Review of Salmonid Artificial Production in the Columbia River Basin

As a Scientific Basis for Columbia River Production Programs

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I Introduction

In July of 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, in turn, 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.

In consultation with the Council and regional fishery managers the SRT elected to conduct the analysis as three tasks, the first two of which would occur concurrently, to provide the background and to establish the database pertinent to the analysis. The third step will be the analysis of the hatchery programs and database, and finalizing the report on the results of the study. Each task will be summarized in separate reports to the Council, and integrated into a final report on the conclusions resulting from the analysis. The conclusions emanating from the study will be articulated as recommendations in a proposed conceptual foundation, detailing what the SRT ascertains as the appropriate role for hatcheries in the Basin. Whether or not this conceptual foundation is adopted as the basis for regional hatchery policy, it is imperative that a scientifically based foundation be established as the basis for regional policies regarding artificial production.

The historical background and the final analysis of artificial production are tasks assumed by the SRT. Development of the database to include all past and current records on artificial production in the Basin is a task provided by a separate contractor. This paper represents the results of the first task of the assessment. It provides the SRT's analysis of the history of artificial production, and hatchery evaluations in the Columbia Basin.

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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 eleven scientists appointed with the assistance of the National Research Council.

Hatcheries have been used in the Columbia Basin for specific purposes, including mitigation for habitat destruction by development activities, more recently to supplement natural production, and for salmon conservation using captive broodstock programs. These roles of hatcheries are defined and discussed in this report, and the state of our knowledge on the genetic and ecological effects of hatcheries is presented. The report concludes with a set of recommendations to guide the development of hatchery policy in the Basin.

a. Scope of the Review

Artificial production has been used in the Columbia River Basin for many purposes over this century. Although several Basin hatcheries have produced resident species, such as sturgeon and rainbow trout, the primary concern associated with hatchery production addresses almost exclusively anadromous salmonids. Coho and chinook salmon, and steelhead trout, have been the focus of Basin hatchery production, and have been the central species in sport and commercial fisheries management, as well as the objects of recovery measures undertaken in the Basin. Understandably, therefore, the issue facing the Council in developing policy recommendations must address anadromous salmonids as the species of primary importance. However, the results of the analysis will have application to a much broader spectrum of species. Most, if not all, of the scientific information relating to the performance and ecological impacts of anadromous salmonid hatcheries applies equally to the use of hatcheries to produce resident fish, including resident trout, sturgeon, and bull trout. Therefore, in that context, resident fish hatchery policy must also be governed by the same principles in the conceptual foundation that 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 in transit over the migratory corridor in the Basin, it is expected that resident species will be very responsive to the principles guiding policy in anadromous salmonid management. The scope of the review, however, will concentrate on artificial production of anadromous salmonids in the Columbia Basin, but with reference to resident species as well where the same technology is applied.

b. Artificial Production as Defined and Applied in This Review

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 all the way to captive rearing of migrant juvenile salmonids on formulated diets in concrete raceways. Hatcheries are as simple as gravel incubation boxes in which artificially spawned eggs are incubated to enhance production of salmon or trout in tributary streams. Hatcheries are engineered spawning channels in which salmon enter to spawn naturally on graded substrate and controlled flow to enhance egg to fry survival. Likewise, hatcheries include earthen acclimation ponds in which fingerlings are fed before volitionally dispersed into the natural stream for rearing or migration. Hatcheries are also the tray incubator and concrete rearing raceway systems which provide the entire freshwater feed and residence requirements before the fingerlings are released to migrate seaward. It is this latter incubation and rearing hatchery system that considered the "standard" public hatchery design, and it is this "standard" system being addressed in this review of artificial production in the Columbia Basin.

Columbia River hatcheries were designed around variations of the "standard" incubation and rearing system that has characterized most chinook and coho salmon hatcheries over this century. They generally control 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 multiple females crossed with a composite of two or more males, to a breeding matrix that maximizes maintenance of the variability present. 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.

Assessment of performance of these hatcheries understandably is limited within the rather narrow definition of variables in facility design and operations that is common among such facilities. Assessment of the Columbia River hatchery system, therefore, with the more standardized technology among facilities, will expose differences in performance related to management practices as well as that particular technology itself. Such things as the source of fish, release strategies, relative size and condition of smolts, water supplies, location of the facilities, and location on the migratory corridor over the length of the river, will be contributing factors associated with performance. The context of the present evaluation, therefore, will be the relative performance of a particular class of hatcheries within the confines of river conditions in the Columbia Basin, under agency management responsibility. The assessment will thus 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, the region is embarking on an ambitious exercise aimed at developing a set of scientifically supportable alternatives for the future of the Columbia River especially as it relates to management of fish and wildlife resources[3]. These alternatives are to be analyzed for their ecological impacts, again based on an explicit conceptual foundation. The conceptual foundation includes a set of scientific principles that define the scientific context for the analysis[4].

Our examination of the scientific basis for artificial production and its potential ecological impacts are central to development of the regional framework. The conceptual foundation for artificial production that is developed in this review should be consistent with the set of scientific principles that are being used to guide the framework. In this sense, a conceptual foundation for artificial production is a refinement of the more general framework, and serves to focus the principles specifically on how artificial production should be used. It is our belief that a scientifically supportable foundation, such as that suggested by the framework and potentially refined by our assessment, should be the basis for development of policies in the broader context of fisheries management. To that end, the scientific basis and rationale associated with artificial production in the Basin will form an alternative template on which future options in management can be integrated in the ecological framework. Variations in the template consistent with the scientific principles, are primarily a matter of how and to what degree the options will be applied in the framework. The product forthcoming as the scientific rationale for integration with the ecological framework are the SRT recommendations that represent the conceptual foundation for future artificial production in the Basin.

[3] Ecological Work Group 1998. An ecological framework for the multi-species planning process. Available from the Northwest Power Planning Council, Portland, OR

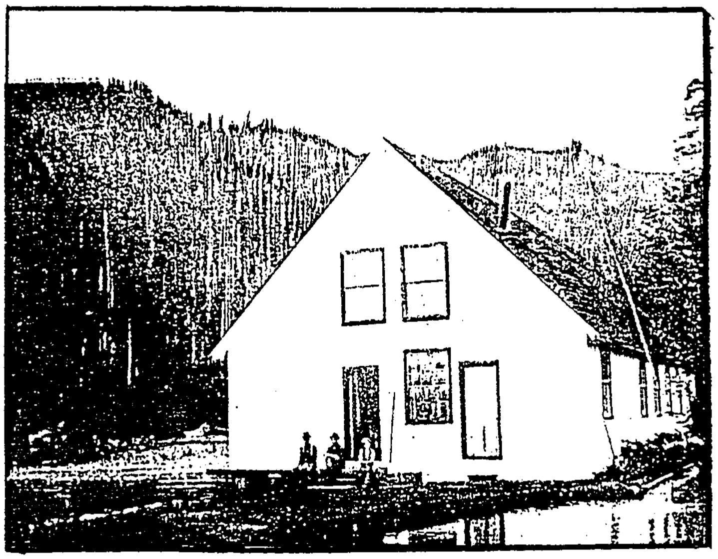
[4] Proposed Scientific Foundation for Development of a Regional Muli-Species Framework. Northwest Power Planning Council report 98-16. Portland, OR

II Historical Overview of Artificial Production

A. Growth of the 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 over harvest -- and he recommended artificial propagation as the solution to those problems. According to Baird, an investment of 15 to 20 thousand dollars in artificial propagation would make salmon so abundant that there would be no need for restrictive regulations (Baird 1875). 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, 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 which was 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 toward maintaining salmon production.



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

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, racked the stream, and supervised its 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). 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 about a decade later (Cobb 1930).

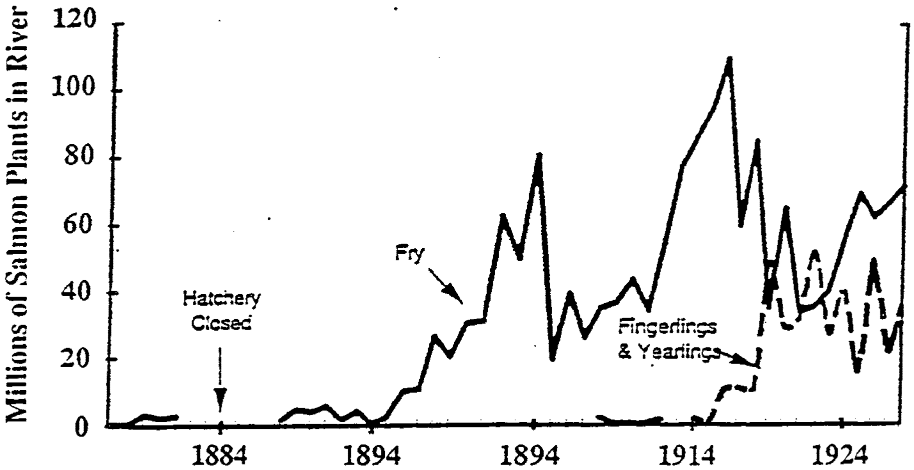


Figure 1. The number of juveniles of all salmon species released from hatcheries in the Columbia River (1877-1928). (Source: Cobb 1930)

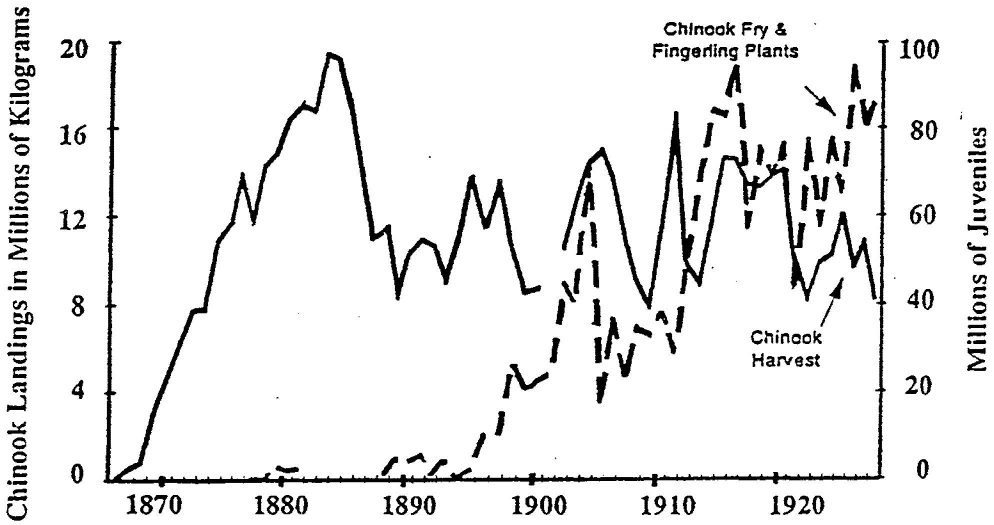


Figure 2. Harvest of chinook salmon and the release of chinook salmon fry and fingerlings from hatcheries in the Columbia Basin (1877-1927). (Source: Beiningen 1976; Cobb 1930)

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 inferior fall chinook (Thompson 1951). Following 1920, the decline in all races of chinook salmon was obvious.

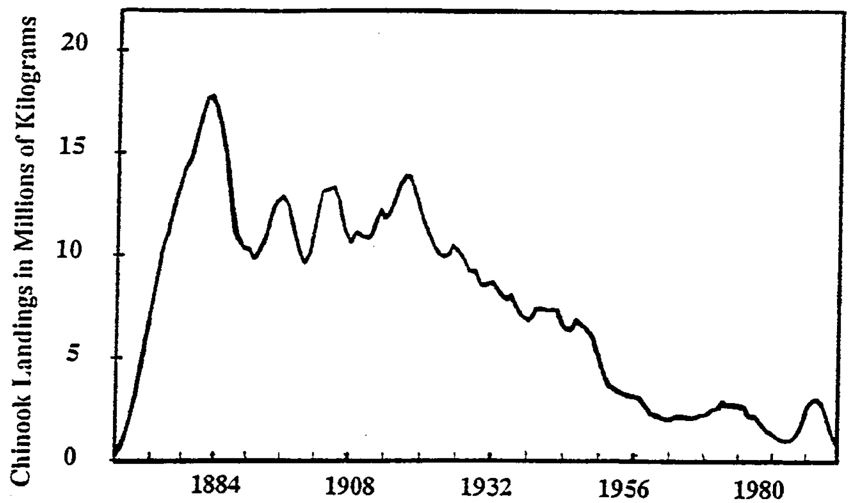


Figure 3. Five year average of chinook harvest in the Columbia River (1866-1992). (Source: Beiningen 1976; ODFW & WDF 1993)

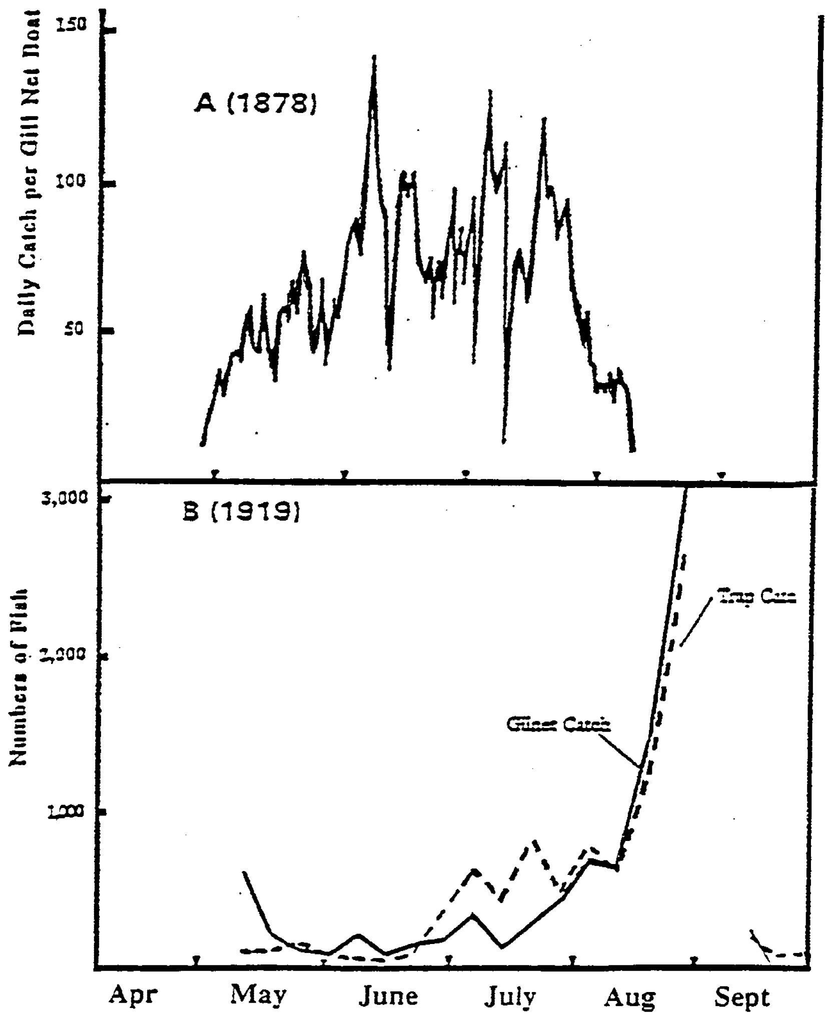


Figure 4. Comparison of the seasonal distribution of the chinook harvest in the Columbia River in 1878 (A daily catch per gill net boat) and 1919 (B weekly catch of 16 gill net boats and 22 traps). (Source: Thompson 1951)

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 again to emphasize the fact that the data here presented 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 (CBFWA 1990), 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.

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. Those problems and the performance of the hatchery program after 1960 are the subject of the analyses carried out in Sections V and VI of the overall report.

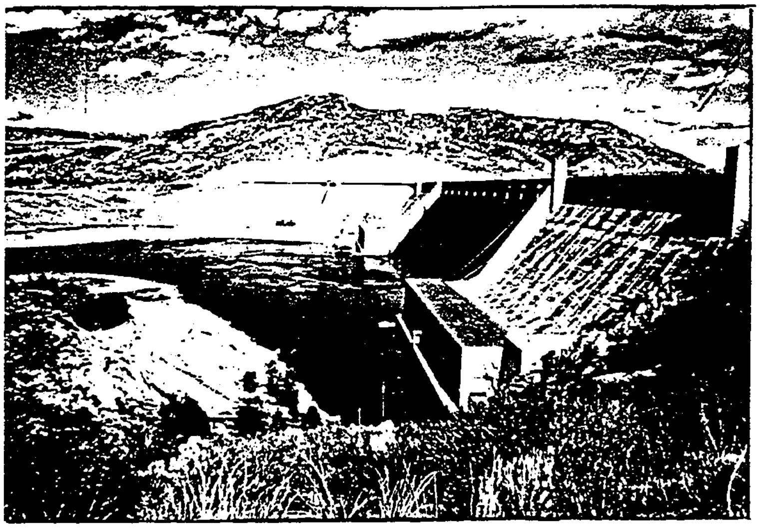
B. Compensation for Loss of Habitat

Most of the hatcheries built during this century were intended to mitigate for 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:

Grand Coulee Fish Maintenance Project - The first major hatchery program designed to compensate for hydroelectric development in the Columbia Basin was the Grand Coulee Fish Maintenance Project. Construction of Grand Coulee Dam blocked access to 1400 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 500 feet, Grand Coulee Dam was too high to successfully pass salmon via a ladder or elevator. Salmon managers considered the construction of a hatchery immediately below the dam, but engineering problems 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 which received the transplanted fish were Wenatchee, Entiat, Methow and Okanogan rivers and Lake Osoyoos (Fish and Hanavan 1948).

The results of the fish maintenance program were evaluated by comparing the contribution of relocated stocks to the Columbia River escapement above Bonneville Dam before and after the 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



Grand Coulee Dam

(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, with some modifications has continued to the present. 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, it was believed that the construction of McNary Dam and the other proposed dams in the upper Columbia and Snake rivers would eventually eliminate salmon in the upper basin. In 1956, Congress changed the purpose of the LCRFDP by adding fishery restoration above McNary Dam and the word "Lower" was dropped from the program title (Delarm et al., 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 river 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% of the program budget was expended on the hatchery program and about 10% on habitat improvement and screening of irrigation ditches. 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). (Source: Neitzel 1998, personal communication Steve Smith NMFS and Rich Berry ODFW)

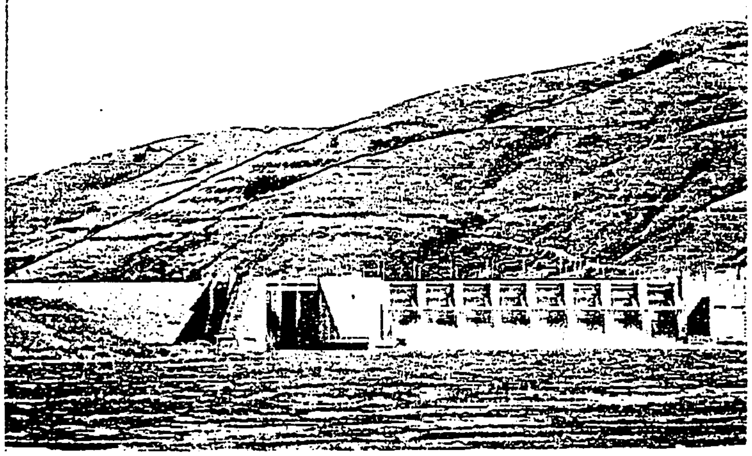
Facility Name	Agency	First Year Operated
Beaver Creek Hatchery	WDFW	1957
Big Creek Hatchery	ODFW	1941
Bonneville Hatchery	ODFW	1909
Cascade Hatchery	ODFW	1959
Clackamas Hatchery	ODFW	1979
Eagle Creek NFH	USFWS	1956
Elokomin Salmon Hatchery	WDFW	1954
Fallert Creek Hatchery	WDFW	1895
Grays River Salmon 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

Mid-Columbia Mitigation – 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.

Mitigation programs in the mid-Columbia evolved in three phases. The first phase was the Grand Coulee Fish Maintenance Project described above. From 1961 to 1967, four hatcheries and a satellite facility were constructed to mitigate for mainstem habitat inundated by five PUD projects. This second phase, originally consisted of three spawning channels (Priest Rapids, Turtle Rock and Wells) and two conventional hatcheries (Rocky Reach and Chelan). The spawning channels were later converted to conventional hatcheries. 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

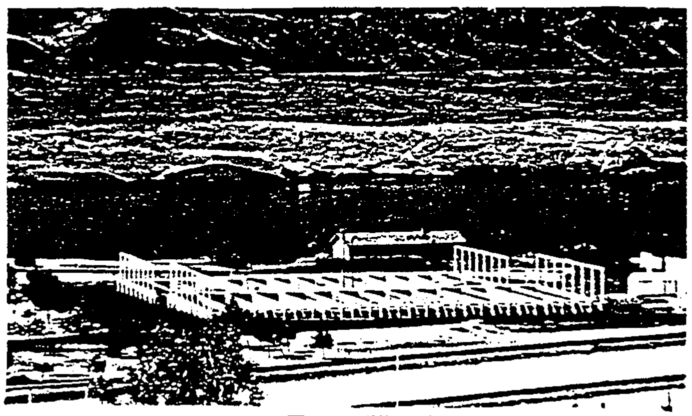
Hatchery. This phase is intended to mitigate for juveniles produced in the tributaries which are lost in passage past Wells and Rock Island Dams.

Lower Snake River Compensation Plan – The Lower Snake River Compensation Plan (LSRCP) was developed to mitigate for the loss of fish and wildlife resources resulting from the construction of Ice Harbor, Lower Monumental, Little Goose and Lower Granite dams. 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.


Lower Granite Dam

The Lower Snake River dams were completed between 1961 and 1969 (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. Presently, 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 are presently extirpated from the Snake River Basin, sockeye salmon are nearly extinct, and under the Endangered Species Act fall chinook are listed as endangered. 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).


Lyons Ferry Hatchery

Other Mitigation Programs – Other mitigation programs include the Willamette Basin, Native American hatcheries, and private industry. Five hatcheries mitigate for dams constructed in the tributaries of the Willamette Basin (Table 3). The program is funded by the U. S. Army Corps of Engineers. Native American hatcheries also operate in the Basin. The Nez Perce Tribe has a spring water fed hatchery developed on Sweetwater Creek near Lewiston, Idaho, and the Yikama Tribe has a large state-of-the-art hatchery located on the Yakima River at Cle Elum, Washington.

Table 2. Major hatcheries that are part of the Lower Snake River Compensation Plan. (Source: 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

Table 3. Major hatcheries that are part of the Willamette mitigation program. (Source: 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 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 the Lewis River.

As demonstrated by the history of artificial production in the Columbia River system, there has been extensive variation in how hatcheries have been applied 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 at the evolution in the role of science as the hatchery concept has developed, concurrently with the history of hatcheries on the Columbia.

III. 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). Science deals with the biological and ecological criteria that are integrated to form a conceptual foundation around the process. 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 attempt to describe the set of assumptions, upon which, we believe the hatchery program was based. Since 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 this assessment (second phase) will begin.

A. The Early Conceptual Foundation of Hatcheries

The early hatchery program was consistent with the over arching 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. The program intention was simply to increase catch by protecting the eggs, maximizing the number of fry released, and harvesting the returns from the sea. Given the hypothetical fecundity of 3000 eggs, a spawning pair may successfully produce something in the neighborhood 500 fry to emergence under natural stream conditions. Under the same scenario, artificially spawning and incubating those 3000 eggs would result in about 2500 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 hatchery fry production could bestow. Moreover, it was a concept that when properly employed has brought substantive results, as demonstrated in an example that will be discussed 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.

It was the natural extension of the concept that if protecting the incubating eggs from such harm would result in a five fold improvement of 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 further, of the 500 wild fry emerging naturally 45 might be expected to reach the smolt stage and enter marine waters, from which 2 to 5 adults would return. However, extrapolating the hatchery survival advantage to the next life history stage, if the now 2500 fry successfully incubated from 3000 eggs in the hatchery were reared and protected through the succeeding freshwater rearing period, 2000 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 3000 eggs. Rather than 2 to 5 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 Basin (Figure 5). Experience has demonstrated, however, that successful production of juveniles in hatcheries is not so simple and that hatchery production by itself can not guarantee a sustained increase in catch, or even an increase in catch for that matter. 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 hatcheries throughout the Pacific Northwest. That presumptive view has not changed substantially, and production augmentation is presently being executed 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 which separated the development of fisheries science from the major developments in ecology. 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).

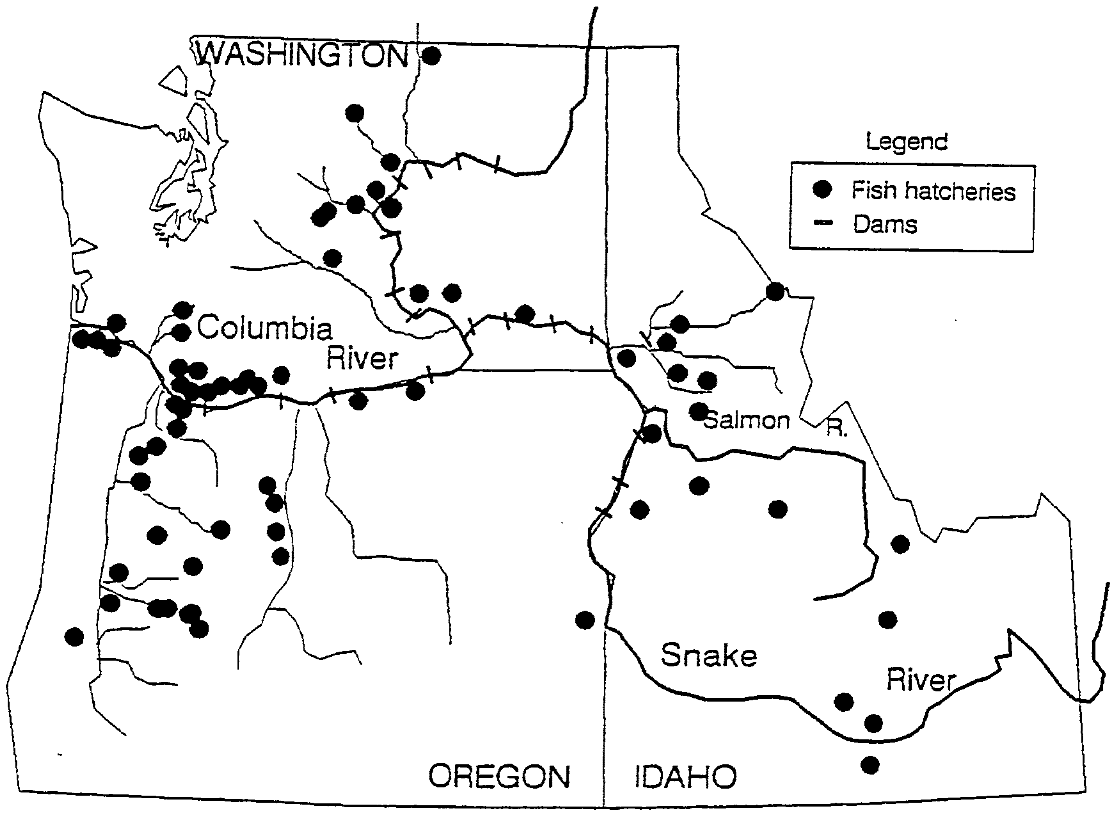


Figure 5. Columbia River Basin State, Tribal and Federal hatchery locations.

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 agriculture commodities in the Pacific Northwest, has demonstrated production capabilities even better than the original hatchery practitioners envisioned, because the fish farmers control the entire life cycle from spawning to adult harvest and realize the equivalent of 1800 marketable adult size fish per spawning pair. However, while the application of agricultural principles has been beneficial in some aquacultural enterprises, when applied to anadromous salmonids released to experience over three quarters of their life in the natural environment, it has generally failed.

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. 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 productivity of the ocean relatively unlimited. Consequently, the belief that increased survival of fry and fingerlings in the hatchery would translate proportionately to increased adult return as 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 upon which the hatchery program was constructed. 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 six general assertions:

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

B. Basic Derivations in the Hatchery Framework

Development of a conceptual foundation applicable to Columbia Basin hatchery programs has to be consistent to 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 species, including stock specific differences, will fail. Pacific salmonids have evolved specific characteristics and population structures in synchrony with their native habitat (Brannon in press), and ignorance, or disregard, of that synchrony 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 salmonid species, including those differences within the mixture of stocks representing the species.

The pervasiveness of genetic characteristics in the life history of salmonids, and hence the importance of organismic synchrony with the spatial and temporal environmental variables defining their habitat, cannot be over stated. As part of the freshwater ecological system, all of the salmonids show temporal and spatial specificity within their respective population structure. That timing of adult return and spawning is controlled by the genetic predisposition of the fish. As most apparent in chinook salmon (Figure 6), adult timing has evolved in response to mean incubation temperatures associated with the natal stream, and thus specific to each population across their entire range (Brannon in press). Because of the adaptive advantage endowed through selection, changes in temperature brought about by human perturbation, or natural phenomena such volcanism or fire, will result in asynchrony of temporal specificity and fitness will fall. If such changes exceed the rate of genetic compensation, it would lead to extirpation.

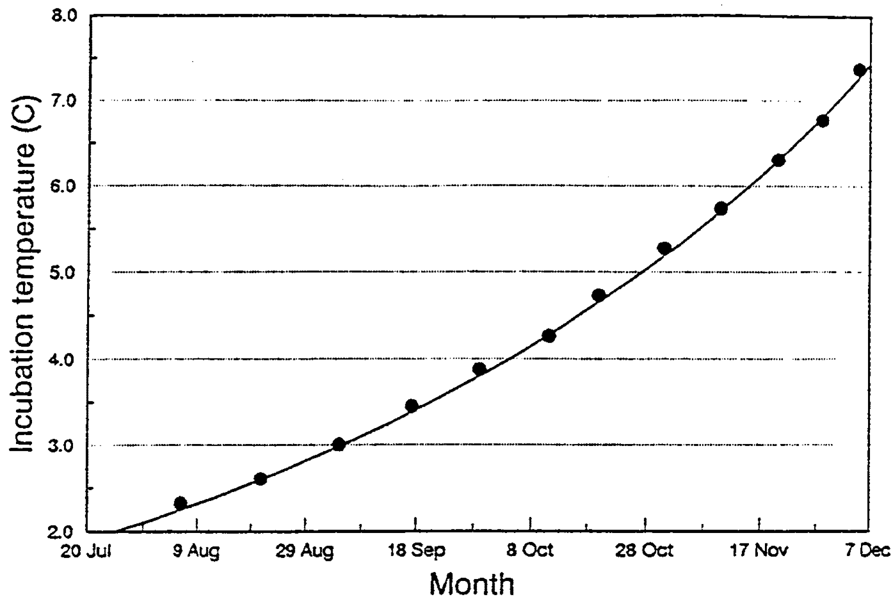


Figure 6. Relationship between mean incubation temperature and adult return time for chinook salmon.

Mean incubation temperatures dictate the temporal pattern in parental spawning because selection has timed emergence to occur in the optimum spring period for subsequent growth and survival. Since temperature controls rate of incubation, to achieve such temporal synchrony, spawning must advance progressively from early to later timing when mean incubation temperatures advance respectively from cool to warmer incubation environments (Figure 7).

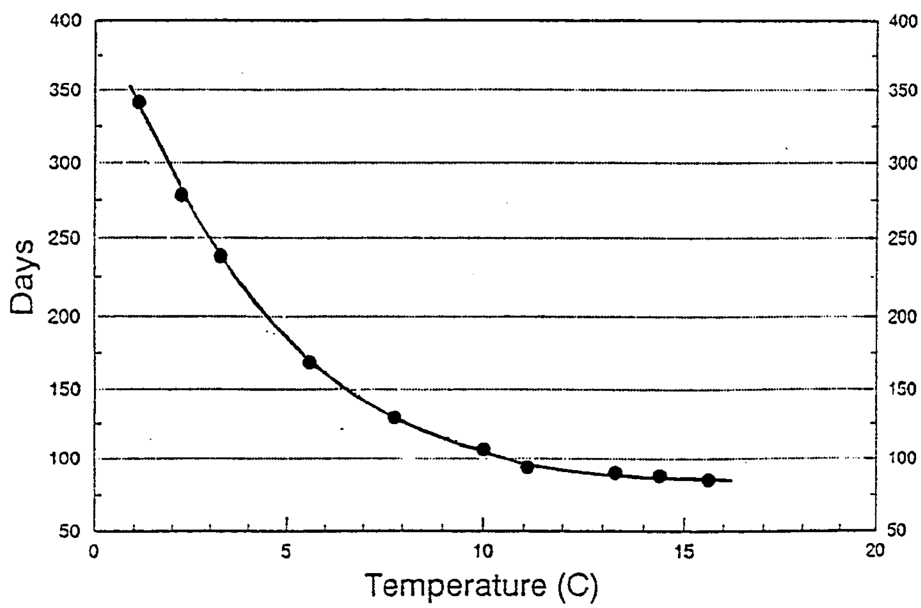


Figure 7. Relationship between temperature (°C) and number of days of incubation to alevin yolk absorption.

Temperature is the single most important environmental factor in the adaptive evolution of salmonids, and its importance in life history strategy has been a basic oversight in artificial propagation. Hatchery management characteristically has moved stocks of fish throughout the Basin, or intercepted fish destined upstream for propagation in the lower Columbia. Such practices have major impacts on the ability of the fish to survive. Unless the fish are maintained as a hatchery stock for fishery augmentation, in which case the native traits are displaced by the control that hatcheries exert on temperature, feed, and release date, those fish will not perform well in the natural environment. Fish expected to spawn naturally from such origins are out of synchrony with their new environment and any production will perform poorly compared to their wild counterparts. If mean incubation temperature is different from their native waters by only 1° C, emergence timing will change by four weeks, markedly reducing their ability to compete under the new regime. The width of the population spawning curve is representative of the temporal tolerance around the optimum, and when that curve is very narrow, the tolerance of the population to temporal perturbation is diminished (Brannon in press). The single most critical factor responsible for limited success establishing natural runs with hatchery fish is the incongruity in temporal paragons.

Perhaps the best example of genetic specificity in rheotaxis and orientation of sockeye fry migrating from their stream incubation site to their nursery lake (Brannon 1972). The emerging fry are naive to any experience that would assist in that journey and must totally depend on innate responses for guidance. Millions of small fry are involved in the migratory process, and timeliness under river conditions of limited food resources for that number of fry is essential to their future success. Some must only migrate downstream to reach the nursery lake, but others have to swim upstream, and still others swim down one stream and up another in almost a mechanical rheotactic drive to their goal.

The genetic role in rheotaxis is demonstrated by the example of sockeye populations in the Fraser River in British Columbia (Brannon 1972). Chilko Lake has a major outlet spawning population in Chilko River, and the fry must swim upstream to reach the lake. Stellako River sockeye, on the other hand, spawn above Fraser Lake, and the emerging fry migrate downstream to reach the nursery area. Emerging fry from these populations were tested in an artificial stream and each showed the appropriate rheotactic response necessary to reach their respective lakes (Table 4), even when they were incubated under laboratory conditions over a hundred miles away from their native systems. The strong genetic control of the behavior was demonstrated definitively by the hybrid cross between populations showing an intermediate response to that of the parental populations.

Table 4. Rheotactic response of emerging sockeye fry and hybrid crosses from Chilko and Stellako river incubation areas under laboratory conditions (Brannon 1972).

	Percent Response	
Stock	Upstream	Downstream
Chilko	90.1	9.9
Stellako	10.2	89.8
Hybrid cross	48.9	51.1

Predetermined or preferred directional orientation was also demonstrated among these populations after they enter the nursery lake system. Sockeye fry follow a migratory pattern that distributes the population throughout the system, presumably to optimize food resources. In a test maze where the fish could select any direction, Chilko fry preferred a SE direction, while Stellako fry showed a NE preference (Figure 8), which corresponded to the initial direction the fry would negotiate in distributing down the axis of their lake. Quinn (1985) reconfirmed the genetic basis of the behavior and demonstrated that the innate orientation would shift corresponding with an artificially induced electromagnetic field when tested under laboratory conditions, indicating that juvenile sockeye used magnetic fields to orient along genetically predetermined pathways.

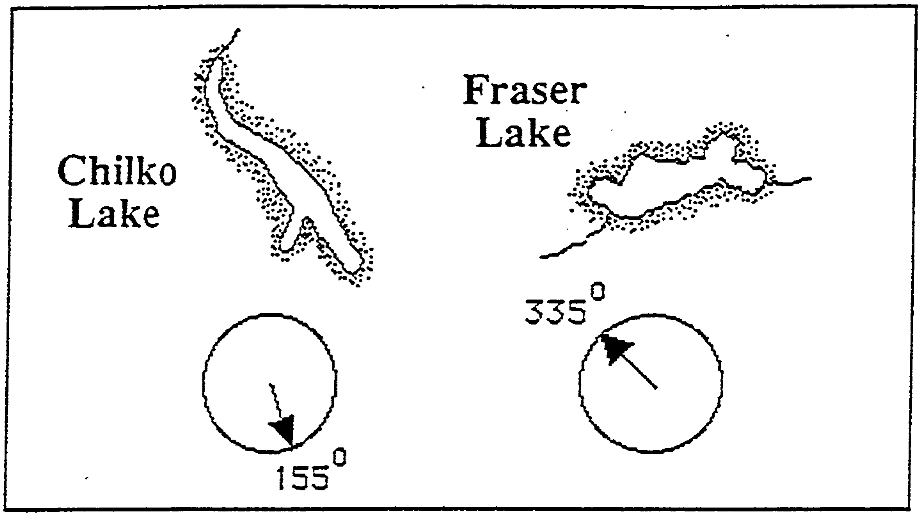


Figure 8. Directional preference of post-emergent fry from Chilko and Fraser lakes, in British Columbia, when tested in orientation arena in the absence of velocity (Brannon 1972).

The point of the above discussion is to demonstrate that natural populations of salmonids are genetically programmed to optimize survival, and execute temporal and spatial patterns of behavior most favorable to maximum fitness. Disconnecting the organismic and environmental linkages effectively disrupts the synchrony 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 to encourage the development of natural runs, are doing a disservice to both the resource and to the hatchery system they represent. These fish will have little contribution value to natural production, and by continually or even intermittently spreading stocks around the system, they keep the fish perpetually biologically incompetent for those 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. Hatcheries have to eliminate the Johnny Appleseed approach, and concentrate on understanding the organism, life history strategy they espouse, and the habitat limitations of the streams they contribute to.

C. The Conceptual Foundation as an Adaptive Process

In the complexity of freshwater life history strategies among anadromous salmonids, chinook are at one end of the extreme and pink salmon are at the other, with coho, steelhead, sockeye, and chum salmon in between, in that order. 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. These species are generally limited only by the spawning area of the stream, since the productivity of their nursery environment most often exceeds the capacity of the spawning grounds available.

In development of the conceptual foundation of hatchery programs, the process must allow for differences inherent in the fish targeted. 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 they 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 9). 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% to 13.0% (Figure 10) 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; Olsen 1993). Success in the PWS hatchery program was experienced by working within the life history definition of the species, and has succeeded for 20 generations.

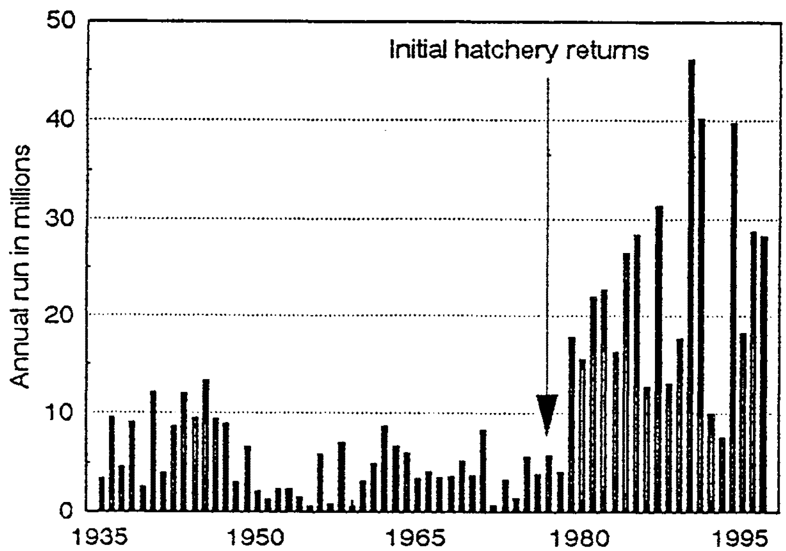


Figure 9. Annual run size of pink salmon returning to hatchery and natural production streams in Prince William Sound, Alaska.

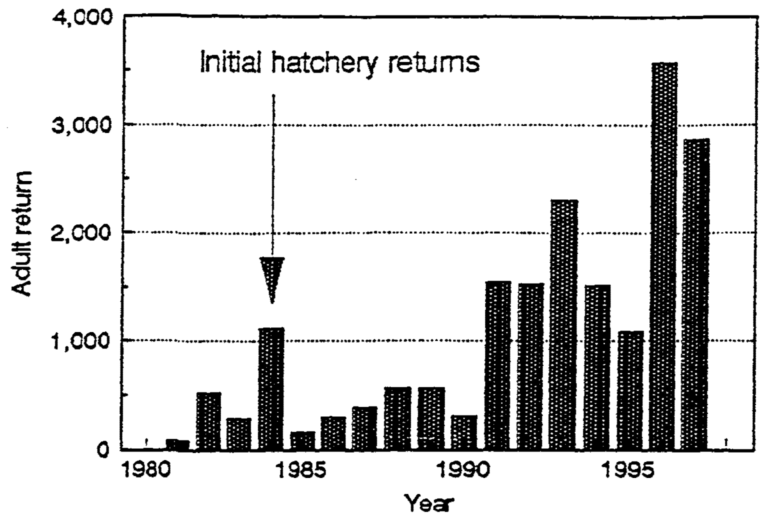


Figure 10. Percent survival of pink salmon fry released from Armin F. Koernig hatchery in Prince William Sound, Alaska.

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 was 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%, 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 11).

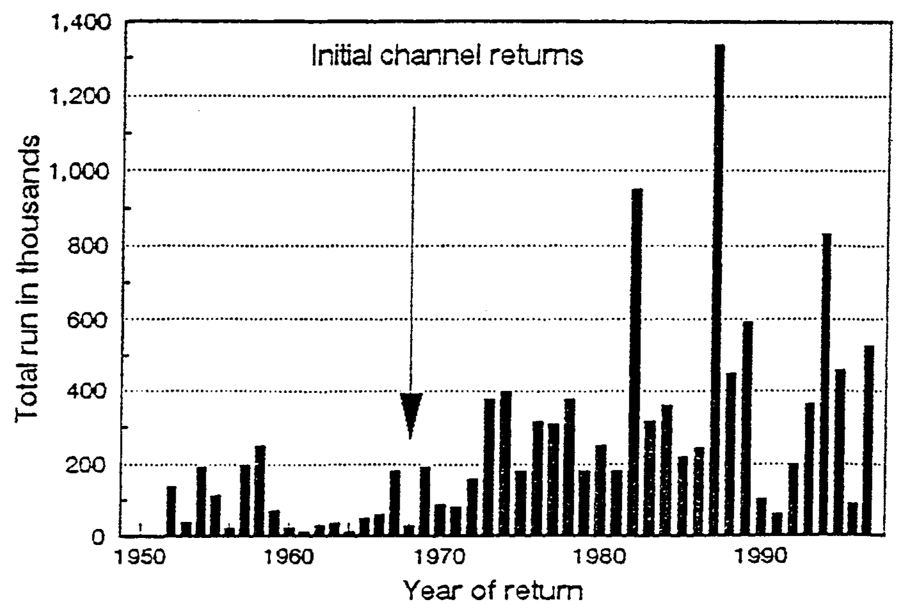


Figure 11. Annual run size of sockeye salmon returning to Weaver Creek in British Columbia.

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 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 minimum 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. The Sooes River chinook population was being seriously threatened by clear-cut watershed instability, runoff from log yards, and over-fishing by the coastal and Canadian fisheries. Fewer than 100 fish were reaching the spawning grounds on 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 12). By the late 1990s well over 2000 fish were returning from both the hatchery and the natural production.

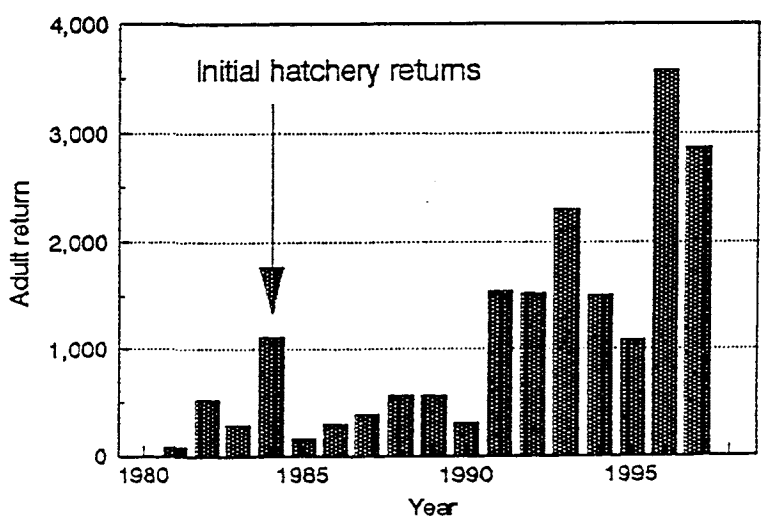


Figure 12. Chinook salmon annual return to Sooes River, Washington, from hatchery and natural production.

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 stock were not compromised by introductions of other chinook that would have suffered from incongruity with that coastal system. Also attributing to their success is the 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 conceptual framework of such measures is critically important to the development of functional enhancement systems. Admittedly, none of the above examples are 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 restore some of the runs to self sustaining populations, the conceptual foundation has to be that much more specific to the task. To integrate the hatchery complex into the Columbia Basin ecosystem, and still reach the commercial, tribal, and public fishery objectives, the model has to be rigorously defined and the biology of the component species well understood, to meet the challenge.

IV. 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 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.

Table 5. Organization and classification of artificial production.

Harvest				
Augmentation	Mitigation			
Fishery	Maintenance	Recovery	Preservation	Restoration

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 artificially spawning and incubation in hatcheries was the general motivation behind construction of the first Columbia Basin hatchery in 1876, located on the Clackamus 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. Anadromous salmonid population reduction occurred so extensively in the Columbia that augmentation was used simply to compensate for overfishing, and was never able to be applied in that system for harvests expanded beyond what occurred historically from 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) Natural production is limited by the freshwater environment, (2) ocean carrying capacity exceeds natural production potential, and (3) hatchery production will not negatively impact natural populations. These assumptions still prevail, and are 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 criteria have credence, but the lower productivity threshold of the marine environment is a very powerful limiting force on natural and hatchery production, regardless of the freshwater production magnitude. Augmentation of harvest through hatchery production has been demonstrated most recently with pink salmon in Prince William Sound as seen in Figure 9, and highly correlated with marine conditions (Willette 1992). Several hatchery programs in Alaska demonstrate very positive augmentation success, routinely above 10% survival of fingerling rsockeye, and higher than 20% among some groups on fingerling coho (Marianne McNair ADF&G personal communication).

However, 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 13). 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 14).

Commercial ocean ranching is another hatchery program that has demonstrated variability in return associated with marine productivity. McNeil (1991) reported the very positive influence of ocean ranching hatchery production on commercial landing of coho in the Oregon Production Index (OPI) area during the 1970s (Figure 15). With the expansion of ocean ranching production and favorable marine conditions, coho catch in the OPI reached unprecedented high levels in the 1960s to late 1970s, exceeding previous natural production by 60%, with 26% of the entire coho catch in the OPI attributed to hatchery production from one ocean ranching facility. Performance in production success varied along the same pattern as the natural coho success, in a cyclic manner associated with ocean conditions, but representing a hatchery smolt survival rate ranging from 1.3% to over 20%.

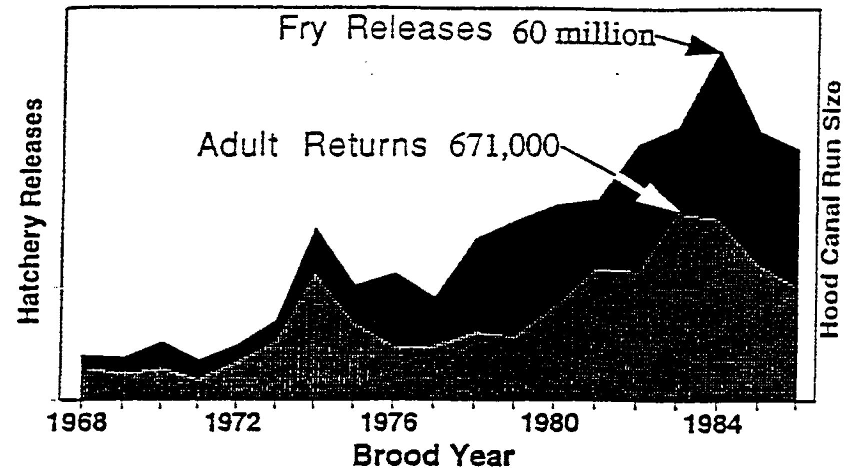


Figure 13. A comparison of Hood Canal chum salmon releases and subsequent run size. (Fuss 1989)

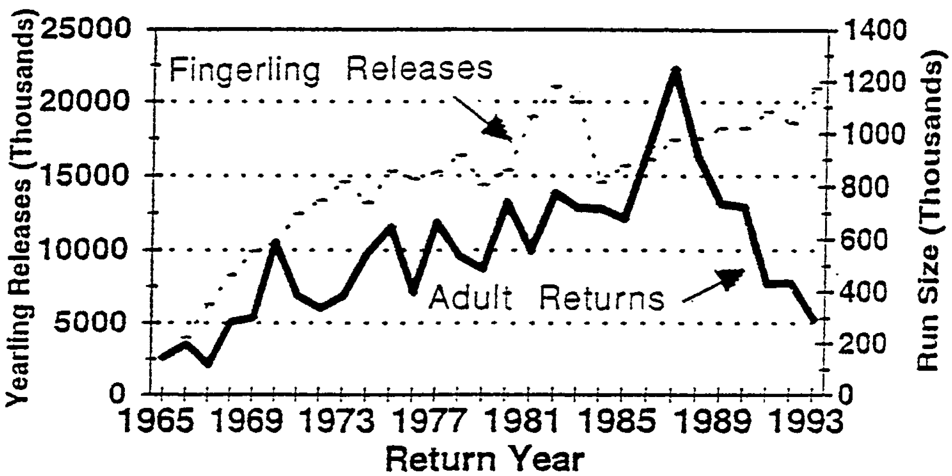


Figure 14. A comparison of hatchery releases of Puget Sound 1+ coho with subsequent run size. (Fuss 1998)

However, in the context of ecosystem management, the second and third criteria create major problems in 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 application of hatcheries outside the Basin, and the measured ecological impacts, should be undertaken.

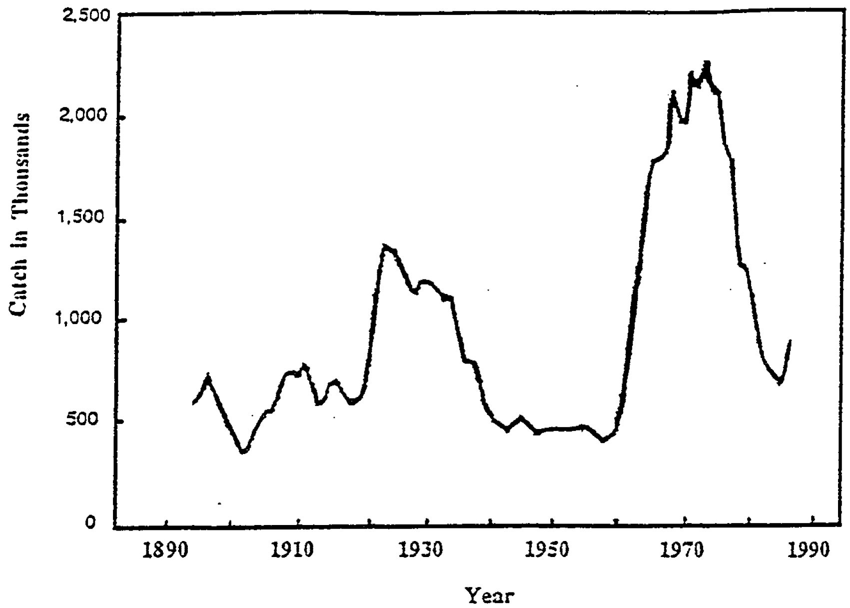


Figure 15. Five-year running average of the total coho salmon harvest in the Oregon Production Index area. (McNeil 1991)

B. Mitigation

With the development of water resources in the Columbia River, nearly half of the accessible river system is deprived of salmon, and much of the remaining habitat has been significantly compromised for incubation and rearing to some degree. Mitigation for these losses has been through the development of hatcheries, and major hatchery programs now prevail in the Columbia River system, and presently represent a significant and continuing investment. Conceptually, mitigation hatcheries are meant to replace harvest potentially lost as a result of habitat alteration associated with the various projects on the river. 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 for via hatchery production. 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 presently operated for mitigation purposes.

It is not without 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 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 in the Columbia River, 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, falls within four different categories associated with degrees of salmon extirpation, including maintenance, recovery, preservation, and restoration.

(1) 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.

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. Maintenance, in its most basic rendition, is to maintain contribution of salmon and steelhead approximate to those levels immediately preceding developments affecting their productivity.

(2) 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 (Ryman 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 in synchrony 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 these synchronies between the native stocks and their environments, and this perspective is the central theme of mitigation in recovery.

(3) Preservation is the most extreme of measures in mitigation to retain representation of stocks at risk of 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 from which to rehabilitate a population through maintenance of captive broodstock. Maximizing reproductive potential under captive breeding over two generations can multiply the numerical base from which reintroductions can take place by several hundred fold, and 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, 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 included in routine population recover 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 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 facilitate synchrony with controlling environment phenomena. Matching genetic predispositions to optimize the likelihood of success is key to 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, and using these features to select candidates for introduction most like that demonstrated by the native phenotype is the optimum strategy.

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. Hatcheries environments are secure and forgiving of timing asynchronies 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 augmentation and mitigation hatcheries, it is apparent that the objective identifies the determinant criteria. Moreover, the criteria is 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 it 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 straight forward. 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 intercourse 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.

V. Synthesis of Artificial Production Reviews

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 with regard to the long-term benefits to the health of the resource 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 that 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. As general background on the topic, 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. Other forms of artificial production was not included

A. Early Hatchery Evaluations

While it would appear that use of a major program such as hatchery production to augment and mitigate for loss of legendary fisheries would be evaluated to determine if it is achieving its objectives, 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 ideological 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 operation, claims of success for the hatchery program were based on short-term correlations; evidence that was weak at best, or on no evidence at all. 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 hatcheries 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 over dependence on hatchery production as a substitute for stewardship;
2) a <u>criticism</u> of hatchery performance 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.

The assertion that scientific evaluations did not exist in the early decades of the hatchery program, has been challenged by state salmon managers pointing specifically to a marking experiment carried out from 1895-1900 (Dehart 1997). In this experiment, 5000 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% 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 5 pounds heavier than the average for the Columbia River—one supposed 3-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 which had two practical purposes: 1) to determine the value of hatchery work; and 2) to understand the differences in early life history between spring and fall chinook (Rich 1920). Rich also initiated several marking experiments at hatcheries in the Basin to test the efficiency of hatchery practices and to test the homing ability of chinook salmon (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 and 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. The results of many of those studies are summarized by Wallis (1964).

Extended rearing in the hatcheries prompted research into the nutritional requirements of juvenile salmon and the prevention and treatment of diseases. 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%. Overall, an estimated 14% of the fall chinook salmon caught in the sport and commercial fisheries from southeast Alaska to northern California originated from the Columbia River hatcheries (Wahle and Vreeland, 1978).

The NMFS repeated the fall chinook evaluation with the 1978 to the 1982 broods. Total survival for all four brood years and all facilities was 0.33% 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% 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 their 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% of the salmon and steelhead in the Basin were hatched and reared in hatcheries. From 1981-1991 expenditures on hatcheries accounted for 40% of the budget for salmon restoration. Fifty percent of the increase in salmon production of salmon from 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, 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 population 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.

It was 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 Rive 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 artificial produced fish add to existing natural production or do they replace it, i.e., does the hatchery operation generate a cost to natural production through mixed stock fisheries, domestication, and genetic introgression?

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.

They 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 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" broodstock 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 anadromous salmon sustainability. 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.

They 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 US 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 work being conducted. 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.

C. Relevance of Past Assessments to the Present Task

As general background on the how hatcheries got started on the Pacific Coast, and the Columbia River in particular, the origin and the evaluations in the preceding sections are most worthwhile. It was made obvious that to proceed with artificial production "as usual" is poorly advised, and even the assumptions basic to the hatchery program that have carried over from the early years need to be corrected in light of what is known about specific life history requirements of the different salmonid species that are managed. The most compelling 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 in 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 (1) generally failed to meet its objective, (2) imparted adverse effects on natural populations, and (3) failed to evaluate hatchery programs, there was further significant consensus on seven other issues. (4) There was agreement that past programs were based on untested assumptions. (5) They felt there was a need to link supplementation with habitat improvements. (6) A need to include genetic considerations, and (7) eliminate stock transfers and introductions of non-native species. A need to (8) develop a new role for artificial production, using (9) more experimental approaches, and (10) using hatcheries as temporary refuges, rather than in long-term production management. These efforts provided insights that need to be accommodated 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 which are pertinent to decision making about hatchery application. University scientists dominated or were well represented on the review panels. The NRC for example was made up of 15 participants, of which 12 were associated with a university. 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 critical that the understanding and implications of the 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, the science must be the basis of any approach.

VI. Impacts Associated with Artificial Production

As evidenced 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. 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.

Risks Associated with Failure and Success - Originally, the goal of the hatchery programs was production for harvest, so the measure of success was the numbers 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 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 others are presently 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 their 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 captive broodstock 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 which 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 likelihoods of the various negative effects that hatchery operations might have on wild stocks.

Contrasting the Evidence with the Theory - The practical science of hatchery management is more than 100 years old. During that time hatchery technology has progressed to the point that 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 in natural production. The magnitude of this relative advantage is in 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, which demonstrates the mechanisms that theory is based on, 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 on interaction with hatchery fish, as well as even the poor success of hatchery fish on hatchery practices, such evidence, at best, is indirect and neglectful of the other major environmental perturbances in the system. The task of making linkages is a formidable one, but necessary in the fair resolution of hatchery assessment.

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 the 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, there are probabilities that hatchery fish may have negative impacts on wild stocks, which can occur even when hatcheries are managed for supplementation or recovery of wild stocks. The positive effects of increased survival in the hatchery could be overwhelmed by negative effects 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 make take into account both 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. To get the information needed to answer hard questions, it would mean a major reorganization of how hatchery programs are conducted, including interim changes and re-prioritization in 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.

A. 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, offers 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 synchrony between genetic attributes of populations and the environment associated with their natal systems has generally characterized hatchery management policy over 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 have altered some hatchery operations in an attempt to address problems with fish quality and wild/hatchery fish interaction. The existing track record, however, is dominated by former management practices, many of which are still represented among Columbia River hatcheries.

To assess Columbia Basin hatcheries, technology such as lack of cover in raceways or training on artificial diets, may be an issue, but the compelling questions deal with the potential impact of the hatchery program. 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 be available to meet the objectives required of artificial production to be compatible 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.

B. 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 effect 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 section, 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? (2) What is the evidence that the effects be managed or mitigated?

Extinction

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 could theoretically 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% 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 could contribute to extinction caused by hatcheries (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), and steelhead (Brown 1995).

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 are 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.

Loss of Genetic Diversity Within Populations

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 addition, 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 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 taxa, 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 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 effects nearly all of the factors that theoretically influence genetic drift and inbreeding. These include the number and proportion of founders or broodstock 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, which shows that 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 Sonoran and Mexican poeciliids (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. 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, found that mosquito fish populations founded 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 will interact to reduce fitness even in moderately large populations. This has not been examined in Pacific salmon.

Ability to Mitigate—Theory suggests that loss of genetic diversity and inbreeding in hatchery populations can be controlled by managing brood fish number, sex ratios, and age structure (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 effecting 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.

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 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 trout 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 a variety of organisms, including marine copepods (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.

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) or 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. Estimated heritabilities of many traits were compiled by Tave (1993). 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 of 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 Pacific salmon, Reisenbichler and McIntyre (1977) found that progeny of hatchery fish only two generations removed from the wild had about 80% survival of wild, but the opposite pattern was true in the hatchery. 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 the 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% as successful in producing surviving smolts and adult progeny as wild fish. The hatchery stock used in this study, however, was of not native to the stream and was of mixed ancestry. Consequently, the reproductive success of this stock reflects more than domestication effects.

Ability to Mitigate—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 presently 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 differentials for key fitness traits if we could identify which traits they were, how they were correlated with other traits, and what environmental conditions led to selection. This knowledge is not currently available.

C. 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, and 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 fingerprint through which present population structure can be understood.

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. 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". 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".

Diversity is inherent to the stability of the species in the larger context of the river basin. The sub-basin environments, with their component population networks, are the sanctuaries of variability from which recolonization and extension take place, and which are referred to as core populations by Williams et al. (in press). When viewed from the basin wide perspective, the member populations within the river system form a aggregation of unique populations, identified by their return times, return destinations, spawning times, incubation periods, rearing strategies and migratory behavior (Brannon in press). When these member populations are taken in combination, they are what is referred to as a metapopulation within the context of the basin they inhabit (Hanski and Gilpin 1991). Major basins such as the Columbia River are massive enough to represent nearly the entire range of the wide spectrum of environmental extremes tolerated by salmonids. Moreover, the extent to which population structure is represented, is not simply the extension of common forms to a wider array of habitat types. Representatives of the composite Basin populations exist as unique forms of the species in synchrony with the environmental attributes that have been responsible for the evolution of the life history strategies they demonstrate. Without that habitat, that diversity will not survive. Moreover, the strategies they demonstrate reflect the optimum behavior in the complexity of selective pressures exerted on them. Proper management, therefore, must include only measures that are consistent with those life histories, or severe impacts on the native populations will occur.

Return spawners within a population usually represent less than five percent of the broodyear potential. That level of mortality, already exemplifies a tenuous balance that swings several percentage points in either direction in response to environmental variability that occurs naturally in biological systems. Each of these populations that have evolved their unique strategy for maximum benefit, has a different level of fitness based on the restraints each has experienced, and articulate a different level of tolerance to perturbation based on the phenotype. Major influences on wild fish can be realized from management scenarios that don't take into consideration the biological and ecological realities of wild stocks sympatric with hatchery releases. Relatively small changes can have major influences if wild stock fitness is already approaching a maintenance threshold. Moreover, life history strategies, such as ocean-type and stream-type chinook salmon forms, have evolved around environmental parameters in which size and number of conspecifics are part of the selective pressures responsible for the strategy expressed, and the survival success to the point of adult return.

Ecological effects of artificial production, therefore, are not simply competitive in scope, but rather can represent major alterations in the selective environment affecting population structure. For example, there is a positive relationship between smolt size and survival of hatchery fish, which has encouraged hatchery managers to release larger smolts to maximize hatchery returns. The problem is that wild chinook life history strategies have evolved based on the sizes they have been able to achieve under the temperature and nutrient limitations of the natural environment. Potentially negative impacts of such hatchery management scenarios on survival success of wild fish can be translated in two separate but major avenues. One is the immediate impact on the ability of wild fish to avoid competition and predation pressures compounded by the presence of abundant, larger hatchery fish. The other, and perhaps more serious, is the long-term selective pressure being exerted on wild fish to accommodate the "new" compromising force of larger conspecifics in the ecosystem.

Another potential negative impact is asynchrony in timing of hatchery and wild fish smoltification. Closely related to the size issue around hatchery fish survival is management efforts to optimize release times for hatchery survival benefits. Here again this is in stark conflict with life history evolution of wild fish. The number and timing of hatchery releases can disrupt the synchrony that has evolved in life history strategy of anadromous wild salmonids to minimize losses from predation while maximizing growth opportunity. Hatchery releases are not insignificant, and the overwhelming numbers from hatcheries entering the migratory ecosystem can disrupt the timing patterns that have evolved in the wild counterpart by altering the selective pressures that have identified the optimum window of opportunity for migration. The "new" forms are a force that has not been accommodated in the adaptive evolution of the species, and the magnitude of hatchery releases at times asynchronous to wild migration timing has not been given appropriate consideration as a potential hatchery threat to wild fish success.

Of course the more obvious impact of hatchery management on ecological status of wild fish is the pre-smolt releases on stream carrying capacity through competition. Hatchery fish are seldom released in numbers that are related to the carrying capacity of the receiving stream. Whether as smolts or pre-smolt juveniles, these fish will compete and, in most cases, stress the native stock when numbers released approach or exceed the carrying capacity of the stream. Smolt releases are based on the assumption that only the transit system is being used, but not all of the fish released are at the smolt transit stage, and some won't smolt at all. These residuals and pre-smolt juveniles will compete with their wild counterparts and lower the wild fish success by changing optimum habitat utilization of the wild fish. As stressed above, restoration requires detailed understanding of the interactive, biophysical attributes and processes that control the survival of salmonids. Management policy has been negligent in assessing even the competitive impacts of hatchery fish on wild populations, and is a prime example where historical reconstruction of population structure and contemporary ecological theory need to be employed in management planning, even when applied evidence is lacking, or is unattainable without commitment to years of applied research. The risk of failure in reaching wild fish production goals is certain where such wild fish management priorities are not considered.

Another example of ecological impacts of artificial production, again has been created by how fisheries management has developed around the original goal of maximizing harvest. 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 were undoubtedly an important source of nutrients to freshwater systems that habitually export nutrients downstream. 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.

D. Populations and Production Trends Over time

As referenced above in the history of the early hatcheries, 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 that began in the 1930s and continued for half a century (Figure 16), habitat was not only lost upstream from the barriers of Grand Coulee and Hells Canyon dams, but spawning and rearing habitat was altered and lost from the nearly continuous line of reservoirs that now represent the trunk streams between Bonneville and the upper barrier dams.

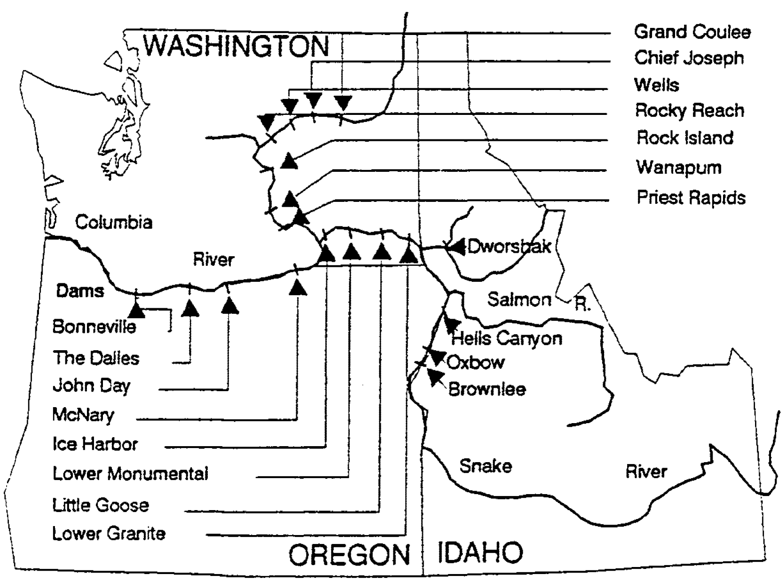


Figure 16. Dams on the Columbia and Snake rivers.

The 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 to 150 million by 1979, and has remained around 120 million since that time.

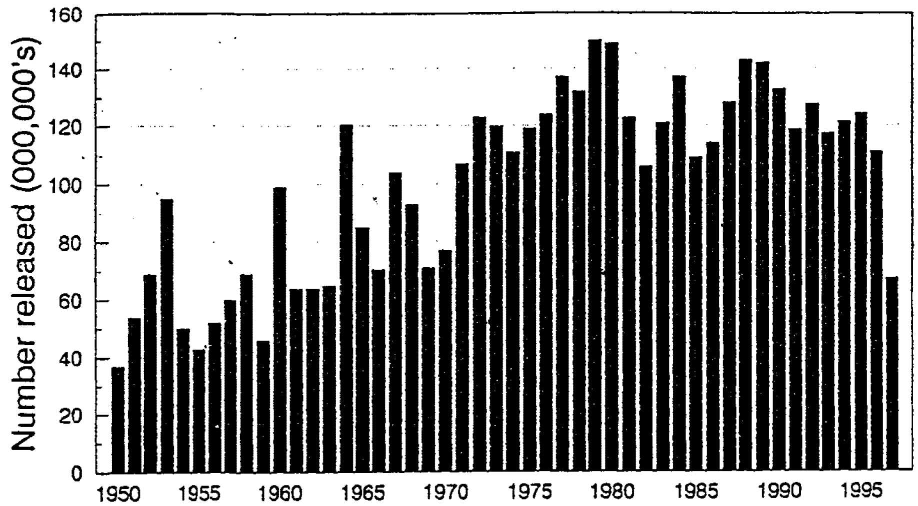


Figure 17. Hatchery contribution to Columbia Basin juvenile salmonid emigration. (Mahnken et al, 1997: Fish Passage Center)

In the meantime, the results of the 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). Peak return was in 1987, following a weak but general trend with increased hatchery production. However, while hatchery production surged to an increase of over 100% from 1969 to 1980, returning adults are shown to have simultaneously decreased about 30% over the same time period.

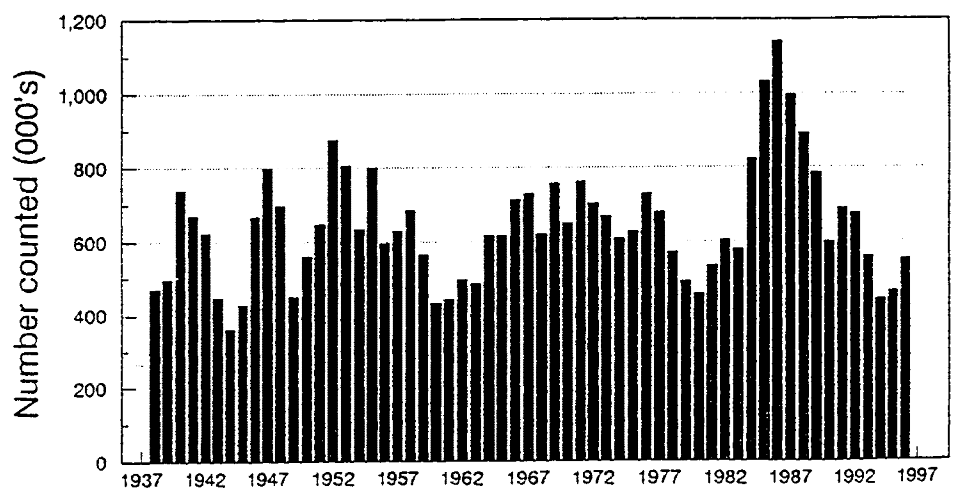


Figure 18. The trend in returning anadromous salmonid populations counted over Bonneville Dam on the Columbia River. (SteamNet 1996)

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 for which hatcheries were built to overcome. Total return of all anadromous salmonids, including commercial landing, have shown a relatively level trend up to the 1990s, and a significant dropping off after that point (Figure 19), while hatchery production remained the same.

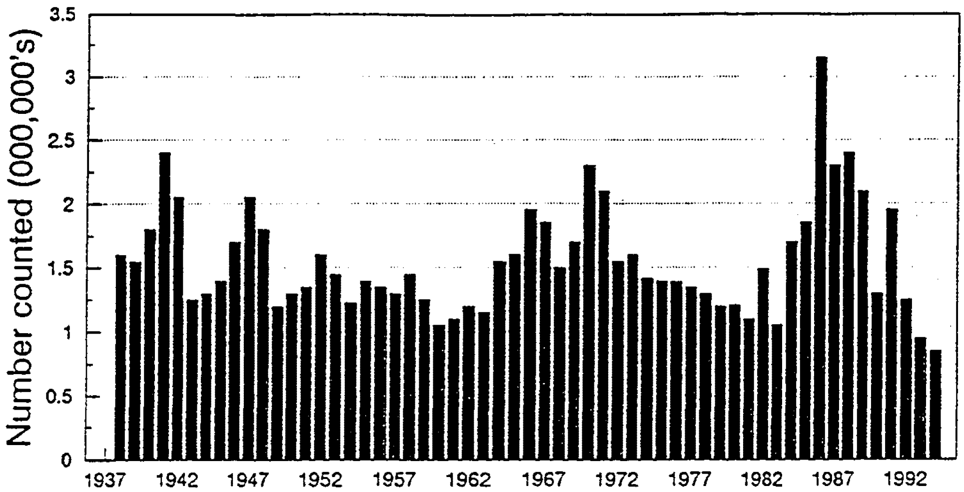


Figure 19. The trend in total return production of returning anadromous salmonid populations to the Columbia River plus commercial landings. (SteamNet 1996)

In retrospect, returning numbers of salmon have been maintained over the years up to the 1990's. 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.

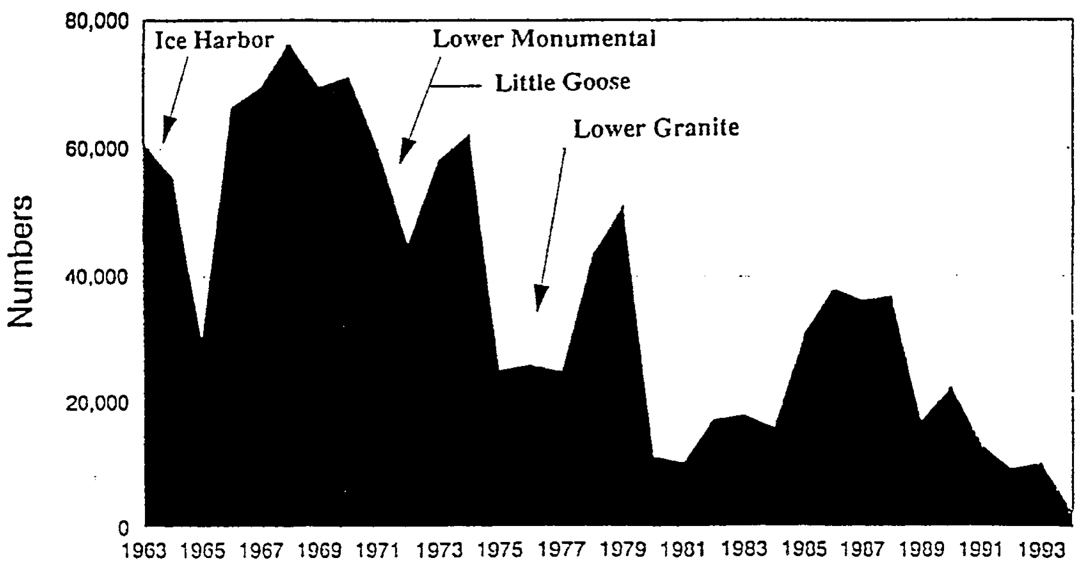


Figure 20. Chinook salmon returns to the Snake River related to the years when Lower Snake Dams were built.

The major 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 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 had been any hope of reaching the mitigation objective of replacement, the corridor passage in the Snake River will have to be resolved.

The ascendancy of the ecosystem management in the Columbia has further complicated the problem on addressing the 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 an objective of equal weight as the objective to mitigation for lost harvest, which means the original process of satisfying mitigation will have to change. Hatchery success is no longer viewed just 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 over harvest of wild fish in mixed stock fisheries. Hatchery fish can sustain higher harvest rates because of lower escapement needs (<10%) to supply production requirements. Wild fish, requiring higher escapements (30% to 60%) 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. That was not an issue before ecosystem health became a fisheries management objective, as demonstrated by the willingness to extirpate runs above Grand Coulee and Hells Canyon dams.

The ecological impacts of hatchery fish reviewed above 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.

E. Management Response to Impacts of Artificial Production

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. That 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. 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. This dual role of artificial propagation is recognized by many salmon biologists and culturists. They 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 questions: what problems did the programs have in the past and specifically how were those problems resolved? Because of the unique, dual role of hatcheries, we have to be sure that the past is really past, and that hatchery products are able to fit in the larger picture of ecosystem function that is being advocated as the new management paradigm.

Hatchery technology has continuously changed over the past 120 years. Hatchery operational design has been improved, the nutritional value of feeds has been increased, disease treatments have been developed, tagging technology has allowed us to monitor contribution and survival of hatchery reared fish, control over hatchery environments such as water temperature and pathogens has increased, and geneticists are integrating genetic principles in fish husbandry practices. Many of the problems that plagued hatchery operations have been resolved, but 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 object 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 undertaken to secure that objective is primary anecdotal

Restoration programs that intend to produce a new future for the river and its salmon must be historically informed, because in a sense the past is never really past. Programs and their philosophical underpinnings evolve which means "new " programs carry in them 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.

VII. Concluding Recommendations

The Scientific Review Team was formed as a subcommittee of the Independent Scientific Advisory Board for the Northwest Power Planning Council, to review artificial production in the Columbia River Basin for the purpose of assisting the Council in recommending to Congress a set of policies to guide the use of federally funded hatcheries. Artificial production in this review refers specifically to the standard production hatcheries of the state, tribal, and federal agencies charged with the responsibility of augmenting harvest and mitigating for loss of natural anadromous salmonid production caused from the economic development of the river.

The committee was made up of seven scientists in the fields of fisheries management, fish culture, population dynamics, genetics, ecology, and salmonid life history. The seven members bring with them backgrounds in fisheries management, artificial production, academia, Native Americans, and the angling public; providing a balance of interests typically associated with hatchery production on the Columbia.

The review process includes three parts, each of which will culminate in a report to the Council; a review of the science associated with artificial production, the preparation of the database, and the analysis of hatchery performance, finalizing the recommendations on policy. The present report is the first phase of the review, the state of the science on artificial production.

A. Scientific Framework

Hatchery production on the Columbia River started before the turn of the century for the purpose of augmenting harvest of chinook salmon in the commercial fishery. By providing optimum incubation conditions in the protection of a hatchery environment, contribution of fry from single females increased five-fold over natural productivity. However, this had little or no impact on overall production in the system. The relative number of fish spawned was small compared to natural spawners, limiting the magnitude of hatchery contribution. Moreover the fry they produced were poorly timed and planted in strange environments showing little reciprocal augmentation. The effort failed because the limiting factor for a stream dwelling species such as chinook salmon is not poor egg survival, but the carrying capacity of the rearing area. When hatcheries switched from egg incubation to rearing of fingerlings for release, production suffered from different problems related to health, habitat, and poor preconditioning for residence in natural streams. Rearing to the smolt stage appears to have been the most promising, but health and preconditioning were also factors in their poor success through a migratory corridor congested with barriers, altered water quality, and exotic species.

The role of science in this process varied from very little in the beginning, apart from the development of fish husbandry, to more formal attention to nutrition, genetics and pathology in recent years. That attention, however, was again centered primarily in the technology of fish husbandry, with little coupling of the concerns about hatchery fish interaction with wild fish, or with the natural (post-release) environment. With the new paradigm of ecosystem function, and the development of the ecological framework, 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 were no longer an accepted template for addressing augmentation or mitigation needs of the resource, and much greater emphasis is placed on the new conceptual foundation under which artificial propagation should proceed.

The architects of the conceptual foundation that guides the use of hatcheries in the Columbia Basin, however, cannot be oblivious of the fact that the Columbia and Snake rivers are systems substantially altered from the historical conditions in which anadromous salmonids evolved. Given that natural populations were assumed to have been highly fit, changes in the migratory corridor will have already disrupted the synchronies critical to survival in the anadromous species. No one doubts the influences of the developed corridor on the survival success of the anadromous populations, which has to be taken into consideration assessing hatchery performance. What isn't recognized, however, and even more serious than the physically induced mortality, is the disarray those influences are having on the biological dynamics of fitness. Not only has the physical habitat markedly changed around flow regimes, velocities, and water temperatures, but community composition of competing and predating species has undergone substantial changes also. All of these factors, apart from any hatchery effect, have major impacts on the reproductive success of wild runs through their disruptive effects on fitness. Those processes carry a heavy toll on performance, especially when the effects of hatchery propagation and barging could retard the adaptive processes wild fish must undergo in the altered ecosystem. Some differences in survival success of Columbia Basin wild and hatchery fish compared with observed success outside the Basin can be attributed to the physical conditions the migrants must face in the altered mainstem of the river, and some of the survival differences could also be attributed to a fitness level discordant with phenotypic needs in the present system.

B. Recommendations

This is not a commentary establishing the role of artificial production in 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 is on the state of the science that relates to artificial production, and in that regard presents recommendations on the appropriate measures to take when artificial production is undertaken in the system. These recommendations, taken with the results of the Phase 2 analysis of hatchery performance, will constitute substantive contribution in the development of policy to guide the use of federally funded hatcheries in the Basin. The recommendations within the scope of Phase 1, the science around artificial production, is in three parts; in the first SRT derived recommendations from three recent reviews (ISG, NRC, NFHRP). The second is based on the SRT's scientific assessment of artificial production. The third addresses what is considered the necessary research to resolve problems with both the technology and management of hatchery programs.

(1) Points of General Agreement with Recent Reviews.

The three recent independent reviews of hatcheries 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 revision of hatchery policy. Ten general conclusions were made, and are listed below.

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

The SRT agrees with the first seven of the ten conclusions, and therefore recommends to the NPPC that those seven elements should be considered in the development of the hatchery policies.

Recommendation 1. Linking supplementation with habitat improvements, and monitoring of hatchery programs are required through formal studies and increased emphasis on hatchery related research.

Justification: It is understood that the goals sought by hatcheries have changed over the years, and the most recent efforts of supplementation and captive broodstock production may have succeeded in their numerical production objectives, as had earlier hatcheries with regard to juvenile releases. The issue is that the result of that production on increased return has generally not been demonstrated. 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 below the lower Columbia dams was considered an 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 refereed literature, which is needed to provide fair analyses of programs. Issues around genetics, stock transfers, and limited effort to avoid overfishing wild stocks mixed with hatchery fish, are symptomatic of the previous philosophy minimizing natural production. Given the present emphasis on the ecosystem approach, these issues are now important and are given priority in the development of the new conceptual foundation for artificial production.

Of the remaining three conclusions, the SRT concedes that *stock transfers and introductions of non-native species* is a practice that can place serious risk on native stocks of fish and should be discontinued except in those situations where a stock of fish has gone extinct and restoration is the objective.

Recommendation 2. Stock transfer should be eliminated from hatchery programs, except in those situations where the purpose is to restore an extirpated run.

Justification: Weak native runs have been scheduled for replacement in the development of hatchery programs, such as the original plan regarding Sooes River fall chinook salmon. Such action must not be tolerated. Diversity is the key to the long-range success of salmonid populations, and adaptive traits should never be willfully abandoned. In those 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 based simply on egg availability, but careful analysis is required to assure environmental relationships between donor and target streams are as compatible as possible for the stock selected.

Conclusions that *artificial production should have a new role in fisheries management,* and *hatcheries should be used as temporary refuges, rather than for long-term production,* are considerations that require assessment or research on the specific issue before such conclusions should be part of a policy recommendation. The primary role of hatcheries in the Basin is mitigation for the loss of harvest as a result of reduction of habitat. Given the extent of habitat loss from economic development of the Columbia and Snake rivers, and the present encroachment of man 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, none-the-less they account for the majority of production in the Basin.

Changing the role of hatcheries is probably not an option, but changing the manner in which hatcheries address their role is the hope sustaining the conviction that hatcheries can succeed. Based on the past performance of hatcheries 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 expectation 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 meets both ecological and economic objectives.

(2) Recommendations from Scientific Analysis

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

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

(a) *Technological Principles*

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). Some of the items listed in recommendation 3 are already practiced at some hatcheries. 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 is the list only reaffirms the importance place on them.

Recommendation 3. Continue using and developing technology to more closely resemble natural incubation and rearing conditions in hatchery propagation to include:

a. incubation in substrate and darkness
b. incubation at lower densities
c. rearing at lower densities
d. rearing with shade cover available
e. exposure to in-pond, natural-like habitat
f. rearing in variable, higher velocity habitat
g. non-demand food distribution during rearing
h. exposure to predator training
i. minimize fish-human interaction
j. acclimation ponds at release sites
k. volitional emigration from release sites

Justification: Lower rearing densities, minimum exposure to humans, and shade cover over raceways enhances fish quality and maintain 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. These are positive advancements in hatchery production operations that are applauded and encouraged to continue. Although accelerated rearing can easily overcome any size deficiency of the fry experienced at the time of emergence, what isn't known are the other potential requirements natural incubation conditions impart to the normal ontogeny from embryo to fingerling.

Recommendation 4. New hatchery facilities need to be incorporated in hatchery programs that are designed and engineered to represent natural incubation and rearing habitat, simulating incubation and rearing experiences complementary with expectations of wild fish in natural habitat.

Justification: Hatchery technology in the Columbia has been based primarily on standard tray incubation, concrete raceway design technology based on engineering designs around efficiency and convenience for culture operations. Qualities associated with natural habitat have not been incorporated in such designs, and fish reared in standard concrete raceways learn behavior (conditioned) 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 incorporate new 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 simulate natural conditions. Training would include exposure to conspecific size variability and exposure (limited) to predation.

Recommendation 5. 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.

Justification: Assuring that technological advances in hatchery propagation are part of hatchery operational plans is critical to the implementation on 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.

(b) *Management Principles*

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 is to 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. Detail on these issues are in the following resolutions, but it needs to be understood that in many cases where scientific principles are advocated, applied evidence is not available to demonstrate the precept. Theory and the forthcoming principles to address problems they exemplify are 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 is an example. May 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.
The several recommendations pertaining to management principles are listed below.

Recommendation 6. 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

Justification: As an integral component in a complex ecological system, salmonid stocks have evolved in synchrony 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 Ståhl 1980; Allendorf and Utter 1979) is 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.

Recommendation 7. Hatchery propagation should use large breeding populations to minimize inbreeding effects and maintain what genetic diversity is present within the population.

Justification: One of the potential negative effects of artificial production is that relatively small breeding populations are involved in hatchery programs. Even when a hundred thousand fingerlings are scheduled for supplementation, that number represents a little over 25 females for broodstock, 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 risk in using small breeding populations is loss of diversity, and also 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.

Recommendation 8. To mimic natural populations, hatchery production strategy should target natural population parameters in size and timing among emigrating juveniles to synchronize with environmental selective forces shaping natural population structure.

Justification: 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 which 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.

Recommendation 9. Hatchery policy should utilize ambient natal stream habitat temperatures to reinforce genetic compatibility with local environments and provide the temporal synchrony between stock and habitat that is responsible for population structure of stocks from which hatchery fish are generated.

Justification: Temperature unequivocally is argued as the factor determining 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 the most critical environmental factor 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.

Recommendation 10. Hatchery incubation and rearing experiences should use the natal stream water source whenever possible, to enhance homestream recognition when supplementation projects are designed for natural populations.

Justification: 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 recommendation 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 sited on locations where access to appropriate water sources is available.

Recommendation 11. 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. 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.

Justification: 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 natural population from which the brood lot was derived.

Recommendation 12. New 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.

Justification: 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 most 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 recommendation 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.

Recommendation 13. Hatchery supplementation programs must avoid using strays in breeding operations with returning fish. Stock hybridization breaks down genetic homeostasis and disrupts adaptive linkages which lowers the fitness of the local stock and defeats the objective.

Justification: 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. Examples of reduced fitness from hybridization was demonstrated by Reisenbichler (1998). 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.

Recommendation 14. 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.

Justification: 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 re-work to establish specificity with the environmental conditions. Restoration can use different genetic-based approaches, depending on the situation, but the characteristics in the donor stock(s) is 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.

*Recommendation 15. **Germ plasm repositories 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.***

Justification: One of the most important considerations in the Columbia Basin fisheries management plan is to preserve the genetic diversity that presently exists. Diversity is inherent to the stability of the species and 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 presently being employed with some ESA listed salmonid stocks. This effort needs to be examded, 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.

*Recommendation 16. **The physical and genetic status of all natural populations of anadromous and resident salmonids need to be understood and routinely reviewed as the basis of management planning for artificial production. Information should include life history, population structure, and the habitat utilized.***

Justification: Knowing the status of the endemic stock where hatchery fish are involved is imperative under the ecological framework of fisheries management. 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.

(3) Recommendations 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. The following recommendations address the research and monitoring needs associated with management under the ecological framework.

*Recommendation 17. **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.***

Justification: 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.

Recommendation 18. ***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 andreturn.***

Justification: 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 functional in honing hatchery programs.

Recommendation 19. ***A study is required to determine cost of monitoring hatchery performance, and source of funding.***

Justification: 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.

Recommendation 20. ***Regular performance audits of artificial production objectives should be undertaken, and where they are not successful, research should be initiated to resolve the problem.***

Justification: 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.

Recommendation 21. ***The NPPC should appoint an independent peer review panel, to develop a Basin-wide artificial production program plan to meet the ecological framework goals for hatchery management.***

Justification: 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, is an essential element early in the planning process. The responsibility will require an appointment of an independent peer review panel that through solicitation of agency, tribal, public interests, can give careful and appropriate consideration to the experience represented in the management community.

The SRT has identified the minimum scientific basis in the conceptual foundation on artificial production in the Columbia River Basin. With review of the hatchery program and production data, more hatchery specific assessment will be provided as a broader treatment of artificial production for hatchery policy recommendations to the Council.

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Appendix

Regional Scientific Questions on Artificial Production

*1. What are the ecological impacts of artificial productio*n 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, predation at different rates? If they do, then should the agencies and tribes in their management program 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 over

harvested. 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 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 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?
- o Can these wild native populations be recovered using supplementation where wild brood stocks are used in the hatchery program?
- o Can hatchery supplementation increase the numbers of fish while maintaining the productivity (fitness) of the affected population over time?
- o 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 residence fish.