Review of Artificial Production of Anadromous and Resident Fish in the Columbia River Basin

Part I: A Scientific Basis for Columbia River Production Programs

April 1999

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Independent Scientific Advisory Board

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Scientific Review Team
Independent Scientific Advisory Board

April 22, 1999

Mr. Todd Maddock, Chair
Northwest Power Planning Council
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Dear Mr. Maddock:

I am pleased to transmit to you the first phase of the Scientific Review Team's (SRT) report on hatchery programs in the Columbia River Basin. This version updates our December version and adds considerations of resident fish artificial production.

The report includes an historical overview of artificial production within the basin, a review of the state of the science with respect to effectiveness of artificial production as a means to augment harvest, a review of the state of the science with respect to ecological and genetic effects of artificial production on wild spawning populations, and a set of recommendations in the form of guidelines that might guide policy on artificial production so as to be consistent with a sound scientific foundation.

The proposed guidelines at this point are based on our review of the published science, which completes this phase of our task in the Review of Artificial Production. In the next phase we will determine whether analysis of existing monitoring data resolves any of these hypotheses more conclusively, in the specific context of the Columbia Basin.

The Artificial Production Review is consistent with other recent scientific reviews that considered this topic (the Northwest Power Planning Council's Independent Scientific Group (ISG), 1996; the National Research Council (NRC), 1996; and the National Fish Hatchery Review Panel (NFHRP), 1994). There is considerable consensus among the three previous scientific reviews and our own, regarding the status of the science associated with artificial production.

We understand very well that the priorities of fisheries management have changed significantly in recent years, so the needs that hatcheries should serve are also changing. The ecosystem based management approach places artificial production in the basin in a very different role than employed in the recent past. In particular, the reality of increasing numbers of Endangered Species Act listings of anadromous and resident fish puts a much higher emphasis on wild stocks and naturally spawning stocks. This increases the concern over the potential for artificial production to cause genetic and ecological harm to such stocks. But it also raises the possibility that hatcheries may serve some more positive role in this era of new priorities.

The historical track record does not reassure us that hatchery programs can respond to changing realities and changing scientific knowledge. We hope that ways will be found to ensure that in the future this important component of the fisheries management system will evolve more rapidly and constructively. Even by the standards of the old objective of simply augmenting harvest to mitigate for lost and impaired habitat, artificial production of anadromous salmonids in the Columbia basin would need careful re-evaluation because of the perceived less-than-effective return of adults. However, under the new ecosystem management paradigm, performance assessment of hatchery programs in light of the potential impacts on native fish becomes most critical.

Other major factors besides hatcheries, including some factors that are beyond human control, surely are playing some role in the salmon decline. And some hatcheries have performed considerably better than average, contributing substantially to harvest, and maintaining runs of the hatchery stock. One hope in undertaking the SRT evaluation is to identify causes for the differences in performance between hatcheries, in order to develop recommendations for improving average hatchery performance, as well as to add to our understanding of how hatcheries should fit into the new ecosystem management concept.

There has not been adequate monitoring and evaluation of Columbia Basin salmon stocks. Monitoring and analysis to date has been sufficient to document rather disappointing numbers. But the monitoring and analysis has not been sufficient to pin down the causes of the poor performance, nor has it been sufficient to determine why some hatcheries perform better and some perform worse. The challenge in the concept of ecosystem management is how to reconcile local objectives of providing harvest opportunities, sometimes with exotic species, with larger ecosystem objectives.

Ecological and genetic science does provide plausible hypotheses about what some of the avoidable causes of poor performance might be among the anadromous salmonid hatchery fish. These include: inbreeding, domestication, inappropriate life history timing, inappropriate physiological and behavioral conditioning, over-reliance on too small a number of life history types, and exceeding carrying capacity in some key portions of the natural environment. Our report reviewing the science explains how these plausible ecological and genetic mechanisms could be operating in hatchery stocks.

Given the new management emphasis on wild stocks, it is especially distressing to learn that these mechanisms that might account for poor performance of hatchery fish could also have very negative effects on naturally spawning fish that interact ecologically and genetically with the hatchery product. Our report reviewing the science explains plausible mechanisms of interaction between the hatchery products and wild spawning fish.

Ecological and genetic science suggests that artificial production must be carefully integrated into the functioning of the entire ecosystem. Both the ecosystem and artificial production need to be managed to some normative standard, in order for artificial production to be effective in meeting the basin's goals. Our report reviewing the science offers recommendations on how this integration and management might be accomplished.

Uncertainty places a premium on experimental management to better diagnose the causes of the problems, and to refine the solutions. The effectiveness of experimental management depends critically on a comprehensive program of monitoring and analysis to detect responses to experiments, and to alter management according to what is learned. The programs of monitoring and analysis now in place in the Columbia Basin may not be equal to this task. The region, through the Council, needs to implement a scientifically valid, comprehensive monitoring and evaluation program to assess hatchery procedures, production, impact on natural populations, and achievement of goals.

We note, finally, our analysis under the new concept of ecosystem management in the basin must place hatcheries in the experimental framework, and most certainly in the perspective of ecosystem function we conclude that the outcomes of these experiments are not yet known. Yet artificial production has been implemented on a scale that will continue to commit a large percentage of the region's restoration resources, a large percentage of the available watersheds, and a large percentage of the remaining stocks to a single, unproven technology. There may be merit to reconsidering these priorities.

The SRT will continue its review of hatchery programs, compilation of available data, and analysis of those data. We expect to finalize our review and recommendations by June 30, 1999.

Sincerely yours,

Willis E. McConnaha, Chair
Scientific Review Team

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Review of Artificial Production of Anadromous and Resident Fish in the Columbia River Basin

Part I: A Scientific Basis for Columbia River Production Programs

I. Introduction

In July 1997, the U.S. Senate[1] directed the Northwest Power Planning Council, with the assistance of the Independent Scientific Advisory Board (ISAB),[2] to "conduct a thorough review of all federally funded hatchery programs operating in the Columbia River Basin…" with the intent to ensure that federal dollars are spent "wisely" and "in a cost-effective manner that maximizes the benefits to the fish resource." The Council is to assess the "operation, goals and principles of state, tribal and federal hatcheries..." with regard to the effectiveness of their role in the broader context of fisheries management. The Council is to recommend to Congress a set of policies that would guide the use of Columbia River hatcheries.

In response to the Congressional directive, the Council consulted with the ISAB and appointed a Scientific Review Team (SRT) to provide an independent assessment of the basin's artificial production program. The SRT includes four members of the ISAB, two additional independent scientists, and a scientist from the Council staff as chair of the team. The SRT will review hatchery programs in the basin, analyze their effectiveness in meeting mitigation responsibilities, assess their success in enhancing salmonid production, and evaluate their role in supplementation of natural salmon and steelhead runs. The SRT analysis will provide the biological basis for the Council's recommendations to Congress.

To provide timely advice for the Council's report to Congress, the SRT is conducting the analysis as three sequential tasks:

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[1] U.S. Senate Energy and Water Development Appropriation Bill, 1998, Report 105-44.

[2] The ISAB was created jointly by the Northwest Power Planning Council and the National Marine Fisheries Service to provide independent scientific advice regarding fish and wildlife management in the Columbia River Basin. The ISAB consists of 11 scientists appointed with the assistance of the National Research Council.

1. A summarization of current scientific knowledge on artificial production and its implications for Columbia River programs.
2. A compilation of the data relating to the performance of artificial production in the Columbia River Basin.
3. An analysis of this information in light of current knowledge to assess the performance of artificial production in the Columbia River Basin.

This report addresses the first task, which is to provide background information on the state of the science that relates to artificial production in the basin. The scientific rationale developed in this report takes the form of guidelines that could form the basis of recommendations regarding artificial propagation, in the context of ecosystem management. The second task, assembling the database of all past and current records on artificial production in the basin, has been assigned to a contractor. The third task will be the analysis of hatchery programs and the database, and finalizing the report. Each task will be summarized in separate reports to the Council and then integrated into a final report.

This paper provides the SRT's analysis of the history of artificial production and other hatchery evaluations related to the Columbia basin. Hatcheries initially were used to augment the fishery, later to mitigate for habitat destruction by development activities, and more recently to supplement natural production and conserve salmon using captive brood stock techniques. These roles are defined and discussed in this report, and the state of current knowledge of the genetic and ecological effects of hatcheries is summarized, as well.

The next phase of the SRT report, where applicable, will use guidelines associated with uncertainties as a basis to evaluate hatchery performance. The evaluation should identify production and operational strategies that can assist in development of hatchery policy. Performance evaluation will use production return criteria and/or fulfillment of mitigation objectives as the basis of assessment. The two evaluations, with recommendations emanating from both the scientific analysis and hatchery performance evaluation, will be articulated in a proposed conceptual foundation for the Columbia River Basin's artificial production program. Whether or not this conceptual foundation is adopted as the basis for regional hatchery policy, it is imperative that policy is based on a scientific foundation and that adaptive management is pursued using performance criteria.

A. Scope of the Review

Artificial production has been used in the Columbia River Basin for many purposes during this century. Although basin hatcheries have produced resident species, such as sturgeon and rainbow trout, hatchery production has focused almost exclusively on anadromous salmonids -- primarily coho and chinook salmon and steelhead trout.

These three species also have been the focus of sport and commercial fisheries management in the basin and, ironically, recovery measures, as well. Due to the ecological, economic, recreational and cultural importance of these species, the Council's policy recommendations must address anadromous salmonids primarily, but also apply to a much broader spectrum of species.

In the Columbia River Basin, there are hatcheries for both anadromous and resident fish.[3] Many resident fish hatcheries in the basin, like many anadromous fish hatcheries, are intended for mitigation and are located upstream from Grand Coulee and Hells Canyon dams, which are complete barriers to anadromous fish passage. Netboy (1986) estimated that 40 percent of the original spawning areas for Columbia Basin salmonids had been lost because of blockage due to dams. *Return to the River* estimates a 55-percent loss (45 percent remaining; Page 353). Of the original salmon and steelhead habitat available in the basin, 55 percent of the watershed area and 31 percent of stream miles are now inaccessible to anadromous salmon, having been blocked by dam construction (NRC 1996, pg. 63). Furthermore, much of this inaccessible habitat was irreplaceable natural spawning habitat, located mainly in headwater regions of the basin. Thus, successful artificial production of resident fish is a necessary and crucial component to fully mitigate anadromous fish losses in these blocked areas. In addition, many native resident fish species are currently federally listed as threatened or endangered under the U.S. Endangered Species Act, based on their imperiled biological status. As with anadromous salmonids, numerous at-risk resident fish populations (e.g. bull trout, white sturgeon, and various resident salmonids) are also the focus of recovery measures.

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[3] Newsdata Corp., a Seattle-based news service on fish, wildlife and energy issues, estimates there are 148 fish hatcheries in the Columbia River Basin, but this number does not include privately financed hatcheries. The information is online at http://www.newsdata.com/fishweb/.

The scope of our review concentrates on artificial production of anadromous salmonids in the Columbia Basin. However, most, if not all, of the scientific information relating to ecological impacts of anadromous salmonid hatcheries applies to the use of hatcheries that currently produce more than a dozen ecologically and economically valuable species of resident fish. Therefore, resident fish hatchery policy must be consistent with the principles in the conceptual foundation that the SRT will recommend to the Council for anadromous salmonids. In fact, because resident species do not have the distribution range of salmon and steelhead, and thus are not exposed to the same risks facing anadromous salmonids over their migratory corridor, we expect that resident species will be very responsive to the principles guiding policy in anadromous salmonid management. Throughout the review, we make connections between anadromous and resident fish production with regard to principles and technologies.

B. Definition of Artificial Production

Artificial production and hatcheries are generally viewed as synonymous terms in that both refer to the same range of fish culture technologies, encompassing everything from releases of unfed, substrate-incubated fry to captive rearing of migrant juvenile salmonids on formulated diets in concrete raceways. The most common type of fish hatchery is a cluster of buildings and concrete raceways located adjacent to a tributary stream. But a hatchery also can be a gravel-lined incubation box in which artificially spawned eggs are incubated to enhance fish production. Or, a hatchery can be an engineered spawning channel that salmon enter to spawn naturally on graded substrate, where water flow is controlled to enhance egg-to-fry survival. Or, a hatchery even can be an earthen acclimation pond in which fingerlings are fed before dispersing into the natural stream on their own volition for rearing or migration.

In this report, our focus is on the "standard" public hatchery design -- the cluster of buildings beside a tributary, with tray incubators and concrete raceway rearing systems that provide the entire freshwater feed and residence requirements before the fingerlings are released to migrate seaward. Columbia River hatcheries were designed around variations of this “standard” incubation and rearing system. It is a system that has been used for most chinook and coho salmon, and steelhead trout, hatcheries over this century.

This type of hatchery generally controls the entire freshwater juvenile life cycle, except the migratory passage. Adults are intercepted and spawned artificially, based on a breeding plan that varies from simply crossing multiple females with a composite of two or more males, to a breeding matrix that maximizes the available genetic variability. Eggs are usually incubated in trays until hatching or to the point of emergence when yolk stores are nearly exhausted. Some form of substrate is often included in the incubation compartment to reduce alevin activity and prioritize stored energy for growth. At or before the emergence phase, the young fry are placed in troughs or tanks for swim-up and early rearing, and then transferred to raceways for production rearing until they are distributed for release as smolts or presmolts to natural waters. Formulated diets are used throughout rearing, based on nutritional requirements, and fed as mash or graded pellets to accommodate the size of the fish as they grow. The system is well defined in a program to maximize efficiency of operations.

Hatchery performance assessment understandably has been limited within the rather narrow definition of variables in facility design and operations common to such facilities. Because Columbia River hatcheries use the standard technology, performance differences have as much to do with management as with application of the technology itself. Variables such as the source of fish, release strategies, relative size and condition of smolts, water supplies, location of the hatchery and its location on the migratory corridor over the length of the river will affect performance. Therefore, the context of our evaluation is the relative performance of a particular class of hatcheries within the confines of river conditions in the Columbia Basin, under agency management responsibility. Consequently, our assessment will be an assessment of the policy and location as much as the technology involved.

C. Relationship Between this Review and Development of the Regional Multi-Species Framework

As this review is being undertaken, states, tribes and agencies of the federal government in the Pacific Northwest are collaborating on a multi-species planning process for fish and wildlife in the Columbia River Basin. The multi-species planning process is guided by a framework that links Columbia Basin fish and wildlife policy to a vision that balances the many values provided by the natural resources of the Columbia River and its tributaries. The multi-species framework will be based on an ecological, conceptual foundation that recognizes that the river and its species are interrelated parts of a whole.

The multi-species framework will include principles, goals and objectives that reconcile seemingly inconsistent and uncoordinated approaches to fish and wildlife policy in the region. These principles, goals and objectives will be expressed in a set of scientifically supportable alternatives for the future of the Columbia River -- especially as it relates to management of fish and wildlife resources.[4] As they are developed, these alternatives will be analyzed for their ecological impacts, based on an explicit conceptual foundation. The conceptual foundation includes a set of scientific principles that define the scientific context for the analysis.[5]

Once it is developed, the multi-species framework will provide systemwide direction and specific strategies for fish and wildlife programs, as well as objectives against which results can be evaluated. The conceptual foundation for artificial production developed in this review should be consistent with the set of scientific principles guiding development of the multi-species framework. In this sense, a conceptual foundation for artificial production is a refinement of the more general conceptual foundation for the multi-species framework, and serves to focus scientific principles on decisions about how to use artificial production. We believe that a scientifically supportable conceptual foundation, such as that guiding development of the multi-species framework and potentially refined by our assessment, should be the basis for developing future hatchery policies.

D. Definition of the Columbia Basin Ecosystem

Natural and cultural attributes define an ecosystem (ISG, 1999). The modern Columbia River ecosystem is far different than the ecosystem that existed before the encroachment of modern civilization -- as that ecosystem was different from the one that existed before Native Americans began exploiting the Columbia River fishery. Man's actions irrevocably altered the Columbia River ecosystem, and those impacts define the parameters for ecosystem management today.

As major hydroelectric facilities multiplied in the Columbia River Basin, the free-flowing river became a series of linked reservoirs. This new environment favored species previously limited by higher velocities and cooler water temperatures. Predator and competitor species assumed new levels of abundance in the river system previously dominated by salmonids. For example, the northern pikeminnow (previously named the northern squawfish), a native salmon predator,

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[4] Ecological Work Group 1998, "An Ecological Framework for the Multi-species Planning Process." Available from the Northwest Power Planning Council, Portland, OR., or at the Framework Project website at www.nwframework.org; click on Ecological Analysis.

[5] "Proposed Scientific Foundation for Development of a Regional Multi-Species Framework," Northwest Power Planning Council Report 98-16. Portland.

increased in number -- and impact on salmonids -- as a result of the increased reservoir habitat. (Zimmer 1953, USFWS 1957, Thompsom 1959, Beamesderfer and Rieman 1991, Poe et al. 1991, Rieman et al. 1991.

Perhaps even a more serious impact in the evolutionary sense, however, were the many exotic fish brought into the basin by private, state and federal entities, such as American shad, channel catfish, largemouth and smallmouth bass, blue gill, yellow perch, brown trout, brook trout and lake trout (Simpson and Wallace 1982). While many of these fish were introduced for sportfishing diversity before the ecological impacts were fully appreciated, and have now become an important part of the species selection offered the sportfishing public, they nevertheless have permanently changed the Columbia River ecosystem. Although most of the exotic species were introduced half a century ago, interactions among the various non-native and native fish species are likely to continue to evolve toward a new equilibrium (as yet unknown).

Substantive and even drastic changes in species composition and habitat utilization have occurred over the last several decades. Preliminary surveys in the lower reaches of the Yakima River over the last half of 1996, for example, revealed that about two-thirds of the species encountered were exotics, and smallmouth bass represented over 60 percent of all fish intercepted (Monk 1997). Sampling gear tended to exclude fish larger than 10 centimeters in length, but as an index of general abundance, the survey demonstrated how dominant these species have become in some areas of the Basin. The impact of these newcomers, through competition or predation on endemic species, is unknown, but the success of exotic species has come at a cost to native fish.

Major changes in the operation or configuration of the hydrosystem also will affect interactions among fish species. Changes that increase normative conditions, such as natural river drawdown in the lower Snake River or a major drawdown of John Day Dam (system configuration alternatives currently being studied by the National Marine Fisheries Service or the U.S. Army Corps of Engineers) would promote an equilibrium that favored coldwater native fish species over warmwater native and non-native fish species.

This dynamic mix of native and non-native species defines the modern Columbia Basin ecosystem. Where anadromous species have been eliminated by barrier dams, mitigation has been in the form of replacement resident fisheries, and sometimes those fisheries include exotic species. Moreover, resident fish hatchery programs often will not be complementary with the ecosystem management perspective adopted for anadromous hatchery production. Nor can mitigation in these cases necessarily imply that hatchery production will be temporary until natural production can sustain the population. In some cases resident fish populations have been established where none existed before and will be entirely dependent on artificial production. Thus, in some cases the concept of using supplementation hatcheries to rebuild naturally reproducing populations does not necessarily apply to resident fish .

Another difference between anadromous and resident fish hatcheries is performance measurement. Traditionally for anadromous programs, we have measured hatchery production success in terms of harvest return. This is often an inappropriate statistic in resident fish hatchery performance. More realistic performance goals for resident fish might include catch and release only, or simply having fish in the system available for viewing. Thus, for both anadromous and resident production, performance criteria should be matched with the fisheries management objective of the specific program or facility and in recognition of the community of fishes that are now in the basin. What constitutes the Columbia Basin ecosystem, therefore, is basic in how hatchery production is viewed, and why "normative" is such a key concept that accommodates the biological realities with the cultural and economic changes that define the present ecosystem.

II. Hatchery Management and the Salmon Crisis

There is no doubt among fisheries managers that there is a crisis of major proportions confronting anadromous salmon and steelhead runs in the Pacific Northwest. This crisis is characterized by depleted populations especially in Oregon, Washington, Idaho and California, massive shrinking of the salmon's range, collapsed fisheries and large-scale protection under the federal Endangered Species Act, and nowhere in such proportions as the Columbia River Basin. Although the salmonid crisis receives a majority of scientific, managerial, and public attention in the Columbia Basin, inspection of the status of all Columbia Basin fish species reveals a wide array of resident fish also involved in crisis situations (e.g. bull trout, white sturgeon, and various native non-anadromous salmonids).

Hatcheries play a unique role in this predicament. They have been identified as one of the causes of the current crisis, while at the same time they are also considered part of the solution. Many salmon biologists and culturists recognize this dual role of artificial propagation of anadromous and resident fish. These biologists and culturists resolve the apparent contradiction by declaring that the hatchery programs made mistakes in the past, but things are different now.

At the present time, hatcheries consume about 40 percent of the annual budget for the Council's Fish and Wildlife Program (ISRP, 1997). If artificial propagation is going to consume such a large proportion of the tens of millions of dollars spent on salmon restoration, it is critical that there be specific answers to the following questions:

1) What problems did the programs have in the past, and
2) Specifically, how were those problems resolved?

Because of the unique dual role of hatcheries, we have to be sure that the past is really passed, and that hatchery fish are able to fit in the larger picture of ecosystem function that is being advocated as the new management paradigm.

Anadromous and resident fish hatchery technology has continuously changed over the past 120 years. Improvements include:

- Better operational design,
- Increased nutritional value of feeds,
- Better disease treatments,
- Development of tagging technology to allow monitoring the contribution and survival of hatchery-reared fish,
- Increased control over hatchery environments such as water temperature and pathogens, and
- Integration of life history traits and requirements and genetic principles in fish husbandry practices.

In short, many of the operational problems that plagued hatchery operations in the past have been resolved. However, the distinction between intrinsic hatchery operations and management of hatcheries must be addressed separately. Included in management resolution is the effect of sustained fisheries on adult salmon of hatchery origin (Campton, 1995). It is the latter, Campton argues, that is the source of most genetic effects of hatcheries on wild stocks. Moreover, management is the major source of ecological impact of hatchery fish on wild stocks, and the subject of controversy regarding poor survival of artificially propagated fish. If the manner in which hatcheries are used is, in fact, contributing to poor performance of hatchery fish, the negative effects of hatcheries due to poor management decisions can be resolved by changing the philosophy and priorities of management (Campton, 1995).

To determine if changes in management philosophy and priorities have corrected the past problems of hatcheries, we have to look beyond the changes in technology that have occurred over the past century. Changes in philosophy are directly related to changes in fundamental assumptions that underlie hatchery and fisheries management. To determine if things really are different, it is critical to identify the fundamental assumptions that guided hatchery management in the past and compare them to the assumptions that guide hatchery management today. That can only be done through a historical analysis. Culturists who believe that "things are different now" often see little value in such analyses, with the result that fishery scientists have produced few analytical studies of earlier program performance (Smith, 1994). Consequently, the specifics that would clarify past programs and the assumptions that guided them are not well known. Information is generally good with regard to hatchery operations. Hatchery population inventory, health status, feeding levels, condition and outplanting dates are in the archives of daily logs kept by the agencies. The missing detail is the rationale behind their hatchery programs. Understandably, the objective was increased production for harvest, but what motivated the approach is primarily anecdotal.

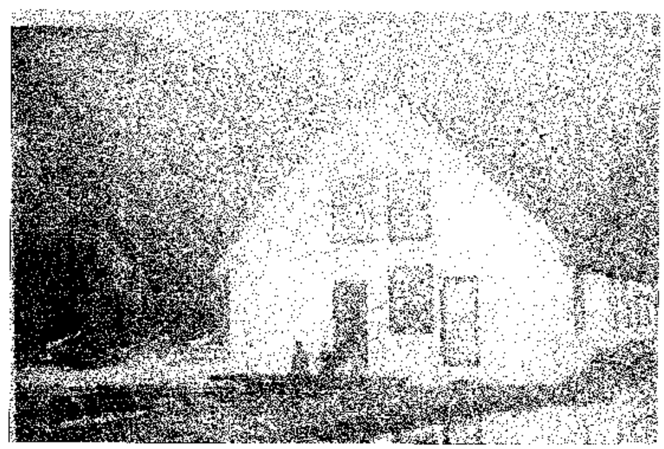
As noted earlier, restoration programs that intend to produce a new future for anadromous and resident fish populations in the Columbia River Basin must be historically informed, because in a sense the past is never really abandoned. Programs and their philosophical underpinnings evolve, and this means "new " programs carry strands of ideas and assumptions that have their roots in the distant past. We cannot merely assume that hatchery programs today are detached from their historical roots without a review of those roots and their influence on current assumptions that drive the program.

III. Historical Overview of Artificial Production

In this section, we explore the history of Columbia River Basin hatcheries to1960. Post-1960 operations will be analyzed in our next report, when reliable data about individual hatcheries will be available.

A. Growth of the Artificial Propagation Program

Spencer Baird, the U. S. Fish Commissioner, set the stage for the arrival of artificial propagation in the Columbia basin. In a report he completed in 1875, Baird listed the threats to the continued productivity of Pacific salmon in the Columbia Basin -- dams, habitat change and overharvest -- and he recommended artificial propagation as the solution to those problems. According to Baird, an investment of $15,000 - $20,000 in artificial propagation would make salmon so abundant that there would be no need for restrictive regulations (Baird 1875).



Typical turn-of-the-century salmon hatchery.
(Dungeness River)

Given his scientific background, Baird's endorsement of hatcheries in 1875 is puzzling. The first hatchery for Pacific salmon had been opened in the Sacramento River just three years earlier in 1872, and so the first brood of artificially propagated chinook salmon had not yet returned as adults. Baird had no credible scientific information upon which to base his recommendation. However, the concept of maintaining and increasing the abundance of salmon through artificial propagation was consistent with the prevailing ideology. For example, the belief that hatcheries could eliminate the need for restrictive regulations supported the laissez-faire access to natural resources, a policy the public supported and the government encouraged. It's clear Baird's endorsement had social and political roots rather than scientific. From this rather inauspicious start, hatcheries quickly became the preferred approach to maintaining salmon production.

The first hatchery in the Columbia Basin was a joint venture composed of private capital, largely from cannery operators, and expertise supplied by the U. S. Fish Commission. In 1877, Baird sent

Livingston Stone to Astoria to meet with the board of directors of the Oregon and Washington Fish Propagating Company (OWFPC). The company had raised $31,000 to build and operate a hatchery, and Stone was one of the few individuals on the West Coast with experience in artificial propagation. (Stone 1879; Hayden 1930). Stone selected a site on the Clackamas River, built the hatchery building, raked the stream, and supervised initial operation. OWFPC closed the hatchery in 1882. In 1888, it was leased to the State of Oregon and reopened (OSBFC 1888; 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 1).

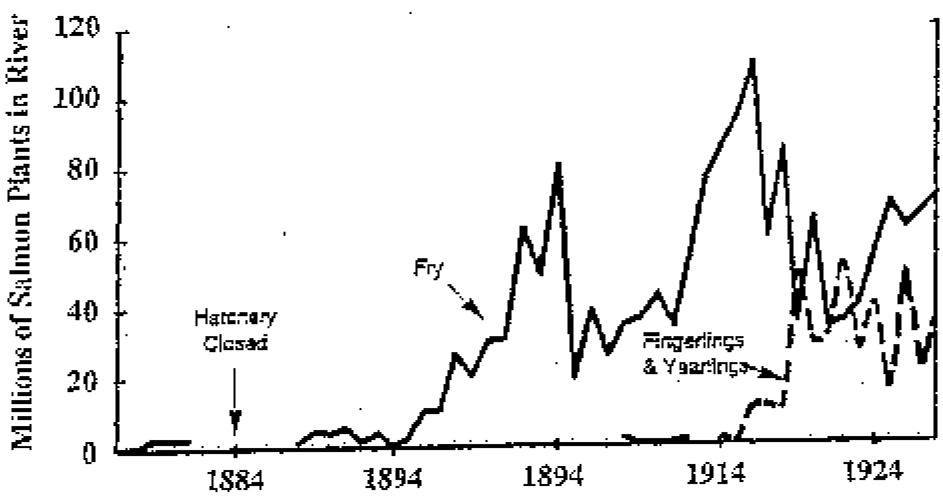


Figure 1. The number of juveniles of all salmon species released from hatcheries in the Columbia River (1877-1928). (Cobb 1930)

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 2); however, when the abundance and harvest of chinook salmon began to decline, the fishery switched to other species, and that switch was mimicked by the hatchery program. Coho salmon and steelhead were propagated in hatcheries beginning about 1900; chum and sockeye salmon were propagated beginning about a decade later (Cobb 1930).

The chinook harvest appeared to enjoy a period of relative stability from 1889 to 1920 (Figure 3). However, later analysis clearly demonstrated that the apparent stability was an artifact of significant qualitative shifts in the fishery (Figure 4). In fact, the prime spring and summer runs were in decline, and to maintain the catch, the fishery had shifted to fall chinook (Thompson 1951). After 1920, the decline in all races of chinook salmon in the Columbia Basin was obvious.

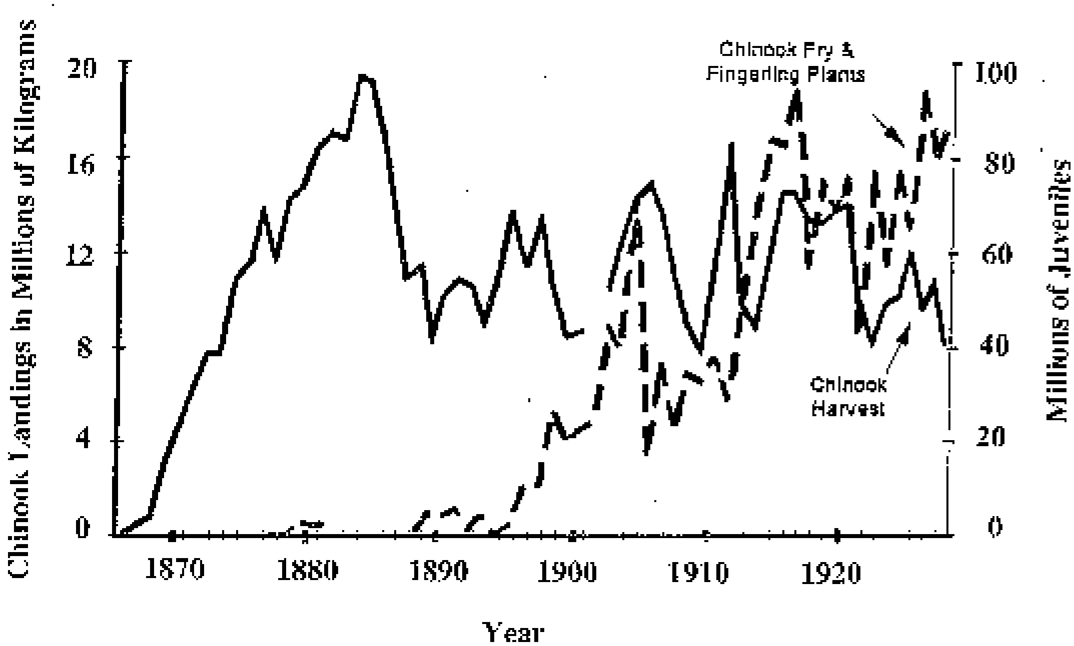


Figure 2. Harvest of chinook salmon and the release of chinook salmon fry and fingerlings from hatcheries in the Columbia basin (1877-1927). (Beiningen 1976; Cobb 1930)

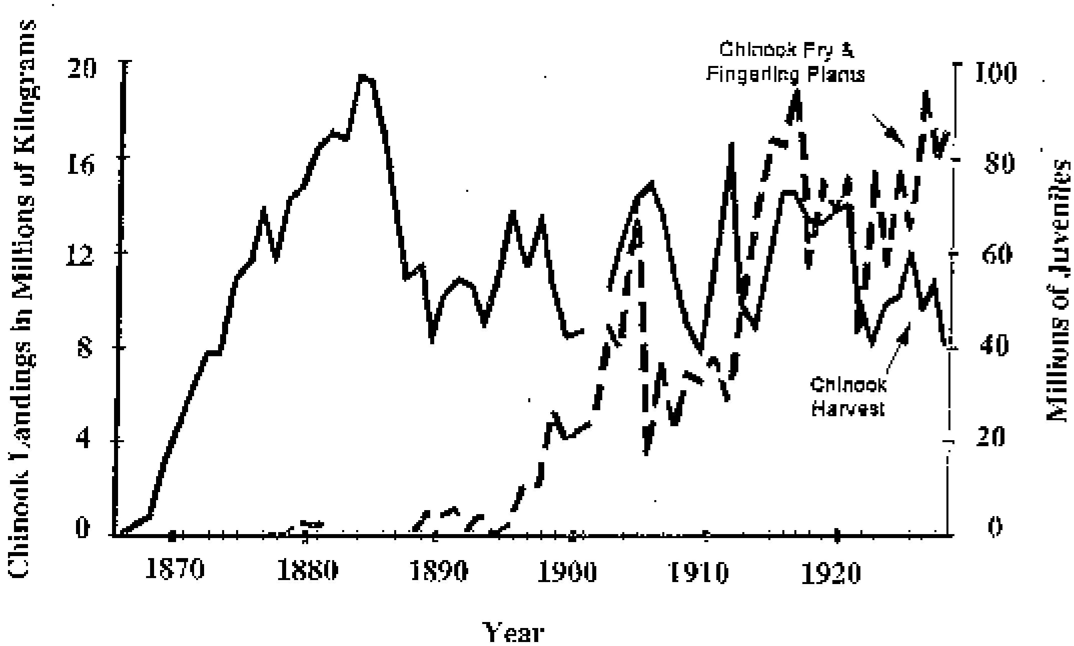


Figure 3. Five year average of chinook harvest in the Columbia River (1866-1992). (Beiningen 1976; ODFW & WDF 1993)

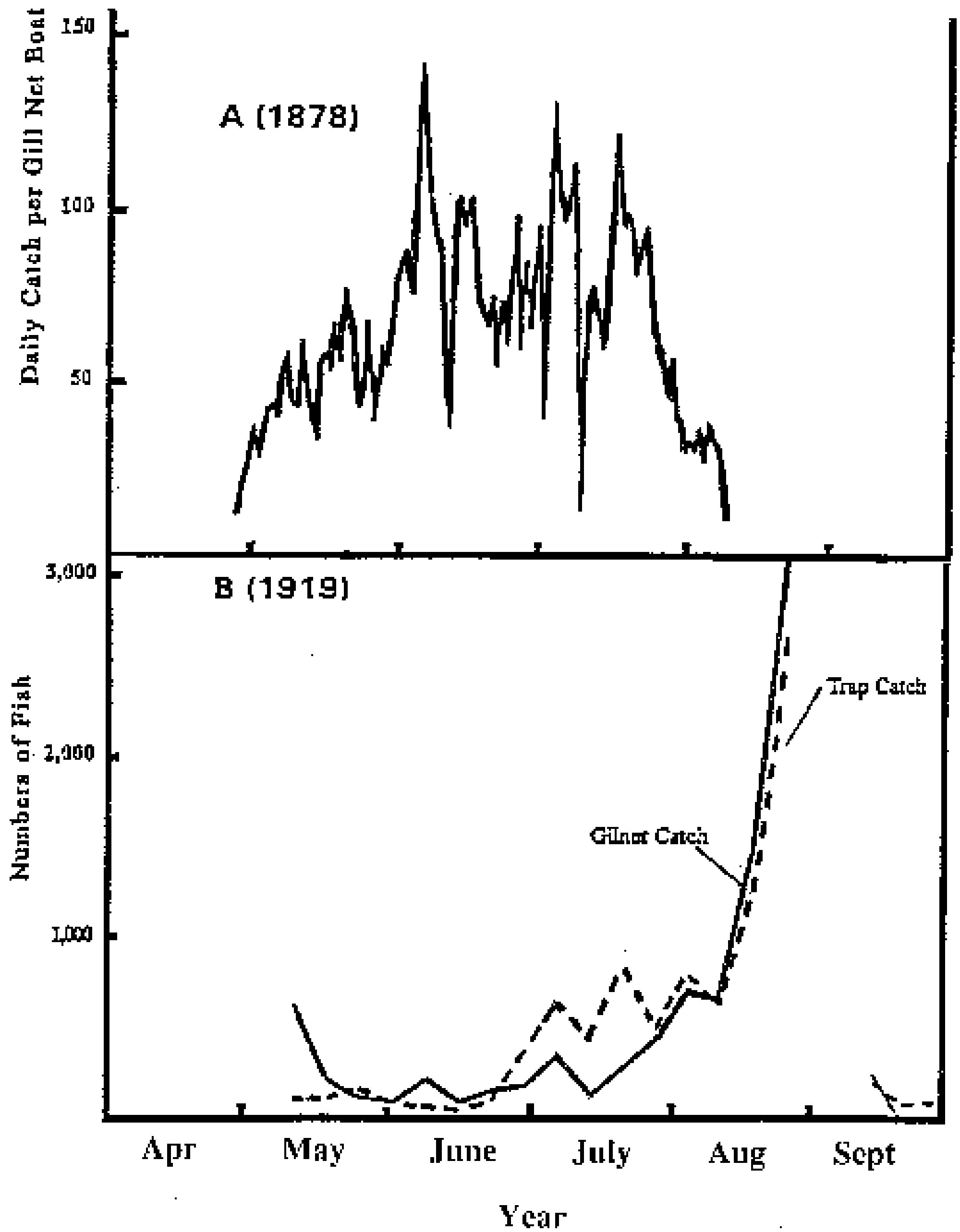


Figure 4. Comparison of the seasonal distribution of the chinook harvest in the Columbia River in 1878 (A: daily catch per gill net boat) and 1919 (B: weekly catch of 16 gill net boats and 22 traps). (Source: Thompson 1951)

In their contemporary analysis of salmon harvests, competent biologists like Willis Rich were deceived by the aggregated catch statistics: "the chinook salmon has held up remarkably well..." in spite of an intense fishery, "but the record since 1920 is one of constantly decreasing catches" (Rich 1948). He attributed the resiliency of chinook salmon and the apparent stable harvest to hatchery programs. Rich admitted that he had no evidence that hatcheries were in fact supplementing the production of chinook salmon. However, he believed it was "quite possible that there is a causal relationship that we do not understand between intensive artificial propagation and the resistance to exploitation that the species [chinook salmon] has shown" (Rich 1941).

Rich's positive speculation regarding benefits of hatcheries, like Spencer Baird's earlier recommendation, is curious because he had completed the only study of the effectiveness of artificial propagation in the Columbia basin. In that study, Rich concluded:

> "… that there is no evidence obtainable from a study of the statistics of the pack and hatchery output that artificial propagation has been an effective agent in conserving the supply of salmon. The writer wishes to emphasize the fact that the data presented here do not prove that artificial propagation may not be an efficient measure in salmon conservation. These data prove only that the popular conception, that the maintenance of the pack on the Columbia River is due to hatchery operations, is not justified by the available science." (Rich 1922).

During the 1930s and 1940s, questions about the efficacy of artificial propagation, combined with budget problems during the Depression, resulted in many hatchery closures. Given their poor prior performance, hatcheries would not have played a big a role in salmon management in the Columbia River following World War II except for the fact that rapid construction of mainstem dams required a mechanism to address the impact anticipated on fisheries. Artificial propagation was once again chosen to compensate for development even though scientific support for that decision was lacking. (CBFWA 1990)

Prior to 1960, hatcheries in the Columbia River contributed little to the overall salmon production (CBFWA 1990). After that date, with the development of better disease treatment, more nutritious feeds and better hatchery practices, survival from smolt to adult improved dramatically. However, the ability to produce large numbers of hatchery adults created a new set of management problems. The genetic and ecological effects of hatchery programs are discussed in Section VI of this report.

B. Compensation for Loss of Habitat

Most of the hatcheries built during this century were intended to mitigate the impact of human activities (National Research Council (NRC) 1996). Since the construction of Grand Coulee Dam, most of the growth in the hatchery program in the Columbia River has been tied to mitigation for the construction of the basin's hydropower system. Many of the mitigation hatcheries are part of specific programs including:

<u>Grand Coulee Fish Maintenance Project:</u> The first major hatchery program designed to compensate for hydroelectric development in the Columbia River Basin was the Grand Coulee Fish Maintenance Project. Construction of Grand Coulee Dam blocked access to 1,400 miles of salmon habitat (Fish and Hanavan, 1948). Salmon production above the dam has been estimated to have been 21,000 to 25,000 thousand fish (Calkins et al. 1939). This included some of the largest chinook in the Columbia River, the so-called "June Hogs."

With a height of 350 feet from the base of the spillway to the top of the dam, Grand Coulee 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 made an alternative necessary. The final plan 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 tributaries below Grand Coulee Dam and allowed to spawn naturally; and 3) the remaining fish were held and spawned at Leavenworth hatchery. The streams that 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 and after Grand Coulee cut off salmon migration. 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 (1972) gave a more pessimistic appraisal of the program and concluded that it salvaged nothing. More recently, Mullan et al. (1992) concluded that the fish maintenance program conserved the genetic diversity of the salmon stocks in the area. An examination of the historical record combined with an analysis of allelic variation in the chinook salmon led to the conclusion that 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). Grand Coulee mitigation is implemented through Entiat, Methow, and Leavenworth hatcheries.

Lower Columbia River Fishery Development Program: The initial Lower Columbia River Fishery Development Program (LCRFDP), 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 has continued to the present with some modifications. The program is closely associated with the Mitchell Act, the enabling legislation that permitted federal cost sharing at state hatcheries. 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, in the late 1940s, it was believed that the construction of McNary Dam and the other proposed dams in the upper Columbia and Snake rivers eventually would 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., 1987).

The original LCRFDP had six principal parts:

1. Remove migratory obstructions in the tributaries to the lower Columbia River. This part of the program included stream clearance work that removed large woody debris and probably 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., WDF 1953), but it is no longer practiced unless the obstruction presents a complete unnatural block to migration. The relocation of stocks from the upper to the lower Columbia followed the approach used in the Grand Coulee program. Artificial propagation was one of six parts of the program, but within a few years it became the dominant part (Lichatowich et al. 1996). In 1986, 79 percent of the program budget was expended on the hatchery program and about 10 percent on habitat improvement and screening of irrigation ditches (the remainder was mainly for administrative costs). Today 20 hatcheries are supported through Mitchell Act funds (Table 1). The original goal of the LCRFDP was to maintain a harvest of about 32 million pounds of anadromous salmonids from the Columbia River (Laythe 1948). However, it was conceded that this might not be possible.

Table 1. Major hatcheries that are part of the Columbia River fisheries development program (Mitchell Act Hatcheries). (Neitzel 1998, personal communication Steve Smith NMFS and Rich Berry ODFW)

Facility Name	**Agency**	**First Year Operated**
Beaver Creek Hatchery	WDFW	1957
Big Creek Hatchery	ODFW	1941
Bonneville Hatchery	ODFW	1909
Cascade Hatchery	ODFW	1959
Clackamas Hatchery	ODFW	1979
Eagle Creek NFH	USFWS	1956
Elokomin Salmon Hatchery	WDFW	1954
Fallert Creek Hatchery	WDFW	1895
Grays River Salmon Hat.	WDFW	1961
Kalama Hatchery	WDFW	1958
Klaskanine Hatchery	ODFW	1911
Klickitat Salmon Hatchery	WDFW	1949
Little White Salmon NFH	USFWS	1989
North Toutle Salmon Hat.	WDFW	1951
Oxbow Hatchery	ODFW	1913
Ringold Springs Hatchery	WDFW	1963
Sandy Hatchery	ODFW	1951
Skamania Hatchery	WDFW	1956
Spring Creek NFH	USFWS	1901
Washougal Salmon Hat.	WDFW	1959

<u>Mid-Columbia Mitigation:</u> Construction of the five mid-Columbia projects (Priest Rapids, Wanapum, Rock Island, Rocky Reach and Wells) eliminated 149 miles of mainstem habitat from Chief Joseph Dam to the Hanford Reach below Priest Rapids Dam. Spawning and rearing habitat was lost from the production of several thousand fall and summer chinook in this reach (NPPC 1986) with additional impacts to the survival of downstream-migrating salmon produced in tributaries above Priest Rapids Dam.

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 the five PUD dams. 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. Implementation of the third phase began in 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 that are lost in passage at Wells and Rock Island dams.

Lower Snake River Compensation Plan: The Lower Snake River Compensation Plan (LSRCP) was developed to mitigate the loss of fish and wildlife resources resulting from the construction of Ice Harbor, Lower Monumental, Little Goose and Lower Granite dams. Construction of these dams eliminated 137 miles of mainstem fall and summer chinook habitat and the annual production from that reach. The dams also impacted survival of downstream- and upstream-migrating salmon produced upstream from Ice Harbor Dam.

The Lower Snake River dams were completed between 1961 and 1975 (Lavier 1976). Planning for the program began in 1966, Congress gave its approval in 1976, and the first hatchery (McCall) was completed in 1979. Over the next eight years, several other hatcheries and satellite facilities were constructed. Currently, there are nine hatcheries funded under the LSRCP (Table 2). 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 Lower Snake River Compensation Program did not include production objectives for Snake River coho salmon or Snake River sockeye salmon. Few resources were devoted to Snake River fall chinook, with only one hatchery being devoted to this race at Lyons Ferry. Coho salmon populations currently are extirpated from the Snake River Basin, sockeye salmon are nearly extinct, and under the Endangered Species Act fall chinook are listed as threatened. The adult return goals for the Lower Snake River Compensation Program include: 18,300 fall chinook, 58,700 spring/summer chinook, and 55,100 summer steelhead (Herrig 1998).

Table 2. Major hatcheries that are part of the Lower Snake River Compensation Plan. (Neitzel 1998, Herrig 1998)

Facility Name	Agency	First Year Operated
Clearwater Hatchery	IDFG	1992
Hagerman NFH	USFWS	1933
Irrigon Hatchery	ODFW	1984
Lookingglass Hatchery	ODFW	1982
Lyons Ferry Salmon Hatchery	WDFW	1984
Magic Valley Hatchery	IDFG	1987
McCall Hatchery	IDFG	1979
Sawtooth Hatchery	IDFG	1985
Wallowa Hatchery	ODFW	1920

Other Mitigation Programs: Other mitigation programs include the Willamette River Basin hatcheries, and hatcheries operated by Native American tribes and private industry. Five hatcheries mitigate for dams constructed in the tributaries of the Willamette River Basin (Table 3). The program is funded by the U. S. Army Corps of Engineers. The Nez Perce Tribe has a springwater-fed hatchery developed on Sweetwater Creek near Lewiston, Idaho, and the Yakama Tribe has a large state-of-the-art hatchery located near the Yakima River at Cle Elum, Washington. The Kootenai Tribe of Idaho has been operating a hatchery near Bonners Ferry, Idaho, originally in conjunction with the Idaho Department of Fish and Game, to protect the endangered Kootenai River population of white sturgeon from extinction. This facility was just upgraded to more reliably fulfill its conservation function, and to address the needs of other at-risk populations in the Kootenai River Basin, including native kokanee salmon. Most of the tribal production facilities are funded by Bonneville Power Administration ratepayers through the Northwest Power Planning Council's Columbia River Basin Fish and Wildlife Program.

Table 3. Major hatcheries that are part of the Willamette mitigation program. (Neitzel 1998)

Facility Name	Agency	First Year Operated
Leaburg Hatchery	COE	1953
Marion Forks Hatchery	COE	1951
McKenzie River Hatchery	COE	1975
South Santiam Hatchery	ODFW	1968
Willamette Hatchery	COE	1911

Several hatcheries have been financed by private industry to mitigate for loss of salmon and steelhead habitat by the construction of dams. Some of the main projects are listed below:

- The effects of dams constructed in Hells Canyon by the Idaho Power Company are mitigated through four hatcheries operated by the Idaho Department of Fish and Game.
- On the Deschutes River, Round Butte Hatchery mitigates for the construction of Pelton and Round Butte Dams by Portland General Electric Company.
- Two hatcheries on the Cowlitz River mitigate for dams constructed by Tacoma City Light.
- Two hatcheries on the Lewis River are funded by PacifiCorp to mitigate for hydroelectric development on that river.

As demonstrated by the history of artificial production in the Columbia River system, there has been extensive variation in how hatcheries have been used to address needs of fisheries management. In the earlier years, the basis on which hatcheries were developed was opinion and adherence to a popular concept for increasing the magnitude of salmon runs. As hatchery programs developed better technology over the years, there were concomitant changes in what constituted hatchery management policy, and changes in the extent to which biological rationale influenced that policy. There have been differences in the quality of hatchery fish and improvements in the survival performance of fish released from hatcheries, but also a performance that has been highly variable among hatcheries. It is instructive, therefore, to look simultaneously at the evolution of the role of science as the hatchery concept developed and at the history of hatcheries on the Columbia.

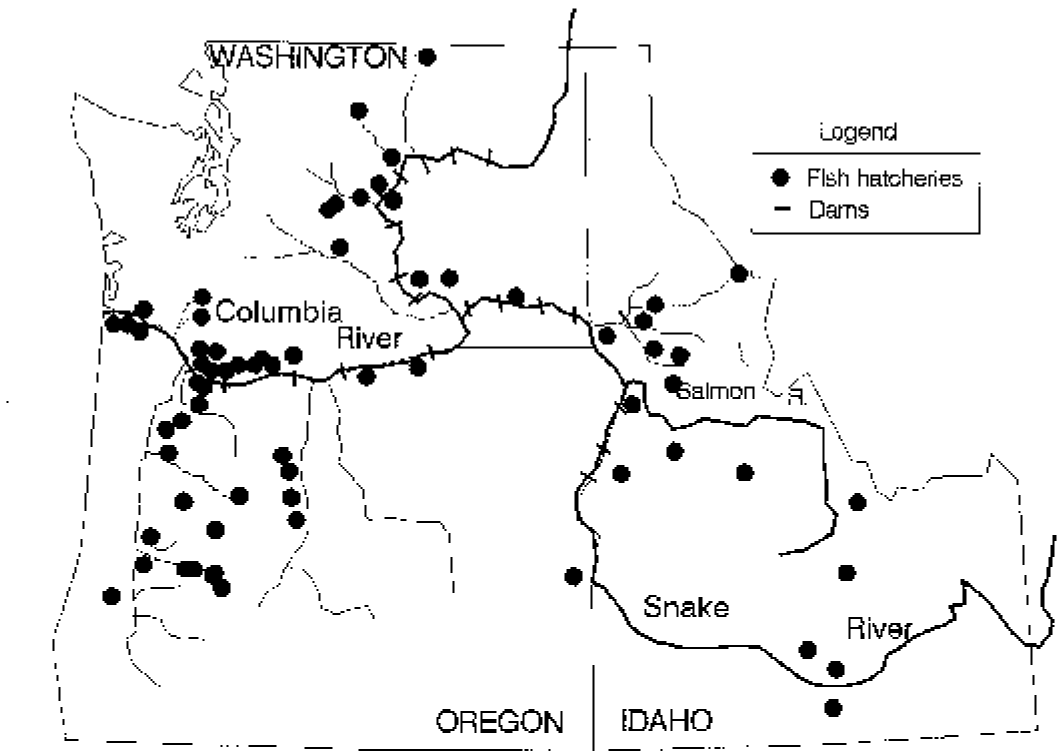


Figure 5. Columbia River Basin state, tribal and federal hatchery locations.

IV. Scientific Foundation

All salmon management programs are derived from a scientific foundation -- a set of assumptions, theories and principles that describe how the salmon ecosystem functions (ISG 1996 The foundation is a powerful part of any management program. It is used to interpret information, identify problems (impediments to achieving objectives) and select restoration strategies. Unfortunately the conceptual foundation is rarely explicitly stated or evaluated, and as a consequence programs can suffer from errors in concept. When limited scientific inquiry and false assumptions are a part of the process, the program derived from them will have a high likelihood of failure.

The conceptual foundation of the Columbia River hatchery program has never been specified or examined in detail. In this section, we describe the set of assumptions we believe were the basis of the hatchery program. Because it has never been explicitly stated, the conceptual foundation described here had to be derived from our review of the program -- its apparent objectives, assumptions stated by practitioners and its measures of performance. The conceptual foundation we present is thus qualified as our interpretation of the historical record, and accounts for the period ending in the 1960s; the point at which the hatchery assessment (the second phase of our report) begins.

A. The Early Conceptual Foundation of Hatcheries

The early hatchery program was consistent with the overarching assumption that salmonid production systems could be simplified, controlled, and made more productive. Hatchery technology not only simplified and controlled production, it circumvented the need for natural ecological processes and freshwater habitat. This philosophy was also reflected in the subsequent development of resident fish hatcheries. The program intention was simply to increase catch by protecting the eggs, maximizing the number of fry released, and harvest fish returning from the sea. Given the hypothetical fecundity of 3,000 eggs, a spawning pair may successfully produce something in the neighborhood of 500 fry to emergence under natural stream conditions. Under the same scenario, artificially spawning and incubating those 3,000 eggs would result in about 2,500 fry to emergence under the hatchery scenario, or a five-fold increase over natural incubation because of the protection against predation, disease, poor incubation conditions and scouring floods. So the rationale of the early practitioners was not an unreasonable expectation of the advantage of hatchery fry production. Moreover, it was a technique that, when properly employed, had brought substantive results, as demonstrated by an example we discuss in the next section (B).

The problem in the beginning was one of dimension. Even with a five-fold improvement in egg survival, the number of females intercepted was insignificant compared to the number spawning naturally, even when the run was seriously depressed. The primary problem, however, was that fry were distributed to a variety of streams with little or no information about the suitability of habitat or risk for young fish. This also was true of the often haphazard stocking of non-native or exotic fish. In Idaho alone, 30 exotic species of resident fish have been introduced since the late 1890s. (Simpson and Wallace, 1982).

It was the natural extension of the concept that if protecting the incubating eggs from such harm would result in a five-fold improvement in fry production, and hence the extrapolation to a five-fold improvement in adult returns, then why not control the rest of freshwater rearing to reduce losses from predation, disease, starvation, and environmental alterations in the natural stream? Therefore, taking the simple equation one step farther, of the 500 wild fry emerging naturally, 45 might be expected to reach the smolt stage and enter marine waters, from which two to five adults would return. However, extrapolating the hatchery survival advantage to the next life history stage, if the now 2,500 fry successfully incubated from 3,000 eggs in the hatchery were reared and protected through the succeeding freshwater rearing period, 2,000 fingerlings could be produced to the smolt stage, equating to a total hatchery production benefit nearly 44 times greater than natural production of the original 3,000 eggs. Rather than two to five adults returning per pair of natural spawners, given marine survival equal to natural fry, the hatchery benefit would equate to over 100 returning adults from the same pair of spawners. The simple extrapolation of hatchery survival to return success was the presumptive expectation of the hatchery enthusiasts, and the basis for the expansion of the hatchery building program that has spanned a half century to the present distribution of artificial production throughout the Columbia basin (Figure 5).

Experience has demonstrated, however, that successful production of juveniles in hatcheries is not so simple and that hatchery production by itself cannot guarantee a sustained increase in catch. However, the point in laboring the expectation that ushered in the development of hatcheries is that the fundamental premise is very similar to the basic assumption inherent in the subsequent development of Pacific salmon and many resident fish hatcheries throughout the Pacific Northwest. That presumptive view has not changed substantially, and production augmentation currently is being undertaken in at least the Columbia River Fishery Development Program, but with a more conservative expectation of benefit.

Part of the problem is that early salmon managers viewed rivers as agri-ecosystems capable of being simplified, controlled and through cultivation (artificial propagation) brought to higher levels of production (Bottom 1997; Lichatowich et al. 1996). The agricultural approach to management led to an emphasis on single species production objectives that separated the development of fisheries science from the major developments in ecology for anadromous and resident species. Fisheries adopted agricultural objectives and supporting science instead of the holistic approach advocated by early fisheries workers such as Forbes (McIntosh 1985; Bottom 1997). Viewing rivers as farms led to the belief that individual enterprise alone could overcome any natural limits to production (OSBFC 1890). As late as 1960, the Washington Department of Fisheries still believed that fish farming was closely linked to farming on land and shared the same principles and rewards (WDF 1960).

An agricultural model for salmon production was expressed by several early salmon managers. The following is a sample of their statements:

> *"Professor Baird often said 'one acre of water was worth seven acres of land, if properly cultivated, ' but I am convinced that the Professor erred only in this, that I believe one acre of the waters of any salmon stream in Oregon, if judiciously cultivated under favorable circumstances, and if not paralyzed by ignorant vicious legislation, is worth more as a medium for the product of a food supply than forty acres of the best land in the State."* (Hume, 1893)

> *"It has been the habit to cultivate the land and neglect the water…. We have tilled the ground four thousand years; we have just begun to till the water…. Less care and labor are needed to raise fish than to raise other animals, or even to raise vegetables."* (Oregon State Board of Fish Commissioners, 1890)

> *"Modern incubation equipment for fish propagation compares with greenhouse methods to increase the survival of plants… As man makes ready the soil for growing of better crops, so may he improve the water for the growing of fish. The steps to be taken in the harvest of surplus seed, the surplus crops, the preparation of land or water follows the same fundamental requirements."* (Washington Department of Fisheries 1960)

Commercial aquaculture, or fish husbandry for commercial markets with other agricultural commodities in the Pacific Northwest, has demonstrated production capabilities even better than the original hatchery practitioners envisioned. This is because fish farmers control the entire life cycle from spawning to adult harvest and realize the equivalent of 1,800 marketable adult-size fish per spawning pair. However, while the application of agricultural principles has been beneficial in some aquacultural enterprises, it generally has failed when applied to anadromous salmonids, which are released to experience more than three-quarters of their life in the natural environment.

In retrospect, when we look back to the era of "farming nature," in light of the major leaps that agriculture has made and continues to make in animal husbandry, the assumption that watersheds could be treated as farms and managed like agricultural enterprises was understandable. This logic led to the belief that natural limits on production could be ignored and, through fish culture levels of production greatly increased. Initially production from natural populations was assumed to be limited by spawning success, and production of the ocean relatively unlimited. Consequently, it was believed that increased survival of fry and fingerlings in the hatchery would translate proportionately to increased adult return. This is epitomized in the following excerpts.

> *"It is imperative, therefore, that some means be adopted to counteract the depletions arising from this source (habitat degradation); but the most important reason for the artificial propagation is the fact that the natural method is extremely wasteful, which is not true of the artificial method."* (Smith 1919, p. 6)

> *"In my opinion, if the salmon runs of this state are to be maintained and increased, it is going to be necessary to constantly construct new hatcheries. The much greater effectiveness of hatchery operations, as compared with natural propagation, has in my judgment been so effectively proven as to no longer permit discussions among those who are acquainted with the situation."* (WDFG 1921, p. 17)

> *"There can be no doubt in the mind of anyone who has studied the question, that the future prosperity of our salmon fisheries depend largely upon artificial propagation... I am convinced that not more than 10 percent of the ova spawned in the open streams are hatched, owing principally to spawn-eating fish that prey on them... while from artificial propagation 90 percent are successfully hatched. What more need be said in favor of fish culture?"* (Oregon State Fish and Game Protector 1896, p. 33)

> *"Nature ... produces great quantities of seed that nature does not utilize or need. It looks like a vast store that has been provided for nature, to hold in reserve against the time when the increased population of the earth should need it and the sagacity of man should utilize it. At all events nature has never utilized this reserve, and man finds it already here to meet his wants."* (Stone 1884, p. 21)

The assumptions that watersheds could be made more productive through agricultural practices and that natural limits on production could be circumvented were the foundation of the Columbia Basin hatchery program. Moreover, hatchery production was assumed to be additive to natural production, with no interaction or impact on natural populations. Given the expected translation of hatchery survival to adult returns, practitioners also assumed that the principle measure of success for a production hatchery should be the numbers of juveniles released. Obviously, there would be an associated expectation that harvest level should also increase, but accounting for catch over many fisheries and jurisdictions was much more difficult and less practical than simply monitoring numbers of juveniles produced.

In summary, the fundamental assumptions governing the development of the Columbia River hatchery program before 1960, and the genesis of the early conceptual foundation of hatchery production, was centered on five general assertions:

- It was not only possible but also desirable to simplify and control production of anadromous salmonids to increase their abundance.
- Anadromous salmonids could be effectively managed through the application of agricultural practices and science.
- Production limitations during freshwater life stages could be circumvented by hatcheries, and the capacity of the ocean was relatively unlimited.
- Artificially propagated fish released to the rivers added to production from natural populations. There were no negative interactions.
- The probability of success was so high that evaluation of adult returns was not necessary.

B. The hatchery framework as an adaptive process

Development of a conceptual foundation applicable to Columbia basin hatchery programs has to be consistent with what is known about salmonid life history and ecological processes. Any fisheries management effort that does not integrate the management criteria around the inherent life history strategies that have evolved among the specific salmonid and native resident fish species, including stock-specific differences, will fail. Pacific salmonids have evolved specific life history patterns and population structures compatible with their native habitat (Brannon, in press), and ignorance, or disregard, of that compatibility will weigh heavily against any management attempts to sustain or build wild fish populations. In essence, the conceptual foundation must be flexible enough to accommodate derivations in life histories among all fish species, including those differences within the mixture of stocks representing the species.

Natural populations of salmonids are genetically programmed to survive and behave in ways that maximize long-term fitness in their natural environments. Disconnecting the organismic and environmental linkages effectively disrupts the timing and reduces fitness back to the level of a founding population. Survival success returns to the odds of happenstance, and adaptive evolution must start over again. Typical central hatchery programs that follow such management plans, and repeatedly distribute fish around the watershed can not effectively address the concept of ecosystem management. These fish will have little contribution value to natural production, and by continually or even intermittently spreading stocks around the system, fish will remain biologically incompetent for those foreign environments.

The challenge in developing the conceptual foundation for hatcheries is to re-prioritize production and operation goals to address the biological needs of the stock being propagated. In freshwater, chinook life history strategy is the most complex among the anadromous salmonids and pink salmon the simplest, with coho, steelhead, sockeye, and chum salmon intermediate. Stream-dwelling species, such as chinook, coho and steelhead, are limited most often by the rearing capacity of their stream. Generally, factors associated with spatial and nutritional requirements of stream-dwelling salmonids determine the upper limit of population biomass that can be sustained within the stream, and strategies to maximize productivity around those parameters evolve to define the population. Sockeye, chum, and pink salmon use freshwater streams only for spawning, with the juveniles immediately migrating to their nursery environments in lake (sockeye) or marine (chum and pink) waters for rearing. Only the spawning area of the stream generally limits these species, as the productivity of their nursery environment most often exceeds the capacity of the spawning grounds available.

In developing a conceptual foundation for hatchery programs, the process must allow for differences inherent in the fish targeted and whether they have adopted anadromous or resident life histories. It appears that successful applications of the hatchery concept are those cases that do not deviate significantly from the biological repertoire of the fish, and were successful in addressing the limiting factors in the natural life history of the species. The Prince William Sound (PWS) pink salmon hatchery program is a good example (Linley, in press). In the early 1970s the commercial fishery on pink salmon was threatened by the low return of fish into the sound, and hence it was believed the relatively small numbers of fry naturally produced were insufficient to rebuild the run.

The non-profit hatchery program was started, involving the artificial spawning and incubation of fry for release into PWS. Fry releases were synchronized with the beginning of the spring plankton bloom, which was the biological optimum for rapid growth. Their success was unprecedented (Figure 6). Adult returns improved four-fold over the previous ten-year average of 5 million adults, and has reached numbers as high as 45 million returning fish. Percent survival of fry released to achieve those levels of return success ranged from 0.9 percent to 13.0 percent (Figure 7) at the Armin F. Koernig hatchery (Linley, in press), far exceeding the survival performance of any fingerling or smolt production hatchery on the Columbia. The survival variability was attributed to variations in marine productivity, temperatures, and predation, based on annual monitoring of those conditions in the sound (Willette 1992). Success in the PWS hatchery program was experienced by working within the life history definition of the species, and has succeeded for ten generations.

Similar success addressing production restraints from loss of habitat was experienced with sockeye returning to Weaver Creek on the Fraser River (IPSFC and PSC annual reports). Logging had caused high variability in flows, and the loss of redds and low returns were threatening the viability of the run. The Salmon Commission built an artificial spawning channel on the stream in which flow was controlled and much of the silt and fine material prevented from infiltrating the graded spawning substrate. Natural spawners used the channel with egg-to-fry survival rates averaging well over 60 percent, or about 10-fold better than survival in the adjacent stream. Adult returns showed a marked improvement, amounting to an average of about 250,000 fish annually (Figure 8).

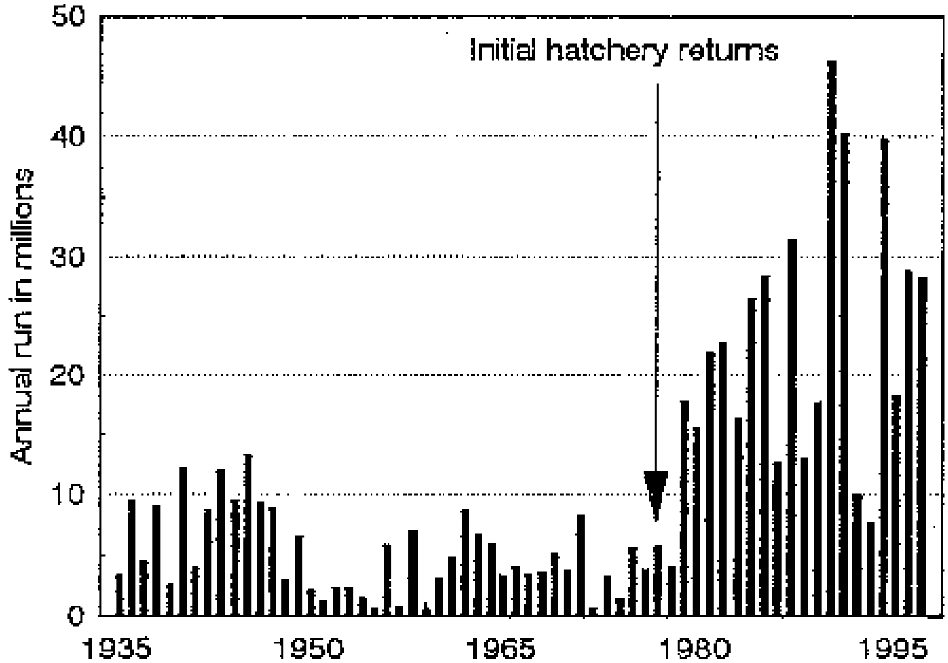


Figure 6. Annual run size of pink salmon returning to hatchery and natural production streams in Prince William Sound, Alaska.

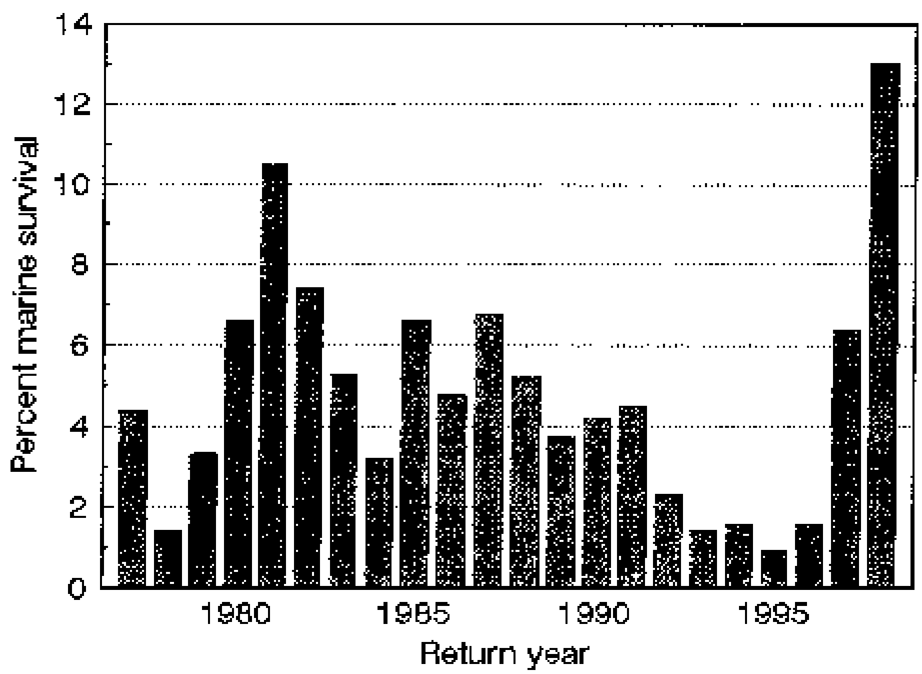


Figure 7. Percent survival of pink salmon fry released from Armin F. Koernig hatchery in Prince William Sound, Alaska.

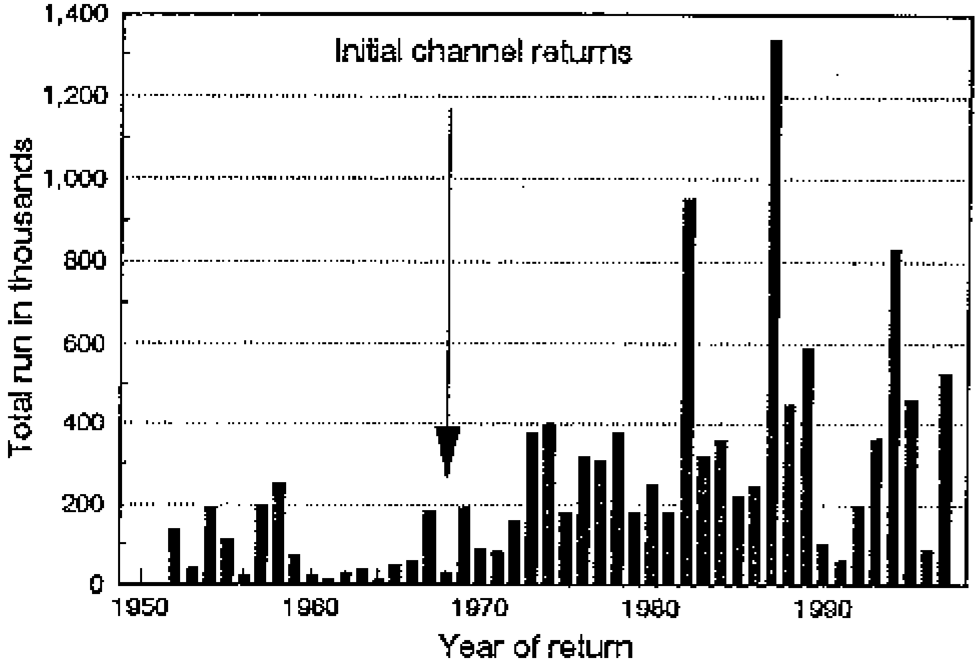


Figure 8. Annual run size of sockeye salmon returning to Weaver Creek in British Columbia (IPSFC/PSC Rept).

The Weaver Creek channel (hatchery) concept succeeded because the operation was complementary to the biology of the species, and addressed only that portion of the life history that was limiting the population. In both the PWS pink salmon hatchery program and the Weaver Creek sockeye salmon spawning channel, the conceptual foundation was consistent with the species life history and integrated the solution to the production problem effectively. However, these species present a different kind of challenge than that facing the Columbia basin hatcheries. Sockeye and pink salmon are normally limited by freshwater spawning area, and the hatchery approaches used in both cases addressed that limitation with relatively minimal intrusion in the ecological system. The stream-dwelling species (chinook, coho, and steelhead) create a different problem when limited rearing habitat is the primary source of population decline. Hatchery rearing programs have a more difficult task of integrating cultured fish into the natural system because, unlike artificial incubation programs, under present hatchery rearing environments the fish are removed from everything that would resemble or prepare them for the natural stream environment they must compete in once they are released. However, even under these conditions, hatchery programs have shown success in increasing production. The Makah Nation Fish Hatchery is a good example.

In the late 1970s, the Makah Indian Nation sought to increase the production of anadromous salmonids associated with the streams on their reservation in far northwestern Washington state. The Sooes River chinook population was being seriously threatened by clear-cut logging watershed instability, runoff from log yards, and overfishing by the coastal and Canadian fisheries. Fewer than 100 fish were reaching the spawning grounds in some years. In cooperation with the USFWS, the Makah National Fish Hatchery was built on the Sooes River, entering the Pacific Ocean just south of Cape Flattery. Plans were initiated to introduce chinook from other hatcheries, but the Makahs insisted that only Sooes chinook be propagated, even if the hatchery was not fully utilized in the first few years. They felt Sooes River fall chinook were uniquely adapted to that coastal system, with large eggs and an early migration timing to marine waters. Therefore, the hatchery program was to enhance the Sooes River chinook population, and a breeding plan was followed to maintain the diversity present. Fish excess to hatchery needs were permitted to spawn naturally, and in theory both the hatchery population and the naturally spawning fish commingled as a single population. Age-3 returns from hatchery propagation started in 1984, and by 1988 hatchery contributions were a significant share of the total return (Figure 9). By the late 1990s well over 2,000 fish were returning from both the hatchery and the natural production.

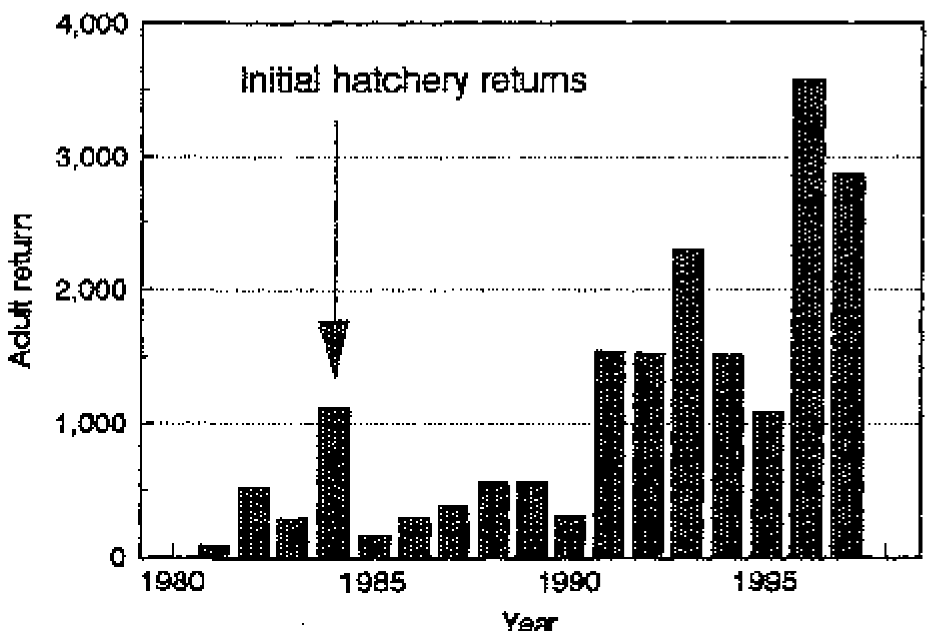


Figure 9. Chinook salmon annual return to Sooes River, Washington, from hatchery and natural production.

The Sooes River chinook salmon hatchery program success is attributed in part to the emphasis on the native stock. The selective advantage of the adaptive traits manifest in the physical and behavioral characteristics of the Sooes stock were not compromised by introductions of another stock that would have been incompatible with that coastal system. Also contributing to their success is the hatchery's proximity to the marine environment. Naturally produced fish have a relatively brief period of freshwater residence, and the hatchery fish can be in brackish water within an hour after release from the hatchery.

These examples of pink, sockeye, and chinook hatchery programs that have had good success in reaching their production objectives demonstrate that the appropriate conceptual framework is critically important to the development of functional enhancement systems. Admittedly, none of the above examples is subject to the severely anomalous conditions facing Columbia River salmon and steelhead. The point in fact, however, is that if Columbia Basin hatcheries are to have success in enhancing natural production and restoring some of the runs to self-sustaining populations, the conceptual foundation has to be that much more specific to the task. To meet the challenge of integrating artificial propagation into the Columbia Basin ecosystem and reach the commercial, tribal, and public fishery objectives, the model has to be rigorously defined and the biology of the component species well understood.

Many of the previous requirements for successful anadromous salmonid hatchery programs also apply directly to resident fish. As with the previous examples of successes with pink, sockeye, and chinook salmon, resident fish hatcheries also share the success of meeting their goals. It is important to note that the goals of anadromous and resident fish hatchery programs can differ considerably due to differences in program application and purpose, as well as differences in life history strategies and requirements of the species targeted. Nonetheless, the two following examples of successful resident fish hatchery programs provide substantial recreational fishing opportunities, increased numbers of angler trips, and very important local economic benefits. Their success was judged by the contribution of recreational fisheries to the local economies and the quality of life in the interior Columbia Basin. These two examples involve Sprague Lake in eastern Washington, and Lake Roosevelt, in northeastern Washington.

Resident hatchery stocks of rainbow trout and Lahontan cutthroat trout were successfully introduced into Sprague Lake following complete elimination of carp , stunted yellow perch and additional undesirable non-native fish species through the use of rotenone (Whalen 1989; Willms 1989; Willms et al. 1989). Prior to rotenone treatment, and the introduction of rainbow and cutthroat trout, the estimated annual angler pressure was believed to be approximately 1,700 angler days (approximately 13,600 angler-hours; Willms et al. 1989). Following rotenone treatment, removal of undesirable species, and introduction of rainbow and cutthroat trout, the estimated 13,600 angler-hours rose to over 200,000 in 1987 and 1988 (Figure 10; Willms et al. 1989). One of the goals of this resident trout introduction program was to generate $500,000 annually for the local economy. The program has since provided over $1 million annually to the local economy - 20 times the original target goal (Willms et al. 1989). These authors also determined that in 1986, 46.6 percent of all rainbow trout stocked into Sprague Lake were returned to the creel during the same year. This return is more than forty times that of documented adult anadromous salmon returns, which illustrates the need for separate and appropriate evaluation criteria of resident and anadromous fish hatchery programs. In this case, the newly established resident trout fishery in Sprague Lake illustrates the benefits of resident hatchery programs, which provided a popular fishery in a previously little-used lake.

The second example of successful resident fish hatchery programs involves Lake Roosevelt, the Spokane Indian Tribe's resident fish hatchery, and rainbow trout. The Spokane Tribal Hatchery program began stocking Lake Roosevelt with rainbow trout and kokanee salmon in 1991 in order to establish and enhance resident fisheries in the lake as mitigation for anadromous salmon resources permanently lost due to dam construction. From 1991 through 1994, rainbow trout catches increased nearly five-fold (Figure 11), angler trips nearly tripled ((Figure 12), and estimated annual revenue generated by hatchery-supported resident fisheries increased nearly four-fold (Figure 13, Cichosz et al. 1996).

Figure 10. Comparison of angler-hours during pre-stocking (1985) and post-stocking (1987, 1988) periods at Sprague Lake, Washington (Data from Willms et al. 1989)

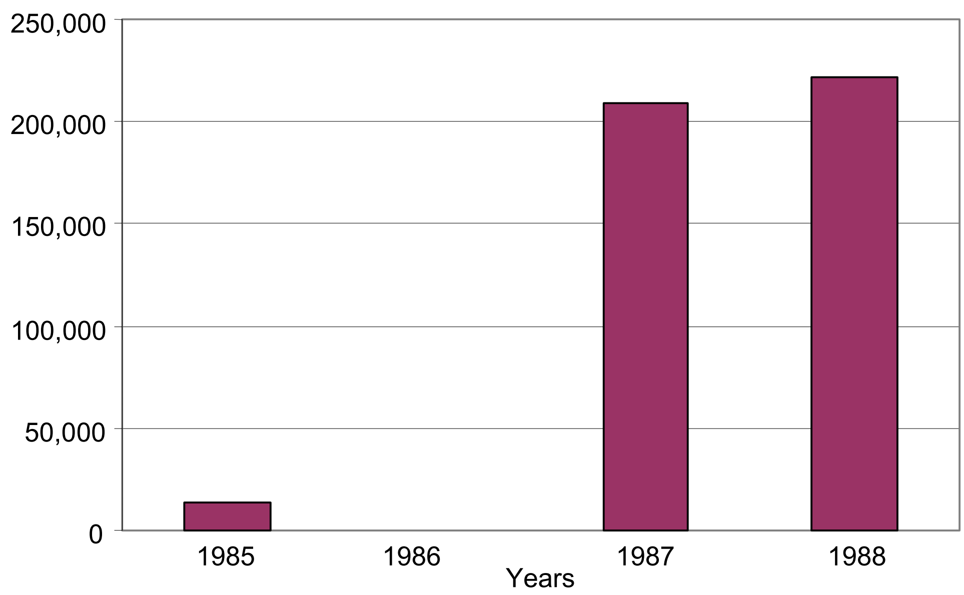


Figure 11. Comparison of rainbow trout catch before (1990,1991) after stocking (1992-1994) in Lake Roosevelt (Data from Cichosz et 1996).

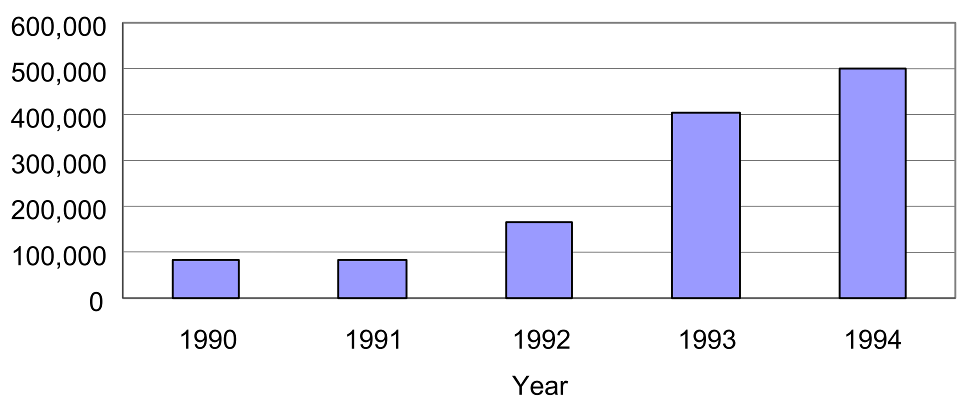


Figure 12. Comparison of angler-trips on Lake Roosevelt before and after rainbow trout stocking (Data from Cichosz et al.)

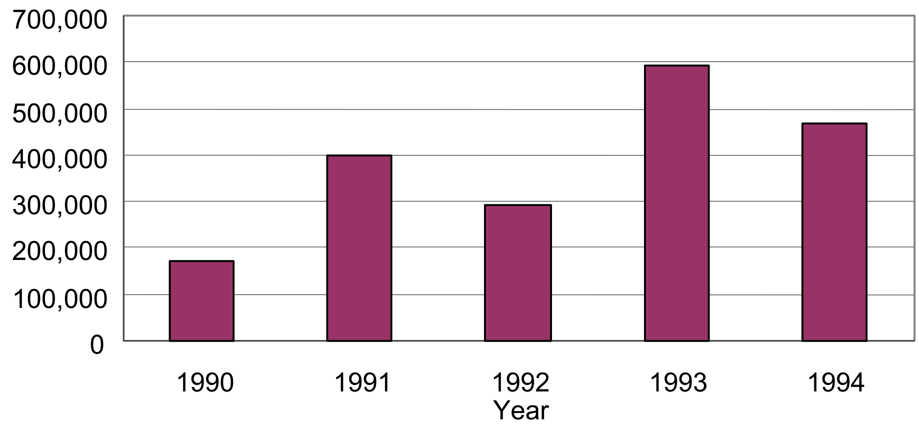
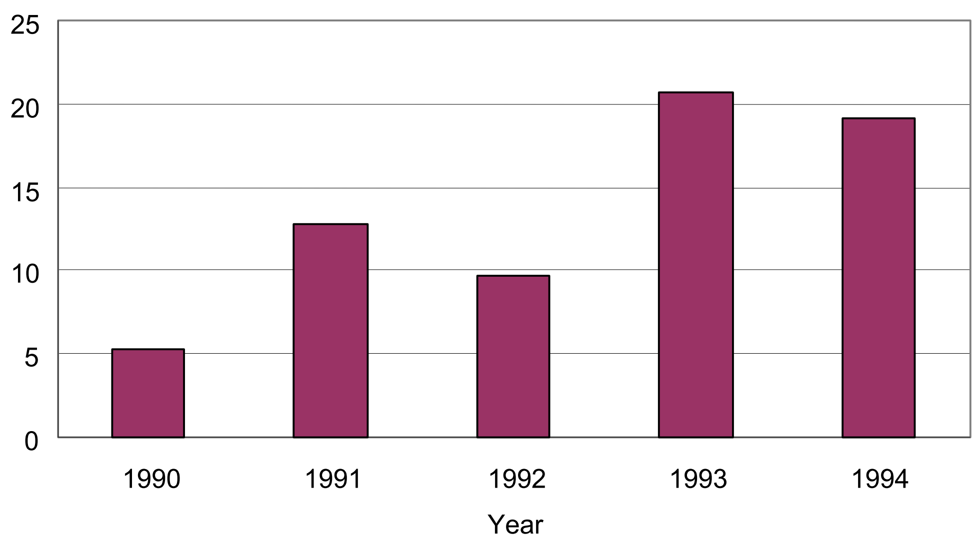


Figure 13. Comparison of economic value (millions of dollars) of fishery before (1990) and after rainbow trout stocking program (Data Cichoz et al.1996)



V. Organization and Classification of Artificial Production

We have stated that implicit in the artificial production of salmon, and the fundamental premise behind development of salmon hatcheries in the basin, was the belief that increases in the number of juvenile salmon produced and released from hatcheries would result in a proportional increase of harvestable adults. Although expectations of artificial production have matured to something more qualified by experience, that basic premise has continued to be a strong impetus behind hatchery substitution for habitat loss and reduced access to historical spawning grounds. New hatcheries are being constructed in anticipation of markedly increased adult returns resulting from such operations. How these new hatchery complexes integrate into the basin ecosystem will be defined by how management applies the conceptual framework to meet the objectives they have for the fishery.

The application of the hatchery model in the management of salmon fisheries, and hence the basis on which performance of such hatcheries must be judged, depends entirely on the objectives or strategies being addressed (Table 5). With the possible exception of hatcheries that are used solely to restore specific populations nearing extirpation, all anadromous and resident fish hatcheries are intended to provide fish for harvest. Management strategies fall under two categories of purpose, one to augment natural production for harvest, and the other to mitigate for the loss of harvest as a result of the diminution or elimination of salmon-producing habitat, and excluding their access to that habitat. It is instructive, therefore, to define more precisely the nature of augmentation and mitigation in the Columbia basin because of their application in mandates of Congress to enhance production or compensate for its loss as the river has developed around other societal needs. It is also essential to understand the classification of hatcheries in this document if assessment of past performance and current status is to provide the intended framework on which future management decisions and policies will be based.

A. Harvest Augmentation

Early in the development of mid-nineteenth century salmon fisheries, and as commercial harvests of Columbia River chinook salmon were doubling every season, artificial production was given serious consideration as a means to augment the harvest of salmon beyond that which could be sustained by natural production. Freshwater production of young salmon in natural river systems was correctly assumed to be limited by spawning success and habitat, and hatcheries were conceived as a means to overcome such constraints on natural production. The fact that egg-to-fry survival could be increased as much as ten-fold through the process of artificial spawning and incubation in hatcheries was the general motivation behind construction of the first Columbia Basin hatchery in 1876, located on the Clackamas River. The expectation followed that adult returns would materialize from such technological interventions, reminiscent of philosophical deductions from technological advancements in agriculture and animal husbandry. This same pervasive philosophy was incorporated into the development and maintenance of mitigation hatcheries that propagated resident fish species. Overfishing reduced the abundance of anadromous salmonids so extensively in the basin that augmentation actually tried to compensate for the fishery and was never able to expand harvests beyond historical natural production.

Although attempts to assess hatchery contribution to the harvest did not occur until more recent times, and in spite of divided opinion within the scientific community about hatchery success (Lythe, 1948), the belief that artificial production contributed to the fishery has been responsible for development of substantial hatchery effort. There were three fundamental assumptions associated with the use of hatcheries for the purpose of harvest augmentation. (1) the freshwater environment limits natural production, (2) ocean carrying capacity exceeds natural production potential, and (3) hatchery production will not negatively impact natural populations. Belief in these assumptions still prevails, and they exist as criteria that need to be carefully assessed in applications of harvest augmentation programs to justify use of such technology for that objective in the Columbia River.

The first and second assumptions have credence, but the lower end of the productivity threshold in the marine environment is a very powerful limiting force on production, regardless of the magnitude of production in freshwater. Augmentation of harvest through hatchery production has been demonstrated most recently with pink salmon in Prince William Sound as seen in Figure 6, and highly correlated with marine conditions (Willette, 1992). Several hatchery programs in Alaska demonstrate very positive augmentation success, routinely above 10-percent survival of fingerling sockeye, and higher than 20 percent among some groups on fingerling coho (Marianne McNair, ADF&G, personal communication).

Successful augmentation hatchery programs are not rare in Washington and Oregon, either. The old Washington Department of Fisheries was formed to manage marine fisheries in the state specifically for commercial harvest, and augmentation was the objective of Washington State hatcheries. Hood Canal chum salmon hatchery production is a good example (Fuss, 1998). The size of the chum salmon run in Hood Canal has been directly related to the level of hatchery fry releases (Figure 14).

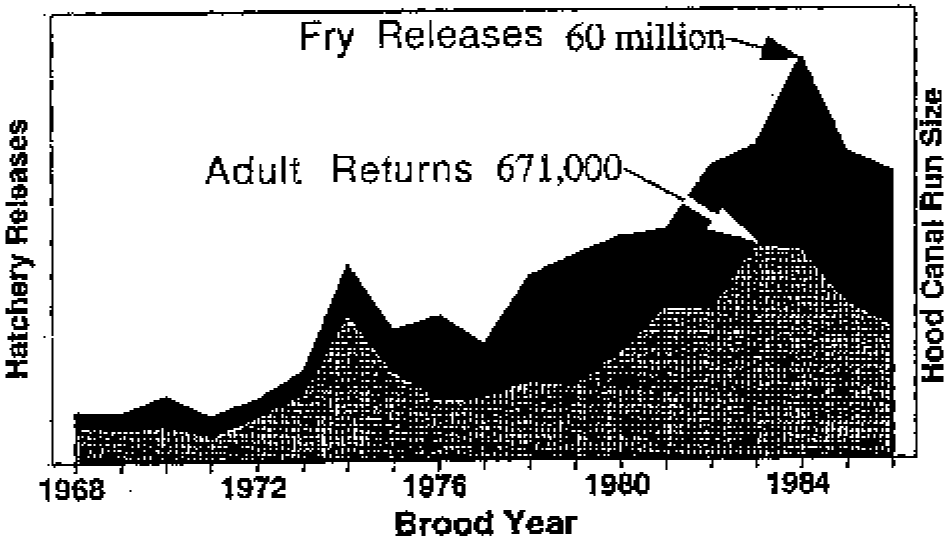


Figure 14. A comparison of Hood Canal chum salmon releases and subsequent run size. (Fuss 1989)

Similarly, coho production in Puget Sound shows a strong relationship between hatchery production and return run size. Fuss (1998) points out however, that regardless of hatchery contributions, if the environmental restraints are limiting the carrying capacity, production levels off or declines to whatever the environment will support (Figure 15).

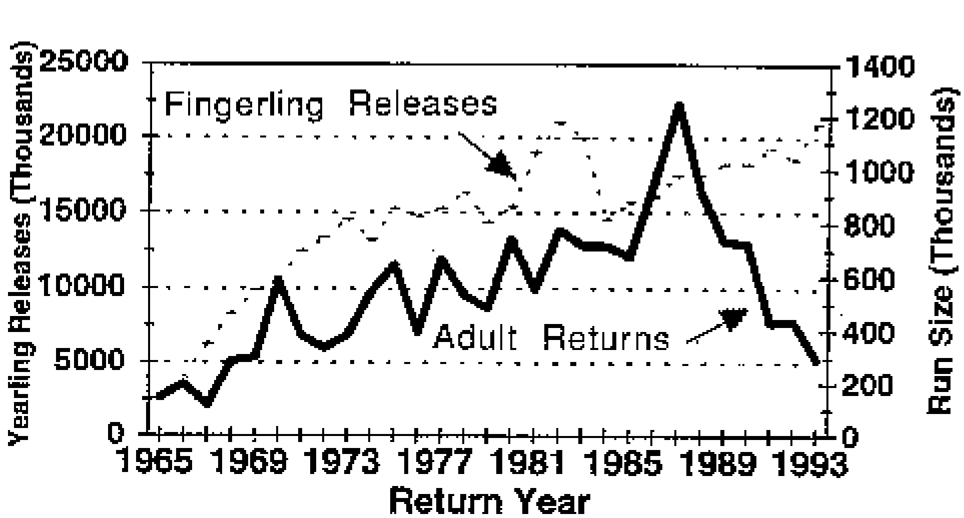


Figure 15. A comparison of hatchery releases of Puget Sound 1+ coho with subsequent run size. (Fuss 1998)

In the context of ecosystem management, the second and third assumptions listed above create major problems for attempts to accommodate harvest augmentation objectives. Ecosystem management and harvest augmentation are basically conflicting strategies that must be resolved consistent with the long-range goals for the fishery. The real question is not whether hatcheries are able to successfully produce salmon and steelhead artificially; that has been demonstrated many times. The deciding issue is whether hatchery production can integrate within the ecological framework on which future salmon management is proposed to operate. It follows, therefore, that before resolution can be addressed on the use of augmentation strategy in the Columbia River, careful assessment of harvest augmentation success through the use of hatcheries outside the basin, and the measured ecological impacts, should be undertaken.

B. Mitigation

With the development of water resources in the Columbia River, about 40 percent of the originally accessible river system is now inaccessible to salmon, and much of the remaining habitat has been significantly compromised for incubation and rearing. These losses were mitigated through artificial propagation, and major hatchery programs now prevail in the Columbia River system, and currently represent a significant and continuing investment. Conceptually, mitigation hatcheries are meant to replace harvest potentially lost as a result of habitat alteration. These losses, related to dams, water diversions, and habitat degradation, have been justified or made "socially acceptable" (Christie et al., 1987) by the precept that the resulting losses in natural production of salmon would be compensated through hatchery production of anadromous and resident species. Consequently, with the extensive development of the Columbia River, most of the 93 artificial production facilities (hatcheries, ponds, and release sites) in the river system are operated for mitigation purposes.

There is concern that these major program developments, like augmentation, have progressed extensively without careful assessment of their effectiveness in meeting their primary objectives. The problem in making such assessments of mitigation hatcheries on the Columbia, however, is that their application has been somewhat equivocal, with some taking on a distinct augmentation role to increase harvest, while others have been applied in supplementation to strengthen the numerical base of wild populations. With the decline of naturally reproducing stocks of salmon and resident fish throughout the Columbia River Basin, and the contemplated further use of hatcheries to overcome these losses, assessment of their effectiveness, limitations, and application must be made. Mitigation must also be viewed in the broader perspective of its present use in the Basin, including measures to stem the risk of extinction. Classification of mitigation hatcheries, therefore, fall within four different categories associated with degrees of salmon extirpation, including maintenance, recovery, preservation, and restoration. An additional category of resident fish hatcheries involves resident fish substitution programs, such as those discussed on pages 34 and 35 of this report and in the Northwest Power Planning Council's Columbia River Basin Fish and Wildlife Program. These hatcheries propagate resident fish for harvest as either on-site or off-site mitigation for lost salmon resources. Here is a more detailed look at the four classifications of mitigation hatcheries:

(1) Maintenance
Maintenance is consistent with the original objective of mitigation as a mechanism to maintain those runs of salmon that would otherwise be reduced or extirpated by river developments resulting from habitat degradation or migratory impasse. For example, with the construction of dams on the river, especially those without fish passage, the risk of partial or total loss of the run was mitigated by replacement with hatchery fish. The objective is maintenance of the pre-existing run of salmon at or near its previous abundance. Maintenance hatcheries may substitute or circumvent the need for natural habitat, characterized by attempts to mitigate development of the hydro-system in the upper Columbia and Snake rivers, or they can supplement the number of naturally spawning salmon affected by development. Maintenance, in its most basic rendition, is to maintain contribution of salmon and steelhead approximate to those levels immediately preceding developments affecting their productivity.

With the present emphasis on sustaining natural runs of salmon, supplementation has taken a much greater role in maintenance conservation. Conceptually, supplementation is meant to reinforce populations without loss of the genetic structure. Supplementation, therefore, is employed to enhance the native stocks of salmon and steelhead by increasing their reproductive base through artificial propagation, using only the native gene pool in the process.

(2) Recovery
Recovery has become an increasing responsibility of mitigation. Compelled by the decline of salmon and steelhead in the Columbia system, major efforts are being expended on rebuilding runs to levels that are considered sustaining under the stress imposed on these populations in the migratory corridor of the mainstem river, and the condition of their endemic habitat. In the context of

mitigation with emphasis on native populations, supplementation is by definition the rebuilding of the native population of anadromous salmonids. Application of artificial propagation in rebuilding populations has been thwarted by the disregard of population genetics and careful breeding programs (Remain and Ståhl, 1980; Allendorf and Utter, 1979; Cross and King, 1983), as well as poor conditioning of fish while in the hatchery environment (Swain and Riddell, 1990). Salmonids have evolved to be compatible with their environments, and each population, therefore, has adapted to the specific characteristics of their respective habitat. Spawning time, emergence timing, juvenile distribution, marine orientation and distribution are not random, but occur in specific patterns of time and space for each population (Brannon, 1984). In the technical sense, therefore, enhancement of specific wild salmonids must observe this compatibility between native stocks and their environments., This perspective is a central theme of mitigation for recovery for all native anadromous and resident fish species in the basin.

(3) Preservation

Preservation is the most extreme measure used to prevent extinction, and characteristically has been implemented when numbers have degenerated to such low levels that risks associated with emigration and marine life phases threaten extinction. Preservation is approached along two different avenues. The first is to increase the numerical base in captivity through maintenance of captive brood stock. Maximizing reproductive potential under captive breeding over two generations can provide the numerical advantage and genetic predisposition necessary for recovery. Such a preservation approach is meant to be short-term, involving only a limited number of generations. However, when a major cause of the decline persists, such as the problems with the migratory corridor on the Snake and Columbia rivers or habitat destruction or overfishing, for example, then such preservation programs may have to continue until conditions favor natural recovery.

The second avenue in preservation is to provide repositories of genetic diversity for future introduction and recovery. Captive brood can be applied in such approaches, but germ plasm repositories are the most feasible, inexpensive, long-term approach. Rather than the "choice of last resort," germ plasm preservation should be proactively included in routine population recovery measures. Healthy populations need to be the target for gamete cryopreservation to assure that repositories contain representative genetic diversity, and from which domestication and inbreeding can be avoided in mitigation hatcheries. Both avenues are meant to preserve genetic diversity or to keep stocks from demographic extinction, and assist in recovery when habitat and migratory passage are restored.

(4) Restoration

Restoration is the re-establishment of a salmon or steelhead run in the place of an extirpated natural population. Understandably, establishing a successfully reproducing run requires sufficient similarity between the introduced fish and the extirpated population to ensure compatibility with controlling environmental phenomena. Matching genetic predispositions to optimize the likelihood of success is key to the restoration strategy. Important among the environmental factors are winter stream temperatures and length of the freshwater migratory pathway. These features determine timing and distribution patterns of native stocks. The optimum strategy is to use these features to select candidates for introduction most like those demonstrated by the native phenotype.

Restoration mitigation is a difficult task, and necessarily of greater duration to realize functional re-establishment of a run because of the generation time required for the adaptive evolution or re-creation of the appropriate form. The critical measure of success is not the number of returning fish to the hatchery. Hatchery environments are secure and forgiving of timing inconsistencies that can easily be amended by feeding programs that exaggerate size at time of release. Restoration criteria must target only the naturally reproducing segment of the run, and hatchery programming should be altered to accommodate the spawning, incubation and migratory timing patterns evolving among those fish. Differentiation between what is observed among hatchery contributions and returns from natural reproduction is a difficult and long-term process, but restoration cannot be accomplished with anything less. To have successful restoration is to have established a self-perpetuating wild run, free of hatchery dependence.

C. Determinants of Performance

In determining the performance of anadromous salmonid augmentation and mitigation hatcheries, it is apparent that the objective identifies the determinant criteria. Moreover, the criteria are only satisfied in terms of the adult return response, as measured in the harvest fishery or the return destination. Augmentation has the objective of increased harvest, or contribution of returning adults to the fishery. Mitigation has the objectives associated with maintenance, recovery, preservation, or restoration measured as contribution of reproductive adults in the target population. In both augmentation and mitigation hatchery programs, genetic and demographic concerns must be addressed. In the former, if genetic compatibility is not a management concern, then isolation of the returning fish from neighboring native stocks must be at least be assured or the level of straying non-consequential. In the latter, genetic identity and diversity are basic to the objectives sought in each of the mitigation functions. In this particular document, the key assessment criteria are listed below, and apply to both augmentation and mitigation programs.

1) Has the hatchery achieved its objective?
2) Has the hatchery incurred costs to natural production?
3) Are there genetic impacts associated with the hatchery production?
4) Is the benefit greater than the cost?

These criteria are relatively simple and straightforward. However, their resolution has an uncertain complexity because of the overriding influence of marine conditions, the effects of mixed stock fisheries, interaction among runs of fish, and the influences of the dynamic interaction within ecological communities on the ultimate return success of a run. Therefore, in as much as it is possible, the performance measures involved in the SRT assessment will be qualified based on relative information on annual variations in marine productivity, temperature trends and associated predator occurrence, distance up the freshwater migratory corridor, and other controlling influences unrelated to the actual hatchery variables involved.

Artificial production of resident fish in the Columbia Basin should not be evaluated using specific Basin anadromous salmonid propagation criteria for several reasons. First, the purposes of anadromous and resident fish propagation programs may be considerably different. For example, a resident fish artificial propagation program may represent mitigation for an extinct salmon run, extirpated by blockage of its spawning habitat by dams. Mitigation using resident fish programs or exotic fishes represents an acceptance that the natural ecosystem is no longer sound and intact.. In this case, the resident fish propagation program might raise non-native fish to provide a warm-water fishing opportunity in the newly created reservoir as mitigation for the extinct salmon run. Thus, evaluation of this resident fish propagation program using an anadromous fish propagation criterion -- such as the degree to which a hatchery stock enhanced a native run -- would be irrelevant because the run is extinct and thus cannot be enhanced. Secondly, life histories and migratory patterns of anadromous salmonids and resident fish in the basin can be completely different. For example, an anadromous salmonid propagation evaluation criterion of percent adult return (i.e. return to the rack) would be an irrelevant measure of the success of a resident fish program with a goal of establishing a put-and-take recreational fishery. Rather, in this resident fish example, perhaps a measure of angler satisfaction, or return to the creel would serve as an appropriate evaluation criteria. It is extremely important, therefore, that serious consideration is given to developing biologically meaningful and accurately measurable evaluation criteria to evaluate the success of resident fish propagation programs throughout the basin with the same rigor as applied to anadromous salmonid programs.

VI. Synthesis of Artificial Production Reviews

Differing points of view on the value and importance of artificial production are not lacking in fisheries science. Hatchery production has been the center of controversy as long as hatcheries have existed on the Pacific Coast. Both the ecological and economic points of view have been debated without resolution because the conclusions usually reflect the preconceived perspective of the reviewers. One side of the issue is dominated by practitioners who base their point of view on the evidence of hatchery returns, but tend to ignore the ecological implications of hatchery fish on endemic stocks or the larger biological community. The other side is dominated by scientists who base their point of view on theory and ecological principles, in spite of societal benefits of a propagated fishery.

Scientists and fish culturists should be concerned about the findings of three independent scientific panels that concluded hatcheries have generally failed to meet their objectives. The findings of those panels are discussed in detail later in this report. As general background, it is informative to examine the reviews on the subject and get a better appreciation of the issues confronting the use of artificial production. It is important to keep in mind, however, that artificial production in these assessments is narrowly defined around the standard production hatchery where tray incubators and concrete raceways provide the artificial incubation and rearing habitat.

A. Early Hatchery Evaluations

It might seem that use of a major program such as hatchery production to augment and mitigate for loss of historical fisheries would be evaluated to determine whether it is achieving its objectives. However, that did not occur in the Columbia River hatchery program. Part of the explanation for this failure comes from the ideological rather than scientific roots of the programs (see Historical Overview of Artificial Production). A major shortcoming of ideology-driven technology is that it is not allowed to fail. Its success is assured by ignoring the signs of failure so by the time the failure is recognized, great damage has usually already occurred (Dyson 1997). This observation clearly describes the Columbia River hatchery program prior to 1960, and to a lesser extent after 1960 as well.

During their first 80 years of hatchery operation, claims of success for the program were based on short-term correlations; evidence that was weak at best, or on no evidence at all. Extravagant and undocumented claims of hatchery effectiveness characterized the early history of the program. 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). This again illustrates the disconnect between science and the hatchery program in its early developmental period.

Perhaps the first serious evaluation of the hatchery program came from Marshall McDonald, who succeeded Spencer Baird. He concluded:

> *". . . 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 three important concerns regarding the use of hatcheries including:

1) a <u>warning</u> regarding an overdependence on hatchery production as a substitute for stewardship;
2) a <u>criticism</u> that hatchery performance was based on the quantity of juveniles released rather than the quality of the adult populations; and
3) a <u>recommendation</u> to evaluate the quality of the receiving waters in watersheds to be stocked with hatchery fish.

To varying degrees all of these concerns are still valid today.

State salmon managers challenge the assertion that scientific evaluations did not exist in the early decades of the hatchery program. The managers point specifically to a marking experiment carried out from 1895-1900 (Dehart 1997). In this experiment, 5,000 chinook salmon eggs were transferred from the Sacramento River and incubated at the Clackamas Hatchery in the Columbia basin. The fry were marked by removing the adipose fin and released, and for the next several years cannery men recorded the appearance of these fish in their facilities. Sex and weight were determined for some of the fish. However, to label this experiment scientifically valid, the following would have to be accepted:

1) That 5,000 chinook salmon eggs transferred from the Sacramento River and released as marked fry in the Clackamas River achieved a minimum 10 percent return as adults just to the canneries.
2) That the majority of adults returned in their third year, a year earlier than average, and they were five pounds heavier than the average for the Columbia River -- one supposed three-year old weighed 57 pounds.
3) That the cannery operators reliably identified the marked salmon and accurately recorded their weights. The fish commissioner apparently did not personally inspect the fish that the cannery operators claimed to be marked.

The validity of the experiment is questionable, and the results were questioned by at least one contemporary biologist (Gilbert 1913).

Other experiments relied on short-term correlations. The common practice before 1910 was to release juvenile salmon shortly after hatching and before they started to feed. In 1911, hatchery managers held a group of chinook salmon and fed them for several months before release. 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..."* (Oregon Fish and Game Commission 1919).

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. Instead, the increase in harvest from 1914 to 1920 was consistent with the pattern of variation in harvest for the previous 20 years (Figure 3) 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 that 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). Rich also initiated several marking experiments at hatcheries in the basin to test the efficiency of hatchery practices and the homing ability of chinook salmon (Rich and Holmes 1929). The 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.

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.

Nationally, by the 1920s biologists were beginning to question the efficacy of fish culture during its first 50 years. As a result, hatchery programs came under increasing criticism (Wood 1953). Rich (1922) completed a statistical study of the Columbia River hatchery program discussed in the previous section, but that study was never published. The lack of rigorous, scientific evaluation of the hatchery programs for Pacific salmon led Cobb (1930) to conclude that artificial propagation could become a threat to 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.

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. Wallis (1964) summarizes the results of many of those studies.

Extended rearing in the hatcheries prompted research into the nutritional requirements of juvenile salmon and the prevention and treatment of diseases. Through the 1950s, the development of new feeds, better prevention and treatment of diseases, and improved hatchery practices such as the optimal size and time of release (Hagger and Noble 1976) started to produce tangible results. By the 1960s smolt-to-adult survival had increased significantly.

In the early 1960s, Congress placed a moratorium on new hatcheries until their effectiveness was evaluated. In response, 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 fin clipped before release so their contribution to the sport and commercial fisheries could be estimated. 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 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 (Wahle et al. 1974). These evaluations were well designed and executed, but they only addressed the first question listed among the four criteria on determents of performance.

B. Recent Review Summaries of Independent Panels

Three independent scientific panels recently reviewed the use of hatcheries in Pacific salmon management, including the Northwest Power Planning Council's Independent Scientific Group (ISG), 1996; the National Research Council (NRC), 1996; and the National Fish Hatchery Review Panel (NFHRP), 1994. The three panels were in general agreement on three important points: (1) In spite of some success, hatcheries generally failed to meet their objectives, (2) hatcheries have contributed to the decline of wild salmon, and (3) the region's salmon managers have failed to conduct adequate monitoring and evaluation to determine if the hatchery objectives were achieved. These reviews conclude that over the last century, massive funding for hatcheries not only failed to achieve objectives, but more importantly the lack of monitoring and evaluation meant that the region passed up the opportunity to learn adaptively about artificial propagation of Pacific salmon (NRC 1996).

The individual reviews are summarized below.

ISG – Return to the River **:**

The ISG concluded that artificial production has been institutionalized in the Columbia River Basin. Today 80 percent of the salmon and steelhead in the basin are hatched and reared in hatcheries. From 1981-1991, expenditures on hatcheries accounted for 40 percent of the budget for salmon restoration. Fifty percent of the increase in salmon production under the NPPC's program is expected to come from artificial production. The historical assumption by management institutions was that artificial production could compensate for habitat destruction, which led to less emphasis on habitat protection and more emphasis on hatchery construction. More recently hatchery programs have been intended to augment declining natural production due in large part to habitat degradation throughout the basin and to maintain a supply of salmon for the fishing industry.

In the context of the entire history of the hatchery program and salmon management in the Columbia River Basin, the ISG concluded that artificial production has failed to replace or mitigate lost natural production of salmonids due to habitat degradation. Since 1960, total releases from hatcheries have increased substantially, but the number of adult salmon entering the river has not increased. Furthermore, hatchery-reared fish have become the dominant portion of the run.

It was determined that artificial production can have adverse effects on wild fish including increased mortality in mixed stock fisheries, genetic interactions that can cause reduced fitness of wild populations and loss of genetic variability, spread of disease, and increased competition with wild fish. The ISG recommended that hatchery populations should be evaluated for evidence of selection, and changes in fitness or genetic diversity associated with residence in the hatchery environment.

The ISG felt that new roles for artificial production need to be defined. Artificial production should likely have a more limited role than at present. The use and role of artificial production needs to be coordinated with the overall Columbia River Basin restoration goal, as well as with subbasin-specific goals. Hatcheries may need to serve as temporary refuges for endangered or critically depressed stocks until factors limiting their abundance can be corrected. Ideally, supplementation should be viewed as a small-scale and temporary strategy to boost natural production. New supplementation projects should follow the guidelines developed by the Regional Assessment of Supplementation Program (RASP). Supplementation should be used in conjunction with, but not in place of, habitat restoration and modification of downstream mortality factors. Supplementation should be approached cautiously in an experimental framework that relies on careful design, rigorous evaluation, and incorporates adaptive management.

The ISG concluded that the role of artificial production in salmon restoration has to be redefined. Hatcheries should have a more limited role in salmon production and restoration and should be integrated into strategies that focus on habitat restoration, reduction of human-induced mortality, and conservation of existing genetic and life history diversity in natural populations. Hatcheries could have a useful role as temporary refuges for dwindling populations while causes of natural mortality are alleviated, or a temporary role in rebuilding depressed populations through supplementation.

A comprehensive evaluation of hatchery programs in the Columbia River Basin has never been conducted. The ISG believes an evaluation should be undertaken and should address the following questions: 1) Do 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 the 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 produced fish add to existing natural production or do they replace it; i.e., does the hatchery operation generate an impact to natural production through mixed stock fisheries, domestication, and genetic introgression?

NRC – Upstream:

The national debate on the use of hatcheries has gone on for most of this century, but with the serious decline of anadromous salmonids across the nation, and hatcheries being proposed as part of the recovery plan, the NRC launched a review of hatchery performance, and made sweeping determinations on how hatcheries should be employed.

The NRC concluded that management of hatcheries has had adverse effects on natural salmon populations. Hatcheries can be useful as part of an integrated, comprehensive approach to restoring sustainable runs of salmon, but by themselves they are not an effective technical solution to the salmon problem. Hatcheries are not a proven technology for achieving sustained increases in adult production. Indeed, their use often has contributed to the damage of wild runs. In many areas, there is reason to question whether hatcheries can sustain long-term yield because they can lead to loss of population and genetic diversity. It is unlikely that hatcheries can make up for declines in abundance caused by fishing, habitat loss, etc., over the long term. Hatcheries might be useful as short-term aids to a population in immediate trouble while long-term, sustainable solutions are being developed. Such a new mission for hatcheries – as a temporary aid in rehabilitating natural populations – could be important in reversing past damage from hatcheries as well as from other causes.

The NRC proposed that the intent of hatchery operations should be changed from that of making up for losses of juvenile fish production and for increasing catches of adults. They should be viewed instead as part of a bioregional plan for protecting or rebuilding salmon populations and should be used only when they will not cause harm to natural populations. Hatcheries should be considered an experimental treatment in an integrated, regional rebuilding program, and they should be evaluated accordingly. Great care should be taken to minimize their known and potential adverse effects on genetic structure of metapopulations and on the ecological capacities of streams and the ocean.

Special care needs to be taken to avoid transplanting hatchery fish to regions in which naturally spawning fish are genetically different. The aim of hatcheries should be to assist recovery and opportunity for genetic expression of wild populations, not to maximize catch in the near term. Only when it is clear that hatchery production does not harm wild fish should the use of hatcheries be considered for augmenting catches. Hatcheries should be audited rigorously. Any hatchery that "mines" brood stock from mixed wild and natural escapements should be a candidate for immediate closure. It is useful for all hatchery fish to be identifiable. Marking hatchery fish externally is particularly important when fishers and managers need to distinguish between hatchery and wild fish.

It was concluded that current hatchery practices do not operate within a coherent strategy based on the genetic structure of salmon populations. A number of hatcheries operate without appropriate genetic guidance from an explicit conservation policy. Consistency and coordination of practices across hatcheries that affect the same or interacting demes and metapopulations is generally lacking. All hatchery programs should adopt a genetic conservation goal of maintaining genetic diversity among and within both hatchery and naturally spawning populations. Hatchery practices that affect straying – genetic interaction between local wild fish and hatchery-produced fish – should be closely examined for consistency with regional efforts.

The NRC recommended that hatcheries should be dismantled, revised, or reprogrammed if they interfere with a comprehensive rehabilitation strategy designed to rebuild natural populations of sustainable anadromous salmon. Hatcheries should be tested for their ability to rehabilitate populations whose natural regenerative potential is constrained severely by both short- and long-term limitations on rehabilitation of freshwater habitats. Hatcheries should be excluded or phased out from regions where the prognosis for freshwater habitat rehabilitation is much higher.

The NRC also recommended that decision-making about uses of hatcheries should occur within the larger context of the region where the watersheds are located and should include a focus on the whole watershed, rather than only on the fish. Coordination should be improved among all hatcheries – release timing, scale of releases, operating practices, and monitoring and evaluation of individual and cumulative hatchery effects, including a coast-wide database and wild fish proportions and numbers. Hatcheries should be part of an experimental treatment within an adaptively managed program in some regions but not in others.

NFHRP:

The Director of the U.S. Fish and Wildlife Service (USFWS) asked the National Fish and Wildlife Foundation to conduct a review and assessment of the USFWS federal fish hatchery program and make recommendations for the future role of the National Fish Hatchery Program in ecosystem management of fisheries resources. The National Fish and Wildlife Foundation (through a contract to the Conservation Fund) convened a panel of 16 fisheries and conservation authorities (NFHRP) to conduct the review.

The Panel felt the National Fish Hatchery Program needed a fundamental redirection of programs, personnel and facilities toward supporting ecosystem management whether it relates to restoring depleted anadromous populations or the recovery of ESA-listed stocks. A well-defined national fisheries program with definite goals, objectives, implementation and evaluation strategies did not exist.

The Panel identified habitat alteration or destruction as the primary causes of decline and noted that resource managers have responded to declines in returning salmon by requesting hatcheries to produce more fish for release, with very little assessment or evaluation. The assumption that more fish would solve the problem of decline had very little evaluation to verify the approach.

Mitigation based solely on hatchery production (involving 38 of the 78 USFWS hatcheries) has failed to halt population declines; therefore, as a better alternative, habitat protection and restoration were believed to be the key to survival of native fish stocks.

The Panel concluded its report by proposing a new role for hatcheries and a new approach to resource management in which hatcheries would serve a support function to managers, producing only those species, stocks, strains, races and numbers that were compatible with ecosystem management plans and specifically identified in those plans. Fisheries management plans should include genetic and ecological assessments of native stocks and strains in any ecosystem subject to new fishery resource projects for restoration or enhancement or for the stocking of newly created waters. This should be followed by careful risk assessment. Restoration of sport fishing in altered or newly created waters should involve the use of propagated fish of the most similar native stock known to inhabit the same type of habitats. Before any hatchery fish are planted, a comprehensive assessment, analysis, and a fisheries management plan should have been completed to address concerns about native stocks. Similarly, in efforts to restore depleted populations or to re-establish new populations, resource managers should avoid stocking any non-native strains or species.

It is apparent that considerable attention has been given to evaluation of anadromous hatchery programs. However, no comprehensive reviews of basinwide resident fish artificial propagation have been undertaken. The situation is largely due to the fact that resident fish hatcheries are generally successful in fulfilling their mission to supply fish for management purposes where migratory success or return performance have not been relevant criteria. However, their absence from hatchery evaluations, especially when resident fish are applied in such a diversity of circumstances, leaves a void when addressing the role of resident hatchery fish in ecosystem management, or even the economic benefit of resident fish hatchery programs. This situation illustrates the need to include resident fish hatcheries in the overall hatchery evaluation and to develop appropriate resident fish hatchery evaluation criteria.

State agency and tribal interests in the basin have participated in other reviews or assessments of artificial production. These have been directed at review, determination of research needs, production alternatives, program coordination and monitoring of artificial production. These assessments are based on the experience of practitioners that not only have great confidence in the potential of artificial production, but have developed standards that are expected to improve the performance of hatcheries. In many cases these documents provide a substantive foundation on which such work can proceed. Below we discuss two of these assessments, the Regional Assessment of Supplementation Project and the Integrated Hatchery Operations Team.

RASP: The Regional Assessment of Supplementation Project

In 1992, the first phase of the Regional Assessment of Supplementation Project (RASP) was completed. It provided an overview of ongoing and planned activities associated with supplementation, and development of a model to estimate potential benefits and risks from supplementation. It also was a plan to coordinate research and monitoring on supplementation in the Basin. It provided guidelines for the use of supplementation aimed at minimizing negative genetic and ecological interactions between wild and hatchery-produced fish.

At the core of the RASP guidelines are five steps that address planning, implementation and evaluation of restoration projects. Although specific instructions for carrying out each of the steps are provided, RASP recommends that within the framework of the five steps, each project should develop specific details and approaches that are appropriate for the local situation. The five basic steps contained in RASP are:

1. Objectives:

Project objectives should be clearly stated and contain measurable end points, i.e., criteria for determining when the project objectives have been achieved. The objective should also include consideration of resource quality as well as quantity. Resource quantity refers to a target number of fish -- the number of salmon harvested in the sport fishery, the number of salmon escaping to spawn in a stream, or the number of smolts migrating out of a stream into the ocean. Resource quality refers to such things as the distribution of the catch by area or fishery, stock selection or run timing. For example, if the objective were to establish a fishery on the returns from artificially propagated fish, it may be desirable to specify in the objective an extended run timing to spread the fishery over a longer time interval. This specification would place conditions on the quality of the eggs used. They would have to come from all segments of the spawning migration and from an appropriate stock from the genetic standpoint that exhibited normal run timing.

2. Analysis of Limiting Factors:

RASP recommended comparing what is known about the character of healthy habitat and salmon populations in a target stream with current conditions in the stream and the populations to be enhanced. This comparison is used to identify potential limiting factors, and to identify the specific problem the project is or should be trying to overcome.

3. Treatment:

This step simply identifies the activity or restoration tool selected to overcome the problem identified in the previous step. The treatment must be consistent with the objective as well as the problem. It is important that the right tool be selected to do the job described in steps one and two. Treatments might include artificial propagation in one or more of its various forms, habitat improvement, public education, or political activities to change statutes or regulations.

4. Risk Analysis:

All salmon restoration projects contain uncertainties that should be identified during the planning phase. Uncertainties are like red warning flags -- they identify the potential risks that must be addressed if the project is to achieve success and avoid unintended problems. Risk analysis helps establish the priorities for monitoring and evaluation.

5. Monitoring and Evaluation:
Part of the reason salmon stocks are in trouble today is that past restoration efforts were approached with so much optimism, especially when hatcheries were involved, that monitoring and evaluation were considered unnecessary. Many programs that produced little or no benefits or were detrimental were continued for several years or decades. The region and the salmon can no longer afford long-term investments in unproductive or counterproductive programs. It is critical to determine whether specific restoration activities are working and, if not, adjust them to improve the chances of success.

IHOT: Integrated Hatchery Operations Team

Hatcheries in the Columbia basin are funded, co-managed, and operated by many different entities for many different purposes. The NPPC's *Strategy for Salmon* (NPPC 1992) recognized the potential for hatcheries to help rebuild salmon production but also the need to improve the co-ordination and operation of these facilities. To address these latter needs, the Council called for the development of the Integrated Hatchery Operations Team (IHOT) to develop hatchery policies for operating within the Basin. The preface of the IHOT report (1994) clearly states the content and intent of this report:

> "The hatchery policies presented in this manual are not intended to establish production priorities. Rather, the intent is to guide hatchery operations once production numbers are established. Hatchery operations discussed in this report include broodstock collection, spawning, incubation of eggs, fish rearing and feeding, fish release, equipment maintenance and operations, and personnel training. Decisions regarding production priorities must be provided by fishery managers through a comprehensive plan that addresses both natural and hatchery fish production."

The IHOT report presents regional policies for hatchery coordination, performance standards, fish health, ecological interactions and genetics. The policies and procedures outlined were a substantive contribution undertaken by the hatchery management agencies to standardize artificial production operations to maximize production performance and minimize impacts on naturally producing stocks in the basin. Because records on hatchery production and operations are maintained by all basin hatcheries under their own state, federal and tribal programs, the implementation and monitoring of these IHOT parameters (see discussion below) at the different hatcheries can be initiated within the present management structure, and will be a valuable contribution to hatchery assessment in the future.

The IHOT report is not a hatchery assessment or review of their technical merit, rather it is an operations manual. The report is notable for establishing regional policy statements and goals that members agreed to pursue in operating the region's hatcheries. The actual procedures and standards to be used to guide operations were identified, and performance measures described how compliance would be monitored and evaluated. The report states that it includes performance standards encompassing all aspects of hatchery facilities and operations that influence the hatchery's "final product." The product is defined as "a fish that has minimal impact on wild stocks and also contributes to harvest opportunities and natural spawning populations." (pg. 19). However, whether the "final product" achieves this goal is not assessed.

The report further recognizes:

- that many of the facilities in the basin originally were developed to meet management objectives that are different from objectives today;
- that hatchery production may be established by several existing authorizations and agreements;
- that production goals for hatcheries have been established through a variety of fish management, political, and administrative processes; and
- that environmental conditions (e.g., ocean conditions and in-river habitats) outside of hatcheries have "overriding influences that control production capacity."

Consequently, IHOT addresses operational guidelines for handling, rearing, and releasing of fish (i.e., issues within the control of facility managers) and notes that these will change over time in response to new management objectives.

The report proceeds to provide detailed recommendations on facility environmental conditions, and general guidelines for hatchery operations, and fish health policies and procedures. Chapters on ecological interactions and genetic policies are much less like a cookbook than the previous chapters (indicative of the state of knowledge in these topics), and IHOT defers to the involvement of experts to assist in these areas. However, the policy statements for these greatly overstate our knowledge and our capabilities to monitor potential impacts. For example, the policy on ecological interactions states "that artificial propagation programs will be designed and implemented to minimize ecological interactions that adversely affect the *productivity of aquatic ecosystems*"(emphasis added). The genetic policy states that these programs will "*maintain adequate genetic variation and fitness in populations* and protect the biological diversity of wild, natural, and cultured anadromous salmonid populations" (emphasis added). IHOT provides some general guidelines expected to be consistent with these policies and to minimize impacts, but the basin lacks evidence that these controls are effective or adequate. It is a notable development, however, that the IHOT members acknowledged an increasing need to incorporate ecological and genetic guidelines in the management and culture of hatchery salmonids.

In reviewing the role of hatcheries in the Columbia Basin, the IHOT report and associated hatchery audits demonstrates a commitment to consistent operational procedures with an aim to improving production efficiency. The report is clearly able to draw on extensive research and experience in fish culture and fish health. However, there is an equally clear need for monitoring and assessment of the ecological and genetic guidelines.

The IHOT report infers an important message: that hatchery staff should be accountable for the quality of cultured fish, but policy makers must clearly communicate objectives and resource managers must advise how to integrate hatchery and natural production. The parties to IHOT agreed to a policy to coordinate the operation of fish hatchery programs to meet basinwide resource management needs. The IHOT report does not consider hatcheries at this programmatic level, nor does it address the adequacy of monitoring and assessment programs to achieve this integration.

In 1995, the draft Programmatic Environmental Impact Statement on Impacts of Artificial Salmon and Steelhead Production Strategies in the Columbia River Basin was prepared for federal hatchery programs by the Columbia Basin Fish and Wildlife Authority. This was a document directed at alternatives for how hatcheries might be used and the effects that alternative strategies would have on overall production, stock diversity, and social/economic conditions associated with the basin.

In 1998, a summary of independent audits of salmonid hatcheries based on IHOT performance measures was compiled for the Northwest Power Planning Council by Sampsel Consulting Services. Following IHOT guidelines, the summary reviewed 20 Oregon Department of Fish and Wildlife hatcheries, seven Idaho Department of Fish and Game hatcheries, 20 Washington State Department of Fish and Wildlife hatcheries, and 12 U.S. Fish and Wildlife Service hatcheries. Considerable detail was provided on facility descriptions and protocols for hatchery operating procedures, with limited production and cost data. Unfortunately and curiously, no overall assessment of these audits has been conducted.

Assessment of hatchery performance has also been conducted by agencies with regard to certain hatchery programs over the years that provided valuable insights on hatchery fish behavior after release to the stream environment. An example of such assessment the annual report of Mitchell Act Hatcheries in 1996, by Ashbrook, Byrne, and Fuss. Stock characteristics in the hatchery, migratory behavior of hatchery fish and evaluation of hatchery practices from selective breeding to hatchery habitat were assessed. The results of this work allowed operations to be altered to change the quality of the product released.

C. Relevance of Past Assessments to the Present Task

The history and evaluations in the preceding sections are valuable to our understanding of the origins of artificial production on the Pacific Coast and the Columbia River. It should be clear that to proceed with artificial production "as usual" would be poorly advised. Even the assumptions basic to the hatchery program that have carried over from the early years need to be modified in light of what is known about specific life history requirements of the different salmonid species that are managed.

The most compelling development point, however, is the change in the general philosophy on resource management that hatchery programs must now address. The human influence on the environment is so pervasive and domineering that resources no longer can demonstrate the resiliency and forgiveness of abuse that was so common in past exploitation. The ecosystem approach to fisheries management is not so much a new paradigm as it is a necessity for the preservation of the fisheries resources. Fish species and their component populations cannot sustain themselves apart from the habitat they evolved with. Ecosystem management is not a revolutionary approach, it is the exercise of common sense to curb the loss of natural productivity and to maintain the health of fisheries resources for public use under the concept of the “normative ecosystem” (Williams et al., in press).

Regarding the three recent independent reviews of hatcheries by the ISG, NRC, and NFHRP, it is noteworthy that apart from primary agreement among reviews that artificial production had generally failed to meet its objective, that it imparted adverse effects on natural populations, and that evaluation of performance was needed, there was further significant consensus on other issues. There was agreement that:

- Supplementation needed to be linked with habitat improvements;
- Genetic considerations needed more emphasis in hatchery programs;
- Stock transfers and introductions of non-native species should be eliminated;
- A new role for artificial production needed to be developed, using more experimental approaches, and using hatcheries as temporary refuges, rather than in long-term production management.

These points of view provided insights that need to be considered in hatchery management. They were comprehensive enough that retracing that ground by the SRT would only be repetitive and add no further resolution to the problems that were identified. It is important to point out that the reviews were not a referendum against hatcheries, but rather a very creditable assessment of hatchery success in reaching their objectives and how programs should change.

We must also recognize that the practitioners’ view was not represented on the three panels, nor was the view of commercial harvesters or that of the angling public, all of whom are pertinent to decision-making about hatchery application. University scientists dominated or were well represented on the review panels. The NRC committee, for example, was made up of 15 participants, of whom 12 were associated with universities. There were no members experienced in hatchery production or aquaculture on the NRC panel. Even the NFHRP panel, charged to assess USFWS hatcheries, did not have equitable representation from hatchery production management. Moreover, the reviews were largely based on ecological theory, biological principles, and some empirical evidence, but little rigorous analysis of actual data was undertaken. This is not a criticism of the process, because it is important that the understanding and implications of hatchery production be grounded in the basic science relevant to the subject. This is necessary regardless of how successful hatchery programs are or can become. To adequately manage the resource on a sustained basis, there can be no compromise with the requirements of biological processes. Whether society decides that other priorities supersede the need to maintain a specific population or a habitat is another issue, but if fisheries management is serious about building naturally sustained production, science must be the basis of any approach.

In the agency and tribal hatchery assessments such as RASP and IHOT, the practitioners' viewpoint and the value of their experience was acknowledged as important to improved effectiveness of basin hatchery programs. The forthcoming science-based SRT recommendations serve as an independent confirmation of IHOT's policies, and show that the SRT is addressing elements pertinent to the interests of artificial production.

The RASP effort provided an important overview and also a model for evaluating supplementation in the second phase of the SRT review. The IHOT program primarily was oriented toward operations, and again is most applicable to the second phase of the phase of the independent assessment. However, because both the RASP and IHOT efforts did not conduct actual hatchery performance evaluations, their primary contribution will be the use of their monitoring protocols. Hatchery compliance with the operating protocol will be one criterion of the SRT assessment procedure.

VII. Impacts Associated with Artificial Production

A. Background

As apparent from the historical overview, Columbia basin hatchery programs have been motivated by several goals, with the most recent perhaps incompatible with those of previous years. Attainment of some goals may even be considered detrimental to others, and not merely because of competition for programmatic resources, but because of conflicting outcomes.

The practical science of hatchery management is more than 100 years old. During that time hatchery technology has progressed to the point that the success rate of the "hatchery phase" in the life cycle of salmon and steelhead is very high. In fact, it is expected that a hatchery program will produce more smolts per spawner than natural production. The magnitude of this relative advantage is on the order of 10-fold, but this advantage is restricted to the hatchery phase. It is quite a different story when considering success in the post-release phase of the life cycle. Hatchery fish experience substantially less survival success in the wild. This is another issue of concern in the present assessment. In particular, what is the relative survival of the hatchery-bred fish, their reproductive ability, their ecological costs, and their genetic impacts on wild fish.

In nearly all cases, when hatchery production rationale is assessed under ecological, genetic and evolutionary theory, the result is unequivocally negative, but of an unknown magnitude. There are some limited experimental data, generally from other taxa and in specific situations, that demonstrates the mechanisms that underlie theory. But relevant empirical information related to salmonids is generally anecdotal, lacking in adequate controls, and insufficient in quantity to be conclusive. Thus, while we are confident that such mechanisms can apply to hatchery-produced salmonids, there is limited empirical evidence on hatchery impacts in the Columbia basin. Although some are tempted to attribute the decline of wild stocks in the basin to interaction with hatchery fish, as well as blaming the poor success of hatchery fish on hatchery practices, such evidence, at best, is indirect and neglectful of the other major environmental impacts in the system. The task of making linkages is a formidable one, but necessary in the fair resolution of hatchery assessment.

B. Risk Management

In addressing the various impacts of artificial production, it is worthwhile to first think about the risks associated with hatchery propagation and conflicting outcomes. To address this problem, risk management is an option that needs to be considered, but this may prove ineffective unless the goals are ranked so that priorities can be established to adopt measures that address the resolution of competing risks.

1. Risks associated with failure and success:

Originally, the goal of anadromous and resident hatchery programs was production for harvest; so the measure of success was the number of returning harvestable adults of hatchery origin. However, in actual practice over the years, and perhaps as a matter of convenience, hatcheries tended to report their performance in terms of numbers of smolts released rather than adults returning, with the assumption that adult return responsiveness was in proportion. The problem with this criterion is that the rate of adult return for the number of smolts released varies enormously from hatchery to hatchery and from year to year, leaving smolt production actually an unreliable indicator of expected harvest. Concentrating on smolt production and not adult return diverts attention from the central issue and results in the risk of not succeeding in reaching the harvest goal, or the risk of increasing failure. One component of the present review, therefore, is to assess the effectiveness of hatcheries in meeting production goals for harvest, attempting to find patterns that might account for the success of some and the failure of others.

Unfortunately, with the passage of time native runs of Columbia basin salmon have declined to such low levels that local extinctions have taken place, and many other populations currently are at risk. In this new era of concern for wild fish, the question naturally arises whether the operation of hatcheries is a contributing factor in the decline. In addition to the pessimism raised about even new state-of-the-art production hatcheries, these concerns also apply to supplementation operations as well as to captive brood stock programs. Ironically, there are some plausible scenarios in which the greater the success of the hatcheries in producing harvestable fish under the original set of goals, the greater the damage they would cause to the affected wild stocks that are the focus of new goals consistent with ecological health. These are the risks of success. Accordingly, the second component of the present review is to assess the magnitudes and likelihood of the various negative effects that hatchery operations might have on wild stocks.

2. Risk Analysis and Risk Management:

Fishery scientists must deal with two major factors in making decisions about how to assess and manage risks of hatcheries: (1) the uncertainty in predicting success or failure and (2) the potential conflicts between multiple attributes of success. One major attribute of success is the increase of fish for harvest; another is the impact on wild stocks.

Depending on how fisheries managers and the public value the probability of success in terms of producing fish for harvest, the annual investment in the hatchery system might be considered worthwhile. There is a probability that this investment will deliver a return in harvestable fish, and a probability that it will not, in which case the odds may justify making the investment. Evidence demonstrating that hatcheries contribute to harvest continues to stimulate interest in the use of hatcheries for harvest augmentation and mitigation.

At the same time, it is probable that anadromous and resident hatchery fish may have negative impacts on wild stocks, which can occur even when hatcheries are managed for supplementation or recovery of wild stocks. Negative effects could overwhelm the positive effects of increased survival in the hatchery during the wild phase of the life cycle. Here, the gamble is on wild stock recovery. Managers must not only assess biological uncertainties but also the trade-offs. In a recovery program, balancing may involve the probability of decreasing the risk of extinction during the hatchery phase versus the probability of increasing mortality during the wild phase of the life cycle. On a broader scale, managers must take into account both the harvest goals and goals to protect wild stocks. However, from a strictly ecological perspective to preserve and recover wild fish, there can be no such compromise.

The critical uncertainties that dominate decision making are amenable to empirical resolution if the right things are measured in a controlled, systematic, and powerful experimental design. Getting the information needed to answer hard questions would mean a major reorganization of how hatchery programs are conducted, including interim changes and re-prioritization of hatchery production goals. Hatchery research, focusing on programmed study plans around appropriate experiments to quantify the effects of hatcheries and hatchery practices, would need to be the initial priority. The long-term priority would be to return to production goals with management and technologies reconditioned to maximize the benefits of artificial production in a manner that complements the ecological health of the system.

C. Management Impacts on Artificial Production Effectiveness

Although controversy about the effectiveness and impact of anadromous fish hatcheries has existed since hatcheries first appeared on the Columbia River, there needs to be a distinction in the object and substance of such controversy between those factors associated with hatchery technology and those associated with hatchery management. Hatchery technology occurs in many different forms, from juvenile rearing on formulated diets in concrete raceways to unfed fry releases from incubation in artificial substrate. The chinook hatchery on Sooes River, Washington; pink salmon hatcheries in Prince William Sound, Alaska; and the Weaver Creek sockeye spawning channel in British Columbia, are examples of successful hatchery programs resulting in significant enlargement of their respective salmon populations. In contrast, and yet with similar technology, sockeye production at the Leavenworth hatchery on Icicle Creek, Washington; coho and chinook production at Grays River hatchery on the lower Columbia River; and the Priest Rapids chinook spawning channel in the mid-Columbia, are examples of hatchery programs that have demonstrated no success, and may have had negative impacts on returns. The point is that hatchery propagation takes many different forms, and each can demonstrate highly variable performance, even when the same technology is used. Most certainly, present technology can be improved, and advancements associated with reduced fish density, natural-type habitat, and measures to reduce conditioning of fish to circumstances associated with culture operations offer promise of producing fish more similar in behavior and performance with that of wild fish.

However, the overriding influence on hatchery performance, and the basis of the long-term controversy, is related more to hatchery management practices of the fisheries agencies than to fish culture practices. Variability in hatchery performance is not so much related to technology as it is to the manner in which that technology has been applied. The consistent oversight in hatchery propagation is that management has not been careful to provide for the biological needs of the young salmon after release to the natural environment. Hatcheries are generally managed from the central office, well displaced from the fish and the streams being stocked, with little appreciation of the fact that these fish must integrate into a very complex environmental system. A disregard for stock structure and the compatibility between genetic attributes of populations and the environment associated with their natal systems has generally characterized hatchery management policy in the past. Moreover, objectives such as producing the maximum number of smolts possible with the flow available, and fish release programming based on space needs among competing species or year classes, contributed significantly to poor quality of fish and negative impacts on fish in the receiving environment. More recently, concern about these issues has altered some hatchery operations in an attempt to address problems with fish quality and wild/hatchery fish interaction. The record, however, is dominated by former management practices, many of which are still represented among Columbia River hatcheries.

The compelling issue in assessing Columbia basin anadromous and resident hatcheries is not so much technology, such as whether raceways should be covered or the value of training on artificial diets, but management policy. That is a very different matter. Management policy dictates the manner in which hatcheries are employed. Management policy affects what genetic stocks are used, the breeding protocol, and where and in what numbers hatchery fish are planted. Management policy is what motivates knowing the status of the endemic stock where hatchery fish are planted, making sure the genetics are complementary, and knowing the carrying capacity of the target streams. Technology can help meet artificial production objectives, such as ensuring compatibility with native stocks, but management must assure that it is applied. The impact of management on the application of artificial production is the overwhelming and decisive factor that determines the effectiveness of hatchery programs. Good management is the key to successful integration of hatcheries into a functioning and dynamic ecosystem.

D. Genetic Impacts of Artificial Production

Better understanding of nutrition, disease, stress, and water quality has given aquaculturists increasing control over the unpredictable nature of raising fish. Only recently, however, have salmon aquaculturists become aware of genetic concerns. Artificial production can lead to unwanted or unanticipated genetic changes in wild and hatchery populations. These changes are a concern because the productivity and resiliency of populations to environmental change depend on the genetic diversity they contain. Unlike disease or nutritional problems, which can be controlled nearly immediately, the impacts of unwanted genetic changes can affect productivity for many years.

In recent years, a variety of authors have cataloged the potential genetic impacts of artificial production (Hindar et al., 1991; Waples, 1991; Busack and Currens, 1995; Campton ,1995; Waples, 1995; Allendorf and Waples, 1996). These impacts can be classified into four major types: (1) extinction, (2) loss of within-population genetic variability, (3) loss of among-population variability, and (4) domestication (Busack and Currens, 1995). The impacts are not necessarily independent. For example, domestication -- or loss of fitness in the wild of a population adapted to a captive environment -- may also be associated with loss of genetic diversity within that population. This has led to increasing awareness that managing genetic impacts will require assessing the trade-offs between the major types of impacts or between using artificial production or not (Hard et al., 1992; Currens and Busack, 1995).

In this subsection, we review the evidence for genetic impacts of artificial production. For each of the four impacts, we ask two basic questions that are important to decision-makers: (1) What is the evidence that the impact occurs? and (2) What is the evidence that the effects can be managed or mitigated?

<u>1. Extinction:</u>

Definition -- Extinction is the complete loss of a population and all its genetic information.

Theory -- Unlike other genetic impacts, extinction is usually associated with three nongenetic causes of large changes in population abundance (Shaffer, 1981). These include demographic or random changes in survival and reproductive success, fluctuations in the environment, and catastrophes.

Captive environments, such as hatcheries, offer greater control over environmental variation and the potential for increased reproductive success. These should counter natural risks of extinction. Consequently, artificial propagation theoretically could reduce the short-term risk of extinction (Hard et al., 1992).

In certain circumstances, however, hatchery programs can increase the demographic and catastrophic risks of extinction. Hatchery programs may mine small, natural populations if they take fish for brood stock but are unable to replace them. For example, hatcheries that take female salmon with 4,000 eggs would be mining the wild stock if they have much less than 0.05-percent egg-to-adult survival. Inbreeding, a genetic phenomenon, can theoretically contribute to irreversible declines in abundance in very small or wild populations (Gilpin 1987). When most or all of a population is taken into captivity, disease, power failures, predation, and dewatering in the hatchery could be catastrophic.

Evidence for Extinction -- We found evidence of conditions that suggest hatcheries could contribute to extinction (Flagg et al., 1995a). To date, however, there are no records of hatcheries directly causing the extinction of stocks. In contrast, artificial propagation has been used to reduce short-term risk of extinction for sockeye salmon (Flagg et al. 1995b), chinook salmon (Bugert et al., 1995; Carmichael and Messmer, 1995; Appleby and Keown, 1995; Shiewe et al., 1997), steelhead (Brown, 1995), white sturgeon (USFWS, 1998), and bull trout (Montana Bull Trout Scientific Group, 1996) and other resident salmonids (Rinne et. al., 1986; Dwyer and Rosenlund, 1988).

Ability to Mitigate -- Evidence suggests that the probability of extinction caused by artificial production can be mitigated if the reproductive success of naturally spawning and hatchery spawning fish is monitored and adequate safeguards are established to prevent catastrophes in hatcheries. We did not conclude whether the lack of hatchery-caused extinction indicates that these safeguards are in place or simply a fortuitous turn of events.

<u>2. Loss of Genetic Diversity Within Populations:</u>

Definition -- Loss of within-population diversity is the reduction in the quantity, variety, and combinations of alleles in a population. It is associated with two genetic phenomena: genetic drift and inbreeding. Both of these are most important in small or declining populations: the smaller the effective population size, the greater the rate of inbreeding and loss of genetic information through genetic drift.

Theory -- The relationship between small population size, loss of genetic diversity, and increased inbreeding is one of the cornerstones of theoretical population genetics. Considerable theory has been developed to explain the generality of this relationship (Wright, 1938; Crow and Kimura; 1970; Goodnight, 1987; 1988; Caballero, 1994) and its importance for short-term and long-term survival (Lande, 1988; Mitton, 1993; Burger and Lynch, 1995; Lande and Shannon, 1996; Lynch, 1996). In tion, general population genetic theories have been refined to fit the specific life histories of Pacific salmon (Waples, 1990a 1990b; Waples and Teel, 1990). They have also been extended to examine the effect of increasing natural population size through artificial production (Ryman and Laikre, 1991; Ryman et al., 1995).

Evidence for Genetic Drift -- Many years of experimental work have demonstrated the relationship between population size and loss of genetic diversity (reviewed by Wright, 1977, Rich et al., 1979, Leberg, 1992) in many varieties of laboratory animals.

Support for the theory from natural populations is less available, because fewer opportunities have existed to measure levels of genetic diversity as population sizes changed. Low levels of genetic diversity have been measured in animals that have undergone known drastic reductions in population size. These include elephant seals (Lehman et al., 1993), koalas (Houlden et al., 1996), prairie chickens (Bouzat et al., 1998a, 1998b), and chinook salmon transplanted to New Zealand (Quinn et al., 1996). Island populations of many different taxonomic groups, which were presumably founded and maintained by few individuals, also have lower levels of genetic variability than mainland counterparts (Frankham, 1997, 1998). Where barrier dams have fragmented the range of steelhead, rainbow trout that survive above barrier dams have levels of genetic diversity that are lower than anadromous populations and that are often comparable to small populations isolated above ancient barriers (Currens, in prep.).

Lower levels of genetic variation in anadromous and resident hatchery stocks compared to their counterparts in the wild (Allendorf and Phelps, 1980; Ryman and Stahl, 1980; Vuorinen, 1984; Waples et al., 1990) suggest that genetic variation has been lost under some kinds of artificial propagation. Conditions necessary for genetic drift exist in many Pacific salmon hatcheries, and evidence is growing that it occurs (Gharrett and Shirley, 1985; Simon et al., 1986; Withler, 1988; Waples and Teel, 1990). Salmon aquaculture affects nearly all of the factors that theoretically influence genetic drift and inbreeding. These include the number and proportion of founders or brood stock taken from the wild, sex ratios, age-structure, and variation in family size as measured on adult progeny. Recent increased monitoring of genetic diversity in many hatcheries will help resolve this question further.

Evidence for Inbreeding and Inbreeding Depression -- Considerable experimental evidence shows that inbreeding can reduce fitness (reviewed in Wright, 1977 Thornhill, 1993, Roff, 1997, Lynch and Walsh, 1998). Tave (1993) compiled evidence for fish, including trout and salmon, thus representing anadromous and resident life history forms, showing that they respond to inbreeding similarly to other organisms.

In natural populations, concerns arise when estimated levels of inbreeding are comparable to inbreeding that led to depression in experimental environments. For example, estimates of increased inbreeding have been associated with reduced fitness in certain Sonoran and Mexican topminnows (Quattro and Vrijenhoek, 1989; Vrijenhoek, 1996), white-footed mice (Jimenez et al., 1994), butterflies (Saccheri et al., 1998), and the evening primrose (Newman and Pilson, 1997) in natural environments. Frankham (1998) estimated levels of inbreeding in 210 island populations of birds, mammals, insects and plants and observed that based on inbreeding in laboratory studies these levels of inbreeding could explain the higher extinction rates on islands.

Evidence for Loss of Fitness from Artificial Propagation -- There is little direct evidence of significant losses of fitness from genetic drift and inbreeding associated with salmon hatcheries, and probably fewer investigations of this phenomenon associated with resident fish hatchery programs. Theory and observation, however, indicate that the ability to predict or measure the effects of fitness using existing tools would be limited. Consequently, such losses, if they occurred, may not have been detectable. First of all, enzyme or DNA markers, which have been used most often to measure loss of genetic variation, are not the best ones to show the effects on fitness (Lynch, 1996). No studies of salmon have attempted to document the loss of multilocus, adaptive genetic variation and its consequences on fitness as have been done for experimental animals (e.g., Bryant et al., 1986; Bryant and Meffert, 1991). Furthermore, logistical difficulties of maintaining a powerful, experimental design may prohibit many such studies (Roff, 1997). Second, changes in fitness in small populations may also reflect the confounding effects of inbreeding depression or accumulation of deleterious mutations. Leberg (1990), for example, observed that mosquito fish populations derived from small numbers of related founders grew at much slower rates than control populations. Similar scrutiny has not been applied to salmon hatcheries. Using evidence from fruit flies, Lynch (1996) argued that under some kinds of artificial propagation, the accumulation of deleterious effects and random genetic drift would interact to reduce fitness even in moderately large populations. This has not been examined in Pacific salmon.

Theory suggests that managing brood fish number, sex ratios, and age structure can control loss of genetic diversity and inbreeding in hatchery populations (Falconer and Mckay, 1996). For integrated programs, where brood stock are taken from the wild and some hatchery fish spawn naturally, theory suggests that controlling loss of genetic diversity may be much more difficult (Ryman and Laikre, 1991; Ryman et al., 1995). Logistically, controlling loss of genetic diversity and inbreeding in captive hatchery programs or integrated programs will be difficult. Monitoring the genetic parameters affecting loss of genetic diversity is also difficult. Few programs have attempted to directly monitor the effective breeding size of the population (Hedrick et al., 1995). Variation in family size, which theory shows as being critical for determining the rate at which genetic diversity is lost, cannot be directly estimated without a pedigree of all the fish in the population. These are currently unavailable and unlikely to become available in the future for most populations.

3. Loss of Genetic Diversity Among Populations

Definition -- Loss of among-population genetic diversity is the reduction in differences in the quantity, variety, and combinations of alleles among populations. In artificial production situations, it is caused by unusually high levels of gene flow that arise when fish or eggs from different populations are transferred between hatcheries, when fish are stocked in non-native waters, or when phenotypic changes in hatchery fish cause them to stray at greater rates or to different streams than normal.

Theory -- The relationship between gene flow and population differentiation is another of the cornerstones of evolutionary biology (reviewed in Slatkin, 1985). Mathematical models show that unless gene flow rates are low, differences among populations will be lost (Haldane, 1930; Wright, 1931 1943; Hanson, 1966; Barton, 1983). Evolutionary theory predicts that loss of genetic diversity among populations can decrease the evolutionary potential of the species. In addition, theory indicates that extensive interbreeding of genetically differentiated populations (outbreeding) may lead to more immediate losses of fitness or outbreeding depression (Dobzhansky, 1948; Shields, 1982; Templeton, 1986; Lynch, 1991). Documentation of the genetic mechanisms remains elusive (Lynch and Walsh, 1998). At least one model of outbreeding depression is available for salmon (Emlen, 1991). An important conclusion of basic theory is that some forms of outbreeding depression will not be predictable. Consequently, the importance of outbreeding depression may need to be solved empirically (Roff, 1997).

Evidence of Loss of Genetic Diversity -- Evidence of loss of genetic diversity among natural populations from gene flow is extensive. It is especially important in western North America, where extensive hatchery programs have spread cultured forms of Pacific salmon and resident trout and other species into watersheds where they have interbred with local populations (reviewed in Behnke, 1992; Leary et al., 1995; Waples, 1995). Loss of genetic diversity from interbreeding with introduced fish has been inferred for populations of the same species (Allendorf et al., 1980; Campton and Johnston, 1985; Gyllensten et al., 1985; Reisenbichler and Phelps, 1989; Currens et al., 1990, 1997a; Forbes and Allendorf, 1991; Reisenbichler et al., 1992; Williams et al., 1996, 1997; Currens, 1997) and different species (Busack and Gall, 1981; Leary et al., 1984; Allendorf and Leary, 1988). Lack of extensive interbreeding in some areas where hatchery fish have been introduced (Wishard et al., 1984; Currens et al., 1990; Waples, 1991; Currens, 1997) indicates that loss of genetic variation cannot be predicted simply from knowledge of hatchery stocking rates or migration.

Evidence for Loss of Fitness -- Evidence of outbreeding depression from populations in natural habitats is available from studies of a variety of organisms, including certain marine crustaceans (Burton, 1987, 1990a, 1990b), plants (reviewed in Waser, 1993), *Daphnia* (Deng and Lynch, 1996), and fish (Leberg, 1993). Most concern about outbreeding depression in Pacific salmon is based on evidence that Pacific salmon are locally adapted (reviewed in Ricker, 1972, Taylor, 1991) and theoretical and experimental results from other animals that demonstrate that interbreeding of different locally adapted populations could result in outbreeding depression. Limited evidence suggests that outbreeding depression can occur in Pacific salmon, but rigorous experiments designed to detect outbreeding depression in Pacific salmon are missing from the scientific literature. Gharrett and Smoker (1991) reported that F2 crosses of pink salmon from odd and even-year runs had lower survivals and greater morphological asymmetry than F1 crosses, which is consistent with outbreeding depression. Currens et al. (1997) found that a hybrid swarm of introduced coastal rainbow trout and native inland rainbow trout had lower levels of resistance to a lethal disease, ceratomyxosis, than native populations. They attributed that to interbreeding with introduced coastal rainbow trout, which lacked genetic resistance to the disease.

Ability to Mitigate -- Two of the three major sources of loss of genetic diversity -- transfer of fish or eggs from different populations between hatcheries and stocking fish in non-native waters -- can be mitigated by management measures such as developing local brood stocks or building fish-sorting barriers where marked, non-native returning adults can be removed from a population. Control of straying that is promoted by hatchery practices is more difficult. Although increased straying is correlated with a variety of hatchery practices (Quinn, 1993, 1997), modifying these practices may not always be easy or desirable. For example, transportation of fish to increase post-release survival may also increase straying (McCabe et al., 1983; Solazzi et al., 1991). Monitoring the potential loss of genetic diversity from straying can be accomplished with existing genetic techniques. Monitoring potential outbreeding depression is much more difficult and probably logistically possible for only a few experimental situations.

4. Domestication

Definition -- Domestication is the adaptation of a captive population to its captive environment. It reflects the changes in quantity, variety, and combination of alleles within a captive population or between a captive population and its natural complement. Selection is the primary genetic mechanism, although it does not occur independently of genetic drift and mutation. We include both intentional (artificial selection) and unintentional selection (natural selection in a new environment) as domestication. Others have limited domestication selection to unintentional selection (Campton, 1995).

Theory -- The theoretical and empirical basis for selection is the foundation of biology (reviewed by Bell, 1997). The main principles were described in the early part of this century (reviewed in Wright, 1968, 1977). The fundamental theory predicts that organisms will respond to selection when they have adequate genetic variation for selection to act on (measured as heritability) and when there is a selection differential. For over 60 years, these principles have provided the theoretical basis for modern plant and animal breeding programs (Lush, 1937; Falconer and Mackay,

1996) and our understanding of domestication. Theory has not yet been refined to answer genetics questions about interbreeding of hatchery salmon and natural populations

Evidence for Domestication -- Even before modern genetics, animal breeders recognized and promoted domestication. Darwin (1898) considered domestication inevitable for captive animals. The development of captive populations for experimental genetics in the early 1900s, however, provided the first documentation of the genetic mechanisms of how organisms adapt to captive environments (reviewed in Wright, 1977). Concern about domestication in Pacific salmonids comes from two sources:

First, considerable evidence shows that many behavioral and physiological traits would respond to selection if selection differentials also existed. Tave (1993) compiled estimated heritabilities of many traits. A variety of authors have argued that strong selection differentials exist in novel, captive environments such as hatcheries (Doyle, 1983; Frankham et al., 1986; Kohane and Parsons, 1988). Together, these would lead to domestication.

Second, evidence of behavioral and physiological changes in hatchery populations compared to wild populations is increasing. Few data are available, however, to examine the fitness effects on a natural population interbreeding with hatchery fish that have undergone different levels of domestication. Early studies of domestication found evidence of behavioral change in captive brook and brown trout populations (Vincent, 1960; Green, 1964; Moyle, 1969; Bachman, 1984). More recently, Petersson et al. (1996) documented the change in morphology and life history of a hatchery strain of Atlantic salmon over 23 years. Likewise, Kallio-Nyberg and Koljonen (1997) found that growth rate and age of maturation in Atlantic salmon changed over several generations in a hatchery.

In steelhead, Reisenbichler and McIntyre (1977) found that progeny of hatchery fish only two generations removed from the wild survived in the wild only 80 survived in the wild only 80 cent as well as wild fish, but in the hatchery environment hatchery fish survived better. Fleming and Gross (1989, 1992, 1993, 1994) and Fleming et al. (1996) documented changed behavior and decreased reproductive success of hatchery Atlantic salmon and coho salmon in artificial spawning channels compared to wild fish. Swain and Riddell (1990) concluded that greater aggressive behavior of juvenile hatchery coho salmon than wild fish reared under the same environment was because of domestication selection. Berejikian (1995), however, found that hatchery steelhead raised in the same controlled environment as their wild counterparts were more likely to be eaten by a native predator. Compared to naturally spawning wild steelhead in the same stream, Chilcote et al. (1986) and Leider et al. (1990) found that naturally spawning hatchery steelhead were about 10-30 percent as successful in producing surviving smolts and adult progeny as wild fish. The hatchery stock used in this study, however, was not native to the stream and was of mixed ancestry. Consequently, the reproductive success of this stock reflects more than domestication effects.

Theory indicates that controlling domestication selection may be very difficult. Busack and Currens (1995) reviewed domestication and concluded that it is one of the costs of using hatcheries. The only way to remove domestication selection is to remove the selection differential. In practical terms this translates to removing the differences between the hatchery and wild environments. This is currently unimaginable. Hatcheries are successful because they offer a better environment in which early survival is greater than in the wild. It may be possible to reduce selection for key traits if we could identify the traits, how they correlate with fitness, and what environmental conditions led to selection. This knowledge is not currently available.

E. Ecological Effects of Artificial Production:
A healthy ecosystem is often equated with conditions that characterized river basins prior to encroachment of modern civilization. Ecosystems are dynamic, and any point in time is only a snapshot in the geophysiographic transition in environmental circumstances over time. In many cases, return to historical conditions is not possible even if human influences could be eliminated. Descriptive reconstructions of historical conditions, however, are invaluable in helping to explain current observations that are the outcome of past processes (Lichatowich et al., 1995). Contemporary ecological theory recognizes the importance of considering not only the biology of organisms, but also the biogeochemical processes that control the distribution and production of biota, and human influences on those processes (Stanford et al, in press). Such historical reconstructions viewed under the guidelines of ecological theory provide the descriptive lens through which present population structure can be discerned.

In *Return to the River* (Williams et al., in press), the ISG developed a conceptual foundation for restoration of Columbia River salmonids in which the "normative ecosystem" was defined as a mix of natural and cultural features that typifies modern society. It was implicit, however, and consistent with ecological theory, that environmental equity in the "normative ecosystem" would have to be sufficient to sustain all life stages of a diverse mixture of healthy wild anadromous salmonids, concurrent with cultural and economic development of water resources. The ISG stated, “Restoration requires detailed understanding of the interactive, biophysical attributes and processes that control the survival of salmonids rather than a simple accounting of numbers of fish at various points and time in the ecosystem." The concept of ecosystem health infers that whatever changes occur through man-made alterations of the river system that define the “normative ecosystem," maximum effort is exerted to maintain existing habitat for the full exploitation of anadromous salmonids. Restoration, therefore, refers to measures that enhance the natural production of native salmonids, even to their fullest diversity possible within the potential of the “normative ecosystem."

The fundamental benefits and risks of artificial production rest in the ability of aquaculturists to isolate fish from all or part of their natural habitat and ecological processes. Since their inception, hatcheries have been operated as agricultural enterprises that strived for biological independence from one or more of the ecological processes that fish face in rivers and streams (Bottom 1997). Hatcheries were first used to circumvent natural ecological processes, such as predation and physical damage to eggs, that reduced the potential productivity. Later hatcheries were used to circumvent entire river reaches whose natural ecology had changed from the construction of dams or other human activities. Production from hatcheries was often treated as production from a super tributary without consideration of biological interactions. Consequently, until recently, the ecological effects of raising and releasing hatchery fish have had little research attention.

It is instructional to review the evidence for ecological interactions between hatchery fish and their post-release environments, and in wild fish communities between hatchery and wild fish. The continuing decline of natural populations and listings under the federal Endangered Species Act have focused attention on ecological factors of decline that have been previously ignored, such as predation, competition, disease, and nutrient flows. In addition, the attempt to increase natural production through hatchery supplementation has also stimulated interest in ecological effects. As previously mentioned, in *Return to the River* the ISG developed a “normative ecosystem” concept for restoration and management of both wild and hatchery salmonids in Columbia River salmonids (Williams et al., in press).

In salmonid ecosystems, ecological interactions are complex and occur at different levels of biological organization from the organism to the population to the community. In this subsection, we focus on five main issues: effects on carrying capacity, competition, predation, disease, and behavior, while recognizing that these occur and interact at different levels of biological organization.

1. Effects on carrying capacity

In this subsection, we review evidence that the number of fish released from hatcheries has exceeded the carrying capacity of the ocean or freshwater environments. Competition, which can occur among individuals as a consequence of stocking at or near the carrying capacity, is discussed in another section.

Definition -- Carrying capacity is the upper limit on the steady-state population size that an environment can support. Carrying capacity is a function of both the populations and their environments.

Theory -- A large body of ecological theory postulates that population growth is limited by the amount of available resources and the relationship between these limits and environmental variation (Krebs 1985). Under steady state models of population growth, as a population approaches carrying capacity, its growth rate is reduced to zero (Lotka 1925, Volterra 1926). This view of population regulation assumes that there is a deterministic relationship between the abundance of a species and the abundance or condition of the available resources. Abundance of populations is density dependent because with each additional individual fewer resources are available. Although the notion of a carrying capacity is conceptually useful, other theorists have suggested that population growth may be largely controlled by unpredictable changes in environments and resources (Andrewartha and Birch 1954, Strong 1986).

A. Ocean carrying capacity impacts

Evidence -- The effects of hatchery releases on ocean carrying capacity have been studied for coho salmon in the Oregon Production Index (OPI). The Oregon Department of Fish and Wildlife first addressed the question of ocean carrying capacity relative to hatchery releases by analyzing whether ocean mortality of coho salmon was the result of density-dependent or density-independent factors (ODFW 1982). Density-dependent mortality would indicate that the capacity had been exceeded; density-independent mortality would indicate otherwise.

The results of this analysis were inconclusive, but it did stimulate other studies (Lichatowich 1993). Seven additional papers addressed the question of whether carrying capacity in the ocean for coho salmon in the OPI was limiting production. The question, however, remains unresolved. The studies generally analyzed the same data, but they used different analytical methods and arrived at different answers to the question. The strength of the conclusions varied. In general, three studies concluded that the evidence for density dependence was weak or nonexistent (Clark and McCarl 1983; Nickelson and Lichatowich 1983; Nickelson 1986). Three other studies concluded there was evidence for density dependence or at least enough evidence for caution (McCarl and Rettig 1983; McGie 1983; Emlen et al. 1990). One study pointed out statistical weaknesses in Nickelson (1986) and cautioned managers regarding its conclusion. Studies of salmon in other ocean production areas, including Japanese and Russian chum (Ishida 1993), Bristol Bay sockeye (Rogers 1980), and British Columbia and Bristol Bay stocks of sockeye (Peterman 1984) suggest salmon densities are approaching capacity. As with the studies of Oregon coho salmon, however, the evidence is not conclusive.

Since work on OPI coho salmon, researchers have identified patterns of changing ocean productivity (Ware and Thomson 1991; Beamish and Bouillion 1993; Francis and Hare 1994). This pattern of shifting ocean productivity suggests that the carrying capacity of the ocean, especially in specific areas, is also changing. If that is the case, then continuing to release large numbers of hatchery fish during periods of low productivity (reduced capacity) might not be the appropriate strategy (Beamish and Bouillion 1993).

B. Freshwater carrying capacity impacts

Evidence -- Research documenting an effect of hatchery fish on the freshwater carrying capacity of salmonid streams is largely lacking. Many fishery managers assumed that effects on carrying capacity depend on the time and age of release. Large releases of fry or presmolts might have significant ecological effects on carrying capacity because they could use limited food and cover. In the lower Columbia River, for example, stocking hatchery fry in excess of carrying capacity was identified as one of the factors leading to the collapse of wild coho populations (Flagg et al. 1995). The mean density of emergent, wild coho fry in lower Columbia River tributaries was estimated at three fry per lineal stream meter (fry/m). By comparison, hatchery fry were stocked in similar sized streams in Oregon at a rate of 16 fry/m and in Washington at 22 fry/m. This suggests that overstocking streams could have displaced wild fry in the Lower Columbia River tributaries (Flagg et al. 1995). The use of presmolts to supplement natural production in underseeded streams (supplementation) also raises the possibility that large release of hatchery fish could exceed the capacity of the stream habitats unless stocking levels are carefully researched and controlled. Determination of stocking densities for supplementation projects is complicated by the need to consider the existing abundance of wild fish relative to carrying capacity (Stewart and Bjornn 1990).

In contrast, in the 1950s and 1960s many hatcheries adopted the practice of holding juveniles until they smolted. Smolted hatchery fish were expected to use the river only as a conduit to the sea, which theoretically minimized carrying capacity problems. Even where smolts are released, however, and expected to migrate immediately to sea, release of too many fish could exceed capacity of the stream. In his examination of Washington's hatchery program for steelhead trout, Royal (1972) speculated on what he called a "density barrier" that could have resulted from a combination of competition with other species, environmental factors and poor physiological condition of the hatchery fish. Once the barrier was reached, increasing the number of hatchery fish produced little or no additional benefit.

An indirect effect of the hatchery-harvest management strategy on freshwater carrying capacity is the reduction in nutrient recycling to the system from carcasses. With reduced escapement needs to sustain hatchery programs, harvest has been given a greater share of the return, generally associated with the management concept of Maximum Sustained Yield (MSY). This has not only impacted escapements of wild fish in mixed stock fisheries, but it has affected nutrient recruitment from carcasses that enriched otherwise nutrient-impoverished systems. Carcasses undoubtedly were an important source of nutrients to freshwater systems that habitually export nutrients downstream (Bilby, et. al. 1998) The dependence on artificial production has exaggerated the deficit in nutrient transfer caused by management around MSY from that historically experienced, because of even further limited escapements required to sustain hatchery production. Consequently, reduction of carcass contribution to nutrient loads in salmon spawning streams is an indirect, but significant ecological impact of hatchery management.

Because managers have complete control over the number of fish released, preventing hatchery releases from exceeding carrying capacity of freshwater or marine environments is easy if the carrying capacity can be known. Determining the carrying capacities of dynamic, natural systems, however, is very difficult. Attempts to adjust hatchery releases to carrying capacities must take into account changes in climatic patterns, habitat, and communities that can cause variation in capacity. The Council has had a measure in its fish and wildlife program to determine the carrying capacity of the Columbia River relative to the basin's hatchery production levels (Measure 7.1G NPPC 1994). While work on this measure was undertaken, the measure has not been fully implemented, and carrying capacity has not been determined.

2. Competition

Definition -- Competition is the negative interaction between two or more individuals that occurs when a necessary resource is in short supply or when demand is greater for higher-quality resources.

Theory -- Competition is one of the fundamental ecological interactions between individuals. Many ecologists believe that it is the major factor determining the structure and organization of ecosystems (Cody and Diamond 1975). The theoretical treatment of competition in the ecological literature is extensive and well-developed (see Krebs 1985, or a similar text for an introduction).

Evidence -- Competition is very difficult to demonstrate (Fausch 1988). Conditions for competition between hatchery and wild fish may occur, however, if the hatchery fish are released before they are ready to migrate to sea and they residualize or remain in freshwater for an extended period of time. Conditions may be aggravated by differences in size or behavior between the wild and hatchery fish. Salmonids often form dominance hierarchies in streams, where dominant individuals defend the best holding or feeding areas against subordinate fishes (Fausch 1988).

In experiments using enclosures placed in the Teanaway River, Washington, residual hatchery steelhead reduced the growth of wild rainbow trout but did not influence the growth of juvenile chinook salmon (McMichael et al. 1997). When the stocking of catchable-sized hatchery rainbow trout was terminated in a section of the Madison River, Montana, the biomass and numbers of the fall population of two-year-old brown trout increased by 160 percent and the number of wild rainbow trout increased by 868 percent. The impact of stocking may have been caused by the disruption of the existing social structure in the wild population (Vincent 1987).

In an attempt to supplement underseeded coastal streams in Oregon, ODFW stocked some streams with coho salmon of hatchery origin. They left some streams unstocked as controls. The total summer density of juveniles increased by 41 percent in the stocked streams. However, 44 percent of the wild juveniles in those streams were replaced by the hatchery presmolts. Nickelson et al. (1986) attributed the displacement of wild fish to the larger size of the hatchery presmolts at the time of stocking.

An important goal of management programs that make use of hatcheries should be to integrate the natural and artificial production systems (Lichatowich and McIntyre 1987). Hatchery fish should not replace existing wild fish. Such integration requires knowledge of the natural production system. Once obtained, it has to be explicitly used to plan and implement the hatchery program. Follow-up monitoring is critical. This approach is not impossible, but it would be difficult to implement, and at the present time it is the exception and not the rule in hatchery management.

3. Predation:

Definition -- Predation is an ecological interaction where one individual becomes a food source for another. Predation is one of the fundamental ecological interactions observed between many species. The theoretical treatment of predation in the ecological literature is extensive and well-developed (see Krebs 1985, or a similar text for an introduction).

Evidence -- Under different scenarios, hatchery salmonids can be predators or prey. Predation of one salmonid on another can be an important source of mortality. Hatchery fish released at a large size are potential predators on smaller wild salmonids (Stewart and Bjornn 1990). Parker (1971) observed that predation by coho salmon accounted for a large fraction of early sea mortality in chum and pink salmon. If a predator such as coho salmon is enhanced through artificial propagation it could increase predation and cause the decline of other important salmonid. Johnson (1972) observed that chum salmon returns to hatchery racks was inversely related to hatchery coho production in Puget Sound. Although his study did not show a cause-and-effect relationship, Johnson (1972) concluded that managers should be concerned about the effects of the hatchery coho salmon program on the total production of chum. Stewart and Bjornn (1990) cited a paper by Sholes and Hallock (1979) that reported heavy predation on wild steelhead and chinook fry by larger yearling chinook salmon stocked into the Feather River, California.

Rearing in artificial environments can make hatchery fish more vulnerable to predation than wild salmonids (Olla et al. 1998). Hatchery fish released at a small size are vulnerable to predation by other larger salmonids or other non-salmonid fishes. In addition, hatchery fish may lack appropriate behaviors, perhaps from lack of prior exposure to predation, and may undergo secondary stresses such as disease (Stewart and Bjornn 1990), which may make them more vulnerable to predation. White et al. (1995) speculated that this may explain the poor post-stocking survival of hatchery fish. For example, feeding salmonids at or near the surface of the hatchery pond gives them a surface orientation that can make them more vulnerable to avian predation. Disease infection may also enhance the vulnerability of salmonids to predation (Mesa et al. 1998).

Habitat modification that removes cover, modifies temperature and obstructs passage may increase the vulnerability of hatchery fish to predation (Spence et al. 1996). Habitat alteration may also enhance the predator population and lead to greater mortality. For example, the creation of Rice Island in the lower Columbia River from the disposal of dredge spoils created habitat for Caspian terns. The tern colony on Rice Island has grown dramatically and is now the largest in North America. The terns may be consuming between 5 and 20 million juvenile salmonids annually (ODFW 1998). The recovery of PIT tags on Rice Island suggests that hatchery fish may be more vulnerable than wild fish to predation by terns (Roby et al. 1997). The conversion of the free-flowing Columbia River to a series of reservoirs is another habitat change that has enhanced predation on salmonids by the northern pike minnow (Rieman et al. 1991). Shively et al. (1996) observed a rapid shift in the diet of the northern pike minnow from largely non-fish items to a diet composed mostly of juvenile salmonids following a release from Dworshak National Fish Hatchery. The shift was observed away from the release site in an area where the river changed from free-flowing to impounded.

Any manipulation of hatchery practices to reduce predation will require better understanding of the ecology of the receiving waters than we have today. The size, time and place of release of hatchery fish might be altered to reduce predation on the wild salmonids or reduce predation on the artificially propagated salmonids. The importance of predator avoidance behavior has led to suggestions that salmonids undergo specific training to enhance their recognition of predators, improve their ability to escape and increase their post-release survival (Maynard et al. 1995). Predator training in the hatchery is showing some promise in reducing predation on artificially propagated salmonids, but it is far from being universally implemented. Managers should also consider the indirect effects of habitat change in enhancing predation, especially if a hatchery is operating in the watershed.

4. Disease:

Definition -- Disease is the negative ecological interactions between a host, a pathogen, and the environment that results in an impairment that interferes with or modifies the performance of normal functions of the host.

Theory -- The theoretical aspects of disease dissemination have been extensively studied in humans and some animal populations (see Anderson and May 1979, 1982; May and Anderson 1979; Grenfell and Dobson 1995). Theoretical treatment of disease processes in fish, however, have been only recently been explored for Atlantic herring, Clupea harengus (Patterson 1996); European flounder, Platichthys flesus (Lorenzenen et al. 1991); guppies, Poecilia reticulata (Scott and Anderson 1984), and domesticated trout (Bebak 1996). Reno (1998) has reviewed many of the critical factors involved in constructing models of disease dynamics for fish populations, but he did not specifically address transmission between hatchery and wild fishes.

Evidence -- Diseases and their effects on fish populations result from multifactorial and interacting causes making cause-and-effect relationships difficult to determine (McVicar 1997). Detecting and verifying the transmission of disease between hatchery and wild fish is very difficult. Nevertheless, several examples illustrate the potential. Two examples come from Norway. In 1985, infected Atlantic salmon smolts transferred from Scotland introduced frunculosis into Norway. The disease has spread to 20 Norwegian rivers (McVicar 1995). In 1975, the parasite Gyrodactylus salaris from an infested hatchery in Sweden was introduced into the Lakselva River, Norway. Atlantic salmon parr, (Salmo salar), which were susceptible to the parasite, were heavily infected and within two years the abundance of parr had collapsed (Sattaur 1989).

A recent example from the United States is the spread of salmonid whirling disease (Mysobolus cerebralis). The disease was first found in the United States in Pennsylvania in 1956. Since then it has gradually spread to a least 21 states. The likely cause of the spread of the parasite is the shipment of infected fish to new areas (Bergersen and Anderson 1997, Modin 1998).

The introduction of new diseases to areas with no previous history of that pathogen is one way hatcheries can influence the mortality of wild fish. Another way is through the direct transmission of an endemic disease in a watershed from infected hatchery fish to the wild fish. This would be difficult to identify, and we could find no documented examples.

Management agencies recognize the importance of this problem and have taken steps through the IHOT process to prevent the transfer of infected fish (IHOT 1994). The adequacy of the IHOT policies are discussed elsewhere in this report.

5. Behavior:

Hatcheries may alter the behavior of cultured fish as a consequence of domestication (genetic change) and as a consequence of acclimation to the hatchery environment without genetic change. Evidence for behavioral changes due to domestication is presented in the section on genetic impacts of artificial production.

Differences in spawning behavior have been observed in comparative studies of wild coho salmon and coho salmon that were captured in a stream as emergent fry and reared in a hatchery environment until mature. Salmon reared in the hatchery from fry to maturity exhibited all the normal reproductive behaviors and they successfully spawned. However, when mixed with wild fish their reproductive success was reduced because of a diminished competitive ability (Berejikian et al. 1997). Wild males dominated access to spawning females in 86 percent of the spawning events observed. Hatchery-reared females constructed fewer nests and started the typical spawning behavior later than wild females. Since these differences in behavior were observed after less than one generation in the hatchery, the observed effects were probably due to environmental effects on the phenotype (Berejikian et al. 1997). Fleming and Gross (1992 and 1993 cited in Jonsson 1997) observed similar results in their experiments with hatchery and wild coho salmon. Fifth-generation hatchery Atlantic salmon also showed less aggressive spawning behavior than wild fish (Jonsson 1997).

The obvious way to reduce the effect of the hatchery on spawning behavior is to minimize the differences in the hatchery and natural environments. However, which aspects of the hatchery environment need to be changed and how much change is needed is not known.

F. Populations and Production Trends Over Time

As discussed elsewhere in this document, hatcheries were started in response to the decline of returns from overfishing. Whether or not early hatchery production made any contribution, hatcheries were still viewed as the solution to mitigate for the anticipated loss in harvest resulting from river development. With successive construction of the dams beginning in the 1930s (Figure 16), habitat was not only totally eliminated upstream from the barriers of Chief Joseph/Grand Coulee, Dworshak and Hells Canyon dams, but spawning and rearing habitat were also altered and lost below these dams as the result of the nearly continuous line of reservoirs that now represent the portions of the mainstem rivers "accessible" to anadromous salmonids.

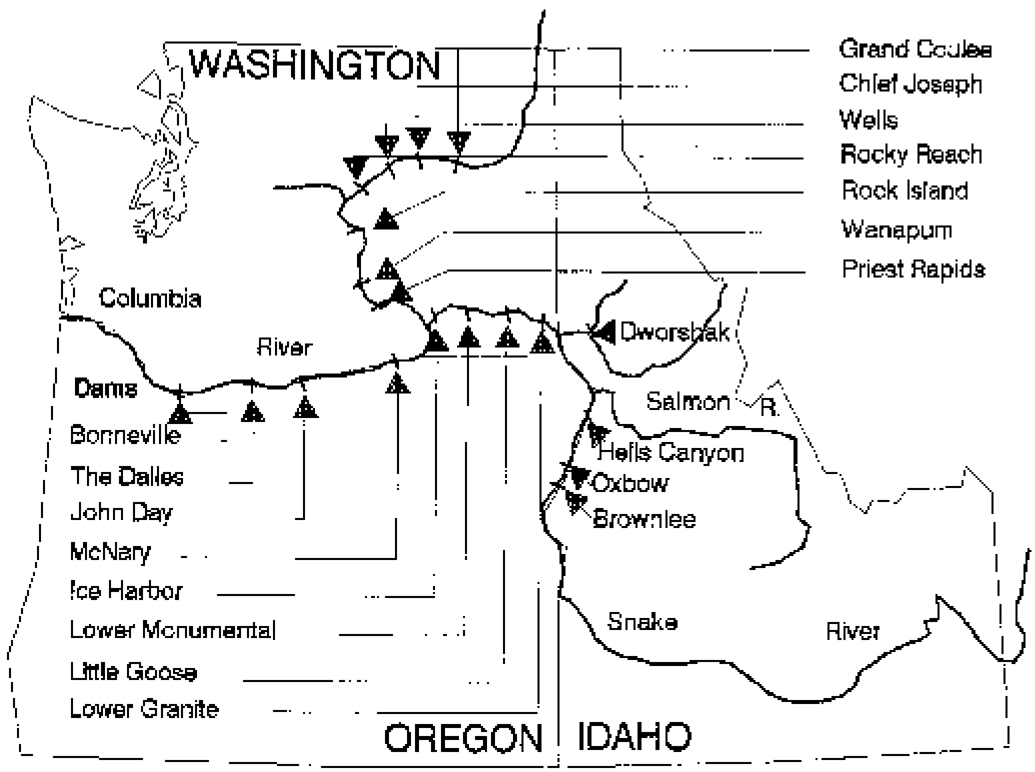


Figure 16. Dams on the Columbia and Snake rivers.

In response to the anticipated reduction in natural production from loss of habitat, hatchery construction went forward with major facilities designed to replace the anticipated loss in harvest. Hatchery production responded with a consistent and growing contribution over the years (Figure 17). Since 1950, the contribution from hatcheries increased from 38 million juveniles to 150 million by 1979, and has remained around 120 million since that time.

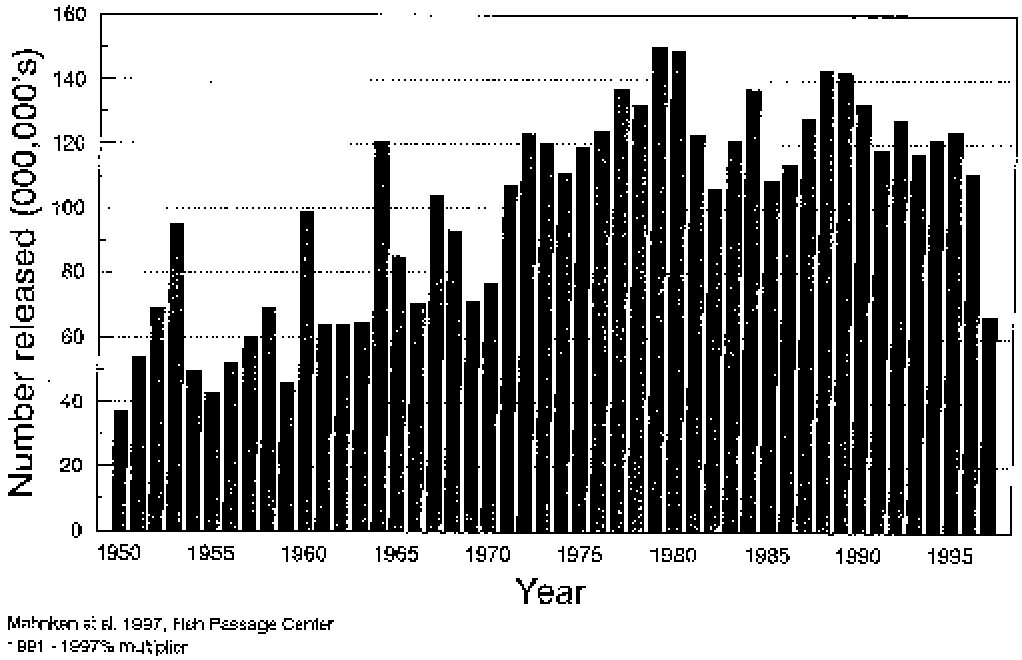


Figure 17. Hatchery contribution to Columbia basin juvenile salmonid emigration. (Mahnken et al, 1997: Fish Passage Center)

In the meantime, the results of increased hatchery production were equivocal in terms of influencing the returning numbers of adult salmon and steelhead. Salmonid populations entering the Columbia River have shown a fluctuating range in escapement from 420,000 to 650,000 fish from counts over Bonneville Dam (Figure 18). The peak return in recent years was in 1987, following a weak but general trend with increased hatchery production. However, while hatchery production surged to an increase of over 100 percent from 1969 to 1980, returning adults are shown to have simultaneously decreased about 30 percent over the same time period.

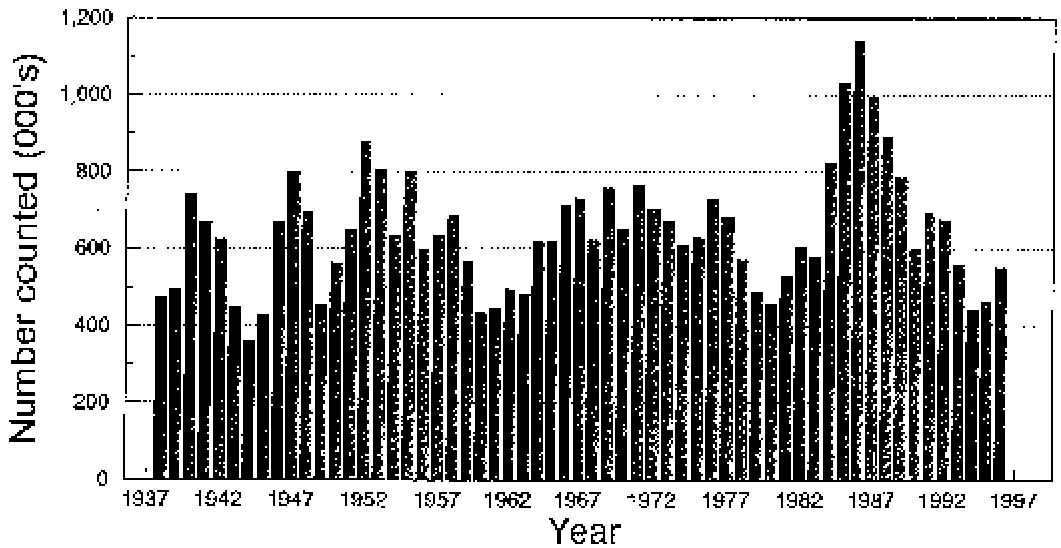


Figure 18. The trend in returning anadromous salmonid populations counted over Bonneville Dam on the Columbia River. (SteamNet 1996)

The contrasting trends between artificial production and return over these years makes it uncertain what portion of the return can be attributed to hatchery production, and underscores the need to complete the intensive examination of hatchery performance. The loss of habitat from dam construction reduced the natural production potential, which hatcheries were intended to replace. Total return of all anadromous salmonids, including commercial landings, has shown a relatively level trend to the 1990s, and a significant decline after that (Figure 19), while hatchery production remained the same. It should be noted, however, that salmon abundance already was depressed by the 1930s -- and hatcheries had been operating for 60 years.

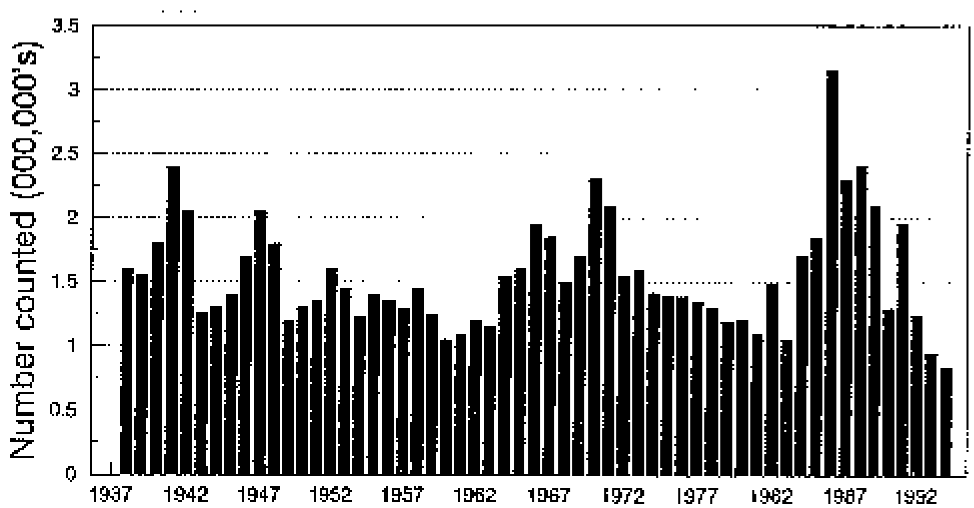


Figure 19. The trend in total production of returning anadromous salmonid populations to the Columbia River plus commercial landings. (SteamNet 1996)

In retrospect, the number of returning adult salmon was relatively level from 1938 through 1990. The precipitous loss of returning chinook entering the Snake River (Figure 20) accounts for a major share of the decline that has occurred in total return to the Columbia.

A serious impact on the recent returns to the Columbia River Basin, therefore, appears to have been from the construction of the four lower Snake River dams. Mitigation has not maintained adult returns to the Snake River at the level that existed prior to the construction of Ice Harbor Dam. However, there has been a high mortality of emigrating juveniles while making their migratory journeys through the altered mainstem corridor. The cumulative effects of the successive developments along the corridor impacted the hatchery fish as well as the wild fish, creating a more complex problem as developments expanded than what was probably anticipated. If there is any hope of reaching the goal of replacement, survival through the lower Snake River will have to improve before the mitigation objective can be reached.

The ascendancy of ecosystem management in the Columbia has further complicated the problem of addressing mitigation responsibilities on the river. Mitigation with hatchery production was not founded on the paradigm of ecosystem management, but simply one of replacing fish for fish in the harvest. Under the new concept, ecosystem health is a priority of equal importance as mitigation for lost harvest, which means the original process of satisfying mitigation will have to change. Hatchery success is no longer measured solely by the number of adults returning. Part of the problem in the decline of wild fish production is attributed to the impact of the very hatchery fish meant to mitigate for harvest reduction through overdrafts of wild fish in mixed stock fisheries. Hatchery fish can sustain higher harvest rates because of lower escapement needs (less than 10 percent) to supply production requirements. Wild fish, requiring higher escapements (30 percent to 60 percent) for adequate production, suffer the same rate of exploitation in mixed stock fisheries targeting hatchery fish. The cumulative effect, uncontrolled, is to drive natural populations down to eventual extinction. Prior to ecosystem management, and the pivotal importance of maintaining natural production in the basin, hatchery fish were viewed as a replacement option for wild fish, and could be used as the rationale for over-fishing wild fish in mixed stock fisheries. It was with the same justification that hatchery fish could be viewed as mitigation for extirpating the runs above Grande Coulee and Hells Canyon dams.

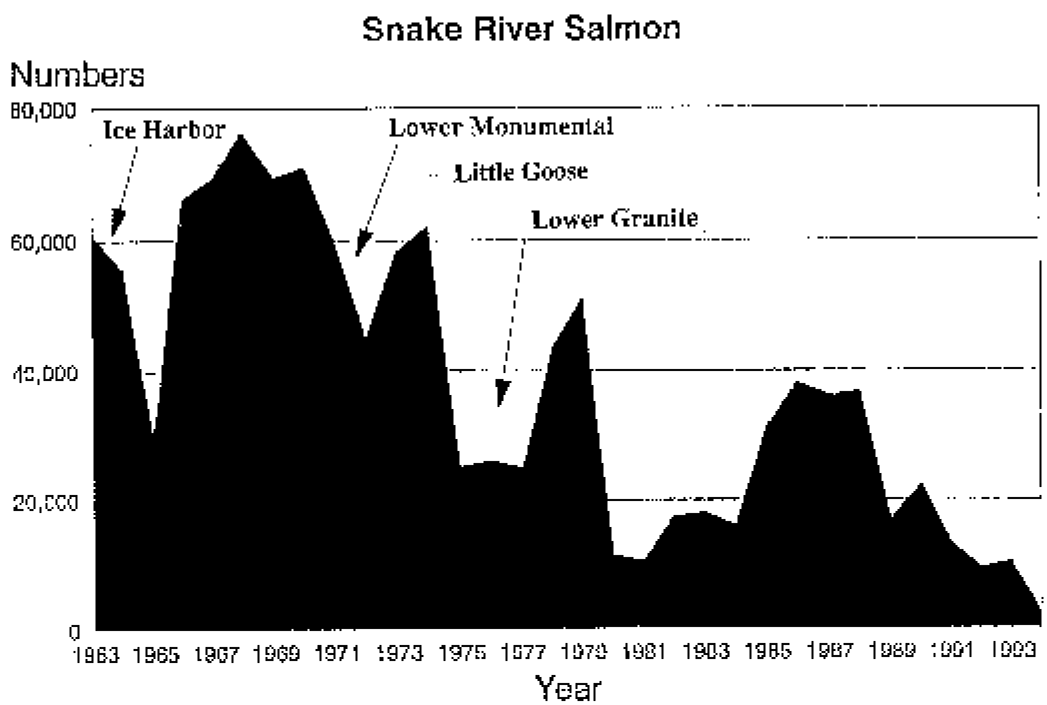


Figure 20. Chinook salmon returns to the Snake River related to the years when lower Snake dams were built.

The ecological impact of hatchery fish is an issue of equal importance to mixed stock fisheries with regard to the long-term health of natural populations. Although there is little evidence to support some of the more theoretical concerns about hatchery fish altering the fitness of wild populations (Campton, 1998), the premise is not disputed, only the direction and degree to which such effects are manifest.

VIII. Conclusions and Guidelines

To briefly review, hatchery production of Columbia River Basin salmon started before the turn of the century for the purpose of augmenting harvest of chinook salmon for the commercial fishery. Science initially had only a small role in the process -- primarily the development of fish husbandry. Over time, the role of science evolved to include formal attention to nutrition, genetics and pathology. That attention, however, centered primarily on the technology of fish husbandry, with little attention to concerns about hatchery fish interaction with wild fish, or with the natural (post-release) environment.

With the new paradigm of ecosystem function, science articulated a refreshed interest in community balance, food chain dynamics, population structure, and integration of hatchery fish as a functional component of the ecosystem. Standard hatchery procedures no longer were accepted as a means of addressing augmentation or mitigation, and much greater emphasis is placed on developing a new conceptual foundation under which artificial propagation should proceed. The architects of this new conceptual foundation cannot be oblivious to the fact that the Columbia and Snake rivers are systems substantially altered from the historical conditions in which anadromous salmonids evolved.

This report is not a commentary establishing the role of artificial production in future Columbia River fisheries management, or recommending the degree to which hatchery production should contribute in the basin. That is the responsibility of the state and tribal fisheries managers. This report concerns the state of the science that relates to artificial production, and in that regard presents guidelines that we believe should be the foundation of recommendations on the appropriate use of artificial production in the future. Following the points of general agreement with the three recent scientific reviews that broadly addressed hatchery operations (ISG, NRC, NFHRP), the guidelines are presented in two parts. First are guidelines based on our scientific assessment of artificial production that includes hatchery practices, ecological, and genetic considerations. Second are guidelines that address what we consider the necessary research to resolve problems and questions about the technology and management of hatchery programs.

To provide further background for our guidelines, it is appropriate to discuss generally what is known and not known about hatchery effectiveness and hatchery effects. The level of knowledge varies considerably for different aspects of the effects of hatchery management and policy. The three major divisions of this material are knowledge about:

1. Effects of hatchery practices on the egg to smolt phase of the life cycle of hatchery fish;
2. Effects of hatchery practices on the post-release phase of the life cycle of the hatchery product, and,
3. Effects of the hatchery product on the wild stocks with which they interact ecologically and genetically.

The amount and certainty of the knowledge in each of these three divisions is so different that we cannot reasonably attain the same level of conclusiveness about them from our review of the science.

In order to attune our conclusions with the differing levels of certainty, we offer our advice in the form of recommendations, guidelines and hypotheses. And we urge our audience to be sensitive to the distinction and the implications of these guidelines, recommendations and hypotheses. Basically, the current state of the science can support firm "recommendations" about practices to enhance the performance of the hatchery product in the egg-to-smolt phase of the life cycle. The science is less comprehensive and conclusive about the post-release performance of the hatchery product. For this aspect we can offer tentative "guidelines" for practices that we are reasonably sure will generally improve post-release performance somewhat, but we can't be sure how much, and we can't offer assurances that these guidelines in themselves will be sufficient for meeting objectives of the program. The science is even less conclusive about the effects of the hatchery fish on wild stocks. The science can identify specific genetic and ecological mechanisms that must be operating in the interaction between hatchery and hatchery fish, but the degree of quantification and empirical verification in this important aspect of our knowledge is so low, that for the most part we can only state important, plausible "hypotheses." The monitoring, analysis, and experimentation necessary to arrive at conclusions about these hypotheses should be elevated in priority for the future. In the meanwhile, we advise managers and policy makers to adopt a precautionary approach in the decisions where these hypotheses have a bearing.

The picture is further complicated by the very real possibility of working at cross-purposes by simultaneously attempting to manage for improved egg-to-smolt performance within the hatchery, improved smolt-to-adult returns of hatchery fish, enhancement of wild stocks through supplementation, preservation of wild stocks with captive breeding, and minimization of potential negative effects of augmentation hatchery operations on wild stocks. Practices that are good for one objective could be bad for another. A successful overall hatchery policy will have to be cognizant of these possible effects "between compartments." We will discuss these trade-offs in the third, synthesis phase, of our review.

A. Points of General Agreement with Recent Reviews

The three recent independent reviews of fish and wildlife recovery efforts in the Columbia River Basin addressed hatcheries among other issues -- one report addressed hatcheries specifically. These reviews collectively represent a concerted effort to assess hatchery production from the scientific perspective. There was consensus among the three panels, which underscores the importance of their contributions in revising the scientific foundation for hatchery policy. The ten general conclusions made by the three panels are listed below.

1. Hatcheries generally have failed to meet their objectives.
2. Hatcheries have imparted adverse effects on natural populations.
3. Managers have failed to evaluate hatchery programs.
4. Rationale justifying hatchery production was based on untested assumptions.
5. Supplementation should be linked with habitat improvements.
6. Genetic considerations have to be included in hatchery programs.
7. More research and experimental approaches are required.
8. Stock transfers and introductions of non-native species should be discontinued.
9. Artificial production should have a new role in fisheries management.
10. Hatcheries should be used as temporary refuges, rather than for long-term production.

Given the present degree of uncertainty about hatchery success, the SRT agrees that unified hatchery management policies should include plausible hypotheses that test some of the uncertainties inherent in these conclusions.

In particular, with respect to the hypothesis that the future role of hatcheries in fisheries management will evolve considerably, we note that the priorities of fisheries management have changed significantly in recent years, so the needs that hatcheries should serve are also changing. The ongoing reality of increasing numbers of Endangered Species Act listings of anadromous and resident fish puts a much higher emphasis on wild stocks and naturally spawning stocks. This increases the concern over the potential for artificial production to cause genetic and ecological harm to such stocks. But it also raises the possibility that hatcheries may serve some positive role in this era of new priorities.

B. General Considerations of the State of the Science and the Technology

The goals sought by hatchery programs have changed over the years. However, like earlier hatchery programs, the most recent efforts of augmentation, supplementation and captive brood stock production may have succeeded in their numerical production objectives with regard to juvenile releases. The issue is that the effect of that production on increased return has generally not been demonstrated, and that effects on naturally spawning stocks have not been adequately investigated. Agencies have evaluated some hatchery procedures, such as the effect of size and time of release on return success, but there has been a general lack of effort at the programmatic level. Only recently has natural production in the Columbia basin been given priority. Previously, the approach of concentrating artificial production of Pacific salmon downstream from lower Columbia dams was considered a viable mitigation option for providing the necessary production from the system, based on general trends in hatchery production returns. However, if evaluations demonstrating the consistent production benefits of hatcheries have been undertaken, they have not been published in the peer-reviewed literature. Such publications are required to provide fair analysis of these hatchery programs. Issues of genetics, stock transfers and limiting effort to avoid overfishing wild stocks mixed with hatchery fish are symptomatic of the previous philosophy downplaying the role of natural production and the human alteration of the natural Columbia River Basin ecosystem. Given the present emphasis on the ecosystem approach, these issues are now important and should be given priority in the development of the new conceptual foundation for artificial production.

In the past, weak native runs have been replaced with other fish in the development of hatchery programs, such as the original plan regarding Sooes River fall chinook salmon. Such action is inconsistent with present values. Diversity is now believed to be one of the keys to the long-term success of salmonid populations, and adaptive traits should never be willfully abandoned. In situations where a stock has been extirpated, managers need to have the option of introducing non-native fish to establish the nucleus on which restoration can take place. Even in this situation, however, the donor stock chosen should not be simply based on egg availability. Careful analysis is required to assure environmental relationships between donor and target streams are as compatible as possible for the stock selected. Frequently, appropriate donor stocks will come from ecologically similar and geographically adjacent streams or watersheds.

Stock transfers and introductions can place serious risk on native fish stocks and should be discontinued from hatchery programs except when the purpose is to restore an extirpated run or population. Introductions also might be justified when genetic diversity is so low as to threaten the persistence of a population.

The primary role of hatcheries in the basin is mitigation for the loss of harvest as a result of reduction of habitat from economic development of the Columbia and Snake rivers. Given the present encroachment of habitat modification and degradation into the riparian and adjacent lands of these river systems, it is unlikely that natural production in a recovered ecosystem would satisfy commercial, tribal, and sports harvest interests. The options, therefore, are (1) to be content with lower production from managed natural populations and use hatcheries in a more temporary role for rehabilitation, or (2) to manage for greater harvest potential from a combination of natural production and hatcheries mitigating for habitat no longer accessible. Mitigation hatcheries are a long-term commitment involving significant cost. Although Columbia Basin hatcheries have not satisfied their objective of sustaining production thus far, nonetheless they now account for the majority of production in the basin.

Changing the manner in which hatcheries address their role is the hope that hatcheries can succeed. Based on past hatchery performance in the basin, such expectation is bereft of proof. But abrogation of the concept based only on the past is also imprudent when hatchery management has made such serious mistakes and the fish still persist. As Reisenbichler (1998) reasoned after observing fish in the hatchery environment, ".. substantial adaptation to hatchery conditions [occurs]... and holds promise that modifying hatchery conditions can reduce deleterious genetic differences between hatchery and wild fish." The hope is that with care given to appropriate changes in the hatchery environment, the response of hatchery fish can be compatible and complementary to the natural population structure of the native species. The normative ecosystem is an equitable mix of natural and cultural features with environmental equity to sustain all life stages of a diverse mixture of healthy wild anadromous salmonids, concurrent with cultural and economic development of water resources. Hatcheries can have a mitigation role in the normative ecosystem. These may become rehabilitation programs that secure the endurance of native runs. They may also become perpetual programs to supply commercial or angling opportunities. The challenge is to redevelop the concept of a hatchery to assure enhanced production to meet both ecological and economic objectives.

C. Relation to an Ecological Framework

It is imperative that priority be given to the development of a set of scientific guidelines that serve as a conceptual foundation for the Columbia basin hatchery program. These also must be consistent with the eight elements of the basin-wide ecological framework (NPPC Document 98-6) that is to guide management of the Columbia River as an ecological system. The eight ecologically based elements are listed below.

- The abundance and productivity of fish and wildlife reflect the conditions they experience in their ecosystem over the course of their life cycle.
- Natural ecosystems are dynamic, evolutionary, and resilient.
- Ecosystems are structured hierarchically.
- Ecosystems are defined relative to specific communities of plant and animal species.
- Biological diversity accommodates environmental variation.
- Ecosystem conditions develop primarily through natural processes.
- Ecological management is adaptive and experimental.
- Human actions can be key factors structuring ecosystems.

The set of scientific principles that relate to artificial production, and emphasized by the latter two elements listed, are meant to minimize unintentional human influences on ecosystem structure. These principles can be divided along technological and managerial lines, differentiating between how hatchery fish are produced and how hatchery fish are used.

D. Guidelines on Hatchery Practices, Ecological Integration and Genetics.

Management of all hatcheries should be consistent with the life history of the cultured stock and the environmental conditions of the watershed, especially the annual temperature regime of the relevant section of native habitat represented in the stock of fish propagated. Life history strategies demonstrate the optimum course of action in the complexity of selective pressures exerted on them (Brannon, in press). Proper management, therefore, must include only measures that are consistent with those life histories, or severe impacts on the native populations should be expected. Management policy on such conventions as stock introductions (listed above), size and time of release, magnitude of release, genetic agenda, and recovery strategies are of major importance to the success of hatchery programs. Details on these issues are in the following guidelines, but it needs to be understood that in many cases where scientific principles are advocated, applied evidence is not available to demonstrate the precept. In these cases, it may be more appropriate to view the guidelines as hypotheses that need to address problems they exemplify -- as safeguards against unforeseen events that could destroy the viability of the runs managers are attempting to conserve. Some theories are troublesome to practitioners because their experiences do not support the axiom. Concerns about inbreeding are an example. Many populations of salmonids are small and inbred by the nature of the environment describing their habitat. In fact, where certain traits are critical to their survival, such as an innate complex orientation pattern to reach a destination, specificity rather than diversity defines fitness. This appears contrary to the theory, but in the broader range of the species, diversity is still the key to species stability. Measures taken to maintain the diversity present, or to prevent potentially negative effects of induced inbreeding, even within naturally inbred lines, are precautions that safeguard against artificially imposing a deleterious artifact of hatchery production on a population.

Present technology is bringing into application measures that improve the quality of fry at the time of emergence and at readiness of juveniles to enter the migratory phase. Providing required nutritional needs in a form available in artificial diets were some of the first advancements in hatchery technology (Hublou, 1963), and nutritional develops have continued (Forster and Hardy, 1995).

Substrate and darkness during incubation to maximize energy efficiency for growth are now employed routinely. These conditions were found to more accurately simulate natural incubation environments and produce larger fry at emergence than open tray or basket incubators (Brannon, 1965). Other technologies are also being employed, and their appearance in the list only reaffirms the importance placed on them.

Guideline 1. Technology should be developed and used to more closely resemble natural incubation and rearing conditions in salmonid hatchery propagation.

In developing hatchery technology, hatchery programs should work toward the goal of providing environments that resemble natural conditions during artificial propagation. These may include:

- Incubation in substrate and darkness;
- Incubation at lower densities;
- Rearing at lower densities;
- Rearing with shade cover available;
- Exposure to in-pond, natural-like habitat;
- Rearing in variable, higher velocity habitat;
- Non-demand food distribution during rearing;
- Exposure to predator training;
- Minimize fish-human interaction;
- Acclimation ponds at release sites;
- Volitional emigration from release sites.

Rationale: Lower rearing densities, minimum exposure to humans, and shade cover over raceways enhances fish quality and maintains a behavior more similar to that of wild fish. Also, volitional migration when the fish are ready to begin their journey to sea is a technology practiced at some hatcheries, promoting natural transit behavior and less impact on the carrying capacity of the receiving stream or other water body. These are positive advancements in hatchery production operations that are encouraged to continue. Other practices need research on potential indirect effects. For example, although accelerated rearing can easily overcome any size deficiency of the fry experienced at the time of emergence, what isn't known are the potential impacts accelerated rearing will have on the normal biological development from embryo to fingerling, or the impact that large hatchery fish have on their wild counterparts.

Guideline 2. Hatchery facilities need to be designed and engineered to represent natural incubation and rearing habitat, simulating incubation and rearing experiences complementary with expectations of wild fish in natural habitat.

Rationale: Hatchery technology in the Columbia basin has relied primarily on standard tray incubation and concrete raceway technology based on engineering designs that emphasize efficiency and convenience for fish culture operations. Qualities associated with natural habitat have not been incorporated in such designs, and fish reared in standard concrete raceways learn behavior conducive to those situations, and out of harmony with what they will experience when released into natural conditions. Comparatively poor survival success of hatchery fish is attributed in part to such experiences atypical of natural conditions. Technology needs to design facilities that utilize engineered earthen stream channels that represent natural habitat with cover, glides and pools, woody debris and flow patterns mimicking natural habitat. Incubation and rearing could take place in the same channel facility, at densities appropriate to encourage natural feed (supplemented with formulated diets) and provide learning opportunities under simulated natural conditions. Training would include exposure to size variability among other species that share the habitat, and limited exposure to predation.

Guideline 3. New hatchery technology for improving fish quality and performance needs to have a plan for implementation and review at all hatchery sites, where appropriate, to assure its application.

Rationale: Assuring that technological advances in hatchery propagation are part of hatchery operational plans is critical to the implementation of changes meant to improve the quality and performance of hatchery fish in the natural environment. Often such implementation occurs only among those hatcheries where a willingness to make changes exists, given that information on new technology is even transmitted. It is important that technological advancements are first verified and the mechanism through which such technology enhances quality or performance is well understood. Then there needs to be a process for implementing the technology, with accountability for its installation and review to make it as routine as feed delivery, assuring its application and evaluation.

Guideline 4. To mimic natural populations, anadromous hatchery production strategy should target natural population parameters in size and timing among emigrating anadromous juveniles to synchronize with environmental selective forces shaping natural population structure.

Rationale: Hatchery programs have tended to concentrate on large-size fish at the time of release, as well as varying the timing of release, to facilitate higher return success. Although such rationale is understandable from the standpoint of improving hatchery fish survival, such practices introduce atypical migrants that create an alteration in the natural continuity of events around which population strategies have evolved. With the exception of fall chinook that normally show variation in migratory distribution patterns, such practices with other anadromous salmonids are believed to have negative effects on fitness of wild fish, and may perturb population structure to the disadvantage of natural populations. Based on interpretations of population structure and life history patterns (Brannon, in press), avoiding atypical size and time at migration among hatchery fish is desirable, even with the immediate disadvantage it may have on hatchery return success. The point is that hatcheries should focus on mimicking the natural environmental selective forces within the target watershed so hatchery-produced emigrating juveniles exhibit the same size distributions as juveniles from the natural population.

Guideline 5. To mimic natural populations, resident hatchery production strategy should target population parameters in size and release timing of hatchery-produced resident juveniles to correspond with adequate food availability and favorable prey to maximize their post-stocking growth and survival.

Rationale: Post-stocking mortality of a wide array of resident fish species could be reduced by implementing release strategies that match released fry or fingerlings with periods of adequate production and availability of planktonic and invertebrate food items. Attention to vulnerability of stocked resident fish fry or fingerlings as prey, and abundance and behaviors of potential predators in receiving waters can also significantly improve initial post-stocking survival.

Guideline 6. Supplementation hatchery policy should utilize ambient natal stream habitat temperatures to reinforce genetic compatibility with local environments and provide the linkage between stock and habitat that is responsible for population structure of stocks from which hatchery fish are generated.

Rationale: Temperature is a crucial factor affecting adult salmonid return timing and spawning (Brannon, 1987), and is an important factor affecting the length of time juveniles spend in stream residence before migrating to sea. This fundamental influence has formed the framework around the evolution of salmonid population structure. Temperature demonstrates its pivotal effect on the evolution of life history forms through temporal influences on egg incubation and juvenile growth as the basis for differentiation of adult timing and juvenile residence behavior, respectively.

It is argued, therefore, that temperature is one of the most critical environmental factors affecting life history forms peculiar to their respective stream system. Temperature is the environmental parameter motivating the evolution of stock predispositions selectively reinforced over time to represent genetically distinct units. Temperature regimes during early life history are typically altered from the natural pattern by hatchery use of ground water for incubation. Hatchery management policy should adhere to using the ambient temperature regime of their natal environments to maintain the compatibility of hatchery fish with the natural system and the effectiveness of hatchery contribution to the natural spawning population. In some cases, wild fish spawn on spring-fed reaches of streams, and the appropriate incubation temperatures in those situations would be incubation substrate temperatures. However, when it comes to the rearing phase where the growth rate is determined by temperature (Brett et al, 1969), it is the daily ambient mean temperature that is important to follow.

Guideline 7. Salmonid hatchery incubation and rearing experiences should use the natal stream water source whenever possible to enhance homestream recognition.

Rationale: Another factor associated with the natal habitat and homing accuracy is the homestream odor profile that provides the fingerprint ultimately identified with the homestream spawning and incubation site. Hatchery programs not only use ground water for incubation, but hatcheries are usually away from the natal environment to which local stocks have adapted. The assumption is that by planting the fish in the proper location, hatchery fish will home to that stream on return. While this is true, imprinting is sequential (Brannon and Quinn 1990; Quinn et al. 1990), and the incubation environment is the first odor cue on which alevins imprint and the ultimate identity sought by returning fish (Brannon 1982). Strays are common in some hatchery populations and lack of having imprinted during the incubation phase is suggested as being responsible for higher stray rates. To assure the continuity between hatchery fish genetics and local stream habitat, the water sources closely linked with the natal environment are most desirable. This guideline is most difficult to incorporate with present hatcheries because the capital structure and water system have been established without those priorities. New facilities, however, should be located on sites with access to appropriate water sources.

Guideline 8. Hatchery release strategies need to follow standards that accommodate reasonable numerical limits determined by the carrying capacity of the

receiving stream to accommodate residence needs of non-migrating members of the release population.

Rationale: Standards should include impact considerations on the wild fish residing in the system, and should be based on life history requirements of the cultured stock. Hatchery releases of cultured fish into receiving streams occur under the assumption that the river is used primarily as a migratory conduit to the estuary. This is true for only those fish (smolts) at emigration readiness. Fish not ready to migrate will take up transitional residence in the stream, causing the potential negative interactions with wild fish present. Care should be taken to limit release numbers consistent with the estimated rearing capacity of the system to minimize impacts on wild fish. Moreover, the practice of releasing fish to make space for other broods should be discontinued. Release of hatchery fish must fit a schedule consistent with life history requirements of the natural population from which the brood lot was derived.

Guideline 9. Hatchery programs should dedicate significant effort in developing small facilitates designed for specific stream sites where supplementation and enhancement objectives are sought, using local stocks and ambient water in the facilities designed around engineered habitat to simulate the natural stream, whenever possible.

Rationale: Hatcheries are most often developed around the concept of a central facility from which fish are outplanted to many other streams or acclimation ponds, not always using native stocks in each instance. The rationale is usually related to the major capital expenditures for hatcheries under the old hatchery concept. It is much more desirable to locate smaller, stream-specific operations to maintain stock identity with the particular stream targeted. Nothing larger than a station capacity of 100,000 eggs or 25,000 fingerlings would be required on smaller tributary systems. This would require no more than a rearing channel to accommodate such small inventories, but small numbers in natural-like habitat is the ideal for supplementation of native salmonids. Even fry releases can be a feasible option to consider under these circumstances associated with the natural habitat, when conditions for supplementation can call for such limited, and perhaps temporary, artificial application. Again, this hypothesis is impossible with present facilities located where they are and with capital commitments in water and concrete. However, with new artificial production facilities, part-time stations of this nature would address both the biological and ecological requirements that future operations must satisfy.

Guideline 10. Genetic and breeding protocols consistent with local stock structure need to be developed and faithfully adhered to as a mechanism to minimize potential negative hatchery effects on wild populations and to maximize the positive benefits that hatcheries can contribute to the recovery and maintenance of salmonids in the Columbia ecosystem.

Rationale: As an integral component in a complex ecological system, salmonid stocks have evolved with their environments. Spawning time, emergence timing, juvenile distribution, marine orientation and distribution are not random, but rather occur in specific patterns of time and space for each population (Brannon 1984), and include behavior that evolved under historical abundance constraints in natural populations. The appropriate seed stock is key to producing viable, healthy fish for the respective system. Given the ecosystem concept for management protocol in the Columbia Basin, population genetics and the natural environment salmonid stocks have evolved under have to become blueprints in hatchery programming. Differences between the genetics of wild stocks and hatchery fish (Ryman and Sthl, 1980; Allendorf and Utter, 1979) are considered by the SRT as a major source of poor hatchery fish performance in the wild. Development and adherence to strict genetic guidelines and breeding protocols consistent with local population structure is essential for effective hatchery contribution to wild production and maintenance of local genetic diversity.

Guideline 11. Hatchery propagation should use large breeding populations to minimize inbreeding effects and maintain what genetic diversity is present within the population.

Rationale: One of the potential negative effects of artificial production is that relatively small breeding populations are involved in hatchery programs. Even when 100,000 fingerlings are scheduled for supplementation, that number represents a little over 25 females for brood stock, and a relatively limited representation of the gene pool. In the Idaho captive rearing project where juveniles are intercepted and reared to maturity as a means to avoid demographic risks of cohort extinction, only enough parr are captured to provide 20 spawners for each population, which is even a smaller representation of the gene pool. The risks in using small breeding populations are loss of diversity and magnifying the effect of deleterious genes. Hatchery survival can increase the contribution of the artificially propagated fish out of proportion with number, with the result that over time the hatchery population will become increasingly more represented among the natural spawners. The issue is not just inbreeding, because many healthy natural populations are very site-specific in unique environments and represent inbred lines. The risk is that hatchery production can accelerate the potential harmful effects of inbreeding by involving only a small portion of the returning adults in the artificial breeding population. To avoid these negative effects of hatchery production, a large number of spawners should be included in the breeding protocol. When the run is relatively small, this may require live spawning, and removing only a portion of the eggs from each female and subsequently releasing the fish to continue spawning naturally.

Guideline 12. Hatchery supplementation programs should avoid using strays in breeding operations with returning fish.

Rationale: In situations where strays constitute a substantial proportion of hatchery return populations, care should be taken to avoid inter-stock hybridization because of the loss of adaptive traits in the resulting progeny. Reisenbichler (1998) demonstrated examples of reduced fitness from hybridization. Stock hybridization breaks down genetic homeostasis and disrupts co-adaptive gene complexes, which lowers the fitness of the local stock. A policy needs to be developed to minimize the contribution of strays to the local hatchery stock. In the situation where a hatchery is supplementing a native population, inter-stock hybridization should be avoided to prevent loss of adaptive fitness.

Guideline 13. Restoration of extirpated populations should follow genetic guidelines to maximize the potential for re-establishing self-sustaining populations. Once initiated, subsequent effort must concentrate on allowing selection to work by discontinuing introductions.

Rationale: When undertaking restoration projects where populations have been extirpated, restoration strategies need to be given careful consideration and reference to genetic guidelines. Where neighboring populations represent appropriate characteristics, stock transfer may be the best strategy. When suitable stocks are not available, or when information is insufficient with which to match a donor stock, then inter-stock hybridization may be an alternative. Inter-stock hybridization breaks down co-adapted gene complexes and releases genetic variability on which selection can work. Restoration can use different genetic-based approaches, depending on the situation, but the characteristics of the donor stock(s) are critical. The key is to follow through with the strategy selected and allow sufficient time for the founders to be selectively established by avoiding continued introductions in the target stream.

Guideline 14. Germ plasm repositories should be developed to preserve genetic diversity for application in future recovery and restoration projects in the basin, and to maintain a gene bank to reinforce diversity among small inbred natural populations.

Rationale: One of the most important considerations in the Columbia Basin fisheries management plan is to preserve the existing genetic diversity. Diversity is inherent to the stability of the species. The various systems, with their component population networks, are the sanctuaries of variability. Recovery and enhancement of natural production in the basin will not be a rapid process, and in the meantime further loss of diversity may occur, with some populations becoming extinct. It is critical, therefore, to launch an immediate program to preserve germ plasm by collecting and cryopreserving milt from all naturally spawning populations that can be reached. The technology is available and currently is being employed with some ESA-listed salmonid stocks. This effort needs to be expanded and given greater priority. Germ plasm should be collected from each population on more than one broodyear to develop as complete a repository as possible. The availability of germ plasm for future use in maintenance of diversity or restoration of extirpated runs will be invaluable in the long-term ecological framework of the managed river.

Guideline 15. The physical and genetic status of all natural populations of anadromous and resident fishes need to be understood and routinely reviewed as the basis of management planning for artificial production.

Rationale: Knowing the status of the endemic stock where hatchery fish are involved is imperative under the ecological framework of fisheries management. Information should include life history, population structure and the habitat utilized. This knowledge must include, in addition to the traditional numerical status of the run, details on its population structure, distribution patterns, size and timing of migration, and the level of genetic specificity and diversity within the population. The habitat status associated with the population must also be known, including the area available, the condition of the habitat, new areas that can be developed, and the carrying capacity. This information is essential to the management of all native anadromous and resident species in the Basin, which will require ecological expertise at the programmatic and hatchery levels.

E. Guidelines on Research and Monitoring

Good management is the key to successful integration of hatcheries into a functioning and dynamic ecosystem. Research to improve artificial production, the extent of its application, and its limitations is basic to the effective management of hatcheries in the basin. In this regard, monitoring is also a critical element in the management process. Knowing what is successful and what must change is impossible without appropriate monitoring programs.

Guideline 16. An in-hatchery fish monitoring program needs to be developed on performance of juveniles under culture, including genetic assessment to ascertain if breeding protocol is maintaining wild stock genotypic characteristics.

Rationale: The NPPC needs to design a scientifically valid monitoring program for the basin hatcheries. Special attention should be paid to the collection of valid data that applies to routine assessment of juvenile performance in the hatchery incubation and rearing phase, up to the point of release. Genetic monitoring of the stock inventory would include descriptive evaluation at first feeding and at release time to assess if hatchery propagation is altering genotypes from that of the wild population.

Guideline 17. A hatchery fish monitoring program needs to be developed on performance from release to return, including information on survival success, interception distribution, behavior, and genotypic changes experienced from selection between release and return.

Rationale: The NPPC needs to design a scientifically valid monitoring program for hatchery fish performance after release from the culture facilities. In addition to return success, attention should be paid to relative interception distribution (tag analysis) of hatchery fish to compare performance parameters with native fish. Special attention should also be given to descriptive genetic assessment at time of return to determine if genotypes surviving are representative of genotypes released, and compatible with the native stock. With the advent of the PIT tag system, opportunities to gather more specific information exists. Significant insights can be gained on straying, migratory route and timing that are key to honing hatchery programs.

Guideline 18. A study is required to determine cost of monitoring hatchery performance and sources of funding.

Rationale: A study should be undertaken to consider how much monitoring programs will cost and what reallocation of effort in the production programs would be required to fund adequate monitoring efforts where additional funds cannot be secured.

Guideline 19. Regular performance audits of artificial production objectives should be undertaken, and where they are not successful, research should be initiated to resolve the problem.

Rationale: Routine audits of hatchery production objectives should be established (for example, every five years) to determine if they are achieving their objectives. In those cases where programs or hatcheries are not showing any production benefit, they should be re-prioritized to research-only until the problems can be resolved. In some cases, research may disclose that the objectives are not attainable. In those situations, emphasis can then be redirected, programs changed, or discontinued.

Guideline 20. The NPPC should appoint an independent peer review panel to develop a basinwide artificial production program plan to meet the ecological framework goals for hatchery management of anadromous and resident species.

Rationale: With the development of the broad ecological framework in the basin placing emphasis on hatchery management in the arena of conservation fisheries and ecosystem function, it will be necessary for practitioners and fisheries scientists to work together in developing the appropriate hatchery program plans to achieve the ecosystem goal. Problems that have prevented hatcheries from achieving their goals, or insights on what may be impossible to achieve in the ecosystem approach at the hatchery level, cannot be ascertained without major contribution from hatchery managers experienced in the system. Also, the inherent conflict between the concept of ecosystem management and the concept of management for harvest mitigation has to be resolved within the ecosystem framework. Those resolutions, and the development of the hatchery program plan addressing specific actions needed to achieve the goal, are essential elements early in the planning process. The responsibility will require appointment of an independent peer review panel that can give careful and appropriate consideration, through solicitation of agency, tribal and public interests, to past management experiences.

Given the new management emphasis on wild stocks, special consideration must be given to the possibility that some of the maladaptive traits developed by hatchery fish in hatcheries could be expressed even more deleteriously when those fish attempt to spawn naturally (in a supplementation program) or when they interact genetically (as strays) with natural spawning populations, or as they interact with natural stocks ecologically throughout the post-release portion of the life cycle. While these possible risks are in some sense the most alarming, they are also the most poorly documented, and the quantitative strength of the underlying forces are not well understood. Therefore, a large research and monitoring effort needs to be directed at these questions of genetic and ecological effects of hatchery fish on naturally spawning stocks. The results of these studies are needed to lay to rest some of the fears about worst-case scenarios, and they are also needed to teach us how to modify hatchery management to achieve the most positive kinds of interactions with wild stocks.

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APPENDIX

Regional scientific questions on artificial production addressed in this report:

1. What are the ecological impacts of artificial production in the Columbia River Basin?

General
- o What are the positive biological/ecological contributions of artificial production in the Columbia River?
- o What are the negative biological/ecological impacts of artificial production in the Columbia River?
- o Does it not make sense to alter stock composition in hatcheries based on ocean conditions?

Fitness
- o Can hatcheries be used to rebuild wild, native salmonid populations and maintain their genetic and life history attributes, their fitness and the evolutionary capacity of the populations?
- o Are hatchery salmonids less fit for survival in the natural freshwater and ocean environments? If they are, what are the changes that must be made in the hatchery operation to make hatchery fish as fit as wild fish?
- o Is there a differential survival between hatchery and wild salmonids throughout their life cycle stages? Is there a differential survival rate for hatchery and wild fish as they encounter the human changes in the system? For example, do wild and hatchery fish survive dam passage, barging and predation at different rates? If they do, then should the agencies and tribes in their management programs acknowledge this differential survival rate?
- o Where have hatchery stocks caused the decline or extinction of wild stocks? Where have hatcheries enhanced the restoration of a wild stock?
- o Can the biological diversity, fitness and productivity of a wild, native salmonid population be maintained with a hatchery?
- o Do hatchery programs exist in the Columbia Basin or the region that have been shown to do a good job supporting biological diversity, genetic and life history attributes, fitness and productivity of the native population they interact with? Can they serve as a model for the basin and region?
- o Should a coordinated gene flow management policy be developed to control stray hatchery fish in the basin?

Disease
- o Are hatchery disease treatment programs likely to create resistant pathogens that could pose a health risk to wild salmonids? What should be done to eliminate or manage this risk?

2. What is scientific context for the use of artificial production in the Columbia Basin?

- o What are the major research questions associated with artificial production?
- o How does the existing level of scientific uncertainty affect the use and management of artificial production?
- o What are the priority research questions that need to be answered to integrate hatchery and wild production so that there is no loss of fitness and productivity in either the hatchery or wild populations?
- o What is the historic relationship between natural production and harvest?

3. How has artificial production performed relative to its management goals?

General
- o How effective has artificial production been relative to stated objectives in the Columbia River?

Harvest
- o How does artificial production affect harvest regimes and vice versa? What has been the affect of this relationship on natural production?
- o How do we mitigate fisheries with the least impact on wild fish?
- o As the proportion of hatchery fish increases and harvests are targeted on them, a mixed stock harvest problem is created where the wild, native population is exposed to high harvest rates. In this way the hatchery program fuels the harvest management program and wild fish are overharvested. What are your recommendations for reducing or terminating this problem? Can hatchery fish be used as a buffer to protect wild fish or is this a rationalization to justify not making changes in fishery management?
- o If harvest rates are constrained by natural production, then how can we alter hatcheries to meet compensation goals?

Mitigation
- o Can hatcheries be used to double the runs and, at the same time, maintain the biological diversity, fitness and productivity of the individual subbasin populations? Or is there a conflict between these two goals set forth by the fish agencies and tribes through the Power Planning Council? What are your recommendations for resolving this conflict, if it exists?
- o Mitigation has been carried out in such a way that the effect is the replacement of wild, native salmonids with hatchery fish. Is this effective mitigation? Have the mitigation agreements and goals been met in each relevant case in the Columbia? If hatchery mitigation is not working, what should it be replaced with that would protect wild populations?
- o Given that hatcheries are a necessary tool to mitigate for lost natural production, where does is make most sense, (i.e. most effective in production and cost) to locate production facilities?
- o Have mitigation hatcheries been successful in replacing numerical losses in the basin? Have they been successful in replacing the biological diversity and fitness of the wild, native runs that were lost?

4. What is the scientific basis for the use of supplementation?

- o What is the potential, and what are the associated risks, for artificial production to augment or supplement natural production in a biologically sound and sustainable manner?
- o What are the hatchery protocols needed to prevent a hatchery population from diverging from the wild donor population?
- o Can it be assumed that a hatchery population derived from a wild donor population will not diverge from the donor population in genetic, life history traits, and fitness?
- o How should a hatchery program be operated when reintroducing a salmonid population into a stream where the species has gone extinct if the goal is to promote a healthy, self-reproducing new population?
- o Does hatchery supplementation of wild salmonids work? Is there evidence in the scientific literature that shows hatchery supplementation is able to maintain the biological diversity, abundance, distribution, productivity and fitness of the original wild, native population? If not, should the region continue to fund new hatchery supplementation projects?

- Can these wild native populations be recovered using supplementation where wild brood stocks are used in the hatchery program?
- Can hatchery supplementation increase the numbers of fish while maintaining the productivity (fitness) of the affected population over time?
- Should hatchery and wild salmonids be integrated so that they function as single reproductive unit within a subbasin? Or should the two be kept separate, including the separation of spawning time to reduce crossbreeding between hatchery and wild fish?

5. What is the application to resident fish?

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