

Factors Affecting Puget Sound Coho Salmon (*Oncorhynchus kisutch*) Runs¹

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Summer streamflow, apparently affecting survival of zero-age coho salmon (*Oncorhynchus kisutch*), is shown to be an important determinant of Puget Sound run strength since 1952. Recently, hatchery production has also been a significant factor. Earlier studies indicated a relationship between rearing flows and coho run strength beginning in 1935. The persistence of the correlation between streamflow and run strength for more than 40 yr is noteworthy. Although the mechanism is unclear, survival of hatchery coho may also be positively dependent upon the same environmental conditions that affect stream-reared coho; a compensatory mortality relationship between abundance of hatchery coho and abundance of stream-reared coho is postulated.

Key words: coho salmon, survival, run prediction, hatchery contribution

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Le débit des cours d'eau en été, qui semble influencer sur la survie des saumons coho (*Oncorhynchus kisutch*) d'âge zéro, s'avère un important facteur d'abondance des remontées dans le Puget Sound depuis 1952. Récemment, la production en écloserie a été aussi un facteur important. Des études antérieures ont démontré une relation entre l'écoulement d'élevage et l'abondance des remontées de saumons coho depuis 1935. Cette corrélation entre débit du cours d'eau et abondance de la remontée, qui a persisté pendant plus de 40 ans, est remarquable. Bien que le mécanisme ne soit pas clair, la survie des saumons coho d'écloserie peut également dépendre des mêmes conditions ambiantes que celles affectant les saumons élevés en cours d'eau; nous supposons une relation de mortalité anticompensatoire entre l'abondance des saumons d'écloserie et celle des saumons élevés en cours d'eau.

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COHO salmon (*Oncorhynchus kisutch*) is an important species of salmon contributing to commercial and sport catches in Puget Sound. Recent United States commercial net catches in Puget Sound have approached 1 000 000 coho annually, while sport catches have approximated 200 000 (Washington State Department of Fisheries, Annual Statistical Reports). The demand for salmon far exceeds its supply, and this necessitates intense management of the harvest to prevent over-exploitation. Successful stock management requires a good understanding of the major factors affecting survival and subsequent run size. This information, in turn, is used in developing run prediction models, which are key tools for managing harvests.

Juvenile coho salmon reside in freshwater through

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one summer and emigrate to saltwater the following spring as yearling smolts. During their stream residence, young coho are subjected to numerous stresses that diminish the population. These include predation, high temperature, low dissolved oxygen, disease, stranding, and overcrowding which may be associated with streamflow conditions. Smoker (1955) was first to document clearly a relationship between streamflow and Puget Sound coho production. He found a positive correlation ($r = 0.92$, $n = 20$ yr) between the commercial catch of coho salmon from western Washington in year t and the annual water runoff from western Washington streams in year $t-2$. He also found a lesser but significant correlation ($r = 0.80$) between the June-September runoff in year $t-2$ and the catch. By about 1967 the correlation between annual runoff and catch had declined, and summer flows were better than annual flows for predicting coho runs.³ Others (McKernan et al. 1950; Wickett 1951; Neave 1949; Pear-

³Observation of the senior author when developing a management forecast of the 1968 Puget Sound run for the Washington State Department of Fisheries.

son et al. unpublished MS⁴) had found positive relationships between summer flows and stream survival of coho. For the 1950s and early 1960s a significant positive correlation existed between coho catch by the Oregon commercial troll fishery and total runoff in Oregon coastal streams for the 17 mo each brood spends in freshwater; however, summer flows did not correlate significantly with Oregon catch (D. Scarnecchia, Colorado State Univ., Dep. Fish. Wildl., Fort Collins, CO, personal communication).

During the 1960s and continuing into the 1970s, hatchery production played an increasing role in contributing to net catches of coho salmon. Recent estimates indicate that more than half of all Puget Sound-caught coho are now of hatchery origin (Zillges 1977). Despite the increased hatchery plantings and numerous recent changes in fishing regulations, a relationship persists between summer streamflows and commercial net catches of coho salmon in Puget Sound. The Washington State Department of Fisheries (WDF) continues to depend largely on summer flow data for developing management forecasts of Puget Sound coho runs (Zillges 1977; G. Zillges, Washington State Department of Fisheries, Olympia, WA, personal communication).

The objectives of this paper are to document the continuing relationship between summer flow and run strength of Puget Sound coho, update the run prediction model by regression analysis to account for hatchery production, and indicate that survival of hatchery-reared coho as well as stream-reared coho also may vary with summer flow. The survival dependence of stream-reared coho on summer flows has obvious probable mechanisms. It is less clear why survival of hatchery smolts to adults in year i also should depend on summer flows in year $i-2$. Possible mechanisms are discussed below.

Methods

ADULT PRODUCTION

Because spawning escapements, other than at hatchery racks and a few fishways, are not enumerated, the best long-term index of coho run strength is the total commercial net catch by American fishermen in Puget Sound (Table 1). This is taken by gill nets, reef nets, and purse seines, mainly in September and October. Prior to 1957 about 25% of the catch was taken by an ocean net fishery in the vicinity of Cape Flattery, but since then ocean net fishing has ceased by United States-Canadian agreement. A portion of the Puget Sound production is harvested in the ocean troll and sport fisheries and is unassignable to Puget Sound. Hatchery mark-recovery studies indicated that the ocean hook-and-line fisheries took about 40 to 50% of the total catch plus escapement for the three consecutive years 1967-69 (Senn 1970a, b; Senn and Satterthwaite 1971). More recent but incomplete mark-recovery data for

⁴Pearson, L. S., K. R. Conover, and R. E. Sams. Factors affecting the natural rearing of juvenile coho salmon during the summer low flow season. Ore. State Dep. Fish. Wildl. 65 p. mimeo.

the 1974-76 runs indicate that the ocean catch fraction may now be more variable than during 1967-69 (Olson 1978), which may be due to changing fishing regulations or hatchery release strategies that affect marine distributions of the fish. A segment of the Puget Sound coho population resides in Puget Sound throughout its marine life. This has been a minor portion of the total (Zillges 1977), except most recently when supplemented by hatchery coho specifically reared and delayed in release date so as to remain inside Puget Sound and contribute to the year-round sport fishery therein (Mathews and Buckley 1976). This "resident" sport catch is not felt to be indicative of overall Puget Sound coho production, and we have not added this to the net catch.

About one-third of the American catch of coho salmon in Puget Sound originates in southern British Columbia, according to interception percentages for various Puget Sound fishing areas generally agreed upon by United States and Canadian scientists for ongoing salmon interception negotiations between the countries (Zillges 1977). It is likely that southern British Columbia and Puget Sound summer streamflows are correlated; therefore it seems valid to attempt prediction of the combined total from Puget Sound streamflow indices.

Catch-per-unit-effort (CPUE) is not considered as good an index of run strength as total catch because both gear and management practices have changed substantially over the years, affecting the coefficient of catchability. However, CPUE correlates fairly well with total catch (Table 1; $r = 0.76$).

STREAMFLOW INDEX

Our index was drawn from U.S. Geological Survey records (U.S. Geological Survey (USGS) 1950-76), which list average daily flow for a number of western Washington streams. We attempted to choose streams that would be geographically representative of the Puget Sound basin, contain coho salmon, and be unaffected by artificial regulation or water withdrawals. The choice was limited to those streams that have had continuously operating gauging stations.

We computed streamflow indices based on the mean daily flows of the 60 lowest consecutive days from June 1 through September 30 for the following Puget Sound streams: South Fork Nooksack River, North Fork Stillaguamish River, Wallace River, Issaquah Creek, Rex River, Newaukum Creek, Greenwater River, Mineral Creek, Deschutes River, and South Fork Skokomish River. The flows for each stream then were converted to percentages of the 26-yr (1952-77) mean. Simple averages of these percentages for the 10 streams were used for an overall Puget Sound index for each year (Table 1). This basic methodology of computing flow indices on the basis of consecutive low flow days was developed by Zillges (1974) for predicting Puget Sound native coho runs returning after 1964.

Summer flows depend upon summer rainfall and snowpack the previous winter. Perhaps widely varying summer flow indices could be developed from the USGS records. However, we found that the choice of streams, time periods, and method of weighting the data are not critical in determining which summers were dry and which were wet.

OTHER VARIABLES

Several other variables were examined by multiple regres-

TABLE 1. Statistics for prediction of Puget Sound coho net catch.

Year <i>i</i>	Puget Sound commercial net catch 000s of fish yr <i>i</i>	Puget Sound CPUE ^a	Summer flow index yr <i>i</i> -2 ^b	Puget Sound hatchery plant t of yearlings yr <i>i</i> -1	Washington and Vancouver Island ocean catch 000s of fish yr <i>i</i> ^d	Washington troll catch from Westport north 000s of fish yr <i>i</i>	Data source
1952	654	17.2	1.19	20.0	1483	768	1. Washington commercial catch and effort 1952-75, Puget Sound, Grays Harbor, Willapa Harbor, and Columbia River bound statistical volumes of the Wash. Dept. Fish. (WDF), Olympia, WA; 1976-78, personal communication, Dale Ward, WDF Olympia, WA. 2. Washington coastal sport catch, 1952-75, 1975 Fisheries Statistical Rep. WDF, Olympia, WA; 1976-77, personal communication, Gene Nye, Olympia, WA. 3. British Columbia troll catches 1952-77, B.C. catch statistics by area and type of gear as reported on sales slips received by the Government. Can. Dept. Fisheries and Oceans, Fisheries Management, Vancouver, B.C. (Title of Dept. as of 1979). 4. Hatchery plants, 1951-76, annual statistical reports on hatchery production and plantings by the WDF, Olympia, WA; titles of reports are variable
1953	342	8.1	0.60	20.0	1269	595	
1954	214	6.3	0.72	21.8	901	338	
1955	300	7.0	0.89	36.3	979	412	
1956	409	15.8	1.56	36.3	1372	611	
1957	294	9.9	1.28	25.4	1510	662	
1958	352	10.0	0.93	34.0	1489	523	
1959	348	12.2	0.82	37.2	1577	506	
1960	104	5.2	0.59	30.4	549	131	
1961	384	17.4	1.12	34.5	1500	425	
1962	414	16.8	1.08	48.5	1780	524	
1963	233	8.0	0.80	58.5	1730	463	
1964	402	18.0	1.15	35.8	1808	457	
1965	405	17.8	0.94	98.0	2653	650	
1966	635	26.1	1.82	106.1	2335	701	
1967	288	12.4	0.83	104.8	1955	543	
1968	450	22.6	0.76	203.7	2816	529	
1969	360	19.7	0.65	250.8	1710	306	
1970	850	30.8	1.25	264.0	2249	553	
1971	551	19.1	0.86	311.2	3633	780	
1972	529	19.5	0.77	333.8	1802	346	
1973	781	19.7	1.20	359.7	2518	593	
1974	875	22.8	1.15	351.5	3037	840	
1975	935	20.2	0.67	424.1	1834	609	
1976	667	14.0	1.09	365.6	3561	1058	
1977	1000	22.0	1.23	426.8	2556	562	
1978	(735) ^c	—	1.47	(407.8) ^c	—	—	

^aEffort in form of gillnet landings. Purse seine and reef net landings were converted to gillnet units by effort standardization procedures.

^bDerived as explained in text from flow records for the following streams: Newaukum Creek, Wallace River, N. Fork Stillaguamish River, S. Fork Nooksak River, Issaquah Creek, Rex River, Greenwater River, Mineral Creek, Deschutes River, S. Fork Skokomish River.

^cPreliminary.

^dWashington troll and sport catch from Westport north; B.C. troll catch in areas 20-27, and C.

sion analysis to determine their degree of influence, if any, on Puget Sound coho runs. These included (1) stream-flows during smolt outmigration (May), (2) estuarial temperatures during smolt outmigration (Elliott Bay), (3) ocean water temperatures (west coast of Vancouver Island) during various periods of the coho's marine residence, (4) growth rates and size during the 1st and 2nd yr of marine residence, (5) ocean troll catches, (6) fishing effort by the ocean troll fishery and by the Puget Sound net fishery, and (7) ocean upwelling indices.

Results and Discussion

Hatchery production has increased very sharply since 1960, increasing catches (Table 1). According to intensive fin-marking studies at all Puget Sound hatcheries for three consecutive brood years, hatchery-reared coho constituted 18% of the 1967-69 Puget

Sound net catch (Senn 1970a, b; Senn and Satterthwaite 1971). Release of coho smolts from Puget Sound hatcheries affecting catch during those 3 yr averaged 203 t. Present levels of annual production have risen to 350-400 t, and hatchery fish may now exceed 50% of the catch (Zillges 1977). Hatchery-produced coho, in addition, probably have added to stream spawning escapements, which have been recently showing an upward trend (Washington State Department of Fisheries, unpublished data), and may have tended to increase stream-reared production.

Hatchery coho, which are reared to a yearling stage in the semicontrolled environment of the hatchery, should not be directly affected by summer streamflow conditions. Consequently, the increasing trend in catch of hatchery coho might tend to mask a correlation between summer streamflow and total net catch.

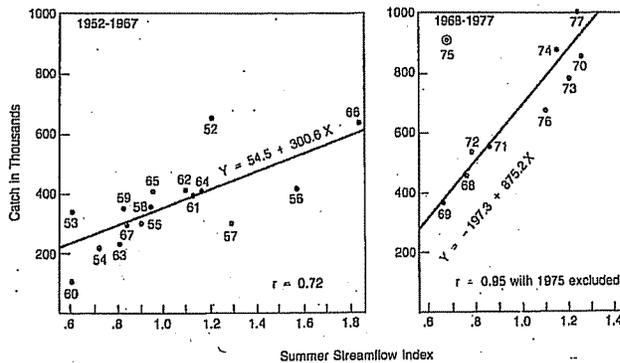


FIG. 1. Puget Sound commercial net catch of coho salmon in year i vs. summer streamflow index in year $i-2$.

One way to demonstrate the effect of summer streamflow on catch with the trend in hatchery production removed is to split the data series into an early set, wherein hatchery contribution was relatively minor, and a late set, wherein hatchery contribution was more important. Hatchery production began rising sharply in the mid-1960s; therefore we arbitrarily split the data into a 1952-67 set and a 1968-77 set for separate regressions (Fig. 1). For both sets the relationship between catch and summer streamflow was positive and significant ($P < 0.05$). For the early years $r = 0.72$. For the later set $r = 0.64$; but when the apparent outlier, 1975, is removed, $r = 0.95$. According to mark-recovery data the ocean availability of Puget Sound coho was unusually low in 1975. Of 6 recent years wherein substantial numbers of marked Puget Sound coho were in the fisheries, 1967-69 and 1974-76, 1975 had the lowest ratio of offshore to inshore recoveries (Senn 1970a, b; Senn and Satterthwaite 1971; Olson 1978). Apparently summer streamflow has an important influence on the total coho run size in Puget Sound despite the increased hatchery contribution to the catch.

The trend in hatchery contribution to the catch can also be treated by multiple regression. The following model was assumed:

$$Y = a + b_1X_1 + b_2X_2$$

where,

Y = Puget Sound net catch in year i in thousands of fish.

X_1 = tonnes of hatchery yearling coho released in year $i-1$.

X_2 = summer flow in year $i-2$.

This model fitted over the entire 26-yr time period was

$$Y = -25.528 + 1.293X_1 + 316.685X_2$$

In a stepwise regression analysis, hatchery plant was the first independent variable entered ($F = 42.59$, $P < 0.01$) and flow the second (F to enter = 17.50, $P < 0.01$). Hatchery plant alone explained 64% of the total variation in catch; and with flow these two

independent variables explained 79% of the variation in catch. Serial correlation between hatchery plant (X_1) and streamflows (X_2) was insignificant ($r = -0.01$). The difference between hindcasted catch from this model and actual catch averaged 21% of the actual catch for the 26-yr series.

Inclusion of Puget Sound net fishing effort in the regression improved the model significantly (R^2 from 0.79 to 0.86, $P < 0.01$), but we would exclude this independent variable from a management forecast model because of (1) major gear improvements such as hydraulic drums and deeper and lighter nets from 1952 to 1960 which could not be accounted for in our index of effort, (2) the beginning of intensive terminal-area fisheries in 1973, and (3) parallel trends in fishing effort and hatchery releases since 1960 ($r = 0.79$).

For 1978, final catch and hatchery production values are not available, and one of the streamflow gauging stations used for our index was discontinued in 1976; however, summer flows were above average for all the remaining index streams, and the hatchery plant continued high. The 1978 catch was above average, indicating a good probable fit to the above regression model.

We were unsuccessful in finding any measure of ocean catch or catch-per-unit-effort that was useful for inshore run prediction. There has been a significant positive correlation ($r = 0.60$) between Northern Washington-Vancouver Island ocean catch (Table 1) and Puget Sound net catch but this only reflects the upward trend in both from increased hatchery production. Ocean catch as a third independent variable in attempted stepwise regression analysis did not enter significantly for the entire data series, the early data set (1952-66), or the late set (1967-77). Other measures of ocean abundance attempted in regression included Washington troll catch from Westport north and Washington troll catch-per-landing. The results were inconclusive. For the early data set (1952-67), a good correlation was obtained between Washington troll catch (Table 1) and Puget Sound net catch ($r = 0.81$), but for the entire data series $r = 0.50$, indicating little recent relationship between these two variables.

Other indices of environmental conditions during important life stages of coho salmon (streamflows and estuary temperatures during smolt outmigration, ocean seawater temperatures, fish growth, ocean upwelling during spring of outmigration) did not appear to affect significantly the size of the Puget Sound net catch. The failure of ocean upwelling indices to correlate with Puget Sound catch is noteworthy because Gunsolus⁵ (unpublished MS) recently found a high correlation between Oregon coastal upwelling during April-June of year $i-1$ and Oregon coho salmon production in

⁵Gunsolus, R. T. The status of Oregon coho and recommendations for managing the production, harvest and escapement of wild and hatchery-reared stock. Ore. Dep. Fish. Wildl. 59 p. (Mimeo).

TABLE 2. Release size and return rate of Puget Sound hatchery coho.^a

Year of return <i>i</i>	Avg. wt per yearling released in yr <i>i</i> -1 g (fish/lb)	Avg. return rate (adult return to hatchery in yr <i>i</i>) ÷ (no. yearlings released in yr <i>i</i> -1) × 100	Summer flow index yr <i>i</i> -2
1960	8.8 (51.6)	0.75	0.59
1961	8.1 (56.2)	1.48	1.12
1962	8.5 (53.3)	1.74	1.08
1963	8.8 (51.7)	1.07	0.80
1964	8.0 (56.5)	1.80	1.15
1965	14.4 (31.4)	1.83	0.94
1966	15.8 (28.7)	3.19	1.82
1967	19.7 (23.0)	1.69	0.83
1968	22.0 (20.6)	1.65	0.76
1969	25.9 (17.5)	1.52	0.65
1970	25.9 (17.5)	2.57	1.25
1971	25.8 (17.6)	1.44	0.86
1972	24.8 (18.3)	1.39	0.77
1973	24.4 (18.6)	1.02	1.20
1974	24.8 (18.3)	1.99	1.15
1975	30.5 (14.9)	0.90	0.67
1976	26.9 (16.9)	0.90	1.09
1977	26.2 (17.3)	0.85	1.23

^aAveraged over the following hatcheries: Nooksack, Samish, Skagit, Skykomish, Issaquah, Green, Puyallup, Minter, George Adams, Hoodspout.

Date sources: Annual hatcheries statistical reports of production and plantings of the Wash. Dept. of Fish., Olympia, 1959-77. (Reports variously titled.)

year *i*. None of the upwelling indices derived by Gun-solus, including one for the Cape Flattery area, entered into a Puget Sound prediction equation as a significant variable.

There is evidence that adult production of the hatchery-reared segment of the run responds positively to summer flow as does the stream-reared segment. Although the hatchery contribution to the net catch is not precisely known except for years 1967-69 when there were fin-marked coho from all Puget Sound hatcheries, it appears that the relatively good catches from 1973 to 1978 had strong hatchery components. In 5 out of 6 of these years, summer flows 2 yr previously had been above average.

Further evidence of a positive effect of summer flow on hatchery survival is provided by adult return rates to hatchery racks (Table 2). Analyses of such data are complicated by an increasing trend in average release size with time, and by the increasing trend in harvest rate of hatchery coho provided by terminal area fishing. But return rates show good correlation with summer flow indices for return years 1960-77 (Fig. 2). Circled are the points for years 1973-77, the time period for which terminal harvest management policy would have negatively affected hatchery rack return rates. For the remaining years (1960-72) $r = 0.89$, $P < 0.01$. The possibility that nonhatchery fish at the

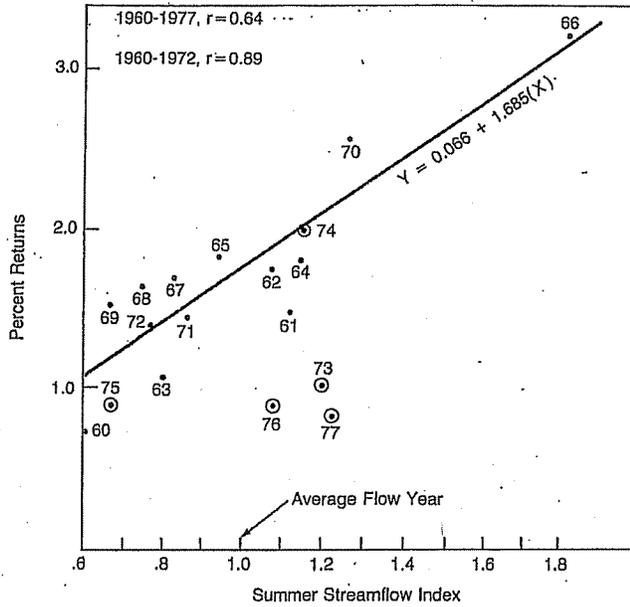


FIG. 2. Adult return rate to Puget Sound hatcheries in year *i* vs. summer streamflow index year *i*-2.

racks may have significantly affected hatchery return rates is unlikely. Most of the hatcheries are on streams so small that nonhatchery abundance at the racks is relatively slight. Washington State Department of Fisheries estimates summarized by Olson (1978) indicate a strong correlation ($r = 0.89$, $P = < 0.01$) between hatchery escapement and the total Puget Sound hatchery run (net catches, sport catches, and escapement) for 1965 through 1974. Thus, return rates to the racks prior to changes in terminal area harvest management in the early 1970s are probably good indices of hatchery survival.

Several reasons can be advanced for the positive effect of summer streamflow on hatchery coho survival. First, dry summers are generally warm summers, and hatchery water sources in such summers could become both lower and warmer, stressing the fish without necessarily killing them. This could lead to lower quality smolts. There is little evidence to substantiate this hypothesis. In analyzing rearing records for individual hatcheries, we could find no indication that total rearing mortalities per brood varied with summer flow or that the extent of rearing mortality affected the adult return rate. A more likely hypothesis is that summer flow does not influence hatchery survival directly but that the abundance of nonhatchery fish, varying with summer flow, may affect survival of hatchery fish in the marine environment through depensatory natural or fishing mortality mechanisms. Nonhatchery fish could "buffer" predation or ocean fishing mortality of hatchery fish, causing survival rates of the latter to increase with increasing abundance of the former.

Depensatory mortality mechanisms have been documented for pink salmon (*O. gorbuscha*) and chum

- salmon (*O. keta*) by Neave (1953) and Hunter (1959). Peterman and Gatto (1978) present an excellent theoretical review of density dependence in salmon populations and cite several examples of depensatory as well as compensatory relationships. Recently, a depensatory survival mechanism was postulated for two populations of British Columbia sockeye salmon (*O. nerka*) that share the same estuary but not the same rearing lake (Manzer 1976). We postulate a similar mechanism for the relationship between survival of hatchery-produced coho and stream-reared coho in Puget Sound, noting that ocean fishing mortality as well as natural predation may be depensatory and account for the relationship. Although this mechanism appears to explain largely year-to-year variability in survival of hatchery-produced coho, there are not yet sufficient years of data to extend this hypothesis to long-term trends in survival as affected by increased hatchery production.
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