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Pacific Salmon Hatcheries in British Columbia

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Abstract.—Of the many technologies used by the Canadian Salmonid Enhancement Program (SEP, established in 1979), hatcheries have been a major tool used to increase the freshwater survival of selected wild, native stocks of coho salmon *Oncorhynchus kisutch*, Chinook salmon *O. tshawytscha*, and chum salmon *O. keta*, both to address conservation concerns and to provide fishing opportunities. Salmonid Enhancement Program hatcheries have contributed substantially to the fisheries for coho and chum salmon, and less so to the fisheries for Chinook salmon. Although hatcheries have successfully provided high survival environments in freshwater, once released, artificially propagated fish are subject to the same environmental constraints and high mortality rates as are naturally propagated fish. Wild fish from both these components of coho and Chinook salmon stocks encountered substantially lower marine survival in the 1990s compared to the 1980s. Salmonid Enhancement Program tag studies show that marine survivals of hatchery salmon stocks have also been extremely variable, in spite of fairly consistent smolt release strategies. The approach taken by SEP to fully integrate hatchery and naturally produced components of endemic wild stocks of Pacific salmon, in conjunction with improvements in habitat and harvest management, should maximize long-term stock viability in Canada.

Background

British Columbia has a large landmass (950,000 km^2) with a small human population (~4 million) that is concentrated in a few urban centers (85% urban), partly because the province is extremely mountainous (75% is more than 1,000 m in elevation; Cannings and Cannings 1996). The tiny amount of flat, arable land (98.5% of the land area has moderate or severe restrictions for agriculture; McGillivray 2000) makes renewable natural resource extraction, including fisheries, especially important for economic activity in the province. There are almost 10,000 spawning populations that have been identified as stocks of Pacific salmon in British Columbia, with stock sizes ranging from a few fish to several million (Slaney et al. 1996). Because the province's topography is dominated by a mountainous landscape with narrow valleys, almost all human activities have major effects on salmon freshwater habitat. These impacts can only increase as the population of the region increases in the future (Lackey 2003).

Fish culture has a long history in the management of Pacific salmon stocks in Canada. Early hatchery programs (1894–1938) concentrated on sockeye salmon *Oncorhynchus nerka* and involved collecting and hatching hundreds of millions of eggs to make up for the combination of destruction of freshwater spawning habitat brought on by gold mining and logging, and high exploitation rates in the commercial fishery. The large hatchery programs of the early 1900s involved planting eyed sockeye eggs or sac-fry into lakes and resulted in only minor demonstrable improvements to natural production (Foerster 1968). This fairly ineffective technique could not make up for the resource extraction of the industrial fishery, and under funding pressure during the Great Depression of the 1930s, all Canadian Pacific salmon hatcheries were shut down by 1938 (Roos 1991).

In 1974, Peter Larkin, one of the deans of Canadian fisheries science, wrote an essay that reaffirmed the biological, economic and social justification of improving the freshwater survival of salmon through a variety of "enhancement" measures and recommended the formation of an agency with "the single responsibility of salmon enhancement" (Larkin 1974). Larkin assumed that the high historical abundance of salmon

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indicated that there was sufficient ocean carrying capacity for higher production and that the main productivity bottleneck occurred during freshwater in "natural" conditions. At that time, the federal government (now Fisheries and Oceans Canada) operated one spawning channel each for pink salmon *O. gorbuscha* (at Jones Creek since 1953), chum salmon *O. keta* (at Big Qualicum River since 1959) and sockeye salmon (at Fulton River since 1965), as well as four combination Chinook salmon *O. tshawytscha*/coho salmon *O. kisutch* hatcheries (at Big Qualicum River since 1967, Capilano River since 1971, Robertson Creek since 1972, and Quinsam River since 1974). After a few years of planning, the Salmonid Enhancement Program (SEP) was initiated in 1977–1979 with the long-term goal of doubling salmon catches in British Columbia. The SEP consisted of an ambitious program of hatcheries, spawning channels, obstruction removal, lake enrichment, and other enhancement techniques in a process that included oversight and involvement by a wide range of interested parties, particularly local community and resource user groups.

Unlike other salmon hatchery programs in the Pacific Northwest, which had transplanted fish from one watershed to another without concern for local adaptation (Taylor 1999), the SEP was specifically designed to enhance the freshwater productivity of wild, native salmon stocks. The best genetic and fish-culture information was gathered from the successes and failures of previous programs in the United States and Japan to ensure that the fish temporarily raised in hatcheries and other enhancement projects maintained their genetic adaptation to the natural environment. Salmonid Enhancement Program facilities only enhance wild salmon—no domesticated stocks have ever been introduced and no evidence of any in-hatchery selection (domestication) that is outside the normal range of naturally produced salmon populations has ever been detected. While fish reared in a hatchery may appear slightly different (e.g., in body size, shape, or color, or in some behaviors) because of artificial rearing conditions, they are genetically the same as their naturally produced cousins, and these superficial differences fade away as the fish adapt to oceanic conditions (MacKinlay and Howard 2002).

In Canada, the federal government has jurisdiction over all fish and fisheries through the Fisheries Act of 1867 (with several revisions: http://laws.justice.gc.ca/en/F-14), but has delegated to the provincial government the authority over freshwater fishes in British Columbia, including rainbow trout *O. mykiss* and cutthroat trout *O. clarkii* (which also have anadromous stocks—steelhead and sea-run cutthroat). SEP carries out some steelhead and sea-run cutthroat propagation in cooperation with the B.C. government, which also has its own independent management and propagation programs.

Outline of the Salmonid Enhancement Program

The main goals of the SEP have changed somewhat since its inception, with less emphasis on fish production for harvest and more emphasis on conservation and the integration of enhancement, habitat, and harvest activities (Perry 1995). The current goals can be summarized as follows:

- Restore depleted stocks to higher levels of abundance (by increasing freshwater survival directly using hatcheries and spawning channels or indirectly through habitat improvement);
- Mitigate for major habitat losses (including from dams and urbanization impacts);
- Provide for harvest opportunities (especially for terminal or selective fisheries).
- Re-establish extirpated stocks (by introduction of fish from similar stocks into abandoned, and presumably underutilized, habitat);

The SEP has taken a multipronged approach to enhancing wild salmon stocks that includes

- Hatcheries: provision of controlled spawning, protected incubation, and, usually, rearing to fry or smolt size,
- Spawning channels: groundwater or river-fed, manned and unmanned structures to increase the available area and improve conditions for spawning and in-gravel incubation,
- Seminatural fish culture structures: incubation boxes, side-channel spawning/rearing, and so forth, to increase freshwater survival with low tech/low-cost intervention,
- Fishways: placement of structures or removal of obstructions to improve fish passage past barriers,
- Habitat improvements: placement or removal of structures to increase spawning and rearing productivity,
- Lake and stream enrichment: addition of nutrients/carcasses to lakes and streams to increase primary productivity, leading to greater food avail ability for juvenile salmon,
- Public education: classroom and educational ac-

tivities, outdoor-club, aboriginal, and other community-based activities to increase awareness and stewardship of fish stocks and habitat and to provide economic opportunities in remote communi ties.

The approach taken in the SEP meets or exceeds the recommended guidelines for the use of cultured fish in resource management, as outlined by the American Fisheries Society (Anonymous 1995). In short, those guidelines recommend that the following categories be considered before implementing a stocking program:

- Biological feasibility: assessment of the carrying capacity of the target ecosystem was covered by the extensive bioreconnaissance and feasibility studies done by SEP prior to implementation of all major facilities.
- Effects analysis: the main problem of genetic effects from introduced fish on local populations is not a concern when the cultured fish are from the local, wild population.
- Economic evaluation: SEP carried out thorough benefit:cost analyses on all major projects, including nonmonetary criteria (see Box 1).
- Public involvement: encouragement of public participation has been a mainstay of the SEP.
- Interagency cooperation: another major part of the SEP original structure.
- Administrative considerations: clear management objectives, operational guidelines for each facility and strategic plans both for biological and agency processes have been part of SEP's continual re definition of itself since its inception.

Box 1. Enhancement facilities – Performance measures

The current criteria for performance indicators include

- Rebuilding/conservation benefits - measured in terms of the conservation goals of the project and the probability of the project successfully meeting the goals.
- Fishery benefits - previously measured as the benefit/cost ratio. Fishery benefit is now a subjective measure of the importance of the enhanced production to commercial and recreational fisheries.
- Rebuilding potential - measured in terms of the value of the facility to respond to local conservation programs given its existing superstructure.
- First Nation benefits - measured in terms of the cultural, economic and relationship importance of the facility to aboriginal communities.
- Assessment benefits - measured in terms of the project's importance for salmon stock assessment.
- Regional integration and fish habitat stewardship benefits - measured in terms of the project's integration with other enhancement, research, restoration, and stewardship initiatives.
- Joint ventures/partnerships - measured as significant partnerships that contribute to delivering all aspects of the program.

The objectives of enhancement facilities and the indicators that measure them are

Enhancement objectives	Indicators
1. Production objectives (conservation, rebuilding, sustaining a fishery, etc.).	1. Rebuilding benefits 2. Fishery benefits 3. Rebuilding potential
2. Maximize social benefits.	4. First Nation benefits
3. Collect and provide data for assessment and performance evaluation.	5. Assessment benefits
4. Support stewardship, education, and community involvement.	6. Regional integration and fish habitat stewardship
5. Promote joint venturing/partnerships.	7. Joint ventures/partnerships

Operating guidelines are used to ensure that enhancement activities

- Minimize impact on other fish stocks
- Optimize survival and minimize disease
- Maintain genetic diversity
- Minimize negative environmental and ecological impacts

Salmonid Enhancement Program hatcheries fall into three main categories (Tables 1–3, Figure 1):

- Major facilities: Currently, 18 facilities are operated by professional fish culturists who are government employees (two projects are contracted out) and who follow relatively consistent procedures with technical oversight from regional specialists (biologists, data managers, engineers, administrators, etc.).
- Community development projects (CDP): Currently 21 facilities are operated by employees of local community groups under contract to the government with technical oversight from local community advisors.
- Public involvement projects (PIP): These projects are operated mostly by volunteer and part-time staff, with some technical assistance from community advisors. There are currently 178 PIPs, incorporating a wide range of sizes, from classroom incubators to quite substantial hatcheries. The active volunteer workforce in all SEP hatcheries amounts to about 10,000 people, with about double that number being involved in additional projects in public education and habitat improvement.

The SEP was incorporated into a new Habitat and Enhancement Branch (HEB) in 1996, with no substantive changes in the role or operation of hatcheries, save ongoing budgetary shortfalls.

This paper concentrates on coho, Chinook, and chum salmon that are raised in major facility hatcheries. It does not discuss SEP spawning channels, incubation boxes, engineered side-channels, fish passage projects, lake enrichment, classroom incubators, or the myriad habitat restoration, conservation, or creation projects that have been carried out to improve the freshwater survival of salmon beyond the "natural" conditions.

Fish Culture Strategies and Guidelines in SEP

The strategy for enhancing populations of local, wild salmon in SEP hatcheries has been to mimic the optimal natural conditions and life history characteristics of each species as much as possible in a program that integrates (HSRG 2003) the naturally produced and hatchery-produced portions of the target wild stocks. This is compatible with current scientific thought on minimizing negative effects from fish culture operations on the "wildness" of salmon stocks (Miller and Kapuscinski 2003). The SEP strategy includes

- Using local broodstock wherever possible (more than 95% of cases);
- Using mating procedures that provide adequate

Table 1. Summary of fish released from major hatcheries of the Salmonid Enhancement Program in 2002 (does not include releases from spawning channels or other low-tech projects).

	Species						
Project	Chinook	Chum	Coho	Pink	Sockeye	Steelhead	Cutthroat
Big Qualicum River Hatchery	4,681,331		1,219,928				
Capilano River Hatchery	612,809	8,441	885,474	3,867		18,384	
Chehalis River Hatchery	2,737,186	5,885,195	1,164,298			88,179	20,695
Chilliwack River Hatchery	1,590,378	1,612,557	2,108,776		3,715	131,879	
Conuma River Hatchery	2,283,828	4,152,899	167,714			10,157	
Inch Creek Hatchery	307,169	1,174,630	670,914			19,934	
Kitimat River Hatchery	1,752,095	4,921,186	498,328			46,566	1,288
L Qualicum River Hatchery	3,115,729						
Nitinat River Hatchery	3,730,065	30,256,682	350,270			9,823	
Pallant Creek Hatchery		410,365	305,455				
Pitt River Hatchery					11,142,175		
Puntledge River Hatchery	5,004,563	3,505,768	1,447,375	2,360,276		76,497	
Quinsam River Hatchery	4,025,938		1,454,810	6,279,294		14,557	6,433
Robertson Creek Hatchery	6,419,764		921,913			71,244	
Shuswap River Hatchery	908,200		92,800		757,650		
Snootli Creek Hatchery	2,310,779	6,860,828	192,000		833,817		
Spius Creek Hatchery	371,775		187,673				
Tenderfoot Creek Hatchery	1,358,856		459,602	791,516			
Major facilities total	41,210,465	58,788,551	12,127,330	9,434,953	12,737,357	487,220	28,416

Table 2. Summary of fish released from Community Development Program (CDP) hatcheries of the Salmonid Enhancement Program in 2002.

	Species						
Project	Chinook	Chum	Coho	Pink	Sockeye	Steelhead	Cutthroat
Clayoquot Hatchery	564,000						
Cowichan River Hatchery	3,228,287						
Deadman River Hatchery			34,248				
Fort Babine Hatchery	104,678		155,998				
Gwa'ni Hatchery	138,888	5,526,105	139,213		100,752		
Hartley Bay Creek Hatchery			62,000				
Heiltsuk Hatchery		1,079,608	187,383		25,954		
Kincolith River Hatchery	75,100						
Klemtu Creek Hatchery		768,521	68,654		22,000		
Masset Hatchery	135,901		50,000				
Nanaimo River Hatchery	545,352	498,706	160,032				
P Hardy/Quatse	44,389	75,767	231,534	1,184,315		45,969	
Penny Hatchery	165,701						
Powell River Hatchery	668,480	696,553	305,104				
San Juan River Hatchery	785,000	3,000	375,000				
Sechelt Hatchery	144,194	331,250	167,317	241,001			
Seymour River Hatchery	7,992	52,366	118,161	432,072		38,963	1,068
Sliammon River Hatchery	161,077	1,141,716	27,000				
Thompson River Hatchery			87,954				
Thornton Creek Hatchery	602,210	607,678	234,329				
Toboggan Creek Hatchery	57,874		112,091				
CDP total	7,429,123	10,781,270	2,516,018	1,857,388	148,706	84,932	1,068

Table 3. Summary of fish released from Public Involvement Project (PIP) hatcheries of the Salmonid Enhancement Program in 2002 (by geographic region).

	Species						
Project	Chinook	Chum	Coho	Pink	Sockeye	Steelhead	Cutthroat
Nass River			80				
Central Coast			8,881				
Georgia Strait N	222,070	667,676	256,324	234,186	32,709		
Georgia Strait S	190,000	97,000	102,587			7,017	3,983
East Vancouver Is	475,500	1,321,815	718,193	3,549,000			
Johnstone Strait	170,225	15,000	813,085	56,160		22,000	
Lower Fraser River	296,553	676,545	714,881	1,509,542		25,310	15,021
North Coast			1,275				
NW Vancouver Island	1,601,571	28,853	572,302			6,435	
Queen Charlotte Islands		70,900	264,414				
Rivers/Smith Inlets	221,585						
Skeena River	233,254		52,502				
SW Vancouver Island	414,236		357,940				
Thompson River	192,911		1,700				
Yukon/Transboundary	33,034	624			250		
Upper Fraser River	3,600						
PIP total	4,054,539	2,878,413	3,864,164	5,348,888	32,959	60,762	19,004

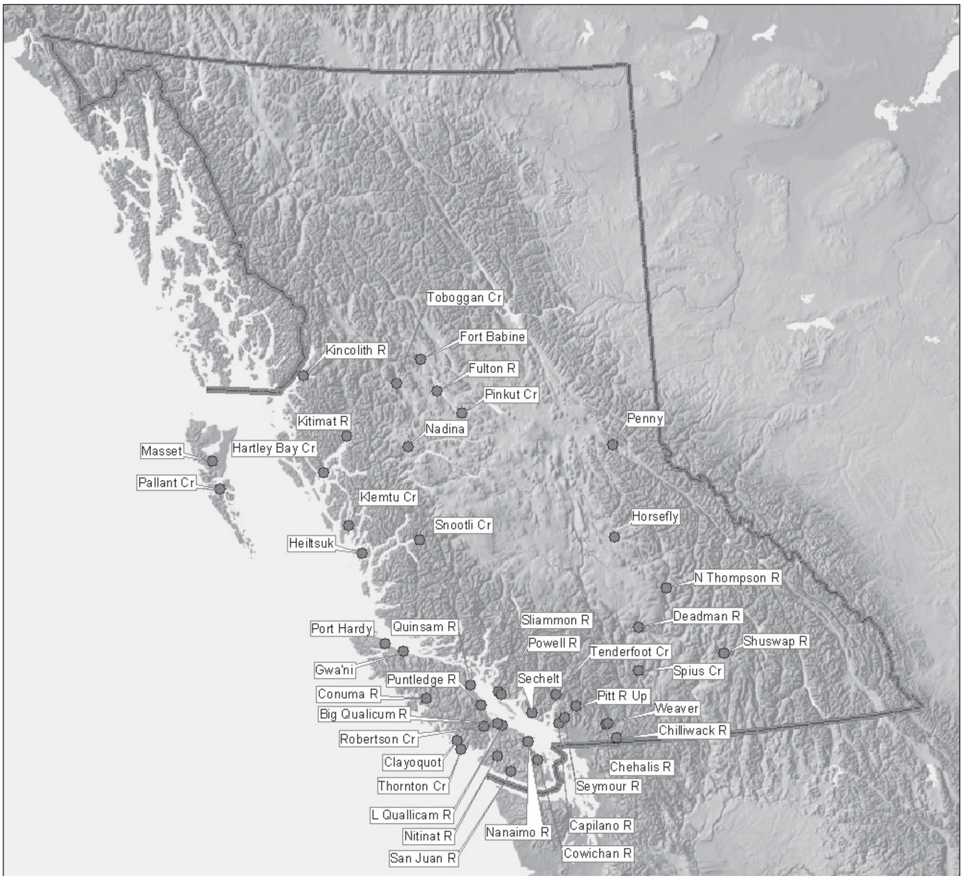

Figure 1. Location of the Community Develpment Program and major Salmonid Enhancement Program hatcheries in British Columbia. (the major spawning channels at Fulton, Pinkut, Nadina, Horsefly, and Weaver are also shown).

genetic diversity (no bulk spawning, use of matrix spawning for small groups);

- Taking eggs from broodstock throughout the extent of the natural spawning timing;
- Releasing smolts at a similar weight to the best surviving naturally produced migrants, so that they migrate quickly and avoid freshwater interactions;
- Timing releases to coincide with natural migrations, usually with volitional release.

Different stocks of the same species exhibit different life history strategies (i.e., length of time spent in freshwater or the ocean) due to natural variability within acceptable limits or in response to different environmental conditions (Groot and Margolis 1991). However, the "natural" conditions that are observed are often not "optimal" for that stock because of varying constraints to its productivity (low nutrients, coldwater incubation, or limited rearing area). In general, SEP has employed very similar strategies (the ones with the best proven survival record) for each species regardless of which stock was being reared. For the common species, these strategies are as follows:

- Coho—Hatchery production of coho usually involves incubation in stacked trays and rearing in concrete or earthen channels to the smolt stage of 15–25 g for release in the spring. This requires incubation and rearing for 1.5 years in freshwater, as is the normal condition for most naturally produced coho (Sandercock 1991).
- Chinook—Chinook culture uses the same basic techniques as coho production, but because some Chinook projects handle very large numbers of fish, there is more use of bigger containers (bulk incubators, large raceways). Smolt size is much smaller for Chinook (3–8 g) than coho, so incu-

bation and rearing can be completed for spring release the year following spawning, as is common for coastal and southern Chinook stocks. Most noncoastal stocks are reared for a year (to 15–20 g) in freshwater, as is the condition for naturally produced inland Chinook (Healey 1991).
- Chum—The Japanese hatchery technique for enhancing chum salmon was adopted with little modification by SEP (McNeil and Bailey 1975). This involves bulk incubation to the eyed stage, placement in gravel-lined channels until swim-up, then rearing in concrete raceways to the 1–3 g size for release in the spring. Naturally spawned chum salmon normally migrate to estuarine areas immediately upon emergence from the gravel, but a short-term of feeding in freshwater has been shown to give a substantial increase in marine survival (Salo 1991).
- Pink—Because pink salmon migrate to the ocean immediately upon emergence from the gravel (Heard 1991), SEP enhancement of pinks has usually involved only provision of incubation assistance, either in a spawning channel or in bulk incubation boxes in hatcheries, with no feeding prior to release. Some short-term sea-pen rearing has improved survival of some stocks.
- Sockeye—Most SEP sockeye come from spawning channels, where only the physical conditions for natural spawning and incubation are controlled to increase spawning and incubation success. Sockeye hatchery projects have used bulk and tray incubators, rearing raceways and (freshwater) net-pens, usually releasing at 1–2 g size. Currently a sockeye captive brood program is being carried out on two sockeye stocks (Cultus and Sakinaw) that have been officially listed as threatened with extinction (http:/ www.cosewic.gc.ca).

Despite their initial time in the hatchery, SEP fish spend by far the bulk of their lives (and gain more than 99% of their body mass) in the natural environment (Table 4). There, they are subject to the same selective pressures as naturally produced fish, so we expect very little selective pressure to cause deviation from the wild genetic composition and adaptability to the natural environment (Amend et al. 2002). The hatchery environment is not as rigorous (deadly) as nature, so we also expect that hatchery fish require some initial acclimation period after release (with attendant increased mortality) to prepare them physiologically and behaviorally for the rest of their lives.

Table 4. Average size at release and maturity, and duration of hatchery phase, for Salmonid Enhancement Program salmon.

Species	Juvenile size at release	Adult size at maturity	Release as % of adult size
Coho	20 (15–25) g	5 kg	0.4
Chinook	5 (3–8) g	15 kg	0.03
Chum	2 (1–3) g	10 kg	0.02
Sockeye	0.15 g	7 kg	0.002
Pink	0.1 g	2 kg	0.005
Steelhead	80 (60–100) g	5 kg	1.6

Species	Total time in hatchery	Total length of life (age)	Hatchery time as % of total
Coho	10 months	36 months	27.8
Chinook	3 months	48 months	6.3
Chum	2 months	48 months	4.2
Sockeye	N/A	48 months	0
Pink	N/A	24 months	0
Steelhead	10 months	36 months	27.7

Salmonid Enhancement Program hatcheries follow a wide range of operational guidelines that are in a constant state of re-evaluation and renewal (see the SEP Web site for the latest versions: www-heb.pac.dfo-mpo.gc.ca, then go to “publications,” then “Guidelines”). These are generally meant to minimize the potential negative effects and maximize the potential positive effects of the hatchery on adjacent nonenhanced stocks. They include

- Genetic guidelines for broodstock collection and spawning (including stock recovery guidelines)
- Genetic guidelines for incubation, rearing, and release
- Guidelines for small-scale enhancement for educational purposes
- Captive broodstock program guidelines
- Introductions and transfer guidelines
- Carcass placement guidelines
- Coho fry planting guidelines
- Sockeye culture guidelines
- Fish health management plans

Program Evaluation

The SEP incorporated an intensive assessment component from the program outset and is arguably one of the most frequently evaluated programs in the Canadian government, with major evaluations being conducted almost every year from the mid-1980s to the mid-1990s (1985, 1988, 1989, 1992, 1993, 1994) by the Department of Fisheries and Oceans Internal Audit and Evaluation Branch or by economic or management consultants. The SEP assessment methodology for component projects was developed to support these evaluations. Regardless of project size, all SEP production has been assessed, with the assessment method dependent on the species and enhancement technology employed. Assessment includes estimates of total production and contribution of enhanced fish to the fisheries and escapement for each project and for the program as a whole. The specific data used in this report were compiled using the methods outlined below.

Methods

Release Numbers

Releases from hatcheries were enumerated from hatchery records by subtracting egg and fry mortalities from the number of eggs taken or by subtracting fry mortalities from fry counted during marking. All release data originating from projects funded by or receiving technical support from the DFO's Habitat and Enhancement Branch (HEB, which includes SEP) are reported and stored in a centralized database maintained by HEB. Copies of these data are also provided to the Regional Mark Recovery Program database (Kuhn et al. 1988) and to the coastwide database maintained by the Pacific States Marine Fisheries Commission. Data for this report were extracted from the HEB database and included information only for projects using hatchery technology. Migration data from spawning channels were not included. Also, release data for provincial trout facilities and some aboriginal community projects funded outside of HEB were not included. A map with the locations of Major Facility and Community Economic Program hatcheries is shown in Figure 1. Release information is presented in Tables 1–3 and Figure 2.

Contribution to Catch

The hatchery contributions to harvests for Chinook, chum, and coho were calculated for commercial fisheries and southern B.C. marine recreational catches (West Coast Vancouver Island and Strait of Georgia recreational fisheries were monitored by creel surveys). Aboriginal fisheries (for food, social, and ceremonial purposes) and northern British Columbia, central British Columbia, and in-river recreational catches were

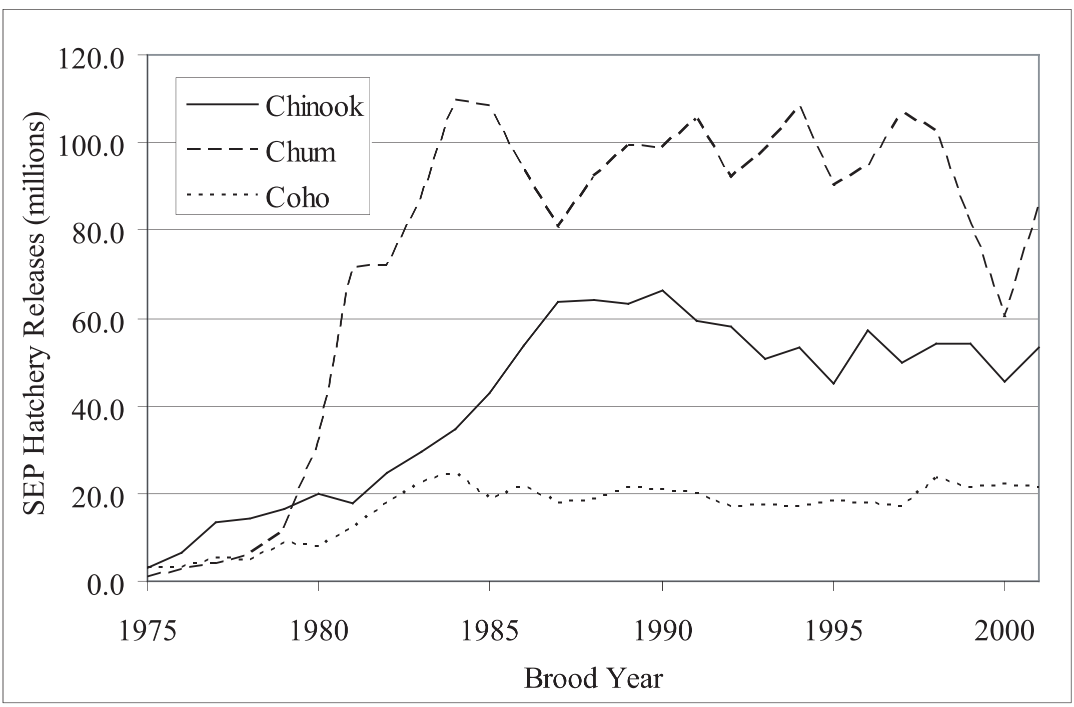

Figure 2. Releases of Salmon juveniles from Salmonid Enhancement Program (SEP) hatcheries.

not included because total catch for these fisheries was either not available or was estimated inconsistently. Total catch for commercial catch came from sales slip records. Total recreational catch was estimated by multiplying the total number of boats fishing in an area and time period (from overflights) by the average catch per boat (from creel surveys). Hatchery contribution and total harvest are shown in Figures 3–6.

Estimates of enhanced contribution to marine fisheries of Chinook, coho, and chum salmon enhancement projects were based on marking a portion of the juveniles released and recovering these marks in the fisheries and escapement. Marking was conducted at the project sites prior to release, while recovery was made through (1) coastwide sampling programs in the sport and commercial fisheries (Kuhn et al. 1988),

Figure 3. Total catch of coho salmon in Canada. Salmonid Enhancement Program hatchery contribution is shown in darker shading.

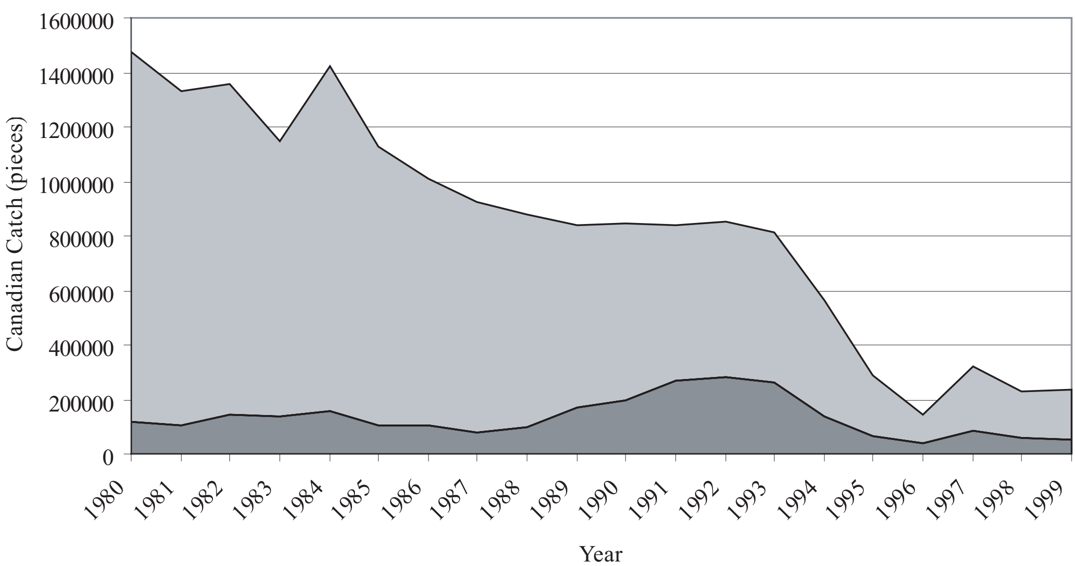

Figure 4. Total catch of Chinook salmon in Canada. Salmonid Enhancement Program hatchery contribution is shown with darker shading.

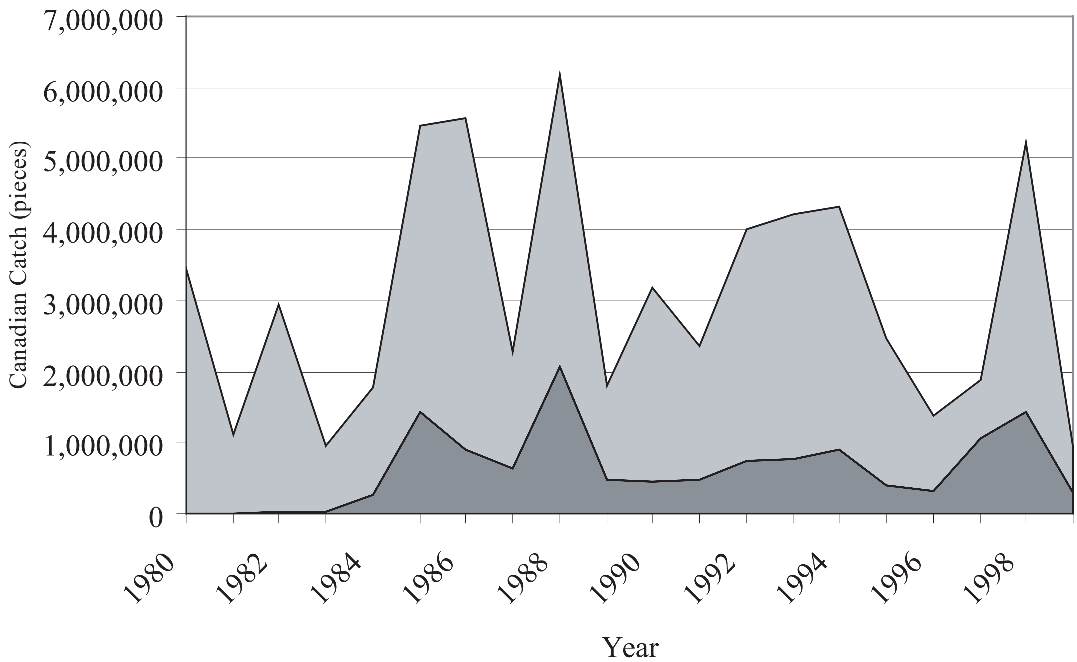

Figure 5. Total catch of chum salmon in Canada. Salmonid Enhancement Program hatchery contribution is shown in darker shading.

(2) counting adult returns to the project site (rack), and (3) carcass recovery programs on the spawning grounds. Mark type was dependent on the species, with coded wire tags (CWTs) used for Chinook, coho, and some chum stocks, and fin clips for other chum stocks. A portion of the release group is marked and assumed to represent the unmarked fish. Tags and fin clips observed in the fisheries are expanded for sample rate and the proportion of the release that was marked, to estimate total enhanced catch. These release groups are known as "associated" releases.

It was not possible, either logistically or financially, to undertake a direct assessment of Chinook, coho, and chum for each enhancement project and release strategy. Release groups which are not represented by a mark are known as "unassociated" releases.

The enhanced contributions of coho and Chinook for unassociated releases were estimated by expanding the catch of associated releases by the proportion of unassociated releases for each area and year. This was done by area and year, to account for annual and regional differences in survival and exploitation rates. Catch was assumed to occur 4 and 3 years after the brood year, for Chinook and coho respectively. To account for survival rate differences between smolt and fry releases, releases of fry were assumed to result in half the calculated catch, consistent with the relationship between smolt and fry survival rates from marked releases.

Beginning in 1996, all coho from southern B.C. production facilities were marked with an adipose fin clip to allow for selective hatchery mark-only fisheries (MSF) in southern B.C. waters. For areas and years with MSFs, the contribution of unassociated coho releases was made using the proportion of adipose marked releases, rather than the total number of fish released, because unmarked fish could not be retained in fisheries.

Estimates for sockeye and pink salmon were not calculated because the majority of enhanced sockeye production originates from spawning channels and few projects produce pinks. There is no marking of sockeye or pink salmon. For these species, adult production is usually estimated using run reconstruction to get average survival rates.

Unlike Chinook and coho, most chum salmon catches are terminal net fisheries. The geographic catch areas sampled are smaller than the catch regions used for Chinook and coho and usually include only a single statistical fishing area. Experiments have shown that there is a 30% higher apparent mortality of marked versus unmarked fish associated with fin clipping. This

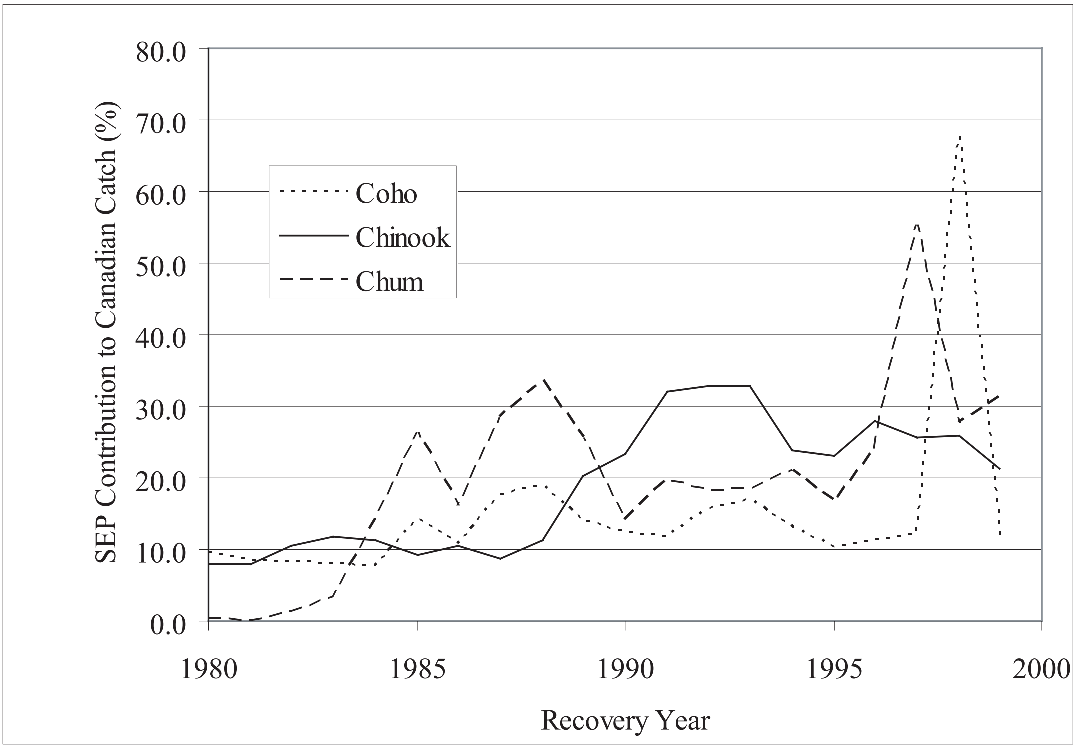

Figure 6. Salmonid Enhancement Program (SEP) hatchery contributions to Canadian salmon fisheries.

is a combination of actual fry mortality and some regeneration of fins so that the fish are no longer identified as having been clipped. Expanded contributions are adjusted to account for this differential mortality. Enhanced contribution of releases that are not associated with marks were estimated by multiplying releases by biostandard survival and exploitation rates. Biostandards are average rates applied to a geographic area obtained from multiple-year marking programs conducted at selected sites with extensive marking and sampling programs. Survival rate biostandards for unfed release stages with no associated marking information were assumed to be half those for fed fry releases.

Marine Survival

Marine survival for each tag code or fin clip was calculated by dividing the total recovery of marked fish in the catch and escapement for all age-classes by the total number of marked fish released. Only those tag codes and fin clips where both the catch and escapement were sampled for marks were included in the analysis. Survival was calculated for each individual tag code representing releases of

- 15–25-g yearling coho smolts from coastal hatcheries
- 3–8-g subyearling Chinook smolts from coastal hatcheries
- 1–3-g spring releases of chum fed fry

Data to calculate survivals of two naturally produced coastal coho stocks (Black Creek on the east coast of Vancouver Island and Salmon River in the Lower Fraser) were also taken from the mark recovery database.

Data were plotted on a logarithmic scale for a large number of tag codes for each species (Figures 7–9). Release groups often had more than one tag code representing their production. This was a function of the lot sizes of tag codes available, and since these lots were not applied randomly, they cannot generally be considered to be true replicates.

Fish Culture Evaluation

There is also an extensive system of record keeping for fish culture data (disease history, feed rates, growth and survival rates, etc.). The performance of SEP hatch-

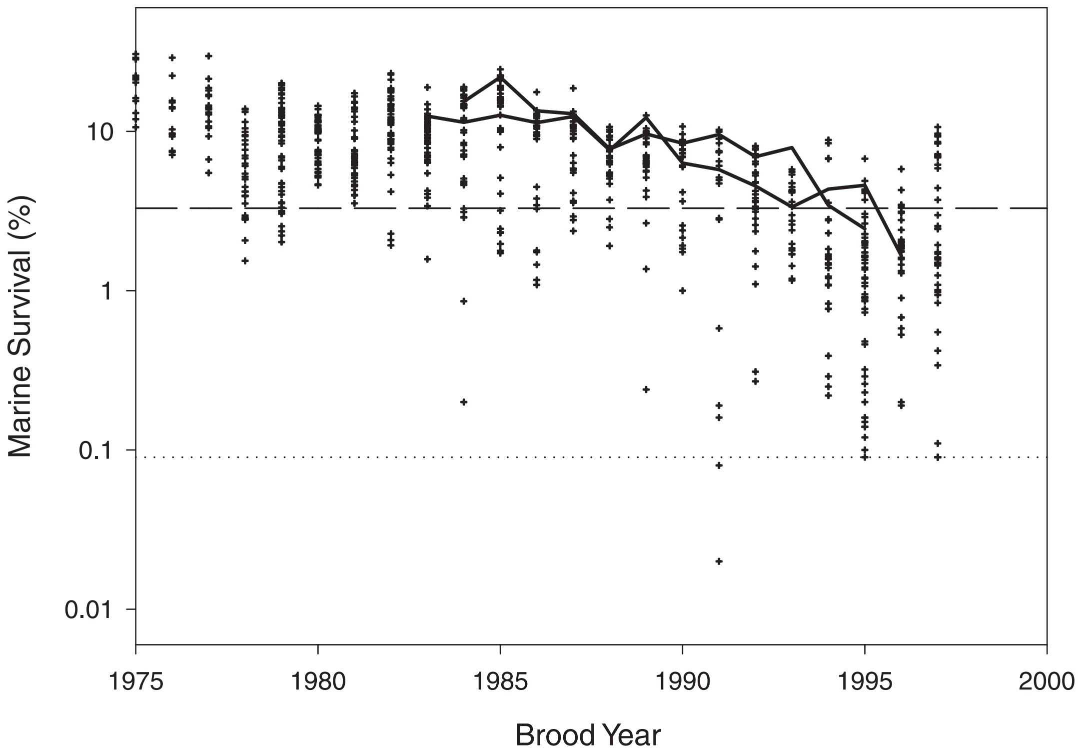

Figure 7. Survival of coho salmon releases from Salmonid Enhancement Program hatcheries. Only yearling smolt releases of 15–25 g size from coastal hatcheries are included. Note that survival scale is logarithmic. The solid lines show the survival of two coastal un-enhanced stocks (Black Cr. and Salmon R.). The horizontal lines represent the replacement survival required for naturally produced fish (upper) and hatchery-produced fish (lower).

eries is monitored following rigorous in-hatchery data collection procedures. Information is stored in on-site databases and summarized in the regional headquarters. The tables and figures presented in this report were prepared using data submitted by the hatcheries in their brood reports. Figure 10 was constructed from a database, including 30 hatchery projects over a period of 30 years, plotting the egg to smolt survivals (the product of the egg-to-fry and the ponding-to-release survivals) for each species.

Results and Discussion

The relative number of juveniles released from the different programs within the SEP is illustrated in Tables 1–3, showing the scale of hatchery production in 2002 for all SEP hatchery programs. More than 80% of Chinook and chum salmon production and 65% of coho production came from major facilities, with 10–15% of the production of Chinook, chum, and coho coming from the CDPs. The PIPs produced about 20% of coho and a small percentage of the other species.

Hatchery releases of coho, Chinook, and chum salmon increased dramatically in the 1980s as new facilities came on line, and broodstock numbers increased with increasing returns of enhanced fish (Figure 2). Full production for Chinook and coho smolt releases was reached in the early to mid-1980s. Variable production in the late 1980s was mostly related to broodstock availability. Decline in Chinook releases in the 1990s was related to the closure of a number of hatcheries that were not meeting adult return objectives due to poor marine survival conditions. In recent years, increased effort has been made to rebuild severely depressed stocks, including upper Skeena and Thompson coho. Since 1995, poor marine survival for some southern B.C. chum stocks led to decreased escapement, resulting in lower production releases. Lower harvest rates and successful rebuilding of Fraser River chum led to reductions in egg targets after 1999.

Chum releases declined precipitously in the late 1990s as hatcheries refocused their efforts under limited-funding constraints to work on stocks and species in greater need of conservation assistance. Both the

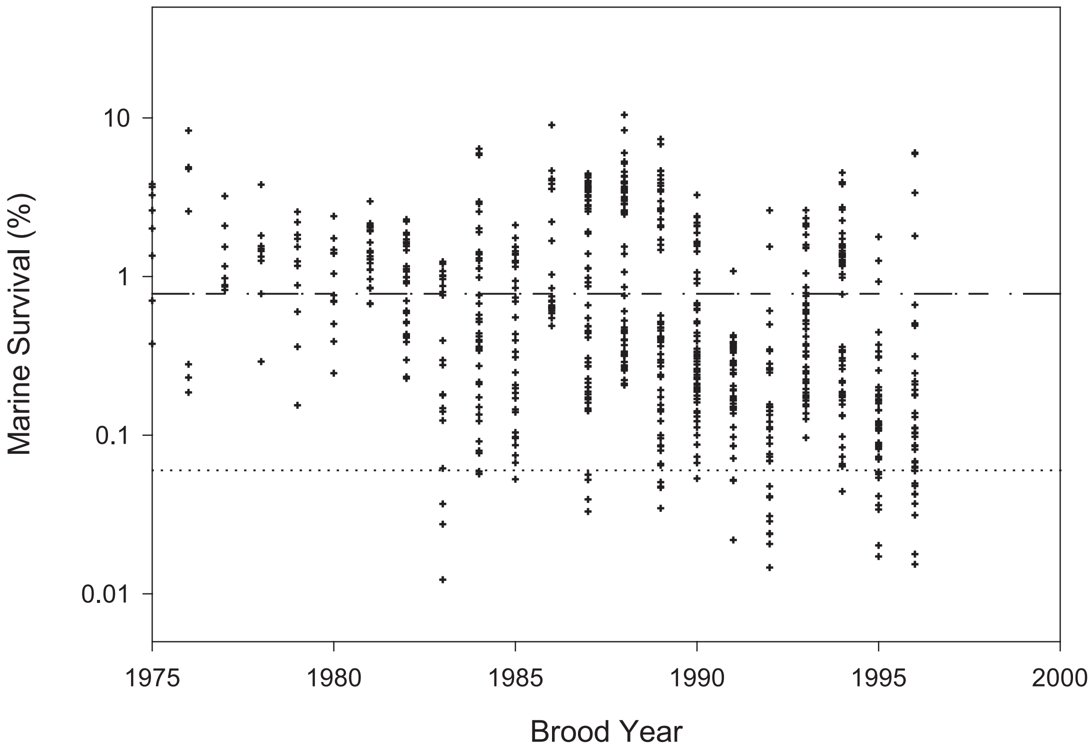

Figure 8. Survival of Chinook salmon smolt releases from Salmonid Enhancement Program hatcheries. Only spring subyearling smolt releases of 3–8 g size are included. Note that the survival scale is logarithmic. The horizontal lines represent the replacement survival required for naturally produced fish (upper) and hatchery-produced fish (lower).

relative abundance of chum salmon, some of it caused by successful rebuilding efforts (Bailey 2002) and some by low fish-market value, led to the reduction or termination of many chum enhancement components in SEP hatcheries.

Since 1998, concern for the depressed upper Skeena and Thompson coho stocks has constrained the harvest of all species, such that the entire coast was managed on the basis of these stocks. No fishing was permitted in areas and times where these stocks were prevalent, and selective fishing gear was required in all fisheries. Fishing for other species was permitted in areas and times where these stocks were not prevalent, with retention of coho permitted only in extreme terminal areas on hatchery stocks. Many of the fisheries which did take place were focused on hatchery-enhanced stocks.

The total catch of coho salmon remained quite high throughout the 1980s, but has declined precipitously since that time (Figure 3). The proportion of the catch that can be attributed to SEP hatchery production increased so markedly since 1996 (Figure 6) because fisheries have been mainly terminal and/or mark-selective for hatchery-produced fish. Total Chinook salmon catches have declined throughout the period except for a short burst in the mid-1980s (Figure 4), even though hatchery production continued to increase (Figure 2).

Severe restrictions have been placed on both coho and Chinook fisheries because of conservation concerns. Part of this strategy is to direct coho fisheries more towards targeting on hatchery-enhanced stocks and less on targeting naturally produced stocks. Chum salmon catch has been extremely variable during the SEP period (Figure 5), due to a combination of market forces and fishing opportunities (that have been constrained by restrictions on the other species).

The decline in stock abundance, as indicated by catch decreases (although recent catch decreases reflect closure of fisheries due to conservation concerns), is also evident in the postrelease survival of coho from SEP hatcheries during the 1990s (Figure 7). This graph summarizes the results of coded-wire tag stud-

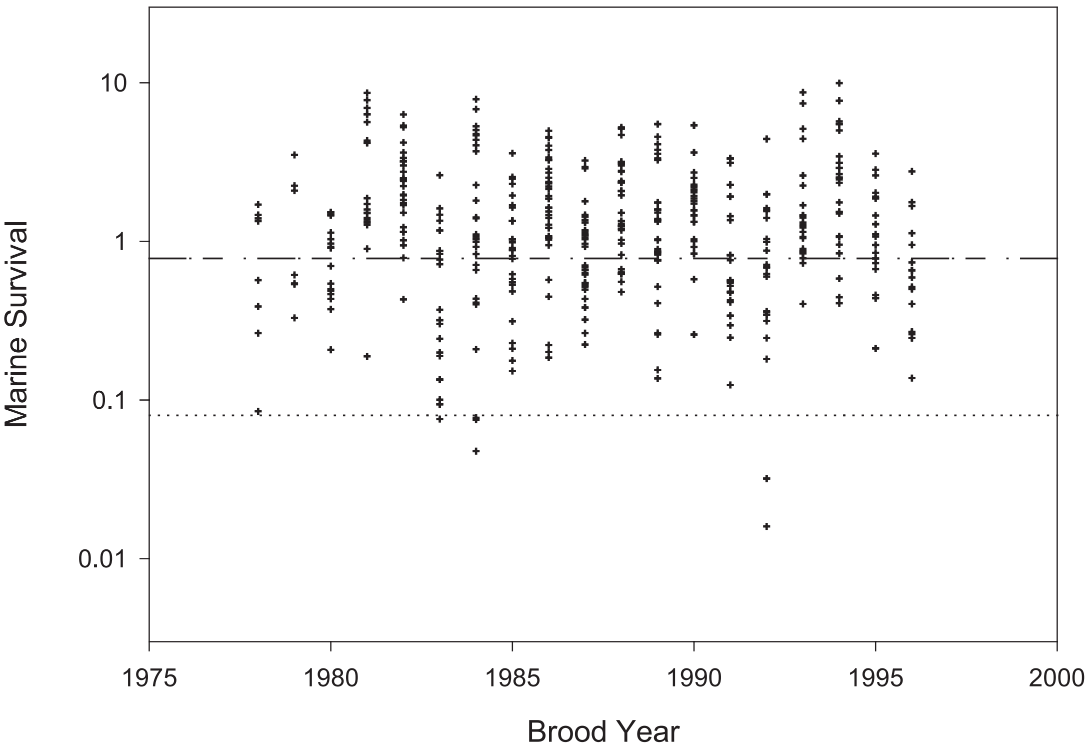

Figure 9. Survival estimates for chum salmon fed fry releases from Salmonid Enhancement Program hatcheries. Only spring fed-fry releases of 1–3 g size are included. Note that the survival scale is logarithmic. The horizontal lines represent the replacement survival required for naturally produced fish (upper) and hatchery-produced fish (lower).

ies of more than 750 groups of coho smolts weighing 15–25 g released from coastal hatcheries (major facilities) during the period of record. Each individually identifiable release group was made up of 10,000–50,000 tagged fish. Survivals were calculated from tag recoveries in fisheries and escapements, expanded to consider factors such as capture and sampling rates (Kuhn et al. 1988).

The striking feature of this graph is the wide intra-annual variation in survival, even on a logarithmic scale. As the survival rate declined, the variation in survival rates increased, partly because the precision of the estimate is degraded by a reduced tag recovery rate caused by fewer returning fish (Kuhn et al. 1988). The same decreasing survival trend is seen from tags placed on naturally produced fish (dark lines from Black Creek and Salmon River in Figure 8). This decrease in marine survivals upholds the evidence from a variety of sources that the North Pacific was in a state of low productivity in the 1990s (Beamish and Noakes 2002) and shows a marked decline compared to a previous update of coho survivals (Cross et al. 1991).

Tagged groups of Chinook salmon show a similar extremely wide intra-annual variation in survival rates, with a noticeable declining trend throughout the 1990s (Figure 8). As with coho, some of this variation may be due to differences in the rearing conditions in the hatchery (feed types, feeding rates, rearing conditions, disease history or treatments, release size, and timing) but the group-to-group, hatchery-to-hatchery, and year-to-year variation indicates that such fish culture differences have minor effects on overall survival.

Chum salmon marine survivals have similar degrees of intra-annual variation as coho and Chinook, but do not show a clear declining trend during the 1990s (Figure 9). This may indicate that they feed in a distinctly different niche in the ocean than do the other two species (Williams 1992; Bakun 1996).

In contrast to the decreased survivals observed after release, survival during incubation and rearing in the hatcheries have generally increased during SEP's history (Figure 10), probably due to refinement of fish culture techniques. This trend does not appear to be caused by any kind of domestication effect because both high and low survivals have been as likely to

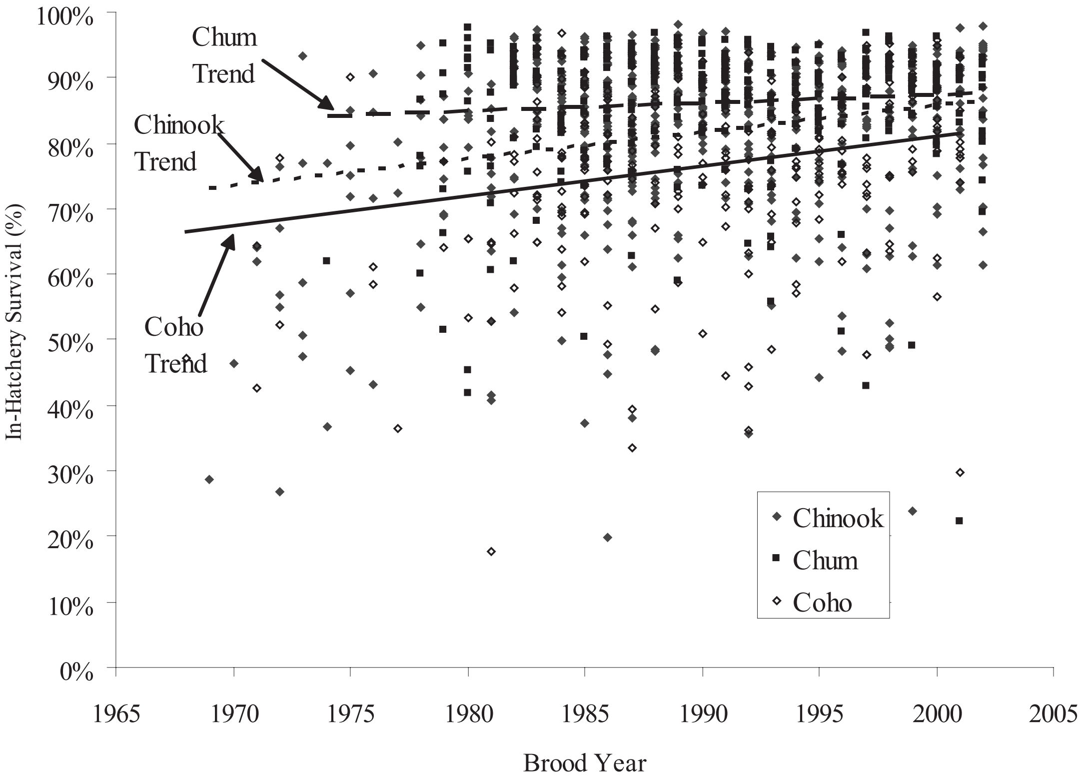

Figure 10. Trends in egg-to-release survival in Salmonid Enhancement Program hatcheries. Data include coho, Chinook, and chum smolts from 30 hatcheries.

occur in stocks that have never been cultured before, as they have in stocks that have gone through several generations of hatchery incubation and rearing. Incubation (spawning to swim-up) survivals are routinely greater than 90% and rearing survivals (ponding to release) are usually greater than 85%. Some stocks can exhibit periodic lower incubation survivals, but rearing survivals have become predictably high because health management practices now limit impacts of diseases, and other fish culture improvements ensure a clean and safe rearing environment. Naturally produced fish encounter much higher mortalities during the freshwater phase than hatchery-produced fish (Bradford 1995).

Overall survival, from egg to spawner, is the product of freshwater and marine survivals. For enough fish to survive to replace the two parents of each mating, naturally produced fish would need to have a substantially higher marine survival than hatchery fish to compensate for their lower survival in freshwater (Table 5). The calculation in Table 5 shows the survival from egg to spawning adult, assuming no harvest. In this case, fish groups that survive at less than the break-even or replacement rate would decline in abundance even without any fishing pressure. The replacement marine survival required for naturally and hatchery-produced fish are shown as horizontal lines on Figures 7–9 for coho, Chinook, and chum, respectively. These graphs illustrate that during the low productivity period of the 1990s, many stocks of unenhanced fish would not have been able to replace themselves, even with zero exploitation from legal or illegal commercial, sport, or aboriginal fisheries.

Hatchery Reform

A healthy scepticism towards the ability of hatcheries to solve all the problems concerning declines of Pacific salmon stocks has led many Pacific Northwest programs to conduct a reassessment of the role that hatcheries can play (IMST 2001; HSRG 2003; ISAB 2003). However, most of the studies cited in the reports that claim poor performance of "hatchery fish" actually refer to "introduced fish," or fish that have been stocked into watersheds from nonindigenous broodstock

Table 5. Marine survival required to sustain populations at break-even levels. This assumes that all returning adults spawn, and therefore precludes any harvest or migration mortality. Typical fecundities and survivals in fresh water for wild fish are taken from Bradford (1995), and for hatchery fish from a conservative approximation of expectations from hatchery records (see Figure 10).

		Wild conditions			Hatchery conditions		
Species	Fecundity	Egg-smolt survival	Smolt output	Marine breakeven	Egg-smolt survival	Smolt output	Marine breakeven
Coho	3000	2.0%	60	3.3%	75%	2250	0.09%
Chinook	4300	6.0%	258	0.78%	75%	3225	0.06%
Chum	3200	6.5%	208	0.96%	75%	2400	0.08%

sources. We believe that it is more probable that these fish are not adapted to the local conditions and that is what makes them less fit (at survival or lifetime reproductive success) than the local naturally produced stock, and not the fact that they spent part of their lives in a hatchery. This subject is thoroughly reviewed in Brannon et al. (2004). As discussed earlier in this report, the SEP has conducted a thorough evaluation of its projects as an on-going part of its regular business and has made continual changes to many aspects of its hatchery program. While some hatchery-enhanced stocks have declined during the SEP, the neighboring naturally produced stocks have also declined; this suggests that it is the natural conditions that have become less productive, and not the fish that have lost fitness characteristics.

However, if SEP were to reform its hatchery program, what aspects should it change: "the objectives, the technology or the fish" (Fuss 2002)? The objectives of SEP have already changed towards a focus on conservation as compared to production for harvest. The protection of wild stocks of salmon is a high priority for Canadians. Hatchery programs can have both positive and negative effects on the naturally produced fish within the same stock, and within neighboring, unenhanced stocks (Table 6). The smolt release strategies of the SEP discussed above are meant to minimize negative effects and maximize positive ones.

Changing the technology might mean putting greater emphasis on habitat protection and restoration initiatives, rather than on hatcheries. However, the general trend for availability of quality freshwater habitat is decidedly in the downward direction due to inexorable pressure from human population growth (Lackey 2003). As shown by several SEP projects (Capilano, Quinsam, Puntledge, Seymour), the near-complete loss of freshwater habitat from dam construction can be successfully replaced by hatchery production of the native wild stock. It is expected that there will be many more situations where the option of habitat restoration will no longer be sufficient to provide freshwater production in the future.

Changing the fish has been taken to mean trying to make the fish released from hatcheries to be more like naturally produced fish in their appearance, behavior, and physiological characteristics (IMST 2000). Manipulation of the fish-culture environment (cover, benthic substrate, complex habitat, crowding, feed delivery, diet formulation, etc.) may lead to hatchery-reared fish acquiring similar characteristics to naturally reared fish and thereby improve their postrelease survival. In principle, it may be possible to produce hatchery fish that are better adapted to marine survival than are naturally produced fish because natural rearing conditions are seldom optimal (proven by high mortality rates). However, as can be seen from Figure 7, hatchery-reared coho do not appear to perform substantially worse after leaving freshwater than naturally reared fish. Because they have such an advantage in freshwater survival, hatchery fish might have an increased impact on adjacent nonenhanced stocks, if they were even more fit for survival in the ocean. The potential for domestication selection in integrated hatchery programs is probably insignificant, especially considering the magnitude of other effects on survival (MacKinlay 2002). In addition, once hatchery fish have lived for a while in the same environment as naturally produced fish, they are indistinguishable from them (MacKinlay and Howard 2002). Therefore, while it is an ongoing goal at SEP facilities to produce high quality smolts for release, it is unlikely that major changes in fish-culture techniques are required or that they could be shown to be demonstrably superior in inducing high marine survivals, especially considering the wide, random variation in marine survivals. However, SEP staff take concerns about the "wildness" of our fish very seriously and consult regularly with the latest scientific literature and an array of experts to constantly evaluate where processes or outputs can be modified to improve wild fish stock enhancement.

Table 6. Potential impacts of hatchery fish on adjacent naturally produced stocks.

Impact type	Possible positive impacts	Possible negative impacts
Demographic – change in fishing pressure on and public concerns about wild salmon	• Provision of supplemental hatchery fish can be used to decrease the exploitation rate on adjacent stocks while maintaining catch levels.* Selective, mark-only fisheries can reduce exploitation rates even further. • Hatcheries and other enhancement projects and activities are at the forefront in promoting the conservation ethic to the public through participation and education programs. • Greater numbers and visibility of fish in streams may lead to greater conservation efforts to protect the habitat.	• If the exploitation rate is increased to harvest high returns of hatchery fish, attendent nonenhanced stocks could suffer. • People might think that hatcheries will solve all the problems of declining stocks and be less vigilant about the other salmon conservation initiatives: reformed harvest management and habitat protection and restoration.
Ecological – change in natural productivity in streams	• Enhanced production can provide more spawners into streams, seeding underutilized habitat with both adults and juveniles • Habitat productivity can be improved through nutrient addition from spawner carcasses. • Large numbers of hatchery fish can reduce the effective predation rate on adjacent stocks.*	• If hatchery-produced fish are added to already saturated ecosystems, competition may decrease the survival of naturally produced stock components • Releases of diseased fish or pathogen-rich effluent from hatcheries could increase disease incidence in the area.
Genetic – change in diversity and fitness of salmon stocks	• Higher survival of wild salmon in the hatchery better maintains the genetic diversity of a stock than allowing it to drop to very low numbers under natural conditions. • Enhancement reduces the selection pressure on fish that are trying to survive in an unnatural, damaged ecosystem. • Small transplants into large wild stocks (hatchery- or naturally produced) can increase their genetic diversity and long-term fitness.	• Some selection for domestic traits may occur in hatchery stocks if they are isolated from their parent stock over many generations (genetic drift). • Transplants of distant stocks into a stream can decrease the short-term fitness of a stock that is already there (outbreeding debression). • A small founding broodstock may not be very adaptively robust (inbreeding depression).

* For example, if a stock of 100 naturally produced fish are being caught (or preyed upon) at a 60% exploitation rate (giving 60 caught and 40 escapees) is supplemented by 500 hatchery fish, the exploitation rate (or predation rate) can be decreased to 10% and still maintain a steady catch of 60 fish, while increasing the naturally-produced escapees to 90.

Conclusions

Pacific salmon hatcheries in British Columbia have been very successful in mitigating for low freshwater productivity (survival), whether caused by human activities or natural cycles. Hatcheries essentially act as superproductive freshwater ecosystems for one life history segment of a portion of a wild salmon stock, avoiding the three main sources of mortality: starvation, predation, and disease. Considering that the assaults on freshwater salmon habitat can only increase with the continuing pressures of expanding human population along the coast and rivers of British Columbia, salmon hatcheries can play a pivotal role in maintaining substantial wild salmon populations in the future.

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