

A Review of the Hatchery Programs for Pink Salmon in Prince William Sound and Kodiak Island, Alaska

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Abstract.—Five hatcheries in Prince William Sound, Alaska, release more than 500 million juvenile pink salmon *Oncorhynchus gorbuscha* each year, constituting one of the largest salmon hatchery programs in the world. Before the program was initiated in 1974, pink salmon catches were very low, averaging 3 million fish per year between 1951 and 1979. Since 1980 the catch has averaged more than 20 million fish per year. However, catches in three other areas in Alaska with substantial fisheries for pink salmon (southeast Alaska, Kodiak Island, and the southern Alaska Peninsula) also increased equivalently during the same period, and the hatchery production did not become the dominant factor in Prince William Sound until the mid-1980s, long after the wild population had expanded. A hatchery program in the Kodiak area provides useful contrast to the Prince William Sound program because it is smaller and more isolated from the major wild-stock-producing areas of Kodiak Island. The evidence suggests that the hatchery program in Prince William Sound replaced rather than augmented wild production. Two likely causes of the replacement were a decline in wild escapement associated with harvesting hatchery stocks and biological impacts of the hatchery fish on wild fish. Published papers disagree on the impact of the 1989 *Exxon Valdez* oil spill, but none of the estimates would account for more than a 2% reduction in wild-stock abundance, and the decline in wild stocks began well before the oil spill. No evidence in the Kodiak area program suggests any impact on wild stocks. This analysis suggests that agencies considering the use of hatcheries for augmenting salmonids or other marine species should be aware of the high probability that wild stocks may be adversely affected unless the harvesting of the hatchery fish is isolated from the wild stocks and the hatchery and wild fish do not share habitat during their early ocean life.

In response to low salmon abundance in the 1960s and 1970s the state of Alaska began several hatchery programs, including the creation of the Fisheries Rehabilitation, Enhancement and Development division within the Alaska Department of Fish and Game (ADF&G). The state legislature also passed the Hatchery Act (1974) and the Fisheries Enhancement Loan Program, which provided for low-interest loans to regional aquaculture organizations (Hull 1993). Under this legislative framework the Prince William Sound (PWS) Aquaculture Corp. (PWSAC) was formed in December 1974 by a group of commercial fishermen based in Cordova, Alaska. It currently operates three pink salmon hatcheries in PWS, and the Valdez Fisheries Development Association (VFDA) operates a single hatchery (Solomon Gulch) in Valdez Arm (Figure 1A). Approximately 70% of the hatchery production in PWS comes from the

three PWSAC hatcheries, but we will use data from the entire hatchery program—that is, both PWSAC and VFDA. Some of the spirit and hope of the early days of salmonid aquaculture in Alaska are captured in Wilson and Buck (1978): “the future potential for significantly increased salmon harvests throughout the state is enormous. Alaska’s approach to salmon aquaculture and fisheries enhancement bears watching in the next decade as this multifaceted program attempts to yield larger harvests and bring new stability to a historically cyclical resource.”

The PWSAC is a private nonprofit corporation funded both by a 2% tax on landings of fishermen in PWS and by sales of fish captured in cost recovery fisheries. It now operates the largest hatchery program in North America, releasing more than 500 million fry of pink salmon *Oncorhynchus gorbuscha* each year and some juveniles of sockeye salmon *O. nerka*, chum salmon *O. keta*, coho salmon *O. kisutch*, and chinook salmon *O. tshawytscha*. Olsen (1994) and Pinkerton (1994) describe the biological and social history of PWSAC.

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Received February 4, 1999; accepted June 9, 1999

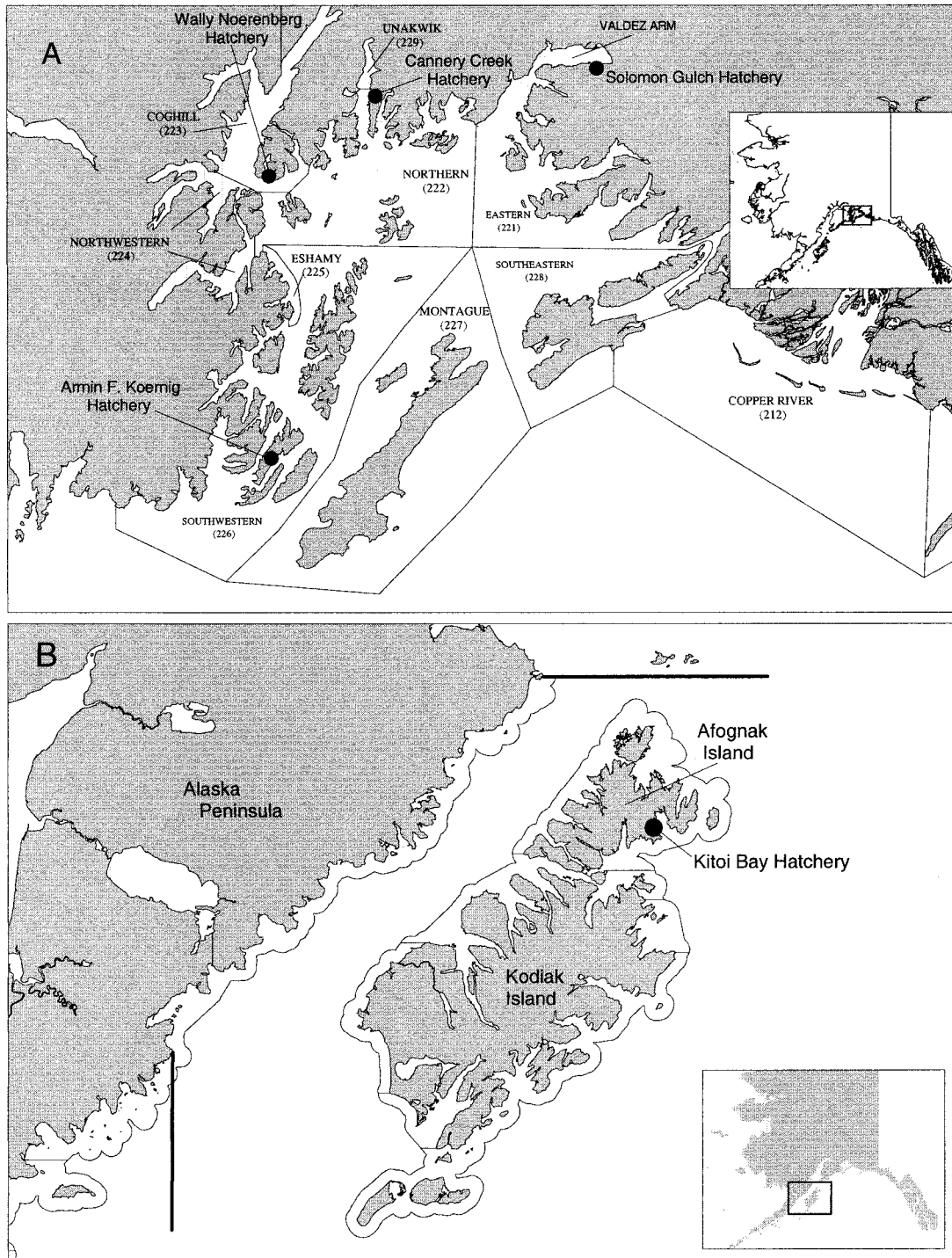


FIGURE 1.—Maps of (A) Prince William Sound (PWS) and (B) the Kodiak area, Alaska, showing locations of the hatcheries and, in PWS (A), the fishing districts (district numbers in parentheses).

The hatchery run of pink salmon to the Kodiak Island area is entirely supported by the Kitoi Bay Hatchery on Afognak Island (Figure 1B). The ADF&G rebuilt the facility, originally constructed in 1956, after its destruction in the 1964 earthquake. The facility was initially operated as a research facility, but emphasis switched to pink salmon production in 1976; it also produces sockeye salmon, chum salmon, and coho salmon. The ADF&G operated the facility before 1987 and Kodiak Regional Aquaculture Association (KRAA) assumed full operation of the hatchery in 1992. The KRAA is funded by a 2% tax on landings by fishermen in the Kodiak area as well as by earnings on a fund created from the proceeds of a one-time terminal area cost recovery fishery that occurred in 1989. This cost recovery fishery occurred because the *Exxon Valdez* oil spill in 1989 prevented harvest of returning salmon in the traditional fishing areas.

Concern about the biological success and economic viability of hatchery programs is increasing (Hilborn 1992; Meffe 1992; Hilborn and Winton 1993), and the PWS and Kodiak pink salmon programs appear to be excellent subjects for evaluating the biological success of large hatchery programs for four reasons. First, both programs are large and spatially quite discrete. Second, there are four regions of Alaska with significant wild pink salmon production, but only in PWS and the Kodiak area are there large-scale hatcheries. The other two areas provide the opportunity for natural controls that depict changes in wild stocks that occurred while the hatchery program came on line. The ADF&G has maintained a regular program of escapement monitoring throughout the PWS and Kodiak areas so that changes in escapement can be documented. Third, unlike the chinook salmon and coho salmon hatchery programs in Canada and the lower 48 United States, which have been ongoing for more than 100 years, the PWS and Kodiak pink salmon programs began in recent years, and there are reliable data on wild stocks before the program began. Finally, significant physical differences exist between the programs in PWS and the Kodiak area: the location of the Kodiak area hatchery is well isolated from the major wild spawning areas whereas the PWS hatcheries are not.

Previous papers have explored the implications of these hatchery programs. Eggers et al. (1991) compared the pink salmon production in PWS with that in the Kodiak area and with other wild Alaskan pink salmon stocks and noted that PWS production had increased at the same time as the other stocks.

They suggested that intense harvest of hatchery fish in PWS had been responsible for the decline of PWS wild stocks, replacing wild production with hatchery production. Tarbox and Bendock (1996) inferred that the hatchery program in PWS was a major contributor to declines in wild stocks. Smoker and Linley (1997) challenged the conclusions of Eggers et al. (1991) and of Tarbox and Bendock (1996) and considered alternatives to replacement of wild stocks by hatchery fish.

The purpose of this paper is to review the biological success of the PWS and Kodiak pink salmon hatchery programs. We now have considerably more years of data than were available to Eggers et al. (1991), and we have examined some additional areas of wild Alaskan pink salmon production. Further we also examined evidence for biological interaction between wild and hatchery fish in PWS and the Kodiak area and changes due to fishing. Finally we consider how our findings from the PWS and Kodiak areas can be applied to other hatchery programs for salmonids and marine species.

Methods

This analysis is strictly retrospective and is based on published data taken primarily from ADF&G reports on wild-stock catches and escapements as well as hatchery runs in southeast Alaska, Prince William Sound, Kodiak Island, and south Alaska Peninsula management areas.

For PWS, total catch numbers and delivery weights of pink salmon for the years 1965–1997 were taken from Morstad et al. (1998). The wild pink salmon peak aerial survey escapement index counts were not reflective of true escapement (Bue et al. 1998b). The escapements in Morstad et al. (1998) were estimated by dividing cumulative spawner-days, based on stream counts from aerial surveys, by the estimated stream residence time of 17.5 d (Helle et al. 1964). Multiyear studies of streams in the PWS aerial survey index program (Bue et al. 1998b) indicate that stream life is similar in streams within districts and between years. These estimates differed from the stream life used in the historical escapement calculations. Stream life estimated for Irish and Hawkins creeks (17.8 d) was used to adjust the index counts for the Eastern and Southeastern fishing districts (Figure 1A), and stream life estimates for the remaining streams were averaged (11.1 d) and applied to the remaining districts.

Runs of pink salmon to PWS hatcheries provide catches in common-property commercial fisheries,

cost recovery catches in hatchery terminal harvest areas, and broodstock. Numbers for catch of private nonprofit hatchery fish in mixed-stock commercial and cost recovery fisheries, as well as broodstock and unused fish, were taken from annual hatchery reports provided to ADF&G. Before 1987 the wild and hatchery fish contributions to the mixed-stock commercial fishery were estimated from the relative magnitude of returns to hatchery terminal areas and wild-stock escapement levels. Estimates of hatchery catches from 1987 to 1997 were based on a coded-wire-tagging program (Geiger and Sharr 1990; Peltz and Geiger 1990), and catches of wild stocks were approximated as the total common-property commercial harvest less the estimated hatchery contribution.

For the Kodiak area, total catch numbers of pink salmon for 1965–1996 were taken from Brennan et al. (1998), and those for 1997 were from ADF&G catch records (K. Brennan, ADF&G, personal communication). Catches of hatchery fish were assumed to be the entire commercial catch and cost recovery in the Izhut Bay, Duck Bay, and Kitoi Bay subdistricts. No significant populations of wild pink salmon exist near Kitoi Bay, and the hatchery there is not near traditional fishing areas for wild pink salmon. Catches of wild pink salmon do not occur in the hatchery terminal harvests, and catches of hatchery fish are negligible in fishing areas outside the terminal harvest area. Estimates of the commercial catch, cost recovery, and broodstock for the Kitoi Bay Hatchery, 1972–1997, were compiled from ADF&G catch records and from hatchery annual reports filed with ADF&G (Steve Honnold, Alaska Department of Fish and Game, personal communication). Wild-stock catch was estimated as total catch less hatchery catch.

Wild-stock escapement estimates were determined from cumulated weir counts and expanded peak counts of live fish derived from aerial or foot surveys (Brennan et al. 1998). Peak counts were expanded by a factor of 1.84 based on estimated stream life (Barrett et al. 1990). Escapements for streams not surveyed were interpolated from surveyed streams in the respective year, based on the historical average odd- and even-year escapement distribution among streams.

For the southern Alaska Peninsula area, total catch numbers of pink salmon were obtained from Campbell et al. (1998). Wild-stock escapement estimates were determined from peak counts of live fish derived from aerial or foot surveys (Campbell et al. 1998). Peak counts were expanded by a factor of 1.4 based on estimated stream life (B. A. John-

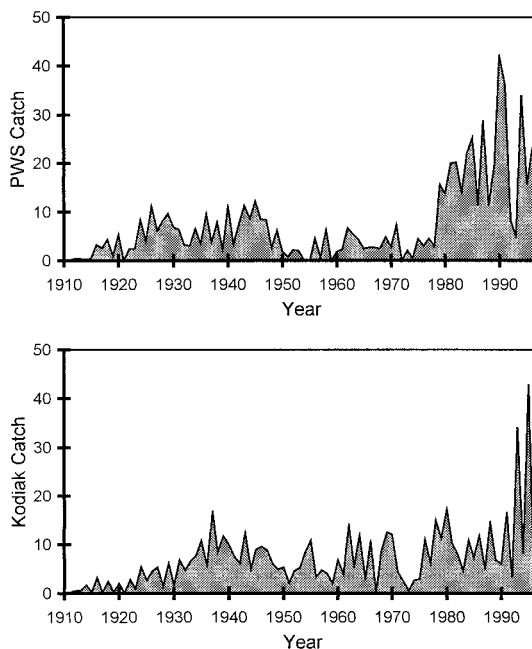


FIGURE 2.—The annual catch (in millions) of pink salmon in Prince William Sound (PWS; top panel) and the Kodiak Island area (bottom panel).

son and B. Barrett, ADF&G, unpublished manuscript).

For southeast Alaska, catches of pink salmon were obtained from ADF&G (1997). Estimates of wild-stock escapement were determined from peak counts of live fish derived from aerial surveys. The index counts were expanded for streams not surveyed in a particular year based on historical estimates of escapement distribution among streams. The index counts were standardized to account for differences in counting bias among individual observers (K. A. Hofmeister, ADF&G, unpublished, 1998). Standardized peak index counts were expanded by 2.5 to account for stream life (Dangel and Jones 1988).

Results

History of Pink Salmon Returns

The long-term history of pink salmon catches in PWS reveals four distinct periods. From 1896 to 1913, annual catch was less 1 million; 1916–1950 catches averaged 5.8 million fish per year; 1951–1979 catches dropped considerably to 3.3 million per year; and since 1980 catch has averaged 20.6 million fish per year (Figure 2). The dramatic rise since 1980 can be taken as evidence for success of the hatchery program. However, the three periods in PWS production since 1916 cor-

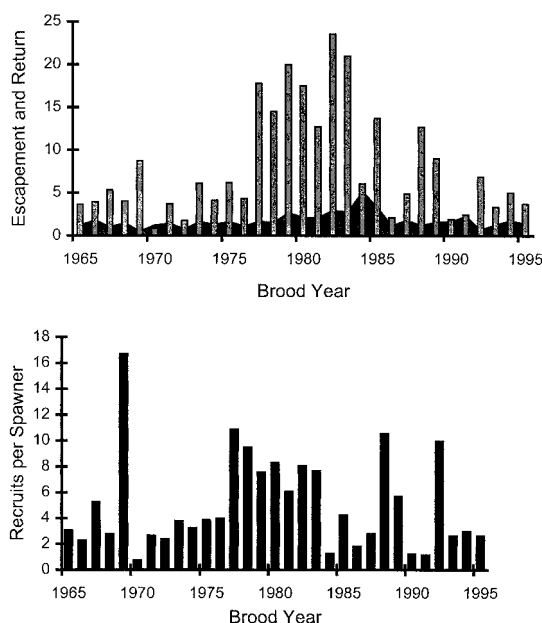


FIGURE 3.—Historical production of wild pink salmon in Prince William Sound, illustrated by (top) total return (vertical bars) and escapement (dark shaded area) of wild pink salmon (millions of fish) and (bottom) the index of wild recruits per spawner.

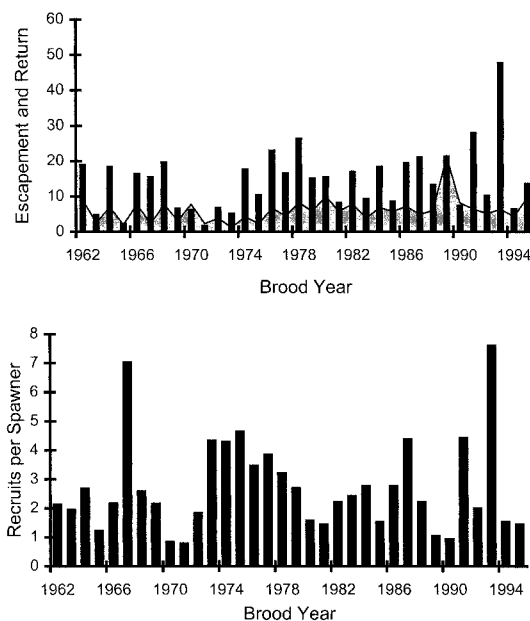


FIGURE 4.—Historical production of wild pink salmon in the Kodiak Island area, illustrated by (top) total return (vertical bars) and escapement (light shaded area) of wild pink salmon (millions of fish) and (bottom) the index of wild recruits per spawner.

respond to general patterns in abundance of pink salmon and sockeye salmon throughout Alaska, and these major changes are generally ascribed to changes in ocean conditions. These three periods are now commonly called “regimes” and fluctuation between regimes is the “interdecadal oscillation” (Francis and Hare 1994; Hare and Francis 1995; Mantua et al. 1997). Interpreting the impact of the hatchery program is closely connected with understanding and interpreting changes in other pink salmon populations in Alaska. Catch from the Kodiak Island area rose less dramatically after 1977 but, on average, was more than double the 1970s levels (Figure 2).

Figure 3 shows a major increase in total run to PWS in the late 1970s followed by an increase in escapement; then in the mid-1980s, wild-stock escapement and total runs declined. The index of wild recruits per spawner was elevated during 1977–1983 then experienced irregular but lower values from 1984 to 1993. In the Kodiak area both escapement and runs began to gradually increase in the mid-1970s (Figure 4).

History of Hatchery Production

The hatchery program in PWS began in the mid-1970s and by the early 1980s produced several

hundred million fry per year (Figure 5). The returns from hatchery production kept pace with the releases such that when pink salmon fry production increased to about 500 million in 1987, the subsequent adult returns were 15–35 million. Ocean survival apparently increased early in the program, but survival was poor in 1990 and 1991. In the 1990s, 20–40% of the total return was taken for cost recovery and broodstock.

In the Kodiak area, fry releases rose throughout the late 1970s and 1980s to about 150 million per year (Figure 6, top). The 1991 brood year produced a high of about 10 million fish and the 1987 brood was slightly lower, but only a few million fish were produced annually in other brood years. Although the Kodiak hatchery program is roughly one third the size of the PWS program in releases, survival is much lower, and only the 1991 hatchery brood year (1993 year of capture) produced a significant proportion of Kodiak pink salmon catch. As in PWS, hatchery ocean survival (Figure 6, middle) was more than 6% in the 1987 and 1991 brood years but only 1–2% in other years since 1980. In contrast, survival in PWS hatcheries was at least double the Kodiak average. Only in brood years 1985–1987 (harvest years 1987–1989) was there any cost recovery harvest

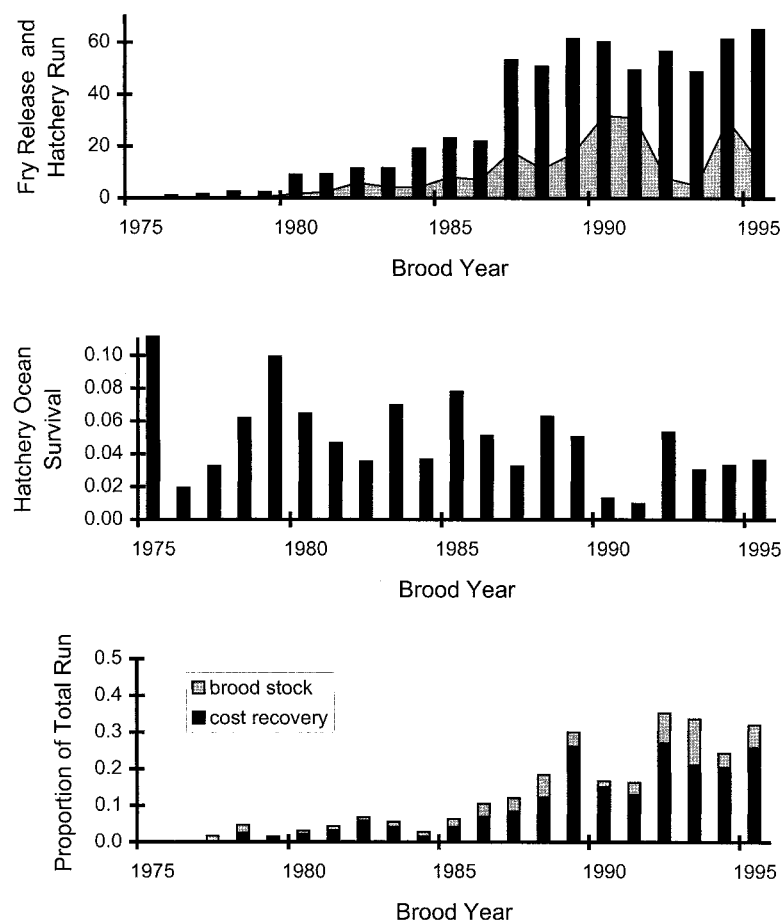


FIGURE 5.—Historical production of pink salmon from hatcheries in Prince William Sound, illustrated by **(top)** fry releases (vertical bars in tens of millions) and hatchery return of adults (shaded area in millions), **(middle)** ocean survival rate for hatchery fish, and **(bottom)** proportion of the total run of pink salmon that has gone to cost recovery fisheries and broodstock.

(Figure 6, bottom), and in 1989 almost all of the run was taken for cost recovery when the ocean salmon fisheries were closed because of the *Exxon Valdez* oil spill.

Pink Salmon Stock Changes Outside PWS

There are two other major pink salmon production areas in Alaska: southeast Alaska (the Alaska panhandle) and the southern Alaska Peninsula. Both of these areas also experienced a major increase in abundance since the 1977 regime shift. Some differences exist in the spawning habitat among areas, PWS having a high proportion of intertidal spawning. Pink salmon in all areas have similar marine life cycles, spending their ocean life in the Gulf of Alaska and northeast Pacific Ocean. Eggers et al. (1991) suggested that other populations of wild Alaskan pink salmon should reflect

what would have happened to PWS pink salmon in the absence of a hatchery program.

In southeast Alaska and the southern Alaska Peninsula, high production beginning in 1975–1976 followed low production in the 1960s and early 1970s (Figure 7). The catch in all four pink salmon regions has increased considerably since the mid-1970s. We normalized the data by dividing them by the average for 1976–1985, obtaining a 5-year running average to smooth the data, and then plotted all four pink salmon areas together in Figure 8. The 5-year running averages of total returns (hatchery and wild) to the four areas, divided by the 1976–1985 average for each area, show little clear discrimination among areas; returns increased in all areas with PWS having the lowest relative value in recent years. It is clear that PWS

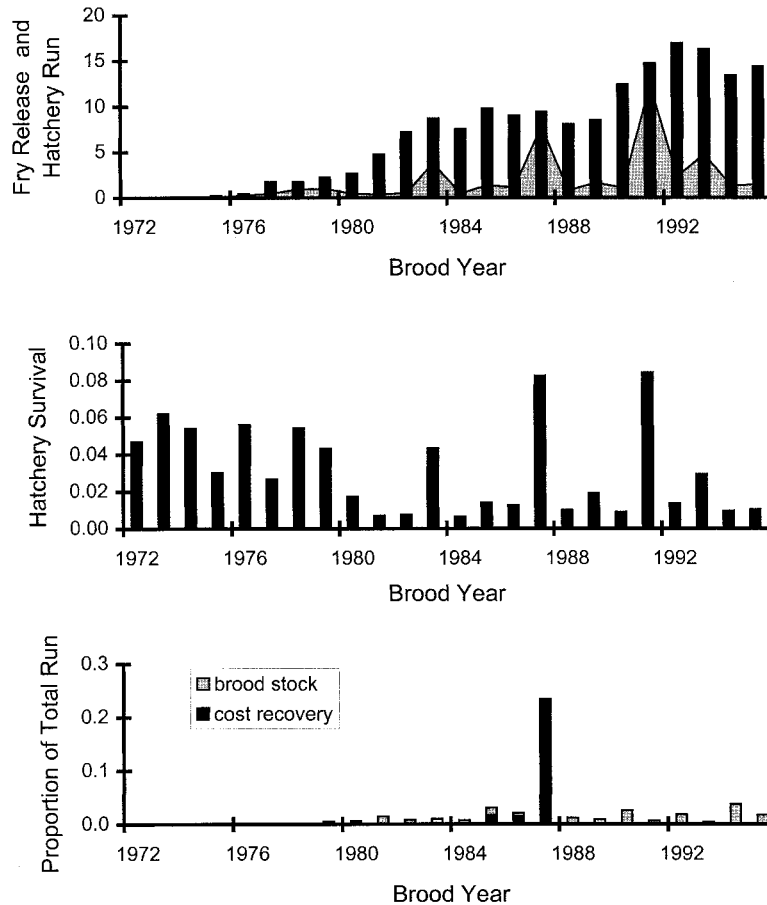


FIGURE 6.—Historical production of pink salmon from hatcheries in the Kodiak Island area, illustrated by **(top)** fry releases (vertical bars in tens of millions) and hatchery return of adults (shaded area in millions), **(middle)** ocean survival rate for hatchery fish, and **(bottom)** proportion of the total run of pink salmon that has gone to cost recovery fisheries and broodstock.

returns increased the most from the period before 1975, but this increase had taken place before 1984 when large-scale hatchery production began. For the 5-year running-average escapement, the general trend indicated increases in all areas except PWS, which has declined dramatically since the mid-1980s. For the 5-year running average of total return and wild return for PWS and Kodiak Island, almost no difference existed between total and wild pink salmon returns in the Kodiak area. In PWS, the wild return declined dramatically beginning in the mid-1980s while the total return stayed roughly constant, indicating that wild stocks were being replaced by hatchery stocks.

When the average return for 1986–1995 was compared with the return for 1965–1975 in each region, south Alaska Peninsula and Prince William Sound both increased roughly sixfold, southeast

Alaska increased 3.5-fold, and Kodiak increased about twofold (Table 1). However with the base period of 1976–1985 (after the improvement in ocean conditions and before large-scale hatchery production affected PWS), PWS, southeast Alaska, and south Alaska Peninsula all experienced very similar increases in returns—1.43, 1.55, and 1.37, respectively—while increases in Kodiak returns lagged behind at 1.13. From the pre-regime-shift base period (1965–1975), PWS and south Alaska Peninsula were highest, but this was accomplished by wild stocks in both PWS and south Alaska Peninsula.

Discussion

The purpose of the aquaculture program in Prince William Sound and Kodiak Island was to stabilize natural variability in the pink salmon runs

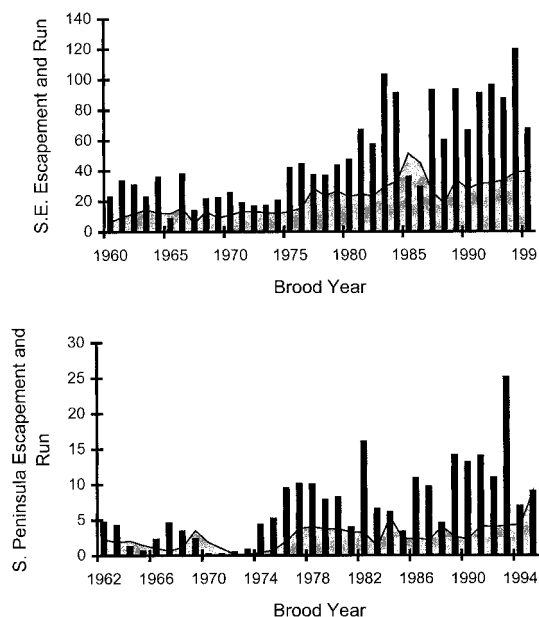


FIGURE 7.—Historical production of pink salmon in **(top)** southeast Alaska (S.E.) and **(bottom)** the southern Alaska Peninsula (S. Peninsula), illustrated by total catch (vertical bars) and escapement (shaded areas); all numbers are in millions.

to the area and to provide for a sustainable and economically viable fishery. The success of any enhancement program depends on meeting a series of biological criteria including (1) the successful production of fish that survive to be captured, (2) adequate survival, sustained for a long period, (3) hatchery production that can be harvested without affecting the production of the wild fish, and (4) production of enhanced fish that does not significantly reduce the survival and production of wild fish (so that there are true net benefits of the enhancement).

The data presented earlier show clearly that criterion 1 has been met: the PWS and Kodiak pink salmon programs produce fish that survive and contribute to the fishery. The survival rates achieved (particularly in PWS) are the envy of hatchery managers for chinook salmon and coho salmon up and down the coast, where a 5% survival rate is considered an incredible success, even for fish reared for a year in the hatchery, fed extensively, and therefore released at a very large size. It is more difficult to determine the long-term success of the fish culture; the middle panels of Figures 5 and 6 provide some indication that survival rates may be declining. However, fish survival rates fluctuate and it is impossible to know

whether the lower survivals in 1990 and 1991 broods portend things to come or are part of natural variation. Further, the estimates of survival rates before 1987 were not derived from coded wire tags (as are later survivals), so these periods may not be comparable.

The biological success of the programs is less obvious. If we accept the trends seen in southeast Alaska and southern Alaska Peninsula stocks as indicative of what would have happened in the absence of hatchery programs in PWS and Kodiak, then there appears to be little if any net production. As discussed earlier, pink salmon production in the other areas increased at the same time, and whereas pink salmon increased in PWS more than in two of the three control areas, the greater increase took place before the onset of large hatchery production.

This interpretation is supported by the increase in wild production in PWS that began in the early 1980s, only to have the wild production replaced by the hatchery production in the late 1980s and 1990s. This pattern of replacement in PWS can be interpreted as a classic example of the following concern stated by Brannon and Mathews (1988). "In the first place, rather than supplementing natural populations, hatchery production tended to replace natural production, with the result that naturally spawned fish no longer contributed effectively to the fishery. The net gain from hatchery propagation in this regard may have been very little." There is no evidence of replacement in the Kodiak area.

There are two independent items supporting the replacement theory for PWS. (1) The stocks in other areas without hatcheries increased at the same time, and (2) the wild stocks first increased in PWS, then as hatchery production increased, wild production declined.

These observations do not constitute "proof"; the other areas are not randomized controls, but rather "natural" controls with all of the possibilities of another covariate being responsible. Furthermore, the apparent replacement of wild fish by hatchery fish in the 1980s is based on an effective sample size of 1—that is, we only have one time series of data from hatchery and wild production in PWS.

Alternative Explanations for the Decline in PWS Wild Salmon

Why did the wild stocks decline after the 1985 brood year? There are four possible hypotheses, including harvesting, competition with wild fish,

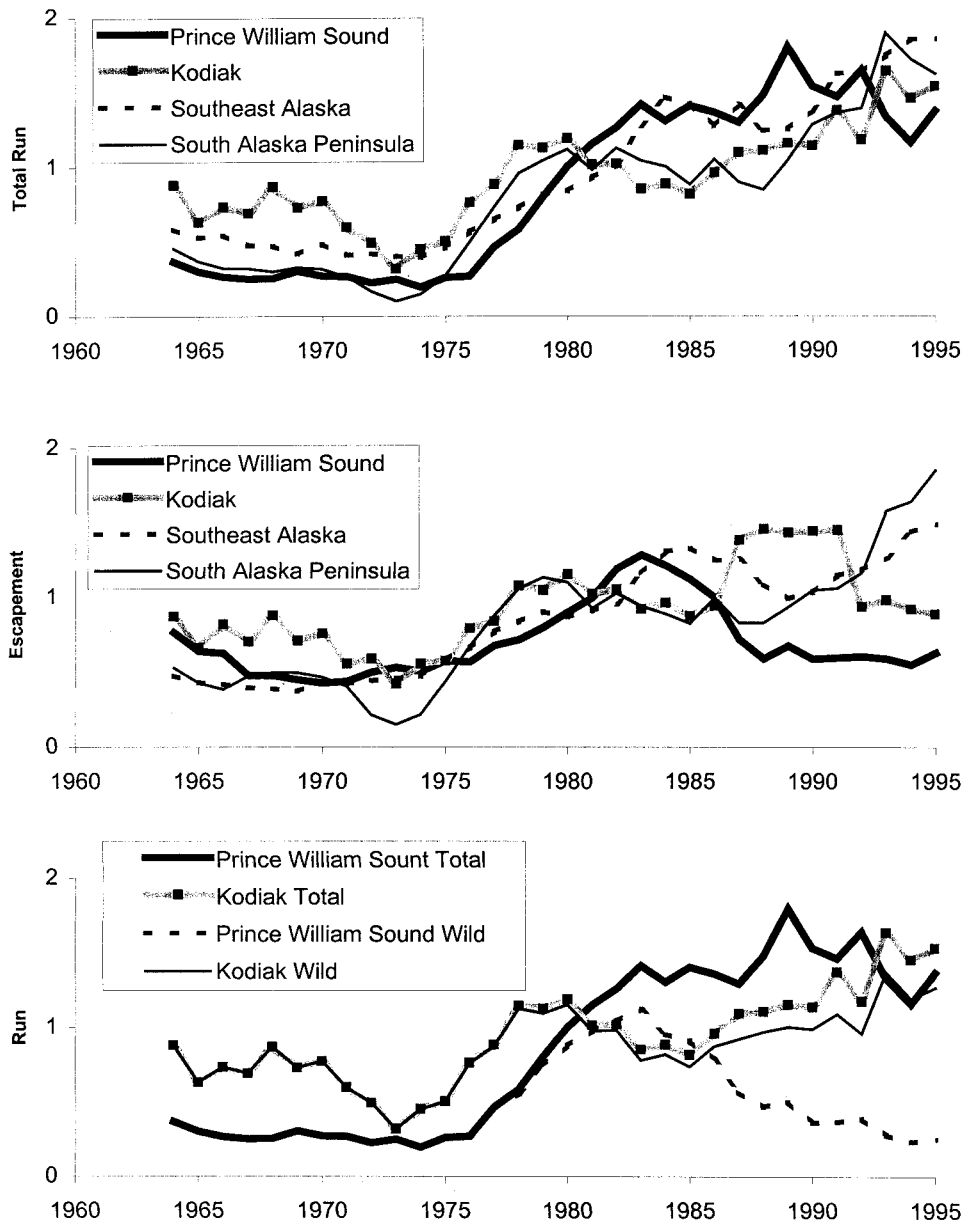


FIGURE 8.—Five-year running averages of run, escapement, and total run for the four pink salmon production areas in Alaska, scaled by the 1976–1985 average values for each area. (**Top**) Running average of total run (hatchery plus wild); (**middle**) running-average escapement; and (**bottom**) running averages of wild pink salmon run and total run including hatchery plus escapements (Prince William Sound and Kodiak areas only) divided by the average total run including hatchery for each area.

natural changes, and straying or genetic impacts of hatchery fish. We will deal with each of these in turn.

Impacts due to changes in escapement.—To examine the decline of the wild stocks in PWS we divided the data into two periods: (1) brood years

1977–1985, characterized by large returns after the rebuilding from the low runs of the 1960s and early 1970s, and (2) brood years 1986–1995, the recent period of low returns of wild fish.

The average wild return to PWS in the later period was 32% of the return in the first period,

TABLE 1.—Ratios of average run for 1986–1997 to averages for 1965–1975 and for 1976–1985, in four Alaskan pink salmon regions.

Base period	Region			
	Kodiak Island	Prince William Sound	Southeast Alaska	South Alaska Peninsula
1965–1975	1.90	5.74	3.54	5.93
1976–1985	1.13	1.43	1.55	1.37

whereas the escapement was 56% and the recruit per spawner was 57% of that during 1977–1985 (Table 2). Thus, we can conclude that part of the decline in wild stocks was due almost equally to a reduction in average escapement and a reduction in recruits per spawner. The escapement goal for PWS during both periods (brood years 1977–1995) was 1.8 million pink salmon; thus the average escapements in the 1977–1985 period were above the goal while the escapements from brood years 1986–1995 were slightly below the goal. Figure 9 shows the pattern, typical of net fisheries management, in which the actual wild-stock escapement during 1960–1985 and 1986–1995 in PWS increased with larger runs rather than the “ideal” of escapement holding constant regardless of run size. A strike by commercial fishing boat operators occurred in 1984, resulting in an escapement of 5.2 million fish, thus the data point for that year was not plotted. Two important conclusions can be drawn from Figure 9. First, the lower escapements in the later period appear to be due to the lower runs. Second, we see no difference in the escapement–return relationship between the two time periods. The analysis, at the PWS-wide scale, does not support a conclusion that the fishery was managed differently after large hatchery returns began.

It has been suggested that the presence of large hatchery runs led to higher exploitation and lower escapements. For instance, Geiger (1994) states “the entire 1992 wild run was needed for spawning escapement. Yet, for a variety of reasons related to the need to harvest the hatchery return, the har-

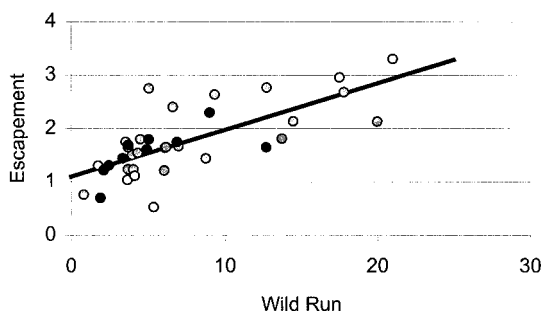


FIGURE 9.—Relationship between wild-stock escapement and total wild-stock return (both in millions of fish) in Prince William Sound for brood years 1960–1985 (gray dots; 1984 data excluded) and 1986–1995 (black dots).

vest rate on wild salmon was held to nearly the recent average.” The 1992 run is the lowest black dot in Figure 9 and may constitute a single instance of PWS-wide overharvest of wild stocks, but it is clearly not an indication of a systematic pattern of changed harvest policies in recent years.

However, when we look at the spatial pattern of escapements we see more evidence that the presence of hatchery fish led to a changed harvest pattern. The fishing districts in the north and west of PWS were heavily affected by the fishery for the hatchery stocks, whereas districts in eastern PWS were much less affected by these fisheries (Figure 10). The districts where the hatchery stocks passed have shown much stronger declines in escapement than the lightly affected districts.

The passage from Geiger (1994) above suggests that the economic pressure to exploit hatchery stocks in common-property fisheries was a major contributor to the reduced escapements in some parts of PWS, but overall we conclude that the reduced escapements after 1988 would have occurred regardless of the presence of large hatchery returns.

Impacts due to biological competition.—The lower escapement only explains part of the decline in wild stocks. There was also a reduction in the recruits per spawner in PWS to 57% of what it had

TABLE 2.—Data for Prince William Sound wild stocks, fry release, and common-property (CP) harvest rates for a period of high wild-stock runs (brood years 1977–1985) and low wild-stock runs (brood years 1986–1995).

Brood years	Average total wild return (millions)	Average brood year escapement (millions)	Average recruits per spawner	Average fry release (millions)	CP harvest rate
1977–1985	16.3	2.7	6.0	76	0.82
1986–1995	5.2	1.5	3.5	502	0.74

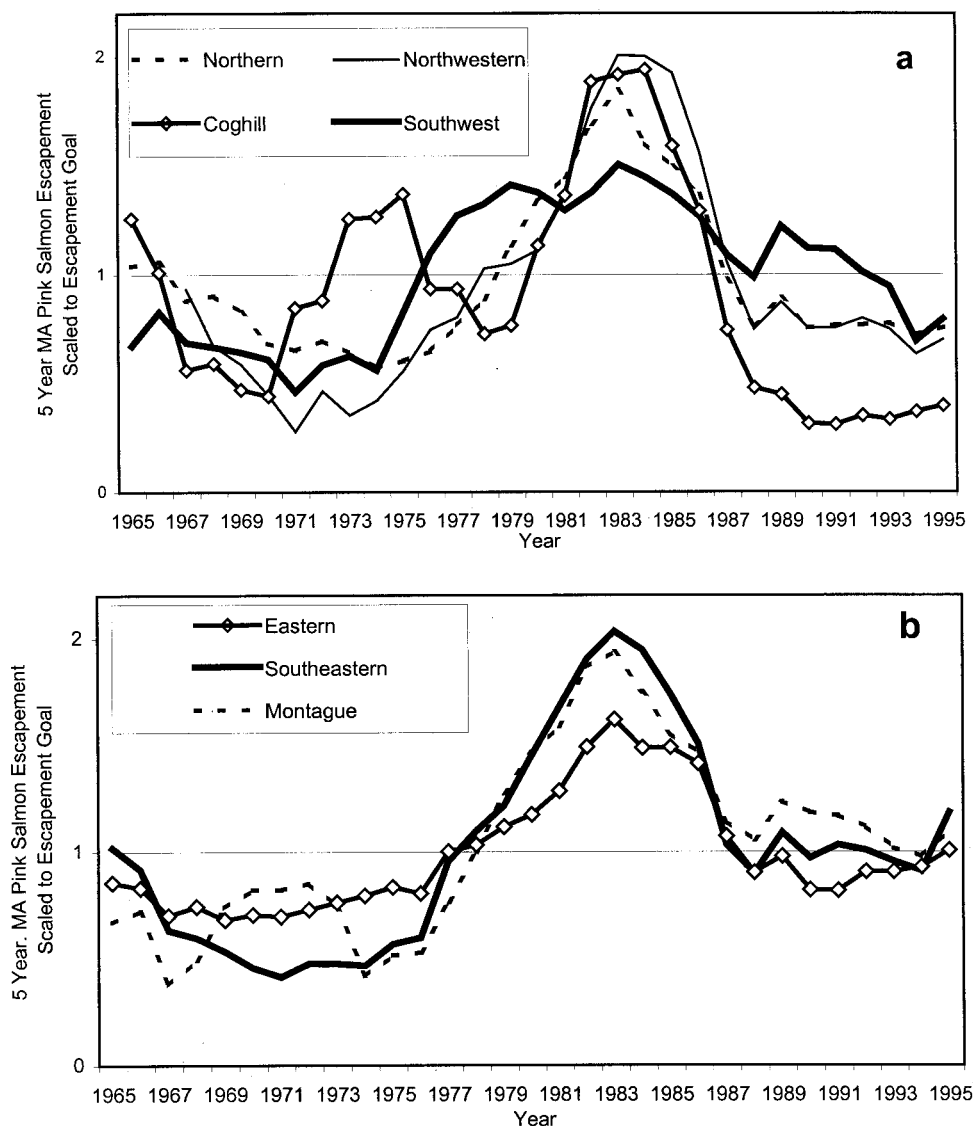


FIGURE 10.—Trends in escapement in different fishing districts within Prince William Sound (PWS). The 5-year moving average (MA) divided by the 1962–1997 average is plotted, which illustrates by contrast (a) four districts in the northwest and southwest of PWS that are strongly affected by hatchery production and (b) three fishing districts in the south and east that are less affected by the hatcheries.

TABLE 3.—Total return divided by escapement index for the four major regions producing pink salmon in Alaska.

Brood years	Region			
	Kodiak Island	Southeast Alaska	South Alaska Peninsula	Prince William Sound
1977–1985	2.32	1.98	2.37	6.03
1986–1995	2.39	2.46	3.03	3.47

been in the earlier period. The escapement numbers are more likely reliable as an index rather than as an unbiased count; therefore it is the change in the ratio of total return to escapement (Table 3), rather than the absolute level, that is of more interest.

In Kodiak Island, southeast Alaska, and the southern Alaska Peninsula, the return per spawner increased after 1985 while it decreased in PWS. A major difference between these regions is the

level of hatchery release in PWS and the close proximity of PWS hatcheries to the wild-stock production areas. In the Kodiak area, hatchery and wild stocks are physically separated, thus minimizing interaction and competition. Only PWS saw reduced recruits per spawner and only PWS had a large hatchery program during the more recent period.

Marine competition and freshwater genetic impacts by the hatchery stocks have both been hypothesized as mechanisms for hatchery impacts on survival of wild stocks. Sharp et al. (1994) documented high straying rates of coded-wire-tagged hatchery fish into wild streams in PWS, which suggests that this straying may lead to a decline in wild-stock productivity due to hybridization with hatchery strains. Using thermal marking of hatchery fish, T. Joyce and D. G. Evans (ADF&G, unpublished) confirmed very high rates of straying into streams near the hatcheries. Thus, if the hatchery stocks have poorer fitness when spawning in the wild, the intense straying by these fish is a plausible explanation for the decline in wild recruits per spawner.

In examining the impact of changes in both escapement and hatchery releases, we graphed the relationship between escapement and the natural logarithm of recruits per spawner in PWS (Figure 11, top). This is the traditional graph for fitting the Ricker curve to salmon data. The best-fit linear trend showed a decline in \log_e recruits per spawner as escapement increased, but the data were noisy.

We also graphed the relationship between wild recruits per spawner and the number of hatchery releases in the year the wild fish went to sea and presumably competed with the hatchery releases (Figure 11, bottom). Again we saw a downward trend, but the data were noisy with two outliers representing occurrences of high recruits per spawner in years of large hatchery releases. It happens that both of these outliers correspond to years of low escapement.

We fit a Ricker model treating smolt releases as an auxiliary variable (Hilborn and Walters 1992: equation 7.7.4), which we write as follows:

$$R_{y+2} = S_y \exp \left\{ \alpha \left[1 - \frac{S_y}{b} - c(H_{y+1} - \bar{H}) \right] \right\},$$

where R is the recruitment, S is the spawning stock, H is the number of smolts released from the hatchery system, \bar{H} is the average smolt release, $\exp(\alpha)$ is the recruits per spawner in the absence of density dependence, b is the value wherein recruits equals

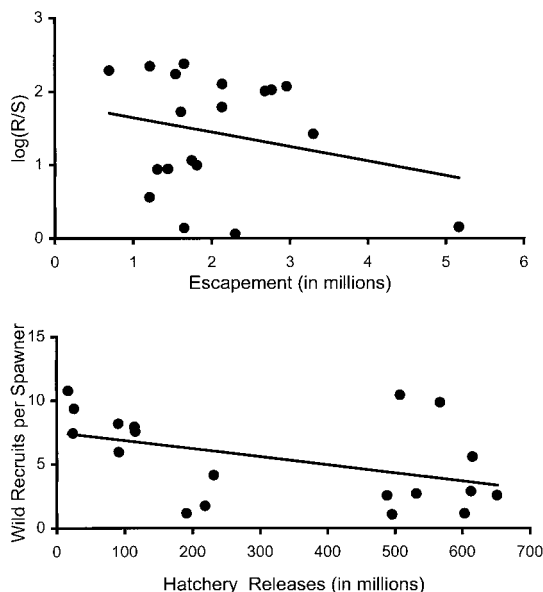


FIGURE 11.—(Top) Natural logarithm of recruits per spawner (R/S) for wild pink salmon in Prince William Sound plotted against escapement in the same brood year (for brood years 1977–1995). (Bottom) Wild recruits per spawner plotted against the hatchery release in the year the wild fish migrated to sea.

spawners, c is a parameter indicating the magnitude of the decrease in recruits due to smolt releases, and y is the calendar year.

Table 4 shows the results for five recruitment models. Our first model assumes that recruitment is constant with no effect of escapement or smolts. Next we fit the model above assuming no density dependence or hatchery effect; that is, b was set equal to a very large number and c was assumed to be 0. This second model assumes recruitment is proportional to escapement. The improvement in fit is highly significant ($P = 0.0087$), indicating that more spawners do produce more recruits (Figure 12, upper left). Values for P were calculated using a likelihood ratio test (Hilborn and Mangel 1997). Next we fit the normal Ricker model, which assumed $c = 0$ (Table 4, third model; Figure 12, upper right). The improvement in fit was indicated by $P = 0.16$ when compared with the proportional recruitment model. Then we fit a model with proportional recruitment and a hatchery effect; b was set equal to 10^{12} so there was no density dependence, and $P = 0.06$ (again compared with the proportional recruitment model; Table 4, fourth model; Figure 12, lower left). Finally we fit the full model with both density dependence and smolt effect. When compared with the proportional re-

TABLE 4.—Negative log likelihood and *P*-values for five models predicting pink salmon recruitment for the 1977–1995 brood years.

Model	df	Negative log likelihood	Model compared to	<i>P</i>
Constant recruitment	18	27.18		
Recruitment proportional to escapement	18	22.28	Constant recruitment	0.0018
Regular Ricker model	17	21.69	Proportional recruitment	0.28
Smolt impact only, no density dependence	17	20.31	Proportional recruitment	0.047
Both density dependence and smolt impact	16	17.18	Proportional recruitment	0.006

cruitment, $P = 0.006$ for this model (Figure 12, lower right). These statistics show that the best explanation for what happened to PWS wild pink salmon is a combination of changes in escapement and increasing hatchery releases. The *P*-level for the model with both effects is impressive, however hatchery releases were highly correlated with year, and the result could be due to any factor that changed with time in a similar fashion. Implications of these model fits are summarized in Figure 13: in the presence of larger smolt releases, expected recruitments are lower. The optimum escapement to maximize harvest of wild stock in the absence of smolt releases is 2.1 million.

We can now use this model to predict what

would have happened if no smolts had been released. Table 5 shows the wild escapement, wild recruits, and predicted recruits from the model just presented; “log residual” is the logarithm of observed recruitment divided by the predicted recruitment and is an estimate of the environmentally induced deviation in that year. Brood years 1990 and 1991 had very negative residuals whereas brood years 1989 and 1992 had very positive residuals. Scenario 1 (Table 5, column 6) shows what the run would have been using this model if the escapement had been 2.1 million each year and no smolts were released. Scenario 1 is unrealistic in that we have seen that managers do not control escapement to a fixed target. Scenario 2 (Table 5,

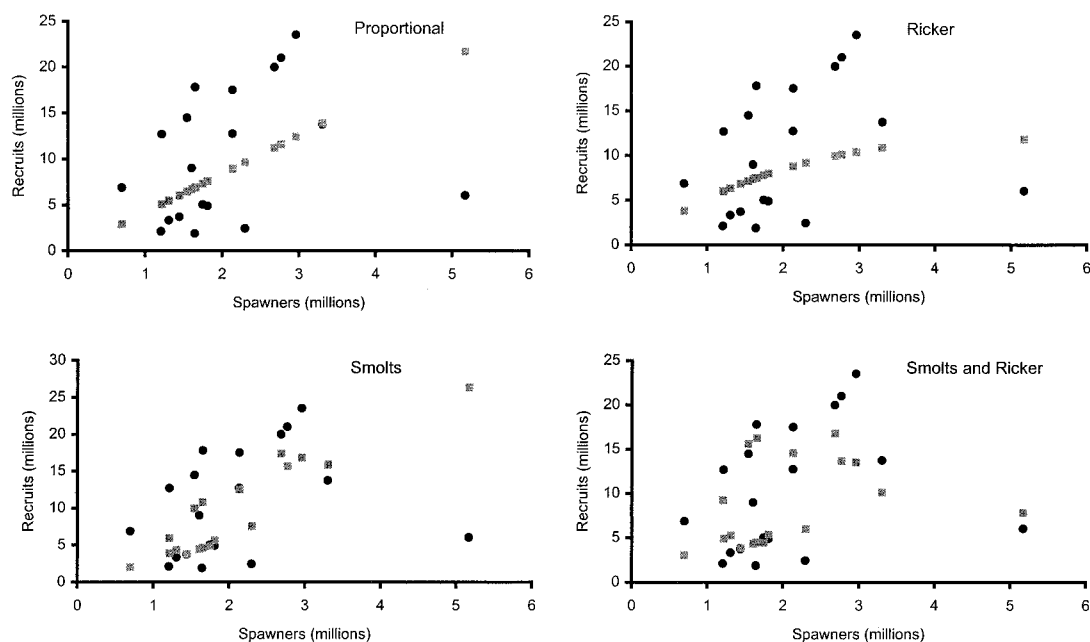


FIGURE 12.—Observed recruitment (circles) and predicted recruitment (squares) for four models (see Discussion, Table 4) of wild pink salmon recruitment in Prince William Sound from brood years 1977–1995.

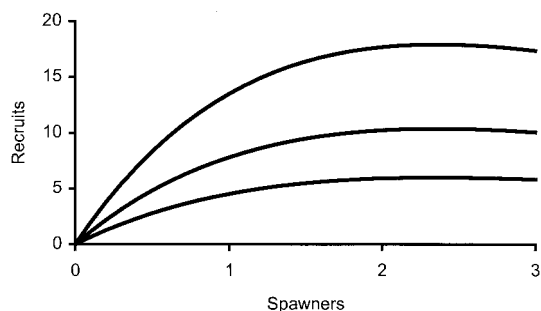


FIGURE 13.—Average expected wild-stock recruitment plotted against wild-stock escapement with releases of 0 (upper line), 250 million (middle line), and 500 million hatchery smolts (lower line).

column 7) shows what the run would have been using the actual escapements in the model and if no smolts were released. Scenario 2 is unrealistic also, because the anticipated higher wild returns without smolts would have led to higher realized escapements. The “predicted escapement” (Table 5, column 8) is what the escapement would have been if the solid line in Figure 9 had been used to predict the escapement based on the predicted total wild run under Scenario 3—what the total return

would have been if the simulated escapements had been used and no smolts were released (Table 5, last column). We believe this scenario is most realistic for the actual escapement.

With the averages for brood years 1986–1995, we would have expected 20.57, 17.52, and 19.05 million pink salmon returning under the three scenarios we just discussed. These expectations compare with an actual total return of 24.5 million during those years. Using our Scenario 3 we would thus estimate that the net increase due to hatchery production during this period was 5.5 million fish per year.

However, the other pink-salmon-producing areas all showed increased recruits per spawner in the later period, indicating better ocean conditions than during the earlier period. The average ratio of recruits per spawner in the later period to recruits per spawner in the former period for the other three areas is 1.18, indicating those areas saw an 18% average increase in recruits per spawner during brood years 1986–1995. The bottom row of Table 5 shows the predicted total returns allowing for an 18% increase in the later period. Thus our best estimate of the net production due to the

TABLE 5.—Predicted total returns in selected scenarios, all if no smolts were released. All numbers are millions.

Brood year	Wild escapement	Observed recruits	Predicted recruits	Log residual	Predicted run with:			Predicted run with simulated escapement (scenario 3)
					2.1 M escapement (scenario 1)	Actual escapement (scenario 2)	Simulated escapement using Figure 9	
1975								6.16
1976								4.32
1977	1.65	17.80	16.29	0.09	19.44	18.47	1.63	18.40
1978	1.54	14.48	15.64	-0.08	16.47	15.31	1.47	15.04
1979	2.68	19.99	16.85	0.17	21.10	21.08	2.70	21.06
1980	2.14	17.51	14.60	0.18	21.35	21.38	2.41	21.49
1981	2.13	12.74	14.57	-0.13	15.56	15.58	2.93	15.28
1982	2.96	23.54	13.55	0.55	30.91	30.29	2.97	30.26
1983	2.77	21.00	13.71	0.43	27.27	27.10	2.43	27.45
1984	5.17	6.05	7.88	-0.26	13.66	9.19	5.17	9.19
1985	3.30	13.74	10.13	0.30	24.13	22.82	3.49	22.28
1896	1.21	2.12	9.25	-1.47	4.08	3.42	1.89	4.01
1987	1.81	4.90	5.40	-0.10	16.14	15.72	3.04	15.70
1988	1.22	12.70	4.92	0.95	45.94	38.63	1.44	41.64
1989	1.61	9.00	4.36	0.73	36.78	34.66	2.46	37.01
1990	1.65	1.90	4.50	-0.86	7.51	7.13	4.73	5.56
1991	2.30	2.45	6.04	-0.90	7.21	7.26	4.33	5.80
1992	0.70	6.88	3.08	0.80	39.72	23.86	1.58	37.20
1993	1.31	3.34	5.31	-0.46	11.21	9.76	1.60	10.55
1994	1.75	5.04	4.48	0.12	20.00	19.32	4.34	16.03
1995	1.44	3.71	3.87	-0.04	17.07	15.48	2.01	16.97
1986–1995 average	1.50	5.20	5.12	-0.12	20.57	17.52	2.74	19.05
Average with 18% increase					24.27	20.68		22.48

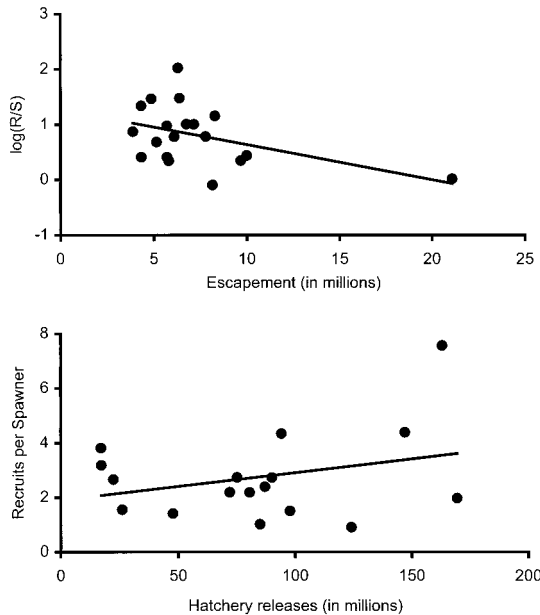


FIGURE 14.—(Top) Natural logarithm of recruits per spawner (R/S) for wild pink salmon in the Kodiak Island area plotted against escapement in the same brood year (for brood years 1977–1993). (Bottom) Wild recruits per spawner plotted against the hatchery release in the year the wild fish migrated to sea.

hatchery program (using Scenario 3) is 2 million pink salmon per year.

We repeated the same analysis for the Kodiak area, examining the relationship between $\log_e(R/S)$ and escapement and the relationship between recruits per spawner and hatchery releases (Figure 14). There was some evidence for density dependence, but only based on one year (1989) with a very high escapement, and no evidence that higher hatchery releases have led to fewer wild recruits per spawner.

We repeated the range of models for Kodiak that we had used for PWS. The proportional and smolt models (Figure 15, left top and bottom panels, respectively) did not provide an improvement in fit over the hypothesis that returns were constant, and only the Ricker model provided a significant improvement in fit, which was clearly due only to the one data point. We concluded there was no evidence that hatchery production affected wild production in the Kodiak area.

Decline in Wild Stocks in PWS was a Natural Change

This possibility cannot be eliminated. We know of no quantitative way to assess this probability because it depends on the degree to which the other areas serve as effective controls on ocean condi-

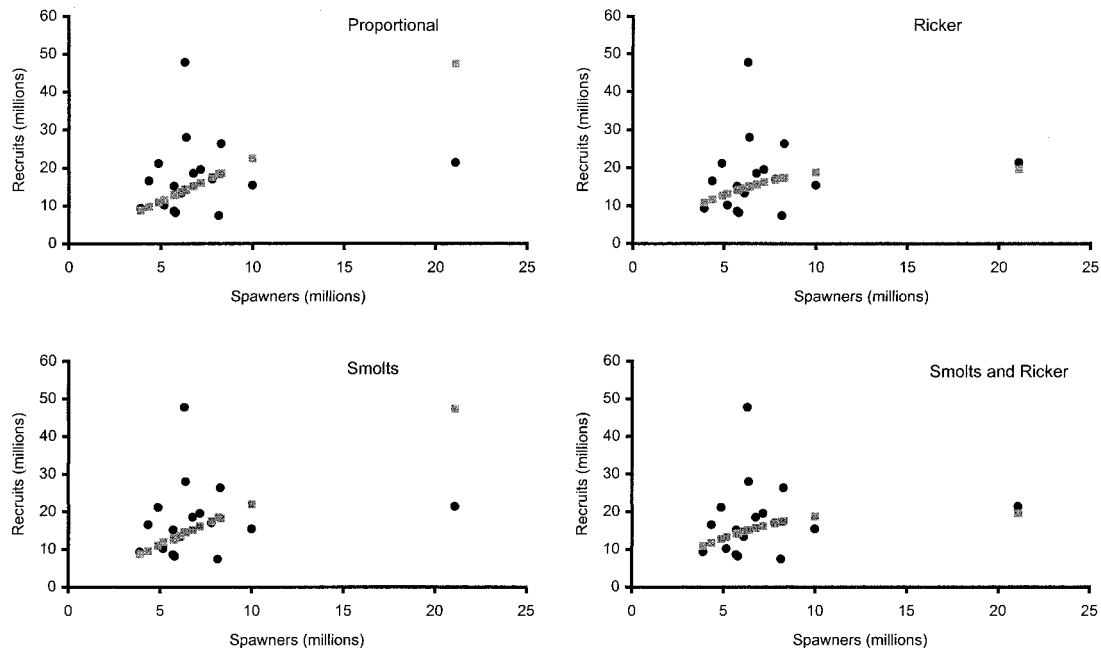


FIGURE 15.—Observed recruitment (circles) and predicted recruitment (squares) for four models of wild pink salmon recruitment in the Kodiak Island area for the 1977–1993 brood years.

tions and we accept that there is an unexplained factor that changed in the mid-1980s in PWS.

Earlier we discussed two plausible mechanisms for the hatchery impacts—genetic degradation due to straying and competition in the early life history. Smoker and Linley (1997) discussed these mechanisms and suggested they are unlikely given the short hatchery rearing period for pink salmon. Similarly, Smoker and Linley discounted the possibility of marine competition. Higher hatchery releases in PWS coincided with lower wild recruits per spawner, but it is possible that something in PWS changed starting in brood year 1986.

It is widely recognized that the *Exxon Valdez* oil spill in 1989 might have affected wild spawning pink salmon. There is disagreement regarding the amount of loss caused by the oil spill. Some investigators (Bue et al. 1996, 1998a; Geiger et al. 1996) estimated pink salmon damage ranged as high as 2% of the total wild return to PWS, whereas others (Brannon and Maki 1996) argued that even this loss was an artifact of the sampling regime and not a real effect. Thus none of the published work has suggested that the loss from the oil spill would even be detectable on a PWS-wide basis. The decline in wild recruits per spawner in PWS, illustrated in Figure 3, began well before the oil spill (beginning in the 1984 brood year); and brood years 1988 and 1989, most affected by the oil spill, had among the highest recruits per spawner in the period after 1986. Thus we found no evidence that the *Exxon Valdez* oil spill could account for the decline in recruits per spawner seen after 1986.

Smoker and Linley provided a defense of the PWS hatchery program, arguing that because escapements declined throughout PWS in the 1990s, it was a phenomenon unrelated to hatchery production. Their argument has a number of problems. First, the escapement clearly declined in the Southeastern District (Smoker and Linley 1997: Figure 1) from a high in the early 1980s, the same pattern as seen in PWS as a whole. We have shown that in areas where the wild stocks pass through the fisheries targeting on hatchery fish (Figure 10), escapement declined more than in areas less affected by the hatchery-oriented fisheries. Given our understanding of the relationship between escapement and total run (Figure 9), we conclude that the decline in escapement was due to the decline in the wild-stock run, which in turn was due to a decline in recruits per spawner, shown to be related to smolt releases.

Conclusions

The Prince William Sound and Kodiak Island pink salmon programs provide what may be the best opportunity to determine if mass production of juvenile fish can increase total fish production. The hatchery systems for chinook salmon, coho salmon, and steelhead *O. mykiss* throughout North America are so ubiquitous that it is difficult, if not impossible, to evaluate the impact of hatchery fish on wild production because there are few areas that can be considered to be controls. Further, escapement of chinook salmon and coho salmon are very difficult to monitor. In the PWS and Kodiak pink salmon fisheries we have the best possible situation: very large programs, which makes impacts more detectable, and areas of pink salmon production without large hatchery programs.

We suggest there was little if any increase in total abundance due to the hatchery program in PWS. Our best estimate is 2 million fish per year. The program was conceived in a period of low abundance of wild fish, but by the time large-scale hatchery production came on-line the wild production had increased. Hatchery production increased and wild production then declined. In contrast, abundance of wild stocks in the three other pink-salmon-producing areas of Alaska increased as much and stayed high while wild production in PWS declined. The Kodiak area appears to have experienced no impact of hatchery fish on wild production for three reasons. (1) The program there was smaller relative to the wild stocks; (2) the hatchery was physically isolated so there was little mixed-stock fishing on hatchery and wild fish, and there was little interaction by these fish during their early life history; and (3) the hatchery survival rates were much lower than in PWS, therefore the ratio of hatchery return to wild return was much lower.

This conclusion has wide consequences—because there are dozens, if not hundreds, of hatchery programs existing or planned—for many marine species around the world. Planners and operators of these programs rarely if ever consider negative impacts on wild production, and no marine hatchery program has any form of experimental design in place that could determine if the hatchery would replace wild production.

To our knowledge no one now argues that existing hatchery programs in the United States and Canada produce fish at a cost comparable with the value of the fish, but it is generally assumed by hatchery operators, politicians, and the public that

hatcheries augment total production. The lesson from PWS, however, is just the opposite: we should expect hatchery production to replace wild production rather than augment it whenever there is biological interaction and mixed-stock fishing. The PWS hatchery program for pink salmon provides by far the most dramatic evidence for this effect.

These conclusions apply to mass hatchery production where wild stocks are present. Obviously, if there are no wild stocks or if they are severely depleted at the onset of the hatchery program, the potential for the loss of wild-stock production is less. Also, these conclusions are not really relevant to various forms of supplementation hatcheries that use hatchery rearing as a short-term measure to rebuild wild production. There are many problems in evaluating supplementation hatcheries (Winton and Hilborn 1994), but we do not believe that the Prince William Sound or Kodiak Island hatchery programs are relevant models.

Acknowledgments

We thank Brian Bue, Brian Bigler, Claribel Coronado, Hal Geiger, Al Maki, Don Rogers, Jim Seeb, Bob Wilbur, John Winton, three anonymous reviewers, and numerous staff members of ADF&G for supplying data, discussion, and comments on the manuscript; R. Hilborn was supported in part by Exxon Corp.

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