and decision-making?). Others have focused on what to measure. As we consider a new conceptual foundation, it is important to recognize the evolution that has already occurred.

• Policy. That there should be monitoring and evaluation is uncontested and well supported by the 1994 Program. The issue is whether it has been sufficient. Lists of things to monitor have grown longer and the need for prioritization became evident. Notions of the relative value of information became a criterion for project selection, without answering the question of what makes information valuable.

• Scientific. MEG (1988) clearly stated the main scientific issue: a measure of progress for the Program should not only determine progress (such as toward doubling goals), but should also provide information to increase understanding, decrease uncertainty, and permit the Program to be refined over time. The recent issue is a matter of how the Program and its monitoring and evaluation have been focused by prevailing beliefs. Ideally, there should be an objective analysis of all information, aided by alternative hypotheses. A critical issue is whether current beliefs are sufficiently supported by the evidence. This review suggests that a new belief structure may be more productive than previous ones.

• Program focus. With a multitude of influences and management efforts related to fish and wildlife in the Columbia River basin, especially salmonids, identification of positive results from actions derived specifically from the Council's Fish and Wildlife Progam is difficult. There are factors beyond human control, such as cycles of ocean productivity and temperature (El Nino), management of harvest rates outside the Program, and programs funded by other agencies (such as the Corps of Engineers) that affect total populations but may not be fully integrated into the Fish and Wildlife Progam (Northwest Power Planning Council, 1992). Assigning credit for accomplishments is not just an administrative exercise, for it is germane to estimating whether specific actions have been effective and which have not.

• Observation vs. analysis. Sufficiency of numerical fish counts for evaluating overall Program success is questionable. Although the Fish and Wildlife Progam goal is stated simply as a doubling of runs, what and where to measure is not straightforward. Observational methods are insufficient without analytical methods that use these data in population-level models to estimate trends and correlations with environmental factors (Monitoring and Evaluation Group of the Northwest Power Planning Council, 1988). Analytical methods build upon numerical observations to increase information content by integrating environmental indices, research results and monitoring data into mathematical expressions that are hypotheses for explaining trends in observational data. But the critical question of what constitutes the population to be modeled remains to be determined.

• Index life stage(s). The point in salmonid life cycles that counts should be made to best represent success is uncertain (Monitoring and Evaluation Group of the Northwest Power Planning Council, 1988). Counts of juvenile emigrants has the appeal of being a rapid and direct measure of the effects of many Fish and Wildlife Progam actions in the freshwater part of the life cycle. This avoids survival problems in the ocean over which the Fish and Wildlife Progam has no control and the delay to maturity of up to five years in the case of chinook salmon. Yet smolt monitoring has logistical difficulties, it contributes to a continued fragmented approach, it fails to consider smolt quality, and tells only part of the salmonid story. In lieu of direct counts, however, there is the opportunity to use various smolt indices, such as those collected by the Fish Passage Center. Adults are seen as a better "bottom line" for evaluation, but it is difficult to separate the effects of Program actions from other factors. MEG recommended four indices: (1) a measure of annual juvenile production, (2) an estimate of annual adult equivalent production, (3) a life-cycle analysis of stock productivity, and (4) a program to monitor genetic effects of management actions.

• Analytical tools. The best analytical tools are not evident. Statistical methods can be used to discern relationships between variables such as run size and flow during emigration. A life-cycle approach uses a computer model as a conceptual basis for explaining trends displayed by the observational indices. Each has its appropriate uses and drawbacks (Monitoring and Evaluation Group of the Northwest Power Planning Council, 1988). MEG concluded that, because no single measure of Program progress could be found to identify effects of the Program from non-Program effects, either existing or that could be developed, the effects would have to be isolated by analytical methods such as life-cycle models. Thus was spawned a flurry of models by different agencies aimed at integrating all of parts of the life cycle (CRiSP, FLUSH, SLCM). Recent evaluations of alternative life-cycle models indicates that they are very sensitive to initial assumptions ("belief systems") and that, as such, they can be better used to frame and test hypotheses (different beliefs) than to make predictions about the future (Barnthouse et al., 1994). This weakness of models is often overlooked in the search for an objective means of selecting management options.

• Experimental design. The costs of monitoring can exceed benefits unless attention is paid to the likely use of information. Monitoring can be seen as an "experiment" in which key information is needed to verify (or not) certain hypotheses (although it is not really an experiment but a way of obtaining information useful in testing hypotheses). The hypotheses can be coded in the life-cycle models. MEG (1988) proposed monitoring of subbasin plans and specific additional research to fill gaps. An important issue is how to maintain long-term data collections (often extending for 30 years or more) while also focusing on key parameters that need valuation for population models.

• Information system. Coordination and organization of large amounts of monitoring information are as important as the program to collect it. The information must be made available to decision makers in a timely and effective manner. This factor was recognized in the 1987 Program {§ 206(d)(C)} and a Coordinated Information System (CIS), now called StreamNet was implemented. Items for CIS attention were not just data archiving, but documentation of data sources, procedures and quality; consistency of data collection to ensure comparability of data sets; and development of ways to communicate data and analytical results in a timely and clearly understandable way.

Hard-copy reports often have been inadequate for effective adaptive management. Although BPA publishes progress and final reports, there is often a lag of several years between completion of the manuscript by the authors and the actual publication date (as indicated by the date given with the document number on the back cover). The publication mechanisms have lead to information being unavailable, not provided in a timely manner, provided by informal routes susceptible to misinterpretation, and with a variety of citation formats. The Fish Passage Center provides weekly reports of smolt monitoring data and relevant management actions that are mailed to those who request them.

Recent availability of the World Wide Web on the Internet has opened the way for rapid communication of monitoring data on demand. For example, the Corps is now placing daily fish count and environmental data from its projects on the Web. Others, such as the University of Washington, have life cycle models (CRiSP) on its Web site. An emerging issue is how to make effective use of this new mode of accessibility for data and analytical tools.

• Effective adaptive management. Monitoring and evaluation are justified as being needed for "effective adaptive management." The reality is, however, that we have few documented examples of adaptive management. Until examples are collected and discussed, the skeptics with regard to adaptive management will remain reluctant to test and use it. McConnaha and Paquet (*in press*) have summarized adaptive strategies for management of ecosystems in the perspective of the Columbia River experience.

• Overall assessment of monitoring and evaluation. The bottom line is whether the monitoring and evaluation portion of the Fish and Wildlife Progam is providing an accurate and thorough scientific basis for actions that improve salmon populations. The key criterion by which the effort is judged is whether salmonid stocks improve. They have not. Monitoring and evaluation of a downward spiral in fish numbers signals that we did not learn enough from the data collection and analysis to reverse the trend of decline.

Monitoring of fish populations

Monitoring of fish migrations has been part of the Fish and Wildlife Progam from the outset to provide information on the migrational characteristics of the various stocks of salmon and steelhead with in the Columbia Basin. This program has included monitoring of adults passing through fish ladders, index counts of redds in spawning areas, and monitoring of outmigrating juveniles principally at dams. The monitoring was not initiated with the Fish and Wildlife Progam, but was a continuation, extension and refinement of adult counting conducted by dam operators and state agencies at fish ladders, redd counting by agencies, and other monitoring programs. The emigrant monitoring effort has been standardized and coordinated in recent years by the Fish Passage Center of the Columbia Basin Fish and Wildlife Authority. Considerable effort has been made to shift smolt monitoring from a role of merely documenting numbers for the historical record to one of rapid data processing so that the numbers can be used during migrations for management purposes, such as adjusting river flows with the intent of assisting peak migrations.

We reviewed the process of monitoring and the evaluation of monitoring data and we examined the development of techniques for monitoring, the types and intensity of monitoring in the basin, and the ways data are handled and evaluated. We concentrated on monitoring of juveniles, as the dam-counts of adults is standardized and familiar. Results of monitoring to date, such as trends in fish numbers, are discussed in Section III and elsewhere in this report.

Historical Record

The Fish and Wildlife Program is documenting the historical record of salmonids and their habitats in the Columbia River basin. The federal Bureau of Fisheries (now the National Marine Fisheries Service) conducted stream habitat surveys in parts of the basin from 1934 to 1942. These surveys were intended to cover streams in the Columbia River Basin that provided, or had provided, spawning and rearing habitat for salmon and steelhead to evaluate their condition, availability and usefulness for migration, breeding, and rearing of migratory fishes (Rich 1948). Most of the quantitative records of those surveys had been lost. Surviving material consisted of summaries or brief, qualitative accounts (Rich, 1948; Bryant, 1949; Bryant and Parkhurst, 1950; Parkhurst, 1950; Parkhurst, 1950). Despite their brevity, these summaries have formed the basis for estimating habitat losses and conditions in the Columbia River Basin (Fulton, 1968; 1970; Thompson, 1976; Northwest Power Planning Council, 1986).

Recently, field notebooks from the early fishery surveys were discovered. The data are now archived and stored in the Forest Science DataBank at Oregon State University and have been published as exact replicates of the originals as part of the Fish and Wildlife Progam. The habitat surveys include the Umatilla, Tucannon, Asotin, and Grande Ronde river basins (McIntosh et al., 1995), the Clearwater, Salmon, Weiser, and Payette river basins (Mcintosh et al., 1995), the Willamette River basin (McIntosh et al., 1995), the Cowlitz River basin (McIntosh et al., 1995), and the Yakima River basin (McIntosh et al., 1995). These records, as noted by the compilers of the present publications, are the earliest and most comprehensive documentation available of the condition and extent of anadromous fish habitat before hydropower development in the Columbia River Basin. They are unique because they are the only long-term data set that quantifies fish habitat in a manner that is replicable over time. Other surveys, such as Thompson and Haas (Thompson and Haas, 1960) inventoried extensive areas but in a manner that was mostly qualitative. Knowledge of past and present quantity and quality of habitat for anadromous fishes is essential to efforts to enhance fish populations. Habitat condition has to be recognized as a key element in monitoring and evaluating progress toward the Council's restoration goals.

The data sets include detailed information on the character of the watershed and station, marginal vegetation and extent of erosion, elevations and slopes, observed flows and fluctuations, water and air temperatures, pool and riffle characteristics, character of the bottom, areas available that were suitable and unsuitable for spawning, obstructions, diversions, pollution, fish observations (redds, run sizes and timing, juvenile rearing), non-salmonid fish observed, extent of sport fishing, and miscellaneous field observations and opinions of the surveyors.

Stock Summary Reports

Under the Columbia River Coordinated Information System (CIS), the Fish and Wildlife Progam has attempted to compile summaries of tributary stocks of salmonids in the river basin. Draft, hard-cover reports were published in 1992 and the material is stored in retrievable electronic form at the CIS offices at the Columbia River Inter-Tribal Fish Commission (Hymer, 1992; Hymer, 1992; Kiefer et al., 1992; Olsen et al., 1992; Olsen et al., 1992). The CIS effort to develop stock summaries of major tributaries is a valuable guide to information that is available. Many of the stocks for which information has been compiled have not been systematically monitored but have scattered records. In the sections that follow, we have concentrated on stocks with long-term records or current studies that are specifically part of the Fish and Wildlife Progam.

Use of Passive Integrated Transponder (PIT) fish tags

Adaptation of passive integrating transponder (PIT) tags for fisheries applications (Prentice, 1990) has been a major advancement in smolt monitoring. These are small electronic packages (about the size of a grain of rice) that are inserted into a fish's body cavity. They are programmed with a unique code that is matched to information such as tagging date, location, fish size, and other information. This code is formatted in a tiny radio-frequency transmitter. The PIT tags can be detected and the code "read" at any later time and location by a radio transmitter-receiver that, when placed near the fish, energizes the tag, causes it to send its information, and records it. PIT tags have been developed for fish monitoring over the past decade at the National Marine Fisheries Service, Northwest Science Center, Seattle, largely with funding through the Fish and Wildlife Progam.

Detectors have gradually been added to the fish bypass systems at Snake River and mainstem dams. Currently, full-service PIT-tag detectors are in place at Lower Granite, Little Goose, Lower Monumental, and McNary dams. There is currently the ability to detect at the John Day gatewell site, also. This is a monitoring point that has existed for many years. A single gatewell is sampled via an airlift pump. All fish sampled in this facility are checked for PIT tags. The sample rate, however, is very low and so it is of limited value compared to the other sites.

Development of fish-migration information from PIT-tag detections at dams is complex. Not all fish are guided away from turbines and into bypass systems, and the proportion that are guided varies with flow, time of day, and degree of smoltification of the migrating fish (Giorgi et al., 1988). Numbers of fish detected can be corrected to give an estimate of total numbers by use of a fish guidance efficiency for the particular dam's configuration of turbine screens and bypass system. Release of water at a dam's spillways (spill) further reduces the percentage of fish, including those tagged, that pass through the fish-bypass detectors. Spill does not affect fish guidance efficiency at the turbine; spill does affect the fish passage efficiency, however. This is the proportion of fish approaching the project that pass by means other than through the turbines. The volume of water spilled, both mandated spills during low flows and involuntary spills during high flow times, must be taken into account when the fish guidance efficiency is calculated for the time of collection.

Because some PIT-tagged fish that are not detected at one dam (for the above reasons) could be detected at the next dam, and also possibly at one or more dam detectors thereafter, detection totals, percentages, and timing need to be calculated thoughtfully. An experiment has been underway for three years at Lower Granite Dam to test several statistical models to relate different combinations of detection to location and timing of releases of specially marked fish (Iwamoto et al., 1994; Muir et al., 1995; 1996). This study followed a detailed evaluation of statistical methods for estimating smolt survival (Dauble et al., 1993) and consultation of state-of-the-art statistical documents (Burnham et al., 1987). The study has, with great attention to detail, field tested and evaluated the single-release, modified single-release, and paired-release models for estimating survival probabilities of migrating juvenile salmonids, identified operational and logistical constraints to collection of data for the models, and collected some useful information on smolt travel time and survival under the extant river conditions and dam operations. Although the statistical procedures have been questioned, a separate peer review led by the ISG established that the methods, though not perfect, are the best available and are appropriate for obtaining survival estimates (Independent Scientific Group, 1996).

The Snake River monitoring experiment (Iwamoto et al., 1994; Muir et al., 1995; Muir, 1996) has incrementally obtained information of immense value to future monitoring efforts. Nonetheless, it has limitations. Estimates of survival from this study can be made only for specific reaches of the river. A problem with mixing of fish in the river has not yet been overcome (fish under the single release model seem to mix satisfactorily, however fish released under paired or multiple releases do not always mix as well). In 1993, only hatchery yearling chinook salmon were tested over a fraction of the migration period. In 1994, the research was expanded to include releases of wild yearling chinook salmon and hatchery steelhead. The 1994 studies covered a longer duration of the migration period and a greater length of the Snake River. Primary release sites for test fish were in the Snake River about 37 km upstream of Lower Granite Dam (this simulates fish coming downriver from upstream PIT-tagging operations at index traps and in tributaries; e.g., (Achord et al., 1995; Buettner and Brimmer, 1995). Test fish also were released in forebays, turbine intakes, collection channels of juvenile bypass facilities, and bypass flumes (downstream of the PIT-tag detectors) to quantify effects within portions of the dam and bypass system. While the NMFS studies appear to provide a good means of assessing reach survival, they only address a limited portion of the river system currently covered by PIT tag detectors and so answer only a portion of the overall problem. Fully instrumenting the river system is needed and require a major commitment of funds and effort.

Use of marked fish for monitoring and estimating in-river timing and survival is made more complicated by the fish transportation system in place on the Snake River. Transportation normally collects downstream migrants at upriver dams (Lower Granite, Little Goose, and Lower Monumental) and barges or trucks them to the river below Bonneville Dam (see section of this report dealing with transportation). All bypassed (and thus PIT-tag-detected) fish would, under this scenario of operations, be transported and thus not available for PIT-tag detection at downstream dams. The obstacle that fish transportation would thus present to information gathering has caused bypasses to be equipped with slide gates to selectively return PIT-tagged fish to the river to continue their migration and allow for multiple dam detections (Muir et al., 1995). Currently, transport does not appear to affect PIT tag studies because of this ability to put PIT-tagged fish back in the river and not transport them. Alternatively, detectors at the bypasses can account for those tagged fish that were transported.

The Snake River monitoring experiment has shown that assumptions of the single-release and paired-release models are generally satisfied (Iwamoto et al., 1994; Muir et al., 1995; 1996). Detection of fish at an upstream site did not influence the probability of its subsequent detection downstream or its survival. Fish mixed across the river downstream of a dam as expected. There was no significant mortality after a fish was detected and its remixing with fish using other passage routes. Thus, the single-release model was deemed appropriate for estimating survival probabilities for the primary release groups. A surprising result of these detailed monitoring trials has been quantification of survival much higher than estimated in earlier years (Raymond, 1979) and relatively little mortality in Lower Granite Reservoir (Muir et al., 1995). Based on the 1993 and 1994 research, it is anticipated that existing models can be used with selective tagging and releases to make precise estimates of juvenile salmonid passage survival through individual river sections, reservoirs, and hydroelectric projects in the Columbia and Snake rivers.

A monitoring program is being developed to detect PIT-tagged adults returning to the basin (Newman, 1995). Lower Granite Dam is the sole facility on the Columbia River system that possesses a PIT-tag detector for returning salmon and steelhead. Because of small sample sizes so far, the work has concentrated on *how* to analyze returns, with emphasis on statistical approaches. PIT tags have been implanted in juvenile wild and hatchery emigrants since 1985, with the first substantial numbers released in 1987, primarily to assess their emigration and survival (see monitoring of downstream migrants, below). Detections of adults at Lower Granite Dam have begun, and the data are stored in the PTAGIS2 information system maintained by the Pacific States Marine Fisheries Commission. Adult PIT-tag returns will be important to monitor to evaluate the river conditions that not only provide for downstream passage but ultimate survival of spawning adults.

Spawning Stocks

1. Hanford. The Hanford reach of the Mid-Columbia River has been monitored annually for spawning fall chinook salmon ("upriver brights") since 1948 (Dauble and Watson, 1990). Aerial redd counts have been made in the 90-km reach between Richland, Washington and Priest Rapids Dam to provide an index of relative abundance among spawning areas and years. They have also documented the onset of spawning and intervals of peak spawning activity. This monitoring has documented a dramatic increase in returns of fall chinook to Hanford reach in recent years. The relative contribution of this stock to fall chinook runs in the Columbia River increased from about 24% in the early 1980s to 50-60% of the total in the late 1980s. Estimated numbers of visible redds ranged from a low of 65 in 1955 to a high of 8630 in 1987. Aerial counts have limitations due to visibility, so it is believed that a large, but unknown, proportion of total redds are not detected.

2. Snake River Spring/summer chinook salmon index stocks. An ad hoc, interagency Biological Requirements Work Group (Biological Requirements Work Group, 1994) evaluated Snake River spring/summer chinook salmon stocks to identify which ones had been monitored sufficiently well that data are available on spawning adults for developing historical population profiles. Populations within the Snake River metapopulation consist of about 40 breeding units from 11 river systems that are more-or-less discrete and segregated temporally and/or geographically, based on a NPPC presence/absence database. Eight index rivers and stocks were identified by the BRWG (1994), and are briefly presented below. Spawner and recruit data for index stocks consist of time series of indices for spawning escapements (redd counts) and age composition of spawners. Time series for the index stocks include observations from the 1950s and 1960s to the present.

a) Minam River, tributary to Grande Ronde River (spring chinook). The data series includes 1954-1993 (and continuing) redd counts, adult age composition from carcass surveys, and scale analyses to determine hatchery/natural origin. Monitoring has been according to the Grande Ronde Subbasin salmon and steelhead production plan (Oregon Dept. of Fish and Wildlife, 1990). The Minam River is managed for native stock but stray hatchery fish from nearby Lookingglass Hatchery (upstream of the Minam River) have been recovered on the spawning grounds. The drainage is mostly in wilderness and contains excellent quality spawning and rearing habitat.

b) Lostine River, tributary to Grande Ronde River (spring chinook). A 1954-1993 data series is available (and continuing). Monitoring has been according to the Grande Ronde Subbasin salmon and steelhead production plan (Oregon Dept. of Fish and Wildlife, 1990). The river characteristics are similar to the Minam, although there is localized riparian and instream habitat degradation from grazing.

c) Catherine Creek, tributary to Grande Ronde River (spring chinook). Monitoring has been according to the Grande Ronde Subbasin salmon and steelhead production plan (Oregon Dept. of Fish and Wildlife, 1990). No data are presented in BRWG (1994).

d) Mainstem Imnaha River (spring/summer chinook). A data series 1952-1993 (and continuing) includes redd counts, adult age composition, from carcass surveys, and scale analyses to determine hatchery/natural origin. Monitoring has been according to the Imnaha River Subbasin salmon and steelhead production plan (Nez Perce Tribe, 1990). The riverine habitat is relatively pristine with headwaters in wilderness. Both hatchery and wild fish are present, but hatchery contributions are accounted for (Biological Requirements Work Group, 1994).

e) Marsh Creek, tributary to Middle Fork Salmon River (spring chinook). Redd counts and adult age composition from carcass surveys are available 1957-1993 (and continuing). Monitoring has been part of the Lower Snake River Compensation Plan. The entire Middle Fork Salmon River is managed for wild, native spring/summer chinook salmon and steelhead (Kiefer et al., 1992). Overall habitat quality in Marsh Creek is good, although cattle grazing occurred until 1993. High quality habitats occur in most tributaries.

f) Bear Valley/Elk creeks, tributary to Middle Fork Salmon River (spring chinook). A 1957-1993 (and continuing) data set exists for redd counts and adult age composition from carcass surveys. Monitoring has been part of the Lower Snake River Compensation Plan. Major habitat impacts from grazing, mining, and logging have been reduced through habitat improvement projects of the Fish and Wildlife Progam (Andrews and Everson, 1988). The entire Middle Fork Salmon River is managed for wild, native spring/summer chinook salmon and steelhead (Kiefer et al., 1992).

g) Sulfur Creek, tributary to Middle Fork Salmon River (spring chinook). The data series covers 1959-1993 (and continuing) for redd counts and adult age composition from carcass surveys. This is a wilderness drainage with excellent riparian and instream habitat, although there are occasional stray cattle.

h) Poverty Flats area, tributary to the South Fork Salmon river (summer chinook). A data series 1957-1993 (and continuing) is available for redd counts and adult age composition from carcass surveys. Monitoring has been part of the Lower Snake River Compensation Plan. The South Fork Salmon river is managed for natural and hatchery summer chinook and wild steelhead (Kiefer et al., 1992). The Poverty Flats area is located 13 miles downstream from the McCall Hatchery weir, but appears to be minimally affected by dropout of unmarked hatchery spawners. The drainage has been degraded through erosion and sedimentation but there has been subsequent rehabilitation since 1966 (Megahan et al., 1980). Complete habitat recovery has not occurred.

Tributary Production

Certain monitoring and evaluation projects were established in the Program by tributary basins to monitor natural production of anadromous fish, evaluate habitat improvement projects under the Program, and develop a record for off-site mitigation projects.

1. Stanley Basin (Idaho) Sockeye Salmon. The Idaho Department of Fish and Game and the Shoshone-Bannock Tribe established a sockeye salmon monitoring program for historically important salmon spawning and rearing areas in the Stanley Basin in 1991 (Kline, 1995). The program has several objectives. One is to estimate, annually by age class, the population size, density, and biomass in four Stanley Basin lakes (Redfish, Alturas, Pettit, and Stanley). Another is to evaluate emigration characteristics of smolts from two locations (Redfish and Alturas lakes) including run sizes and the travel time and survival of PIT-tagged fish to lower Snake River dams. A third is to establish location and timing of spawning for natural salmon production in Redfish and Alturas lakes. The program also includes work of a less monitoring nature, including estimates of predator populations and determination of the origin of Stanley Basin sockeye salmon through otolith chemistry.

The recent Stanley Basin monitoring efforts follow a history of fragmented data collection at these sites that partially document the ups and downs of the stock (Kline, 1995). In the late 1800s, Evermann (Evermann, 1895) made observations on the presence and abundance of sockeye salmon in the Stanley Basin lakes. Parkhurst (1950) recorded the return of sockeye salmon to Redfish Lake in 1942 after decades of local extirpation by small dams. Bjornn et al. (1968) presented the most thorough assessment of Redfish Lake sockeye salmon for the period of 1954 to 1964. Chapman et al. (1990) recount the history. Hall-Griswold 1990 chronicled Redfish Lake spawners in the 1980s.

2. Crooked River/Upper Salmon River. One monitoring and evaluation project involves spring chinook salmon and summer steelhead in the Crooked River and upper Salmon River in Idaho (Kiefer and Lockhart, 1995). There, the Idaho Department of Fish and Game (1) estimates egg deposition using weir counts, redd counts, and carcass surveys, (2) uses parr counts developed by snorkeling and stratified random sampling to estimate parr abundance and egg-to-parr survival, (3) PIT tags representative groups of parr and uses PIT-tag detections at the lower Snake and Columbia river smolt-collecting dams to estimate parr-to-smolt survival, and (4) used adult outplants into tributary streams to estimate carrying capacity. The agency uses these data to (1) estimate parr production attributable to habitat projects, (2) quantify relationships between spawning escapement, parr production, and smolt production, and (3) use smolt production as a basis for assessing habitat improvement benefits. Habitat features that may relate to smolt productivity include substrate, riparian vegetation, and channel quality.

3. Umatilla River Basin. The Umatilla River basin salmonid resources are monitored by the Confederated Tribes of the Umatilla Reservation (Conf. Tribes of the Umatilla Indian Reservation, 1995). Monitoring and evaluation are part of Umatilla River Basin Fisheries Restoration Plan to rehabilitate runs in this heavily impacted basin that had once had abundant summer steelhead and spring chinook salmon (Conf. Tribes of the Umatilla Indian Reservation, 1984; Oregon Dept. of Fish and Wildlife, 1986). Irrigation and agricultural development throughout the basin in the early 1900s is believed to be the primary causes for decline of steelhead and extinction of chinook salmon. Results of watershed enhancement and rehabilitation, hatchery construction and operation, juvenile and adult passage facilities, holding and release facilities, trapping and hauling of fish around irrigation-dewatered reaches, and flow augmentation actions are being monitored and evaluated. Three phases of monitoring and evaluation have been established: (1) collection of baseline data relating to life histories, distribution, abundance, survival, natural production, habitat, and production potential of salmonids; (2) intensive adaptive management and the development of a streamlined monitoring program using the results of phase 1, and (3) risk-containment monitoring after the major remaining risks are identified. Phase 1 (baseline data collection) is in operation 1992-1997. Phases 2 & 3 are scheduled to begin intensely in 1997 and 2004, respectively. Results have been published only for the 1992-1993 season.

Downstream Migrants

1. Basinwide Smolt Monitoring Program. Downstream migrants are monitored primarily through the Smolt Monitoring Program (SMP) coordinated by the Fish Passage Center of the Columbia Basin Fish and Wildlife Authority (and mandated by the 1994 Program, § 5.9A). The SMP is overseen by a peer review group, the Fish Passage Advisory Committee. The SMP is a major component of the Fish and Wildlife Progam and has been a part of the Council's program since its inception in 1982. The SMP has undergone a series of changes since its inception. Since the 1987 version of the Program, the SMP has focused on monitoring characteristics of the smolt migration for in-season water management and post-season analysis of smolt movement in relation to runoff conditions. Monitoring data are collected at three dams on the Snake River, three dams on the lower Columbia River, one dam on the mid-Columbia, and at five river trap sites on the Snake River and tributaries.

The SMP consists of five major projects, each of which contain several specific projects. The five major projects are: Project 85-323 which funds Idaho Department of Fish and Game to operate the Lewiston, Clearwater , and Salmon River taps and to tag salmon and steelhead at these traps; Project 84-014 which funds NMFS to collect samples of fish at John Day and Bonneville dams; Project 87-401 which funds the USFWS to collect information on smoltification and the prevalence of disease for marked groups of salmon and steelhead used in the SMP and to develop an index of smolt condition for real-time use in water management and evaluation; Project 87-127 which funds smolt monitoring at Rock Island Dam, tagging of fish at Idaho hatcheries, tagging and monitoring at Lower Granite Dam by WDFW, tagging and monitoring at McNary Dam and the Hanford Reach by WDFW, monitoring at Lower Monumental Dam by WDFW, tagging and monitoring at Little Goose Dam by ODFW, tagging in the Grande Ronde and Imnaha rivers by ODFW, and monitoring in the Imnaha by the Nez Perce Tribe; and Project 91-029 which funds NMFS to tag spring/summer chinook parr in their natal streams in Idaho and monitor their emigration as smolts. These projects are discussed in more detail below.

We concluded a review of the SMP in March 1995 (Independent Scientific Group, 1995). From a programmatic standpoint, the ISG found the program to be well operated and to have relatively clear goals and objectives. Several recommendations were made to improve the scientific content of the program. These included (1) establish closer contact with data users to review kinds of data collected and technologies for getting them; (2) review and possibly adjust the sampling rates and numbers of fish collected to meet scientific objectives; (3) provide similar quality control among sites; (4) reevaluate the number of monitoring sites to meet program needs; (5) determine ways to minimize handling of fish, especially weak stocks, at collector dams; (6) increase evaluation efforts to find relationships among survival, travel time, and various river and operational variables; (7) reexamine the Fish Passage Index and alternative measures for utility for fish and water management decisions; (8) identify promising new monitoring technologies for study and potential application; and (9) improve communication among monitoring staff and researchers about the overall goals of the program and to generate useful feedback for planning.

2. Snake River Basin Above Lower Granite Dam. One goal of monitoring is to characterize the emigration timing and pattern of different wild stocks from spawning tributaries of the Snake River basin and to relate migration timing to environmental factors (Achord et al., 1995). Before 1989, data on the timing of individual populations of wild fish as they passed through the lower Snake River were limited. Raymond (1979) reported timing of smolts (mostly wild) arriving at Ice Harbor Dam from 1964 through 1969, based on gatewell sampling by the Bureau of Commercial Fisheries (predecessor of NMFS). The migration period spanned early April through mid-June, with peak migrations varying from late April to late May. Raymond (1979) distinguished between timing of individual tributary populations from Eagle Creek, and Imnaha, Grande Ronde, and Wallowa rivers in Oregon and the Lemhi and East Fork of the Salmon rivers in Idaho using marked fish. Sims and Ossiander (1981) summarized migrations of juvenile chinook salmon and steelhead in the Snake River from 1973 to 1979. Lindsay (1986) monitored wild smolts from the John Day River as they entered John Day Dam from 1979 through 1984. Although patterns of migration were evident, sample rates for individual tributaries were low at the dams and the results were unsatisfactory.

Achord et al. (1995) reviewed Raymond's unpublished field notes and data to determine if there was unpublished material of value for present questions. They concluded that his results do not provide the scope or precision that is currently required. Individual tributary populations received minor attention. Methods were primitive by today's standards. The marking methods (hot brands, alcohol/dry ice and liquid nitrogen cold brands) used to mark small parr in the fall would not have produced many marks identifiable the following spring. Marked fish were not representative of the entire stream population, and numbers were low. As hatcheries in the basin became operational, branded hatchery fish recaptured at index traps and dams provided much of the migration data.

To provide information on smolt movement prior to arrival at the lower Snake River reservoirs, the Idaho Department of Fish and Game (IDFG) has monitored the daily passage of smolts at the head of Lower Granite Reservoir since 1988 (Buettner, 1991; Buettner and Brimmer, 1993; Buettner and Brimmer, 1995). Three locations are used for trapping fish for counting and marking. A Snake River trap is located approximately 40 km downstream from the interstate bridge between Lewiston, Idaho and Clarkston, Washington (see Figure 1 of Buettner 1991). This location is at the head of Lower Granite Reservoir, 0.5 km upstream from the confluence of the Snake and Clearwater rivers. The exact location of the trap was established based on information from radiotelemetry of juvenile steelhead which suggested a significant proportion passed the specific trap site (Liscom and Bartlett, 1988). A Clearwater trap is installed 10 km upstream from the convergence of the Clearwater and Snake rivers. It is 4.5 km upstream of slack water in Lower Granite Dam at normal pool elevation. A Salmon River trap is installed 1.6 km downstream from the White Bird Gauge, 86.6 km upstream of the confluence with the Snake River.

The IDFG monitoring project collects data on daily fish numbers, relative species composition, hatchery and wild ratios, travel times and migration rates. It applies freeze-brands and PIT-tags for subsequent detection of juvenile migrants at the Snake River trap, Lower Granite Dam, and subsequent Snake and Columbia River dams with detectors (and of adults returning past Lower Granite Dam when adult detectors are in place). It provides a detection site at the Snake River trap for PIT-tagged smolts, marked on other projects, at the end of their migration in a riverine environment and at the beginning of their migration in reservoirs. Water temperature and turbidity are measured at each trap daily. River discharges were available at nearby USGS gauges and at Lower Granite Dam for correlation with fish movements.

NMFS began a cooperative study with the U.S. Army Corps of Engineers in 1988 to PIT tag wild spring and summer chinook salmon parr for transportation research. This project continued through mid-1991. Tagged emigrating smolts were monitored during spring and summer 1989-91 as they passed Lower Granite, Little Goose, and McNary dams where readers were installed in the fish bypass systems (Matthews et al., 1990; Achord et al., 1992; Matthews et al., 1992). The study allowed evaluation of the juvenile fish collection, transportation, and bypass facilities; e.g., (Monk et al., 1992). Aside from the transportation applications, these studies demonstrated that timing of various stocks through Lower Granite Dam differed among streams and also differed from patterns for hatchery fish (Achord et al., 1995). Generally, the emigrations of wild spring chinook salmon were later and more protracted than for hatchery fish, and timing patterns were variable over the three years. Summer wild chinook salmon were, conversely, earlier than hatchery fish, although also more protracted.

From the summer of 1991 to the present, the PIT-tag monitoring program on the Snake River by NMFS has been funded by Bonneville. However, only one report, covering 1991 tagging and 1992 detections, has been issued (Achord et al., 1995). Wild spring and summer chinook salmon were collected by seining and electrofishing and PIT-tagged in July to October from areas of know high parr concentrations in 13 streams in Idaho and 3 streams in Oregon. Surviving PIT-tagged fish migrated volitionally through the hydroelectric complex of the Snake and Columbia rivers. Of eight dams passed, three were equipped with complete smolt collection and PIT-tag monitoring systems in 1992: Lower Granite, Little Goose, and McNary. At collection dams, all smolts guided away from the turbine intakes and into juvenile bypass systems are electronically interrogated for PIT tags as they pass through the system. All detected data are transferred daily to a computer operated in Portland, Oregon by the Pacific States Marine Fish Commission.

3. Lower Snake River. One of the critical questions regarding juvenile emigrants that has emerged over the past two decades is the relationship between river flow and migration speed in the lower Snake River, which is presumed to indicate better survival at higher flows. Monitoring by NMFS first provided evidence that rate of migration through certain segments of the Snake and Columbia rivers was influenced by prevailing discharge volumes (Giorgi, 1993). NMFS investigators measured and reported indices of travel time for the period 1973 through 1983 (Sims and Ossiander, 1981; 1984), with their last synthesis including data acquired only through 1982 (Sims et al., 1983). The Fish Passage Center has continued to add to this smolt travel time data set since 1984. Their most comprehensive synthesis was published in the open literature (Berggren and Filardo, 1993). The gradual accumulation of data for years of different flows during the main yearling smolt migrations is showing an increase in travel time through the lower Snake River with lower flows. There is little change at flows above about 80-100 cfs but a major slowing of movement as flows decline below this level. Confidence in these results has been impaired by the relatively small number of data points at lower flows, although the drought of the early 1990s has added more important data.

Smolt survival estimates initially accompanied NMFS annual calculations of smolt travel times, and continued through the 1960s, most of the 1970s, and early 1980s (Giorgi, 1993). Tha annual system survival estimates, or indices, represented overall smolt survival from the upper dam on the Snake River where marked fish were released to a lower Columbia River sampling site, usually John Day or The Dalles dams. The indices represented the combined effects of reservoir residence and dam passage. Results seemed to reflect the travel time estimates (Sims et al., 1983). The reliability and relevance of these survival estimates (especially lack of statistical properties) was questioned in the early 1980s, and travel time replaced survival as the key performance measure for juvenile passage.

Moving more toward evaluation than direct monitoring is the estimation of reservoir mortality. During the late 1980s, the fisheries community suggested that estimates of reservoir mortality would presumably reflect mortality associated with the speed of migration, apart from direct dam passage effects (Giorgi, 1993). Dam passage mortality depended upon the route of passage, which has been estimated at representative sites, whereas reservoir mortality is difficult to determine. Thus, standard estimates of passage-route-specific dam mortality were used to subtract dam mortality from system survival estimates from 1970, 1973-79, and 1980 to yield reservoir mortality estimates apportioned evenly throughout the system on a per-mile basis (McConnaha 1990). These methods have been criticized as not being consistent with actual data collected by Raymond (1974), for example (Giorgi, 1993). Rather than being informative, these estimates have hidden the important details regarding the location and magnitude of mortality in reservoirs, the mechanisms causing smolt mortality, and thus the opportunities for correcting specific mortality problems.

Adult returns have been used as measures of flow effects, as another way to evaluate monitoring data, especially for the lower Snake River (Petrosky 1993). Annual numbers of adults in index populations in Marsh Creek and Rapid River have been compared to yearly emigrant river flow for several years. Because of the numerous covariates with flow such as spill (known to be more benign than turbine passage), these estimates have little power to establish flow, per se, as the cause of mortalities (Giorgi, 1993). Remedial measures might better be aimed at increasing spill, even in low-flow years, than at augmenting flow.

Monitoring of Environmental Data

Efforts to correlate salmonid migration behavior and other population features with environmental variables has been made difficult by lack of environmental monitoring. Achord et al. (Achord et al., 1995) reported that many of the formerly active hydrological stations of the U. S. Geological Survey (USGS) used to record flow information in the upper Snake River basin were no longer operational. No continuous water temperature information was available from any of the five operational USGS sites. Our review found that habitat variables are generally not well monitored. Rather than dwell on specific deficiencies of the current program, we concentrated our review on environmental features that need to be monitored under a new paradigm, the normative river.

New Metrics for the Normative River and Ecosystem

An integrated ecosystem monitoring and evaluation program with emphasis on suitable habitat is badly needed, in addition to monitoring of fish. In Chapter 5 we describe how habitats have been degraded in spawning and rearing areas by various land uses such as logging, mining, agriculture (including riparian grazing) and urbanization. We also describe mechanisms, such as reregulation of hydrographs to allow period flooding, to restore habitat and to provide enhanced salmonid food production that occurs during periods of high water. We have also shown that dams and reservoirs can be built and operated in ways that can better simulate the natural habitat of salmonids and thus foster increased survival. Monitoring of quantity and quality of available habitat and utilization of habitat by various stocks is essential to the objective of conserving or increasing the productivity of each life history stage.

However, uncertainty exists as to what constitutes quality habitat. We mapped and qualitatively evaluated major alluvial reaches of the Columbia River system that most closely match reaches of known high productivity (e.g., the Hanford Reach, Figure 2.6). (Map of alluvial reaches was unavailable in a form suitable for this publication at time of printing) Some of these appear to be reasonably intact and potentially functional, others are degraded. Nonalluvial, constrained reaches also must support migrants during their passage. A more precise inventory of habitat types is needed and coupled with research that demonstrates a suite of variables that can be used to describe habitat quality (McCullough and Espinosa, 1996). Considerations include:

- the degree of channel and flood plain connectivity via surface and groundwater pathways
- locations of groundwater influent or upwelling
- availability of microhabitat types (e.g., deep pools, shallow riffles, undercut banks, point bars, eddy bars, back bar channels and other slack water environments)
- availability of flow cues, such as turbulence and wave phenomena, as well as thalweg flow
- substratum size distribution, including woody debris
- suspended and deposited fine particulate inorganic and organic matter
- water quality conditions (baseline; point and nonpoint pollution sources)
- riffle and slack water food web conditions and community ecology (e.g., indices of biotic integrity including species composition, forage and predatory categories, production rates; percent non-natives)
- riparian conditions (e.g., successional state, species composition; percent canopy; production rates; indices of grazing use and resilience to grazing; percent non-natives; seasonality of flooding).

Best management practices (e.g., reregulation of flows; forestry and riparian grazing prescriptions, pollution abatement; crop rotation) have been fostered to reduce habitat degradation but few if any of these practices have been empirically (experimentally) evaluated. They need to be examined in terms of habitat variables given above or in terms of cumulative catchment effects such as water and fine sediment and organic matter yield. Long term comparisons of undisturbed and managed areas (small catchments) are needed to properly evaluate BMPs and should be required of all land management agencies and corporations with salmonid production zones. Evaluations should use the normative river condition, to the extent we know it, as the standard of measure.

Stock status (wild and cultured) in mapped habitat types is needed for each sub-basin, including annual determinations of spawners, redds, life history growth patterns from scales and otoliths and juvenile recruitment in rearing habitats (e.g., sloughs, shorelines, eddies and other shallow or slack waters). Much of this work can be a logical extension of monitoring already underway.

Mortality estimates for each life history stage are needed. Such estimates require well-planned tagging programs. PIT tags are effective if detectors are located at the right places to determine mortality (or survival) by habitat type and life history stage. Curently, few detectors are in place where habitat evaluations are most needed. Detectors in each of the major fish bypass systems at dam and in adult samplings (terminal fisheries and fishladders at dams) is essential.

We need a measure of migrant vitality to assess bottlenecks associated with reservoir and dam transit and food web variations in different habitat types. Perhaps a measure of energy reserves (whole body lipid content) would suffice, but research on this subject is required.

Metapopulation Monitoring Under the Normative River Concept

In developing this section, we assumed that 1) metapopulation processes are important in maintaining regional persistence and abundance of Columbia basin salmonids, and 2) accomplishment of the Fish and Wildlife Progam goals will require reestablishment of metapopulation integrity in subbasin watersheds and mainstem areas. Under the Normative River concept, a central question that a monitoring program must be designed to address is, "How is restoration of metapopulation organization progressing within subbasins and region-wide?" From a metapopulation perspective monitoring and evaluation should focus on systems of local populations or subpopulations, their spatial arrangement or distribution within watersheds and the relationship of this distribution to spatial and temporal variation in habitat conditions, and connectivity among local populations which is related to their proximity and the favorability of connecting habitats. Thus, monitoring metapopulation organization necessarily must be linked to habitat monitoring in an integrated habitat-metapopulation monitoring system appropriate at watershed scales. Moreover, where possible, reconstruction of historic habitat conditions and life history distributions, e.g., (Sedell and Luchessa, 1981; Lichatowich and Mobrand, 1995; McIntosh et al., 1995) must be undertaken to establish a normative river template against which progress toward the normative river can be measured.

Monitoring under the Normative Ecosystem conceptual foundation will differ in some degree from present monitoring programs within the basin. Present monitoring efforts focus primarily on life stages of individual stocks extant in the basin today. Under the Normative Ecosystem concept, not only the status of individual stocks but also their spatial association and diversity would be emphasized. Furthermore, stocks and life histories that were extirpated in the past may need to be restored to reestablish metapopulation integrity and ensure the opportunity for operation of metapopulation processes. Thus monitoring programs will need to assess not only the status of extant stocks and their life histories but also the progress of reestablishment of extinct stocks, their life histories, and their habitats. To ensure that recovering metapopulations are adequately protected, the local populations or subpopualtions making up a metapopulation should be monitored at critical points during their migration through the mainstem Columbia and Snake rivers. Measure 4,3C in the Fish and Wildlife Progam (population monitoring) should be modified to take into consideration the metapopulation structure of salmonids in the basin.

Under the Normative Ecosystem concept, the following needs should be addressed by a monitoring program:

1) Identification and protection of healthy core and satellite populations throughout the region. This includes the Hanford stock of fall chinook as well as other healthy populations spawning in mainstem and headwater areas. To facilitate the design and implementation of metapopulation monitoring, the subregional process (measure 3.1D in the Fish and Wildlife Progam) should be organized so that the geographic range of a metapopulation is not split among two or more subregions.
2) Restoration of core populations and their habitats at critical locations within each physiographic region in the Columbia basin. Reestablishment of metapopulation organization will require restoration of vital core populations that are presently extinct (Rieman and McIntyre, 1993; Schlosser and Angermeier, 1995). Areas where core populations were historically abundant need to be identified as high priority areas for restoration. Many of these areas likely were extensive alluvial reaches of rivers. Monitoring will need to assess the progress of restoration of both core populations and their habitats.
3) Improved survival of extant satellite populations and reestablishment of some extinct satellite populations. This is especially critical in the Snake River basin where chinook salmon metapopulation integrity appears to have been severely compromised.
4) Development of measures of spatial diversity of local populations and life history types within watersheds (Rieman and McIntyre, 1993). Restoration of extinct life history patterns will probably be an early indication of habitat restoration and indicate progress toward redevelopment of metapopulation structure.
5) Identification, protection, and reestablishment of key physical linkages among local populations and between core and satellite populations to facilitate dispersal.

<u>Dam-Passage Evaluation</u>

We have shown that the ability of juvenile salmon to pass downstream through dams is now constrained by passage routes that defy, rather than simulate, the migrational behavior patterns in a normative river. Migration "habitat" at dams needs to be evaluated carefully in the context of the normative river. Specifically, we need to:

1) Develop estimates of smolt mortality rates assignable specifically to mortality in turbines, tailraces, reservoirs, and forebays, to identify areas of highest mortality and to be able to treat them individually with the most appropriate measures. Initial studies should be followed by monitoring as bypass measures to better simulate the normative river atre taken.

2) Further evaluate the surface ice and trash sluiceways as a passage route for juvenile salmonids. Studies should be designed to compare relative numbers of fish passing through the turbines relative to the sluiceways at spill levels and powerhouse loads chosen to obtain measurements at specified intervals, covering an appropriately wide range, rather than depending on observations made under normal operating patterns.The purpose is to develop a regression equation that can be used to predict sluiceway and spill effectiveness at different levels of spill. Secondarily, the information can be used to evaluate engineering changes that might be made in the sluiceways to improve their effectivenes as collectors of surface-oriented fish, such as modifications in the upstream openings or flow volumes.

3) Further evaluate the procedure used to determine spill levels required at the Snake and lower Columbia river projects to achieve the fish passage goals set by the Council and NMFS. These should be done to contrast normal spill and surface spill (which more closely approximates the surface orientation of downstream migrants). The purpose is to refine the amount of spill required at each project (by using surface spill, the amount of water should decrease). To accomplish this requires evaluation of data used at each project to predict the mix of species and stocks expected to occur at various time periods during the emigration, data on FGE for those species and stocks , and data on spill effectiveness.

4) Evaluate new designs for spill deflectors or other gas abatement measures at dam spillways that minimize gas supersaturation in water that is spilled. The purpose would be to design an abatement method that is effective over a wide range of spill levels, particularly high levels associated with flood events.

Relation of basic research and peer review to routine monitoring and evaluation

This review of monitoring and evaluation underscores the need for basic research to resolve uncertainties associated with the ecology of the Columbia River. Many of these uncertainties are revealed from routine analysis of monitoring data. Actions to recover fisheries have not been successful in the Columbia River largely due to lack of scientific synthesis and peer review as key attributes of the funding process for recovery efforts. Moreover, the General Accounting Office noted that very little basic research has been funded by the Fish and Wildlife Progam prior to 1992 (General Accounting Office, 1992) and we note little, if any, change in that trend to date.

Recent scientific syntheses (see Table 1.1), coupled with conclusions from various sections of this report, have identified the primary uncertainties in the ecosystem science of the Columbia River. These uncertainties have to be resolved through basic research. That research currently is not being effectively accomplished and will not be under the current mechanism of program implementation.

The standard of science is publication of research results in scholarly journals that have rigorous peer review protocols. Publication of research results is much easier and credible if the research that is being reported is derived from a peer reviewed research plan. Successful competitive grants programs, as administered for example by the National Science Foundation, National Atmospheric and Space Administration and the National Institutes of Health, require detailed and well planned research proposals and honest and constructive peer review prior to funding. This provides credibility to research and the funding process and generally increases the likelihood of the study producing significant results.

A new or at least a revised mandate is needed in the Fish and Wildlife Progam that requires all ecological research, monitoring and evaluation results that are funded by the Fish and Wildlife Progam be published in juried formats. Also, the Fish and Wildlife Progam should provide for a competitive grants program for funding research to resolve uncertainties in management actions to recover salmonid populations. No research organization or individual should be locked out research funding due to agency management jurisdictions. Funding of research and monitoring and evaluation projects should be based on the quality and innovation expressed by the proposal and the professional expertise of the proposers as evaluated and ranked through peer review.

As noted above we have previously provided a guidance document for conducting peer review of proposals (Independent Scientific Group, 1995). These guidelines should be used. Only through the mechanism of peer review will progress toward resolving key uncertainties in the recovery of Columbia River fisheries proceed effectively and cost-efficiently. We recognize that agencies and tribes have a legal mandate to manage fisheries resources, but that does not mean that new information should be just the purview of management entitlements. Rather, management, monitoring, evaluation and research should be interactive and adaptive as new information is forthcoming to resolve uncertainties in an ecosystem context (e.g., Stanford and Poole, in press). The solution is for the Fish and Wildlife Progam to be revised to clearly articulate priorities and protocols for management, monitoring and evaluation and research funding and all funding, with the exception of actions that are clearly policy related and based on clear implications of scientific analyses, should be based on peer review.

Conclusions (level of proof)

1. A large amount of effort is being expended in monitoring of salmonids in the Snake and mid-Columbia basins in conformance with high Fish and Wildlife Progam emphasis on monitoring and evaluation including various index life stages (adults, redds, fry/smolt emigration, adult-equivalent production, life-cycle productivity) through a variety of state, federal, and utility programs and these efforts appear to be directed toward valid technical needs (1);
2. Monitoring data are generally compiled and made available in databases (e.g., FPC and CIS) and written reports, although user-friendliness and suitability for specific needs further attention (1);
3. The focus of monitoring and evaluation has evolved to be larger than just the hydrosystem (befitting life cycles that extend from mountain streams to the ocean, and resident fishes in storage reservoirs) (1);
4. Observations generally exceed analyses (evaluation) (2);
5. Monitoring effort has been heavily focused by current beliefs and oriented toward establishing relationships among volume of flow, water travel time, and fish travel time, usually between dams and most commonly in the lower Snake River (1)
6. Current beliefs that focus the monitoring effort do not always have explicit statement, rigorous examination of the evidence in support of those beliefs (evaluation), framing of alternative hypotheses, and design of monitoring and evaluation to fairly test all reasonable hypotheses (1);
7. Population models have become a popular analytical (evaluation) method, but models have pitfalls because results are determined to a large extent by beliefs built into their structure (1);
8. Both collection of long-term data sets and monitoring with an experimental design to test hypotheses are being conducted in the basin (2);
9. Despite considerable effort, monitoring and evaluation are not adequate for the present needs, especially the level of evaluation and assessment (1).

Critical uncertainties

1. Importance of alternative hypotheses to design of routine monitoring and monitoring experiments are not well articulted.
2. Thoroughness and validity of evaluation (need for scientific synthesis) of monitoring results are not emphasized in the Fish and Wildlife Progam.
3. Information on life stages are not now monitored or integrated well with existing monitoring (e.g., in ocean and estuary).
4. The degree to which beliefs bias evaluation of monitoring results.

Recommendations

1. Maintain monitoring and evaluation as a major objective for the Fish and Wildlife Progam and include new metrics that permit monitoring of normative river conditions (e.g, effectiveness of peak flows in maintaining habitat structure; ground water controls on surface temperatures and productivity; integrity of riparain communities; composition and dynamics of slack water communities, including but not limited to salmonid populations).
2. Maintain basic collection, archiving and dissemination of index data;.
3. Encourage explicit statement of current beliefs that affect monitoring programs, rigorous examination of evidence for beliefs, framing of alternative hypotheses, and design of monitoring and evaluation to fairly test all reasonable hypotheses (through basic data collection and/or conduct of monitoring experiments);
4. Encourage integration of other agency efforts (and funding) to extend the monitoring and evaluation for salmonid populations beyond the hydropower system to the estuary and ocean.
5. Install and operate PIT detectors at key monitoring points and implement a tagging program that is statistically valid to estimate mortality of all life history stages of salmonid stocks based on our normative river conceptual foundation.
6. Mandate peer review using guidance documents for competitive research and management proposal evaluation previously produced by the ISG and require that studies and evaluations be submitted to professional journals for review and publication.
7. Implement a competitive grants program for research that is responsive to uncertainties derived from periodic syntheses of monitoring data and general ecological science pertaining to the Columbia River Ecosystem.

Literature Cited

Achord, S., J.R. Harmon, D.M. marsh, B.P. Sandford, K.W. McIntyre, K.L. Thomas, N.N. Paash and G.M. Matthews. 1992. Research Related to Transportation of Juvenile Salmonids on the Columbia and Snake Rivers, 1991, U.S. Army Corps of Engineers.

Achord, S., D.J. Kamikawa, B.P. Sandford and G.M. Matthews. 1995. Monitoring the Migrations of Wild Snake River Spring and Summer Chinook Salmon Smolts, 1993. Portland, Bonneville Power Administration. Oregon.

Andrews, J. and L.B. Everson. 1988. Middle Fork and Upper Salmon River Habitat Improvement Implementation Plan, FY 1988-1992. Portland, Bonneville Power Administration. Oregon.

Barnthouse, L.W., L.W. Botsford, R.B. Deriso, J.F. Kitchell and S.B. Saila. 1994. Columbia River Basin Salmonid Model Review. Oak Ridge, U. S. Department of Energy
Bonneville Power Administration. Tennessee**:** 174.

Berggren, T.J. and M.J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. North. Am. J. Fish. Manage. 13: 48-63.

Biological Requirements Work Group. 1994. Analytical Methods for Determining Requirements of Listed Snake River Salmon Relative to Survival and Recovery.

Bjornn, T.C., D.R. Craddock and D.R. Corley. 1968. Migration and survival of Redfish Lake, Idaho sockeye salmon, *Oncorhynchus nerka*. Trans. Amer. Fish. Soc. 97: 360-373.

Bryant, F.G. 1949. A Survey of the Columbia River and Its Tributaries with Special Reference to Its Fishery Resources. No. 2. Washington Streams from the Mouth of the Columbia River to and Including the Klickitat River (Area I), U.S. Fish and Wildlife Service.

Bryant, F.G. and Z.E. Parkhurst. 1950. Survey of the Columbia River and Its Tributaries, Number 4, Area III. Washington Streams from the Klickitat and Snake Rivers to Grand Coulee Dam, U.S. Fish and Wildlife Service.

Buettner, E.W. 1991. Smolt Monitoring at the Head of Lower Granite Reservoir and Lower Granite Dam. Portland, Bonneville Power Administration. Oregon.

Buettner, E.W. and A.F. Brimmer. 1993. Smolt Monitoring at the Head of Lower Granite Reservoir and Lower Granite Dam: Annual Report 1992. Boise, Bonneville Power Administration. Idaho**:** 64.

Buettner, E.W. and A.F. Brimmer. 1995. Smolt Monitoring at the Head of Lower Granite Reservoir and Lower Granite Dam. Annual Report for 1993 Operations. Portland, Bonneville Power Administration. Oregon.

Burnham, K.P., D.R. Anderson, G.C. White, C. Brownie and K.H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. Am. Fish. Soc. Monogr.(Monograph 5).

Chapman, D.W., W.S. Platts, D. Park and M. Hill. 1990. Status of Snake River Sockeye Salmon. Boise, Don Chapman Consultants, Inc., 3653 Rickenbacker, Suite 200. Idaho: 90.

Conf. Tribes of the Umatilla Indian Reservation. 1984. Umatilla Basin Recommended Salmon and Steelhead Habitat (Hatchery Passage) Improvement Measures. Pendleton, Conf. Tribes of the Umatilla Indian Reservation. Oregon.

Conf. Tribes of the Umatilla Indian Reservation. 1995. Umatilla Basin Natural Production Monitoring and Evaluation. Annual Progress Report 1992-1993. Portland, Bonneville Power Administration. Oregon.

Corps of Engineers. 1975. Special Report - Lower Snake River Fish and Wildlife Compensation Plan. Lower Snake River, Washington and Idaho. Walla Walla, U.S. Army Corps of Engineers. Washington.

Coutant, C.C. and G.F. Cada. 1985. Analysis and Development of a Project Evaluation Process. Portland, Bonneville Power Administration. Oregon.

Dauble, D.D., J. Skalski, A. Hoffmann and A.E. Giorgi. 1993. Evaluation and Application of Statistical Methods for Estimating Smolt Survival. Portland, Bonneville Power Administration. Oregon.

Dauble, D.D. and D.G. Watson. 1990. Spawning and abundance of fall chinook salmon (Oncorhynchus tshawytscha) in the Hanford Reach of the Columbia River, 1948-1988. Richland, U. S. Department of Energy
Pacific Northwest Laboratory. Washington.

Evermann, B.W. 1895. A preliminary report upon salmon investigations in Idaho in 1894. Bull. U.S. Fisheries Commission 15: 253-284.

Everson, L.B., C.J. Campbell, R.E. Craven and T.L. Welsh. 1989. Habitat Evaluation and Monitoring in the Columbia River Basin. Portland, Bonneville Power Administration. Oregon.

Fulton, L.A. 1968. Spawning areas and abundance of chinook salmon (Oncorhynchus tshawytscha) in the Columbia River Basin--past and present., USDI, Fish and Wildl. Serv., Special Sci. Rpt--Fisheries No. 571.

Fulton, L.A. 1970. Spawning areas and abundance of steelhead trout and coho, sockeye, and chum salmon in the Columbia River Basin--past and present, USDC, NOAA, NMFS.

General Accounting Office. 1992. Endangered Species: Past Actions Taken to Assist Columbia River Salmon. Washington. District of Columbia.

Giorgi, A.E. 1993. Flow Augmentation and Reservoir Drawdown: Strategies for Recovery of Threatened and Endangered Stocks of Salmon in the Snake River Basin. Portland, Bonneville Power Administration. Oregon.

Giorgi, A.E., L.C. Stuehrenberg and J. Wilson. 1988. Juvenile Radio-Tag Study: Lower Granite Dam 1985-86. Portland, Bonneville Power Administration. Oregon.

Hymer, J.a.t.c.-a. 1992. Stock Summary Reports for Columbia River Anadromous Salmonids. Volume III: Washington below the Snake River. Portland, Columbia River Inter-Tribal Fish Comm. Oregon.

Hymer, J.a.t.c. 1992. Stock Summary Reports for Columbia River Anadromous Salmonids. Volume IV: Washington Upper Columbia and Snake River. Portland, Columbia River Coordinated Information System, Columbia River Inter-Tribal Fish Commission. Oregon.

Independent Scientific Group. 1995. Smolt Monitoring Program Review, SRG**:** 11.

Independent Scientific Group. 1996. Summary of Statistical Reviews of the NMFS/UW Survival Studies.

Iwamoto, R.N., W.D. Muir, B.P. Sandford, K.W. McIntyre, D.A. Frost, J.G. Williams, S.G. Smith and J.R. Skalski. 1994. Survival Estimates for the Passage of Juvenile Salmonids through Snake River Dams and Reservoirs, 1994. Portland, Bonneville Power Administration. Oregon.

Kiefer, R.B. and J.N. Lockhart. 1995. Intensive Evaluation and Monitoring of Chinook Salmon and Steelhead Trout Production, Crooked River and Upper Salmon River Sites. Portland, Bonneville Power Administration. Oregon.

Kiefer, S.W., M. Rowe and K. Hatch. 1992. Stock Summary Reports for Columbia River Anadromous Salmonids. Volume V: Idaho. Portland, Bonneville Power Administration. Oregon.

Kline, P. 1995. Research and Recovery of Snake River Sockeye Salmon, Annual Report 1993. Portland, Bonneville Power Administration. Oregon.

Lichatowich, J.A. and L.E. Mobrand. 1995. Analysis of chinook salmon in the Columbia River from an ecosystem perspective, Mobrand Biometrics.

Lindsay, R.B., W.J. Knox, M.W. Flesher, B.J. Smith, E.A. Olson and L.S. Lutz. 1986. Study of Wild Spring Chinook Salmon in the John Day River System. Portland, Bonneville Power Administration. Oregon.

Liscom, K.L. and C. Bartlett. 1988. Radio Tracking to Determine Steelhead Trout Migration Patterns at the Clearwater and Snake River Migrant Traps near Lewiston, Idaho. Boise, Idaho Dept. Fish and Game. Idaho.

Lohn, D.R. 1995. Letter to interested parties, Bonneville Power Administration.

Matthews, G.M., S. Achord, J.R. Harmon, O.W. Johnson, D.M. Marsh, B.P. Sandford, N.N. Paasch, K.W. McIntyre and K.L. Thomas. 1992. Evaluation of Transportation of Juvenile Salmonids and Related Research on the Columbia and Snake Rivers, 1990, U.S. Army Corps of Engineers.

Matthews, G.M., J.R. Harmon, S. Achord, O.W. Johnson and L.A. Kubin. 1990. Evaluation of Transportation of Juvenile Salmonids and Related Research on the Snake and Columbia Rivers, 1989, U.S. Army Corps of Engineers.

McConnaha, W.E. and P.J. Pacquet. *in press*. Adaptive strategies for the management of ecosystems: the Columbia River experience. Multidisciplinary Approaches to Reservoir Fisheries Management. Bethesda, Amer. Fish. Soc.

McCullough, D.A. and F.A. Espinosa. 1996. A monitoring strategy for application to salmon-bearing watersheds. Portland, OR, Columbia River Inter-Tribal Fish Commission.

Mcintosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Clearwater, Salmon, Weiser, and Payette River Basins, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Cowlitz River Basin, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Umatilla, Tucannon, Asotin, and Grande Ronde River Basins, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Willamette River Basin, 1934-1942. Portland, Bonneville Power Administration. Oregon.

McIntosh, B.A., S.E. Clarke and J.R. Sedell. 1995. Summary Report for Bureau of Fisheries Stream Habitat Surveys: Yakima River Basin, 1934-1942. Portland, Bonneville Power Administration. Oregon.

Megahan, W.F., W.S. Platts and B. Kulesza. 1980. Riverbed improves over time: South Fork Salmon. Watershed Management Symposium, Irrigation and Drainage Division, Boise, Idaho, Amer. Soc. of Civil Engineers.

Monitoring and Evaluation Group of the Northwest Power Planning Council. 1988. Recommendations for a Program to Monitor and Evaluate the Fish and Wildlife Porgram of the Northwest Power Planning Council. Portland, Northwest Power Planning Council. Oregon.

Monk, B.H., B.P. Sandford and J.G. Williams. 1992. Evaluation of the Juvenile Fish Collection, Transportation, and Bypass Facility at Little Goose Dam, 1990. Seattle, National Marine Fisheries Service, Northwest Fisheries Science Center. Washington.

Muir, W.D., S.G. Smith, R.N. Iwamoto, D.J. Kamikawa, K.W. McIntyre, E.E. Hockersmith, B.P. Sandford, P.A. Ocker, T.E. Ruehle and J.G. Williams. 1995. Survival Estimates for the Passage of Juvenile Salmonids through Snake River Dams and Reservoirs, 1994. Portland, Bonneville Power Administration. Oregon**:** 187.

Muir, W.D.a.t.c. 1996. Survival Estimates for the Passage of Yearling Chinook Salmon and Steelhead through Snake River Dams and Reservoirs, 1995 (draft). Seattle, Northwest Fisheries Science Center, National Marine Fisheries Service. Washington.

Newman, K. 1995. Adult Salmonid PIT-tag Returns to Columbia River's Lower Granite Dam. Portland, Bonneville Power Administration. Oregon.

Nez Perce Tribe, C.T.o.t.U.I.R., and Oregon Dept. of Fisheries and Wildlife,. 1990. Imnaha River Subbasin, Salmon and Steelhead Production Plan. Portland, Northwest Power Planning Council. Oregon.

Northwest Power Planning Council. 1986. Council Staff Compilation of Information on Salmon and Steelhead Losses in the Columbia River Basin. Portland, Northwest Power Planning Council. Oregon.

Northwest Power Planning Council. 1988. Staff Issue Paper: Salmon and Steelhead Research and Monitoring. Portland, Northwest Power Planning Council. Oregon.

Northwest Power Planning Council. 1992. Strategy for Salmon, Vol. 1. Portland, Northwest Power Planning Council. Oregon**:** 43.

Northwest Power Planning Council. 1994. 1994 Columbia River Basin Fish and Wildlife Program.

Olsen, E., K. Hatch, P. Pierce and M. McLean. 1992. Columbia River Coordinated Information System Project Phase II: Stock Summary Reports for Columbia River Anadromous Salmonids, Volume I: Oregon Below Bonneville Dam. Portland, Columbia River Coordinated Information System Project. Oregon.

Olsen, E., K. Hatch, P. Pierce and M. McLean. 1992. Columbia River Coordinated Information System Project Phase II: Stock Summary Reports for Columbia River Anadromous Salmonids, Volume II: Oregon Above Bonneville Dam. Portland, Columbia River Coordinated Information System Project. Oregon.

Oregon Dept. of Fish and Wildlife. 1986. A Comprehensive Plan for Rehabilitation of Anadromous Fish Stocks in the Umatilla River Basin. Portland, Bonneville Power Administration. Oregon.

Oregon Dept. of Fish and Wildlife, C.T.o.t.U.I.R., Nez Perce Tribe, Washington Dept. of Fisheries, and Washington Dept. of Wildlife. 1990. Grande Ronde River Subbasin, Salmon and Steelhead Production Plan. Portland, Northwest Power Planning Council. Oregon.

Parkhurst, Z.E. 1950. Survey of the Columbia River and Its Tributaries, Part 6, Area V. Snake River from the Mouth through the Grande Ronde River, U.S. Fish and Wildlife Service.

Parkhurst, Z.E. 1950. Survey of the Columbia River and Its Tributaries, Part 7, Area VI. Snake River from above the Grande Ronde River through the Payette River, U.S. Fish and Wildlife Service.

Parkhurst, Z.E. 1950. Survey of the Columbia River and Its Tributaries, Part 8, Area VIII. Snake River above Payette River to Upper Salmon Falls, U.S. Fish and Wildlife Service.

Prentice, E.F. 1990. PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. American Fish. Soc. Symposium 7: 323-334.

Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975. 108(6): 505-529.

Rich, W.H. 1948. A Survey of the Columbia River and Its Tributaries with Special Reference to the Management of Its Fishery Resources, U.S. Fish and Wildlife Service.

Rieman, B.E. and J.D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. Ogden, US Forest Service, Intermountain Research Station. Utah**:** 38.

Schlosser, I.J. and P.L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Amer. Fish. Soc. Symp. 17: 392-401.

Sedell, J.R. and K.J. Luchessa. 1981. Using the historical record as an aid to salmonid habitat enhancement. Acquisition and utilization of aquatic habitat inventory information. N. B. Armantrout. Bethesda, American Fisheries Society**:** 210-223.

Sims, C. and F. Ossiander. 1981. Migrations of Juvenile Chinook Salmon and Steelhead in the Snake River, from 1973 to 1979, a Research Summary. Seattle, National Marine Fisheries Service. Washington.

Sims, C.A., A. Giorgi, R. Johnsen and D. Brege. 1983. Migrational Characteristics of Juvenile Salmon and Steelhead in the Columbia Basin - 1982. Seattle, National Marine Fisheries Service. Washington.

Sims, C.W., A.E. Giorgi, R.C. Johnsen and D.A. Brege. 1984. Migrational characteristics of juvenile salmon and steelhead in the Columbia River basin 1983, U.S. Army Corps of Engineers and National Marine Fisheries Services**:** 31 + appendix.

Thompson, K. 1976. Columbia Basin Fisheries: Past, Present and Future. Portland, Pacific Northwest Regional Commission. Oregon.

Thompson, R.N. and J.B. Haas. 1960. Environmental Survey Pertaining to Salmon and Steelhead in Certain Rivers of Eastern Oregon and the Willamette River and Its Tributaries. Clackamas, Fish Commission of Oregon, Research Division. Oregon.

CHAPTER 10. THE MARINE ENVIRONMENT

A. The Columbia River Estuary

TRANSITION FROM RIVER TO OCEAN

Pacific salmon undertake extensive migrations extending from headwater streams hundreds of kilometers inland to distant oceanic rearing areas. Twice during their migrations salmon must undergo extensive physiological changes to make the transition between radically different environments: when they migrate from freshwater to saltwater as juveniles and the reverse as adults. The estuary is where that transition between salt and freshwater takes place and the estuary is part of the salmon's ecosystem that, in general, has received little attention (Simenstad et al., 1982).

By standing at a critical transitional stage in the anadromous salmonid's life history, the estuary can be a key regulator of overall survival and year-to-year variation in abundance. The ecological state of the Columbia River estuary has been compromised by extensive habitat alteration from human activities in the estuary itself and in upriver areas. Many of those changes are of potential importance to salmon production. Because the estuary is the terminus of the river, it is where the cumulative impacts of upriver actions all have focused (Simenstad et al., 1992), including potential adverse effects from pollution, changes in biological and non-biological input and alteration of seasonal flow patterns. The estuary is critical habitat that can constrain total salmon production, particularly of the more estuarine dependent species such as chinook salmon.

Earlier in this report (Chapters 2 and 5), salmon habitat was equated to beads on a string. Beads were the places where salmon carried out important parts of their life cycle such as spawning, rearing, holding or avoiding predation; and the string was equated to migration corridors giving salmon access to those places. The estuary is a critical part of the string, a migratory corridor connecting riverine and oceanic habitats, and a place (bead) where some juvenile salmon may rear for extended periods prior to their migration to the sea.

ESTUARINE INFLUENCE ON SALMONID LIFE HISTORIES

Salmon have evolved a variety of strategies to utilize the estuary and move between freshwater and marine areas. Juvenile sockeye and coho generally spend a limited time in the estuary and move quickly from the riverine to the marine environment (Groot and Margolis, 1991; Pearcy, 1992). Pink and chum use the estuary for spawning as well as an early rearing phase that may last from days to weeks (Pearcy, 1992). Chinook salmon display a variety of estuarine strategies. Reimers (1973) identified five different juvenile chinook life history strategies in the Sixes River based on size and timing of entry into the estuary. Schluchter and Lichatowich (1977) observed seven patterns in the use of the estuary by juvenile chinook in the Rogue River.

In the Columbia River, utilization of the estuary by juvenile chinook salmon has received little attention. However, differences in estuarine strategies can be distinguished at least at the level of the two major life history types. Sub-yearling or ocean-type chinook salmon enter the estuary gradually as part of their protracted downstream rearing and growth phase. They spend several weeks to months in the estuary prior to a long marine migration (Bottom et al., 1984; Healey, 1991). The yearling or stream-type life history, on the other hand, appear to spend little time in the estuary (Healey, 1991; Pearcy, 1992). Given the variety of estuarine strategies displayed by juvenile chinook salmon in the Sixes and Rogue rivers and the variety of freshwater habitats in the Columbia River, it seems likely that the actual number of strategies for estuarine utilization in the Columbia River far exceeds the general, ocean- or stream-type life histories.

Estuarine habitats

Simenstad et al. (1982) hypothesized three important functions for estuaries which enhance the growth and survival of Pacific salmon:

Physiological Transition Zone Salmonids undergoing physiological change may benefit from the gradual change from fresh to salt water within the estuary.

Predator Avoidance Although the abundance of predators is higher in the estuary, juvenile salmon may disperse into habitats that offer protection from predators. In addition, during the period of juvenile residence in estuaries turbidity is higher, reducing the efficiency of predators.

Optimum Foraging Conditions The size, distribution and density of many prey organisms in the estuary appear to be optimal for juvenile salmon.

The Columbia River plume, which is the freshwater lens that extends into the nearshore ocean, could be considered an extension of the estuary. The plume may provide extended estuarine rearing or possibly a refuge for juvenile salmon. Changes in the hydrograph of the Columbia River have altered the size and structure of the plume during the spring and summer when many juvenile salmonids are entering the ocean (Pearcy, 1992). More research is needed on the ecological importance of the Columbia River plume in the life history of juvenile salmonids.

Given the number of potential predators in the estuary and in the nearshore ocean, the optimal foraging conditions found in the natural estuarine food webs may be the most important function of the estuaries. Rapid growth in the estuary allows the juvenile salmon to grow out of their vulnerability to predators (Simenstad et al., 1982). For that reason, changes in the estuary that impact the food web for juvenile pacific salmon could represent an important constraint on production.

Changes in the estuary that affect the quality of habitat for salmonids come from two principal sources:

Within the estuary, for example, diking that separates marshes from the main channel,

Outside the estuary, for example, dams and storage reservoirs that alter the flow regime through the estuary.

HUMAN INFLUENCES

Changes in the extent and nature of the Columbia River estuary result from a combination of natural and human-caused factors. Natural aging of the estuary results from the interplay between accretion of sediments derived from upriver areas, and the gradual rise in sea level since the last glaciation (Day et al., 1989). The process of estuary filling is accelerated by attached vegetation that acts to trap and stabilize sediments (Day et al., 1989). In the Columbia River estuary, the most important plant species in this regard is Lyngby's Sedge (*Carex lyngbei*) an emergent grass (Thomas, 1983). This grass is common in shallow brackish or freshwater embayments in the estuary and acts to trap sediments.

Accretion of sediment causes a gradual uplifting of the estuary that is countered to some extent by the continuing increase in sea level since the last glaciation. As the estuary builds up, marsh is gradually converted to willow and spruce swamp. Swamp dominated floodplain is the end product of the estuarine process in the Columbia River (Thomas, 1983).

In addition to the slow filling of the estuary over time, natural processes act to move and modify the estuary continuously, often in a very rapid and dramatic fashion. The result is a continuously changing and dynamic physical structure. Sherwood et al. (1990) analyzed early navigational charts and noted profound changes in the river entrance from year to year. The pre-development river mouth was characterized by shifting shoals, sandbars and channels forming ebb and flood tidal deltas. Prior to dredging and maintenance, the navigable channel over the tidal delta varied from a single, relatively deep channel in some years to two or more shallow channels in other years (Sherwood et al., 1990).

Although the process of erosion and deposition is ongoing and often dramatic, the overall rate of estuarine change due to natural aging is generally slow. Relative to the rate of change caused by human actions, natural aging of the estuary is likely insignificant over the last century (Thomas, 1983). Most of the human alteration of the estuary results from attempts to stabilize and simplify a naturally dynamic and complex environment.

Early activities in the estuary attempted to stabilize the navigation channel. Jetties were constructed on the north and south shores of the river to hold a channel in place, while a regular dredging program deepened the channel (Sherwood et al., 1990). Material dredged from the main channel was deposited in shallow water areas. Many of these areas were subsequently diked and removed from the estuary.

Dredging, filling and diking resulted in important changes in the morphology of the estuary (Thomas, 1983; Sherwood et al., 1990). Total volume of the estuary inside the entrance has declined by about 12% since 1868 (Sherwood et al., 1990). Thomas (1983) estimated that 40% of the original estuarine area has been converted to developed floodplain by diking and filling. Overall, development since the mid-19th century has resulted in a loss of 77% of the tidal swamps, 62% of the tidal marshes and 7% of the tidal flats (Thomas, 1983). Flow patterns were drastically altered in the mid-1970s changing the seasonal input of freshwater to the estuary. Other human induced changes in the Columbia Estuary are either too recent or have not had sufficient study to demonstrate linkages to the status of Pacific salmon.

The strength of the spring freshet was appreciably diminished when upriver storage projects were used to shift water into the winter (Figure 10.1). The result has been a general flattening of the seasonal hydrograph **.** In addition, the timing of the spring freshet has been moved forward about one month. The biological impacts of these changes have not been studied, however, changes in physical parameters with potential biological impacts have been significant. Changes in estuarine bathymetry and flow have altered the extent and pattern of salinity intrusions into the river and have increased stratification and reduced mixing (Sherwood et al., 1990). Ebbesmeyer and Tangborn (1992) present evidence that the shift of spring flow into the winter has altered sea surface salinities along a large part of the North American coast.

Development has changed the circulation patterns and increased the shoaling rates in the estuary. Sediment input to the estuary has declined due to the altered hydrograph but the estuary is now a more effective sediment trap. Although the Columbia river is characterized as a highly energetic system, it has been changing as a result of development and is now similar to more developed and less energetic estuaries throughout the world (Sherwood et al., 1990). More research on the possible linkages between changes in the estuary and the Pacific salmon is needed.

THE ESTUARINE FOOD WEB

These changes internal to the estuary and in the watershed above it have altered the food web in ways that are detrimental to Pacific salmon. The estuarine food webs that support juvenile salmon are apparently detritus-based (Bottom et al., 1984; Salo, 1991), and in the Columbia Estuary, the detritus-based food web has undergone an important shift in response to development. Macrodetritus derived from emergent marsh vegetation has undergone a dramatic reduction due to the loss of shallow water habitat. The loss of those production areas reduced emergent plant production by 82 percent (Sherwood et al., 1990). Sherwood et al. (1990)

estimate that, prior to development, the standing crop of organisms that feed on the macrodetritus would have been 12 times the current standing crop. Since those organisms are prominent prey of juvenile salmonids, it is not unreasonable to assume that a reduction in the food web supported by macrodetritus has had a negative impact on the Pacific salmon. However, Sherwood et al. (1990) could not provide empirical evidence of a linkage between the food web and the status of salmon in the Columbia Basin.

Bottom et al. (1984) found that the index of feeding intensity (IFI) was lower in subyearling chinook salmon from the Columbia estuary compared to the IFI for chinook salmon in either the Fraser (British Columbia) or Sixes (Oregon) estuaries. The IFI is the total weight of the stomach contents expressed as a percent of the fish's total weight.

The food web based on macrodetritus which is characterized by shallow water, benthic consumers has largely been replaced by a food web composed of deep water, benthic and pelagic consumers. Apparently, primary production of pelagic algae has increased in the impounded stretches of the mainstem Columbia and Snake rivers and the resulting microdetritus input to the estuary is nearly equivalent to the macrodetritus cut off from the estuary by diking the wetlands (Sherwood et al., 1990). The new food web is favored by fishes such as Pacific herring, smelts and the nonnative American shad (Sherwood et al., 1990). The American shad is one of the dominant species in the Columbia estuary (Bottom and Jones, 1990). It should be noted that American shad have been increasing in abundance whereas chinook salmon have been declining.

INFLUENCES OF HATCHERY STOCKS

The extensive use of artificial propagation to maintain salmon production in the Columbia River, has altered the patterns of use and movement through the estuary in ways that tend to reduce survival of juvenile salmonids. The release of large numbers of hatchery reared fish over a short time interval could create a density barrier in the river (Royal, 1972) or the estuary and near shore ocean (Oregon Dept. of Fish and Wildlife, 1982).

The relationship between massive hatchery releases and a density dependent limitation in the survival of juvenile coho salmon in the near shore ocean and estuary has been the subject of at least ten studies (Gunsolus, 1978; Oregon Dept. of Fish and Wildlife, 1982; Clark and McCarl, 1983; McCarl and Rettig, 1983; McGie, 1983; Nickelson and Lichatowich, 1983; Peterman and Routledge, 1983; Nickelson, 1986; Peterman, 1989; Emlen et al., 1990). The studies produced contradictory findings so the issue is still not resolved (Lichatowich, 1993).

Hatchery releases and subsequent downstream migration of juveniles often differ from the natural emigration of wild Pacific salmon. Some of those differences include the mass releases from hatcheries instead of the sequential movement of juveniles from individual tributaries, the pulsed movement of hatchery fish (all fish from a hatchery released at the same time) compared to the natural migration over a longer time interval, and hatchery juveniles that are usually larger than their wild counterparts. Hatchery fish may be the wrong size or they may arrive at the wrong time to exploit the food resources of the estuary (Simenstad et al., 1982) For example, wild chinook salmon from the Lewis River, Washington are in healthy condition (Washington Dept. of Fisheries, 1993) and it is one of the largest and most stable populations in the Columbia Basin (McIsaac, 1990). One of the reasons for the success of this stock might be the timing of juvenile migration through the estuary. The migration of fall chinook salmon from Lewis River peaks two months after all other salmonids and is later than the other subyearling fall chinook stocks (McIsaac, 1990).

CONCLUSIONS

1. Development in the estuary and in the river have altered the historical estuarine food webs in a way that is likely to have negative impacts on the survival and growth of juvenile salmonids (2).

2. Regional consideration of the biological impacts of flow modification in the Columbia River as being limited to areas above Bonneville Dam ignore the potential impact of these alterations on the physical and biological nature of the estuary (2).

3. Other changes in the physical estuarine processes may influence salmon production, but additional research is needed to document the linkages (3).

4. Hatchery operations may have altered the patterns of estuary usage by salmonids and further reduced their survival and growth (3).

B. THE PACIFIC BASIN:
PATTERNS AND PROCESSES INFLUENCING COLUMBIA RIVER SALMON

The decline of Pacific salmon stocks extends well beyond the boundaries of the Columbia River basin. Loss of coastal as well as interior populations is widespread throughout the southern edge of the range of Pacific salmon species in Washington, Oregon, and California (Nehlsen et al., 1991). This coherent pattern suggests a systemic problem rather than just a series of localized effects. Recent studies reveal large-scale changes in oceanic and atmospheric conditions across the entire Pacific Ocean Basin that may regulate temporal patterns of variation in salmon and could be a factor in regional patterns of salmon decline. Although the specific mechanisms are poorly understood, the results underscore the importance of the larger oceanic and atmospheric system within which the Columbia River Basin and its migratory stocks of salmon are embedded.

RELEVANCE OF THE OCEAN ENVIRONMENT TO SALMON PRODUCTION

Until recently, changes in salmon abundance were attributed primarily to poor habitat conditions in freshwater. These ideas were formalized in theoretical population models, which emphasized the role of density-dependent mortality during egg and early juvenile stages, and in hatchery programs, which assumed that annual production would be increased by eliminating various causes of freshwater mortality (Lichatowich et al., 1996; Bottom, In Press). The first serious challenge to these assumptions came after 1976 when abundance of Oregon coho salmon (*Oncorhynchus kisutch*) precipitously declined despite continued increases in the production of hatchery smolts (Bottom et al., 1986). This poor performance offered convincing arguments that annual production of salmon adults could be regulated by conditions in the marine environment (Jeffries, 1975). The successful prediction of adult returns from the previous year's run of precocious males (jacks) provided compelling evidence that survival of juvenile coho salmon sometime within their first six months in the ocean could determine production of adults for an entire year class (Gunsolus, 1978).

In the last several decades, oceanographers have described dramatic changes in marine fish assemblages and food chains that have important implications for salmon conservation. From analysis of fish scales deposited in anaerobic marine sediments off Southern California, researchers documented large fluctuations in abundance and shifts in the dominance of pelagic species that occurred well before intensive fisheries had any impact on fish stocks (Soutar and Isaacs, 1969; Soutar and Isaacs, 1974; Smith, 1978). Regional fluctuations in fish populations have been linked to large-scale climatic changes. For example, strong El Nino conditions in the tropics have been associated with changes in marine fauna throughout the Northeast Pacific including northern range extensions for marine, fishes, birds, and plankton (McClain and Thomas, 1983; Pearcy et al., 1985; Mysak, 1986); reduced reproductive success of Oregon seabirds (Graybill and Hodder, 1985); changes in the migration routes of adult sockeye salmon (*O. nerka)* returning to the Fraser River in British Columbia (Wickett, 1967; McClain and Thomas, 1983); and reduced size, fecundity, and survival of adult coho salmon off Oregon (Johnson, 1988). Shifts in abundance of dominant species may reverberate throughout marine food chains with unpredictable effects on the abundance of associated species. For example, Sherman (1991) reported that overfishing on the northeast continental margin of the United States was responsible for sudden flips in the biomass of dominant pelagic species with cascading effects on marine birds, mammals, and zooplankton. Coincidental declines in the abundance of several bird and marine mammal populations has raised similar concerns about the potential effects of intensive harvest of walleye pollock (*Theragra chalcogramma*) on pelagic food chains of the Bering Sea and Gulf of Alaska, e.g., (Springer, 1992). Although poorly understood, the risks of harvest-mediated effects on many marine ecosystems may be increasing. Pauly and Christensen (1995) estimate from 24 to 35% of the primary production of fresh water, upwelling, and continental shelf ecosystems of the world is required just to sustain current levels of fishery harvest.

Variability in marine ecosystems raise fundamental issues for salmon conservation. First, although fishery managers cannot control environmental variations in the ocean, this does not mean that they can afford to ignore them. For example, in the 1960s and early 1970s, the assumption that hatcheries were responsible for increases in adult returns led to continued growth in hatchery programs and in ocean fisheries during a period of unusually favorable conditions for marine survival of salmon. As noted above, abundance of salmon later collapsed along with the overinflated fishery after the return to less productive ocean conditions. But by this time, overharvest of wild populations had already reduced escapement and stock diversity in Northwest rivers and compromised the capacity of coho salmon to withstand subsequent environmental fluctuations (Bottom et al., 1986). The failure to account for natural variability may lead to faulty conclusions about the response (or lack of response) of salmon to hatchery practices, fishery quotas, habitat restoration efforts, or other management prescriptions (Lawson, 1993). To avoid choices that undermine conservation, restoration programs in the Columbia River basin must account for the "background" of environmental change upon which management actions are superimposed.

Second, changes in the ocean environment raise important questions about the appropriate scales and indicators of biological response. Traditionally, management programs for salmon have emphasized year-to-year variations in adult abundance and, in studies of environmental factors, the spatial scales of freshwater habitats, stream reaches, or river systems (meters to tens of kilometers). But changes in salmon production involve processes that vary over periods of decades and longer and extend for distances greater than the thousands-of-kilometer migrations of individual fish. Unlike the well-defined and relatively restricted boundaries of streams and watersheds, oceans are highly "open" systems in which physical and biological properties are linked across vast distances. Short (days to years) and long-period signals (decades to centuries) propagate through the ocean and atmosphere and change (e.g., become amplified or dampened) through their interaction. Oceanic and atmospheric influences on salmon production therefore involve multiple spatial and temporal scales of variability. Decadal or longer changes in ocean productivity may not be understood by simply tracking annual harvest and escapement. Furthermore, appropriate indicators of oceanic changes affecting salmon may include species other than salmon. Salmon are members of complex marine communities. Significant shifts in the distribution of predators or in the structure of food chains may be important factors in the dynamics of salmon populations, whose ocean distributions, physical environments, and biotic interactions are at least partially predetermined by the migratory route they must follow to and from their home streams.

Third, large-scale changes in ocean climate and current regime undermine simple distinctions between density-dependent and density-independent factors that may inhibit understanding of population regulation. Researchers have long debated without resolution, for example, whether the coastwide collapse of Oregon coho salmon was the result of density-dependent or density-independent effects (Lichatowich, 1993). But if fluctuations in the ocean environment involve qualitative shifts in the structure of entire communities and in the physical distribution of species, food, and nutrients, how do we separate density-dependent from density-independent effects? Do we emphasize the proximate density-dependent influences of food limitation or predation? Or do we highlight the ultimate density-independent effects of an unstable ocean environment that may reset the successional clock after every storm, spring transition, or El Nino event, and, therefore, may regulate the specific array of biotic interactions at a particular place? Sinclair (1988) proposes that populations of marine fish can suffer losses via "spatial" processes that physically displace individuals from the appropriate area needed to sustain themselves or through energetics processes associated with starvation, predation, or disease. Both kinds of processes may involve density-dependent as well as density-independent causes. In the case of salmon, a changing background of current or upwelling conditions each year of smolt migration may create new sets of potential "winners" and "losers" among different salmon stocks based on when and where they enter the ocean and tend to migrate. More important than arbitrarily characterizing coastwide trends in salmon abundance as either density-dependent or density-independent is understanding how physical and biological processes interact to influence the relative performance of geographically discrete stocks over a shifting background of oceanic states.

Finally, variability in the ocean underscores the importance of life history diversity to productivity of salmon. Diverse life histories minimize the risk of brood failure in an uncertain ocean environment because not all individuals behave uniformly. Slightly different migration times, for example, may be advantageous in different years depending upon the exact timing of the shift in along-shore surface currents (e.g., the spring transition), the specific location of the Columbia River plume, the location and timing of upwelling events, or the distribution of predators along the coast. These and other conditions in the ocean can vary markedly between years. The diversity of life history characteristics within and among populations, thus may determine the number of individuals that successfully make the transition from riverine to oceanic life. Moreover, this diversity is directly tied to the conditions that regulate salmon survival in the river and estuary. Habitat quality, flow conditions, or other factors that affect mortality during early life history may subsequently limit the range of sizes or times of emigration among surviving juveniles. Loss of life history diversity in the river may thus limit the capacity of salmon to survive variable conditions at sea.

In summary, the fact that salmon production may be regulated by conditions in the ocean argues for a broader management perspective incorporating the entire riverine-estuarine-marine habitat continuum of salmon life cycles. This perspective requires (1) an understanding of the relevant scales of variability influencing the physical and biological conditions of this extended salmon "ecosystem", and (2) an understanding of the relevant geographic discontinuities of the north Pacific Ocean that could affect the structure of salmon populations and regulate their relative production in a shifting ocean environment. This section reviews current understanding of oceanic and atmospheric processes relevant to salmon, their influence on large-scale patterns of salmon abundance, and the implications of these variations for conservation in the Columbia River Basin.

SCALES OF OCEAN PROCESSES

The harvest statistics routinely collected to manage salmon fisheries in the ocean generally provide indices of abundance over large management areas. Consequently, understanding of salmon variability is frequently based on indirect statistical correlations between coastwide trends in survival or production and selected indices of environmental conditions, e.g., (Nickelson, 1986). Fewer data are available regarding the effects of smaller or larger scale processes on salmon production. For example, other than the general surveys conducted in the early 1980s (Pearcy and Fisher, 1990), relatively little is known about the stock-specific migrations of juvenile salmon from Washington and Oregon, conditions that might alter these movements, or the mechanisms that cause the loss of individuals from a population. Reported estimates of survival for freshwater and marine life-history stages of salmon species were recently reviewed by

Bradford (1995). However, difficulties in accounting for smolt abundance, fishing mortality, and total escapement generally limit understanding of ocean survival of wild populations, and, therefore the specific mechanisms that might account for any local differences. At the other end of the spectrum, processes at scales much larger than the size of individual management jurisdictions have only recently been considered with regard to salmon production, and much of this research emphasizes stocks in the Gulf of Alaska (Beamish and Bouillon, 1993; Francis, 1996).

This section of the science review focuses on three scales of processes that play an important role in regulating ocean survival of salmon: local upwelling events, which bring nutrient-rich water to the surface during the spring and summer months and involve periods of 1-10 days and distances of 5-200 kilometers (Barber and Smith, 1981); currents that transport water seasonally along the entire Washington, Oregon, and California coast and determine the character of the water mass affecting salmon along a north-south gradient; and global oceanic and atmospheric changes that regulate both local and regional processes on interannual to interdecadal scales. By influencing survival and selecting migratory or other behaviors among local populations, geographic variations in the ocean environment may be important factors in the development of diverse salmon life histories.

Local Upwelling

When coho salmon production collapsed off Oregon in the late 1970s, biologists first considered whether upwelling conditions in nearshore coastal waters might explain variations in marine survival. The successful prediction of adult returns from the previous year's run of jacks implied that conditions during the first few months in the ocean were most critical. Researchers initially focused attention on the upwelling process along the Oregon coast; e.g., (Gunsolus, 1978; Scarnecchia, 1981), which was known to increase nutrient levels and biological productivity at about the time that salmon smolts entered the ocean. Nickelson (1986) found a positive correlation between the percent survival of hatchery coho salmon released in the Oregon Production Area and average upwelling conditions in the spring and summer. These results further suggested a threshold response to upwelling levels: In years of "strong" upwelling (greater than 625 units) survival of hatchery coho averaged 8% compared with only 3.4% during "weak" upwelling years. Nickelson (1986) also noted a possible negative correlation between surface temperature and survival independent of upwelling. The specific mechanisms of these correlations are uncertain. Furthermore, in the years following the 1976 collapse, the correlation between survival and upwelling changed and, for the last ten years has been negative, suggesting that upwelling alone is not sufficient to explain variation in coho salmon production (Jamir et al., 1994).

The upwelling system of the California Current, which extends along the West Coast of the United States, has been the subject of extensive physical and biological research. Since 1949, large-scale systematic surveys have been conducted off California, primarily south of San Francisco, as part of the California Cooperative Fisheries Investigations (CALCOFI) (Huyer, 1983). Detailed small-scale studies of the coastal upwelling system were completed off central Oregon in the 1960s and early 1970s (Peterson et al., 1979; Small and Menzies, 1981; Smith, 1983). The shorter time frames and local scales of most research off Washington and Oregon are not directly comparable to the larger interannual scales of information collected off California. Several reviewers (Huyer, 1983; 1987; Strub et al., 1987; Landry et al., 1989) have synthesized a variety of data sets to better understand the broader-scale features of the Washington and Oregon coastal ocean. The results indicate considerable variability that may be important in the life history and production of salmon stocks. For example, depending on the specific time and location of their emigration, local populations may enter very different ocean environments. Selection of migratory patterns among stocks and species may have evolved in ways that optimize survival in relation to oceanographic as well as estuarine and riverine environments (Nicholas and Hankin, 1988).

Four major characteristics of the local upwelling system appear to play an important role in the ocean survival of salmon.

1. Variations in the intensity, frequency, and relaxation of upwelling events influence biological production and the recruitment of pelagic marine fishes. Survival strategies associated with these patterns may vary by species.

Small and Menzies (1981) reported differences in the distribution of chlorophyll biomass and its productivity under different upwelling conditions off Oregon. During weak or intermittent periods of upwelling, the band of maximum chlorophyll was located against the coast and had very high concentrations. Productivity of chlorophyll bands during periods of relaxation between upwelling events could be twice that of the strong upwelling state and often 20 times that in the surrounding water. Peterson et al. (1979) found that very high concentrations of zooplankton off Oregon occurred shoreward of the upwelling front (the sharp interface between upwelled water and the warmer ocean water displaced offshore) and were carried below the pycnocline (density gradient) when upwelling relaxed. However, patterns of abundance of zooplankton populations varied by species.

The most favorable upwelling conditions for fish production also likely vary by species. Lasker (1978) found that physical factors associated with upwelling affected the survival of anchovy (*Engraulis mordax*) larvae and explained variations in year-class strength. Successful year classes were associated with calm periods between upwelling events that supported the production of favored prey species. Cury and Roy (1989) found evidence that successful recruitment of pelagic fishes depended on winds that were strong enough to promote upwelling but sufficiently calm to prevent turbulent mixing that disperses concentrations of food required for larval survival. They proposed upwelling speeds of 5-6 m/s as an optimal level. Cushing (1995) further notes that northern anchovy and sardine (*Sardinops sagax*) may have developed different survival strategies for upwelling systems: anchovy grow more slowly and can tolerate periods of low food availability and intermittent periods of stronger upwelling; sardine seem to grow more rapidly and favor a weaker but more persistent upwelling state. But both species appear to avoid spawning locations of the strongest upwelling. Such nonlinear relationships raise questions about the apparent threshold level of upwelling associated with juvenile coho salmon survival in the 1960s and 1970s, e.g., (Nickelson, 1986) or the shift to a negative relationship over the last decade (Jamir et al., 1994).

2. Geographic variations in coastal currents and upwelling affect patterns of biological production off Washington and Oregon. Such variations may be important to the survival and adaptations of salmon populations originating from different river systems and following different migratory paths.

The gradient in atmospheric pressure that produces southward winds along the coast varies with location and with seasonal and daily changes, creating geographic and temporal variation in winds, currents, and the strength of coastal upwelling. South of about 40 degrees north latitude (approximately Cape Mendocino, California), winds are southward throughout the year, while north of this location, winds are northward, and therefore, unfavorable for upwelling during the winter months. Upwelling occurs year-round from San Francisco south (Figure 10.2). Yet upwelling in this region has little influence on temperature distributions much of the year and, therefore, may be ineffective in overcoming the strong California Undercurrent and the downward sloping density gradient associated with it (Huyer, 1983). The average intensity of upwelling is relatively weak northward from the central Oregon coast. Upwelling off the narrow Oregon continental shelf is generally stronger than off Washington and more evenly distributed throughout the summer (Landry et al., 1989). Maximum upwelling off Washington occurs in June, one or two months earlier than along the Oregon coast. South of Coos Bay, coastal currents show considerable short-term variability, while a smoother seasonal cycle is apparent in currents from the central Oregon coast northward (Strub et al., 1987). Complex bathymetry and the orientation of the shoreline also result in considerable local variation in the intensity of upwelling (Huyer, 1983) with uncertain but potentially significant effects on local salmon stocks.

From geographic differences in winds, currents, bathymetry, and upwelling, Bottom et al. (1989) classified three major physical regions of the continental margin north of Cape Mendocino, California: (1) A Washington coastal region south to the mouth of the Columbia River; (2) a northern Oregon coastal region (south of the Columbia River to Cape Blanco); and (3) a southern

Oregon and Northern California region south to Cape Mendocino. The discontinuity in winds and currents at Cape Blanco is particularly noteworthy. The zone of upwelling and increased nutrients is wider south of Cape Blanco than along the central and northern Oregon coast, and influence of the Columbia River plume is reduced. Summer winds and upwelling are stronger and more variable than in regions to the north. Furthermore, strong offshore flow much greater than is explained by typical upwelling processes may have an important influence on the transport of phytoplankton biomass and could explain large-scale patterns of zooplankton in areas of the California Current (Abbott and Zion, 1987). It is interesting that the ocean migration patterns of coastal chinook (*O. tshawytscha*) stocks also show a discontinuity at Cape Blanco: Stocks from Elk River (located on the south side of Cape Blanco) and northward appear to rear in waters from Oregon to Alaska; stocks south of Elk River generally rear off southern Oregon and northern California (Nicholas and Hankin, 1988).

3. The coastal ocean off Washington and Oregon exhibits distinct winter and summer regimes. The shift to the summer upwelling regime occurs suddenly and the specific timing varies between years. While areas of coastal upwelling involve local scale events, the transition to a coastal upwelling regime is regulated by large-scale atmospheric conditions.

The annual northward migration and strengthening of the North Pacific High pressure system causes a shift in wind direction that produces the transition from a winter to a spring/summer regime in the coastal ocean off Washington and Oregon (Huyer, 1983). In the winter, coastal currents over the shelf are northward, sea levels are high, and downwelling occurs. Summer conditions are characterized by reduced sea levels, southward mean surface currents over a northward undercurrent, and a strong density gradient across the continental shelf (Strub et al., 1987). Southward winds and the resulting offshore flow raises cold, nutrient-rich water at the surface along the West Coast of the United States. The zone of active upwelling is generally restricted to a narrow coastal band (about 10-25 km) but the affected region can be much broader. The response of the coastal system to southward winds is very rapid. A single upwelling event of a few days' duration, typically in March or April, may be sufficient to cause the shift to the spring/summer regime (Huyer, 1983). Thus, timing of the onset of the transition relative to the period of smolt migration may be important to the survival of juvenile coho salmon (Pearcy, 1992).

Strub et al. (1987) report that the spring transition in sea level, currents, and temperatures is driven by the large-scale wind system at scales of 500 to 2,000 km at latitudes north of approximately 37^{o} N. Changes in wind patterns causing the transition are associated with the weakening and northward movement of the Aleutian Low Pressure system in March or April and the accompanying strengthening and movement of the North Pacific High. The progression of sea level, wind stress, and temperature from north to south suggests remote factors may be responsible for the large-scale spring transition.

4. The Columbia River plume influences the distribution of nutrients, salinity, and the upwelling front off Washington and Oregon. Changes in the river hydrograph associated with flow regulation may significantly impact coastal ecosystems.

Discharge from the Columbia River is the dominant source of freshwater runoff to the Washington and Oregon coast, particularly during the late spring and early summer. Both the Columbia and Fraser rivers are point sources of high nitrate, phosphate, and silicate near shore in winter and summer (Landry et al., 1989). The low salinity surface water of the plume represents an offshore extension of the estuary that varies seasonally in its location along the coast. During winter when surface currents are predominantly northward, the Columbia River plume forms a low-salinity tongue of cold water near the Washington coastline to the north (Landry et al., 1989). During the spring/summer regime, low salinity water from the Columbia River is located offshore and to the south off Oregon (Figure 10.3). The plume can extend beyond Cape Mendocino, California and its effects are even visible past San Francisco. Measurements in July 1961 reported the maximum depth of the plume as 2 meters off the Columbia River mouth and 0.5 meters off of Cape Blanco (Huyer, 1983). As a result of the influence of the Columbia River plume, variability in surface salinity is much greater in the Pacific Northwest than off California or in the subarctic region (Landry et al., 1989).

The Columbia River plume influences surface density gradients and the cross-shelf properties of coastal waters which may affect patterns of biological production and biomass. Specifically, the plume can retard offshore transport during upwelling, particularly when river flow is maximum (e.g., June). The zone of upwelling influence can be most narrow off northern Oregon where the Columbia River plume forms a partial barrier to the offshore movement of surface water (Huyer, 1983). Interaction between upwelling intensity and the volume of flow from the Columbia River affect the location of the upwelling front and, therefore, the distribution of chlorophyll and zooplankton biomass (see #1 above). During strong upwelling the Columbia River plume is advected far offshore. Changes in the distribution of the upwelling front may not only influence environmental conditions for emigrating juveniles but may be important to the movements of adult salmon. Coho salmon, for example, prefer temperatures between 11 and 14 degrees C, which are intermediate between the offshore ocean water (15 degrees to 17 degrees C) and upwelled water at the coast (8 degrees to 10 degrees C) (Smith, 1983). Short-term changes in temperature and feeding conditions that concentrate or disperse fish, in turn, create significant variations in salmon catch rates and landings (Nickelson et al., 1992).

The region of the Columbia River plume is a summertime spawning area for an endemic subpopulation of northern anchovy (Bakun, 1993). Local stability of the water column and circulation characteristics associated with the plume during the summer may provide the conditions needed to support larval production. A local minimum in wind velocity and upwelling intensity (< 500 m^3/s^3) minimize offshore transport while the low salinity lens of the plume maintains vertical stability and reduces turbulence. Furthermore, the density gradient at the interface of the plume and higher salinity surface waters may provide a counterclockwise circulation (Figure 10.3) that would benefit retention of larvae and other organisms (Bakun, 1993). Because such convergence zones tend to concentrate larvae and food particles, they are often important areas of secondary production.

Ebbesmeyer and Tangborn (*review draft*) conclude that impoundment of summer flows and releases during the winter by Columbia River dams have altered sea surface salinities from California to Alaska. In terms of the seasonal transition in coastal currents, this shift in the hydrograph results in a decrease in the volume of Columbia River water transported off the Oregon coast during the summer and an increase off Washington in the winter. In the last 60 years, salinity has decreased approximately 1.0 ppt over a distance of 500 km to the north and increased 0.6 ppt over the same distance to the south (Ebbesmeyer and Tangborn, *review draft*). The influence of the plume on other physical and biological properties—e.g., temperature, nutrients, density gradients, and the upwelling front—suggests that regulation of Columbia River flows may significantly affect coastal ecosystems of the California Current and subarctic region.

Horizontal Advection

The "classical view" of the eastern boundary regions of the world's oceans has generally assumed that local upwelling is the major factor controlling pelagic production (Bernal and McGowan, 1981). But over the last two decades, new evidence indicates that the productivity of the California Current is not entirely regulated by internal processes, but may be substantially influenced by input from outside the system. Both zoogeographic patterns and fluctuations of plankton biomass in the California Current point to large-scale processes that are not fully explained by upwelling.

The California Current is a transition zone between subarctic and subtropic water masses and the freshwater systems that enter the ocean along its landward boundary (Figure 10.4). Unlike the large semi-enclosed gyres that circulate in the Central and North Pacific, the California Current is a relatively open system affected by annual fluctuations in currents that contribute water of varying properties from adjacent water masses. After traversing eastward across the North Pacific, the Subarctic Current splits into the northward flowing and counterclockwise Alaskan Gyre and the southward flowing California Current. During the upwelling season, the California Current carries cold nutrient-rich water from the subarctic Pacific along the West Coast. When upwelling subsides in the fall and the downwelling season returns, the northward-flowing California Undercurrent (Davidson Current) appears at the surface and carries warm equatorial water inshore (Favorite et al., 1976).

In the 1960s, biogeographers discovered a close association between the major water masses of the Pacific Ocean as characterized by temperature and salinity profiles (Sverdrup et al., 1942) and the boundaries of large biotic provinces of the pelagic ocean as defined by the distributions of planktonic and nektonic species. North of the equator, Johnson and Brinton (1962) identified 3 major biotic provinces of the Pacific Ocean: A Subarctic assemblage associated with the nutrient-rich waters roughly north of 40 degrees north latitude, a Central Pacific faunal group corresponding to the oligotrophic waters of the central Pacific gyre, and a group of Transition Zone species occupying the boundary between these two groups along the east-west path of the Subarctic Current and West Wind Drift. Because these biological provinces correspond generally with the boundaries of large semi-enclosed ocean gyres, McGowan (1971; 1974) suggested that they represent discrete, functional ecosystems.

A major exception to these patterns is the California Current system, where a small number of coastal species endemic to the region co-occur with a larger mixture of subarctic, subtropic, and equatorial species, many near the peripheries of their distributional range (Johnson and Brinton, 1962; McGowan, 1971; McGowan, 1974). Researchers inferred from these results that remote physical factors controlling the input of water and species from other regions may be more important determinants of species composition and abundance in the California Current than biological interactions such as competition and predation (Bernal, 1981; Bernal and McGowan, 1981).

Patterns of zooplankton biomass provide evidence that outside forces may regulate biological productivity within the California Current system. Wickett (1967) first reported that annual concentrations of zooplankton off southern California vary directly and concentrations in the western Bering Sea vary inversely with the southward transport of water at the divergence of the California Current and the Alaskan gyre (see Figure 10.4). The influence of advection in the California Current was further supported by Bernal (1981) and Bernal and McGowan (1981) who correlated zooplankton abundance with the transport of low salinity water from the north. Chelton, et al. (1982) concluded that interannual variations in zooplankton biomass off California are not correlated with wind-induced upwelling but are explained by variations in the flow of the California Current itself. Zooplankton biomass may respond to changes in the amount of nutrients transported southward in the California Current and the depth of the thermocline, which influences the capacity of upwelling to enrich surface waters (Chelton, 1981; McClain and Thomas, 1983). Furthermore, fluctuations in the current are indicated by changes in coastal sea-level and are often but not always related to El Nino occurrences in the eastern tropical Pacific

(Chelton et al., 1982). Thus, physical and biological properties are dominated by a large-scale, interannual signal generated outside the California Current system.

Local upwelling may play a somewhat greater role in interannual variability off the Washington and Oregon Coast than off California. Unlike California (Chelton et al., 1982), monthly anomalies of temperature and salinity off Washington and Oregon in the summer are negatively correlated (Landry et al., 1989), which is an indicator of the upward advection of cold, high-salinity water during upwelling (as opposed to lower salinity water transported from the north). Monthly nutrient (nitrate) anomalies along the midshelf of Washington are also positively correlated with temperature and with upwelling. Landry et al. (1989) conclude that interannual scales of variability off Washington and Oregon are probably influenced by both regional and global scale processes. A global influence is suggested by a consistent pattern of temperature anomalies throughout the California Current and subarctic regions and by the influence of El Nino events in the eastern tropical Pacific. It is likely that a gradient of factors affect biological production along the California Current as evidenced by the north-south pattern in the variability of winds, currents, and upwelling (Figure 10.2); the latitudinal cline in the relative proportions of subarctic, transitional, and equatorial species (Chelton et al., 1982); the north-south gradient in the amount of Columbia River water found along the Oregon coast during the summer (Figure 10.3); and the southward decline in the relative proportion of protected inland bay and estuarine habitat from British Columbia to California (Nickelson, 1984; Bottom et al., 1986).

Interannual variations along this California Current ecotone create special challenges for southern salmonid stocks, which are generally less productive in Washington and Oregon compared with areas located nearer the center of their range (Fredin, 1980). Fulton and LeBrasseur (1985) defined a subarctic boundary based on interannual variations in the distribution of mean zooplankton biomass (Figure 10.5). They reported a large area between Cape Mendocino and the Queen Charlotte Islands where the transition between high and low biomass varied widely between extreme "cold" and "warm" years (e.g., during strong El Nino events). They hypothesized that in years of strong southward advection of cold water, the larger zooplankton characteristic of the subarctic water mass may provide a better source of food for juvenile pink (*O. gorbuscha*) salmon than the smaller species otherwise typical of the California Current. As noted above, the strength of southward advection changes not only during El Nino events. Interannual variations in the subarctic boundary, the location of the divergence of the California Current, and associated changes in temperature, zooplankton, or other conditions may be particularly important to the survival of the southernmost stocks of subarctic salmon.

Attempts to explain variations in the year-class strength of marine fishes have often emphasized effects of food availability on larval survival, e.g., (Lasker, 1978; Cushing, 1995). However, advective processes may also exert a direct physical influence on survival and interannual variability of some pelagic fishes. For example, survival rates to age 1 of Pacific mackerel (*Scomber japonicus*) increases during years of low southward transport (as indicated by high coastal sea level) and relatively low zooplankton biomass, which, in turn, are related to El Nino events in the eastern tropical Pacific (Sinclair et al., 1985). Conversely, poor survival is associated with strong southward flow of the California Current when zooplankton biomasses are generally higher. In this case, Sinclair et al. (1985) proposed that survival rates of Pacific mackerel during early life history may be influenced directly by interannual changes in hydrographic processes rather than by biological interactions. This hypothesis emphasizes that loss of larvae from the appropriate geographic location may be as critical to survival as the condition of the feeding environment.

The influence of advective processes on year-to-year salmon survival is unclear. Unlike larval fishes, salmon are free swimming when they enter the ocean, but at small sizes their distribution may be affected by the strength of surface currents. Pearcy (1992) found that juvenile salmon from Oregon and Washington generally swim northward against the current. However, during May and June soon after they entered the ocean, juvenile coho off Oregon were captured south of the area of ocean entrance, suggesting a southward advection of the smallest fish during their first few weeks in the ocean. Later in the summer, when currents were weaker and fish were larger, most young salmon were caught north of their point of ocean entry. The fact that year-class strength of coho salmon may be decided sometime within the first few weeks in the ocean (Fisher and Pearcy, 1988) suggests that early survival conditions perhaps not far from the point of ocean entry may be critical. Many of the juvenile coho salmon sampled by Pearcy and Fisher (1988) did not migrate long distances northward, although earlier tagging studies (1956-1970) of maturing salmon demonstrated that coho and chinook juveniles from California, Oregon, and Washington migrate into the Gulf of Alaska. In September, during the strong El Nino event of 1983, most juvenile salmon were distributed further north off Washington than in other years surveyed, suggesting either an increased northward migration of fish, or a proportionally greater mortality of those fish remaining in the southern portions of the study area (Pearcy and Fisher, 1988).

The surveys of salmon distribution off Washington and Oregon in the early 1980s (Pearcy and Fisher, 1988; Pearcy and Fisher, 1990) may or may not be representative of the movements of local salmon stocks under variable current conditions. These surveys were completed after wild populations of salmon had been reduced to a small proportion of the total quantity in the region and during a period of relatively warm ocean conditions, poor upwelling, and reduced flow of the California Current. Wild stocks may or may not exhibit these same patterns, and movements could change under conditions of strong upwelling and increased southward transport. However, as proposed for larvae and fry of marine species (Sinclair, 1988), advective processes could have a direct physical influence on early migrant salmon by determining whether the geographic distributions of local stocks are appropriate to prevent losses from populations.

The El Nino-Southern Oscillation Cycle and Influences on Salmon Production

Until 30 years ago, El Nino was believed to be the result of local changes in the winds that produced upwelling along the coasts of Peru and Ecuador (Mann and Lazier, 1991). Oceanographers later discovered that this upwelling system was part of a higher level of organization involving global winds and ocean dynamics across the entire Pacific Ocean basin. They concluded that the upwelling system is a component of the global heat budget such that the physical and biological characteristics of coastal systems change as the thermal budget of the ocean and atmosphere is disturbed (Barber, 1988). While local upwelling may operate somewhat independently, it is also an integral part of the larger thermal structure of the ocean, which determines whether or not upwelling is able to enrich surface waters with nutrients (Barber, 1983). Barber (1988) describes this single interconnected system, which is structured by the El Nino/Southern Oscillation (ENSO) cycle in the tropical Pacific, as the "basinwide ocean ecosystem." Within this large ecosystem, habitats continually shift, producing opposing regions of abundance and scarcity with the displacement of entire water masses and changes in the thermal structure of particular locales (Sharp, 1991). Although not all changes in the North Pacific can be traced to El Nino, the oscillations in the equatorial Pacific nonetheless provide important clues about the basinwide processes that shape the biotic structure and productivity of salmon ecosystems.

The ENSO cycle is reviewed by Mysak (1986), Barber (1988), and Enfield (1989) and is only briefly summarized here. El Nino originally referred to a warm southward current off the coast of Ecuador and Peru that generally begins around Christmas and persists for about three months. In more recent years, the term has been applied to periods of exceptionally strong warming that usually begin around January, last more than one season, and cause economic crisis associated with mortality of pelagic fish and guano birds (Mysak, 1986). El Nino is one part of a basinwide oscillation in the atmospheric pressure gradient of the equatorial Pacific known as the southern oscillation. The oscillation refers to shifts between the South Pacific high pressure system and the Indonesian low pressure system that cause changes in the westward trade winds along the equator. The interaction of the trade winds and mid-latitude westerlies with the ocean creates a slope in the sea level and in temperature, density, and nutrient gradients across the ocean basin (Figure 10.6) (Barber, 1988).

Because the Pacific Ocean is warmest in the west, strong convection and evaporation cause air to rise, creating a low pressure system in the western basin, and contributing to the upward portion of the east-west atmospheric circulation shown in Figure 10.6. Equatorward trade winds in the eastern boundary of the basin cause upwelling of cool subsurface water, which extracts heat from the atmosphere and forms the South Pacific high pressure system. The trade winds associated with this high pressure transport water westward across the basin, where it is warmed by the sun, and maintain the westward tilt in the thermocline. This ocean-air interaction involves a positive feedback system that amplifies initial conditions: The basinwide temperature gradient produces the pressure gradient that forces the trade winds, while the trade winds cause the ocean circulation that sustains the temperature differential between east and west (Barber, 1988).

El Nino occurs when a critical break-point is reached in this feedback process causing a sudden "flip" in the system, which otherwise maintains higher productivity in the eastern portion of the tropical Pacific due to the shallow thermal structure and upwelling of nutrients. Increasing instability in the east-west thermal gradient results as the trade winds continue to increase the volume of warm surface water in the west, causing the warm pool to expand eastward together with the region of atmospheric heating. As the associated low pressure system also migrates eastward, weakening and reversals in the trade winds produce internal waves that cause warm surface water to rush into the eastern basin. These waves and the migration of warm water deepen the thermocline, so that upwelling is less effective in raising cool water to the surface. Further warming and migration of the zone of atmospheric heating eastward finally produces the sustained low productivity state of El Nino (Barber, 1988). Thus the eastern upwelling region takes on the physical and biological characteristics of the less productive western basin.

Through its connections to the equatorial Pacific, the upwelling system, thermal structure, and biotic assemblage of the California Current may be directly affected by El Nino. At the height of El Nino, warm water drains toward both poles, reducing the warm pool in the eastern basin and influencing conditions in the northeast Pacific and the Southern Ocean. The California Undercurrent, which carries warm water northward along the West Coast of the United States, thus may serve as a "release valve" for the build-up of heat in the tropical Pacific, and may be involved in the resetting of the ENSO cycle to the cold (La Nina) phase (Barber, 1988). Following the mature phase of El Nino in the winter and spring, southward flow of the California Current is reduced (Chelton et al., 1982) and the strength of northward flow in the California Undercurrent is increased (McClain and Thomas, 1983; Mysak, 1986). Responses to El Nino along the West Coast of the United States may include elevated sea levels and sea surface temperatures, increased thermocline depths, and the northward expansion of the ranges of southern species (McClain and Thomas, 1983).

Two mechanisms have been suggested to explain El Nino responses along the North American coast (Mysak, 1986). The first involves the northward propagation of coastal Kelvin waves, a class of shallow-water waves, which are generated along the coast by changes in the tilt of the thermocline toward the western Pacific. Evidence of this connection is shown by interannual variations in sea level in the Gulf of California that are correlated with El Nino occurrences and the slowing or reversal of the California Current during strong El Nino events (Mysak, 1986; Mann and Lazier, 1991). Mysak (1986) argues, however, that the strong influence of the 1982-83 El Nino as far north as Alaska may be more indicative of an atmospheric link (teleconnection) with the tropics rather than a direct oceanic influence. The waves generated at the equator may not propagate to the far north because their movement will halt at a point where the thermocline rises to the surface. However, anomalously high temperatures in the eastern tropical Pacific transfers energy to the atmosphere that can influence winds and weather patterns thousands of miles to the north (Norton et al., 1985). Mysak (1986) proposes that atmospheric changes associated with the strengthening of the Aleutian Low Pressure system during the winter may explain warm conditions in the Northeast Pacific. The pattern of anomalous pressure that often forms during the warm phase of El Nino involves an atmospheric chain of low and high pressure systems (Figure 10.7). This pattern brings westerlies further north than usual and causes a southward shift in the paths of storm tracks along the west coast of the United States. During periods of an intensified Aleutian Low pressure system, surface winds along the west coast are generally strong from the southwest, causing a longer than normal period of downwelling and an anomalous onshore transport of warm water from the south.

Although many researchers now emphasize the role of atmospheric teleconnections as the primary link between El Nino and conditions in the North Pacific region, e.g., (Mysak, 1986), recent evidence suggests that direct oceanic linkages might also involve greater distances, higher latitudes, and a longer "memory" of tropical disturbances than previously thought. Jacobs et al. (1994) offer indirect evidence that planetary-scale (Rossby) waves, which are a class of waves that depend on the curvature and rotation of the earth, were reflected westward from the American coasts following the strong 1982-83 El Nino. They hypothesize that these may have crossed the North Pacific and a decade later caused a northward displacement (to approximately 40^{o} N) of the Kuroshio Extension off Japan, a current that advects heat eastward along the path of the Subarctic Current (Figure 10.4). Results of both satellite data and numerical modeling suggest these changes may have caused transport of anomalously warm water into the North Pacific. If these interpretations are correct, then effects of El Nino conditions on North Pacific circulation and weather patterns may persist long after an event has dissipated in the tropics. Chelton and Schlax (1996) note that Rossby waves are important in adjusting ocean circulation to large-scale changes in the atmosphere, but that recent satellite observations suggest a more rapid response than is generally predicted by accepted theory.

While El Nino events usually occur with a frequency of 3 to 7 years, climatologists and oceanographers have also described abrupt shifts in the predominant patterns of atmospheric circulation, oceanic currents, and thermal regimes that may persist for several decades. These interdecadal shifts, which may be linked by teleconnections to conditions in the tropical Pacific and often follow strong El Nino events, involve extended periods of eastward migration and intensification of the Aleutian Low pressure system during the winter half of the year (Trenberth, 1990). The most recent shift occurred in 1976-77, when a strengthened Aleutian Low caused a southward migration of storm tracks, anomalous southerly winds and warming along the west coast of North America and Alaska, and anomalous northerly winds and cold temperatures in the Central North Pacific region (between Japan and 160^{o} N) (Trenberth, 1990; Ebbesmeyer et al., 1991). In the Northeast Pacific, the pattern of strong Aleutian Low is associated with a rise in sea level and ocean surface temperature; reduced flow of the California Current (Mann and Lazier, 1991); and reduced precipitation, increased river temperatures, and low stream flow conditions in Oregon (Greenland, 1994).

The relationship between El Nino and atmospheric and oceanic conditions in the North Pacific is not a simple one-to-one correspondence. For example, ENSO events can occur without causing a change in the Aleutian Low pressure system, and warm water conditions in the North Pacific may be present in the absence of El Nino (Mysak, 1986). A 1972-73 warming off California occurred without a change in the atmospheric circulation, suggesting a direct oceanic connection to a strong El Nino event (Norton et al., 1985), while the moderate El Nino of 1976 produced the strongest Aleutian Low in a 36-year period of record (Mysak, 1986). The climatic effects of large pressure anomalies that often form in response to strong El Ninos also may vary. The degree of warming and the effects on precipitation depend on the particular latitude of storm tracks and the position of the low pressure system relative to the coast (Roden, 1989). The climatic response to El Nino in the Pacific Northwest, for example, may vary with the strength of the teleconnections. Thus the Northwest may fall inside or on the southern edge of a region of lower rainfall following a particular ENSO event (Melack et al., In press).

The frequency and intensity of El Nino events also exhibits patterns of variation. Through a reconstruction of El Nino occurrences over the last 450 years, Quinn et al. (1987) note that intervals between strong and very strong events have averaged close to 10 years, but may range from 4 or 5-year intervals to as high as 14 to 20 years. El Ninos classified as "very strong" such as the 1982-83 event are rare, and have occurred with a frequency of 14 to 63 years. Decadal or longer climatic changes are indicated by extended periods of unusually strong El Nino activity. Examples include the periods 1701-1728, 1812-1832, 1864-1891, and 1925-1932 (Quinn et al., 1987). Recent El Nino activity is also associated with the extended period of climatic change that accompanied the most recent shift in the Aleutian Low pressure system in 1976-77. For example, three major El Nino events have been recorded since 1981 with only one major intervening cold (La Nina) event (Kumar et al., 1994). Furthermore, warm ocean conditions have persisted in the tropical Pacific since 1990. By comparison the only similar episode of sustained warming this century lasted only three years (1939-1941).

Recent changes in the tropical Pacific are raising questions about whether the general warming trend since 1976 might have influenced the frequency of ENSO cycles, and whether the increased heat itself could be an early sign of global warming from greenhouse gases (Kerr, 1994; Kumar et al., 1994). Such concerns are heightened by observations off southern California where, since 1950, the upper 100 meters of the ocean has shown a uniform 0.8^{o} C increase and associated mean sea level has increased by 0.9 mm/year (Roemmich, 1992). This warming has occurred despite an apparent increase in the intensity of upwelling favorable winds off southern California over the same period (Bakun, 1990). Roemmich and McGowan (1995) speculate that increased stratification from ocean warming has made upwelling less effective in raising nutrients to the surface and may account for an approximately 70% decline in zooplankton volume documented since 1951. While the causes of this general warming are not clear, the results illustrate how even moderate increases in temperature and adjustments in the ocean thermal structure might override the benefits of local upwelling to pelagic food chains.

The 1982-83 El Nino is described as the strongest this century. Johnson (1988) summarized the direct effects of this event on Oregon coastal and Columbia River stocks of salmon. The 1982-83 El Nino increased mortality of both adult and juvenile salmon. Evidence of increased mortality was shown by returns of adult coho salmon to the Oregon Production Area and tule fall chinook to the lower Columbia-Bonneville pool area that were much lower than the preseason prediction. Mean sizes of chinook and coho salmon that survived El Nino were much smaller than average, and fecundity of female coho salmon also was reduced. Unlike chinook stocks off southern Oregon and locally distributed stocks from the Columbia River, northward migrating populations from the Columbia River showed little or no decline in abundance during the El Nino (Johnson, 1988).

Similar effects on coho salmon production may have occurred during a strong 1957-58 El Nino (McGie, 1984; Pearcy, 1992). The mean weight of returning adults was low in 1959 (Johnson, 1988), and total ocean landings in 1960 from smolts that entered the ocean the previous year declined to its lowest level since 1917. Anomalously high water temperatures from 1957 to 1960 probably indicate that the relatively strong upwelling during this period was not effective in raising cold, nutrient-rich water above a deepened thermocline (Pearcy, 1992).

From scale analyses of survivors returning to Tenmile Lakes, Oregon, Bottom (Bottom, 1985) reported little interannual variability in the relative growth of juvenile coho salmon over a wide range of upwelling conditions and salmon survival rates (among 13 brood years of salmon sampled between 1954 and 1981). A major exception to these results was the larger than average growth rates among those juveniles that entered the ocean during the 1983 El Nino and survived to return as adults in 1984. These results are consistent with the hypothesis of a brood failure during 1983, which might have caused better than average growth rates among the survivors if ocean habitats were not seeded to their capacity (Isles, 1980; Lichatowich, 1993). Survival of smolts entering the ocean during El Nino was very poor and stock density was likely quite low as indicated by the return of two-year-old coho jacks in the fall of 1983 (Johnson 1988). The direct mortality of adults during this strong El Nino suggests a (Johnson, 1988) different scale, habitat, and mechanism of population regulation than the control of juvenile survival, which occurs soon after smolts enter the coastal ocean (Nickelson, 1986; Pearcy, 1992).

In summary, local responses to remote atmospheric and oceanic disturbances support the concept of an interconnected basinwide ecosystem in which the background conditions for different regions of the Pacific Ocean continually shift in response to the global heat budget (Barber, 1988). It is within this shifting background of oceanic and atmospheric conditions that local and regional scales of processes are embedded. Basinwide forcing produces different responses among regions based on the distribution of atmospheric pressure gradients and their influence on local winds, currents, upwelling, ocean thermal structure, and precipitation patterns. Thus, for example, an increase in the intensity and extent of the wintertime Aleutian Low tends to cause cooling in the western subarctic Pacific at the same time it is warming the eastern subarctic Pacific.

Within the California Current, remote forces regulate the thermal structure and, through advective processes, determine the along shore distribution of nutrients and the location of the subarctic boundary (Figure 10.5). Three types of forcing mechanisms may be involved in periods of warming in the California Current: (1) depression of the thermocline, strengthening of the California Undercurrent, and decreased effectiveness of upwelling during El Nino events; (2) decreased southward advection from the subarctic divergence into the California Current and increased northward advection into the Alaskan gyre related to the strengthening of the wintertime Aleutian Low pressure system; and (3) increased periods of downwelling, decreased intensity of upwelling, and changes in the onset of the spring transition caused by shifts in the regional wind field also associated with patterns of the Aleutian Low (Norton et al., 1985). The specific responses along the Washington or Oregon coast involve the interaction of many scales of variability. Different scales of processes may invoke different mechanisms of population regulation as illustrated, for example, by the interannual influence of upwelling on the survival of juvenile coho salmon (Nickelson, 1986) and the less frequent effects of strong El Nino conditions on the growth and survival of adults and juveniles (Johnson, 1988).

INTERDECADAL CYCLES IN SALMON PRODUCTION

In recent years interdecadal variations in fish populations have been traced to large-scale climatic changes influencing oceanic regimes. Perhaps most dramatic are the analyses indicating synchronous trends in sardine (*Sardinops* sp.) abundance (as indicated by harvest) from three widely separated regions of the Pacific Ocean basin: California, Japan, and Chile (Figure 10.8) (Kawasaki, 1983). The specific relationships explaining the 40-year cycle in abundance is not clear, but all three stocks appear to track variations in mean surface air temperatures in the northern hemisphere. These relationships may be a proxy for changes associated with basinwide winds and conditions in upwelling systems that somehow influence sardine recruitment. In the eastern Pacific, sardine appear to favor shifts from a cool, upwelling-dominated regime to periods of reduced wind strength (Sharp, 1992; Cushing, 1995). Although the region of sardines off Japan is not generally considered an upwelling system, the same large-scale changes in wind stress may influence the frontal system shoreward of the Kuroshio Current to the benefit of sardine (Cushing, 1995). A rapid increase in Japan sardine from a very strong 1970 year class was related to a shift in the Kuroshio Current, which created an expanded sardine spawning area, increased egg abundance, a broad area favoring copepod production, and increased survival of sardine post-larvae (Lluch-Belda et al., 1992). Basinwide regime shifts are not only reflected in patterns of sardine abundance, but involve coherent changes in the organization of entire pelagic assemblages. Anchovies (*Engraulis* spp.) and their associated predators—hake (Merlucidae), mackerel (*Scomber scomber*), bonito (*Sarda* spp.), and seabirds—are abundant during the opposing cooler upwelling periods. On the other hand, Jack mackerels (*Trachurus* spp.), chub mackerels (other *Scomber* spp.), and other Transition Zone predators are associated with the warmer periods favored by sardine (Sharp, 1992).

Climate changes across the Pacific Basin also may explain interdecadal cycles in salmon production. Beamish and Bouillon (1993) document synchronous trends in pink, chum, and sockeye salmon abundance estimated from the combined annual harvests in U.S., Canadian, Japanese, and Russian fisheries. These trends as well as abundance of copepods sampled at Ocean Station P (50^{o}N, 145^{o}W) were associated with an Aleutian Low Pressure Index. Combined all-nation harvest for all salmon species averaged 673,100 t from the mid-1920s to the early 1940s and reached a peak of 837,400 t in 1939. After a period of low catch from the mid-1940s to a minimum in 1974, production again climbed to nearly 720,000 t in 1985. These patterns generally follow trends in the Aleutian Low Pressure Index (Figure 10.9). A profound shift in climatic regime of the North Pacific in 1976-77 (Ebbesmeyer et al., 1991) was associated with the strongest Aleutian Low since 1940-41. In addition to corresponding increases in salmon abundance, this shift is implicated in the almost doubling of chlorophyll *a* in the central north Pacific north of Hawaii (Venrick et al., 1987), a doubling of summer zooplankton abundance in the Alaskan gyral between 1956 to 1962 and 1980 to 1989 (Brodeur and Ware, 1992), simultaneous increases in the abundance of a variety of nonsalmonid fishes in various regions of the North Pacific (Beamish, 1993), and increases in prey availability for marine birds and mammals (Francis, 1996).

Through time series analysis, Francis and Hare (1994) and Francis et al. (1996) describe multidecadal variations in salmon production associated with sudden changes in atmospheric conditions of the North Pacific. Their results show a close correlation between physical and biological conditions of the North Pacific spanning four major oceanic/atmospheric regimes this century: 1900 to 1924, 1925 to 1946, 1947 to 1976, and 1977 to the present. The regimes beginning in 1925 and in 1977 were associated with periods of high salmon abundance in the Gulf of Alaska. Variations in the harvest of coho and chinook salmon from Washington and Oregon also show interdecadal patterns, but these fluctuate out of phase with the more northerly stocks of pink, chum, and sockeye salmon in the Gulf of Alaska (Figure 10.10) (Francis, 1993).

The influence of large-scale atmospheric changes on the ocean environment and, in turn, Oregon salmon, are further indicated by an inverse relationship between salmon harvest and annual mean temperatures in western Oregon (Figure 10.11) (Greenland, 1994). This contrasts with a positive relationship between pink salmon harvest, winter air temperatures, and winter sea surface temperatures in the Gulf of Alaska (Francis and Sibley, 1991). These opposing patterns are consistent with the hypothesis that atmospheric forcing influences the position of the subarctic divergence and relative flows into the Alaska and California Currents: periods of a strong Aleutian Low and increased northward flows into the Alaska Current may reduce southward flows into the California Current and vice versa with inverse effects on the productivities of each region (Wickett, 1967). To explain these regional differences, Francis and Sibley (1991) and Francis (1993) use a model by Hollowed and Wooster (1992), which proposes two average conditions in the North Pacific designated as Type A and Type B. Type B conditions are represented by a strong Aleutian Low centered in the east, increased southwesterly winds and increased downwelling, greater northward advection into the Alaska Current, decreased southward flow of the California Current, and above average temperatures in the northeast Pacific. Type A conditions are characterized by the opposite trends. Francis (1993) proposes that salmon production tracks abrupt shifts in these sets of conditions with periods of high productivity in the Gulf of Alaska generally associated with the type B state. Interestingly, the shift from Type A to Type B conditions over the last 60 years has always coincided with significant El Nino events in the tropical Pacific (Francis, 1993).

Patterns of salmon production in Oregon involve coherent ecological changes in the region of the California Current. Trends in average harvest of coho salmon, for example, appear to follow a similar pattern to the combined biomass of dominant pelagic species (hake, anchovy, and

California sardine) estimated from fish scales deposited in anaerobic marine sediments off California (Figure 10.12) (Smith, 1978; Lichatowich, 1993). Ware and Thomson (1991) identified a 40 to 60-year cycle in wind and upwelling conditions that may influence long period fluctuations in pelagic fish biomass off southern California. They report an extended period of relaxation in upwelling and primary production between 1916 and 1942, which also coincides with the decline in total fish biomass. However, abundances of California sardine this century are out-of-phase with the trends in combined biomasses of pelagic species (including sardine) shown in Figure 10.12 (Lluch-Belda et al., 1992). Sardine populations off California were abundant before the 1950s, very low in abundance between 1950 and the late 1970s, and increased from the late 1970s to the mid-1980s. Both the period of peak sardine production this century and the recent recovery beginning in the late 1970s coincide with periods of relaxation of upwelling, which, as noted above, tend to favor strong recruitment of sardine (Bakun, 1990; Lluch-Belda et al., 1992).

The same climatic conditions that influence the ocean environment of salmon also affect the quality of their freshwater habitats. For example, in a review of the climate on the H.J. Andrews (HJA) Experimental Forest in western Oregon, Greenland (1994) found correlations between various indices of atmospheric circulation with temperature and precipitation. The results indicate that during periods of a strong Aleutian low (as suggested by correlations with the Pacific North America and Central North Pacific teleconnective indices), storms are pushed north of Oregon, causing relatively dry weather during the winter and raising January air temperatures due to the southwesterly flow of warm air into the region. These patterns are also associated with El Nino events. During many El Nino years, winter water year precipitation on the HJA Forest is low, and annual mean temperatures are high, while in La Nina years, winter precipitation increases, particularly a year later, and annual temperatures are below average. The influence of both low precipitation and high stream temperatures in much of the Pacific Northwest may cause a reduced snowpack during El Nino years (Greenland, 1994).

These results underscore the importance of geographic heterogeneity to salmon production in a shifting climate. While interdecadal regimes affect vast areas, the degree of independence between freshwater and ocean conditions may be important to salmon resilience. In western Oregon, stream and ocean conditions affecting salmon survival tend to oscillate in phase. That is, during periods of warm ocean conditions and reduced flow of the California Current, freshwater habitat conditions may also decline due to reduced stream flows and increasing river temperatures in western Oregon (Greenland, 1994). These effects suggest a kind of "double jeopardy" for salmon stocks caused by a synchrony of mortality factors that involve more than one stage of life history. It is also possible that in other regions or among diverse watersheds within large basins like the Columbia River, ocean and river conditions for salmon survival are not in phase so that the effects of large-scale climatic change may be dampened. For example, since 1980, during a favorable regime for salmon survival in the Gulf of Alaska, annual precipitation on the coast of British Columbia has been above average. On the other hand, discharge of the large Fraser River declined during the same period due to reduced snowpack in the interior of British Columbia (Beamish, 1993). These varying degrees of "connectedness" between the environments supporting different salmon life stages illustrate the importance of stock diversity and habitat heterogeneity to dampen the otherwise synchronous effects of large-scale climatic change.

SALMON MANAGEMENT IN A SEA OF CHANGE

The Pacific Ocean and atmosphere do not move toward a steady state condition but continually shift in response to changes in the global heat budget. In fact, it is the lack of stability in the basinwide ecosystem that stimulates periods of enhanced biological production (Sharp, 1992). For example, the spring/summer transition to an upwelling regime disrupts a stable water column, raising cold nutrient-rich water trapped below the thermocline and increasing primary and secondary productivity along the Washington and Oregon coast. Interannual shifts in basinwide winds similarly change the flow of the California Current and the southward advection of nutrients from the subarctic region. Shifts in ocean currents and water masses are nonlinear and occur suddenly as environmental variations are amplified by positive feedbacks between the ocean and atmosphere. Thus, the gradual build-up of warm water in the western Pacific, for example, suddenly triggers the shift to El Nino. Strong teleconnections during some ENSO events, in turn, may influence the shift to a strengthened wintertime Aleutian Low and benefit salmon production in the subarctic Pacific to the detriment of production off Washington and Oregon. It is only at a basinwide scale that the shifting of locations of biological increase and decline become apparent.

Regime shifts reset ecological conditions within different oceanic regions by changing the composition of marine assemblages and altering the physical environment. Thus, local salmon populations may encounter different combinations of conditions each year they enter the coastal ocean as determined by the basinwide climatic regime and its interactions with regional and local scales of variation. Such changes alter the carrying capacity "rules" by changing the interrelationships that govern how much of the ocean's productive capacity may be realized by salmon or other species. New interactions might explain, for example, why coho salmon survival was positively correlated with upwelling under one oceanic regime in the 1960s and early 1970s, and negatively correlated under a different regime during the last decade (Jamir et al., 1994). A similar shift in environmental relationships is described by Skud (1982), who concluded that correlations between a species and environmental factors may shift from positive to negative with changes in the dominance hierarchy. In this case, Atlantic herring (*Clupea harengus*) abundance was positively correlated with temperature when herring was the dominant species and negatively correlated when Atlantic mackerel (*Scomber scombrus*) assumed the dominant position (and visa versa). Skud (1982) proposed that abiotic factors determine the overall composition of assemblages but that absolute population density of the subordinate species is regulated by density-dependent interactions. This does not argue that the failure of correlations with physical parameters always involve a shift in dominance. Regardless of the specific mechanisms of control, oceanic regime shifts may introduce new sets of conditions that qualitatively change the relationships between a species and selected environmental indicators. Thus, forecasts based on short-term statistical analyses are likely to fail because the biological response patterns may vary under different environmental regimes (Sharp, 1992).

Nonlinear changes in the basinwide ecosystem that dramatically alter both freshwater and marine conditions for salmon call into question management programs that emphasize constancy of the natural environment. Conservation programs that were designed under one climatic regime may not be appropriately applied under another. For example, the same levels of artificial propagation established during optimum ocean conditions may not be appropriate following a shift to a low productivity state (Beamish and Bouillon, 1993). Genetic or ecological risks of hatchery programs on wild salmonids might increase disproportionately during poor survival conditions due to intensified harvest pressures or interactions with hatchery fish. The costs of hatchery production alone raise questions about continuing high levels of smolt release following a shift to a low survival regime.

Variations in the ocean environment also undermine the assumptions of traditional population models that are often used to establish escapement goals and set harvest levels in fisheries. The maximum sustained yield (MSY) concept is based on a logistic growth curve developed from animal populations held under a constant food supply and environmental conditions (Botkin, 1990). According to this theory, natural populations reach a stable equilibrium level (carrying capacity) which is set by available resources. Stock recruitment models thus assume that abundance of a salmon population is regulated primarily by density-dependent factors during early life stages in fresh water. In practice, spawner-recruit relationships used to manage fisheries rely on multiple years of observation to show an "average" relationship between population size and the resulting recruitment. Thus, rather than trying to understand the effects of environmental change on populations, traditional harvest models assume that change is insignificant by averaging conditions over the period of observation (Cushing, 1995). In a system that oscillates unpredictably between different climatic states, and where physical changes continually reset ecological conditions and regulate ocean survival of salmon smolts, theoretical population models may offer little practical guidance for long-term conservation.

Within the Columbia River basin, salmon management has been designed around efforts to create a stable river system for the benefit of various economic uses. The idea that hatcheries could increase salmon production by eliminating variability ("limiting factors") in the freshwater environment was consistent with efforts to regulate the river (discussed in detail in Chapter 5 of this report). One important result of regulating the river with dams and controlling salmon production in hatcheries has been the narrowing of salmon life histories to conform to the rigid conditions imposed by the management system itself. Hatchery programs replace diverse riverine habitats with a constant rearing environment and replace diverse native stocks with a genetically uniform hatchery "product." By dampening seasonal fluctuations in the hydrograph, dam operations also reduce the diversity of freshwater habitats and the variety of flow conditions represented in the river. Furthermore, release strategies for hatchery salmon are programmed to fit the scheduled releases of water through the dams. Selective advantage is given to those fish that migrate downstream according to the operations of bypass, spill, and transportation systems. Unlike historical patterns of migration, which maximized use of freshwater habitats throughout the year and varied the time of ocean entry through a wide array of migratory behaviors, river operations concentrate the migrations of salmon through narrow "windows of opportunity" prescribed by the management system.

The problem with this approach is that it has failed to account for the effects of environmental control on other ecosystems or life stages of salmon "downstream." Regulation of river flows also directly controls the density and dynamics of offshore waters of the coastal ocean (Ebbesmeyer and Tangborn, *review draft*) and the inland waters of the Juan de Fuca Strait (Ebbesmeyer and Tangborn, 1992) with unknown consequences for natural production processes in these areas. Similarly, control of salmon life histories in the river may directly regulate the subsequent survival of salmon in the estuary and ocean. A variable ocean requires flexibility for anadromous species to successfully respond to a wide array of potential conditions. This flexibility may be particularly important in the highly variable environment of the California Current ecotone, which encompasses the southern edge of a shifting subarctic boundary (Figure 10.5) and the distributional limit of subarctic salmonids. A narrowing of the time of migration and physiological condition of salmon leaving the Columbia River limits the array of possible responses that may otherwise enable species to cope with fluctuations in the ocean. Different times of migration, for example, may be advantageous in different years depending on the onset of the spring/summer transition, the distribution of the Columbia River plume, the timing and location of upwelling episodes, or the northward extent of warming caused by occasional strong ENSO events in the tropics.

Loss of freshwater habitats within the Columbia River basin and the shift to production of a few hatchery stocks may also limit the variety of migratory pathways in the ocean to the detriment of salmon production. For example, since oceanic regimes in the California Current oscillate out of phase with those of the central North Pacific, we might expect north and south migrating stocks to be favored under opposing climatic states. This could explain the recent increasing trend in abundance of upriver bright fall chinook, which spawn in the Hanford area and tend to migrate off Southeast Alaska, and the coincidental decline of tule fall chinook from the lower river, which have a more southerly ocean migration. This pattern was reinforced during the 1982-83 El Nino when abundance of tule fall chinook decreased below preseason predictions while northward migrating populations in the Columbia River showed little or no decline (Johnson, 1988). As in this example, maintenance of a variety of migratory patterns in the ocean may depend on the protection of different freshwater habitats that support different populations and life histories.

The critical point is that the performance of salmon in the estuary or ocean is not independent of the selection processes in fresh water. Management manipulations that alter population structure, life histories, or habitat diversity during the fresh-water phase of life history may directly influence the capacity of salmon to withstand natural fluctuations in the estuary and ocean. Efforts to control variability in fresh water may unwittingly eliminate behaviors that buffer salmon production in an unstable marine environment. By the 1970s, about 2/3 of the coho salmon smolts produced in the Oregon Production Area consisted of only 2 stocks of fish released from numerous hatcheries in the Columbia River basin. Across Oregon, the replacement of a diversity of wild populations and life history patterns with relatively few hatchery-produced stocks may have depressed survival rates of smolts during poor ocean conditions and increased interannual variability of returning adult salmon (Bottom et al., 1986).

The location of Columbia River populations toward the southern range of salmon species and their sensitivity to changes in the coastal ocean raise concerns about the effects of global climate change on salmon production. Neitzel et al. (1991) discuss effects of global warming on fresh-water habitats of the Columbia River basin. Significant ecological changes in the ocean environment could also be critical to local salmon production. For example, Peterson et al. (1993) suggest that El Nino events in the eastern Pacific provide an indication of the kind of biogeographic shifts in the California Current that may accompany global warming. Although it is expected that upwelling favorable winds will increase in the northern hemisphere due to differential heating of the land and ocean (Bakun, 1990), depression of the nutricline will likely cause a decrease in the capacity of upwelling to raise nutrients to the surface (Peterson et al., 1993). This same mechanism has already been suggested as one possible explanation for a significant decline in zooplankton abundance off southern California since 1951 (Roemmich and McGowan, 1995). Increased upwelling will also increase offshore transport and thereby decrease the number of areas and time periods suitable for the spawning of many pelagic fishes such as anchovy and sardine. Peterson et al. (1993) hypothesize a shift in the California Current from short food chains leading to anchovy and sardine production to longer food chains favoring large migratory species such as albacore tuna (*Thunnus alalunga*) and jack mackerel (*Trachurus symmetricus*). Alternative energy pathways may also increase the production of demersal species. While the specific effects may vary in the northern reaches of the California Current off Washington and Oregon, the results may be detrimental to local salmon stocks if El Nino is an appropriate model of the qualities of future change. These results underscore the importance of maintaining habitat complexity and stock diversity in fresh water to help buffer potential effects of global warming on salmon survival in coastal environments.

CONCLUSIONS

1. Global and regional scale processes in the ocean and atmosphere can regulate the productivity of local marine, estuarine, and freshwater habitats for salmon. Although managers cannot control these processes, natural variability must be understood to correctly interpret the response of salmon to management actions in the Columbia Basin.

2. The North Pacific Ocean oscillates on an interdecadal time scale between alternate climatic states associated with changes in the Aleutian Low Pressure system. Years when the winter Aleutian Low is strong and centered in the eastern North Pacific are associated with a weakening of the southward flowing California Current and an intensification of the northward flowing California Undercurrent along the west coast of North America; high mean sea levels and increased ocean surface temperatures in the northeast Pacific; increased southwesterly winds and downwelling off Oregon and Washington; and reduced precipitation levels, low stream flows, and increased water temperatures in Oregon streams. Conversely, periods characterized by a weak winter Aleutian Low centered in the western North Pacific are associated with stronger mean flow of the California Current, enhanced westerly winds and upwelling in the Northeast Pacific, and increased rainfall and stream flows in Oregon. The timing of interdecadal shifts from a weak to a strong Aleutian Low regime may be linked to the Southern Oscillation in the tropics.

3. Because salmon migrations are tied to major ocean circulation systems and, because the life cycles of salmon are shorter than the interdecadal periods of large-scale climatic change, abundance of salmon "tracks" large-scale shifts in climatic regime. The specific mechanisms of this tracking are poorly understood.

4. Salmon abundances in the California Current region (off Washington, Oregon, and California) and in the Central North Pacific Ocean domain (off British Columbia and Alaska) respond in opposite ways to shifts in climatic regime. During periods of a strong Aleutian Low, zooplankton and salmon production generally increase in the Central North Pacific and decrease in the California Current, suggesting geographically distinct mechanisms of aquatic production. Climatic shifts characteristic of the strong Aleutian Low regime occurred twice this century: one beginning about 1925 (to 1946) and another in 1976/77 (to the present). Both periods were marked by precipitous declines in the coho salmon fishery off Oregon.

5. Opposing cycles of salmon abundance between the Central North Pacific and the California Current regions underscore the importance of stock-specific regulation of ocean fisheries. Even during periods of high marine survival off Oregon, harvest limits must ensure that Columbia Basin stocks are not overexploited by northern fisheries trying to compensate for coincidental decreases in the production of stocks from Alaska and British Columbia.

6. Stocks with different life history traits and ocean migration patterns may be favored under (or differentially tolerant of) different combinations of climatic regime and local habitat characteristics. Such differences afford stability to salmon species over multiple scales of environmental variability.

7. Together landscape modifications, construction of dams, overharvest in sport and commercial fisheries, and hatchery programs have simplified the geographic mosaic of habitat conditions in the Columbia River Basin and reduced the variety of salmon life histories formerly associated with this mosaic. Such changes limit the capacity of salmon to adapt to periodic shifts in large-scale atmospheric and oceanic conditions.

8. The cumulative effects of human disturbance may not become apparent until severe climatic stresses trigger a dramatic response. Such interactions may be particularly severe in the Pacific Northwest where periods of reduced ocean survival of salmon and periods of stressful freshwater conditions (due to reduced precipitation, low stream flow, and increased stream temperatures) tend to co-occur. Although climatic fluctuations may be a proximate factor in regional salmon decline, the ultimate causes may involve a longer history of change affecting species and population resilience into the future. Conservative standards of salmon protection may be necessary even during a high productivity state in order to maintain the genetic "slack" needed to withstand subsequent productivity troughs.

9. The dynamics of salmon metapopulations will change under different climatic regimes if, for example, the dispersal of core populations or the rate of extinction of satellite populations is a function of fish density. Habitat fragmentation and loss of local stocks will likely magnify the effects of productivity "troughs" by also increasing freshwater mortality, inhibiting recolonization of disturbed habitats, and slowing rates of population recovery. Thus, in concert with large-scale changes in climate, increases in the rates of local extinction and loss of stock diversity may lead to greater "synchrony" in the dynamics of salmon populations.

Regional patterns of salmon decline in the Columbia Basin and throughout much of the Pacific Northwest are generally consistent with this synchronization hypothesis.

10. Shifts in oceanic regime involve substantial changes in the distribution of species, the structure of marine food chains, and the physical processes of biological production. Anticipating such change and understanding its effects on salmon production in the Columbia Basin will require ecological indicators other than just the abundance of salmon.

CRITICAL UNCERTAINTIES

1. Lack of long-term monitoring of ocean conditions and the factors influencing survival of salmon during their first weeks or months at sea severely limit understanding of the specific causes of interdecadal fluctuations in salmon production. Such understanding is needed if management programs are to adapt to natural variations to insure rebuilding of salmon populations in the Columbia River.

2. Stock-specific distributions of Columbia Basin salmon in the ocean and the migratory patterns of hatchery versus wild salmon are poorly understood. It is important to know whether hatchery practices affect the migratory patterns and potential marine survival of salmon.

3. There is increasing evidence worldwide that ocean fisheries can have a destabilizing influence on marine food chains. Harvest management programs based on stock recruitment relationships and monitoring of individual species do not provide adequate indicators of the effects of harvest activities on ocean food webs.

4. The risks of global warming are potentially great for Columbia Basin salmon due to the sensitivity of southern salmon stocks to climate-related shifts in the position of the subarctic boundary, the strength of the California Current, the intensity of coastal upwelling, and the frequency and intensity of El Nino events. Some modelers believe that persistent warmth in the ocean and increased frequency of El Ninos after 1976 (without intervening "cold" La Nina episodes) may be among the early signs of global warming from greenhouse gases. Others speculate that an observed 70% decrease in the biomass of macrozooplankton off southern California since 1951 could be related to ocean warming associated with the 1976/77 regime shift or a climate-induced change in ocean circulation. While the potential effects of global

warming on ocean circulation patterns are poorly understood, the implications for salmon restoration efforts throughout the Pacific Northwest are tremendous.

RECOMMENDATIONS

1. Research on the uncertainties listed above should be encouraged because salmon management in freshwater must be linked to ocean properties and patterns if our alternative conceptual foundation that builds around the salmon life history ecosystem is adopted.

2. Research on effects of ocean conditions on productivity of salmon must to be integrated with estuarine and riverine research.

Literature Cited

Abbott, M.R. and P.M. Zion. 1987. Spatial and temporal variability of phytoplankton pigment off northern California during Coastal Ocean Dynamics Experiment 1. J. Geophysical Research 92(C2): 1745-1755.

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science 247: 198-207.

Bakun, A. 1993. The California current, Benguela current, and southwestern Atlantic shelf ecosystems: A comparative approach to identifying factors regulating biomass yields. Large Marine Ecosystems: Stress, Mitigation, and Sustainability. K. Sherman, L. M. Alexander and B. D. Gold. Washington, AAAS Press**:** 199-221.

Barber, R.T. 1988. Ocean basin ecosystems. Concepts of Ecosystem Ecology: A Comparative View. L. R. Pomeroy and J. J. Alberts. New York, Springer-Verlag**:** 171-193.

Barber, R.T. and R.L. Smith. 1981. Coastal upwelling ecosystems. Analysis of Marine Ecosystems. A. R. Longhurst. London, Academic Press**:** 31-68.

Barber, R.T.a.C., F. P. 1983. Biological consequences of El Nino. Science. 222**:** 1203-1210.

Beamish, R.J. 1993. Climate and exceptional fish production off the west coast of North America. Canadian J. Fish. Aquatic Sci. 50: 2270-2291.

Beamish, R.J. and D.R. Bouillon. 1993. Pacific salmon production trends in relation to climate. Can. J. Fish. Aquatic Sci. 50: 1002-1016.

Bernal, P.A. 1981. A review of low-frequency response of the pelagic ecosystem in the California current. California Coop. Fish. Investigations 22: 49-62.

Bernal, P.A. and J.A. McGowan. 1981. Advection and upwelling in the California current. Coastal Upwelling. F. A. Richards. Washington, Amer. Geophysical Union**:** 381-389.

Botkin, D.B. 1990. Discordant Harmonies: A New Ecology for the Twenty-First Centure. New York, Oxford University Press.

Bottom, D.J. In Press. To till the water: A history of ideas in fisheries conservation. Pacific Salmon and Their Ecosystems. D. J. Stouder, P. A. Bisson and R. J. Naiman. New York, Chapman and Hall.

Bottom, D.L. 1985. Research and Development of Oregon's coastal salmon stocks. Portland, Oregon Dept. Fish and Wildlife. Oregon.

Bottom, D.L. and K.K. Jones. 1990. Species composition, distribution, and invertebrate prey of fish assemblages in the Columbia River estuary. Prog. Oceanog. 25: 243-270.

Bottom, D.L., K.K. Jones and M.J. Herring. 1984. Fishes of the Columbia River Estuary. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Bottom, D.L., K.K. Jones, J.D. Rodgers and R.F. Brown. 1989. Management of Living Marine Resources: A Research Plan for the Washington and Oregon Continental Margin. Newport, Nat. Coastal Resources Research and Devt. Institute. Oregon.

Bottom, D.L., T.E. Nickelson and S.L. Johnson. 1986. Research and Development of Oregon's Coastal Salmon Stocks. Portland, Oregon Dept. Fish and Wildlife. Oregon.

Bradford, M.J. 1995. Comparative review of Pacific salmon survival rates. Can. J. Fish. Aquat. Sci. 52: 1327-1338.

Brodeur, R.D. and D.M. Ware. 1992. Interannual and interdecadal changes in zooplankton biomass in the subarctic Pacific Ocean. Fisheries Oceanography 1: 32-38.

Chelton, D.B. 1981. Interannual variability of the California current - physical factors. California Coop. Fisheries Investigations Report 22: 34-48.

Chelton, D.B., P.A. Bernal and J.A. McGowan. 1982. Large-scale interannual physical and biological interaction in the California current. J. Marine Research 40(4): 1095-1125.

Chelton, D.B. and M.G. Schlax. 1996. Global observations of oceanic Rossby waves. Science 272: 234-238.

Clark, J. and B. McCarl. 1983. An investigation of the relationship between Oregon coho salmon (*Oncorhynchus kisutch*) hatchery releases and adult production utilizing law of the minimum regression. Can. J. Fish. Aquat. Sci. 40(4): 516-523.

Cury, P. and C. Roy. 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Can. J. Fish. Aquat. Sci. 46: 670-680.

Cushing, D. 1995. Population production and regulation in the sea: A fisheries perspective. Cambridge, Cambridge University Press.

Day, J., John W., C.A.S. Hall, W.M. Kemp and A. Yáñez-Arancibia. 1989. Estuarine Ecology. New York, John Wiley and Sons.

Ebbesmeyer, C.C., D.R. Cayan, D.R. McClain, F.H. Nichols, D.H. Peterson and K.T. Redmond. 1991. 1976 step in Pacific climate: Forty environmental changes between 1968-1975 and 1977-1984. 7th Annual Pacific Climate (PACLIM) Workshop, April, 1990, California Dept. of Water Resources.

Ebbesmeyer, C.C. and W. Tangborn. 1992. Linkage of reservoir, coast, and strait dynamics, 1936-1990: Columbia River basin, Washington coast, and Juan de Fuca Strait. Interdisciplinary Approaches in Hydrology and Hydrogeology, American Institute of Hydrology**:** 288-299.

Ebbesmeyer, C.C. and W. Tangborn. *review draft.* Great Pacific salininty trends caused by diverting the Columbia River between seasons. Review draft. .

Emlen, J.M., R.R. Reisenbichler, A.M. McGie and T.E. Nickelson. 1990. Density-dependence at sea for coho salmon (*Oncorhynchus kisutch*). J. Fish. Res. Board of Can. 47: 1765-1772.

Enfield, D.B. 1989. El Niño past and present. Review in Geophysics 27: 159-187.

Favorite, F., A.J. Dodimead and K. Nasu. 1976. Oceanography of the subarctic Pacific region, 1960-71. Vancouver, Inter. North Pacific Fisheries Commission. British Columbia.

Fisher, J.P. and W.G. Pearcy. 1988. Growth of juvenile coho salmon (*Oncorhynchus kisutch*) in the ocean off Oregon and Washington, USA, in years of differing coastal upwelling. Can. J. Fish. Aquat. Sci. 45: 1036-1044.

Francis, R.C. 1993. Climate change and salmon production in the North Pacific Ocean. Ninth Annual Pacific Climate (PACLIM) Workshop, April 21-24, 1992, California Dept. of Water Resources.

Francis, R.C., Hare, S. R., Hollowed, A. B., Wooster, W. S. 1996. Effects of interdecadal climate variability on oceanic ecosystems of the northeast Pacific Ocean. Proceedings of the Twelfth Annual Pacific Climate (PACLIM) Workshop., California Department of Water Resources.

Francis, R.C. and S.R. Hare. 1994. Decadal-scale regime shifts in the large marine ecosystems of the northeast Pacific: A case for historical science. Fisheries Oceanography 3: 279-291.

Francis, R.C. and T.H. Sibley. 1991. Climate change and fisheries: What are the real issues? The Northwest Environmental Journal 7: 295-307.

Fredin, R.A. 1980. Trends in North Pacific salmon fisheries. Salmonid Ecosystems of the North Pacific. W. J. McNeil and D. C. Himsworth. Corvallis, Oregon State University Sea Grant College Program**:** 59-119.

Fulton, J.D. and R.J. LeBrasseur. 1985. Interannual shifting of the subarctic boundary and some of the biotic effects on juvenile salmonids. El Niño North: Niño Effects in the Eastern Subarctic Pacific Ocean. W. S. Wooster and D. L. Fluharty. Seattle, Washington Sea Grant Program, University of Washington**:** 237-247.

Graybill, M. and J. Hodder. 1985. Effects of the 1982-83 El Niño on reproduction of six species of seabirds in Oregon. El Niño North: Niño Effects in the Eastern Subarctic Pacific. W. S. Wooster and D. L. Fluharty. Seattle, Washington Sea Grant Program, University of Washington**:** 205-210.

Greenland, D. 1994. The Pacific Northwest regional context of the climate of the H. J. Andrews Experimental Forest. Northwest Science 69(2): 81-96.

Greenland, D. 1994. Salmon populations and large scale atmospheric events. Salmon Ecosystem Restoration: Myth and Reality, 1994 Northeast Pacific Chinook and Coho Salmon Workshop, Corvallis, Oregon, Oregon Chapter Amer. Fish. Soc.

Groot, C. and L. Margolis, Eds. 1991. Pacific salmon life histories. Vancouver, University of British Columbia.

Gunsolus, R.T. 1978. The Status of Oregon Coho and Recommendations for Managing the Production, Harvest, and Escapement of Wild and Hatchery-Reared Stocks. Clackamas, Oregon Dept. of Fish and Wildlife. Oregon.

Healey, M.C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, UBC Press.

Hollowed, A.B. and W.S. Wooster. 1992. Variability of winter ocean conditions and strong year classes of Northeast Pacific groundfish. ICES Marine Science Symposia 195: 433-444.

Huyer, A. 1983. Coastal upwelling in the California Current system. Progress in Oceanography 12: 259-284.

Isles, T.D. 1980. Environmental pressure and intra- and inter-year-class competition as determinants of year-class size. Rapports et Proces-verbaux des Reunions 177: 315-331.

Jacobs, G.A., H.E. Hurlbert, J.C. Kindle, E.J. Metzger, J.L. Mitchell, W.J. Teague and A.J. Wallcraft. 1994. Decade-scale trans-Pacific propagation and warming effects of an El Niño anomaly. Nature 370: 360-363.

Jamir, T.V., A. Huyer, W. Pearcy and J. Fisher. 1994. The influence of environmental factors on the marine survival of Oregon hatchery coho (*Oncorhynchus kisutch*). Salmon Ecosystem Restoration: Myth and Reality, 1994 Northeast Pacific Chinook and Coho Salmon Workshop, Corvallis, Oregon, Oregon Chapter Amer. Fish. Society.

Jeffries, E.R. 1975. Role and challenge of fish culture in the Northwest. 26th Annual Northwest Fish Culture Conference.

Johnson, M.W. and E. Brinton. 1962. Biological species, water-masses and currents. The Sea. M. N. Hill. New York, Interscience Publishers. 2**:** 381-414.

Johnson, S.L. 1988. The effects of the 1983 El Niño on Oregon's coho (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawtscha*) salmon. Fisheries Research 6: 105-123.

Kawasaki, T. 1983. Why do some pelagic fishes have wide fluctuations in their numbers? FAO Fish Report 291(3): 1065-1080.

Kerr, R.A. 1994. Did the tropical Pacific drive the world's warming? Science 266: 544-545.

Kumar, A., A. Leetmaa and M. Ji. 1994. Simulations of atmospheric variability induced by sea surface temperatures and implications for global warming. Science 266: 632-634.

Landry, M.R., J.R. Postel, W.K. Peterson and J. Newman. 1989. Borad-scale distributional patterns of hydrographic variables on the Washington/Oregon shelf. Coastal Oceanography of Washington and Oregon. M. R. Landry and B. M. Hickey. Elsevier, Elsevier. 47**:** 1-40.

Lasker, R. 1978. The relation between oceanographic conditions and larval anchovy food in the California Current: Identification of factors leading to recruitment failure. Rapports et Proces-verbaux des Reunions 173: 212-230.

Lawson, P.W. 1993. Cycles in ocean productivity, trends in habitat quality, and restoration of salmon runs in Oregon. Fisheries 18(8): 6-10.

Lichatowich, J. 1993. Ocean Carrying Capacity: Recovery issues for threatened and endangered Snake River Salmon. Portland, Bonneville Power Administration
U. S. Department of Energy. Oregon**:** 25.

Lichatowich, J.A. 1993. Ocean Carrying Capacity. Vashon Island, Mobrand Biometrics, Inc. Washington.

Lichatowich, J.A., L. Mobrand and T. Vogel. 1996. A History of Frameworks Used in the Management of Columbia River Chinook Salmon (Draft). Portland, Bonneville Power Administration. Oregon**:** 117.

Lluch-Belda, D., S. Hernandez-Vasquez, D.B. Lluch-Cota and C.A. Salinas-Zavala. 1992. The recovery of the California sardine as related to global change. California Coop. Fish. Investigations Report 33: 50-59.

Mann, K.H. and J.R.N. Lazier. 1991. Dynamics of Marine Ecosystems: Biological-Physical Interactions in the Oceans. Boston, Blackwell Scientific Publications.

McCarl, B.A. and T.B. Rettig. 1983. Influence of hatchery smolt releases on adult salmon production and its variability. J. Fish. Res. Board of Canada 40: 1880-1886.

McClain, D.R. and D.H. Thomas. 1983. Year-to-year fluctuations of the California Countercurrent and effects on marine organisms. California Coop. Fisheries Investigations Report 24: 165-181.

McGie, A.M. 1983. Commentary: Short-term climatic variability in the northeast Pacific Ocean. The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific. W. G. Pearcy. Corvallis, Oregon State University, Sea Grant ORESU-W-83-001**:** 37-49.

McGie, A.M. 1984. Commentary: Evidence for density dependence among coho salmon stocks in the Oregon Production Index Area. The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific, A Workshop. W. G. Pearcy. Corvallis, Oregon State University Sea Grant College Program**:** 37-49.

McGowan, J.A. 1971. Oceanic biogeography of the Pacific. The Micropppaleontology of Oceans. B. M. Funnell and W. R. Riedel. Cambridge, Cambridge University Press**:** 3-74.

McGowan, J.A. 1974. The nature of oceanic ecosystems. The Biology of the Oceanic Pacific. C. B. Miller. Corvallis, Oregon State University Press**:** 9-28.

McIsaac, D.O. 1990. Factors affecting the abundance of 1977-79 brood wild fall chinook salmon (*Oncoryhnchus tshawytscha*) in the Lewis River, Washington. Seattle, Univ. of Washington. Washington.

Melack, J.M., J. Dozier, C.R. Goldman, D. Greenland, A.M. Milner and R.J. Naiman. In press. Effects of climate change on inland waters of the Pacific coastal mountains and western Great Basin of North America. Hydrological Sciences.

Mysak, L.A. 1986. El Niño, interannual variability and fisheries in the northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 43: 464-497.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Neitzel, D.A., M.J. Scott, S.A. Shankle and J.C. Chatters. 1991. The effect of climate change on stream environments: the salmonid resource of the Columbia River Basin. Northwest Environmental Journal 7: 271-293.

Nicholas, J.W. and D.G. Hankin. 1988. Chinook Salmon Populations in Oregon Coastal River Basins: Description of Life Histories and Assessment of Recent Trends in Run Strengths. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Nickelson, T.E. 1986. Influences of upwelling, ocean temperature, and smolt abundance on marine survival of coho salmon (*Oncorhynchus kisutch*) in the Oregon production area. Can. J. Fish. Aquat. Sci. 43(3): 527-535.

Nickelson, T.E. and J.A. Lichatowich. 1983. The influence of the marine environment on the interannual variation in coho salmon abundance: An overview. The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific. W. G. Pearcy. Corvallis, Oregon State University, Sea Grant ORESU-W-83-001**:** 24-36.

Nickelson, T.E., J.W. Nicholas, A.M. McGie, R.B. Lindsay, D.L. Bottom, R.J. Kaiser and S.E. Jacobs. 1992. Status of Anadromous Salmonids in Oregon Coastal Basins. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Nickelson, T.E.a.L., J. A. 1984. The influence of the marine environment on the interannual variation in coho salmon abundance: An overview. The influence of ocean conditions on the production of salmonids in the North Pacific, A Workshop. Oregon State University Sea Grant College Program, Corvallis, Oregon.

Norton, J., D. McClain, R. Brainard and D. Husby. 1985. The 1982-83 El Niño event off Baja and Alta California and its ocean climate context. El Niño North: Niño effects in the Eastern

Subarctic Pacific Ocean. W. S. Wooster and D. L. Fluharty. Seattle, Washington Sea Grant Program, University of Washington**:** 44-72.

Oregon Dept. of Fish and Wildlife. 1982. Comprehensive Plan for Production and Management of Oregon's Anadromous Salmon and Trout. Part II: Coho Salmon Plan. Portland. Oregon.

Pauly, D. and V. Christensen. 1995. Primary production required to sustain global fisheries. Nature 374: 255-257.

Pearcy, W.G. 1992. Ocean Ecology of North Pacific Salmonids. Seattle, University of Washington Press.

Pearcy, W.G., J. Fisher, R. Brodeur and S. Johnson. 1985. Effects of the 1983 El Niño on coastal nekton off Oregon and Washington. El Niño North: Niño Effects in the Eastern Subarctic Pacific. W. S. Wooster and D. L. Fluharty. Seattle, Washington Sea Grant Program, Univ. of Washington**:** 188-204.

Pearcy, W.G. and J.P. Fisher. 1988. Migrations of coho salmon, *Oncorhynchus kisutch*, during their first summer in the ocean. Fishery Bulletin 86(2): 173-195.

Pearcy, W.G. and J.P. Fisher. 1990. Distribution and Abundance of Juvenile Salmonids off Oregon and Washington, 1981-1985, Nat. Ocean. and Atmos. Administration.

Peterman, R.M. 1989. Application of statistical power analysis to the Oregon coho (*Oncorhynchus kisutch*) problem. Can. J. Fish. Aquat. Sci. 46: 1183-1187.

Peterman, R.M. and R.D. Routledge. 1983. Experimental management of Oregon coho salmon (*Oncorhynchus kisutch*): Designing for yield of information. Can. J. Fish. Aquat. Sci. 40(8): 1212-1223.

Peterson, C.H., R.T. Barber and G.A. Skilleter. 1993. Global warming and coastal ecosystem response: How northern and southern hemispheres may differ in the eastern Pacific Ocean. Earth System Response to Global Change: Contrasts Between North and South America. H. A. Mooney, E. R. Fuentes and B. I. Kronberg. San Diego, Academic Press**:** 17-34.

Peterson, W.T., C.B. Miller and A. Hutchinson. 1979. Zonation and maintenance of copepod populations in the Oregon upwelling zone. Deep-Sea Research 26A: 467-494.

Quinn, W.H., V.T. Neal and S.E.A.d. Mayolo. 1987. El Niño occurrences over the past four and a half centuries. J. Geophysical Research 92(C13): 14,449-14,461.

Reimers, P.E. 1973. The length of residence of juvenile fall chinook salmon in Sixes River, Oregon. Research Reports of the Fish Comm. of Oregon 4(2): 3-43.

Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the west coast of North America. Aspects of Climate Variability in the Pacific and Western Americas. D. H. Peterson. Washington, American Geophysical Union**:** 93-111.

Roemmich, D. 1992. Ocean warming and sea level rise along the southwest U.S. coast. Science 257: 373-375.

Roemmich, D. and J. McGowan. 1995. Climate warming and the decline of zooplankton in the California current. Science 267: 1324-1326.

Royal, L.A. 1972. An Examination of the Anadromous Trout Program of the Washington State Game Department. Olympia, Washington State Department of Game. Washington**:** 176 + app.

Salo, E.O. 1991. Life history of chum salmon (*O. keta*). Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, Univ. of British Columbia Press**:** 231-310.

Scarnecchia, D.L. 1981. Effects of streamflow and upwelling on yield of wild coho salmon (*Oncorhynchus kisutch*) in Oregon. Can. J. Fish. Aquat. Sci. 38: 471-475.

Schluchter, M. and J.A. Lichatowich. 1977. Juvenile Life Histories of Rogue River Spring Chinook Salmon *Oncorhynchus tshawytscha* (Walbaum), as determined from scale analsysis. Corvallis, Oregon Dept. of Fish and Wildlife. Oregon.

Sharp, G.D. 1991. Climate and fisheries: Cause and effect - a system review. Long-Term Variability of Pelagic Fish Populations and Their Environment. T. Kawasaki, S. Tanaka, Y. Toba and A. Taniguchi. Oxford, Pergamon Press**:** 239-258.

Sharp, G.D. 1992. Fishery catch records, El Niño/Southern Oscillation, and longer-term climate change as inferred from fish remains in marine sediments. El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation. H. F. Diaz and V. Markgraf. Cambridge, Cambridge University Press**:** 379-417.

Sherman, K. 1991. The large marine ecosystem concept: Research and management strategy for living marine resources. Ecological Applications 1(4): 349-360.

Sherwood, C.P., D.A. Jay, R.B. Harvey, P. Hamilton and C.A. Simenstad. 1990. Historical changes in the Columbia River estuary. Progressive Oceanography 25: 299-352.

Simenstad, C.A., K.L. Fresh and E.O. Salo. 1982. The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: An unappreciated function. Estuarine Comparisons. V. S. Kennedy. New York, Academic Press**:** 343-364.

Simenstad, C.A., D.A. Jay and C.R. Sherwood. 1992. Impacts of watershed management on land-margin ecosystems: the Columbia River estuary. Watershed Management: Balancing Sustainability and Environmental Change. R. J. Naiman. New York, Springer-Verlag.**:** 266-306.

Sinclair, M. 1988. Marine Populations: An Essay on Population Regulation and Speciation. Seattle, University of Washington Press.

Sinclair, M., M.J. Tremblay and P. Bernal. 1985. El Niño events and variability in a Pacific mackerel (*Scomber japonicus*) survival index: Support for Hjort's second hypothesis. Can. J. Fish. Aquat. Sci. 42: 602-608.

Skud, E.B. 1982. Dominance in fishes: the relation between environment and abundance. Science 216: 144-149.

Small, L.F. and D.W. Menzies. 1981. Patterns of primary productivity and biomass in a coastal upwelling region. Deep-Sea Research 28A: 123-149.

Smith, P.E. 1978. Biological effects of ocean variability: Time and space scales of biological response. Rapports et Proces-verbaux des Reunions 173: 117-127.

Smith, R.L. 1983. Physical Features of Coastal Upwelling Systems. Seattle, Washington Sea Grant Program, University of Washington. Washington.

Soutar, A. and J.D. Isaacs. 1969. History of fish populations inferred from fish scales in anaerobic sediments off California. California Coop. Oceanic Fisheries Investigations Report 13: 63-70.

Soutar, A. and J.D. Isaacs. 1974. Abundance of pelagic fish during the 19th and 20th centuries as recorded in anaerobic sediment off the Californias. Fishery Bulletin 72(2): 257-273.

Springer, A.M. 1992. A review: Walleye pollock in the North Pacific--how much difference do they really make? Fisheries Oceanography 1(1): 80-96.

Strub, P.T., J.S. Allen, A. Huyer and R.L. Smith. 1987. Large-scale structure of the spring transition in the coastal ocean off western North America. J. Geophysical Research 92(C2).

Strub, P.T., J.S. Allen, A. Huyer, R.L. Smith and R.C. Beardsley. 1987. Seasonal cycles of currents, temperatures, winds and sea level over the northeast Pacific continental shelf: 35°N to 48°N. J. Geophysical Research 92(C2): 1507-1526.

Sverdrup, H.U., M.W. Johnson and R.H. Fleming. 1942. The Oceans: Their Physics, Chemistry and General Biology. Englewood Cliffs, Prentice-Hall.

Thomas, D.W. 1983. Changes in Columbia River Estuary Habitat Types over the Past Century. Astoria, Columbia River Estuary Data Development Program. Oregon.

Trenberth, K.E. 1990. Recent observed interdecadal climate changes in the northern hemisphere. Bull. Amer. Meteorological Society 71(7): 988-993.

Venrick, E.L., J.A. McGowan, D.R. Cayan and T.L. Hayward. 1987. Climate and chlorophyll a: long-term trends in the central North Pacific Ocean. Science 238: 70-72.

Ware, D.M. and R.E. Thompson. 1991. Link between long-term variability in upwelling and fish production in the northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 48(12): 2296-2306.

Washington Dept. of Fisheries, W.D.o.W., and Western Washington Treaty Indian Tribes. 1993. 1992 Washington State Salmon and Steelhead Stock Inventory. Olympia. Washington**:** 212.

Wickett, W.P. 1967. Ekman transport and zooplankton concentration in the North Pacific Ocean. J. Fish. Res. Board of Canada 24(3): 581-594.

CHAPTER 11. CONCLUSIONS AND IMPLICATIONS

Humans have made a great hydroelectric, irrigation and transportation system out of the Columbia River and in so doing provided a primary driver for regional economic development. The river today has been characterized as a great organic machine (White, 1995), meaning that even though significant, natural attributes remain (e.g., salmon production in the Hanford Reach and wilderness rivers like the Middle Fork of the Salmon), the river environment is dominated by technological operations (e.g., flood control, hydropower production, irrigation systems, commercial barging). The machine metaphor (Pepper, 1942; Capra, 1982) drives not only economic considerations of water usage and intrastate claims to water ownership, but also conservation efforts for aquatic resources and water quality, including anadromous and resident salmonid fishes (Botkin, 1990).

Indeed, salmon restoration in the Columbia River emphasizes the use of hatcheries, complex bypass systems, artificial habitat structures and other fundamentally technological operations, in part, because managers and policy-makers have adopted the machine metaphor. These technologies evolved over the years and have been used almost exclusively to mitigate, not correct, habitat degradation caused by decades of cultural development. The belief that habitat degradation can be technologically mitigated, as opposed to restoration of normative habitats for all life history stages of salmonids, is ingrained in the Fish and Wildlife Program. The prevailing belief is that the primary problem for anadromous fish is mortality associated with juvenile passage through the dams and reservoirs. The prevailing solution is a combination of hatchery technology, to maximize the number of smolts produced, combined with flow augmentation, to move them as rapidly and efficiently as possible through the hydropower system. This strategy is reflected in restoration expenditures (General Accounting Office, 1992) and in the assumptions implied in the Fish and Wildlife Program (see Chapter 3).

Unfortunately, the restoration program based on the machine metaphor has failed to curtail the decline of salmonid fishes. Moreover, it may be actively interfering with conservation efforts for resident fishes or other management goals in headwater areas not accessible to salmon, e.g., eutrophication controls in Flathead Lake are influenced by discharges from Hungry Horse Reservoir to accommodate late summer smolt movement in the lower Columbia River (Stanford and Hauer, 1992).

Fish and Wildlife Program

We conclude that the Council's Fish and Wildlife Program reflects the dominant paradigm that has governed fisheries management and recovery efforts in the Pacific Northwest for most of this century. This paradigm is based on two principles we find to be fundamentally flawed. The first is that economically desirable fish populations can be managed in isolation from other components of the ecosystem. Consideration of individual species, runs and populations of salmon that are of interest for economic, social or legal reasons (e.g., Snake River spring chinook) in isolation from other species or components of the ecosystem leaves the region with a narrow set of solutions to a complex problem. Problem definition based on an ecosystem perspective would likely lead to a different course of action. This is not to say that the populations currently emphasized by the region are not important or that major actions should not be taken to rebuild these populations. Our message is simply this: how the region asks the questions -- the conceptual foundation for the region's actions -- ultimately restricts the range of options available for consideration. To date, the implied conceptual foundation has led to asking how we can devise technological fixes for a restricted set of problems affecting a few remaining populations, rather than asking how the basin as an ecosystem should operate within the existing social context.

The second principle of the existing paradigm, and one that flows inevitably from the first, is that technological solutions can be devised for each ecosystem alteration that occurs as a result of development of the basin. In effect, it says that we can engineer an alternative system that works as well as the natural ecosystem. Because of the pace and magnitude of technological development in the basin, this suggests the analogy of frantically sticking patches on a sinking ship rather than asking long ago whether the ship was going in the right direction or whether we should steer out of troubled waters. We find the concept that we can engineer our way out of the present crisis to be at odds with the prevailing scientific knowledge. This is not to say that technological solutions to particular problems will have no part in a successful recovery strategy or that the only solution is a return to natural conditions. On the contrary, we conclude that the social context of the Columbia River mandates the use of technology. However, to be successful, that technology must work with the natural physical and biological processes of the salmonid-bearing ecosystem rather than attempting to circumvent it. Strictly applied, this conclusion will lead to fundamentally different ways of approaching and applying technology to the recovery of the Columbia Basin.

Many of the Fish and Wildlife Program measures are responsive to individually documented problems and represent credible scientific approaches to these problems. The Fish and Wildlife Program actions to date represent a good faith effort by the Council and the region's fishery managers to recover salmon and steelhead in the Columbia Basin. Although many measures may show positive incremental results, in total, they have failed to stem the decline of salmon and steelhead. Populations are at all time lows; many do not appear to be able to withstand natural downturns in the ocean or in other conditions that are beyond direct human control.

An overarching conclusion of our review is that the region must change the way it views the Columbia River. We must move from a view that the Columbia River is largely a vehicle for economic development to one that accommodates short-term economic gain and the longer-term regional benefits of a functional salmonid bearing ecosystem. Donald Worster (1985) characterized the Colorado River as "..a part of nature that had died and been reborn as money." He cautioned that the Columbia River was struggling toward this fate as well. The region has the opportunity to fundamentally shift its relationship with the river. We submit that a conceptual foundation like that outlined in Chapter 2 is a key step in this shift.

An Alternative Conceptual Foundation

The conceptual foundation (Chapter 2) is based on three fundamental principles. First, restoration of Columbia River salmonids must address the entire natural and cultural ecosystem, which encompasses the continuum of freshwater, estuarine, and ocean habitats where salmonid fishes complete their life histories. This consideration includes human developments, as well as natural habitats. Second, sustained salmonid productivity requires a network of complex and interconnected habitats, which are created, altered and maintained by natural physical processes in the freshwater, the estuary and the ocean environments. These diverse and high-quality habitats, which have been extensively degraded by human activities, are crucial for salmonid spawning, rearing, migration, maintenance of food webs and predator avoidance. Ocean conditions, which are variable, are important in determining the overall patterns of productivity of salmonid populations. Third, life history diversity, genetic diversity and metapopulation organization are ways salmonids adapt to their complex and connected habitats. These factors contribute to the ability of salmonids to cope with environmental variation that is typical of freshwater and marine environments.

Because a wide array of habitats historically existed, salmonid stock diversity was high. Dispersed production by many stocks provided resilience (i.e., buffering) to natural environmental variation. The conceptual foundation proposes that salmonid productivity is based on a wide array of populations coexisting in a complex and interconnected mosaic of habitats. These habitats are created and maintained as a consequence of natural environmental variation in the freshwater, estuarine and oceanic components of the ecosystem.

The Columbia River Basin historically was dominated by multiple populations and life history types of salmon and steelhead, perhaps organized geographically into complex metapopulations that sustained genetic diversity (National Research Council, 1996) and provided resilience in the face of natural environmental fluctuations . Not only were chinook salmon and steelhead abundant, but, sockeye salmon from 23 rearing lakes contributed to the commercial fisheries. Much, if not most, spawning of fall and perhaps summer chinook occurred in the mainstem of the Columbia and Snake Rivers and in alluvial reaches of the lower sections of the larger tributaries (e.g., Yakima River and others). Available historic evidence (Lichatowich and Mobrand, 1995), the current high abundance of fall chinook in the Hanford Reach, and principles of large river ecology (Stanford, 1996), suggest that large alluvial reaches in the mainstem and lower sections of many tributaries were the fish factories of the Columbia River ecosystem. Mainstem spawning populations may have functioned as vital core populations important in sustaining metapopulation persistence (Chapters 2 and 4). Furthermore, alluvial mainstem areas likely were important rearing areas for juvenile salmonids moving downstream (Chapter 5). Although critically important with respect to biodiversity, many tributaries in the headwaters of sub-basins were probably not significant production areas, owing to their smaller size, lack of nutrients to support food webs, steep gradients, long distances from the ocean and other considerations. Lakes, now mostly blocked to fish passage, contributed substantial anadromous and resident salmonid biomass and diversity.

In the course of human development of the Columbia River Basin, important mainstem spawning and rearing habitat was degraded as a consequence of the construction of dams and associated large water storage reservoirs and various land use activities. Most large mainstem spawning populations and many headwater populations were extirpated, which drastically altered metapopulation organization. At present, salmon production in the basin occurs chiefly in isolated headwater areas with intact habitat and in hatcheries. The current Fish and Wildlife Program focuses restoration efforts on increasing the abundance of these few remaining headwater salmon populations, many of which historically never were very productive, rather than on restoration of productivity through restoration of stock and life history diversity and metapopulation integrity. Moreover, the Fish and Wildlife Program lacks continuity of measures for enhancing remaining stocks. This is, in part, a consequence of the lack of an explicit, conceptual foundation that would provide continuity and internal consistency among measures (Whitney et al., 1993). Large river habitats, which were the key production areas for many productive stocks and essential to all migrants, are largely ignored in the Fish and Wildlife Program. Indeed, the Hanford Reach, which contains the most healthy naturally spawning chinook stock above Bonneville Dam, is not explicitly addressed in the Fish and Wildlife Program. In the same context, measures to protect and reconnect remaining intact habitats containing native resident salmonids are missing or de-emphasized. Lake Okanagan, which contained one-fifth of the rearing lake surface area in the Columbia Basin for sockeye and probably contains about three-quarters of the remaining sockeye is presently occluded with a low head diversion dam and no fish passage facilities.

The tendency with the Fish and Wildlife Program has been to emphasize hatcheries, passage technology, and other activities that may be effective for one or a few stocks or in specific places or at particular times and may yield small increases in specific runs or reduce juvenile mortality at a few places or at certain times. Those measures have considered life history diversity and metapopulation structure and have failed to make significant progress toward the Council's goals. Moreover, the Fish and Wildlife Program does not have an implementation plan or a formalized mechanism for evaluating success or failure of individual measures in general.

Human development of the Columbia basin has led inexorably to loss of life history and population diversity, disruption of metapopulation organization, and declines in salmonid productivity. However, we believe that life history and population diversity can be reestablished and declines in salmonid populations can be reversed by management actions that restore more normative conditions throughout the ecosystem. Technology that attempts to circumvent the normative river (e.g., hatcheries and transportation) should only be implemented on a large scale after intensive evaluation.

Specific Conclusions

We identified three conclusions regarding the alternative conceptual foundation:

1. *We conclude that the lack of progress towards salmon recovery in general and under the Fish and Wildlife Program, is due at least in part to the lack of an explicitly defined conceptual foundation based on ecological principles.*

We recommend that the Council adopt an explicitly defined conceptual foundation that is based on ecological principles, such as the alternative conceptual foundation described earlier in Chapter 2. Failure to adopt a conceptual foundation and to change the approach to salmon restoration in the basin will lead to more extinctions of salmon populations and little progress towards the rebuilding goal. Temporary increases in some populations may occur in response to fluctuations in ocean conditions, but the overall downward trend in returns that has occurred throughout this century will likely continue without a change in approach.

2. *The potential social, economic and biological tradeoffs that will accompany significant increases in normative conditions throughout the Columbia River salmon bearing ecosystem are not known.*

The potential social, economic and biological costs and benefits of moving the basin toward more normative conditions should be compared as part of the regional debate regarding salmon restoration. As a first strategic step, the Council could examine the implications of the normative ecosystem concept; in particular, what steps would move the Columbia River along the continuum from its current state to a more normative state (i. e., the restoration of natural ecological processes consistent with the needs of native fish and wildlife species). Steps including watershed-level restoration in subbasins, manipulation of mainstem flows, permanent drawdowns and dam removal should be evaluated in terms of the social and economic costs to the region, as well as the potential benefits for salmon recovery.

3. *Although there is uncertainty associated with the restoration approach described in RETURN TO THE RIVER, it offers an opportunity to move from the status quo of continuing decline and begin to realize progress toward recovery of salmon and the goals of the Fish and Wildlife Program.*

Because the region lacks experience in the approach to restoration described in RETURN TO THE RIVER, we cannot predict the exact relationship between increasingly normative conditions and salmon production. For example, as the river moves toward more normative conditions, little improvement may be observed until a threshold is reached causing an increase in production to a new level or plateau. Our knowledge of how to restore key attributes in an ecological system as large and complex as the Columbia River is imperfect. A rigorous program of evaluation, monitoring, research and adaptive management will be required. The ecosystem's response to restoration actions has important implications for scaling the region's expectations and the amount of effort required to elicit identifiable changes in salmon abundance. We conclude that an approach based on the principles described in RETURN TO THE RIVER, combined with an implementation program governed by the principles of adaptive management, offers the best hope for preventing large-scale extinction of salmon in the basin and making meaningful progress toward the Council's goals.

The Normative Ecosystem

The opportunity for restoration of normative ecosystem conditions within the Columbia River Basin depends on the location within the basin and the extent of human development. Based on our review of science (Chapters 4-10), enhancement of normative conditions includes careful consideration and implementation of at least the following seven actions:

1. *Recognize explicitly that salmonid fishes in the Columbia River exist naturally as aggregates of local populations, possibly organized as metapopulations, and manage for life history and population diversity as essential to increased total production.*

The normative ecosystem concept is based on the natural adaptive capacity of salmonid fishes and their tendency to develop diverse life histories in response to diverse habitat and other environmental conditions that occur across the different landscapes of the Columbia River basin.

Although much of the natural diversity of salmonid fishes has been lost (Nehlsen et al., 1991; Huntington et al., 1996), we believe that salmonids have the capacity to re-express life history and population diversity if suitable habitat opportunities are provided (Healey, 1994). These habitat opportunities can be provided by normative river processes. Metapopulation structure could be recovered by allowing natural rebuilding from the remaining wild core populations (e.g., fall chinook in the Hanford reach).

2. Freshwater habitat for all life history stages must be protected and restored with a focus on key alluvial river reaches and lakes. Restoring habitat and access to habitat that re-establishes phenotypic diversity in salmonid populations should be a priority.

Native salmonid fishes of the Columbia River cannot be expected to thrive or even persist in the long term without the habitats to which they are adapted. Diversity and productivity of native salmonid populations throughout the Columbia River system cannot recover without restoring spatial (upstream-to-downstream, channel to floodplain, groundwater to floodplain) and temporal connectivity of the habitat mosaic that characterizes the normative river. Because they appear to be centers of population organization for salmonids, large alluvial reaches in the mainstem Columbia and Snake and major tributaries should be foci for management.

At least three generalized actions could be initiated now to begin to rebuild habitat quantity and quality of the mainstem and tributaries. Actions can be refined adaptively as new information is forthcoming through research and monitoring. These actions include: a) provide incentives for watershed planning that emphasizes riparian and upland land use activities that enhance instream and lake habitats; insist on empirical evaluation of effectiveness of management practices; b) re-regulate flows to restore the spring high water peak to revitalize the mosaic of habitats in riverine reaches and stabilize daily fluctuations in flow to allow food web development in shallow water habitats; and c) determine food web composition, trophic interactions and bioenergetics of migrating juveniles in key habitats.

a. Provide incentives for watershed planning that emphasizes riparian and upland land use activities that enhance instream and lake habitats; insist on empirical evaluation of effectiveness of management practices.

Restoration of normative conditions has to be done in the tributaries, as well as the mainstem. Despite extensive expenditures under the Fish and Wildlife Program and other state and federal programs, there is little evidence that habitat restoration has actually improved the productive capacity of streams and rivers for salmonids (Rhodes et al., 1994). In some areas of the basin, habitat degradation of headwater reaches is pervasive from mining, logging and road building (Chapter 5). Priority should be given to key alluvial reaches in tributary streams. A very important point is that these key reaches are not in wilderness or other protected zones; they occur in zones of intense human activity, so incentives will be required to unify stakeholders to restore habitat conditions for anadromous and resident salmonids.

b. Re-regulate flows through the mainstem Columbia and Snake rivers.

1) Use the spring high-water peak to revitalize the mosaic of habitats in riverine reaches.

Peak spring flows can restructure and revitalize habitats in riverine reaches, however, in the existing mainstem sections of the Columbia and Snake rivers where reservoirs dominate, peak flows will not accomplish much habitat restoration. The possibility of restoring historical, but presently inundated, production areas in the mainstem should be evaluated including, permanent drawdown of John Day and, perhaps, McNary pools. Peak spring scouring flows, then could be used to restructure and revitalize habitat in these currently inundated areas. Potential advantages are great in the John Day pool because: the large alluvial reach drowned by John Day pool was a key spawning and rearing area prior to inundation, the upstream part of the reservoir is not developed, and the existing reservoir is a source of high mortality from predation.

Peak flows can be created by using water storage released in concert with natural runoff in the catchment. On wet years, peaks can be re-regulated to provide scouring flows, depending on the storage capability and the flood control realities of the particular river segment. Very high flows are not needed every year to maintain instream and flood plain habitats, nor is the historical duration of floods required because most of the sediment is moved on the rising limb of the hydrograph. In years of average water availability, a modest peak flow can be generated, while also elevating baseflow to accomplish the purposes for which the dams were built. In dry years, little additional water is likely to be available to generate spring peak flows for the purpose of scouring and revitalizing habitat, however, natural spring runoff will still occur. The strategy simply is to lower the baseflow some to build peaks in relation to catchment runoff. Peak or scouring flows have to be tailored for individual riverine segments based on channel morphometry and size distribution of bed materials. In general, scouring flows of sufficient magnitude to move the bed materials of median size are needed.

The integrated rule curves (IRCs) for drawdown and refill of the large storage reservoirs, as developed for Hungry Horse and Libby Reservoirs (Marotz et al., 1994; Marotz et al., 1996), coupled to an empirical understanding of channel and flood plain morphometry, flood plain land uses, runoff and storage forecasting, and riverine sediment transport efficiency in relation to peak (freshet) flow timing and duration within key alluvial segments, can provide a mechanism for restoring habitats in key alluvial reaches. However, research is needed to clearly relate IRCs to food web dynamics, including reproduction, growth and behavior of salmonids.

2) Stabilize daily fluctuations in flows in riverine reaches to allow food web persistence in shallow water habitats of alluvial reaches that provide important juvenile rearing areas.

In all years, it is essential to prevent short-term dewatering of the nearshore (varial) zone. Such fluctuations often are associated with hydropower peaking operations and effectively kill all organisms in shallow-water habitats in the nearshore zone. These habitats are essential features of the normative riverine landscape and are characterized by both surface and interstitial flow. As a starting point, this means that daily changes in flow (ramping rates) should not exceed the range of variation that likely occurred before regulation.

c. Determine food web composition, trophic interactions and bioenergetics of migrating juveniles in key habitats.

We concluded that the mainstem reservoirs likely are areas of high juvenile mortality, as are reaches of tributaries severely influenced by water diversions (e.g., sections of the Yakima, John Day, Grand Ronde, Umatilla). Problems include lack of riverine habitat, insufficient food, presence of large numbers of native and non-native predators and potentially lethal late summer temperatures. These pressures, and any increased energetic demands related to reduced summer flows, likely compromise energetic requirements of the native salmonids leading to poor health of survivors, particularly those passing through the Snake River reservoirs. Poor condition could contribute to increased mortality at a later stage of downstream migration or in the ocean. Research on food web conditions, mechanisms for improving them, and improved measures of the vitality of migrants is needed.

3. Manage stocks with a more complete understanding of migratory behavior and the limitations that migratory behavior places on modes of river regulation.

Current views of fish migration are insufficient for recovery (Chapter 6). The Fish and Wildlife Program should include research and management measures to determine and protect habitat requirements during fish migration that go beyond increasing bulk water velocity and reducing water travel time through flow augmentation and drawdowns.

4. Reduce sources of mortality and improve effectiveness of mitigation activities within the hydroelectric system. Planning and implementation of mitigation measures should occur *within the context of the normative ecosystem concept and evaluated for effectiveness in reaching stated objectives.*

a. Couple seasonality of flow with usage of spill and most efficiently bypass juveniles and adults around mainstem dams and cue (not flush) them through the mainstem.

Our review showed that spill clearly is effective in reducing mortality of juveniles passing mainstem dams; however, high volume spill at some dams can cause gas supersaturation at levels thought to be lethal to juveniles. More information is needed to clarify this tradeoff because the lethalness of gas supersaturation may be less of a problem inriver (owing to the ability of the fish to move to deep water to adjust to the gas concentrations) than experimental data currently suggest.

Turbine screens, including extended-length screens, do not appear to be effective in achieving the Council's goals for fish guidance efficiency (FGE) for all species, stocks and life history types. It seems unlikely that more than slight incremental improvements can be made to improve the effectiveness of turbine screen bypass systems.

A more promising approach applicable to some dams, appears to be the use of surface collection devices for bypassing migrating juvenile salmonids. This approach takes advantage of the natural surface oriented behavior of juvenile migrants, compared to the turbine bypass systems that force the juveniles to sound prior to entering the bypass system.

b. Resolve mortality from gas bubble trauma with focused field research and installation of devices that reduce turbulence.

Spill can improve survival of smolts up to the point where gas saturation adds mortality beyond what is saved by passage of fish in spill. That point has to be determined for each dam in the mainstem. Freshet flows have to be tailored to optimize the tradeoff of spill and gas bubble disease as more information becomes available and as more of the dams are equipped with better turbulence-reducing devices to reduce gas entrainment.

Gas bubble disease from supersaturation of water with atmospheric gases is a poorly defined, but highly plausible (based on much science), risk to in-river fish, a risk that would need to be better determined to quantitatively establish the net value of spill as a mechanism to reduce mortalities during dam passage. This determination would require a large amount of research and monitoring to achieve desired levels of confidence, and may not be feasible. Because there is still debate on the research approach and need, the best strategy may be to endorse Army Corps of Engineers' plans for installation of gas abatement structures.

c. Transportation likely is selective for particular stocks and life histories

Transportation can provide increases in survival at the point of release for certain life history types of certain species. Transportation has not been shown to be appropriate for completion of the life cycles of all life history types of all endangered salmon species. Furthermore, transportation alone does not appear sufficient to overcome the negative effects on survival of salmon caused by the development and operation of the hydroelectric system. Transportation and additional potential mitigation measures must be developed and evaluated to determine if each is appropriate to protection of the life history diversities of the endangered salmon species. Transportation is desirable only if all life history types are transported, if the currently perceived benefits of transportation are real for all life history stages, and if it is clear that normative habitat in the impounded mainstem cannot be restored. Transportation programs that are selective for specific life histories could run counter to normative attempts to restore life history diversity.

d. Normative conditions will reduce predation rates on migrating juvenile salmon.

The overall rate of predation of squawfish on juvenile salmon has been lowered since 1990. The extent to which any single factor, such as spill or the predator control program, may have contributed to this is uncertain. Spill is a factor that normally should lower the rate of predation by all fish predators in the vicinity of the dams. Restoration of more normative conditions in areas such as the John Day Pool could further reduce predation by creating refugia for migrating salmonids and cooler water temperatures due to increased connectivity with ground-water.

5. Reduce inadvertent negative impacts and improve effectiveness of mitigation actions associated with harvest management and artificial propagation, as well as habitat protection and restoration. Planning and implementation of mitigation measures should occur within the context of the normative ecosystem concept and be evaluated for effectiveness in reaching stated objectives.

a. Habitat restoration has not been emphasized to date in the Fish and Wildlife Program as a primary mitigation need.

Habitat restoration in both mainstem and subbasin areas must receive high priority and be approached in the normative ecosystem context; e.g., restoration efforts should be directed at providing the habitat opportunities that historically supported salmonids in their natural state (Healey, 1994). Restoration effort needs to focus on the tributaries, as well as the mainstem with priority given to key alluvial reaches in tributary streams. An important purpose of habitat restoration should be to facilitate the reexpression of phenotypic and life history diversity in salmonid populations. Habitat restoration in the major subbasins is likely to take longer and be more difficult than restoration of mainstem habitats. In many cases, this difficulty will be a result of a lack of storage water for restructuring habitats via reregulation, as well as the larger number and a more diverse set of stakeholders. Therefore, incentives will be required to unify stakeholders to restore habitat conditions for anadromous and resident salmonids.

b. Mortalities from all other sources (including incidental harvest) should be low enough to sustain stocks before allowing directed harvest.

Long-term conservation of salmon in the face of human population growth requires habitat protection as a prerequisite and conservative harvest management as a constant presence. While appropriate harvest control is necessary for successful salmon conservation, accounting for only directed harvest is not sufficient to provide for the persistence of salmon populations. With degraded habitats, reduced life history diversity, and reduced abundance, it is essential to account for all sources of mortality in all localities to control harvest to levels consistent with salmon recovery.

c. Hatcheries were intended to mitigate salmon losses due to habitat degradation, but they have failed to do so. Reliance on hatcheries should be de-emphasized and new roles for hatcheries defined.

Artificial propagation has failed to achieve its long-standing objective (Chapter 8) of replacing natural production lost due to habitat degradation and construction and operation of the hydroelectric system, and to compensate for overharvest. Because there has been a lack of comprehensive evaluation throughout the 120-year history of hatcheries in the basin, it is going to be difficult and expensive to learn if it may be possible to integrate hatchery operations with natural production in the basin. Although interactions between wild and hatchery fish have been examined in only a few studies, existing evidence points to negative effects on wild fish. There is clear evidence that the hatchery paradigm coupled with harvest management practices (mixed-stock fisheries, where harvest rates are set according to presumed production of cultured fish) have accelerated the decline of wild stocks.

Artificial propagation must be viewed as an experiment to be implemented within an adaptive management framework. It should be used in a manner consistent with the conceptual foundation, and, at the subbasin level, the role and scale of artificial production should be consistent with the rebuilding goal for natural production within that subbasin. An independent review of the purpose and scope of hatchery operations in the basin is needed.

d. An integrated ecosystem monitoring and evaluation program is needed

A great deal of monitoring that is relevant to the Fish and Wildlife Program is being done for index life stages and locations, with appropriate data compilation and reporting. But evaluation and thus, feedback to monitoring design has lagged or been too narrowly focused by current beliefs to fully support management actions by the Council and other agencies. Monitoring, and especially evaluation, remain inadequate for present needs (Chapter 9). Monitoring should not be limited solely to attributes of salmon, or even salmonids in general. Information on habitat dynamics and food web community ecology is also needed. A major impediment to effective evaluation of the Fish and Wildlife Program, is the lack of a clearly defined framework of goals and objectives to provide a standard for evaluation.

6. *Recognize estuary and ocean dynamics as controllers of salmon productivity, which require responses in management actions for all other aspects of the life cycle under human control, such as directed harvest and hydrosystem operations. Management activities should increase or maintain biodiversity in salmon populations to minimize the effects of change in the marine environment. Obtain better understanding of estuarine and oceanic food webs (Chapter 10).*

The Pacific Basin ecosystem does not move toward an equilibrium condition, but oscillates between alternate states. Traditional management approaches based on equilibrium population models and assumptions of environmental stability fail to account for this nonlinear behavior and, therefore, have led to incorrect expectations of response in freshwater management actions on the productive capacity of the Columbia River Basin for salmon.

Not much can be done about biophysical conditions in the ocean, beyond support for fisheries harvest protocols that maintain or enhance favorable food web conditions and insure adequate escapement of salmonids to freshwater spawning areas. Estuarine habitats can be improved by pollution abatement and continuing enhancement of the spring freshet plume associated with restoration of the normative riverine flow regime. Management actions affecting freshwater parts of the salmon’s life cycle should emphasize the reexpression of phenotypic diversity as a buffer against fluctuating ocean conditions.

7. *It is critical to protect remaining core populations and restore habitats with the potential to re-establish core populations at strategic locations within the basin. One way to accomplish this would be to reevaluate the concept of salmonid reserves. Reserves could*

protect habitats that currently support remaining viable core populations. They could serve as foci for rebuilding salmonid abundance and metapopulation structure throughout the Columbia Basin. The region should give priority to evaluation of the potential for a salmon reserve in the vicinity of the confluence of the Snake and Columbia Rivers including the Hanford Reach.

The concept of salmon reserves has been discussed by salmon managers for over 100 years, including at least four recommendations for the inclusion of reserves in the Columbia Basin. In spite of this long history, no salmon reserves have ever been implemented in the basin. Curiously, reserves have been used effectively for at least the last several decades or more for protection and management of several resident salmonids. Westslope cutthroat trout in the Clearwater (Kelly Creek) and Salmon rivers (Middle Fork) in Idaho occur in *de facto* reserves as a result of their proximity to wilderness areas and the implementation of catch-and-release angling regulations.

The Hanford Reach in the mid-Columbia River is the only remaining free-flowing river segment and contains the largest natural spawning population of fall chinook in the watershed above Bonneville Dam. Over the last two decades, Hanford Reach fall chinook have continued to be productive while other stocks have declined. These fish exhibit characteristics of a core population both in their resiliency, being the only remaining mainstem population of significance, and because they are contributing to spawning populations elsewhere in the basin (marked individuals have been recovered at other mid-Columbia and Snake river sites). The Hanford chinook stock likely has remained productive because normative conditions were retained by the reregulation of flows. During spawning and incubation on Vernita Bar, a flow regime is maintained that is designed to prevent exposure of the salmon eggs (Bauersfeld, 1978; Chapman et al., 1983). In spite of the apparent viability of the Hanford Reach fall chinook, habitat problems exist in the reach that can be improved through additional reregulation to stabilize daily fluctuations in flow and ensure the occurrence of flood flows during spring runoff.

Establishment of a salmon reserve from the Hanford Reach to the confluence of the Columbia and Snake rivers, combined with flow reregulation and improvement of habitat quality in the lower reaches of adjacent tributaries, would provide the basis for testing the normative concept. Information needed to test the normative concept could be obtained through monitoring habitat quality, complexity and connectivity, along with abundance, life history diversity and fitness of naturally reproducing salmon. In addition, metapopulation theory predicts that large abundant core populations should enhance or restore salmon populations in adjacent tributaries through dispersal of individuals into those systems. Therefore, monitoring of fall chinook abundance in the lower reaches of adjacent tributaries where habitat improvement has occurred would test the linkage between normative conditions and metapopulation rebuilding.

While testing the normative ecosystem concept in the Hanford Reach area, the region should search for other candidate areas in the Columbia and Snake rivers where spawning and rearing habitat can be restored, and natural population and metapopulation structure reestablished. Efforts should be made to identify both mainstem areas and subbasins where restoration may be possible. Metapopulation rebuilding is likely to be enhanced if candidate mainstem and subbasin areas are adjacent to one another. The John Day summer steelhead, and certain resident stocks of bull trout (e.g., Quartz, Kintla, and Hungry Horse stocks in the Flathead River Basin) and cutthroat trout (e.g., Salmon River, Middle Fork) are the among the last remaining healthy populations of native salmonids in the Columbia Basin. Establishing reserves for the protection of these populations and others that may be identified through a thorough analysis of each subbasin should be given high priority.

Literature Cited

Bauersfeld, K. 1978. The Effect of Daily Flow Fluctuations on Spawning Fall Chinook in the Columbia River, Washington Dept. of Fisheries. Washington.

Botkin, D.B. 1990. Discordant Harmonies: A New Ecology for the Twenty-First Centure. New York, Oxford University Press.

Capra, F. 1982. The turning point.

Chapman, D.W., D.E. Weitkamp, T.L. Welsh and T.H. Schadt. 1983. Effects of Minimum Flow Regimes on Fall Chinook Spawning at Vernita Bar 1978-82. Boise, Don Chapman Consultants, Inc. Idaho.

General Accounting Office. 1992. Endangered Species: Past Actions Taken to Assist Columbia River Salmon. Washington. District of Columbia.

Healey, M.C. 1994. Variation in the life history characteristics of chinook salmon and its relevance to conservation of the Sacramento winter run of chinook salmon. Conservation Biology 8: 876-877.

Huntington, C., W. Nehlsen and J. Bowers. 1996. A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California. Fisheries 21(3): 6-14.

Lichatowich, J.A. and L.E. Mobrand. 1995. Analysis of chinook salmon in the Columbia River from an ecosystem perspective, Mobrand Biometrics.

Marotz, B.L., C. Althen and D. Gustafson. 1994. Hungry Horse Mitigation: Aquatic Modeling of the Selective Withdrawal System--Hungry Horse Dam, Montana. Portland, Bonneville Power Administration. Oregon**:** 29.

Marotz, B.L., C. Althen, B. Lonon and D. Gustafson. 1996. Model Development to Establish Integrated Operational Rule Curves for Hungry Horse and Libby Reservoirs - Montana. Portland, Bonneville Power Administration. Oregon**:** 114.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Report on the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids for the National Research Council of the National Academy of Sciences. Washington D. C., National Academy Press.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Pepper, C. 1942. World Hypothesis.

Rhodes, J.J., D.A. McCullough and J. F. A. Espinosa. 1994. A Coarse Screening Process for Evaluation of the Effects of Land Management Activities on Salmon Spawning and Rearing Habitat in ESA Consultations. Portland, Columbia River Inter-Tribal Fish Commission. Oregon.

Stanford, J.A. 1996. Landscapes and catchment basins. Methods in Stream Ecology. F. R. Hauer and G. A. Lamberti. San Diego, Academic Press**:** 3-22.

Stanford, J.A. and F.R. Hauer. 1992. Mitigating the impacts of stream and lake regulation in the Flathead River Catchment, Montana, USA: An ecosystem perspective. Aquatic Conservation 2: 35-63.

White, R. 1995. The Organic Machine: The Remaking of the Columbia River. New York, Hill and Wang.

Whitney, R.R., L.D. Calvin, C.C. Coutant, J. M W. Erho, J.A. Lichatowich, W.J. Liss, W.E. McConnaha, P.R. Mundy, J.A. Stanford and R.N. Williams. 1993. Critical Uncertainties in the Fish and Wildlife Program. Portland, Bonneville Power Administration. Oregon**:** 17.

Worster, D. 1985. Rivers of Empire. New York, Pantheon Books, div of Random House, Inc.

APPENDICES

Appendix A

The Independent Scientific Group:

History and Relation To The Current Independent Scientific Advisory Board Of The Northwest Power Planning Council and National Marine Fisheries Service

History of the Scientific Review Group and the Independent Scientific Group

The Independent Scientific Group (ISG) was formed in February 1995 and evolved directly from its predecessor group, the Scientific Review Group (SRG). The SRG was formed in 1989 from a Memorandum of Understanding between the Bonneville Power Administration (BPA) and the Columbia Basin Fish and Wildlife Authority (CBFWA), the latter acting on behalf of the state, federal, and tribal fisheries managers. The Implementation Planning Process (IPP) established a set of guidelines for selection of the members and for procedures to be followed by the Policy Review Group (PRG) and SRG that were designed primarily to ensure independence and impartiality in the conduct of SRG assignments, to protect the SRG from outside pressures, and to provide mechanisms for separation of policy issues from technical issues. The SRG was devoted to critical scientific review of specific projects or programs conducted under BPA's IPP, as well as synthesis of broader scientific questions, such as identifying critical uncertainties in the Fish and Wildlife Program.

Members were appointed to the SRG (now ISG) in May 1989 by the Policy Review Group. The PRG consisted of managers as well as representatives of institutions concerned with the effects of the FWP on their constituents. Membership in the SRG/ISG included six scientists from both inside and outside the region from a variety of biological and statistical disciplines. Membership in the SRG (and ISG) was based on specific scientific expertise, regardless of institutional affiliation. Initially, three additional members (Participating Technical Advisors) who had technical expertise and were active participants in Columbia Basin fisheries management also participated in the SRG. In 1994, on the recommendation of the ISG members, the distinction was eliminated by the Policy Review Group and the Participating Technical Advisors were designated full members.

The Independent Scientific Group was formed in February 1995 from the SRG in response to measure 3.2B.1 in the Northwest Power Planning Council's 1994 Fish and Wildlife Program. The ISG's duties included conducting a biennial evaluation of the FWP on its scientific merits, identifying specific key uncertainties with respect to the program measures, and responding to questions submitted by the Council or through the implementation process. The latter included providing objective scientific advice in prioritizing and evaluating actions funded by BPA under the FWP.

The ISG normally meets monthly, or more frequently, depending upon the work load. The ISG operates by consensus, as did the SRG. Our reports are adopted only after full input and agreement from each member . While the matters for action by the SRG and ISG were frequently selected and referred by the PRG, the SRG and ISG have independently identified questions of importance or areas that deserve more emphasis. The ISG may organize panels of scientists and convene meetings to facilitate review of scientific issues.

Relation to the Independent Scientific Advisory Board

The Independent Scientific Advisory Board (ISAB) was established on May 28, 1996 through a joint agreement between the Northwest Power Planning Council (NPPC) and the National Marine Fisheries Service (NMFS). The ISAB is composed of eleven senior scientists from the United States and Canada, from a variety of biological and statistical disciplines. Nominations to the ISAB were provided by constituents throughout the Columbia Basin and elsewhere. Nominations were reviewed by a Selection Panel that included criteria and oversight from the National Research Council. Seven members of the Independent Scientific Group and two members of the National Research Council's Committee on Protection and Management of Pacific Northwest Anadromous Salmonids are among the eleven members of the ISAB.

The duties and procedures of the ISAB follow logically from those of the SRG and ISG. The Independent Scientific Advisory Board will provide independent scientific advice and recommendations regarding scientific issues posed by the respective agencies on matters related to their fish and wildlife programs. The NPPC has specified a series of tasks in its Fish and Wildlife Program of December 1994 (section 3.2), while NMFS has statutory obligations under the Endangered Species Act and other federal laws requiring independent scientific review.

The ISAB will address scientific and technical issues relating to the NPPC fish and wildlife program and the NMFS recovery program for Snake River salmon and other anadromous fish stocks, including related marine areas. Its purpose is to foster a scientific approach to fish and wildlife recovery and the use of sound scientific methods in research related to the programs of the Northwest Power Planning Council and the National Marine Fisheries Service. It is understood that the interests of the National Marine Fisheries Service relate particularly to anadromous fish conservation and management, while those of the Council include all fish and wildlife populations affected by operation and development of the hydroelectric system

Appendix B

Fisheries Restoration Plans

1. Fraser River Restoration

The current program to restore Columbia River salmon can trace its roots back to 1948 and the program developed by fishery agencies to mitigate for impacts on salmon created by federal hydroelectric development in the basin (Laythe 1948). A decade earlier another major restoration program on an important salmon producing river in the northwest was also initiated. On August 4, 1937 the United States and Canada ratified a convention for the protection, preservation and extension of the sockeye salmon fishery of the Fraser River system. The convention which created the International Pacific Salmon Commission (IPSFC) was the culmination of 45 years of negotiation and meetings between the United States and Canada (Roos 1991).

Fishermen from the United States and Canada harvested sockeye salmon returning to the Fraser River so there was a need for an international convention to coordinate and rationalize the fishery and prevent over exploitation. In addition, the sockeye salmon runs to the Fraser River were rapidly depleted after 1913 by a dramatic change in their migratory habitat at Hell's Gate, a narrow gorge in the Fraser Canyon 130 miles from the sea. The velocity of flow through the narrow canyon at Hell's Gate was known to delay sockeye migration under natural conditions. However, in 1911 and 1912, during the construction of a railroad grade, large amounts of rock were dumped into the river creating very turbulent conditions which completely cut off salmon migration at certain flows. In 1913, fishermen took a record harvest of 32 million sockeye salmon bound for the Fraser River. Those fish that escaped the fishery massed below Hell's Gate unable to ascend the river to their natural spawning areas and most dies without spawning. The average annual run of sockeye salmon to the Fraser River between 1894 and 1916 was 11.4 million fish compared to an average run of 3.31 million fish from 1917 to 1949 (Roos 1991).[1]

The IPSFC’s initial program had four key elements: 1) Correct the problem at Hell's gate. The blockage at Hell's gate was an obvious bottle neck that had to be corrected. 2) Protect the watershed. One of the early policy statements of the IPSFC put the Canadian Government on notice of its intent to protect salmon habitat in the watershed. 3) Protect the stocks. The IPSFC recognized that sockeye salmon in the Fraser River were separated into different socks, each with

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1916 was the last year of returns to the river from spawning prior to the Hell's Gate construction. 1949 was the last return to be unaffected by actions of the IPSFC.

specific spawning and rearing areas, run timing and environmental requirements. Management had to be based on stock conservation. 4) Hatcheries were given a low priority (Roos 1991).

In 1936, following a ten year research program, British Columbia closed all its sockeye salmon hatcheries (Foerster 1931, 1936, 1938; Pacific Fishermen 1936). The purpose of Foerster's study was to test the primary assumption which had justified the use of artificial propagation during its first 60 years on the west coast. Until Foerster's study it was assumed that artificial propagation was much more efficient than natural reproduction, however, the study found that artificial propagation did not have a statistically significant advantage over natural spawning. Although the fishing industry was interested in artificial propagation as an alternative to reduced harvest, the IPSFC placed it at a low priority and gave highest priority to natural production and the protection and restoration of habitat (Roos 1991).

Although hatcheries were given a low priority, the IPSFC did achieve some success with artificial spawning channels, however when it proposed a major construction program for additional spawning channels, the Canadian Government failed to give its approval so the program was never implemented. The IPSFC had to rely on better harvest management to boost escapement and increase production. The question of artificial propagation came up again in 1960, in response to proposals to build major hydroelectric and flood control dams in the Fraser River, many of them downstream from juvenile rearing areas in the basin. The IPSFC reviewed the prospects of mitigation through hatchery propagation of sockeye salmon and concluded that hatcheries were not a safe and proven method of maintaining even small localized stocks of Fraser River sockeye and pink salmon (Andrew and Green 1960).

The IPSFC's program was successful. From 1950 to 1978 the total annual run averaged 5.55 million fish compared to 3.31 million fish form 1918 to 1946 (after Hell's Gate but before IPSFC actions took effect). Recent run sizes have been 12 million fish in 1991, 13 million in 1985, 15 million in 1986, and 22 million in 1990 (Roos 1991; PSC 1991; PSC 1994). The total budget for the 48 year life of the IPSFC was 42.7 million dollars including about 4.5 million for construction. The IPSFC ceased to exist in December 1985. It was replaced by the Pacific Salmon Commission (Roos 1991).

References for Appendix B

Andrew, F. J. and G. H. Green. 1960. Sockeye and pink salmon production in relation to proposed dams in the Fraser River system. International Pacific Salmon Fisheries Commission, Bulletin 11, New Westminster, CAN.

Foerster, R. E. 1931. A comparison of the natural and artificial propagation of salmon. *Transactions of the American Fisheries Society,* 61st Annual Meeting.

Foerster, R. E. 1936. Sockeye salmon propagation in British Columbia. *Biological Board of Canada,* Bulletin No. 53, Ottawa, CAN.

Foerster, R. E. 1938. An investigation of the relative efficiencies of natural and artificial propagation of sockeye salmon (*Oncorhynchus nerka*) at Cultus Lake, British Columbia. *Journal Fisheries Research Board of Canada,* 4:3 151-161.

Laythe, L. L. 1948. The fishery development program in the lower Columbia River. Transactions of the American Fisheries Society 78th Annual Meeting.

Pacific Fisherman. 1936. All sockeye hatcheries closed in British Columbia. *Pacific Fisherman,* 34:5 17.

Pacific Salmon Commission, Fisheries Management Division. 1991. Report of the Fraser River Panel to the Pacific Salmon Commission on the 1990 Fraser River sockeye salmon fishing season. Vancouver, B. C.

Pacific Salmon Commission, Fisheries Management Division. 1994. Report of the Fraser River Panel to the Pacific Salmon Commission on the 1991 Fraser River sockeye and pink salmon fishing season. Vancouver, B. C.

Roos, J. F. 1991. *Restoring Fraser River Salmon.* Pacific Salmon Commission, Vancouver, CAN.

2. Restoration of east coast Striped bass populations

From a population high in 1970, the east coast striped bass (*Morone saxatilis*) population crashed through the 1970s and early 1980s until drastic management measures were taken in the mid-1980s. The population has since rebounded and measures have been relaxed (Dorazio et al., 1994). The striped bass is an estuarine fish native to the eastern coast of North America from Nova Scotia to north Florida and along the northern coast of the Gulf of Mexico. As adults, the species occupies coastal ocean waters in the northern part of its range and resides mostly in rivers south of Cape Hatteras, North Carolina. As juveniles (up to 2 years old), the species occupies shallow estuarine or lower river waters. Changing water temperature induces long-distance coastal migrations of adults between summer and winter and warm water restricts suitable habitats for adults in summer. Adults spawn in the freshwater tidal zones of estuaries, particularly the Hudson River in New York and rivers tributary to the estuarine complex of Chesapeake Bay in Maryland and Virginia. Historical runs to the Delaware River estuary in Pennsylvania and New Jersey were extirpated by pollution in the lower river at Philadelphia and Trenton.

Major threats to the striped bass in the period of decline were pollution of estuarine spawning grounds, entrainment of eggs and larvae into cooling systems of power plants on estuaries, habitat degradation of estuaries (that reduced macrophyte-populated nursery areas and deoxygenated cool water adult refuges), and overfishing. With recognition that habitat restoration was necessary but a long-term effort, the state of Maryland imposed a total fishing ban for striped bass in 1985. This ban was expanded through the Atlantic States Marine Fisheries Commission and the federal Atlantic Striped Bass Conservation Act to include all coastal waters. Schemes were developed for compensating commercial fishers put out of business by the administrative acts. A federally-funded research program developed credible monitoring programs by states and relevant research studies. A major Chesapeake Bay habitat restoration program was begun, and pollution-control efforts were speeded up on Delaware Bay.

The outstanding parallel with the current Northwest salmon decline is the demonstrated importance of reducing fishing take to allow the population to rebuild while still facing other threats. This temporary measure, though unpopular initially (and causing many of the same social dislocations), provided a decrease in mortality so that striped bass stocks weakened by habitat degradation and other sources of mortality would not continue to decline. Gradual habitat restoration and other measures to enhance survival are presumably acting to facilitate population rebound and to compensate for gradually renewed fishing. A major lesson has been that sustained fishing pressure, especially on reproductive and immediately prereproductive ages (as in the ocean and coastal salmon fisheries) can be devastating when other impediments to survival are high.

Appendix C

Hierarchical organization in genetic structure of Washington state chinook salmon populations.

Marshall et. al. (1995) examined the genetic structure of chinook salmon populations from Washington state waters in the Columbia Basin and identified two major ancestral lineages (MAL) and ten genetic diversity units (GDU) (Table 1). Their hierarchical classification was similar to that shown in Figure 4.2. A GDU is defined as:

> *A group of genetically similar stocks that is genetically distinct from other such groups. The stocks typically exhibit similar life histories and occupy ecologically, geographically, and geologically similar habitats. A GDU may consist of a single stock* (Busack and Shaklee, 1995) p A-3.

A GDU is similar to the evolutionarily significant unit (ESU) of Waples {1991}. A MAL is:

> *A group of one or more GDUs whose shared genetic characteristics suggest a distant common ancestry, and substantial reproductive isolation from other MALs. Some of these groups are likely the result of colonization and diversification preceding the last period of glaciation* (Busack and Shaklee, 1995) p A-5).

Table 1. MALs and GDUs for chinook salmon in Washington waters of the Columbia Basin.

Major Ancestral Units (MAL)	***Genetic Diversity Units (GDU)***
Upper Columbia and Snake River	Snake River Spring
Spring Chinook	Upper Columbia River Spring
	Yakima Spring
Upper Columbia Summer and Fall	Upper Columbia Summer
Snake Fall	Upper Columbia Fall
Mid- and Lower Columbia Chinook	Mid-Columbia and Snake Fall
	Mid and Lower Columbia Spring
	Mid-Columbia "Tule" Fall
	Lower Columbia "Bright" Fall
	Lower Columbia "Tule" Fall

Matthews and Waples (1991) combined the spring and summer chinook of the Snake River into a single ESU which is probably similar to the Snake River Spring GDU in Marshall et al. (1995). Within the Snake River spring/summer chinook ESU, NMFS {1995} identified 12 stocks and 37 breeding units based on genetic and geographic information (Table 2).

Table 2. Snake River spring/summer chinook salmon classification by subbasin and subpopulation. (Source: NMFS 1995). (sp = spring chinook population; su = summer chinook population)

RIVER SYSTEM/STOCK	BREEDING UNIT/SUBPOPULATION
TUCANNON RIVER	Watershed population (sp)
GRANDE RONDE RIVER	Minam River (sp)
	Lostine and Upper Wallowa River tributaries (sp)
	Wenaha River (sp)
	Catherine Creek (sp)
	Upper Grande Ronde (sp)
IMNAHA RIVER	Mainstem (sp/su)
	Big Sheep and Lick Creek
SNAKE RIVER MAINSTEM	Asotin Creek (sp)
	Mainstem, Sheep Granite (sp)
LOWER SALMON RIVER	Mainstem tributaries, mouth to and including Horse Creek (sp)
LITTLE SALMON RIVER	Watershed expect Rapid River (sp)
	Rapid River (su)
SOUTH FORK SALMON RIVER	Mainstem, Blackmare to Stolle (su)
	Mainstem, mouth to Poverty Flats (su)
	Secesh River (su)
	Johnson Creek (su)
	East Fork South Fork (su)
MIDDLE FORK SALMON RIVER	Mainstem, mouth to Indian Creek (su)
	Mainstem, Indian to Bear Valley Creek (sp)
	Marsh Creek and tributaries (sp)
	Bear Valley and Elk Creek (sp)
	Sulphur Creek
	Upper Loon Creek and tributaries (sp)

	Lower Loon Creek (below TM 23) (su) Camas Creek (sp) Lower Big Creek (below TM 23) (su) Upper Big Creek and tributaries (sp)
LEMHI RIVER	Watershed population (sp)
PAHSIMEROI RIVER	Watershed population (su)
UPPER SALMON RIVER	North Fork Salmon River (sp) East Fork, mouth to Herd Creek (su) Herd Creek and Upper East Fork (sp) Yankee Fork and tributaries (sp) Valley Creek above Stanley Creek (sp) Lower Valley Creek (su) Mainstem Salmon below Redfish Lake Creek (su) Mainstem Salmon above Redfish Lake Creek (su)
CLEARWATER RIVER	Not listed under ESA

Appendix D

Fluid Dynamics Of River Flows In Relation To Salmon Downstream Migration

INTRODUCTION

Implicit in the relationships among flow, velocity, and survival for salmonids that have so thoroughly gripped the Columbia River basin is an implied relationship between flow and velocity (Cada et al., 1994, see Chapter 6). That is, there is an assumption that as the volume of water passing through a river-reservoir system per unit of time increases so does water velocity increase at each point along the length of the system. The increased velocity is assumed to be the biologically relevant feature of river flow increase for downstream migrating juvenile salmonids. Increased flushing of fish by higher water velocities is believed to be a major factor determining long-term fish survival. Although a general flow-velocity relationship is valid, presumption of a direct relationship between river flow and velocity at the detail seen by a fish is certainly a simplistic view that is not supported by knowledge in the engineering field of fluid dynamics of open channel flow. There is much more to it than that. There is a lot of complexity in the fluid dynamics that a fish must contend with, and we should recognize the opportunities open for them to become cleverly adapted to take advantage of this complexity.

Fluid dynamics of water flowing in rivers (open channels) is a field of scientific study that matured 15 to 20 years ago (Liggett, 1994) but which has not been brought to bear adequately on questions of salmon migrations. Study of the physical biology of flow has generally been concerned with static life in moving fluids, such as the shapes of organisms in flowing waters, or animal design for propulsion, lift, and minimizing drag (Vogel, 1981). Although methods of computer simulations continue to be developed, the basic mathematical expressions of features of water flow, elevation, and velocity in rivers can be found in textbooks such as Chaudhry (1993), Abbott (1979), Abbott and Basco (1989), Chow (1964), Fox (1989), Cunge et al. (1980), and Mahmood and Yevjevich (1975), and field manuals (Benson and Dalrymple, 1967). There are disciplinary barriers between salmon biologists and fluid-flow engineers that are likely the result of different languages. Fluid dynamics engineering is highly mathematical leading to calculations and computer simulations, largely for the design of the physical structures that determine the fluid dynamics of a water body. Biology is conceptual and empirical leading to narrative and visual explanations of the effects on fish and other aquatic life of man-made or natural structures and the fluid dynamics created by them. We often assume that our organism is well designed and try to determine just why the design is a good one. There are urgent reasons to bridge this gap. Vogel (1981) and Statzner et al. (1988) have tried to do so; Vogel in a general sense for all biology and

Statzner with a review oriented primarily toward stream invertebrate ecology and hydraulics that affect stationary points in a stream.

There are several salient features of fluid dynamics of open channel flow (that is, flow in channels with solid sides and bottoms and a water surface exposed to air). Water rarely moves as uniform flow with no change with downstream distance in either the magnitude or direction of the velocity along a streamline. Flow is most uniform when the depth and width are constant along the direction of flow, a situation unlikely to occur in natural rivers or reservoirs. Similarly, natural streams rarely have steady flow, in which the velocity at a point does not change with time. The normal pattern for a stream, viewed at the scale of a 50 mm to 150 mm fish, is to have velocities that change in often complex ways, whether viewed while moving along a longitudinal stretch or from one stationary point over time. These velocity changes can be in other directions as well as longitudinal (turbulence) and can be longitudinal pulses (traveling surges and flood waves).

WAVES

Increases in flow generally cause an increase in the water surface elevation. This increase in elevation travels away from the point of initiation as a wave, just as a stone tossed in the water creates a ring of waves. These waves move faster than the water particles that make them up. Waves in moving streams can be propagated both upstream and downstream, but the upstream wave can be obliterated by the opposing stream flow. Thus, waves in streams caused by changes in flow (elevation) generally move downstream at a rate that is faster than the actual water mass by a factor of 1.3 (a general factor given first by (Corbett, 1943)) to 4 (experimental data from the Snake River below Hells Canyon Dam in {Koski 1974}. Waves tend to be most prominent in the main channel and less obvious in the shoreline areas, due to damping by shoreline topography and vegetation. Waves interact: faster waves overtake and pass through slower ones; waves reinforce or cancel each other. The height of a stream's waves depends on the depth of the water, just as do waves on a beach. Bottom profiles can determine whether waves are standing waves, breaking waves, or ones that continue to propagate downstream. Small waves moving downstream (such as might result from continually changing flows or upstream disturbances) can coalesce as the bottom profile changes (particularly when depth decreases, as in a riffle or shoal) and form large waves or surges (bores). All of these effects have been described mathematically and the various features (depth, velocity, wave shape, etc.) can be related numerically. More attention has been given to waves on ocean beaches than to those in rivers, for reasons of the high economic value of beach erosion processes (Stoker, 1957; U.S. Army Corps of Engineers, 1984).

Waves moving downstream do interesting things to water particle velocities seen at the size scale of a small fish. Most of this information comes from beach erosion studies, for shore protection measures and coastal protection designs are dependent on the ability to predict wave forms and fluid motion beneath waves, and on the reliability of such predictions. Simple water waves are oscillatory and water particle motion is described by orbits (back and forth movements) that are closed, or nearly so, for the passage of each wave (Figure A.1(a)). However, waves are rarely truly oscillatory and the fluid is generally moved a small amount in the direction of wave advance by each successive wave. Thus, there is mass transport by the wave (for example, submerged jellyfishes just below the surface are moved in the direction of the waves in coastal waters; Figure A.1(b)). The extreme deviation from a pure, oscillatory wave is a solitary wave (also called a wave of translation or a stage wave), which is not oscillatory and has no real trough behind its single crest. It forms by a pulse release of water (naturally, as in a flood or artificially, as from a dam). The crest height is essentially maintained behind the wave front (Figure A.2(a); although here, too, the regularity is broken by a series of small dispersive waves that trail it). In a solitary wave, a significant increase in velocity of water particles occurs at the wave front and a significant amount of water is transported forward. As a solitary wave moves into shallower water (as a downstream-moving wave would in passing from a pool to a riffle area of a stream) the water particle velocity of the wave crest increases further and the wave may break (Figure A.2(b)). Multiple waves tend to coalesce in channel constrictions and become prominent bores with increased velocity . COE (1984, p. 2-55) gives the relevant equations.

It seems likely that a stream would have many "solitary"-type waves, especially in spring when water levels rise with runoff. Pulses of water from tributaries could induce such waves. During the rising limb of a spring freshet, the flow probably increases as a series of "solitary" waves, with velocities quite different from that of the particles of water. Little fluid dynamics study seems to have been directed at this application, even though the theory and general applications are readily available.

With these wave dynamics going on in a stream, it would be surprising if a migratory fish species did not adapt to make use of the localized enhanced velocities and particle movements at wave fronts. Any fish that could position itself in the wave zone of raised velocity and rapid downstream water particle transport would obtain a significant assist. How much assist a fish would get would depend on the initial size of the solitary wave or how much shallower the stream bottom becomes under the wave. The most dramatic assists would occur in riffle areas where waves coalesce and may be on the verge of breaking. The flatter waves in pools may be of little value for migration assists.

Impoundments in a stream and river system could, in principle, affect the suggested wave phenomena (perhaps positively and negatively) and thus influence the migratory capabilities of salmon smolts. Some dams likely release water in pulses, generating a wave effect similar to that in a natural system. On the other hand, the physical barrier of a dam would be an effective terminator of a downstream-propagating wave coming from upstream. Well upstream of the actual dam, a widening and deepening reservoir would, based on wave propagation theory, serve to diminish the wave height and thus the downstream transport of particles in the wave front. Fish riding waves might be left stranded, so to speak, in a small zone of the upper reservoir where they could be vulnerable to predation or other damaging effects.

TURBULENCE AND VORTICES

Turbulence is another feature of natural river hydraulics that might be used by migrating juvenile salmonids, and which is disrupted by impoundments. Two examples come to mind: turbulent bursts and vortices, although there are probably more. A turbulent burst is the high-speed, turbulent ejection of fluid and suspended solids away from the sediment bed, often after encountering a streambed obstruction (Leeder, 1983). At distances 4-5 times the water depth, there are accelerated flow events acting toward the bed and concurrent rapid fluid movements away from the bed (Figure A.3). The rising burst of flow propagates downstream in the water column and is seen at the water's surface as a "boil." A view of the surface of a swiftly moving river such as the unimpounded Columbia at Hanford, Washington, is of a patchwork of these boils. Water velocities in the leading edge of boils exceeds that of the general surrounding water. Sedimentologists are familiar with these features, for unsteady bedload transport is driven by "bursting-type" cycles in the sea (Thorne and Kuehl, 1989) and Carling (1992) has suggested that riverine sediment transport is also related to the inherent turbulent structure of rivers. These velocity bursts are a function of flow rate and water depth; reduction of flow velocity and increase in depth (as in impoundments) would terminate such turbulence structures. As with solitary waves, it seems reasonable that salmonids emigrating in rivers would have evolved to make use of the zones of accelerated velocity in these turbulent bursts to assist them in downstream movement.

Vortices are another feature of turbulent flow, occurring in the horizontal plane rather than the vertical (as in bursts). Rows of vortices are shed behind solid bodies and trail behind in a wake (Figure A.4(a)). If the body is in midstream, there is a wake of roughly parallel vortices, forming first on one side and then the other. Each vortex rotates in the opposite direction of the preceding and succeeding ones. If the body is a projection from shore, the vortices trail in single file in what is often referred to as a shoreline "rip." In either case, water velocities on the outside of the wake of vortices is more rapid than the general (average) water flow. When two structures are placed in proximity perpendicular to the flow, vortices from each can combine to yield a zone of accelerated velocity between the structures (Figure A.4(b)).

BIOLOGICAL EVIDENCE

What evidence is there that fish do, in fact, make use of such velocity assists from downstream-moving solitary waves or features of turbulence? The information is mostly circumstantial and in need of biological investigation. The following train of logic for physical phenomena and biological evidence seems persuasive enough to stimulate rigorous experimentation and field data collection, leading to modification of rivers to move toward a more normative condition that facilitates fish migration.

1. Solitary waves exist in streams, based on the accumulated knowledge of the field of open channel flow hydraulics and empirical evidence from field studies of the Snake River {Koski 1974}; turbulent bursts also occur in streams (Carling, 1992); vortices are a common phenomenon in turbulent rivers;
2. The waves move much faster than the average water particle travel time for the same reach, again, based on hydraulic theory and field evidence; turbulent bursts have velocities faster than the surrounding flow; and vortices from structures in rivers can create channels of higher velocity;
3. A zone of enhanced particle velocity occurs at the crest of a solitary wave and between the wave crest and the water elevation in front of the wave (i.e., near the water surface); turbulent bursts have zones of accelerated velocity at the leading edges of the bursts; vortices also induce zones of higher velocity;
4. Downstream-migrating yearling salmon and steelhead smolts generally migrate near the surface of a stream in the main flow (where solitary waves, turbulent bursts, and vortices from near-shore obstructions also have their main effect);
5. Experiments with drifting fish at thermal discharges at Hanford in the 1960s showed smolts traveling in the leading edges of boils (Becker and Coutant, 1970; Becker et al., 1971);
6. Ultrasonic-tagged adult chinook salmon and steelhead swam in the centers of shoreline rips (Coutant, 1970), possibly using the upstream assist of vortices and suggesting that downstream-migrating juveniles would also be adapted to using such assists in the downstream direction;
7. Averaged over long distances (several kilometers) in the Snake River with considerable length of riverine reach, steelhead smolts traveled faster than the average water particle (Berggren and Filardo, 1993), suggesting either some assist or intense swimming that is difficult to justify based on the likely energy expenditure (Brett, 1967; Trump and Leggett, 1980);
8. Averaged over similarly long distances, steelhead in the mostly impounded mid-Columbia

River moved slower than water particles (Berggren and Filardo, 1993), suggesting that they did not have the benefit of velocity assists from turbulent flow (consistent with there being fewer wave and turbulence effects in deep water of a reservoir);

9. In both steelhead cases, there was more difference between rates of fish and water particle movement at high flows than at low ones (the likelihood of waves being generated and propagated seems higher at high flows, when there are many changes in flow and water elevation over short time periods);
10. Yearling chinook salmon in the Snake River, although not migrating as fast over the long distance as steelhead, nonetheless showed an average migration rate close to that of water particles (Berggren and Filardo, 1993), which implies movement faster than water particles during the limited hours of the diel cycle when they actually move;
11. Spring chinook salmon migrating past Prosser Dam on the Yakima River did so in pulses that corresponded to rising water levels (Mundy, In press), which may have been in the form of waves or surges;
12. Spring chinook smolts followed in their downstream migration with radiotelemetry moved fastest (and faster than average water particles) in the riffle areas of the Willamette River (Schreck et al., 1995) where wave theory would suggest accelerated velocities at wave fronts and vortices from obstructions would create high-velocity channels;
13. Rainbow trout observed in streams by Northcote (1962) in infrared light headed downstream, near the water surface, and swam at a speed greater than the surrounding water (he did not look for waves or turbulence);
14. All downstream migrants probably do not use these mechanisms, because underyearling chinook salmon migrate slowly and tend to orient head upstream until high velocities make them drift (Nelson et al., 1994);
15. Most smolts migrate downstream at night or at low-light periods of dusk and dawn, when their rapid swimming activity designed to put them in the water surface, perhaps at the leading edge of a wave, would make them more vulnerable to sight-feeding predators in daylight;
16. The historical Snake River between Lewiston and Pasco appears to have been the type of channel that could have propagated solitary waves quite effectively, whereas the present string of reservoirs would be unlikely to do so.

RIVER CONTROL OPTIONS

It may reasonably be asked whether the exact mechanism of fish migration matters if the rate of fish movement through the river system is increased by just increasing river flows. Perhaps not, if water were always abundant and reservoir drawdown inconsequential. The increased water volumes from upstream or decreased depth of mainstem reservoirs could, without our paying any attention, convert slow-moving, non-turbulent, waveless reservoirs into reaches with solitary stage waves, turbulent bursts, and vortices to which salmon may have been adapted. A new perspective of the importance of fluid dynamics to salmon migration may, however, allow experimentation and possible selection of river control options that would provide appropriate waves, turbulence, or vortices without drawing reservoirs down as far and with smaller amounts of water. Reservoir pool elevations might then be selected that would accommodate both fish migration (fish ladders and juvenile bypass systems would not be stranded) and other uses such as navigation and recreation. More upstream water could then be used for other purposes such as irrigation and resident fishes in upstream reservoirs.

Creation of waves.

Diel hydropower peaking or spill might be scheduled at especially important times during juvenile salmon migrations to cause elevation changes in the downstream reservoir that would create waves useful in assisting salmon to migrate. Peaking or pulsed operation during spring runoff might be found preferable for fish migration to strict run-of-the-river modes in which flows are maintained at constant high levels. A distinct hydropower peaking pattern is maintained at Priest Rapids Dam on the Columbia River, which discharges to the Hanford reach that is known for its high production of fall chinook salmon. Spills at selected dam gates might be scheduled so that they provide an advantage to smolt migration through their generation of solitary waves in downstream reaches as well as through assisting fish in dam passage.

Control structures.

Control structures placed in reservoir channels might be used to induce turbulence and changes in water velocity that could aid fish movement. In essence, an understanding of the details of how salmon use increased velocities at a fine scale may increase our efficiency in providing conditions conducive to more natural migration while still providing for other water uses. For example, a pair of simple concrete cylinders placed at the edges of the main channel in a reservoir might induce vortices sufficient to accelerate fish movements in the channel (Figure A.4(b)). If such cylinders were placed at intervals along the reservoir, a channel velocity conducive to fish migration might be maintained well into the reach of the reservoir where most turbulent flow and noticeable current normally disappear. Flow augmentation just enough to ensure functioning of this enhanced vortex velocity pattern in the channel might be provided rather than flows large enough to raise velocities across the whole reservoir cross section.

A control structure that has found application in redirecting water velocities to aid sediment movement is the submerged vane, “Iowa Vane” (Odegaard and Wang, 1991). This structure may also be capable of creating or redirecting velocity patterns to aid juvenile salmon migration. The vanes are small, flow-training structures (foils), installed near the riverbed, and designed to modify the near-bed flow pattern and redistribute flow across the channel cross section (Figure 6.15). They are installed at an angle of 15-25° with the flow and their initial height is 0.2-0.4 times the local water depth at design stage. The vanes generate a secondary circulation of flow not unlike other midstream obstacles, but with additional avenues of control. A single vane generates a vertical vortex of flow that would push surface water to the center of a channel (where fish migrate). Vanes in groups generate larger, combined vortices (Figure 6.15(b)). When aligned on opposite sides of a channel, sets of vanes can constrict the flow to a more defined channel (Odeggard and Wang, 1991, Figure 6.15(c)). Although submerged vanes have been applied to sediment control, there has been no experimentation with their use as devices to assist fish migration.

SUMMARY

This short review of fluid dynamics is but an indication of the rich opportunities for understanding salmon migration behavior that could come from a rigorous interaction between biologists and hydraulic engineers. None of the examples given here are yet recommendations for implementation. In the context of the review of science behind the Columbia River Basin Fish and Wildlife Program, it should be recognized that there is a body of science dealing with fluid flow in channels that seems to have important but relatively untapped applications to the problems of fish migration. An interdisciplinary program of theoretical and experimental studies should test these ideas and search for others. The results could have significant impact on managing flows and the hydropower system in the Columbia River basin for benefit of both fish and other water users.

Appendix E

BYPASS, Parts 2 and 3

Mortality Of Smolts At Dams And Development Of Bypass Systems. Part 2: Bypass Measures Called For By Federal Energy Regulatory Commission, The NPPC Fish And Wildlife Program And NMFS Recovery Plan

INTRODUCTION

Combinations of mechanical bypass and spill are required to meet the goals for fish passage (90% survival over 80% of the spring and summer emigration at specified projects for the NPPC, and 80% fish passage during specified spring and summer periods for NMFS/NOAA) at each of the Snake River and Columbia River projects, with the exception of Wells Dam. In the case of those projects with mechanical bypass systems in place, the fish guidance efficiency, FGE, is not high enough to meet the 90% FGE standard set by the council in 1986 and in the 1994 FWP, nor is it likely that this standard can be achieved with turbine intake screens, as discussed in Part I. Thus, the goals for fish passage require spill to make up the difference. As will be explained below, the amount of spill required depends upon the FGE of screens that are present and upon spill effectiveness, i.e. the relationship between percentage of flow that is spilled and the percentage of fish that are passed.

A summary of the current (1995) bypass programs in place at the Columbia River and Snake River projects is provided in Table 3. Also shown are the goals established for fish passage compared with fish passage actually achieved in 1995 {NMFS/NOAA, 1995}; (Center, 1995).

SPILL REQUIRED FOR BYPASS

FERC Requirements for Spill

Background

Because spill is generally accepted to be a safe route for passage of juvenile fish, as explained in detail in Part I where survival of smolts in spill was shown to be 98% to 100%, spill has been included as a measure for improvement of survival of smolts beginning with the mid-Columbia Settlement Agreement of 1979 in which there was a provision for a specified amount of spill (10%) at each of the mid-Columbia projects.

Beginning in 1985, with the Stipulation that extended the mid-Columbia agreement in the FERC proceeding, spill has been identified at some projects as an interim measure to be used to reach a specified percentage of fish passage, with the understanding that as bypass facilities came on line, the successful bypass figure would be included within the percentage figure. The 1985 Stipulation provided for 50% fish passage during an approximate 30 day period at Wells Dam. At Wanapum Dam, a volume of spill was specified that was targeted at achieving 50% fish passage during the 30 day period. At Rocky Reach Dam the target was set at 30% fish passage in spill, because of low spill effectiveness shown by the hydroacoustic studies.

Current FERC Spill Programs

Current (1995) requirements for spill by FERC are shown in Table 3. In a Stipulation for 1994 and 1995, spill levels at Rocky Reach Dam were increased to 15% for 30 days during the spring emigration, (with an option to increase the number of days by up to 6 days if necessary to encompass 90% of the Okanogan River sockeye), and 10% for 34 days between June 15 and August 15.

In 1994, in response to a petition from the fishery parties, FERC required Grant County public utility district, P.U.D., to provide additional spill for juvenile salmonids at Wanapum and Priest Rapids dams, as an interim protection measure. The FERC ordered provision of a spill volume sufficient to ensure passage of 70% of the juvenile salmonids during 80% of the spring emigration and 50% passage during 80% of the summer emigration. (FERC Docket No. E-9569-003, Grant County Phase. Order of May 24, 1994). More on this is discussed under FERC requirements for mechanical bypass, below, and in Part III.

Rock Island Dam has not been included in the FERC mid-Columbia Proceeding after 1984 because issues were undergoing hearing with FERC, which in 1987 culminated in a long-term Settlement Agreement on issues relating to Rock Island Dam, that was adopted by FERC. It included no provision for interim spill, although it contained a clause providing for substitution of spill for bypass development. However, in 1985 FERC ordered spill as an interim measure at a level of 10% spill of the volume of water passing through powerhouse number 2 and 50% of the volume that would have gone through powerhouse number 1 in the absence of spill.

NPPC FISH AND WILDLIFE PROGRAM REQUIREMENTS FOR SPILL

Background

The NPPC Fish and Wildlife Program of 1984 called for a specific percentage of spill (20%) at the mid-Columbia projects. Although no volume of spill was specified for the COE projects on the Snake River or lower Columbia at that time, amendments to the 1984 Fish and Wildlife Program called upon the COE to develop coordinated interim juvenile fish passage plans, including spilling water over the dams, while developing permanent solutions to passage problems at John Day, The Dalles, Bonneville, Lower Monumental and Ice Harbor dams (NWPPC (1984).

Current NPPC Spill Programs

The NPPC Fish and Wildlife program of 1987 spelled out objectives in terms of total percentage of the fish to be passed, rather than a specified level of spill, Table 3. The 1987 FWP required that levels of spill, along with such other bypass facilities as might be available, should be sufficient to guarantee 90% fish survival for the middle 80% of the spring and summer migrations (Northwest Power Planning Council, 1987). That standard remains in effect in the council's 1994 program. In addition, the 1994 FWP calls for 80% fish passage efficiency at each Snake River project from April 15 to July 31 each year and at each Columbia River project (presumably lower Columbia) from May 1 to August 31. The 1994 FWP refers to a 10-year "Spill Agreement", reached in 1988 by The Mainstem Executive Committee (made up of representatives of BPA, the fishery agencies and tribes, and utility representatives), which was the response to the council's call for coordinated interim fish passage plans in the 1984 FWP. The COE agreed to adhere to the provisions of the agreement as these were described in the NPPC Amendments to the FWP for 1989, with some conditions. Levels of spill were specified for Lower Monumental, Ice Harbor, and The Dalles dams during spring and summer emigration periods, and John Day dam during the summer. These are now superseded by the more stringent requirements of the Proposed Recovery Plan described below (National Marine Fisheries Service, 1995).

Box 21. Spill amounts specified in the Spill Agreement of 1989.

The agreement was somewhat complex as, among other things, it attempted to take load factoring into account in determining an appropriate percentage of flow to be spilled. (Source: Fish Passage Managers, 1990)

	Spring Spill		Summer	
Project	Instantaneous %	Daily Average %	Instantaneous %	Daily Average %
Lower Monumental	70%	35%	70%	35%
Ice Harbor	25%	12.4%	25%	12.5%
The Dalles	--	10%	--	5%
John Day	--	-	20%	8.3%

NMFS/NOAA Recovery Plan Requirements for Spill

Background

Now, and for the foreseeable future, the governing factor in implementation of measures for smolt survival in the Snake River and lower Columbia River, is the 1995 NMFS/NOAA Proposed Recovery Plan for Snake River Salmon, being implemented as a result of listing of certain Snake River stocks of salmon as threatened or endangered under the Endangered Species Act {NMFS/NOAA 1995}. Implementation of the provisions of the Plan is accomplished primarily through the Technical Management Team composed of federal managers from NMFS, the U.S. Fish and Wildlife Service, the Bureau of Reclamation, BPA, and the COE.

Box 22. NMFS/NOAA has made a commitment to the Council to coordinate planning and implementation efforts, (Stelle, 1994). (Statement on actions necessary for the recovery of Snake River salmon presented to the NPPC by William Stelle, Jr., Northwest Regional Director, on November, 1994. - Cited in Recovery Plan p. I-12.)

The Proposed Recovery Plan specifies a general strategy whose first two measures focus on: 1) Improvements in downstream survival through increased flows and controlled spill in the Columbia and Snake Rivers; 2) Modifications to dams and their operations to bring about improvements in juvenile downstream passage survival and upstream adult survival. (National Marine Fisheries Service, 1995), p. I-8)

Current NMFS/NOAA Spill Programs

The Recovery Plan calls for 80% fish passage efficiency at each of the dams on the Snake River and lower Columbia, during specified time periods designed to cover the spring and summer smolt migrations (National Marine Fisheries Service, 1995), p. V-2-30). These are shown in Table 3. None of the Snake River or lower Columbia River projects has in place a mechanical bypass system that will meet the NMFS/NOAA standard. To attempt to achieve that passage efficiency in 1995, spill was required at the four lower Snake River dams from April 10 through June 20, and at the lower Columbia River dams from April 20 through June 30 in sufficient amounts to make up the difference between what could be accomplished with the FGE of the intake screens or sluiceways at the given project and the 80% goal, taking into account spill effectiveness at the project as well. (National Marine Fisheries Service, 1995), p. V-2-31.) The required spill amounts are larger than those in the 10 year spill agreement.

Box 23. The Recovery Plan provided an exception during periods of low flow, during which there was to be less spill in order to divert more fish into bypass systems where they could be transported to below Bonneville Dam for release. Low flow was defined for Lower Granite Dam as less than 100 kcfs, and for Little Goose, and Lower Monumental dams as less than 85 kcfs. In 1995, flow at Lower Granite was beneath the specified 100 kcfs before May 7 and after June 22, 1995. At Little Goose and Lower Monumental, flow was below the 85 kcfs before May 3. McNary Dam and the three lower Snake River projects, Lower Granite, Little Goose and Lower Monumental, were designated as "collector dams" where the focus was to be on transportation of smolts by barge as long as river flows remained below the specified limits

The Recovery Plan set an upper limit on spill to be determined by dissolved gas concentrations. Spill was to be reduced at a project whenever a 12-hour average total dissolved gas concentration exceeded 115%.

REQUIREMENTS FOR INSTALLATION OF MECHANICAL BYPASS SYSTEMS.

FERC Requirements for Mechanical Bypass Systems

Background

In the mid-Columbia Settlement Agreement of 1979 and subsequent Stipulations, the parties agreed to work together to improve production of salmonids. Methods agreed upon were identified as 1) provision of spill, 2) investigate diversion of smolts from intakes, and 3) other, such as collection and transportation of smolts, (Offer of Settlement. Public Utility District Number 2 of Grant County, Washington. 10 FERC 61,257 (1980) Adopted by FERC March 23, 1980).

Accordingly, as a preliminary to design and testing of intake diversions, studies to determine the vertical distribution of juvenile salmonids as they approached the powerhouses began in 1980 at Priest Rapids Dam, and soon thereafter at the other mid-Columbia projects. These found that juvenile fish were concentrated at the upper portion of the intakes, as had been found in the NMFS studies at the COE projects, suggesting that similar screens could be effective, Biosonics, (Biosonics, 1981; Biosonics, 1981; Biosonics, 1982; Biosonics, 1982; Biosonics, 1983; Olson, 1983; Hays, 1984; Olson, 1984). Engineering and model studies of turbine intake diversion devices began soon after, followed by prototype design and testing, as discussed below and summarized in Table 3.

Table 3 provides information on the specific FERC requirement for each mid-Columbia project. One situation, not easily summarized in such tabular form is the one that developed with Grant County P.U.D.. In 1992 Grant County P.U.D. proposed to install a full bypass and collection system at Wanapum Dam and to provide transportation of the collected fish for release below Priest Rapids Dam, thereby avoiding the need for intake screens and an associated bypass system at Priest Rapids Dam. The parties to the mid-Columbia proceeding were unable to agree on this proposal and Grant P.U.D. requested a hearing before the FERC Administrative Law Judge, who ruled against the Grant P.U.D. proposal and ordered installation of turbine intake screens, (State of Washington Department of Fisheries v Public Utility District No. 2 of Grant County. FERC Proceeding. Docket No. E-9569-003 (Grant County Phase), re Project No. 2134-024. Ruling of March 23, 1992, Hon. Stephen L. Grossman Presiding.) This ruling does not become final until it is formally adopted by FERC.

Goals for Passage

The long-term Settlement Agreement for Wells Dam set a fish passage goal for the bypass of 80% for spring migrants and 70% for the summer. An interim spill standard in place by FERC applies to Wanapum and Priest Rapids dams, pending installation of mechanical bypasses. The FERC order calls for 70% passage of juvenile fish during 80% of the duration of the migration in the spring, and 50% during 80% of the migration in the summer.

Current FERC Bypass Programs

The bypass at Wells Dam is operated during spring and summer periods agreed upon by the Wells project Coordinating Committee, made up of representatives of Douglas County P.U.D., the fishery agencies, and tribes (parties to the mid-Columbia FERC Proceeding).

Bypass at the four other mid-Columbia projects is provided by spill in amounts that are either set by the agreements filed with FERC (Rocky Reach dam), or by an interim order of FERC (Rock Island, Wanapum and Priest Rapids dams). As noted above, the order of the Administrative Law Judge for FERC calls for installation of bypass facilities for juvenile salmonids at Wanapum and Priest Rapids dams, but the order is not final until adopted by FERC. Meanwhile, Grant County P.U.D. is proceeding on a schedule for installation, as indicated in the table.

NPPC Fish and Wildlife Program Requirements for Mechanical Bypass Systems

Background

Whereas the FERC has authority over license conditions for the mid-Columbia projects, the NPPC is an advisory body established to determine regional policy on power issues and fish and wildlife issues in the Columbia Basin as a whole.

In the 1982 FWP the NPPC called for development of mechanical bypass systems at the mainstem dams and at the five mid-Columbia projects. The 1984 FWP reported on the agreements reached among the parties in the mid-Columbia.

Goals for Passage

The 1987 FWP set a standard of 90% FGE as a design criterion for intake screens - if it can be achieved - and established spill as an interim measure to produce 90% survival during the middle 80% of the spring and summer emigrations.

Current NPPC Bypass Program

The standards set in the 1987 FWP remain in the 1994 FWP. The additional operational objective of 80% fish passage efficiency at the Snake River and Columbia River projects, was mentioned above.

In the 1991 Amendments to the FWP and the 1994 FWP, the Council called for completion of turbine intake screens and juvenile fish bypass systems at all eight federal dams on the lower Columbia River and Snake River by 1998. In addition, the 1994 FWP called for installation of extended screens at McNary (1995), Lower Granite (1996), Little Goose (1996), John Day (1998), and The Dalles (1998), if they prove to be effective. No criteria were given.

The 1994 FWP also set a standard of 98% survival to be achieved in bypass and collector facilities throughout the basin.

NMFS/NOAA Recovery Plan Requirements for Mechanical Bypass Systems

Background

The NMFS/NOAA Recovery Plan, "... is based on the premise that there is sufficient uncertainty about the benefits of transportation to warrant an evaluation of whether improved inriver migration might result in as many (or more) returning adults than does the transportation program.", (National Marine Fisheries Service, 1995, p.V-2-50.) Accordingly, specific standards are established for inriver passage and a study is recommended to compare adult return rates from transported fish with return rates from inriver migrants that have had the benefit of improved inriver conditions.

Turbine Efficiency

The Plan calls for operating turbines at the eight federal projects within 1% of peak efficiency during March 15 through October 31 in the Columbia River and March 15 through November 30 in the Snake River.

Recommended Studies

The Plan calls for studies to improve efficiency in the bypass systems at Columbia Basin hydroelectric projects, and lists 5 kinds of studies, including the following: 1) re-evaluating existing bypass systems; 2) evaluating all new systems; 3) developing new means of collection and bypass; 4) developing better methods for counting fish bypassed and held; and 5) assessing the impacts of supersaturated gas on juvenile and adult salmonids.

Goals for Passage

The Plan sets an interim goal of 80% fish passage efficiency at each dam. Spill is to be used to assist in reaching this goal. The NMFS/NOAA goal provides a refinement over the NPPC goal in the manner in which it distinguishes between the spring and summer migrations. Because the salmonid components of the migrations differ in spring and summer, it is necessary in implementing measures to achieve the goals, to define FGE levels separately for spring and summer for each project. Because the species of concern to NMFS/NOAA are the threatened or endangered species, which include sockeye, and fall chinook, that universally have shown low FGE (Spring/summer chinook, also threatened, show a higher FGE), the NMFS/NOAA goal, in practice, is more stringent than the NPPC goal, as will be shown in the Appendix, Part III. Because FGE varies among the projects, the relative spill amounts required to achieve the standard also vary, as previously discussed in the section on spill, Table 3.

Current NMFS/NOAA Bypass Program

For setting spill levels required to achieve the 80% passage goal, the Plan uses two standard sets of FGE levels, one for spring and one for summer, that were adopted by NMFS/NOAA, using the best available information, (Detailed Fish Operating Plan, DFOP, 1993, according to Fish Passage Advisory Committee, FPAC, 1995). In the absence of better information, it assumes a 1:1 relationship between the percentage of flow that is spilled and the percentage of fish that are passed in spill at each project. It also assumes a 98% rate of survival in spill. (Personal communication, Tom Berggren, Fish Passage Center, FPC.) Spill levels required to achieve the NMFS/NOAA bypass goals are shown in Table 3. The Plan provides strategies for installation, improvement, or testing of bypass facilities at each of the eight projects. These are summarized in Part 3, below

APPENDIX E (continued)

Mortality Of Salmonid Smolts At Dams And Development Of Bypass Systems. Part 3 Conformity In 1995 Of Installation And Operation Of Bypass Systems With Requirements Of FERC, The NPPC Fish And Wildlife Program And NMFS Proposed Recovery Plan Conformity in 1995 with FERC Requirements for Spill and Mechanical Bypass

Background

Requirements by FERC for spill and development of mechanical bypass systems at the mid-Columbia projects have for the most part occurred in the context of agreements reached among the parties to the mid-Columbia Proceeding. These are summarized in Table 4. At Wells Dam, a committee established in the Long-term Settlement Agreement has the responsibility of agreeing upon the schedule for operation of the bypass. The decision is made based upon information from hydroacoustic monitoring at the dam.

At Rocky Reach and Rock Island dams, the FERC requirements for spill are in terms of a daily amount specified as a percentage of spill relative to daily average river flow for a fixed number of days, while at Wanapum and Priest Rapids dams the spill amounts are specified as the daily percentage of spill required to pass 70% of the juvenile salmonids that are passing during 80% of the duration of the spring emigration and 50% of the juvenile salmonids passing during 80% of the summer emigration. The intent of the 80% duration specification is to provide an interval at the beginning of the season during which data can be collected that will indicate the timing of the emigration in the particular year, and likewise to provide some latitude at the end of the emigration. The mid-Columbia Coordinating Committee and the Rock Island Coordinating Committee, made up of representatives of the parties to the mid-Columbia Proceeding, was given the responsibility of implementing the requirements. In particular, because the timing of emigration differs from year to year, the committee has the responsibility of determining when the first 10% of the emigration has appeared in order to commence the spill program at each of the four projects, for interrupting it if the data suggest it, and for determining when the 80% goal has been reached at Wanapum and Priest Rapids.

In practice, based on past experience at Wanapum and Priest Rapids dams, the committee has agreed upon a schedule for a fixed number of days (35) of spill, with an option to apply for additional days if it appears the 80% goal has not yet been reached.

In 1994 the mid-Columbia Coordinating Committee, a body made up of representatives of the parties established by agreement in the mid-Columbia Proceeding found itself in a conflict between the FERC order to spill for fish passage and limits on spill because of water quality standards set by the Washington State Department of Ecology. The FERC order called for sufficient spill to achieve 70% fish passage during 80% of the spring emigration along with 50% for the summer at Wanapum and Priest Rapids dams, while the special permit issued by the Washington Department of Ecology allowed Grant County P.U.D. to exceed the normal limit of 110% gas saturation in the river below the projects, but maintain it below 120% of saturation. In 1994, some exploratory manipulations of spill level were required to comply with the limit on gas saturation.

Spill

A summary of spill programs executed at the mid-Columbia projects in 1995 is provided in Table 3. Operators at Wells, Rocky Reach and Rock Island dams were able to follow the FERC requirements, as described in a previous section. The goal for fish passage was achieved at Wells Dam in spring and summer. And the FERC goal for fish passage in the summer at Priest Rapids was achieved by spill at that project. Achievement of FERC goals at Wanapum Dam in spring and summer and Priest Rapids Dam in the spring was not possible due to limitations on spill because of gas supersaturation. Grant County P.U.D. requested and was granted a variance from Washington state water quality standards, allowing gas saturation levels of 120% at Wanapum and Priest Rapids dams, which permitted higher levels of spill, but not enough to meet the goals.

At Wanapum and Priest Rapids dams in 1995, the committee agreed to a schedule for spill during 24 hours each day that would maintain gas saturation limits within the permitted levels. It was found that effectiveness of spill in passing fish was greatly enhanced by maintaining the spill for 24 hours a day {Hammond, 1995}, when compared to the nightly schedule used in previous years, as discussed in Part I.

Mechanical Bypass

The surface collector at Wells Dam has been fully operational since 1988, with an estimate of 89% fish passage verified over a three year period. Screens tested at Rocky Reach Dam have not performed satisfactorily, as described in Part I. At Rock Island Powerhouse Number 1, tests of an intake screen continue. Screens are not feasible at Rock Island Powerhouse Number 2, Table 3. Although the ruling on the Grant County P.U.D. petition to substitute transportation for screens at Priest Rapids Dam, described above, is not final until it is adopted by FERC, Grant P.U.D. has proceeded with a schedule for installation of intake screens to be completed at Wanapum Dam by 1999 and Priest Rapids by the year 2000.

CONFORMITY IN 1995 WITH NPPC REQUIREMENTS FOR SPILL AND MECHANICAL BYPASS

Background

Since the requirements of the NPPC have been superseded by those in the NMFS/NOAA Proposed Recovery Plan, the reader is referred to the discussion below.

Requirements of the NPPC and NMFS/NOAA with respect to installation and improvement of bypass devices are similar, as shown in Table 4. Although the experiments with the bar screen showed promising results, there were difficulties with debris and the COE elected to proceed with installation of submerged traveling screens (STS's) at all eight of its projects on the Snake River and lower Columbia, (COE Salmon Passage Notes 1992). All but The Dalles are now fully equipped, Table 4. The 1994 FWP called for installation of extended-length screens at McNary Dam by March, 1995, Lower Granite and Little Goose dams by March, 1996, and John Day and The Dalles dams by March, 1998.

CONFORMITY IN 1995 WITH NMFS/NOAA REQUIREMENTS FOR SPILL AND MECHANICAL BYPASS

Background

With respect to the flow and spill requirements, the NMFS/NOAA Recovery Plan set limits on gas saturation at 115% in the forebay, on a 12 hour average, or 120% in the tailrace for 12 hours. The Plan recognizes there are differences among projects in levels of gas saturation produced by given spill volumes, as well as an interaction between gas saturation levels at successive projects, and recommends studies to optimize spill levels within the limits set by gas saturation criteria. The states of Washington, Oregon, and Idaho issued special permits, allowing the COE to exceed their water quality standards normally set at 110% and go to 120%.

Spill requirements, as applied by NMFS/NOAA, vary with the mix of yearling and subyearling chinook, steelhead, and sockeye, because the FGE varies among the species, with the values for yearling chinook and steelhead being much higher than sockeye and subyearling chinook. A further complication is that yearling chinook and steelhead are early emigrants, with sockeye somewhat later, while subyearling chinook, though present through the season, predominate among the later emigrants (Fish Passage Center Annual Reports). Thus the standard values of FGE used by NMFS/NOAA as a basis for determining required amounts of spill to add in order to reach the 80% fish passage goal during the time periods fixed for spring and summer emigrants, are higher in the spring period than in the summer, which might suggest that more spill would be required in the summer in order to achieve the 80% fish passage goal.

Box 24. Standard FGE Used in 1995 by NMFS/NOAA to Calculate Spill Needed to Achieve 80% Fish Passage. (Personal communication, Tom Berggren, Fish Passage Center). The values to be used for 1996 will be somewhat higher in response to installation of extended screens at Lower Granite, Little Goose, Lower Monumental and McNary dams. (Shown in parentheses. Source: Memo of Margaret Filardo, Fish Passage Center, to FPAC, January 18, 1996)

Project	L. Granite	L. Goose	L. Monumental	Ice Harbor	
4/10-6/20	.50 (.57)	.56 (.63)	.55 (.62)		.73
Summer	.25 (..50)	.25 (..50)	.31(..54)		.33
	McNary	J. Day	The Dalles	Bonn.(1 & 2)	
4/20-6/30	.70	.72	.43	.37	.44
Summer	.47 (.58)	.26	.43	.10	.40

This refinement would lead to a situation calling for more relative spill later in the season when FGE is lowest and water is in shortest supply. To circumvent this problem the Plan specifies there should be no spill for summer migrants at Lower Granite, Little Goose, Lower Monumental, McNary or Bonneville dams. The first four are named as “collector dams” where the emphasis is to be on collection of fish for transportation in the barges to below Bonneville Dam.

Box 25. Calculated Spill Amounts (24 hour basis) Required in 1995 to Achieve 80% Fish Passage. Assumes 1:1 relationship of spill % to fish passage %, except at John Day and The Dalles, where specific information is available. (See Part I, and Magne et al 1987, and Willis, 1982.) Sluiceway passage, where present, is included in the 80%. Sluiceway passage at Bonneville Dam is not included. More information is needed there. The complexity of attempting to manage spill levels to attain a passage goal is illustrated in two examples A and B below. Method A is the simplest. It uses the FGE’s averaged over all species, as given in Box 24. The estimation procedure is explained in the footnote. Method B, used in The Detailed Fishery Operating Plan of the Agencies and Tribes (DFOP, 1993) depends upon the FGE’s for each stock, summer and fall, determines spill levels for a 12 hour night period during which a higher percentage of fish are expected to pass and during which there is expected to be less demand for power, and calculates what that spill volume would amount to over a 24 hour period.

Our analysis of diel passage data in Part I suggests both methods probably overestimate the amount of spill required as a percentage of river flow, for two reasons; 1) spill over a 24 hour period may be nearly twice as effective as spill of the same volume for 12 hours (Based on limited data at Wanapum and Priest Rapids dams), and 2) if surface spill is provided, it is likely that fish passage efficiency can be further increased, but further studies are needed. Both methods suffer from lack of adequate information on spill effectiveness at most of the projects. The assumed 1:1 relationship is not based on studies with an adequate range of spill values. Since the standard spill gates open from the bottom at about the same level as the top of the turbine intakes (generally), diel passage rates through existing spill can reasonably be expected to match passage rates measured through the turbines. But the same will not be true for surface spill, where fish can be expected to pass somewhat uniformly throughout the 24 hour period. See Part I.

	A. See Footnote for Explanation		B. Numbers From DFOP (1993)	
	Spring	Summer	Spring Chinook	Fall Chinook (Summer Migrants)
Project	Spill (%)	Spill (%)	Spill (%)	Spill (%)
Lower Granite	60	73	39	49.5
Little Goose	54	73	24	49.5
Lower Monumental	56	71	27	50
Ice Harbor	26	70	47	47
McNary	33	62	24	45
John Day	36*	73*	17.5	42
The Dalles	31*	31*	40	40
Bonneville I	68	77	68	77
Bonneville II	64	67	(powerhouse should not operate)	

* For John Day and The Dalles dams, spill effectiveness curves were used in method A. They differ from the 1:1 relationship assumed for the other projects. See Part I. Spill percentages required for Method A were calculated from the equation $.8N = NX + (FGE)(N-NX)$, where N is the number of downstream migrants, and X is the spill percentage required to provide 80% fish passage. Percentages for John Day and The Dalles were adjusted according to their

If mortality rates of 2% in spill and 2% in bypass systems are assumed, along with an assumed 15% mortality in turbines, the total survival at each project, with 80% fish passage would be a little over 95%

Note: The spill amounts that will be required in 1996 to achieve the 80% passage goal, with new extended screens in place, have been calculated by Margaret Filardo, Fish Passage Center. Generally, they are less than in 1995 by about 10%. (Memo of January 18, 1996 to FPAC)

Spill and Fish Passage. Spill levels could not be increased enough to meet the 80% passage goal in spite of the provision allowing gas saturation levels to 120%, This was true even though by 1995, five of the eight federal mainstem and Snake River projects were at least partially equipped with flip lip spillway deflectors. All were equipped except John Day, Ice Harbor and The Dalles dams, (Detailed Fishery Operating Plan, (DFOP) 1993, and personal communication Larry Basham, Fish Passage Center). At The Dalles Dam the shallow spill basin is not believed to cause high gas saturation (personal communication, Larry Basham, Fish Passage Center, 1996). Ice Harbor Dam will have spill deflectors in place in time for the 1997 migration. John Day Dam will have partial installation in 1997 and complete installation in 1998, (Bruce, 1995). See Table 4.

Box 26. Installation date and numbers of "flip lip" spill bays at COE projects.

(From DFOP, 1993)

Project	*Date*	*Number of Flip Lips*
Lower Granite	2/75	8 of 8 bays
Little Goose	2/76	6 of 8 bays
Lower Monumental	8/74	6 of 8 bays
Ice Harbor	Recommended by NMFS/NOAA Recovery Plan	
McNary	1/76	18 of 22 bays
	(2 outer bays on each end not equipped)	
John Day		none
The Dalles		none
(Spill through the shallow basin is thought not to cause high gas saturation)		
Bonneville	3/75	13 of 18 bays
(3 outer bays on north shore and 2 outer bays on south shore)		

Those spill bays that are equipped are used as the first alternative for spill. Obviously, when spill exceeds the capacity of those bays the remaining spill bays are employed.

At Ice Harbor Dam in 1995, as previously mentioned, outages of units led to forced spill and gas saturation that exceeded the permitted limits, but brought attainment of the fish passage goal. Fish passage goals were not attained elsewhere (except at Wells Dam in spring and summer and Priest Rapids Dam during the summer) because of the limits on gas saturation. At Ice Harbor Dam, the volume of spill observed during the interval specified in the plan amounted to 35.9% of the daily average flow, which exceeded the 26% calculated to meet the 80% passage goal. Gas saturation levels of 130-138% were recorded from May 25 to June 8 in the tailrace. The 115% criterion was exceeded during most of the days between April 20 and June 30.

Average amounts of spill actually provided at the COE projects over the spring period are shown in Table 3, along with estimates of the percentages of fish passage achieved at those levels, (Spill data from the Fish Passage Center; Estimates of fish passage from Fish Passage Center, 1995) Analysis by the Fish Passage Center (Fish Passage Center, 1995) shows that fish passage efficiencies achieved at projects other than Ice Harbor were below the 80% called for in the Biological Opinion, Table 3. They ranged from 50-60% fish passage at Lower Granite Dam to 78% at The Dalles Dam. With the exception of Bonneville Dam at 55-62%, all of the lower river projects achieved fish passages in the 70% range, while the Snake River projects other than Ice Harbor were in the 50-60% range, Table 3.

At a time from late May into June, 1995 during which Snake River runoff could not be regulated within lower levels, and flows at Lower Granite, Little Goose and Lower Monumental dams exceeded powerhouse capacities, there was “inadvertent spill” that went in part toward the goal of attaining 80% passage efficiency, but led to exceeding the gas saturation limits, (Fish Passage Center, 1995). The 115% criterion was exceeded during half or more of the spill period specified in the plan (April 10 to June 20) at three of the four Snake River projects, (Little Goose, Lower Monumental and Ice Harbor dams) and for most of the spill period (April 20 to June 30) at three of the four lower river projects, (McNary, John Day, and Bonneville dams).

Box 27. The 120% criterion was also exceeded for several days at Little Goose Dam, about 10 days at Lower Monumental, and about 3 weeks at Ice Harbor Dam; for several days at McNary Dam, and intermittently over the spill period at John Day Dam.

Mechanical Bypass

The Proposed Recovery Plan calls upon the COE to reduce loss of juvenile fish through structural and operational improvements of bypass facilities. Based on the studies that demonstrated improved FGE with extended-length screens the COE is proceeding with testing and installation of extended-length screens at the eight projects (U.S. Army COE, 1996). Four of the projects, Lower Granite, Little Goose, Lower Monumental, and McNary dams are expected to be equipped in time for the 1996 emigration (Filardo, January 18, 1996 Memorandum to FPAC)

Other measures in the NMFS/NOAA Proposed Recovery Plan in addition to spill that are designed to provide improved survival at the COE projects are also shown in Table 4. The Plan produced by the Snake River Salmon Recovery Team, referred to the success at Wells Dam and called for investigation of the application of surface collection technology at the Snake River and Columbia River projects, {Bevan et al, 1994; NMFS/NOAA, 1995}. Surface collector studies are proposed for 1996 in the Portland District of the COE to cover (a) hydroacoustic evaluations of fish passage, (b) fish condition studies, and radio telemetry for fine scale behavior information of juvenile salmonids in the forebay, through surface passage routes, and through the tailrace at Lower Granite, The Dalles, and Bonneville dams, and for 1997 at Ice Harbor Dam, (Draft COE Mitigation Project 11/2/95). These are intended to be observational studies to determine where the fish are and their movement, particularly as they approach the dams. Criteria are to be developed to design, model and evaluate surface bypass devices in future years. {COE Workshop, 1995}

Further project specific details for installation, testing and improvement of bypass facilities at each of the eight COE projects are shown in Table 4.

SUMMARY AND DISCUSSION.

Wells Dam in the mid-Columbia reach is the only project in the basin with a smolt bypass system that can achieve the fish passage goals established by FERC, the NPPC or NMFS/NOAA for all species without the addition of spill. The best FGE's recorded for yearling chinook at projects in the Snake River and lower Columbia river range from 44% to 88%, with most in the 60% to 70% range. For subyearling chinook they range from 32% to 67% , with most in the 30% to 40% range. For sockeye they range from 14% to 73%, and for steelhead from 34% to 93%, with most in the 80% to 90% range (See Table 7.1 in Chapter 7). Survival rate of smolts once they are in properly tuned and maintained bypass systems generally is about the same as survival in spill. Because FGE of most of the existing turbine intake screens in the Snake and lower Columbia rivers is not sufficient to achieve the stated goals, spill must be added at all of the projects, except Wells Dam, Table 3.

Although a loss of smolts because of high gas saturation levels measured in the Snake River would have been predicted based on laboratory studies and studies of captive fish held in the river, recoveries of PIT-tagged smolts led to estimates of survival from the tailrace at Lower Monumental Dam to the McNary Dam tailrace of 84% in the period April 27 - May 10; 98% in the interval from May 11 to May 24; and 100% in the interval from May 25 to June 11 (Fish Passage Center, 1995). Contrary to expectations the survival of smolts in this river reach was high and did not decrease as the percentage of spill increased.

Box 28. At Ice Harbor Dam, during those three periods, average daily spill was 35.1%, 38.2% and 43.5% of the flow, while at McNary Dam spill was 39.6%, 44.3% and 43.0% of river flow. (Fish Passage Center, 1995)

ACHIEVEMENT OF GOALS

There are difficulties in determining whether the NMFS/NOAA goals are achieved either in terms of fish passage or survival. The standard FGE values used by NMFS/NOAA are projections based on estimates of the probable mix of species and stocks expected at each project at each season, along judgments on the appropriate FGE to use. Among the COE projects, reliable estimates of spill effectiveness are available only for John Day Dam and The Dalles Dam. It is therefore necessary to make an assumption as to the nature of the relationship between spill and fish passage for the other projects. The Fish Passage Center, in calculating fish passage under the given spill levels at the COE projects, followed a generally accepted procedure of assuming a one-to-one relationship of percentage of spill to percentage of fish passed {Fish Passage Center, 1995; DFOP, 1993}. In Part I we reviewed the available information and concluded that this assumption is not warranted at either John Day Dam or The Dalles Dam, where information on spill effectiveness is available. At John Day Dam, the effect would amount to a difference in fish passage of about 10% less at spill levels around 50% of river flow, (See Part I) while at The Dalles Dam, where spill is more effective, 20% spill gives about 50% fish passage {Willis, 1982}. This points to the importance of defining the spill effectiveness relationship for each project, or of grouping projects according to their configurations that would be expected to affect spill effectiveness.

The calculated spill values in the DFOP depend upon an assumption (or conclusion) that there is an advantage to spilling 12 hours at night versus 24 hours a day as a benefit to power production. Our review suggests that it would be worthwhile to conduct a more detailed examination of fish passage data related to duration of spill and of surface spill versus standard spill, in conjunction with costs and benefits to the power system in various scenarios of spill duration, to find an optimum strategy for fish and power.

CONCLUSIONS

None of the turbine intake screens in place or tested to date in the Columbia basin, shows a high enough FGE to meet the 90% standard for all stocks or species or the 80% fish passage standard, particularly for subyearling chinook or sockeye. Spill must be added in sufficient quantities to make up the difference.

As long as limits on gas saturation restrict the relative volume of spill permitted at Snake River or Columbia River projects, spill cannot be used either alone or as a supplement to intake screens, at levels required to achieve fish passage goals established either by FERC, the NPPC, or NMFS/NOAA at any projects except Wells Dam spring and summer (where no spill is required), except Priest Rapids Dam in the summer, and perhaps The Dalles in spring, Table 3. In the summer, out of the 13 projects on the Snake River and Columbia River mainstem, only Wells Dam with a bypass and Priest Rapids with spill will meet fish passage requirements. The flip lip spillways that are in place at some of the COE projects are not effective enough to circumvent this problem.

Although Wells Dam is the only project where surface collection has been successfully applied to date, and the configuration of that project does not allow for direct transfer of the technology to other projects on the river, comparing its performance with other bypass systems in existence, it appears that surface collection offers the best alternative for achieving the fish passage goals, Table 3.

Recommended Study of Spill Effects on Survival Analysis by the Fish Passage Center showing high survival rates of smolts in reaches where gas saturation levels exceeded permitted levels, raises questions about those levels that have been established. One question raised about studies that established those permitted levels is whether fish migrating in the open river would be able to find areas where they could establish an equilibrium with gas levels, for example by seeking water of greater depth and pressure. Further analysis, such as that of the Fish Passage Center, using tagged fish in transit through the river, should be undertaken. The NMFS/NOAA Proposed Recovery Plan states that the spill program it specifies is experimental. The Plan also calls for study of gas saturation. In view of the Fish Passage Center analysis showing high survival of smolts from Lower Granite to McNary Dam during high spill episodes in the Snake River in 1995, we believe further consideration of the limits are in order. Specifically, a study, such as the sort derived by the FPC from data available from the NMFS Snake River survival study, should be designed for the purpose of measuring survival of smolts from upper river to lower river projects under varying volumes of spill relative to river flow

Some studies of survival in spill and in passage through turbines appear to include an element of mortality due to predation below the project. There is a need to be able to separate direct mortality due to spill and turbine passage from indirect sources, such as predation, in order to be able to properly design mitigation procedures.

It is dangerous, in these years of low flow, to overlook the fact that in many years, in spite of increased storage capacity upstream, flow in the river in the spring will exceed the hydraulic capacity of the hydroelectric projects. A foretaste of that was seen in the Snake River runoff in the spring 1995. Forecasts indicate that 1996 will also be one of those years. In other cases, as at Ice Harbor Dam in 1995, turbines will go off line for various reasons, necessitating inadvertent spill. In all of these situations, gas saturation levels will probably exceed permitted limits. Therefore, a critical uncertainty is raised with respect to this issue, i.e. what levels of smolt mortality can be expected during years of high inadvertent spill. Studies should be undertaken to find ways of further reducing gas saturation levels below those currently experienced.

Generalizations

Recent studies have raised a question whether it is reasonable to assume a 15% turbine mortality. The mid-Columbia system mortality studies estimated a loss of 15-16% per project over five projects, which includes reservoir mortality. The study of Iwamoto et al, (1994) produced an estimate of 10% mortality in passing through Lower Granite reservoir and dam, and 14% in passing through Little Goose reservoir and dam. Muir et al, (1995) confirmed the estimate for Lower Granite reservoir and dam (8% to 10% in 1994), and developed estimates of mortality through Little Goose reservoir and dam amounting to 21% for yearling chinook and 22% for steelhead. These estimates all include losses in the reservoir as well as at the project. It must be observed that measures, such as spill and provision of other bypass systems at the projects themselves, can not be expected to ameliorate mortalities in the reservoir. This is not to say that reservoir mortality is not associated with construction and operation of the hydroelectric system, but that other measures must be found to address that source of mortality. It seems advisable to separate smolt mortality into at least four areas where it can occur; turbine, tailrace, reservoir, and forebay of the next project {Ferguson, 1993}; (National Research Council, 1995). Approaches to reduce mortality will be different in each area. Priorities may differ at each project, depending on the location of highest mortality.

The NPPC FWP of 1994 sets a goal of 90% survival at each project, and 80% fish passage efficiency over 80% of the duration of the emigration, while the NMFS/NOAA goal is for 80% fish passage efficiency. As noted previously, if the 80% fish passage goal is achieved, survival at each of the projects would be about 95%. If 90% survival were taken as the primary criterion, rather than 80% fish passage efficiency, then less spill would be required.

Box 29. If McNary Dam is used as an example, assuming 15% mortality of smolts in turbines, 2% mortality in the bypass, and 2% mortality in spill, using the estimate of 70% FGE for the spring, and given the 80% fish passage goal, thus providing 33% spill under the same assumptions previously used, then mortality at the project would be estimated as 3% in turbines, (0.70 X 0.67 = 0.469; 0.67 - 0.469 = 0.201; 0.201 X 0.15 = 0.03): perhaps 0.6% in spill, (0.33 X 0.02 = 0.006), and 0.9% in the bypass (0.469 X 0.02 = 0.009), for a total of 4.5% mortality at the project. The 90% survival criterion of NMFS/NOAA would thus be exceeded by means of the 80% fish passage criterion

The studies at Rocky Reach Dam and Lower Granite Dam suggested an estimate of about 8% would be reasonable for direct turbine induced mortality at those projects. This may be the best number that could reasonably be expected to be achieved as a goal for minimum smolt mortality through the powerhouse, given the performance of present bypass systems and the 80% fish passage goal. Carrying this number for turbine mortality through the procedure just described, we would find total mortality of 2.1% at McNary Dam with 80% fish passage. This is mortality at the concrete, and does not include mortality in the bypass, at the outfall, in the tailrace or in the reservoir below, all of which may be mortality associated with the project.

As a comparison, at Wells Dam, even if we use the estimate of 16% turbine mortality, as estimated for steelhead in 1980 (Weitkamp et al., 1980), and the estimate of 100% survival in spill estimated at that project (Weitkamp et al., 1980), then smolt mortality is perhaps 1.6% at the present time (0.16 X 0.11 = 0.018; with fish passage of 89%).

Box 30. It should be noted that there is a seeming incongruity between the turbine mortality study at Wells Dam and the systems mortality studies, (McKenzie et al., 1983): {McKenzie et al, 1984}**,** each of which produced an estimate of about 15% mortality. This would lead to the conclusion that reservoir mortality, tailrace mortality, and spill mortality would all be zero at Wells Dam

ACKNOWLEDGMENTS

We greatly appreciate the cooperation and assistance provided by personnel of the Fish Passage Center, particularly, Michelle Dehart, Tom Berggren, Margaret Filardo, and Larry Basham in gathering information for Part III. We thank John Williams of NMFS/NOAA, Richard Nason and Charles Peven of Chelan County P.U.D., and John Ferguson of the U.S. Army Corps of Engineers for assistance in locating sources of information for Part I.

Table 3. Bypass Measures Required and Executed at Columbia River and Snake River Projects in 1995. (Sources: **Skalski, 1991**; Chelan County P.U.D.; Grant County P.U.D.; Fish Passage Center, 1995; others listed in text.)

Mid-Columbia Projects			**Requirements in Terms of Fish Passage (FP) or Spill (S)**			**Fish Passage Achieved (Estimated %)**	
Project	**Measure**		**FERC**	**NPPC**	**NMFS**	**(%)**	**Conformity**
Wells Dam							
	Spill		None	None	NA		(Water required to operate the bypass varies with flow from 3-10% of average river flow.)
	Mechanical Bypass (Surface Attraction)						
		Spring	80% FP	80% FP	NA	(89%)	Operation during spring and summer period as agreed upon by representative committee.
		Summer	70% FP	70% FP	NA	(89%)	
Rocky Reach Dam							
	Spill						
		Spring	15% S	20% S	NA		30 days during spring, plus possible 6 more for Okanogan sockeye, if necessary.
		(spill effectiveness equation estimate				10% FP)	
		Summer	10% S	20% S	NA		Two weeks during summer emigration.
		(spill effectiveness equation estimate				6.6% FP)	
	Mechanical Bypass (Screens)		tests	tests	NA	(Table 7.1)	Prototypes tested: STS 1985 to 1988; bar screen 1989 - 1992 and 1994. Not successful
	(Surface Attraction)		-	-	NA		Prototype tested 1995. Results encouraging. Modified prototype to be tested in 1996.

Table 3. Continued
Mid-Columbia Projects - Continued

Project	Measure		Requirements in Terms of Fish Passage (FP) or Spill (S) FERC	NPPC	NMFS	Fish Passage Achieved (Estimated %) (%)	Conformity
Rock Island Dam							
	Spill						
		Spring	17% S	20% S	NA		FERC formula calls for spill of 10% of flow through powerhouse number 2 and 50% of flow
			(spill effectiveness line estimate			27% FP)	through powerhouse number 1. Therefore varies with flow and load distribution.
		Summer	3.3%	20% S	NA	(?)	
R.I. Powerhouse Number 1							
	Mechanical Bypass (Screens)		tests	tests	NA	(Table 7.1)	Prototype tested 1992-1995 shows promise. Further tests scheduled in 1996.
	Surface Attraction		-	-	NA		Being investigated
R.I. Powerhouse Number 2							
	Mechanical Bypass (Screens)		tests	tests	NA	(Table 7.1)	Settlement Agreement provided for tests. Tests indicated screens not feasible due to lack of space in front of horizontally oriented turbines. Agreement provides for spill in lieu of further development of bypass at the option of fishery agencies. Option not exercised to date (1995)
	Surface Attraction		-	-	NA		Any such device would probably serve both powerhouses.

Table 3. Continued
Mid-Columbia Projects - Continued

Project	Measure		Requirements in Terms of Fish Passage (FP) or Spill (S) FERC	NPPC	NMFS	Fish Passage Achieved (Estimated %) (%)	Conformity
Wanapum Dam							
	Spill						
		Spring	70% FP	20% S	NA	(52%)	FERC order requires passage of 70% of fish during 80% of emigration. Spill of 17% for 24 hours a day for 47 days passed 52% of fish. Spill limited by limits on gas saturation imposed for water quality.
		Summer	50% FP	20% S	NA	(25%)	FERC order requires passage of 50% of fish during 80% of emigration. Spill of 14% for 14 hours a day for 63 days passed 25% of fish. Spill limited by gas saturation limits for water quality.
	Mechanical Bypass (Screens)		tests	tests	NA	(Table 7.1)	Prototype bar screens tested. FERC order for installation is not yet final. Grant P.U.D. proceeding on schedule for installation. See Table 4.
	Surface Attraction		-	-	NA		Prototype tested in 1995 will be enlarged for further tests in 1996.
Priest Rapids Dam							
	Spill						
		Spring	70% FP	20% S	NA	(54%)	FERC order requires passage of 70% of fish during 80% of emigration. Spill of 17% for 24 hours a day for 47 days passed 52% of fish. Spill limited by limits on gas saturation posed for water quality.
		Summer	50% FP	20% S	NA	(62%)	FERC order requires passage of 50% of fish during 80% of emigration. Spill of 14% for 14 hours a day for 63 days passed 25% of fish. Spill limited by gas saturation limits for water quality.
	Mechanical Bypass (Screens)		tests	tests	NA	(Table 7.1)	Prototype bar screens tested. FERC order for installation is

Table 3. Continued
Mid-Columbia Projects - Continued

Project	Measure	FERC	NPPC	NMFS	Fish Passage Achieved (Estimated %) (%)	Conformity
	Requirements in Terms of Fish Passage (FP) or Spill (S)					
Priest Rapids Dam - Continued						
	Surface Attraction	-	-	NA		Any device suitable for Wanapum Dam would probably be applied to Priest Rapids Dam.
Snake River Projects						
Lower Granite Dam						
	4/10 through 6/20					
	Spill	NA	80% FP	80% FP		14.6% of average flow spilled May 3 to June 20, 1995.
	Mechanical Bypass (Screens)					
	Combined spill and bypass				(50-56%)	
Little Goose Dam						
	4/10 through 6/20					
	Spill	NA	80% FP	80% FP		21.7% of average flow spilled April 14 to June 30, 1995. Spill volume limited by gas saturation standards.
	Mechanical Bypass (Screens)					
	Combine spill and bypass				(60%)	
Lower Monumental Dam						
	4/10 through 6/20					
	Spill	NA	80% FP	80% FP		16.6% of average flow spilled April 14 to June 30, 1995. Spill volume limited by gas saturation standards.
	Mechanical Bypass (Screens)					
	Combined spill and bypass				(58-60%)	

Table 3. Continued
Snake River Projects - Continued

Project	Measure	Requirements in Terms of Fish Passage (FP) or Spill (S) FERC	NPPC	NMFS	Fish Passage Achieved (Estimated %) (%)	Conformity
Ice Harbor Dam						
	4/10 through 6/20					
	Spill	NA	80% FP	80% FP	(35-44%)	35.9% of average flow spilled April 6 to June 20, 1995 and beyond. Two turbines off line, necessitating spill when river flow exceeded plant capacity.
	Mechanical Bypass (Screens)					
	Combined spill and bypass				(79-84%)	
Lower Columbia River Mainstem Projects						
McNary Dam						
	20 through 6/30					
	Spill	NA	80% FP	80% FP	(40-44%)	39.8% of average flow spilled April 4 to July 4, 1995. Volume of spill limited by gas saturation standards.
	Mechanical Bypass (Screens)					
	Combined spill and bypass				(73-77%)	
John Day Dam						
	4/20 through 6/30					
	Spill	NA	80% FP	80% FP		3.8% of average flow spilled April 25 through June 30, 1995.
	Mechanical Bypass (Screens)					
	Ice and Trash Sluiceway					
	Combined spill and bypass				(72-72%)	
The Dalles Dam						
	4/20 through 6/30					
	Spill	NA	80% FP	80% FP		57.2% of average flow spilled April 27 through June 30, 1995.

Table 3. Continued

Lower Columbia River Mainstem Projects (Continued)

Project	**Measure**	**Requirements in Terms of Fish Passage (FP) or Spill (S)** FERC	NPPC	NMFS	**Fish Passage Achieved (Estimated %) (%)**	**Conformity**
The Dalles Dam (Continued)						
	Ice and Trash Sluiceway					
	Combined spill and bypass				(78%)	
Bonneville Dam						
	4/20 through 6/30 Spill	NA	80% FP	80% FP		34.5% of average flow spilled April 12 through June 30, 1995.
	Mechanical Bypass (Screens)					
	Combined spill and bypass				(55-62%)	

Table 4. Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules. (Sources: NPPC Fish and Wildlife Program, 1987, 1991 and 1994 Amendments; NMFS/NOAA Proposed Recovery Plan for Snake River Salmon, 1995; COE Columbia River Fish Mitigation Project Draft Plan, November 2, 1995; COE Salmon Passage Notes 1992; Various documents part of the FERC record for mid-Columbia Projects.)

MID-COLUMBIA PROJECTS

Project **Requirements by the Federal Energy Regulatory Commission (FERC) and The Northwest Power Planning Council (NPPC)**

Wells Dam

FERC Requirements

Surface Collector Bypass.

In place. Since 1990, operate the bypass spring and summer as scheduled by a representative committee.

Rocky Reach Dam

FERC and NPPC Requirements

Intake Screens.

Tests of bypass systems since 1985. Prototype STS's of various configurations tested 1985-1988, (Peven and Keesee, 1992). Tests 1989-1992 of bar screens, various configurations None performed satisfactorily. Highest measured FGE for chinook yearlings about 50%. Usually lower. Concluded that it would not be possible to meet criteria with intake screens at that project, (Peven and Keesee, 1992). The peculiar configuration of the project with a powerhouse nearly parallel to the river flow and a cul-de-sac between the powerhouse and the right bank leading to development of unusual flow patterns that affect fish behavior, are thought to be factors in the inability to apply the screen technology to this project.

Surface Collector.

In 1995, testing began of a surface collection device. Prototype in test shows promise. Further test of modified device scheduled for 1996.

Rock Island Dam

FERC and NPPC Requirement.

Intake Screens.

License condition requires tests of intake screens. According to terms of Long-Term Settlement Agreement of 1987, adopted by FERC. Rock Island Dam removed from the mid-Columbia proceeding. Included a provision for evaluation of prototype intake screens at powerhouses. Tests continue at powerhouse number 1, but Chelan County P.U.D. concluded that installation at powerhouse number 2 was not feasible due to the limited space available in front of the horizontally oriented bulb turbines. The Agreement allowed for substitution of spill valued at $1 million (in 1986 dollars) if no screens are installed at powerhouse number 2, at the option of the fishery parties to the proceeding. This has not been invoked. Tests at powerhouse number 1 have shown some promise, with FGE's measured in the range of 70 to 75% for chinook yearlings, about 60% for chinook subyearlings, and 45 to 55% for sockeye in 1994, (Peven et al., 1994).

Table 4. Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules. (Continued)

Project **Requirements by the Federal Energy Regulatory Commission (FERC) and The Northwest Power Planning Council (NPPC)**

Rock Island Dam (Continued)

Surface Collector (Not in requirements)

Chelan P.U.D. is investigating the feasibility of using a surface collection device at Rock Island Dam that might serve both powerhouses.

Wanapum Dam

FERC and NPPC Requirements

Intake Screens

Require tests of intake screens. Intake geometry at Wanapum Dam is similar to Priest Rapids, such that the screen con-configuration tested was also similar. Attainment of FGE near 75% for yearling chinook during the spring and 50% for
sub- yearlings during the summer, led to design and testing of an orifice passage system beginning in 1993. Grant
County P.U.D. is proceeding with design and installation of a full bypass system with completion scheduled for 1999, but
at the same time is testing a prototype surface attraction device as an alternative. Prototypes tested in 1990-93 produced
FGE's satisfactory to representatives. Installation scheduled for 1999.

NMFS/NOAA Recovery Plan Requirements

Calls upon Grant County P.U.D. to install flip lip spillways and/or a stilling basin at Wanapum Dam. Grant P.U.D. plans to begin design for installation of flip lips in the spillway at Wanapum Dam in 1996.

Not in Requirements

Surface Collector

Alternative surface collection device being tested in prototype. Enlarged prototype scheduled for testing in 1996.

Priest Rapids Dam

FERC and NPPC Requirements

Intake Screens

Require tests of intake screens. Based on the success of the fixed bar screen design that demonstrated by the earlier NMFS/NOAA tests, the Grant County P.U.D. design for tests in prototype at Priest Rapids Dam used that and other features shown to be desirable. Prototypes tested 1986-1988 produced FGE's satisfactory to representatives, (mid-Columbia Coordinating Committee, 1988). P.U.D. is proceeding with an installation schedule for completion in the year 2000.

Not in Requirements.

Surface Collector

P.U.D. is evaluating surface collection as an alternative to intake screens. Alternative surface collection device being

Table 4. Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules. (Continued)

SNAKE RIVER PROJECTS

Project	Requirements by The Northwest Power Planning Council (NPPC) and National Marine Fisheries Service (NMFS/NOAA)
Lower Granite Dam	NPPC Requirements. Improve Bypass The 1987 FWP called upon the COE to continue to evaluate and improve the effectiveness of the juvenile bypass system, to improve FGE, and continue studies to determine whether it was necessary to modify the existing juvenile fish bypass system to reduce mortalities and injuries. The 1976 studies at Lower Granite Dam required updating. The 1991 amendments to the FWP called for improvement of the existing fish collection and bypass system at Lower Granite Dam by March, 1996. The COE modified gates in the bypass system in 1992. Extended Screens COE has scheduled installation of extended screens by March 1996 (COE Salmon Passage Notes 1992). NMFS/NOAA Recovery Plan Requirements Improve Bypass System By 1997, or as soon as possible, the COE should develop a plan and proceed with improvement of the juvenile facility. Some specific requirements for improvement are listed in the Plan. Extended Screens The Plan calls upon the COE to continue its planned installation of extended length screens in time for the 1996 smolt migration season. Will be ready March, 1996. Surface Collector The Plan calls upon the COE to investigate the application of surface collection technology by June, 1996. The Walla Walla District has proposed a test of a prototype surface bypass and collection device at Lower Granite Dam in 1996, with full installation to follow in 1997 and 1998, depending on the results of tests. The prototype to be tested in 1996 will include configurations similar to those found to be most successful at Ice Harbor in 1995.

Table 4. (Continued) Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules.

Project	Requirements by the NPPC and NMFS. With Compliance
Little Goose Dam	NPPC Requirements. Improve Bypass Little Goose was equipped with turbine intake screens when it began operation in 1970. The 1987 Fish and Wildlife Program called upon the COE to study whether it was necessary to modify the bypass system to reduce mortalities to juvenile fish. However, since 1979-1980 when the conduit was reconstructed to enlarge the system, juvenile mortality had increased. The FWP called for installation of improvements by April, 1989. The COE modified gates in the bypass in 1991. Extended Screens The COE has scheduled installation of extended screens at Little Goose by March 1996, (COE Salmon Passage Notes 1992). NMFS/NOAA Recovery Plan Requirements Extended Screens Calls for the COE to continue its plans to install extended length screens at Little Goose in time for the 1996 smolt migration season.
Lower Monumental Dam	NPPC Requirements. Intake Screens The FWP of 1987 called upon the COE to develop a plan for installation of a juvenile fish bypass system and install a screening and bypass system by April, 1990. There is no sluiceway at Lower Monumental. The COE developed an alternate plan to use Lower Monumental as a collection facility for transportation. However, the Council felt the results were uncertain, and called for prototype testing of turbine intake screens there. The 1991 amendments to the FWP called for Lower Monumental Dam to be equipped with screens and a bypass system by 1992. The COE complied with installation. NMFS/NOAA Recovery Plan Requirements Extended Screens Calls upon the COE to plan for installation of extended length screens and structural modifications to improve gatewell hydraulics, contingent upon the results of prototype testing at Little Goose and Lower Granite dams.

Table 4. (Continued) Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules.

Project	Requirements by NPPC and NMFS. With Compliance
Ice Harbor Dam	NPPC Requirements. Improve Bypass System The COE was called upon to complete a sluiceway injury and mortality study, to develop a feasibility study of alternative juvenile fish passage plans and an installation schedule for a permanent bypass system. Intake Screens Conduct testing of turbine intake screens in prototype, using a 90% FGE standard, and to install a juvenile fish screening and bypass system by April, 1990. The 1991 amendments to the FWP called for installation of screens and a bypass system at Ice Harbor by 1994. The COE complied. Screens were in place in 1993 and the full bypass by 1994. NMFS/NOAA Recovery Plan Requirements Extended Screens Extended length screens and structural improvements to improve gatewell hydraulics should be planned, contingent upon the results of prototype screen testing at Little Goose and Lower Granite dams. Flip Lip The Plan calls for the COE to install stilling basins and spillway modifications (such as a flip lip) to reduce dissolved gas levels at Ice Harbor Dam as soon as possible. The COE plans to design a flip lip spillway for Ice Harbor Dam in 1996 and construct it in 1997. (COE Columbia River Fish Mitigation Project Draft Plan, November 2, 1995.) Surface Collector The Proposed Recovery Plan adopted by NMFS/NOAA in 1995 states that testing of the surface collector approach will begin in 1995 at Ice Harbor and The Dalles dams, to be followed by tests in 1996 at Lower Granite Dam. The Plan states that if successful, they should be installed in 1996 at the spillways tested. In 1995 the COE conducted several studies of prototype surface attraction configurations at Ice Harbor Dam. Not in the NPPC or NMFS Requirements Surface Spill The COE is investigating the possibility of employing surface spill at Ice Harbor Dam, (Biosonics, 1995) (Abstract presented at COE meeting of September, 1995).

Table 4. (Continued) Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules.

LOWER RIVER PROJECTS

Project	Requirements by NPPC and NMFS. With Compliance.
McNary Dam	NPPC Requirements Improve Bypass The Council's FWP of 1987 called for the COE to continue to evaluate and improve the effectiveness of the juvenile fish bypass system at McNary Dam, because of changes that had been made since 1968 when installation of the system was begun. Extended Screens To be installed by April, 1994. The COE scheduled prototype tests for 1995, (COE, 1992). NMFS/NOAA Recovery Plan Requirements Operate Bypass The bypass system should be operated according to criteria that will mitigate adverse warm water conditions in the summer. It calls for shading over the raceways by the end of 1995. Extended Screens The Plan calls upon the COE to continue the scheduled installation of extended-length screens for the 1997 season. The COE completed installation in time for the 1996 emigration. (Filardo memo, January 18, 1996)
John Day Dam.	NPPC Requirements Intake Screens Called upon the COE to proceed with its plan to install a complete bypass system with turbine intake screens by March, 1987, and to evaluate and improve its effectiveness. Screens were in place by 1992 (COE Salmon Passage Notes, 1992)

Table 4. (Continued) Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules.

Project **Requirements by NPPC and NMFS. With Compliance.**

John Day Dam (Continued)

NMFS/NOAA Recovery Plan Requirements

Extended Screens

Extended length screens should be installed at John Day Dam by spring, 1998.

Flip Lip. The Plan calls for the COE to install stilling basins and spillway modifications (such as a flip lip) to reduce dissolved gas levels at Ice Harbor and John Day dams as soon as possible. The COE intends to design a flip lip spillway in 1996 and begin construction in 1997 for completion in 1998. (COE Columbia River Fish Mitigation Project Draft Plan, November 2, 1995)

Surface Collector

If testing of surface attraction is successful at Ice Harbor and The Dalles, the COE should proceed with testing at John Day Dam in 1997. The COE has scheduled studies at John Day in 1997 and 1998.

The Dalles Dam.

NPPC Requirements

Intake Screens

The 1987 FWP says that at the Dalles, where the COE had depended upon an ice and trash sluiceway for juvenile fish bypass, the COE should proceed with installation of turbine intake screens.

Extended Screens

The COE was called upon to complete prototype testing of extended screens by April, 1991, and to complete design and installation of a juvenile fish screen and bypass system by April, 1993. The 1991 amendments to the FWP called for the installation of screens and a bypass system at The Dalles by 1998. In 1992 extended length screens were scheduled by the COE for installation by March 1998 (Salmon Passage Notes. Special Edition, 1992)

NMFS/NOAA Recovery Plan Requirements

Intake Screens

The COE should continue designing a conventional intake screen system for installation at The Dalles. Following prototype testing, a decision should be made whether to continue developing a surface collection system or to proceed with installation of the screens by 1999.

Surface Collector

(See previous entry - Intake Screens.) The Proposed Recovery Plan notes that the COE plans to test a surface collector at The Dalles Dam in 1995. The COE will test the surface collector in 1996.

Table 4. (Continued) Requirements for Installation of Bypass Systems (Flip Lip Spillways, Intake Screens, Extended Screens, Surface Attraction Devices, and Other) at Snake River and Columbia River Projects, With Compliance Schedules.

Project **Requirements by NPPC and NMFS. With Compliance.**

Bonneville Dam.

NPPC Requirements

Improve Bypass

The 1987 FWP called upon the COE to continue feasibility studies of means to improve juvenile fish guidance at the second powerhouse. Because of low FGE measured for the screens at the second powerhouse, the second powerhouse was to be closed when necessary to achieve an 85% juvenile fish passage through combinations of spill and bypass operation at Bonneville Dam. The COE was called upon to provide annual progress reports until an 85% juvenile fish passage is achieved. As of 1995 this goal had not been attained. The 1991 amendments to the FWP called for installation of improved screens and bypass at Bonneville Dam's second powerhouse by March, 1993, and evaluation of FGE at the first powerhouse.

NMFS/NOAA Recovery Plan Requirements

Improve Bypass

Calls upon the COE to relocate the downstream migrant outfalls by spring 1999. {Bypass survival tests at Bonneville Dam suggest that predation in the tailrace may be substantial, (Ledgerwood et al., 1990). The COE should improve hydraulic conditions at the dewatering systems in both bypass systems at Bonneville Dam by the year 2000. The Plan also calls for improved FGE at the Bonneville first powerhouse, with no date specified.

Appendix F

History of the Juvenile Transportation Program

Transportation of juvenile fish began in the late 1960s and early 1970s (Mighetto and Ebel, 1995) The National Marine Fisheries Service originally used modified tanker trucks to transport fish from Little Goose Dam and later expanded to include transport from Lower Granite Dam. In 1976, the Corps acquired a fish trailer for transportation research with a water capacity of 13,253 liters, accommodating 794 kg of fish, which is the equivalent of 10,500 emigrant steelhead or 24,500 emigrant spring and summer chinook. As NMFS design criteria developed, the Corps purchased four more trucks for the transportation program. In 1977, the Corps leased two barges and converted them for fish transportation. After the 1977 season, the Corps purchased two barges with a capacity of 174,167 liters which each could accommodate 10,433 kg fish, 138,000 emigrant steelhead, or 322,000 emigrant spring and summer chinook, for operation in 1978. A third barge of 22,727 kg capacity was completed in 1980 and the fourth barge 378,624 liters, 22,680 kg fish, or 300,000 emigrant steelhead, or 700,000 emigrant spring and summer chinook was completed in 1981. Improvements in the barges included better pumps, better circulation systems, shut off valves, and improved release systems. NMFS continued research on the effects of transportation on stress and survival in juvenile salmon.

In 1981, after 13 years of NMFS research, the Corps began mass transportation of juvenile fish using barging and trucking. The Corps used the existing five tanker trucks and the four barges. This collection and transportation equipment was used through the 1980s.

In 1990, the Corps acquired two new barges to meet the need of transportation as more hatcheries were completed above Lower Granite Dam. The Corps barging was now at full fish capacity, using six barges, as follows: two at 10,455 kg each, two at 22,727 kg each, and two at 567,935, liters, accommodating 34,000 kg fish, which is the equivalent of 450,000 emigrant steelhead, or 1,050,000 emigrant spring and summer chinook each. For 1993, the Corps acquired three fish tanks 568 liters, 34 kg fish, or 450 emigrant steelhead, or 1,050 emigrant spring and summer chinook that can be transported in a pickup truck. During 1994, the Corps added four new tanker trailers similar to the design and capacities previously described, except with stainless steel construction.

Juvenile fish detection systems have been developed and installed in the dams. During the 1980s, the passive integrated transponder, PIT, tag was developed. Juvenile PIT tag detection exists at Lower Granite, Little Goose, Lower Monumental and McNary dams. At these locations, all the fish pass through a slotted gatewell allowing detection. Flip gates, deflecting fish back to the river on detection, are installed in Lower Monumental Dam and McNary Dam. Juvenile PIT tag evaluation systems are installed in John Day Dam and Bonneville Dam, however, only about one percent of the fish are sampled for detection at these dams.

Currently, the Corps operates the juvenile fish collection and transportation system for chinook and steelhead from Lower Granite, Little Goose, Lower Monumental and McNary dams to release sites at Bradford Island and below Bonneville Dam, between River Mile 144 to 141 (Figure 5.1). Fish are collected by screens at the entrance to the turbine galleries, after which they pass through a tunnel or flume to the collection facility. Juvenile fish are separated from adult fish and debris. Then, they are routed into holding tanks, sample tanks, or directly into barges for transportation down the river.

All transported fish are handled according to criteria established with the Fish Passage Advisory Committee (FPAC) of the Columbia Basin Fish and Wildlife Authority {FTOT 1993}. Maximum holding density is currently 0.5 lbs./gallon in raceways. Early and late in the season, when fish numbers are less than 20,000 per day at Lower Granite Dam, the 3,500 gallon fish trucks are used to transport fish. The Corps uses two at Lower Granite Dam, one at Little Goose Dam, one at Lower Monumental Dam, two at McNary Dam and one held in reserve as a spare. These trucks are insulated, equipped with refrigeration, aeration, oxygenation and recirculation equipment. At a maximum density of 0.5 lbs./gallon, each truck can haul up to 1,750 pounds of fish. When fish numbers are higher, the barges are used. Six barges are available, two at 23,000 lbs., two at 50,000 lbs., and two at 75,000 lbs. fish capacity. Pumps are used to circulate river water through aeration chambers to ensure adequate dissolved oxygen and to reduce gas supersaturation. Due to low fish numbers present for summer and fall transport, the three mini-tankers are used. Mini-tankers are not used at McNary Dam because of the presence of large numbers of American shad mixed in with the juvenile salmon and steelhead.

The length of time in transit varies according to location of collection from each dam and whether transportation is by truck or barge. Truck transport from Lower Granite Dam takes 8 to 10 hours; from Little Goose Dam takes 6 to 8 hours; from Lower Monumental Dam takes from 5 to 7 hours, and from McNary Dam takes 4 to 5 hours. Completion of barge transport from Lower Granite Dam takes about 36 hours, while completion of transport from McNary dam takes about 15 hours.

The transportation and release of fish to mid-April is by truck from Lower Granite and McNary Dams to Bradford Island (north end of Bonneville First Powerhouse), where they are released through a pipe into the river (see Figures 7.1 and 7.4). Fish are barged during mid-April to mid-June, from Lower Granite, Little Goose, Lower Monumental and McNary dams to random release sites between buoy No. 92 (RM 144) and Warrendale, Oregon (RM 141). After fish collection drops to about 1,750 pounds per day at Lower Granite Dam, barging shifts to

McNary dam, and trucking resumes from Lower Granite, Little Goose, and Lower Monumental dams. Barging continues from McNary Dam until about the end of July, when trucking resumes. After mid-June to the end of the transportation season, large fish trucks and the 150 gallon mini-tankers are used from the Snake River dams. Trucking continues through the transportation season ending about October 31, but may continue into early December. The transportation system is planned to operate through October 31.

The practice of transportation evolved from research conducted in the Fish Passage Development and Evaluation Program (FPDEP; *see* (Ebel et al., 1973), {Ebel 1980}, (Mighetto and Ebel, 1995) within the North Pacific Division of the COE. The program became a part of the operations within the Walla Walla District of the COE and functioned under the oversight and coordination of the Fish Transportation Oversight Team (FTOT), composed of representatives of COE, state fisheries agencies (Idaho Department of Fish and Game) and federal fisheries agencies (National Marine Fisheries Service). For a time, 1984 to 1987, a representative of the Columbia River Inter-Tribal Fish Commission also participated as a member of the FTOT. The responsibilities of the FTOT can be found on page 5 of Basham et al. {1983}. The Walla Walla District, COE, is preparing a technical appendix to the System Operations Review EIS that will also contain a detailed discussion on the background of transportation. Park {1985}, (1993) also discusses the history of transportation facility development.

The research on fish transportation conducted prior to 1981 was generally accepted, on an interim basis, by the state and federal fisheries management agencies as having demonstrated positive effects in the form of increased survival of juvenile migrants through the hydroelectric system {FPC 1993}. Transportation was perceived within the region to be one of several means that could be employed to reduce losses of juvenile salmon in the hydroelectric system during their annual seaward migration. Other mitigative measures pursued included installation of mechanisms allowing the juveniles to bypass the turbines, and hydroelectric project operation modes that included passing migrants over the spill ways, a path that also allowed the juveniles to avoid the turbines. In addition, short term increases in the volume of water released into the hydroelectric system from storage reservoirs at critical points in the spring in an attempt to move fish more rapidly into collection facilities, and through the hydroelectric system.

As one of a number of survival enhancement techniques of potentially critical importance to the survival of Columbia River Basin salmon, juvenile salmon transportation has received intense scrutiny over an extended period of time, since the possibility was first considered for the Snake Basin by NMFS in 1965 (Ebel et al., 1973). Moving juvenile salmonids around hydroelectric dams and reservoirs by truck or barge in the Columbia River Basin was first tested by the National Marine Fisheries Service, NMFS, in 1968 at Ice Harbor Dam and it has been studied extensively by a number of authorities since then (Matthews et al., 1992). For the purposes of research and evaluation, NMFS implemented transportation of all juvenile salmon collected at Little Goose Dam in 1975, followed in 1976 by Lower Granite Dam, and in 1979 by McNary Dam (Figure 5.1). The concept of mass transportation evolved from the special operations (Operation Fish Run) conducted in 1977 in response to severe drought conditions. A description of this activity can be found in the October, 1977 report, prepared by the Committee on Fishery Operations, titled "Special Drought Year Operation for Downstream Fish Migrants." (D. Geiger, COE, North Pacific Division, personal communication). Based on the apparent success of experimental programs at reducing mortalities of juvenile salmon associated with hydroelectric passage, the mass transportation program was implemented as an operational program under the U.S. Army Corps of Engineers in 1981 at the same three dams {Basham et al. 1982}.

What may have been the earliest transportation work in the Columbia River was done by the Washington Department of Fisheries using 1954 brood year Klickitat River (lower Columbia River above Bonneville Dam) fall chinook {Ellis and Noble 1960}. At the time of the work of Ellis and Noble {1960}, the lower Columbia River had only one dam below the release areas, Bonneville, so the hydroelectric system of that time is not comparable to that of today. In addition, differences in juvenile fish marking procedures make much early work, such as this, difficult to compare with modern transportation research. Transportation research has also been conducted by the Public Utility District of Grant County, Washington, in cooperation with the NMFS {Carlson and Matthews 1992}. The evaluation of transportation from the hydroelectric dams operated by Grant County P.U.D. is part of a Federal Energy Regulatory Commission proceeding bearing on the scientific aspects of transportation (Chapman et al., 1991).

Most recent studies of transportation have been done at Lower Granite Dam (Matthews et al., 1990; Matthews et al., 1992); {Matthews et al. 1985, 1987, 1988, see Figure 5.1}. Transportation research has also been done by NMFS at McNary Dam, below the confluence of the Snake and Columbia Rivers, as it has been done at the Grant County research at Priest Rapids and Wanapum Dams {Carlson et al. 1987a, 1987b, 1988, 1989, and Carlson and Matthews 1992}. Although survival trends and general principles may be similar among all Columbia River Basin transportation programs, the specifics of each species-life-history type-dam combination may be expected to be unique, until proven otherwise. While the physical circumstances of the Columbia River sites are similar to those of the Snake River studies, the comparability of the maturity of the juvenile salmon at McNary, Priest Rapids and Wanapum Dams to the maturity of the juveniles arriving at the Lower Granite Dam on the Snake River is one uncertainty among many. The work at Lower Granite Dam is part of a larger program of study conducted by NMFS (see (Matthews et al., 1992)), and all of this work was also considered by the team.

Other work on the transportation of juvenile salmonids in the Columbia Basin is of interest, but it may not be directly comparable to the physical circumstances of the NMFS research. For example, Slatick has attempted to examine the effects of imprinting prior to transportation and degree of smoltification on the homing ability of transported smolts {*see* Slatick et al. 1988a, 1988b, 1988c}, and experiments involving direct transportation of juveniles from hatcheries have been conducted (for example, R. Bugert, Washington Department of Fisheries and Wildlife, Lyons Ferry fall chinook). In one of the few Snake River studies that was specifically designed to measure rate of return to the point of natal origin, Bjornn and Ringe {1984} looked at return rates of hatchery chinook and steelhead allowed to migrate a short distance before transportation. Return rates of transported fish to the hatchery in Idaho were lower in all cases than those of control fish allowed to transit the river, while return rates to the mainstem below the Snake were higher for transported fish. A survey and synthesis of the literature on fish transportation has been recently completed by Wedemeyer {1994}, and a bibliography on transportation that reviews all aspects of transportation, dam passage, and stress physiology separately, in an interactive electronic format, has also been recently completed {Davis and Schreck 1994}.

Further details on the history of the NMFS transportation program may be found in reviews (Ebel et al., 1973), {Ebel 1980}; {Park 1985 and 1993}; {Shepard 1988; Matthews 1992}, (Matthews et al., 1992); {FPC 1993}; (Mighetto and Ebel, 1995)). The literature reviews provide substantial insights into the scientific and philosophical origins and accomplishments of the program. It is clear that the transportation program was a reaction to the development of the Columbia Basin hydroelectric system. The central thesis of transportation was expressed by Donn Park {1985}, " ... survival of salmonid smolts[i] could be substantially increased if the fish were collected at an uppermost dam, transported to a safe release site below Bonneville Dam, and released into the Columbia River -- thereby bypassing as many as seven dams and their associated problem areas." (p. 2-1; see also {Ebel 1980}.

Literature Cited

Citations in curly brackets are not presently in the literature cited.

Abbott, M.B. 1979. Computational Hydraulics: Elements of the Thoery of Free-Surface Flows, Pitman.

Abbott, M.B. and D. Basco. 1989. Computational Fluid Mechanics: Introduction for Engineers, Longman.

Becker, C.D. and C.C. Coutant. 1970. Experimental Drifts of Juvenile Chinook Salmon through Effluent at Hanford in 1968. Richland, Battelle-Northwest. Washington.

Becker, C.D., C.C. Coutant and E.F. Prentice. 1971. Experimental Drifts of Juvenile Chinook Salmon through Effluent Discharges at Hanford in 1969. Richland, Battelle-Northwest. Washington.

Benson, M.A. and T. Dalrymple. 1967. Chapter A1 - General field and office procedures for indirect discharge measurement. Techniques of Water-Resources Investigations of the United State Geological Survey. Washington, U.S. Geological Survey.

Berggren, T.J. and M.J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. North. Am. J. Fish. Manage. 13: 48-63.

Biosonics, I. 1981. Hydroacoustic Assessment of Downstream Migrant Salmon and Steelhead at Priest Rapids Dam in 1981. Ephrata, Public Utility District No. 2 of Grant County. Washington**:** 24 pp. + figures.

Biosonics, I. 1981. Hydroacoustic Assessment of Downstream Migrant Salmon and Steelhead at Wells Dam in 1981. East Wenatchee, Public Utility District No. 1 of Douglas County. Washington**:** 9 pp. + figures.

Biosonics, I. 1982. Hydroacoustic Assessment of Downstream Migrant Salmon and Steelhead at Wanapum Dam in 1982. Ephrata, Public Utility District No. 2 of Grant County. Washington**:** 28 pp + app.

Biosonics, I. 1982. Hydroacoustic Assessment of Downstream migrating Salmon and Steelhead at Rocky Reach Dam in 1982. Wenatchee, Public Utility District No. 1 of Chelan County. Washington**:** 139.

Biosonics, I. 1983. Hydroacoustic Assessment of Downstream Migrating Salmon and Steelhead at Wanapum and Priest Rapids Dams in 1983. Ephrata, Public Utility District No. 2 of Grant County. Washington**:** 41 pp. + app.

Biosonics, I. 1995. Hydroacoustic evaluation of vertical slots, sluiceway and spill at Ice Harbor Dam. Corps of Engineers Meeting, September, Walla Walla, Washington.

Brett, J.R. 1967. Swimming performance of sockeye salmon (*Oncorhynchus nerka*) in relation to fatigue time and temperature. J. Fish. Res. Board of Canada 24: 1731-1741.

Bruce, S. 1995. 1995 migration exceeds expectations. Salmon Passage Notes, Snake and Columbia River Fish Programs September.

Busack, C. and J.B. Shaklee. 1995. Genetic diversity units and major ancestral lineages of salmonid fishes in Washington, Washington State Department of Fish and Wildlife.

Cada, G.F., M.D. Deacon, S.V. Mitz and M.S. Bevelhimer. 1994. Review of Information Pertaining to the Effect of Water Velocity on the Survival of Juvenile Salmon and Steelhead in the Columbia River Basin. Oak Ridge, Oak Ridge National Laboratory. Tennessee.

Carling, P.A. 1992. Instream hydraulics and sediment transport. The Rivers Handbook: Hydrological and Ecological Principles. P. Calow and G. E. Petts. Oxford, Blackwell**:** 101-125.

Center, F.P. 1995. Summary of the 1995 Spring and Summer Juvenile Passage Season. Portland, Fish Passage Center. Oregon**:** 32.

Chapman, D., A. Giorgi, M. Hill, A. Maule, S. McCutcheon, D. Park, W. Platts, K. Pratt, J. Seeb, L. Seeb and F. Utter. 1991. Status of Snake River Chinook Salmon. Boise, Don Chapman Consultants, Inc., 3653 Rickenbacker, Suite 200. Idaho**:** 520.

Chaudhry, M. 1993. Open Channel Flow. New York, Prentice Hall.

Chow, V.T. 1964. Handbook of Applied Hydrology. New York, McGraw-Hill.

Corbett, D.M.e.a. 1943. Stream-Gaging Procedure. A Manual Describing Methods and Practices of the Geological Survey, U.S. Geological Survey.

Coutant, C.C. 1970. Behavior of Sonic-Tagged Chinook Salmon and Steelhead Trout Migrating Past Hanford Thermal Discharges in 1967. Richland, Battelle-Northwest. Washington.

Cunge, J.A., J. F. M. Holly and A. Verwey. 1980. Practical Aspects of Computational River Hydraulics, Pittman.

Dorazio, R.M., G.R. Shepherd, D.G. Deuel and C. Young-Dubovsky. 1994. Striped Bass Research Study Report for 1992. Washington, D. C., Departments of the Interior and Commerce.

Ebel, W.J., R.F. Krcma and H. Raymond. 1973. Evaluation of Fish Protection Facilities at Little Goose and Lower Granite Dams and Review of Other Studies Relating to Protection of Juvenile Salmonids in the Columbia and Snake Rivers, National Marine Fisheries Service.

Fox, J.A. 1989. Transient Flow in Pipes, Open Channels, and Sewers, Ellis Horwood.

Hays, S.G. 1984. Determination of the Depth Distribution of Juvenile Salmonids in the Turbine Intakes at Rocky Reach and Rock Island Dams. Wenatchee, Chelan County Public Utility District No. 1. Washington**:** 67 pp. + app.

Iwamoto, R.N., W.D. Muir, B.P. Sandford, K.W. McIntyre, D.A. Frost, J.G. Williams, S.G. Smith and J.R. Skalski. 1994. Survival Estimates for the Passage of Juvenile Salmonids through Snake River Dams and Reservoirs, 1994. Portland, Bonneville Power Administration. Oregon.

Ledgerwood, R.D., E.M. Dawley, L.G. Gilbreath, P.J. Bentley, B.P. Sandford and M.H. Schiewe. 1990. Relative survival of subyearling chinook salmon which have passed Bonneville Dam via the spillway or the second powerhouse turbines or bypass system in 1989. Seattle, National Marine Fisheries Service. Washington**:** 64 + app.

Leeder, M.R. 1983. On the interactions between turbulent flow sediment transport and bedform mechanics in channelized flow. Modern and Ancient Fluvial Systems. J. D. Collinson and J. Lewin. Oxford, Blackwell. Special Publication No. t**:** 121-132.

Liggett, J.A. 1994. Finite-difference methods for shallow water flow analysis. Computer Modeling of Free-Surface and Pressurized Flows. M. H. Chaudhry and L. W. May. Dordrecht, Kluwer Academic Publishers**:** 33-61.

Mahmood, K. and Yevjevich. 1975. Unsteady Flow in Open Channels. Fort Collins, Water Resource Publications.

Marshall, A.R., C. Smith, R. Brix, W. Dammers, J. Hymer and L. LaVoy. 1995. Genetic diversity units and major ancestral lineages for chinook salmon in Washington. Genetic diversity units and major ancestral lineages of salmonid fishes in Washington. C. Busack and J. B. Shaklee. Olympia, Washington, Washington Department of Fish and Wildlife. RAD 95-02**:** D-1 - D-62.

Matthews, G.M., S. Achord, J.R. Harmon, O.W. Johnson, D.M. Marsh, B.P. Sandford, N.N. Paasch, K.W. McIntyre and K.L. Thomas. 1992. Evaluation of Transportation of Juvenile Salmonids and Related Research on the Columbia and Snake Rivers, 1990, U.S. Army Corps of Engineers.

Matthews, G.M., J.R. Harmon, S. Achord, O.W. Johnson and L.A. Kubin. 1990. Evaluation of Transportation of Juvenile Salmonids and Related Research on the Snake and Columbia Rivers, 1989, U.S. Army Corps of Engineers.

Matthews, G.M. and R.S. Waples. 1991. Status Review for Snake River Spring and Summer Chinook Salmon. Seattle, National Marine Fisheries Service. Washington**:** 75.

McKenzie, D., D. Carlile and D. Weitkamp. 1983. 1983 System Mortality Study. Report to Mid-Columbia Coordinating Committee. East Wenatchee, Douglas County Public Utility District No. 1. Washington**:** 25 pp. + app.

Mighetto, L.M. and W.J. Ebel. 1995. Saving the Salmon: A History of the US Army Corps of Engineers' Role in the Protection of Anadromous Fish on the Columbia and Snake Rivers. Report to the US Army Crops of Engineers, North Pacific Division. Seattle, Historical Research Associates.

Muir, W.D., S.G. Smith, R.N. Iwamoto, D.J. Kamikawa, K.W. McIntyre, E.E. Hockersmith, B.P. Sandford, P.A. Ocker, T.E. Ruehle and J.G. Williams. 1995. Survival Estimates for the Passage of Juvenile Salmonids through Snake River Dams and Reservoirs, 1994. Portland, Bonneville Power Administration. Oregon**:** 187.

Mundy, P.R.e.a. In press. The historical relation between stream discharge and seaward migration of juvenile spring chinook salmon in the Yakima River. .

National Marine Fisheries Service. 1995. Proposed Recovery Plan for Snake River Salmon. Washington, US Dept. of Commerce, National Oceanic and Atmospheric Administration. District of Columbia**:** 387.

National Research Council. 1995. Science and the Endangered Species Act. Washington, National Academy Press.

Nelson, W.R., L.K. Freidenburg and D.W. Rondorf. 1994. Swimming performance of subyearling chinook salmon. Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook Salmon in the Columbia River Basin. Annual Report for 1992. D. W. Rondorf and W. H. Miller. Portland, Bonneville Power Administration. Report No. DOE/BP-21708-2**:** 39-62.

Northcote, T.G. 1962. Migratory behaviour of juvenile rainbow trout, *Salmo gairdnerii*, in outlet and inlet streams of Loon Lake, British Columbia. J. Fish. Res. Board Canada 19: 201-270.

Northwest Power Planning Council. 1987. 1987 Columbia River Basin Fish and Wildlife Program. Portland, Northwest Power Planning Council. Oregon**:** 246.

Odegaard, A.J. and Y. Wang. 1991. Sediment management with submerged vanes. I. Theory. J. Hydraulic Engineering 117: 267-283.

Odeggard, A.J. and Y. Wang. 1991. Sediment management with submerged vanes. II. Applications. J. Hydraulic Engineering 117: 284-302.

Olson, F.W. 1983. Vertical Distribution of Juvenile Salmonids Entering the Turbines at Wanapum Dam, CH2M Hill. Available from Public Utility District No. 2 of Grant County, Ephrata, WA**:** 39 pp. + app.

Olson, F.W. 1984. Depth Distribution of Juvenile Salmonids Entering the Turbine Intakes at Wells Dam, CH2M Hill. Available from Public Utility District No. 1 of Douglas County, East Wenatchee, WA**:** 31 pp. + app.

Park, L.K., M.A. Brainard, D.A. Dightman and G.A. Winans. 1993. Low levels of intraspecific variation in the mitochondrial DNA of chum salmon (*Oncorhynchus keta*). Molecular Marine Biology and Biotechnology 2(6): 362-370.

Peven, C.M. and B.G. Keesee. 1992. Rocky Reach Fish Guidance System Developmental Testing. Wenatchee, Public Utility District No. 1 of Chelan County. Washington**:** 20.

Peven, C.M., R.R. Whitney and K.R. Williams. 1994. Age and length of steelhead smolts from the mid-Columbia basin, Washington. North Am. J. Fish Mgmt. 14: 77-86.

Schreck, C.B., J.C. Snelling, R.E. Ewing, C.S. Bradford, L.E. David and C.H. Slater. 1995. Migratory Characteristics of Juvenile Spring Chinook Salmon in the Willamette River. Portland, Bonneville Power Administration. Oregon.

Statzner, B., J.A. Gore and V.H. Resh. 1988. Hydraulic stream ecology: Observed patterns and potential applications. J. N. Am. Benthol. Soc. 7(4): 307-360.

Stoker, J.J. 1957. Water Waves. New York, Interscience.

Thorne, R.E. and E.S. Kuehl. 1989. Evaluation of Hydroacoustic Techniques for Assessment of Juvenile Fish Passage at Bonneville Powerhouse I, Biosonics, Inc.

Trump, C.L. and W.C. Leggett. 1980. Optimum swimming speeds in fish: the problem of currents. Can. J. Fish. Aquat. Sci. 37: 1086-1092.

U.S. Army Corps of Engineers. 1984. Shore Protection Manual. Vicksburg, Coastal Engineering Research Center, Waterways Experiment Station.

Vogel, S. 1981. Life in Moving Fluids. Boston, Willard Grant Press.

Weitkamp, D.E., D. McKenzie and T. Schadt. 1980. Survival of Steelhead Smolts - Wells Dam Turbines and Spillway, 1980. East Wenatchee, Public Utility District No. 1 of Douglas County. Washington**:** 39.

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[i] The term, *smolt*, designates the life history stage of the salmon that is in the process of making the transition from freshwater to salt water residence.