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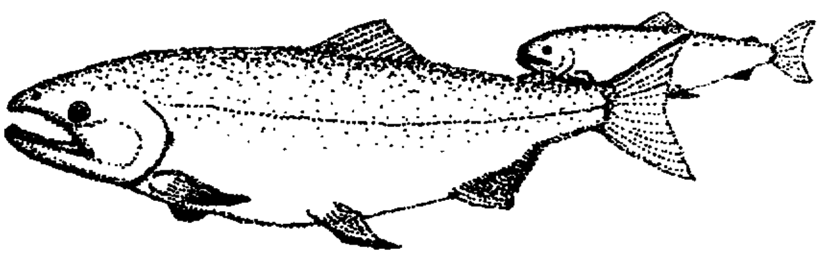

WESTERN WASHINGTON FISHERY RESOURCE OFFICE

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ENVIRONMENTAL FACTORS INFLUENCING SPAWNING ESCAPEMENT OF DUNGENESS RIVER PINK SALMON (*Oncorhynchus gorbuscha*) 1959-1993

Prepared for the

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ABSTRACT

The return to escapement of Dungeness River summer-run and fall-run pink salmon was examined in relation to annual measures of nine environmental factors for the period 1959-1993 using multiple regression analysis. Return to escapement, as indicated by the ratio of spawning escapements in the adult return year to spawning escapement in the corresponding brood year, was regressed against (1) brood year low flow, (2) mean streambed width in the floodplain, (3) level of annual high flow event, (4) mean air temperatures surrounding the year's coldest day, (5) an index of predation by hatchery coho smolts, (6) marine upwelling, (7) marine salinity, (8) sea surface temperature, and (9) low instream flow during adult return. Each independent variable was transformed where necessary to approximate normality and achieve a linear relation to the dependent variable. Relative importance of each independent variable was indicated by the product of its x-coefficient and its standardized mean.

Sea surface temperature had the greatest influence on return to escapement for the summer run population. Peak instream flows and low winter air temperatures were equally important as secondary influences. Low flow between adult return to the river and spawning was third in importance.

Low winter air temperature had the greatest influence on return to escapement for the fall run population; sea surface temperature was next in importance, followed by marine upwelling.

Escapement over the 1959-1993 return years was also examined in relation to four additional factors not amenable to regression analysis: (1) annual acres clearcut in the watershed, (2) volume of mass wasting on one particularly unstable tributary, (3) annual increment in kilometers of riverbank diked or riprapped, and (4) annual release of pink salmon fry into the Dungeness River. Annual acres clearcut over the study period did not coincide with trends in escapement. The immediate effect of slope failures appeared to temporarily depress escapement. The largest increments in streambank protection coincided with the current period's depressed escapement. Fry released in 1976 and 1978 may have acentuated the already high cyclical abundance of the summer run in 1977 and 1979.

I conclude that a summer run restoration program should include, in order of priority, (1) continued water conservation in irrigation to improve instream flow for adult passage to spawning grounds, (2) continued delay in release of hatchery coho to avoid predation on pink fry, and (3) stream habitat modification to improve adult holding conditions.

Fall run restoration should include, in order of priority, (1) continued early closure of the irrigation season to optimize instream flow for fall-run pink spawning, (2) habitat modification to stabilize the lower river spawning grounds, and (3) continued delay in coho smolt releases. Although the relative effect of bank hardening could not be statistically modeled, continued effort to compensate for the detrimental effects of channel confinement and bank hardening appeared important for fall run restoration.

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GLOSSARY

CDFO -- Canadian Department of Fisheries and Oceans

cfs -- Cubic feet per second

EPA -- U.S. Environmental Protection Agency

Escapement -- In this report, the number of fish returning to the river to spawn.

JKT -- Jamestown S'Klallam Tribe

NMFS -- National Marine Fisheries Service

ONF -- U.S. Forest Service, Olympic National Forest

RKM -- River kilometer

RM -- River mile

USACE -- U.S. Army Corps of Engineers

USDI -- U.S. Department of the Interior

USGS -- U.S. Geological Survey

WDF -- Washington State Department of Fisheries, now Washington State Department of Fish and Wildlife

WDFW -- Washington State Department of Fish and Wildlife

WDNR -- Washington State Department of Natural Resources

INTRODUCTION

The Elwha River Ecosystem and Fisheries Restoration Act (PL 102-495) of 1992 established the goal of full restoration of the Elwha River's ecosystem and native anadromous fisheries (Section 3(d)). Federal, state, and tribal fishery agencies plan to accelerate restoration by releasing hatchery-reared juvenile salmonids into the river upstream of the existing dam sites for 8 to 10 yr after safe fish passage is assured (USDI et al. 1994).

The agencies have identified pink salmon (*Oncorhynchus gorbuscha*) among the candidates for hatchery-assisted restoration (USDI et al. 1994). The native Elwha pinks are considered critically depleted (WDF et al. 1993) and not abundant enough to support a hatchery program. Moreover, their confinement to the lower Elwha for 80 yr by the Elwha Dam suggests that this run may no longer be adapted for restocking the upper Elwha. Therefore, the agencies are considering transferring fish from the nearby Dungeness River (USDI et al. 1994).

The Dungeness (Figure 1) supports a wild, native, odd-year summer-run pink population that enters the river in late July and completes spawning by mid-September. Spawning occurs throughout the mainstem from RKM 15.5 (RM 9.7) up to the limit of anadromous passage in the Gray Wolf River and the upper mainstem (East Fork) of the Dungeness, and in the lower 2.4 km (1.5 mi) of Gold Creek (WDF et al. 1993; Figure 2). Spawning grounds are mostly within the hillslope-confined channel upstream of the WDFW Dungeness Fish Hatchery, although a small part of the run spawns in the upper limits of the floodplain. When these fish first enter the river they are ocean-bright, and hold in pools and mature while slowly migrating upstream (WDF et al. 1993).

This run has been considered for introduction in the Elwha River (Hiss 1994) but escapement has remained depressed for more than a decade compared to earlier returns (Figure 3). For this reason, the Dungeness summer pink population will have to be restored to health before transfers can be made into the Elwha. Restoration of Dungeness pink salmon will therefore help achieve the objectives of the Elwha River Ecosystem and Fisheries Restoration Act.

The Dungeness also supports a wild, native, odd-year fall-run pink population which generally spawns in the lower 9.6 km (6 mi) of the river (Figure 2). These fish enter the river in mid-September and complete spawning by late October (WDF et al. 1993). Although lower river spawning distribution makes the run unsuited for introduction into the upper Elwha, it may be suitable for introduction into the lower Elwha if habitat degradation downstream of the dams were remedied (Brad Sele, JKT, pers. comm.). In any case, the run's critically depressed status (WDF et al. 1993; Figure 3) makes it worthy of restoration effort.

Restoration efforts are more likely to succeed if the most likely environmental factors depressing natural production are identified and managed to improve return to escapement. The objective of this study is to identify all measurable factors potentially affecting the escapement of

Dungeness summer and fall run pink salmon, and to assess their relative importance over all years for which spawning escapement has been estimated.

METHODS

Multiple Regression

I used multiple regression to assess the relative importance of nine environmental factors in return to escapement of the Dungeness summer and fall pink salmon runs from 1959 through 1993. The independent variables were:

X1: Low flow during incubation
X2: Streambed width
X3: Level of annual high flow
X4: Air temperatures surrounding year's coldest day
X5: Predation by hatchery coho smolts
X6: Marine upwelling
X7: Marine salinity
X8: Sea surface temperature
X9: Low flow during adult migration

To determine the linearity of each relationship, I inspected a scatter graph of the dependent variable plotted separately against each independent variable. If the relation appeared nonlinear, I fitted a quadratic equation to the plot by trial and error. If the relation appeared linear, I inspected the distribution of the independent variable and transformed it to approximate normality. In the case of linear relationships, correlation was calculated primarily to determine the sign of the slope.

Independent Variable No. X1: Low Flow During Incubation Year

When instream flow falls below a certain level, incubating eggs may die, either from drying out, or by exposure to the extremes of air temperature. The low flow for the incubation year was represented by the magnitude of the minimum 7-day mean flow between July and October (Table 1) at the USGS Dungeness River "Sequim" gaging station, actually upstream of the Dungeness Fish Hatchery (Figure 2).

This variable represents the effect of naturally occurring low flows on the return to escapement of summer-run pinks, since they spawn primarily upstream of irrigation diversion (Figure 2). This variable also represents the combined effect of naturally occurring low flows and irrigation diversion on fall-run pinks, since they spawn (Figure 2) where flows can be visibly diminished by irrigation diversion (Hiss 1993). The model assumes that irrigation diverted a constant proportion of the instream flow available at the USGS gage during the 7-day low flow event during each year of the study period, and that the low flow event occurred after spawning was completed.

Both summer and fall run return to escapement appeared to have a quadratic relation to low flow during the incubation period (Figure 4). I fitted a curve to describe the summer run as

$$X'_S = 0.4 - |(X - 125)/35|^2$$

where X'_S = low flow transformed to reflect its influence on summer run return to escapement, and

X = untransformed low flow in the brood year.

A similar process described the fall return per escapement as

$$X'_F = 0.4 - |(X - 120)/30|^2$$

where X'_F = low flow transformed to reflect its influence on fall run return to escapement.

Independent Variable No. X2: Streambed Width

Streambed width in the unconfined reaches of the river is presumed to indicate perturbation of the incubation habitat. Stream width is the most easily measured link in a hypothetical chain of events beginning with mass wasting and leading to bedload transport through the hillslope-confined channel, aggradation on the floodplain, accelerated sidecutting, and accelerated lateral migration of the stream channels. Accelerated mass wasting is presumed to reduce survival of eggs and fry in the gravel to the degree that the wetted channel moves away from the redds before the fry emerge. Since channels migrate by scour and deposition, survival could be reduced if either high flows wash redds away or suffocate them under a new sediment load.

An index of annual bed width was derived from 1:12,000 scale black-and-white aerial photographs taken by WDNR in 1965, 1971, 1977, 1981, 1985, and 1990. I selected sections of the floodplain unconfined by dikes, and where photos were available in at least five of the six years listed above.

To represent summer-run spawning habitat I chose a stream section beginning at the powerline crossing (Figure 2) and extending south to the Dungeness Fish Hatchery; photos of the more typical summer-run spawning habitat upstream of the hatchery were not available for most years. I assumed that stream width in this section, which includes the upper limits of the floodplain, would represent spawning bed stability throughout the summer-run spawning area within the hillslope-confined channel.

To represent fall-run spawning habitat I chose a stream section beginning at a point between the railroad trestle and the Old Olympic Highway Bridge (Figure 2) and extending south to the Highway 101 Bridge. I assumed that stream width in this section would represent spawning bed stability throughout the fall-run spawning range.

Stream width was measured by overlaying the selected photo with a transparent sheet upon which east-west lines had been drawn at approximately 1-cm intervals. I used east-west lines instead of lines perpendicular to the thalweg to avoid ambiguity in determining the thalweg direction at tight bends and in split channels. Normally, stream width was measured between the east and west boundaries of the tree canopy. In cases where the canopy was broken or scattered, I interpolated from the nearest points north and south that had a solid canopy. Where there were no trees nearby, I substituted the point I interpreted to be the crest of the cut bank. I considered shrubs on river bars to be part of the streambed, and not the tree canopy. Stream width (Tables 2,3) was measured to the nearest mm along each line and averaged over the entire stream section to represent each photo year.

I assigned stream widths by extrapolation or interpolation (Tables 2,3) to each incubation year for which no photographs were taken. Stream width from 1959 to 1963 was presumed to equal the 1965 width. Stream width in 1989 and 1991 was assumed to equal the 1990 width. Stream width for other years when no photos were taken was interpolated along a straight line between the mean widths for the nearest years in which photos were available. Data were $\log_{10}$-transformed (Tables 2,3) to achieve normality for use in the regression model.

Independent Variable No. X3: Level of annual high flow

This variable is assumed to represent the effect of naturally occurring high flow on intragravel survival of both summer-run and fall-run pinks. The high flow during incubation was represented by the 7-day maximum daily flow over each even-numbered water year (Table 4) at the USGS gaging station. Data were $\log_{10}$-transformed to achieve normality for use in the regression model.

Independent Variable No. X4: Minimum Air Temperature

This variable is considered to represent the effect of each winter's most severe freezing event on survival of eggs and fry in the gravel. Cold spells are presumed to reduce survival to the extent that anchor ice forms on the spawning beds, cutting off water circulation.

Low air temperatures influencing the summer run were represented by the mean daily low temperatures at the Elwha Ranger Station averaged over all consecutive freezing days surrounding the year's lowest daily low (Table 5). The Elwha station was chosen because of its location in a mountain canyon similar to the setting of Dungeness summer run spawning. Data were $\log_{10}$ transformed for normality.

Low air temperatures influencing the fall run were represented by the mean daily low temperatures at Sequim, averaged over all consecutive freezing days surrounding the year's lowest daily low (Table 6). The Sequim station was chosen because of its proximity to the floodplain location of the

Dungeness fall run spawning grounds. Data were squared to approximate normal distribution.

Independent Variable No. X5: Predation by Hatchery Coho Smolts

The major directly manageable aspect of predation on pink fry is the timing and number of hatchery coho (*O. kisutch*) smolts released from the WDFW Dungeness Fish Hatchery. Predation by coho smolts on pink fry was documented in Northwest estuaries as early as 1971 (Bonar et al. 1989). On the Dungeness, hatchery releases historically occurred well in advance of the timing of wild coho downstream movement, and this placed coho in the stream at the time of emergence and downstream migration of pink and chum fry (Johnson 1973). To the degree that coho smolt releases overlapped pink salmon fry migration out of the Dungeness River or through Dungeness Bay, unnaturally high pink mortality may have followed (Lichatowich 1992).

The probability of coho predation depends on the number of hatchery coho smolts released and the difference between their release date and the peak wild pink emigration date. A pink fry emigration timing pattern was inferred from the literature (Table 7). An annual predation index was calculated by multiplying the number of coho smolts in each hatchery release by that date's timing factor, and summing over all release dates in each year (Table 7). The index was square-root transformed to obtain a normal distribution.

Independent Variable No. X6: Marine Upwelling

Upwelling is an index of a complex set of physical factors (Bakun and Parrish 1980) influencing annual changes in abundance of both prey (Anon. 1991) and predators (Doherty 1990) of juvenile salmon. Upwelling has a positive effect on marine survival of many salmonid populations in Washington (for example, Hiss and Knudsen 1993) and British Columbia (Dave Blackbourn, CDFO, Nanaimo, pers. comm.). The monthly marine upwelling indices from March through September off Cape Flattery -- 48° N, 125° W -- for each outmigrant year from 1960 through 1992 (Table 8) were combined into two variables to respectively explain the influence of upwelling on summer and fall run return to escapement. First I performed a multiple correlation of return-to-escapement versus the upwelling for each month. Data were standardized for this analysis as described in the section on "Statistical Analysis" below. This allowed me to identify one month in which upwelling positively influenced return to escapement -- March, in the case of the summer run and July in the case of the fall run. To emphasize the contrast between this and the surrounding months I calculated the difference between the positive month's upwelling index and the mean of the monthly indices from April through August. I then inspected the distribution of the resulting index for normality. The summer run index required transformation to achieve normality and to preserve the meaning of the sign. Thus:

$$X'_S = -\mathrm{Log}_{10}|U_3 - \mathrm{avg}(U_4 ... U_8)|$$

where X'_S = transformed summer upwelling index,
U_3 = March upwelling index,
U_4 = April upwelling index, and
U_8 = August upwelling index

The fall index was

$$X_F = U_7 - \mathrm{avg}(U_4 ... U_8)$$

where X_F = fall upwelling index, and
U_7 = July upwelling index.

Independent Variable No. X7: Marine Salinity

Sea surface salinity is used to predict marine survival of Fraser River pinks for fishery management (Blackbourn, pers. comm.). The salinity index chosen for this model was the mean of the monthly sea surface salinities at Amphitrite Point and Race Rocks (Figure 1) from July through August of each outmigrant year (Column 9 of Tables 9 and 10).

Independent Variable No. X8: Sea Surface Temperature

Sea surface temperature can be expected to negatively affect marine survival. I evaluated the monthly mean temperatures from May through August in the Marsden Square -- from 45 to 50° N and 125 to 130° W -- for each outmigrant year from 1960 through 1992 (Table 11). From these I selected one month that best explained the influence of upwelling on summer and fall run return to escapement. Multiple correlation of return-to-escapement versus the standardized temperature for each month indicated that July temperature had the greatest influence on both summer and fall run return to escapement. I then log-transformed the temperatures to approximate normality.

Independent Variable No. X9: Low Flow in Adult Return Year

This variable is considered to represent the combined effect of naturally occurring low flows and irrigation diversion on return to escapement of both runs from river entry to the time that fish are counted on the spawning grounds. This is based on the assumption that irrigation diverted approximately the same amount of water each year during the low flow season. Low flows may contribute to mortality en route to the spawning grounds by blocking or delaying passage, by allowing excessively high water temperatures in holding areas, or by making adults more visible and accessible to poachers and natural predators. Irrigation may affect summer-run adults because this run migrates through reaches whose flows are reduced during the traditional irrigation season, which ends on 15 September. Irrigation may also affect fall-run adults because the irrigation season continues approximately halfway through the fall spawning run.

The low flow for the return year was represented by the magnitude of the 7-day low flow event at the USGS gaging station between July and October for each odd calendar year (Tables 9, 10 last column) from 1961 through 1993. Variable X9 is concerned with the effect of low flow on survival of adults from a given brood year, whereas variable X1 is concerned with the effect of low flow on survival of eggs from the same brood year. According to this model, for example, the eggs from the 1959 brood (Table 9) were hypothetically affected by low flow event of the 1960 water year (Variable X1), whereas the returning adults from the same brood were hypothetically affected by the low flow event of the 1961 calender year (Variable X9).

Dependent Variable: Return to Escapement

The ratio of return to escapement was chosen in preference to simple escapements as a measure of run status because survival ratios could be normalized by the $\log_{10}$ transformation (Figure 3), whereas escapement data remained heavily skewed after transformation. Escapements were estimated by WDFW every odd year from 1959 through 1993 for summer and fall runs (Table 12). The escapement estimate is based on total live plus dead count and is assumed that bias due to methods is random across the generations.

The dependent variable was the return-to-escapement ratio over the life cycle, expressed as:

$$Y = \text{Log}_{10}\ (E_{n+2}/E_n)$$

Where: Y = return-to-escapement ratio,
E = escapement, and
n = brood year, 1959 through 1993.

Statistical Analysis

To enable an unbiased comparison among all independent variables in the model, each was standardized as recommended by Achen (1982):

$$Z_n = (X_n - X_{min})/(X_{max} - X_{min})$$

where: Z = standardized value
n = brood year
X = non-standardized value (certain variables were previously log-transformed)
min = minimum value of X over all years in the study period
max = maximum value of X over all years in the study period

This assigns each variable a standard range of values from zero to one; however, it preserves the differences among means. This is essential in comparing actual importance among the variables (Achen 1982).

The partial regression coefficient (that is, the x-coefficient) was derived by multiple regression in LOTUS Version 2.01. The relative importance of each independent variable was then calculated, following the recommendation of Achen (1982), as:

$$RI = |b_i Z_i|$$

where: RI = relative importance in sample
b_i = partial regression coefficient (that is, the x-coefficient) for variable i
Z_i = standardized mean of variable "i" over the study period.

The significance of the overall regression was based on the F-value, which was calculated as given by Snedecor and Cochran (1967) as:

$$F = (n - k - 1)R^2/k(1 - R^2)$$

where: F = F-statistic for the null hypothesis that all x-coefficients equal zero
n = number of years for which return to escapement was calculated
k = number of independent variables
R^2 = multiple correlation coefficient

Separate analyses were performed on summer and fall runs, using the independent variables described above.

Relative Importance of Management-Related Factors

Of the nine environmental variables modeled, four were partially influenced by management: low flow during incubation, low flow during adult return, hatchery coho release, and streambed width. Regression of the return-to-escapement ratio was repeated on these factors alone to ascertain how much variation would be explained relative to the nine-variable model.

RESULTS

The multivariate regression model for the summer run explained approximately 95 percent of the variance in return to escapement over the study period and was significant at the 0.1 percent level (Table 9). This level is the probability of falsely rejecting the null hypothesis that all the X-coefficients were zero. The fall run model explained 85 percent of the variability and was significant at the 5 percent level (Table 10).

Relative Importance of Variables

Summer-run Pink Salmon

Sea surface temperature had the greatest influence on return-to-escapement ratio of the summer run population (Figure 5; Table 9). Peak instream flows and low winter air temperatures were almost equally important as secondary influences. Low flow between adult return to the river and spawning was third in importance. The fourth level of importance was shared by marine upwelling and salinity, incubation low flow, and coho predation. Stream width had little influence on return to escapement.

Fall-run Pink Salmon

Low winter air temperature had the greatest influence on return to escapement of the fall run population; sea surface temperature was next in importance, followed by marine upwelling (Figure 5; Table 10). Low flow during incubation, high winter flow, and low flow during adult return shared the next level. Marine salinity, coho predation and stream width were least important.

Relative Importance of Management-Related Factors

Of the nine environmental variables modeled, four were partially influenced by management: low flow during incubation, low flow during adult return, hatchery coho release, and streambed width. Regression of the return-to-escapement ratio on these factors alone explained much less of the variation than the total model. The multiple regression coefficients were 0.154 and 0.216 for the summer and fall runs, respectively. Neither value was significant at the 20% level.

Positive and Negative Influences on Return-to-Escapement Ratio

The respective signs of the x-coefficients in univariate regression normally agreed across both the summer and the fall runs (Table 13). The individual effects of the variables may be interpreted as follows:

- The linear model for summer and fall run return-to-escapement versus low flow during incubation yielded very low correlation coefficients and negligible slopes. Transformation to a quadratic function resulted in increased correlation coefficients. This transformation suggested that optimum flow for summer and fall run incubation was near 3.40 m^3/sec (120 cfs), and that higher or lower flows tended to reduce the return-to-escapement ratio (Figure 4).

- Years of higher-than-average streambed width were very weakly associated with increased return per escapement.

- Years having high peak flows strongly reduced summer and fall run return per escapement compared to years with lower peak flows.

- Low air temperatures moderately depressed return per escapement of both summer and fall runs.

- Return per escapement was inversely related to a coho predation index based on numbers of smolts released from the Dungeness hatchery and the presumed outmigrant timing of pink fry.

- March upwelling, in relation to the April-through-August mean off Cape Flattery, had a slight positive effect on summer-run return per escapement. The July upwelling compared to the April-through-August mean off Neah Bay had a weak positive effect on fall-run return per escapement.

- Higher average July salinity in the Strait of Juan de Fuca and on the west coast of Vancouver Island resulted in better return to escapement than in years of relatively low salinity. Marine salinity was more strongly associated with the fall run more than the summer run.

- Years with cooler July sea surface temperatures were strongly associated with increased return to escapement in both summer and fall runs.

- Higher instream flows during adult migration resulted in greater counts of adults on the spawning grounds, compared to the parent generation. However, the effect on the summer run was very weak.

DISCUSSION

Relative Importance of Management-Related Factors

The four variables that were partially influenced by management certainly contributed less as a group to the total variation in return per escapement, than did the uncontrollable variables. This does not discount all value in protecting and improving the habitat, but rather raises the caution that even the best habitat management cannot be expected to yield a steady or highly predictable improvement in fish survival.

Reliability of Data for Assessing Relative Importance of Environmental Factors

Nearly all environmental factors modeled, even those that were represented by relatively unimportant variables, may have actually influenced the return-to-escapement ratio. This is because the available data only roughly approximate the magnitude of the underlying physical and biological forces theoretically controlling survival.

Low Flow in the Incubation Year

Return-to-escapement ratio data in this report indicate optimum incubation conditions for both summer and fall runs when the 7-day summer low flow at the gage was near 3.40 m^3/sec (120 cfs). However, this observation is tentative due to the wide scatter of points around the curves and to the low influence of incubation flows relative to other factors. There is no obvious biological reason to expect egg survival to decrease in years when the summer-fall low flow is higher than the apparent optimum level. However, the usable area for adult migration and fall run spawning only increased along with flow up to a peak level of 4.25 m^3/sec (150 cfs) (Hiss 1993), based on water depth and velocity over potential spawning habitat at various flows. If egg survival is somehow related to the extent of spawning area available to adults, then a curvilinear relationship is not unreasonable.

The relative importance of low flows suggested by the model is probably realistic. Eggs of summer run fish are exposed to the purely natural low flow events every brood year. However, because most spawn upriver, they are not susceptible to reduced flows due to irrigation. Fall run fish spawn downriver, but they do so primarily after the official irrigation season.

Streambed Width

Several factors could have contributed bias to the estimation of streambed width, although the net direction of the bias is not apparent:

- Gaps in photo coverage eliminated over half the unconfined floodplain channel from analysis.
- Varying altitude of aerial photos between years may have caused variation in stream section length covered by the overlay, so that slightly different points were measured each year.
- Photo interpretation could have varied between years due to the uncertain bed boundary in reaches of broken tree canopy or grassy cut banks, in years when these conditions were more common.
- Interpolation and extrapolation of stream width in years for which no photos were taken missed any short-term changes that may have affected egg and fry survival.
- There is no guarantee that bed width in the upper floodplain represents bed stability in the hillslope-confined channel above that point.

For these reasons the weight given in the model is a minimum estimate of the expected biological influence of streambed disruption. The number of measurement errors listed above probably account for the slight and unexpectedly positive relationship between stream width and return per escapement.

Streambed width was not a duplicate measure of peak flow. The correlation coefficient between stream width and peak flow was -0.154 for the upper stream sections and -0.169 for the lower sections.

High Flow

Peak flow events have long been known to reduce Puget Sound pink return per escapement (Johnson et al. 1971). In this study the measure of high flow was the maximum seven-day flow over the water year. However, on the Dungeness, flows below the annual peak have been observed to destroy some redds (Steve Ralph, EPA, pers. comm.). This suggests that some measurement other than peak flow may more accurately represent damage to redds. If so, the actual importance of winter floods may be even greater than estimated in the models developed here.

Coho Predation

The index of coho predation rests on several assumptions:

(1) The timing pattern of pink outmigration coincides with the one derived from limited timing data (Table 7), and is consistent over all years.

(2) Pink survival varies inversely with the number of coho smolts released.

(3) All other factors influencing the tendency of coho to prey on pink fry -- such as relative size of smolts or presence of alternate prey -- remained constant over the years of the study period.

(4) The number of coho released is the number actually reaching the estuary.

(5) The number in the estuary represents fish fully capable of feeding.

(6) All the coho released are of a size large enough to eat pinks.

(7) All the released coho actually eat one or more pinks.

Each assumption introduces a potential bias. In addition, the model does not attempt to incorporate the number of pinks consumed. Despite the potential bias of each assumption, the model suggests that coho predation had a moderate influence on summer run return per escapement. However, the comparatively low effect on fall run return to escapement is difficult to explain.

Marine Conditions

The return per escapement of both Dungeness runs has usually followed a 6-yr cycle characterized by low apparent survival in 1967, 1973, 1979, 1985, and 1991 (Figure 3). This cycle is shared by most pink and sockeye runs of

Washington (Jim Ames, WDFW, pers. comm.). The temperature, upwelling, and salinity variables in the above regression analysis only partially explained the Dungeness pink cycles (Figure 6); residual return to escapement plotted against brood year still retained some cyclic variation. The negative relation between most months' upwelling and return per escapement is unexpected. The use of the difference between March upwelling and the summer mean to partially explain the summer run return per escapement may be justified on the general observation (Jim Ames, WDFW, pers. comm.) that estuarine and marine conditions several months before pink fry arrive may somehow predetermine pink survival, perhaps by influencing food production or predator abundance. The positive influence of July upwelling on fall run return per escapement is easier to explain since pink juveniles are likely to pass through the upwelling zone at this time. The absence of a corresponding positive July influence on summer run pinks is particularly puzzling.

Low Flow in the Adult Return Year

We would expect instream flow to affect the success of spawning even if no irrigation water were diverted from the river. An instream flow of 4.25 m^3/sec (150 cfs) provides maximum spawning area for pink salmon migration and spawning in the vicinity of the Olympic Highway Bridge (Figure 2; Hiss 1993). This flow equals the 50 percent exceedance flow for September upstream of the irrigation diversions (USGS files).

Irrigation introduced an unmeasured variation in adult passage conditions, and the model may have underestimated this effect. The low flow event usually occurs in September or October, although it may happen in almost any week during these months, depending primarily on the arrival of fall rains. Summer run adults generally migrate upstream before flow measured at the gage reaches its lowest level, although irrigation occurs throughout the adult migration.

The historical effect of low flow on migration of summer run pinks was probably greater than at present. In 1994 an official agreement (Seiter et al. 1994) limited irrigation withdrawal to one half the instream flow at the gaging station. This may improve adult survival during migration to the spawning grounds, especially in years when the low flow comes before mid-September.

Fall run adults migrate into the river before, during, or after the natural low flow event, but for the most part after the irrigation season. Observed flow measurements do represent migration flow primarily for early-running fall fish. Historical conditions were probably less favorable than at present, for water users have now agreed to end the irrigation season on 1 September instead of 15 September, except for specialty crops requiring late irrigation (Seiter et al. 1994). In a normal water year, any irrigation withdrawal in September would diminish spawning area for fall-run pinks. Instream flow downstream of the diversions falls as low as 0.85 m^3/sec (30 cfs), causing 50 percent loss of pink spawning area (Hiss 1993). Such low flows have been common in recent years (JKT, unpub. data).

Escapement

The return-to-escapement ratio used in this analysis is a poor index of survival unless we assume the incidental catch is invariant over the study years. This is unlikely, especially for the fall run. The spring run may also be intercepted in various sockeye fisheries in varying degrees (D. Blackbourn, pers. comm.). Despite this potential bias, the spring and fall escapements are highly correlated. This accounts for much of the similarity in rank importance among the independent variables between the two populations.

Data Available but Impossible to Model

Several theoretically important factors had to be ignored in the regression analysis, although time series data were sufficient to allow subjective evaluation over all or most of the study period.

Acres Clearcut

This variable could not be modeled because it is impossible to link the data on acreage clearcut to fish habitat quality in any particular brood cycle (Washington Forest Practices Board 1994). Rather, the influence of clearcutting may best be ascertained by plotting acres cut against escapements over the study period (Figure 7). The number of acres on ONF within the Dungeness watershed clearcut during each brood cycle has been recorded since 1950 (Table 14; Scott Schreier, ONF, pers. comm.). The ONF cutting is probably proportional to the total annual acreage cut in the entire watershed since ONF is by far the largest forest landholder. The fairly even number of acres cut per brood cycle contrasts with the very abrupt declines in escapement, and adds little to our understanding of the causes of declines.

Mass Wasting

Mass wasting could not be modeled because no data were collected before 1968. Since 1968, estimates of the volume of slope failure on Gold Creek have been made (Table 15). However, it is impossible to estimate the resulting annual sediment transport in the streambed (Velimesis et al. 1993). Also, an undetermined volume of mass wasting at the powerline crossing was reported for 1968 (Johnson et al. 1970).

When the magnitude of Gold Creek slope failure is plotted against escapements over the study period (Figure 7), slope failures during or immediately before the 1969 and 1973 brood years coincided with depressed summer run returns relative to the surrounding years. The 1972 failure also coincided with a temporary depression in the fall run escapement. Fine sediment from mass wasting was clearly related to low pink salmon intragravel survival in Gold Creek and the mainstem Dungeness above the Gray Wolf River for the 1971 brood year, and degradation of spawning grounds was expected to continue for several years (Johnson 1972).

However, no long-term sediment sampling was conducted. Consequently, it is impossible to separate the influence of slope failure from other factors depressing survival in subsequent years.

Channel Confinement and Streambank Hardening

Data on the length of riverbed affected by diking or riprap (Table 16) were unsuitable for regression analysis because the total affected mileage inherently increased over the study period. Thus, any correlation with declining return per escapement could be spurious. However, the influence of diking may be assessed by plotting new miles of bank hardened (Table 16) against subsequent escapements (Figure 7).

Aerial photographs strongly suggest that construction of the Dungeness Meadows Dike near RKM 10.5 (RM 7.5) led to streambed widening. Site visits indicated rapid bedload aggradation at the lower end of the dike followed by channel shifts between the dike and the Highway 101 Bridge. It is difficult not to link the dike with accelerated channel migration. This structure, along with irrigation diversion, could have contributed to summer-run adult passage problems observed in 1987 in this area (JKT, unpubl. records). The dike probably had less influence on the quality of fall-run spawning grounds downstream of the Highway 101 Bridge.

Appearance of the upper Beebe Dike near RKM 4 (RM 2.5) was not accompanied by streambank widening in the aerial photos. Its effect on stream habitat quality is difficult to determine.

County records indicate that non-federal dikes were raised on both banks downstream of the Schoolhouse Bridge in 1964 (Joel Freudenthal, Callam County, pers. comm.). Photographs of the town of Dungeness before diking suggest that the unconfined river originally flooded much of the town when high discharge coincided with high storm tides. This may have allowed the river to deposit silt over a wide area, primarily outside the main channel but relatively close to the mouth. At present, the dikes are said to create a backwater reaching upstream beyond the Schoolhouse Bridge when high flow meets a high tide (Freudenthal, pers. comm). This condition might concentrate silt deposition inside the main channel and extend the deposition farther upstream than historically. This would potentially degrade fall-run spawning gravel and consequently reduce survival during incubation.

Pink Fry Releases

Pink salmon fry were released into the Dungeness on three occasions between 1976 and 1988 (Figure 7). Each release coincided with an increase in escapement over the previous year. However, it is impossible to attribute these increases directly to the releases, because the source of stock and the hatchery/wild composition of the escapement were not examined.

Factors Lacking Sufficient Data for Analysis

Several environmental factors were considered for analysis but not used due to insufficient data. These were:

- Marine interception. Annual changes in the incidental catch rate of Dungeness pinks in the commercial fisheries of Puget Sound and southern British Columbia could strongly influence survival to escapement. Unfortunately, catch of Dungeness stock cannot be calculated because of the very small Dungeness run sizes relative to total pink catch in northern Puget Sound (Ames, pers. comm.).

- Eelgrass bed area. The area of eelgrass beds in Dungeness Bay may represent the overall estuarine suitability for pink juveniles during their critical period of seaward migration. The area covered by aquatic vegetation in Dungeness Bay was directly observed and mapped only in 1987 and 1993 (Wilson 1993) and was mapped by remote sensing in 1988 (WDNR unpub. files). This short time frame made it impossible to relate changes in bay habitat composition to pink salmon survival over the study period.

- Potential predators. Annual abundance data for California sea lions (*Zalophus californianus*) and harbor seals (*Phoca vitulina*) are not available for the early years in the study period. Moreover, these population estimates would be difficult to apply to Dungeness Bay or the Strait of Juan de Fuca alone, because they represent all the Pacific coast or all of western Washington (Steve Jeffries, WDFW, pers. comm.). Data on abundance of predatory birds, and predatory fish other than hatchery coho smolts, are not available.

- Instream high temperature. Data are available from Dungeness Hatchery for most of the study period. Unfortunately, these data almost certainly underestimate the severity of high temperatures at points downstream affected by irrigation withdrawals. Sufficiently high temperatures could block adult migration. Summer high temperatures are likely to be closely related to low instream flows.

RECOMMENDATIONS

Summer Run

Management has at least partial control over irrigation withdrawals, hatchery smolt abundance and timing, stream width, bank hardening, mass wasting, and acreage clearcut. The first four of these factors are most likely to have affected pink survival. The models allow us to rank three of these in priority for management action on the basis of relative importance. The following activities are recommended:

(1) Continue to limit irrigation withdrawal. Begin monitoring adult distribution to verify unimpeded upstream migration from the river mouth upstream to the highest irrigation diversion. (Low flow during the adult stage ranked fourth out of the nine factors modeled.)

(2) Continue to delay coho release from the Dungeness Hatchery until 1 June. (Coho predation ranked eight out of the nine factors modeled.)

(3) Stabilize the streambed between the Dungeness Hatchery and the Woodcock Road Bridge in a way to promote pool formation for adult holding. (Streambed width ranked last out of the nine factors modeled.)

Fall Run

The following activities are recommended based on the regression model:

(1) Continue to close the irrigation season on 1 September. (Incubation low flow ranked fourth out of the nine factors modeled.)

(2) Continue to delay coho release from the Dungeness Hatchery until 1 June. (Coho predation ranked eight out of the nine factors modeled.)

(3) Manage the unconfined streambed in a way to promote stable gravel beds for spawning. (Streambed width ranked last out of the nine factors modeled.)

One additional activity is recommended, but no priority can be assigned relative to the factors included in the model:

(4) Continue efforts to compensate for detrimental effects of bank hardening projects. (No rank could be assigned to this item.)

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TABLES

Table 1. Summer low flows and transformation of return/spawner ratio to achieve linear relation to flow. Data are plotted in Figure 4.

Year	Summer flow (cfs)	Return/spawner ratio			
		Summer run		Fall run	
		Observed	Predicted	Observed	Predicted
59	150	0.243	-0.110	0.243	-0.600
61	126	0.735	0.399	0.778	0.360
63	145	-0.626	0.073	-0.845	-0.294
65	105	0.087	0.073	0.125	0.150
67	168	-0.865	-1.109	-0.763	-2.160
69	141	0.426	0.191	0.576	-0.090
71	136	0.243	0.301	-0.336	0.116
73	99	-0.265	-0.152	-0.355	-0.090
75	147	0.141	0.005	0.249	-0.410
77	103	0.203	0.005	-0.065	0.079
79	91	-1.243	-0.544	-1.210	-0.534
81	114	0.271	0.301	-0.084	0.360
83	114	-0.075	0.301	0.370	0.360
85	97	-0.328	-0.240	-0.845	-0.188
87	72	0.777	-1.893	0.369	-2.160
89	92	-0.064	-0.489	0.373	-0.471
91	99	-0.769	-0.152	-0.740	-0.090

Table 2. Streambed width measurements from aerial photos of Dungeness River, 1965-1990, Dungeness Fish Hatchery to powerline crossing (see Figure 2). Source: WDNR files.

River mile	River km	Streambed width on photo (cm) 1965	1971	1977	1981	1985	1990
8.5	13.6	1.2	1.2	0.5	1.3	1.1	0.4
8.6	13.8	0.8	0.7	0.5	0.7	0.5	0.3
8.8	14.0	1.4	0.7	0.3	0.1	0.5	0.5
8.9	14.2	1.0	1.0	0.8	0.8	0.7	0.5
9.0	14.4	0.7	1.3	0.3	0.7	0.2	0.3
9.1	14.6	2.2	0.6	0.4	0.4	1.2	1.7
9.3	14.8	1.3	0.4	0.7	0.7	1.4	1.4
9.4	15.0	1.1	0.6	0.5	1.0	1.9	0.6
9.5	15.2	1.1	0.8	0.8	1.1	1.9	1.6
9.6	15.4	1.9	0.9	1.3	1.0	0.5	0.5
9.8	15.6	1.1	0.7	0.2	0.6	0.3	0.2
9.9	15.8	0.9	0.3	0.6	0.2	0.4	0.3
10.0	16.0	0.1	0.1	0.3	0.4	0.4	0.5
10.1	16.2	1.4	0.6	1.0	0.7	0.9	0.9
10.3	16.4	0.3	0.2	1.7	0.6	0.2	0.2
10.4	16.6	0.5	0.6	0.9	0.3	0.6	0.3
10.5	16.8	0.7	0.6	0.6	0.7	0.5	0.6
MEAN		1.04	0.66	0.67	0.66	0.78	0.64
SD		0.51	0.31	0.38	0.31	0.53	0.47

Brood year	Mean width	Method of calculation
59	1.04	Presumed equal to 1965 measurement
61	1.04	Presumed equal to 1965 measurement
63	1.04	Presumed equal to 1965 measurement
65	1.04	Measured from photo
67	0.91	Straight-line interpolation
69	0.79	Straight-line interpolation
71	0.66	Measured from photo
73	0.66	Straight-line interpolation
75	0.67	Straight-line interpolation
77	0.67	Measured from photo
79	0.67	Straight-line interpolation
81	0.66	Measured from photo
83	0.72	Straight-line interpolation
85	0.78	Measured from photo
87	0.71	Straight-line interpolation
89	0.64	Presumed equal to 1990 measurement
91	0.64	Presumed equal to 1990 measurement

Table 3. Streambed width measurements from aerial photos of Dungeness River, 1965-1990, Highway 101 bridge to vicinity of railroad trestle (see Figure 2). Source: WDNR files.

River mi	River km	Streambed width on photo (cm) 1965	1971	1981	1985	1990
4.6	7.4	1.2	0.8	0.5	0.9	0.8
4.7	7.6	1.2	0.9	0.5	0.9	0.4
4.8	7.7	2.0	0.4	0.9	1.0	0.7
5.0	7.9	2.1	0.8	1.2	1.4	1.4
5.1	8.1	1.3	1.1	1.5	1.6	2.5
5.2	8.3	2.5	1.7	0.9	1.6	1.4
5.3	8.5	1.4	1.9	1.0	1.1	0.6
5.4	8.7	0.8	1.4	0.6	0.8	0.6
5.6	8.9	1.2	0.3	1.2	0.4	0.4
5.7	9.1	0.6	0.8	1.3	1.3	1.7
5.8	9.3	1.6	0.6	0.6	0.8	0.9
5.9	9.5	1.1	0.9	0.7	0.8	0.8
6.0	9.7	1.1	0.8	0.6	0.5	0.8
6.2	9.9	1.0	0.7	0.5	0.5	0.6
6.3	10.0	0.8	0.3	0.4	1.0	0.6
6.4	10.2	1.0	0.8	1.8	1.2	0.8
MEAN		1.31	0.89	0.89	0.99	0.94
SD		0.50	0.44	0.40	0.36	0.54

Brood year	Mean width	Method of calculation
59	1.31	Presumed equal to 1965 measurement
61	1.31	Presumed equal to 1965 measurement
63	1.31	Presumed equal to 1965 measurement
65	1.31	Measured from photo
67	1.17	Straight-line interpolation
69	1.03	Straight-line interpolation
71	0.89	Measured from photo
73	0.89	Straight-line interpolation
75	0.89	Straight-line interpolation
77	0.89	Straight-line interpolation
79	0.89	Straight-line interpolation
81	0.89	Measured from photo
83	0.94	Straight-line interpolation
85	0.99	Measured from photo
87	0.96	Straight-line interpolation
89	0.94	Presumed equal to 1990 measurement
91	0.94	Presumed equal to 1990 measurement

Table 4. Maximum annual seven-day flow on Dungeness River at gaging station. Source: W. Clark, personal communication.

Water year	Q7max(cfs)	Log_{10}
1960	1,296	3.113
1962	828	2.918
1964	1,099	3.041
1966	948	2.977
1968	2,297	3.361
1970	1,096	3.040
1972	1,191	3.076
1974	2,084	3.319
1976	1,951	3.290
1978	987	2.994
1980	2,546	3.406
1982	1,439	3.158
1984	1,689	3.228
1986	1,562	3.194
1988	920	2.964
1990	1,158	3.064
1992	2,063	3.314

Table 5. Minimum air temperature events at Elwha Ranger Station.

Water Year	Lowest daily low (°F)	Duration (days)[a]	Low temperature event Mean daily (°F)	Low temperature event Log_{10}
60	20	6	26.0	1.415
62	15	13	25.1	1.399
64	25	5	27.5	1.439
66	26	6	28.6	1.456
68	19	7	24.4	1.387
70	26	5	27.0	1.431
72	16	10	24.0	1.380
74	19	16	23.4	1.369
76	23	12	28.2	1.450
78	16	9	23.1	1.364
80	13	7	18.9	1.275
82	13	15	25.0	1.398
84	8	17	20.7	1.316
86	10	18	19.2	1.283
88	22	7	27.5	1.439
90	18	20	27.3	1.436
92	26	6	28.7	1.457

[a]Consecutive freezing nights surrounding annual low.

Table 6. Minimum air temperature events at Sequim.

Water year	Lowest daily low (°F)	Duration (days)[a]	Low temperature event: Mean daily low (°F)	Low temperature event: Squared
60	20	12	26.8	716
62	20	9	26.8	717
64	25	2	27.0	729
66	25	2	27.5	756
68	19	8	27.5	756
70	25	4	26.5	702
72	9	13	21.4	457
74	19	12	25.1	629
76	23	8	26.6	709
78	17	7	24.3	590
80	11	6	18.3	336
82	0	15	21.5	461
84	1	11	16.8	283
86	-1	18	14.8	220
88	16	13	24.8	617
90	11	9	23.0	529
92	21	8	26.5	702

[a]Consecutive freezing nights surrounding annual low

Table 7. Index of Dungeness Hatchery coho smolt predation on Dungeness wild pink salmon fry, 1960-1992. Release data were provided by M. Kimble, WDFW.

Predation weight by migration timing

Time period	Predation weight	Event at start of period	Reference
1 Feb+	0.01	First occur in Puget Sound	Simenstad et al. 1982
1 Mar+	0.10	First occur in most streams	Bonar et al. 1989
1 Apr+	0.50	First occur in Dungeness	Johnson et al. 1966
8 Apr+	1.00	Peak begins in Dungeness	Johnson 1973
8 May+	0.50	Peak ends in Dungeness	Johnson et al. 1966
24 May+	0.10	Last occur in Dungeness	Hiss 1994
1 Jun+	0.01	Last occur in Puget Sound	Simenstad et al. 1982
1 Jul+	0.00	Last occur in most estuaries	Bonar et al. 1989

Predation index by release date

Year	Date	Predation weight	Number released		Predation index	
			Daily	Annual	Daily	Annual
1960	23 May	0.50	27000	205692	13500	14588
	1 Jun	0.01	21528		215	
	13 Jun	0.01	19824		198	
	16 Jun	0.01	37350		374	
	20 Jun	0.01	30090		301	
	9 Jul	0.00	26550		0	
	13 Jul	0.00	43350		0	
1962	31 Mar	0.10	55770	55770	5577	5557
1964	24 Mar	0.10	23808	544969	2381	352636
	25 Mar	0.10	32368		3237	
	1 Apr	0.50	29500		14750	
	6 Apr	0.50	54752		27376	
	27 Apr	1.00	60000		60000	
	30 Apr	1.00	34300		34300	
	6 May	1.00	129759		129759	
	13 May	0.50	133490		66745	
	14 May	0.50	27792		13896	
	11 Jun	0.01	19200		192	

Table 7, continued.

Year	Date	Predation weight	Number released Daily	Number released Annual	Predation index Daily	Predation index Annual
1966	15 Apr	1.00	22000	691719	22000	636373
	19 Apr	1.00	30800		30800	
	20 Apr	1.00	30800		30800	
	21 Apr	1.00	30800		30800	
	22 Apr	1.00	30800		30800	
	25 Apr	1.00	11820		11820	
	26 Apr	1.00	11820		11820	
	27 Apr	1.00	3940		3940	
	4 May	1.00	116542		116542	
	5 May	1.00	116652		116652	
	6 May	1.00	175052		175052	
	9 May	0.50	23232		11616	
	13 May	0.50	74300		37150	
	20 may	0.50	13161		6581	
1968	22 Apr	1.00	126330	471818	126330	299074
	10 May	0.50	345488		172744	
1970	23 May	0.50	194985	991159	97493	105454
	3 Jun	0.01	199604		1996	
	9 Jun	0.01	492934		4929	
	18 Jun	0.01	103636		1036	
1972	9 May	0.50	32334	114827	16167	16992
	2 Jun	0.01	82493		825	
1974	2 Jun	0.01	20130	1113456	201	11135
	6 Jun	0.01	292530		2925	
	24 Jun	0.01	727996		7280	
	2 Jun	0.01	72800		728	
1976	may 24	0.10	340340	340340	34034	340340
1978	24 Apr	1.00	6023	796057	6023	122871
	3 May	1.00	110048		110048	
	6 Jun	0.01	679986		6800	
1980	11 Jun	0.01	438875	438875	4389	4389
1982	18 May	0.50	318340	1065932	159170	166646
	21 Jun	0.01	747592		7476	
1984	16 May	0.50	188000	188000	94000	94000

Table 7, continued.

Year	Date	Predation weight	Number released Daily	Number released Annual	Predation index Daily	Predation index Annual
1986	27 May	0.10	320000	320000	32000	32000
1988	8 Jun	0.01	301700	301700	3017	3017
1990	14 Jun	0.01	342700	342700	3427	3427
1992	18 May	0.50	433675	433675	216838	216838

Annual summary

Year	Annual predation	Square root
1960	14,588	121
1962	5,577	75
1964	352,636	594
1966	636,373	798
1968	299,074	547
1970	105,454	325
1972	16,992	130
1974	11,135	106
1976	34,034	184
1978	122,871	351
1980	4,389	66
1982	166,646	408
1984	94,000	307
1986	32,000	179
1988	3,017	55
1990	3,427	59
1992	216,838	466

Table 8. Monthly marine upwelling indices, 1960-1992, at Cape Flattery. Source: Dave Husby, NMFS, Monterey, Calif. (pers. comm).

Standardized upwelling indices

YR	MAR	APR	MAY	JUN	JUL	AUG	SEP
1960	0.55	0.00	0.00	0.44	0.34	0.22	0.72
1962	0.85	0.27	0.54	0.02	0.73	0.05	0.56
1964	1.00	1.00	0.66	0.17	0.19	0.15	0.72
1966	0.00	0.91	0.90	0.00	0.75	0.57	0.50
1968	0.20	0.88	0.41	0.30	0.72	0.19	0.75
1970	0.91	0.79	0.41	0.35	0.57	0.41	0.53
1972	0.51	0.41	0.31	0.25	0.15	0.30	0.75
1974	0.52	0.44	0.33	0.43	0.21	0.42	0.63
1976	0.61	0.44	0.24	0.32	0.00	0.07	0.53
1978	0.88	0.44	0.40	0.27	0.79	0.00	0.00
1980	0.97	0.28	0.74	0.33	0.87	0.80	0.66
1982	0.92	0.48	1.00	1.00	0.46	0.43	0.72
1984	0.55	0.29	0.14	0.35	1.00	0.30	0.50
1986	0.24	0.56	0.19	0.24	0.78	1.00	0.78
1988	0.77	0.49	0.07	0.02	0.73	0.64	0.97
1990	0.77	0.57	0.36	0.02	0.84	0.15	1.00
1992	0.93	0.37	0.59	0.49	0.70	0.31	0.75
MEAN	0.66	0.51	0.43	0.29	0.58	0.35	0.65

Multivariate regression output versus summer run return to escapement

Constant	0.789
Std Err of Y Est	0.679
R Squared	0.166
No. of Observations	17
Degrees of Freedom	9

	Mar	Apr	May	Jun	Jul	Aug	Sep
b	0.057	-0.379	-0.292	-0.496	-0.283	-0.229	-0.283
SE	0.652	0.833	0.783	0.868	0.658	0.748	0.848
Level	0.038	0.192	0.125	0.146	0.163	0.081	0.184

Table 8, continued.

Multivariate regression output versus fall run return per escapement

Constant	0.580
Std Err of Y Est	0.662
R Squared	0.282
No. of Observations	17
Degrees of Freedom	9

	Mar	Apr	May	Jun	Jul	Aug	Sep
b	-0.066	-0.406	-0.271	-0.451	0.232	-0.871	-0.054
SE	0.635	0.812	0.764	0.846	0.641	0.729	0.826
Level	0.043	0.206	0.116	0.133	0.134	0.307	0.035

Unstandardised data

Year	Mar	Apr	May	Jun	Jul	Aug	Sep
1960	-29	-36	-11	39	28	21	7
1962	-6	-16	27	12	54	7	2
1964	5	39	35	22	18	15	7
1966	-70	32	52	11	55	49	0
1968	-55	30	18	30	53	18	8
1970	-2	23	18	33	43	36	1
1972	-32	-5	11	27	15	27	8
1974	-31	-3	12	38	19	37	4
1976	-24	-3	6	31	5	9	1
1978	-4	-3	17	28	58	3	-16
1980	3	-15	41	32	63	68	5
1982	-1	0	59	74	36	38	7
1984	-29	-14	-1	33	72	27	0
1986	-52	6	2	26	57	84	9
1988	-12	1	-6	12	54	55	15
1990	-12	7	14	12	61	15	16
1992	0	-8	30	42	52	28	8
MAX	5	39	59	74	72	84	16
MIN	-70	-36	-11	11	5	3	-16

Table 8, continued.

Data used in final models

Year	Mean(Apr-Jul)	Summer run (Mar - mean)	Summer run $-\mathrm{Log}_{10}$(Mar - Mean)	Fall run Jul - Mean
1960	8.2	-37.2	-1.570	19.8
1962	16.8	-22.8	-1.357	37.2
1964	25.8	-20.8	-1.318	-7.8
1966	39.8	-109.8	-2.040	15.2
1968	29.8	-84.8	-1.928	23.2
1970	30.6	-32.6	-1.513	12.4
1972	15.0	-47.0	-1.672	0.0
1974	20.6	-51.6	-1.712	-1.6
1976	9.6	-33.6	-1.526	-4.6
1978	20.6	-24.6	-1.390	37.4
1980	37.8	-34.8	-1.541	25.2
1982	41.4	-42.4	-1.627	-5.4
1984	23.4	-52.4	-1.719	48.6
1986	35.0	-87.0	-1.939	22.0
1988	23.2	-35.2	-1.546	30.8
1990	21.8	-33.8	-1.528	39.2
1992	28.8	-28.8	-1.459	23.2

Table 9. Multiple regression of nine environmental factors on return-to-escapement ratio of wild Dungeness River summer-run pink salmon, BY 1959-1991. Variables are defined in "Methods" section of text.

Transformed data

BY	Y LOG BY+2/ BY	X1 TRANS. LO-Qi BY	X2 LOG WIDTH BY	X3 LOG HI-Q BY+1	X4 LO-A BY+1	X5 SQRT PRED BY+1	X6 LOG UP BY+1	X7 SAL BY+1	X8 LOG SST BY+1	X9 LO-Qr BY+2
59	0.24	-0.110	0.018	3.11	26.0	121	-1.57	31.0	1.155	126
61	0.73	0.399	0.018	2.92	25.1	75	-1.31	31.1	1.154	145
63	-0.63	0.073	0.018	3.04	27.5	594	-1.25	30.0	1.204	105
65	0.09	0.073	0.018	2.98	28.6	798	-2.01	31.2	1.146	168
67	-0.87	-1.109	-0.039	3.36	24.4	547	-1.91	30.6	1.176	141
69	0.43	0.191	-0.104	3.04	27.0	325	-1.44	31.6	1.138	136
71	0.24	0.301	-0.177	3.08	24.0	130	-1.66	30.0	1.162	99
73	-0.27	-0.152	-0.178	3.32	23.4	106	-1.69	30.2	1.149	147
75	0.14	0.005	-0.176	3.29	28.2	184	-1.51	30.6	1.159	103
77	0.20	0.005	-0.174	2.99	23.1	351	-1.27	31.3	1.168	91
79	-1.24	-0.544	-0.175	3.41	18.9	66	-1.47	31.4	1.173	114
81	0.27	0.301	-0.177	3.16	25.0	408	-1.56	31.0	1.150	114
83	-0.08	0.301	-0.142	3.23	20.7	307	-1.69	30.8	1.150	97
85	-0.33	-0.240	-0.110	3.19	19.2	179	-1.92	30.8	1.159	72
87	0.78	-1.893	-0.151	2.96	27.5	55	-1.53	31.4	1.158	92
89	-0.06	-0.489	-0.197	3.06	27.3	59	-1.52	31.0	1.181	99
91	-0.77	-0.152	-0.197	3.31	28.7	466	-1.40	30.8	1.200	86
MIN	-1.24	-1.893	-0.197	2.92	18.9	55	-2.01	29.97	1.138	72
MAX	0.78	0.399	0.018	3.41	28.7	798	-1.24	31.55	1.204	168

Table 9, continued.

Standardized data

	Y	X1 log-i	X2 WIDTH	X3 HI-Q	X4 LO-A	X5 PRED	X6 UP	X7 SAL	X8 SST	X9 LO-Qr
59	0.736	0.778	1.000	0.399	0.728	0.089	0.581	0.652	0.257	0.563
61	0.979	1.000	1.000	0.000	0.634	0.027	0.920	0.741	0.252	0.760
63	0.306	0.858	1.000	0.252	0.881	0.726	1.000	0.000	1.000	0.344
65	0.659	0.858	1.000	0.120	0.993	1.000	0.000	0.772	0.127	1.000
67	0.187	0.342	0.735	0.908	0.565	0.662	0.136	0.392	0.583	0.719
69	0.826	0.909	0.433	0.250	0.830	0.363	0.746	1.000	0.000	0.667
71	0.736	0.957	0.093	0.324	0.524	0.102	0.460	0.019	0.361	0.281
73	0.484	0.760	0.088	0.822	0.461	0.068	0.424	0.114	0.174	0.781
75	0.685	0.828	0.098	0.763	0.949	0.174	0.660	0.399	0.320	0.323
77	0.716	0.828	0.107	0.156	0.434	0.398	0.974	0.835	0.451	0.198
79	0.000	0.589	0.102	1.000	0.000	0.015	0.713	0.886	0.534	0.438
81	0.749	0.957	0.093	0.492	0.626	0.476	0.586	0.658	0.188	0.438
83	0.578	0.957	0.256	0.635	0.187	0.339	0.428	0.500	0.178	0.260
85	0.453	0.721	0.405	0.565	0.032	0.167	0.126	0.494	0.320	0.000
87	1.000	0.000	0.214	0.094	0.881	0.000	0.632	0.892	0.302	0.208
89	0.584	0.613	0.000	0.299	0.861	0.005	0.649	0.671	0.656	0.281
91	0.235	0.760	0.000	0.813	1.000	0.553	0.796	0.544	0.934	0.146
MEAN		0.748	0.390	0.464	0.623	0.304	0.578	0.563	0.390	0.436

Regression Output:

Constant	1.068
Std Err of Y Est	0.091
R Squared	0.952
No. of Observations	17
Degrees of Freedom	7
F	15.771
P	<0.001

Variable	b	SE	Mean	Level
Sea temperature (SST)	0.765	0.157	0.390	0.299
High flow (HI-Q)	-0.429	0.109	0.464	0.199
Low air temperature (LO-A)	0.308	0.097	0.623	0.192
Low flow, adult return (LO-Qr)	-0.256	0.134	0.436	0.111
Marine upwelling (UP)	0.144	0.129	0.578	0.083
Marine salinity (SAL)	-0.123	0.099	0.563	0.069
Low flow, incubation (LO-Qi)	-0.061	0.124	0.748	0.046
Coho predation (PRED)	-0.138	0.114	0.304	0.042
Stream width (WIDTH)	0.017	0.089	0.390	0.007

Table 10. Multiple regression of 9 environmental factors on return-to-escapement ratio of wild Dungeness River fall-run pink salmon, brood years 1959-1991.

Transformed data

BY	Y LOG BY+2/ BY	X1 TRANS. LO-Qi BY	X2 width by	X3 LOG HI-Q BY+1	X4 SQ LO-A BY+1	X5 SQRT PRED BY+1	X6 UP BY+1	X7 SAL BY+1	X8 LOG SST BY+1	X9 LO-Qr BY+2
59	0.243	-0.600	0.116	3.113	716	121	19.8	31.00	1.155	126
61	0.778	0.360	0.116	2.918	717	75	37.2	31.14	1.154	145
63	-0.845	-0.294	0.116	3.041	729	594	-7.8	29.97	1.204	105
65	0.125	0.150	0.116	2.977	756	798	15.2	31.19	1.146	168
67	-0.763	-2.160	0.067	3.361	756	547	23.2	30.59	1.176	141
69	0.576	-0.090	0.011	3.040	702	325	12.4	31.55	1.138	136
71	-0.336	0.116	-0.052	3.076	457	130	0.0	30.00	1.162	99
73	-0.355	-0.090	-0.052	3.319	629	106	-1.6	30.15	1.149	147
75	0.249	-0.410	-0.052	3.290	709	184	-4.6	30.60	1.159	103
77	-0.065	0.079	-0.052	2.994	590	351	37.4	31.29	1.168	91
79	-1.210	-0.534	-0.052	3.406	336	66	25.2	31.37	1.173	114
81	-0.084	0.360	-0.052	3.158	461	408	-5.4	31.01	1.150	114
83	0.370	0.360	-0.027	3.228	283	307	48.6	30.76	1.150	97
85	-0.845	-0.188	-0.005	3.194	220	179	22.0	30.75	1.159	72
87	0.369	-2.160	-0.018	2.964	617	55	30.8	31.38	1.158	92
89	0.373	-0.471	-0.028	3.064	529	59	39.2	31.03	1.181	99
91	-0.740	-0.090	-0.028	3.314	702	466	23.2	30.83	1.200	86
MIN	-1	-2.160	-0.052	2.918	220	55	-7.8	29.97	1.138	72
MAX	1	0.360	0.116	3.406	756	798	48.6	31.55	1.204	168

Table 10, continued.

Standardized data

	Y	X1 LO-Qi	X2 width	X3 HI-Q	X4 LO-A	X5 PRED	X6 UP	X7 SAL	X8 SST	X9 LO-Qr
59	0.731	0.619	1.000	0.399	0.924	0.089	0.489	0.652	0.257	0.563
61	1.000	1.000	1.000	0.000	0.927	0.027	0.798	0.741	0.252	0.760
63	0.183	0.740	1.000	0.252	0.949	0.726	0.000	0.000	1.000	0.344
65	0.671	0.917	1.000	0.120	1.000	1.000	0.408	0.772	0.127	1.000
67	0.225	0.000	0.707	0.908	1.000	0.662	0.550	0.392	0.583	0.719
69	0.898	0.821	0.376	0.250	0.899	0.363	0.358	1.000	0.000	0.667
71	0.440	0.903	0.000	0.324	0.442	0.102	0.138	0.019	0.361	0.281
73	0.430	0.821	0.000	0.822	0.763	0.068	0.110	0.114	0.174	0.781
75	0.734	0.694	0.000	0.763	0.912	0.174	0.057	0.399	0.320	0.323
77	0.576	0.888	0.000	0.156	0.689	0.398	0.801	0.835	0.451	0.198
79	0.000	0.645	0.000	1.000	0.216	0.015	0.585	0.886	0.534	0.438
81	0.566	1.000	0.000	0.492	0.449	0.476	0.043	0.658	0.188	0.438
83	0.795	1.000	0.149	0.635	0.117	0.339	1.000	0.500	0.178	0.260
85	0.183	0.783	0.276	0.565	0.000	0.167	0.528	0.494	0.320	0.000
87	0.794	0.000	0.203	0.094	0.741	0.000	0.684	0.892	0.302	0.208
89	0.796	0.670	0.142	0.299	0.576	0.005	0.833	0.671	0.656	0.281
91	0.236	0.821	0.142	0.813	0.899	0.553	0.550	0.544	0.934	0.146
MEAN		0.725	0.353	0.464	0.677	0.304	0.467	0.563	0.390	0.436

Regression Output:

Constant	0.467
Std Err of Y Est	0.184
R Squared	0.829
No. of Observation	17
Degrees of Freedom	7
F	3.273
P	<0.05

Variable	b	SE	Mean	Level
Low air temperature (LO-A)	0.632	0.242	0.677	0.427
Sea surface temperature (SST)	-0.720	0.270	0.390	0.281
Marine upwelling (UP)	0.381	0.208	0.467	0.178
Low flow, adult return (LO-Qr)	0.192	0.182	0.725	0.140
High winter flow (HI-Q)	-0.278	0.208	0.464	0.129
Low flow, incubation (LO-Qi)	-0.286	0.325	0.436	0.125
Marine salinity (SAL)	-0.100	0.213	0.563	0.057
Coho predation (PRED)	-0.176	0.189	0.304	0.054
Stream width (WIDTH)	-0.062	0.181	0.353	0.022

Table 11. Mean sea surface temperature in Marsden Square.

Untransformed data (°C)

Year	May	Jun	Jul	Aug
1960	11.19	13.42	14.28	15.78
1962	10.55	12.28	14.27	15.29
1964	9.26	12.11	16.00	15.32
1966	10.17	12.46	14.00	14.74
1968	11.15	12.96	15.01	15.62
1970	11.06	12.54	13.73	14.90
1972	9.61	12.46	14.51	15.85
1974	10.37	11.98	14.10	15.91
1976	9.97	11.88	14.42	15.34
1978	11.14	13.20	14.71	15.69
1980	10.96	12.72	14.90	14.86
1982	10.33	12.57	14.13	15.79
1984	10.64	12.50	14.11	16.34
1986	10.70	13.36	14.42	14.63
1988	10.41	12.52	14.38	15.07
1990	10.59	12.69	15.18	17.05
1992	11.91	13.60	15.84	15.86

Table 11, continued.

Log Transformed data

Year	May	Jun	Jul	Aug
1960	1.049	1.128	1.155	1.198
1962	1.023	1.089	1.154	1.184
1964	0.967	1.083	1.204	1.185
1966	1.007	1.096	1.146	1.168
1968	1.047	1.113	1.176	1.194
1970	1.044	1.098	1.138	1.173
1972	0.983	1.096	1.162	1.200
1974	1.016	1.078	1.149	1.202
1976	0.999	1.075	1.159	1.186
1978	1.047	1.121	1.168	1.196
1980	1.040	1.104	1.173	1.172
1982	1.014	1.099	1.150	1.198
1984	1.027	1.097	1.150	1.213
1986	1.029	1.126	1.159	1.165
1988	1.017	1.098	1.158	1.178
1990	1.025	1.103	1.181	1.232
1992	1.076	1.134	1.200	1.200

Table 11, continued.

Standardized data

Year	May	Jun	Jul	Aug
1960	0.752	0.901	0.257	0.494
1962	0.518	0.245	0.252	0.288
1964	0.000	0.142	1.000	0.301
1966	0.372	0.353	0.127	0.049
1968	0.738	0.644	0.583	0.428
1970	0.706	0.400	0.000	0.119
1972	0.147	0.353	0.361	0.523
1974	0.450	0.062	0.174	0.548
1976	0.294	0.000	0.320	0.310
1978	0.734	0.779	0.451	0.457
1980	0.670	0.505	0.534	0.102
1982	0.434	0.418	0.188	0.498
1984	0.552	0.376	0.178	0.722
1986	0.574	0.868	0.320	0.000
1988	0.465	0.388	0.302	0.194
1990	0.533	0.488	0.656	1.000
1992	1.000	1.000	0.934	0.527
Mean	0.526	0.466	0.390	0.386

Multivariate effect on summer run

Constant	0.591
Std Err of Y Est	0.472
R Squared	0.463
No. of Observations	17
Degrees of Freedom	12

	May	Jun	Jul	Aug
X Coefficient	-0.815	0.371	-1.434	0.414
Std Err of b	0.780	0.669	0.478	0.477
Level importance	0.429	0.173	0.560	0.160

Table 11, continued.

Multivariate effect on fall run

Constant	0.673
Std Err of Y Est	0.242
R Squared	0.495
No. of Observations	17
Degrees of Freedom	12

	May	Jun	Jul	Aug
X Coefficien	0.165	-0.248	-0.653	0.402
Std Err of b	0.399	0.343	0.245	0.244
Level	0.087	0.115	0.255	0.155

Data used in final models

Year	July Temperature (°C)	Log_{10}
1960	14.28	1.155
1962	14.27	1.154
1964	16.00	1.204
1966	14.00	1.146
1968	15.01	1.176
1970	13.73	1.138
1972	14.51	1.162
1974	14.10	1.149
1976	14.42	1.159
1978	14.71	1.168
1980	14.90	1.173
1982	14.13	1.150
1984	14.11	1.150
1986	14.42	1.159
1988	14.38	1.158
1990	15.18	1.181
1992	15.84	1.200

Table 12. Dungeness pink salmon spawning escapement, 1959-1993. Source: Jim Uehara, WDFW (pers. comm.).

Return yr	Escapement		Return/Escapement	
	Summer	Fall	Summer	Fall
59	20000	20000		
61	35000	35000	1.750	1.750
63	190000	210000	5.429	6.000
65	45000	30000	0.237	0.143
67	55000	40000	1.222	1.333
69	7500	6900	0.136	0.173
71	20000	26000	2.667	3.768
73	35000	12000	1.750	0.462
75	19000	5300	0.543	0.442
77	26300	9400	1.384	1.774
79	42000	8100	1.597	0.862
81	2400	500	0.057	0.062
83	4476	412	1.865	0.824
85	3764	966	0.841	2.345
87	1768	138	0.470	0.143
89	10579	323	5.984	2.341
91	9132	763	0.863	2.362
93	1556	139	0.170	0.182

Table 13. Single-variable regression results.

		Variable	Summer run Slope	Summer run r^2	Fall run Slope	Fall run r^2
X1	LO-Qi	Low flow, incubation	-0.000687	0.001	+0.000833	0.001
		quadratic transformation	N/A	0.017	N/A	0.027
X2	WIDTH	Stream width	+0.690	0.010	+1.28	0.023
X3	HI-Q	High flow	-2.78	0.580	-2.37	0.384
X4	LO-A	Low air temperature	+0.0604	0.115	+0.000708	0.072
X5	PRED	Coho predation	-0.000656	0.068	-0.000577	0.048
X6	UP	Marine upwelling	+0.348	0.019	+0.00959	0.082
X7	SAL	marine salinity	+0.342	0.086	+0.493	0.162
X8	SST	Sea temperature	-18.9	0.382	-18.7	0.342
X9	LO-Qr	Low flow, adult return	+0.00219	0.010	+0.00567	0.063

Table 14. Acres clearcut on Olympic National Forest within Dungeness River watershed, 1950-1993. Source: Schreier (pers. comm.).

Year	Acres	Two-year total
1950	35	
1951	0	35
1952	0	
1953	0	0
1954	0	
1955	1145	1145
1956	0	
1957	34	34
1958	0	
1959	47	47
1960	255	
1961	77	332
1962	264	
1963	217	481
1964	243	
1965	141	384
1966	61	
1967	11	72
1968	99	
1969	132	231
1970	441	
1971	76	517
1972	97	
1973	155	252
1974	47	
1975	134	181
1976	37	
1977	243	280
1978	165	
1979	278	443
1980	199	
1981	149	348
1982	200	
1983	433	633
1984	356	
1985	270	626
1986	587	
1987	255	842
1988	209	
1989	195	404
1990	41	
1991	0	41
1992	0	
1993	0	0

Table 15. Annual volume of slope failures reported for Gold Creek. Source: Velimesis et al. (1993).

Year	Volume failed yd^3	Volume failed m^3	Percent of annual mean for Dungeness watershed
68	13000	9975	38.2
69-71	0	0	
72	20000	15300	58.4
73-79	0	0	
80	1000	756	2.9
81-89	0	0	
90	2552	1952	7.5
91	0	0	

Table 16. Federal dike and riprap construction on Dungeness River, 1961-1993. Source: USACE Seattle District maps and WDNR aerial photos.

Year	Name	Builder	Bank	River km Lower	River km Upper	Length (m) New	Length (m) Cum.	Percent increase
1959	Corps Dike	USACE	R	0.0	4.3	[A]	4.3	N/A
1963	Taylor Cutoff	USACE	L	14.9	15.0	0.1	4.4	1.9%
1971	Cline Ditch	[B]	L	11.5	11.6	0.1	4.5	3.6%
1977	D/ness Meadows	USACE	R	12.3	13.0	0.7	5.2	14.0%
1980	Highland Ditch	USACE	R	17.4	17.6	0.2		
1980	Sequim Water	USACE	R	16.6	16.9	0.3	5.7	5.5%
1983	Beebe (lower)	Beebe	L	3.0	4.0	1.0	6.7	17.5%
1985	Kincaid Island	USACE	R	15.5	15.7	0.2	6.9	2.2%
1990	Beebe (upper)	Beebe	L	4.0	4.3	0.3	7.2	4.9%

[A] Corps repaired and raised existing privately-constructed dike. Original construction date not officially recorded.

[B] Presumably constructed jointly by Cline, Clallam, and Dungeness ditch companies.

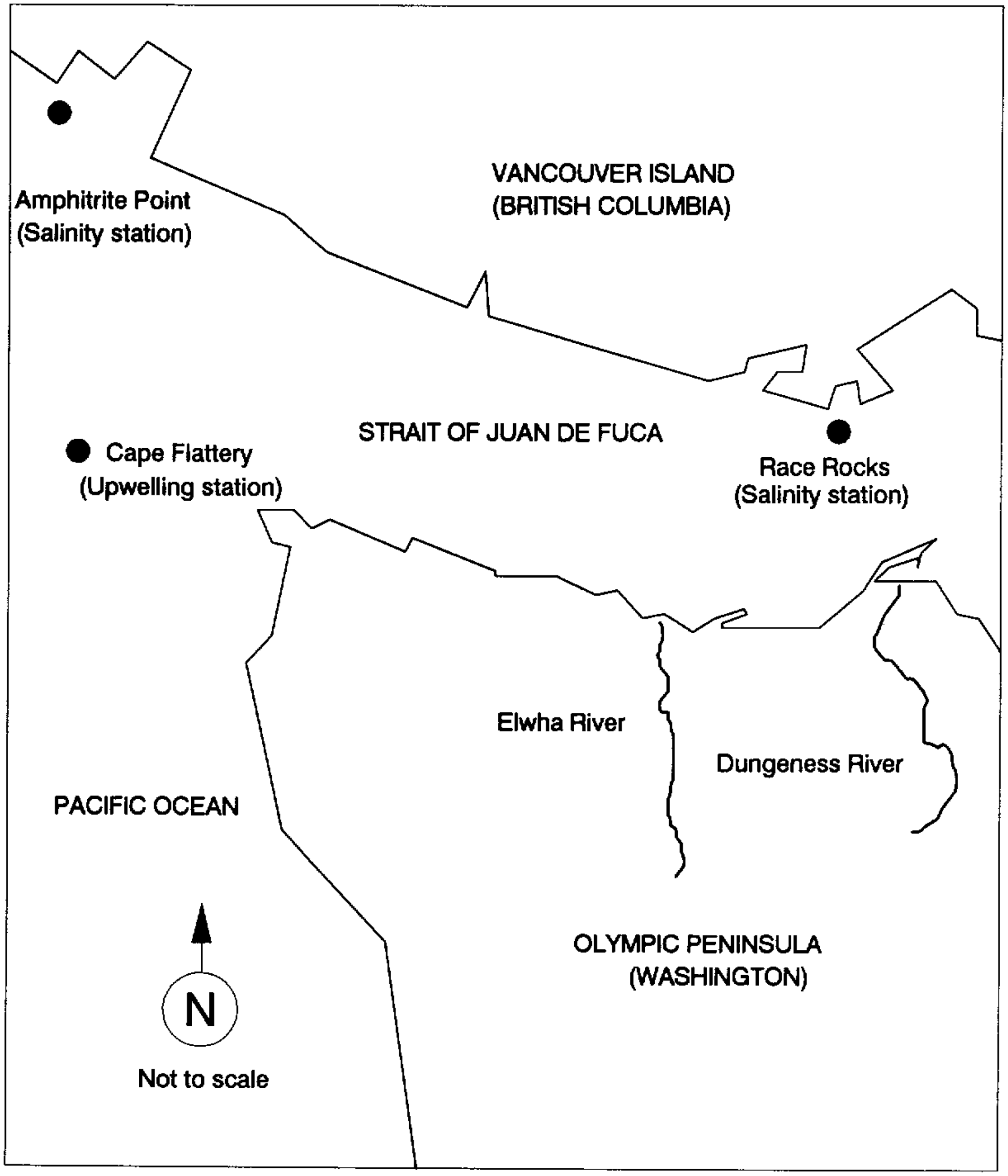

Figure 1. Study area map showing Dungeness River and oceanographic stations used in modeling pink salmon return per escapement.

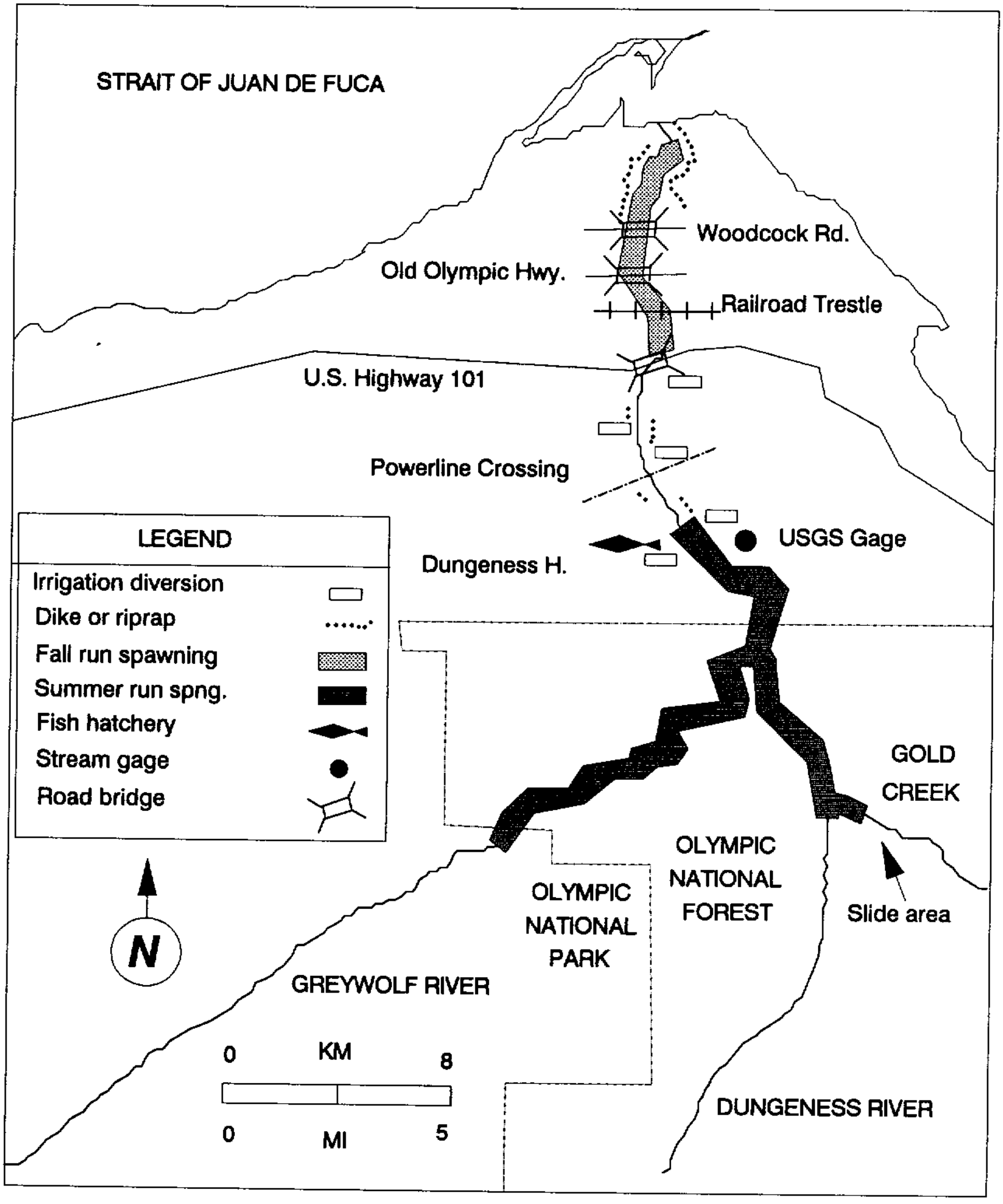

Figure 2. Dungeness River showing environmental features referred to in return-to-escapement model.

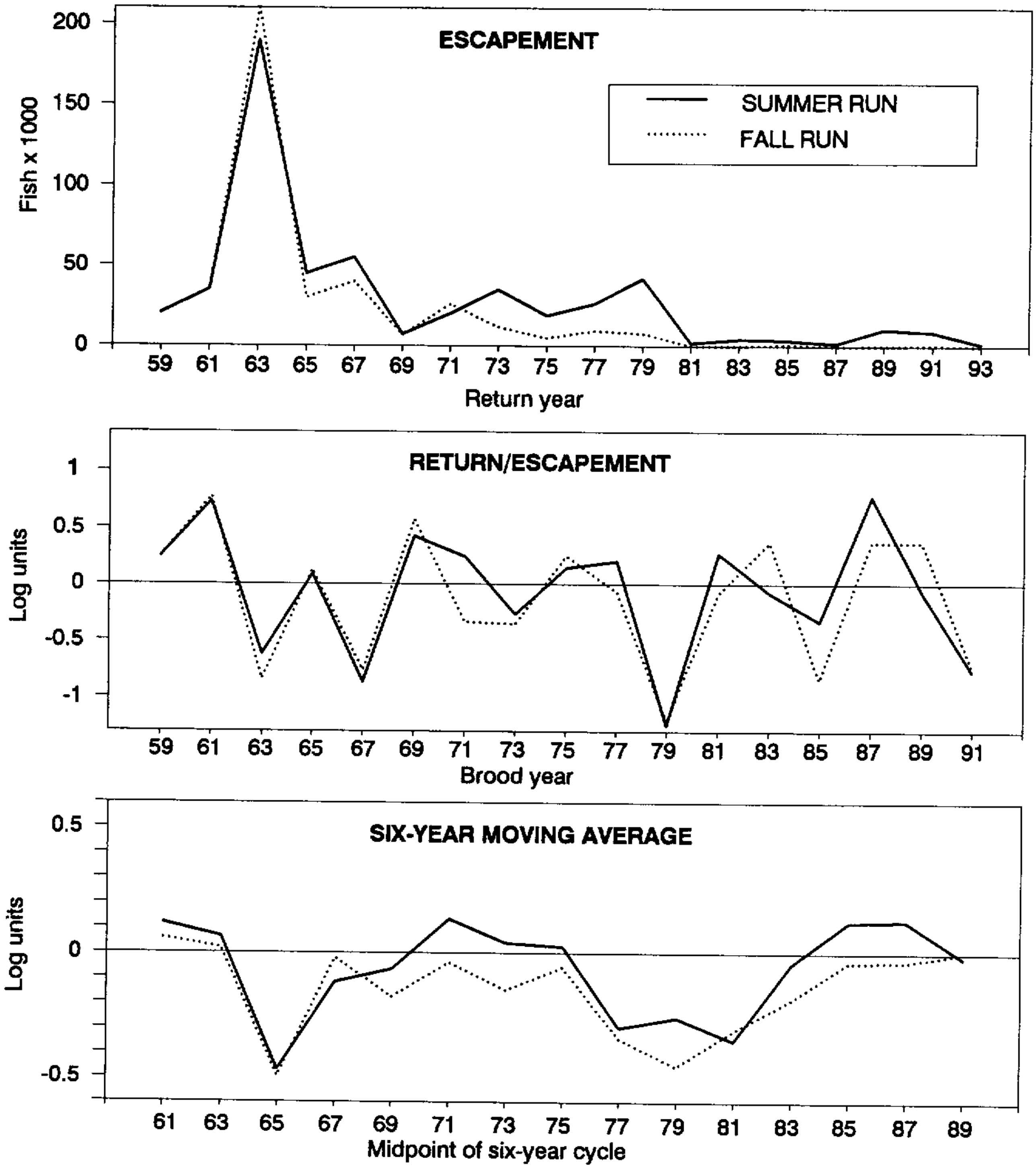

Figure 3. Spawning escapement of Dungeness pink salmon, 1959-1993. Return to escapement is calculated as the Log_{10} (escapement two years after brood year/escapement in brood year). Data from Uehara (pers. comm.). Six-year moving average of return/escapement is keyed to brood year in middle of six-year cycle.

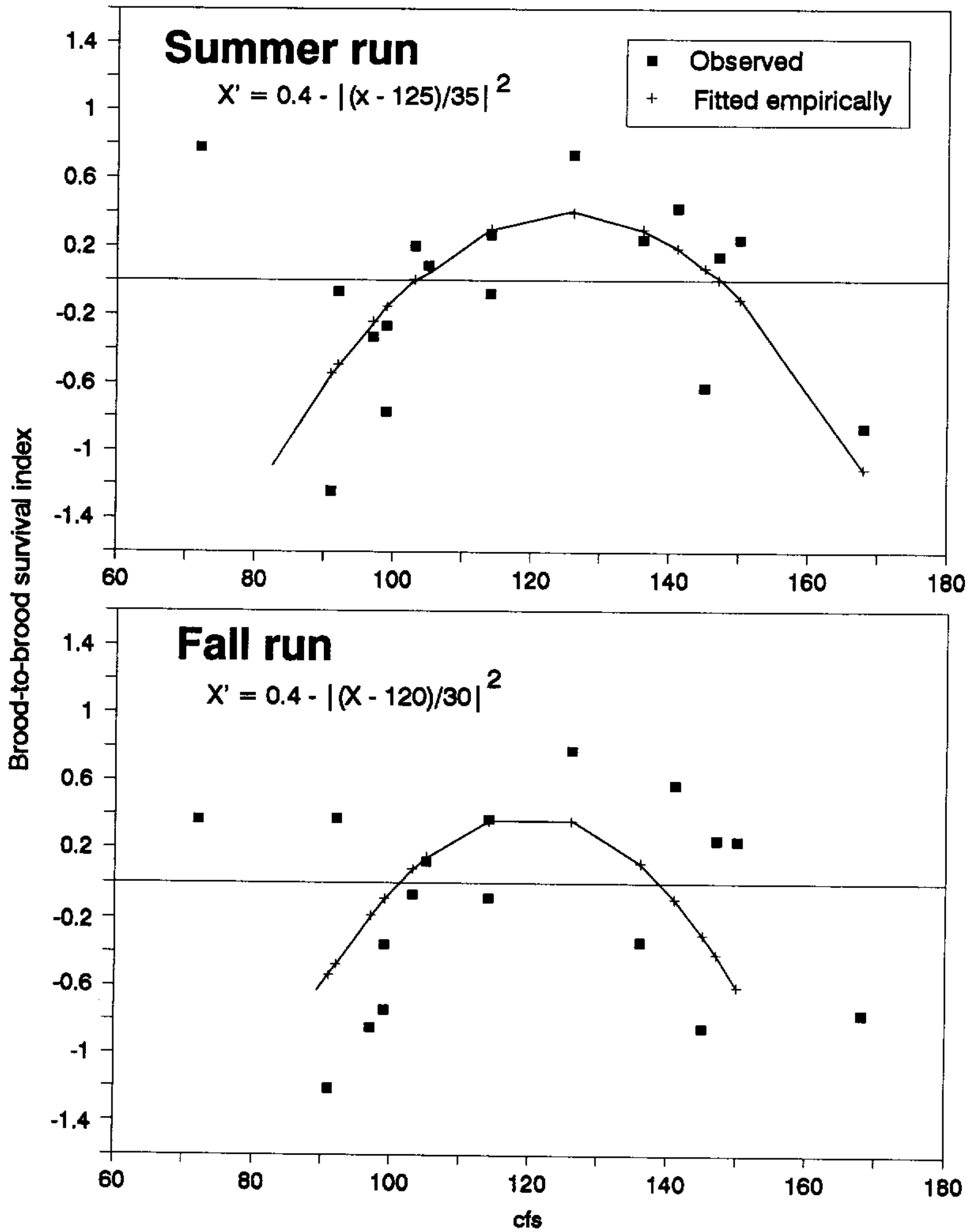

Figure 4. Relationship between summer low flow and return/escapement ratio. Curves were fitted by eye. Equations describing the curves were used to transform the low flow data in Table 1 for use in the multivariate regression models.

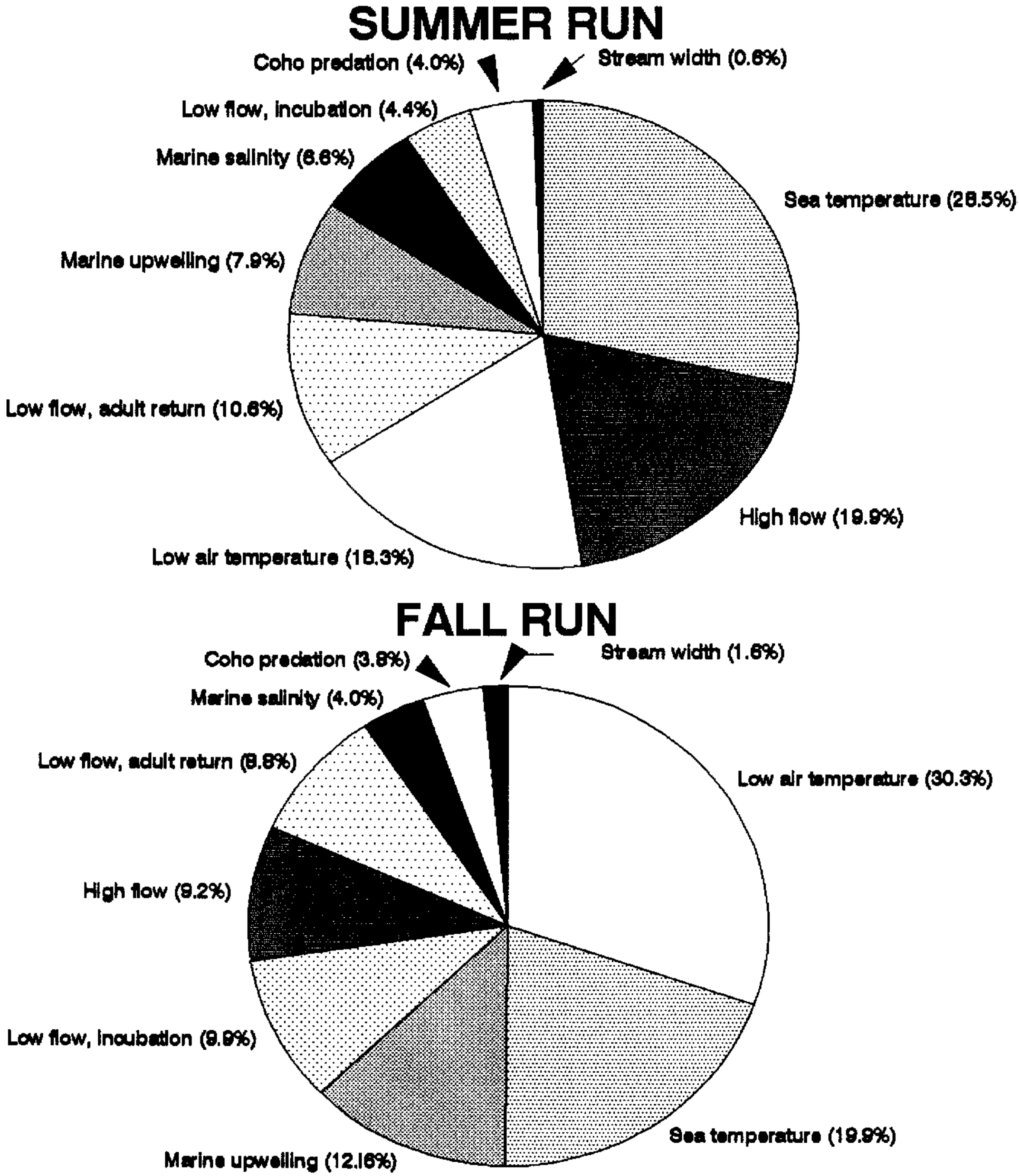

Figure 5. Relative importance (standardized mean x X-coefficient) of seven environmental factors in explaining the level of Dungeness pink salmon escapement. Environmental factors are defined in "Methods" section of text.

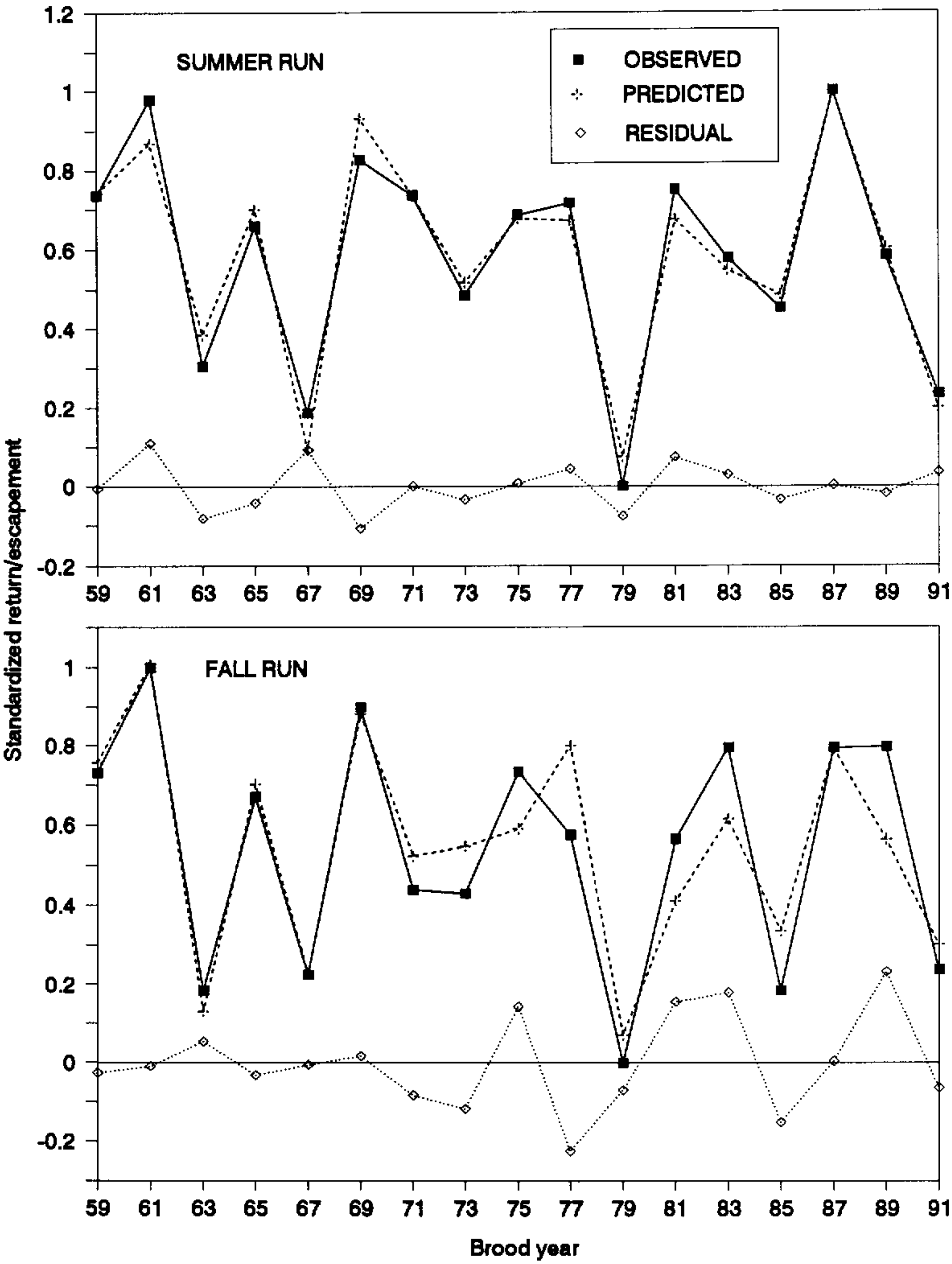

Figure 6. Observed, predicted, and residual return per escapement of Dungeness pink salmon, 1959-1993.

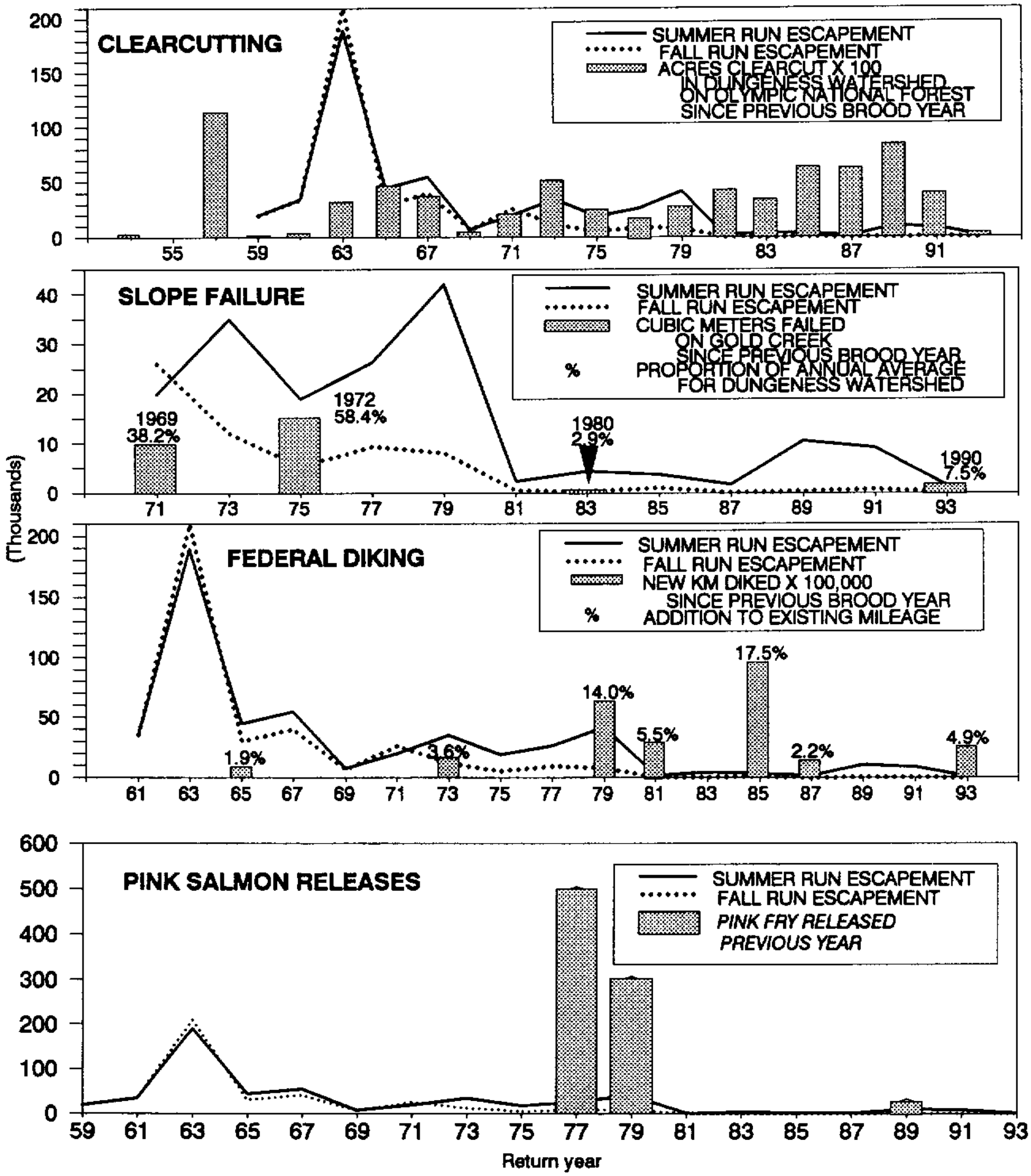

Figure 7. Relation of clearcutting on Olympic National Forest, Gold Creek slope failure, federal diking on the mainstem, and pink salmon fry releases on Olympic National Forest to pink salmon spawning escapements, 1959-1993. Diking data from USACE (Seattle District) maps. Slope failure estimates from Velimesis et al. (1994). Clearcutting data from Schreier (pers. comm.).