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OPTIMIZATION OF ALASKA TROLL FISHERY CHINOOK SALMON YIELD: A MODEL OF THE EFFECTS OF SIZE LIMITS, GEAR RESTRICTIONS, AND TIME-AREA CLOSURES

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[1] This work is based on a thesis submitted in partial fulfillment of the degree of Master of Science at the University of Washington, Seattle.

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ABSTRACT

A yield-per-recruit model is developed for the Alaska troll chinook salmon fishery, incorporating hooking mortality, fishing mortality growth, natural mortality, and maturation rate. The yield-per-recruit model provides a conceptual framework for evaluating the effects of size limits, gear restrictions, and time-area closures. Landed value per recruit is also calculated using a price function which tracks ex-vessel prices through the fishing season. Growth is allowed to vary depending on the age of maturity. Natural mortality is specified as an inverse function of fish age. A size related hooking mortality function is constructed based upon mortality observed under trolling conditions. A relationship between hook size and mouth size is hypothesized to explain the observed increase in hooking mortality with fish length. Fishing mortality is estimated from an analysis of micro-wire tag recovery data. Results of the model are presented as response surfaces of yield with respect to size and fishing mortality. Adding hooking mortality to a yield-per-recruit model causes the yield response surface to decline with increasing fishing mortality so that a global maximum appears on the surface. Response surfaces of yield with respect to size limit and hooking mortality are also presented. The model demonstrates that the optimum size limit is a continuous increasing function of fishing mortality rate and is a continuous decreasing function of hooking mortality. Based on the most likely estimates of fishing and hooking mortalities, a size limit of 24.0 inches would maximize yield in weight of chinook salmon in the Alaska troll fishery and a size limit of 26.5 inches would maximize the landed value of the catch. Gear restrictions to reduce hooking mortality had a negative impact on yield in all cases investigated since the decrease in CPUE associated with the gear restriction outweighed the advantages of reduced hooking mortality. Time-area closures in high-density shaker areas would probably increase yield from the fishery by only 2% to 7%. These relatively minor increases in yield must be balanced against the negative socio-economic impacts of the time-area closures. The most serious shortcoming of the current configuration of the model is the assumption that fishing mortality is independent of maturity stage. More precise estimates of fishing mortality rates by maturity group and age would allow more precise estimation of optimum size limits from the model.

Key words: yield-per-recruit model, computer simulation, hooking mortality, chinook salmon, Alaska troll fishery, shaker mortality, eumetric yield, landed value-per-recruit, gear restrictions, time-area closures, optimization, size limit.

INTRODUCTION

For most fish populations, there is a minimum size of harvest which will maximize the yield in weight from a given number of recruits at a given rate of fishing mortality. Recruits are members of the population present in the fishing area and susceptible to the fishing gear used. The minimum size of harvest giving this maximal or "eumetric" yield (Beverton and Holt 1957) depends on the relationships among the rates of fishing mortality, natural mortality, pre-recruit fishing mortality, and growth.

Current regulations for the Southeastern Alaska commercial troll fishery specify a 28-inch minimum size for chinook salmon. However, minimum size restrictions in troll salmon fisheries are only partially effective because significant mortality results from the capture and release process. Reasonable estimates of mortality for released chinook salmon range from 15% to 45% (Wright 1970), although Ricker (1976) suggests 50% as a conservative estimate and rates as high as 77% (Parker and Black 1959) have been recorded. Previous studies of yield per recruit in troll chinook fisheries (Parker 1960; Parks 1975) have suggested that losses in yield to the fishery from hooking mortality on sublegal fish may exceed the gains in yield resulting from growth and capture at older ages. In fact, Parker (1960) recommended that time and area restrictions be explored as an alternative means of increasing yield per recruit.

Previous yield-per-recruit models did not simultaneously consider changes in natural mortality with age, the differential growth rates of different maturity groups of chinook salmon, and possible variation in hooking mortality with fish size. Realistic modeling of chinook salmon life history should consider these variables since any of them could have a substantial impact on the form of the eumetric fishing curve. In this study, a yield-per-recruit model which includes these variables is developed. In addition, the value of the yield per recruit to the fishermen, is considered, using recent ex-vessel prices, at different combinations of fishing mortality and size limits.

The effectiveness of size limits might be increased by requiring the use of trolling gear which reduces the mortality of sublegal fish, termed "shakers", which are hooked and released. The advantages of using gear restrictions to reduce hooking mortality are quantified in this study in terms of increased yield using the yield-per-recruit model.

Following Parker's (1960) initial recommendation, closures of suspected high shaker-density areas were proposed in the initial drafts of the Southeastern Alaska troll fishery management plan. The proposed closures were rejected on the basis of detrimental socio-economic impacts and undesirable effects of fishing-effort shifts out of the closed areas. While certain fishing areas do have significantly higher shaker catch rates (Funk 1981; Fried 1977), the potential benefits resulting from the closure of these areas have not been quantified in terms of increased yield or value to the fishery. The derived yield-per-recruit model is used to estimate the benefits resulting from several time-area closure schemes.

REVIEW OF PREVIOUS CHINOOK SALMON YIELD-PER-RECRUIT MODELS

The earliest quantitative reference to the influence of hooking mortality on yield in troll chinook fisheries resulted from a tagging study performed by Milne and Ball (1956). While no formal model of yield was employed, they stated:

> In releasing either small coho salmon prior to an opening date or small spring salmon below a minimum size limit, a mortality of one-half would appear to be offset only if the survivors double their weight; but even then no gain in net production could result since only a portion of the fish could be recaptured. Because of this high mortality, any regulation requiring the release of small troll-caught salmon does not appear to be a promising conservation measure.

Parker (1960) was the first to apply a form of yield-per-recruit model to chinook salmon. His model examines the relationship of chinook salmon growth and mortality rates. He computed the natural mortality rate from an ocean tagging experiment (Parker and Kirkness 1956). An unusual growth model was utilized in which growth rate was a function of fish length instead of age. Parker compared the relative growth rates of each maturity group with the natural mortality rate. However, he lacked estimates of the proportions of a given year class destined to be mature at each age and therefore could not obtain a combined estimate of yield from all maturity groups. Parker's model employed high estimates of hooking mortality, with 20% from immediate physical damage followed by 71% delayed mortality from fatigue. The results of Parker's model demonstrated a negative effect of size limits on yield for size limits greater than 22.5 inches, and suggested a probable negative effect down to size limits as small as 15 inches.

Henry (1972) estimated the parameters of a von Bertalanffy growth model for fall chinook releases from two Columbia River hatcheries. The resulting growth models were combined with ranges of natural mortality estimates to calculate total yield from each release at varying rates of fishing mortality for fish aged 3, 4, and 5. Maturity-group proportions were not considered fixed at release time. While the effect of varying the fishing mortality of age-3 fish was examined, the effect of explicitly varying size limits was not. Ocean fishing at ages 3 and 4 tended to decrease the total yield at reasonable levels of natural mortality.

Parks (1975) included an evaluation of size limits in a systems model of the Washington coastal troll, sport, and net fisheries. His model incorporated age-specific fishing mortality rates and discrete levels of hooking mortality for each age. Hooking mortality was high for small fish (80% for age 1) and low for large fish (10% for age 5). Natural mortality was considered not to be age-specific because estimates were not available. Growth was estimated by interpolation in a table of average weights-at-age. Maturity-group-specific functions were not used. Both catch in numbers and landed value of the catch remained constant with size limits up to 22 inches and decreased markedly with larger size limits. The model's results were relatively insensitive to changes in the relationship between hooking mortality and age.

Parker (1959) identified the need for determining the relative abundance of maturity groups in the immature population before the effects of various size limits could be properly evaluated. O'Connor's (1977) model provided the first available estimates of such maturity group proportions at an early life history stage. Using such estimates of maturity-group proportions, a yield-per-recruit model can be constructed to evaluate the combined gains and losses in yield at all ages of each maturity group of an out-migrating year class which result from various management strategies.

METHODS

Structure of the Chinook Salmon Yield-Per-Recruit Model

Yield-per-recruit models are customarily derived from a differential equation describing the rate of accumulation of yield from a single year class of recruits. The rate of yield accumulation is defined as the product of an instantaneous rate of fishing mortality, a model of population size, and a model of average weight at age:

$$dY = F \cdot N(t) \cdot W(t)\, dt$$

where: Y = yield from fishery

t = age

F = instantaneous fishing mortality rate

N = survival model giving the number of fish in the population of age t

W = growth model describing average weight at age t

The differential equation is integrated to express the yield accumulated over the lifespan of the single year class of recruits:

$$Y = F \cdot \int_{t_{\rho'}}^{t_{\lambda}} N(t) \cdot W(t)\, dt$$

where: $t_{\rho'}$ = age of entry into the fishery

t_{λ} = maximum age

It is frequently impossible to obtain a closed algebraic solution to the differential equation because of the complexity of $N(t)$ or $W(t)$. In these cases the integral must be approximated numerically. Ricker (1975) and Paulik and Bayliff (1967) describe some methodologies for the numerical approximation. Yield is usually expressed as yield relative to an arbitrary initial number of recruits to the fishery, hence the term "yield per recruit". In the classical models of yield per recruit (e.g., Beverton and Holt 1957), equilibrium conditions are assumed to exist in the fishery so that the yield accumulated over the lifespan of one year class of recruits is equal to the annual yield from all age classes of the population. Equilibrium conditions result if fishing mortality, natural mortality, and recruitment have been constant for a duration of at least one fishable lifespan, so that a stable age distribution has been reached. Yield per recruit is customarily examined over a range of age-at-entry and fishing-mortality levels. The resulting response surface is then analyzed to determine optimum management strategies.

Since chinook salmon have a relatively fixed life history cycle, it is of interest to merely compute the yield from a single year class over its entire life history, avoiding the assumptions necessary to model annual yield from all age classes. In this manner the "year class" can be viewed as a group of fish released from a hatchery or a group of wild-stock out-migrants from a particular river system. Most current tagging experiments usually provide growth, maturity, and mortality parameter estimates pertaining to such year class groups. The management objective, in terms of the yield-per-recruit model, is to choose a size limit which maximizes the yield in weight from a year class group of out-migrants. Yield-per-recruit models cannot be used to define an optimum fishing mortality rate because the effects of overharvest or underharvest on future recruitment are ignored.

Since ex-vessel prices paid for chinook salmon are a function of fish size, and hence age, it is of interest to examine the landed value of the yield over a range of ages-at-entry:

$$V = F \cdot \int_{t_{\rho'}}^{t_\lambda} N(t) \cdot W(t) \cdot P(t)\, dt \quad ,$$

where V = value in dollars of the yield-per-recruit, and

P = ex-vessel price per pound of a fish of age t

Several features of chinook salmon life history complicate the development of traditional yield-per-recruit models. Chinook salmon mature and leave the ocean to spawn at ages 2 through 6. The proportions maturing at ages 2 and 6 are extremely small and are ignored in the present model. Life history events for maturity groups 3, 4, and 5 are depicted for a typical fall chinook hatchery stock in Figure 1. Spawning occurs in the fall, and fry are released the following spring. Age is measured from a release date of June 15 in the present model. May 15 to September 20 fishing-season dates are also shown. Fish are assumed not to encounter fishing gear during the summer immediately after release. Maturity-group-3 fish are susceptible to encounters with fishing gear for two fishing season; maturity-group-4 fish for three seasons; and maturity-group-5 fish for four fishing seasons. Also shown are the ages at which fish from each

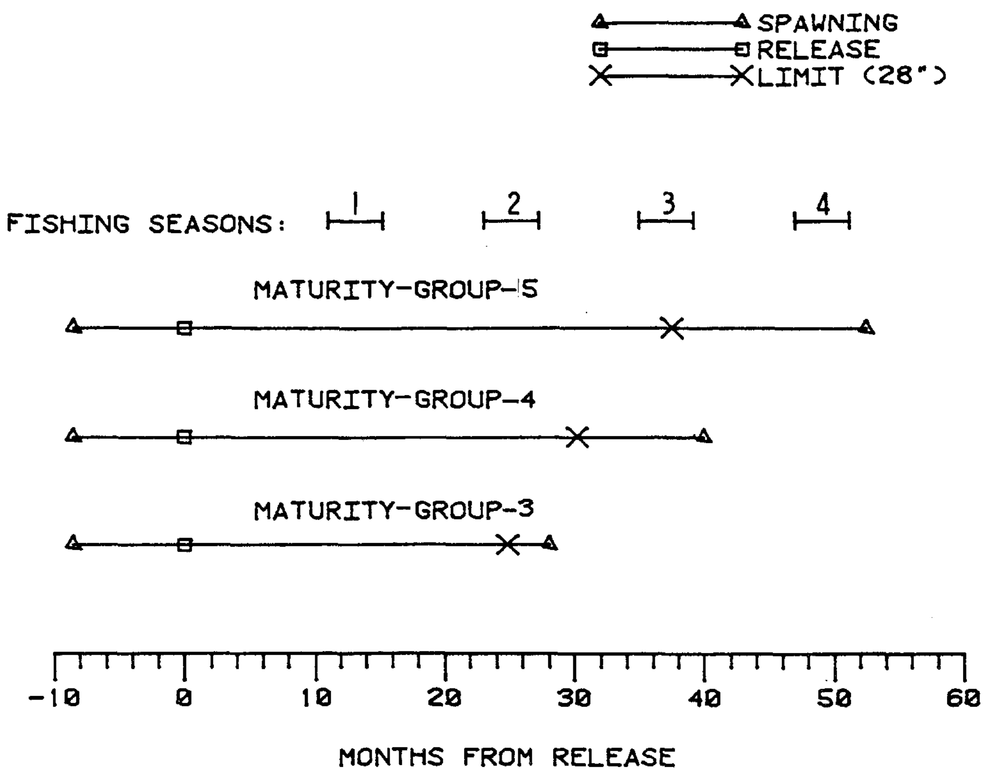

Figure 1. Life history events for a typical fall chinook hatchery stock.

of the maturity groups reach the current 28-inch size limit, using the maturity-group-specific growth functions of O'Connor (1977).

Since parameters of the growth function for chinook salmon are allowed to depend on the age of maturity, the growth function will be expressed as $W_g(t)$, where g is the maturity group. Survival models have been proposed for chinook salmon in which natural mortality is a function of fish age (Henry 1972; Cleaver 1959) or a continuous function of fish weight (O'Connor 1977). The survival model used here is both maturity-group-specific and a continuous function of age, and is identified as $N_g(t)$. Ex-vessel price is a function of fish weight and also fluctuates in a predictable fashion during each fishing season. The price function will be expressed as $P(\tau,$ weight$)$, where τ is time measured within a fishing season. Fishing mortality will be assumed to be constant beyond the age of full recruitment. Fishing mortality will be modified to accomodate partially recruited age classes and hooking mortality. The instantaneous rate of fishing mortality, allowing for partially recruited age classes, will be denoted F_t.

O'Connor (1977) has estimated the proportions of two Columbia River fall chinook hatchery release groups which matured at ages 2 through 5. With these estimates of maturity-group proportions at release time, the yield from each maturity group of out-migrants can be computed independently. The yield from the entire release group can then be evaluated as the sum of the yields from each maturity group. Since fishing does not occur continuously, the integral of the yield equation must be evaluated piece-wise over each fishing season interval $[\tau_1, \tau_2]$ in which each maturity group (g) experiences fishing mortality at each age (t):

$$\text{Total Value} = \sum_{g=3}^{5} \sum_{t=2}^{g} F_t \int_{\tau_1}^{\tau_2} N_g(\tau) \cdot W_g(\tau) \cdot P(\tau, w)\, d\tau$$

Parameter Estimation

The appropriate forms of each of the functions $N_g(\tau)$, $W_g(\tau)$, and $P(\tau, W)$ and available parameter estimates were determined from a review of the literature and from additional data.

Growth:

Two kinds of growth models are used to evaluate chinook yield per recruit. O'Connor (1977 combined a linear length-at-age model with an exponential weight-length model to estimate maturity-group-specific parameters of the growth function:

$$W_g(t) = a_g \cdot (m_g \cdot t + L'_g)^{b_g} \quad ,$$

where $W_g(t)$ is weight in kilograms, t is time from release, L' is length at release, b is the exponent of the weight-length relationship, g is maturity group, and a and m are parameters estimated from the length-at-age model. The data employed in estimating the parameters were derived from several sources and pertain to Columbia River fall chinook in general. O'Connor's (1977) parameter estimates are listed in Table 1. The resulting growth curves for maturity groups 3, 4, and 5 are shown in Figure 2. O'Connor obtained fits with $R^2 > .99$ for the length-at-age model. Goodness of fit for the combined weight-at-age model was not reported, but appears to be high.

Henry (1972) estimated the parameters of a non-maturity-group-specific von Bertalanffy growth equation for several broods of Columbia River fall chinook by

$$W(t) = W_{\infty} \cdot [1-e^{-k(t-t_0)}]^3$$

Henry's (1972) parameter estimates for the 1961 to 1964 broods of fall chinook from the Spring Creek hatchery are: W_{∞} = 12.76 kg, t_0 = 1.02, and k = 1.1. The resulting growth curve is shown in Figure 2. Henry (1972) did not report goodness-of-fit statistics for the von Bertalanffy growth model.

Natural Mortality:

O'Connor (1977) derived a survival model for chinook salmon in which the natural mortality rate was assumed a declining function of fish weight. His model is based on the assumption that natural mortality is inversely proportional to fish weight. He used the previously-discussed growth function and estimated a constant of proportionality, K, for each maturity group from a model incorporating catch, escapement, and tag recovery data:

$$M_g(t) = \frac{K_g}{a_g \cdot (m_g \cdot t + L'_g)^{b_g}} ,$$

where $M_g(t)$ is instantaneous natural mortality in units of 1/month at t months after release. The estimates of K for mortality groups 3, 4, and 5 from the 1961 brood year for Spring Creek fall chinook were: 0.011, 0.015, and 0.019, respectively. The resulting instantaneous rates of natural mortality are shown in Figure 3.

O'Connor (1977) derives a survival model based on the natural mortality rate function. The model is based on the differential equation

$$dN = -[\ M(t) + F\ ] \cdot N\ dt \quad .$$

Substitution of the function $M(t)$ and integration of the differential equation gives O'Connor's survival model (maturity group subscripts have been omitted here for simplicity):

$$N(t) = N_0 \cdot e^{-\left\{[K/(am(1-b))] \cdot [(mt+L')^{1-b} - (L')^{1-b}] + Ft\right\}} ,$$

Table 1. Maturity-group-specific growth parameter estimates for generalized Columbia River fall chinook (from O'Connor 1977).

Maturity Group (g)	a_g (kg/cm)	b_g	m_g (cm/month)	L'_g (cm)
3	$3.950 \cdot 10^{-6}$	3.304	2.542	8.0
4	$3.725 \cdot 10^{-6}$	3.318	2.091	8.0
5	$4.727 \cdot 10^{-6}$	3.263	1.685	8.0

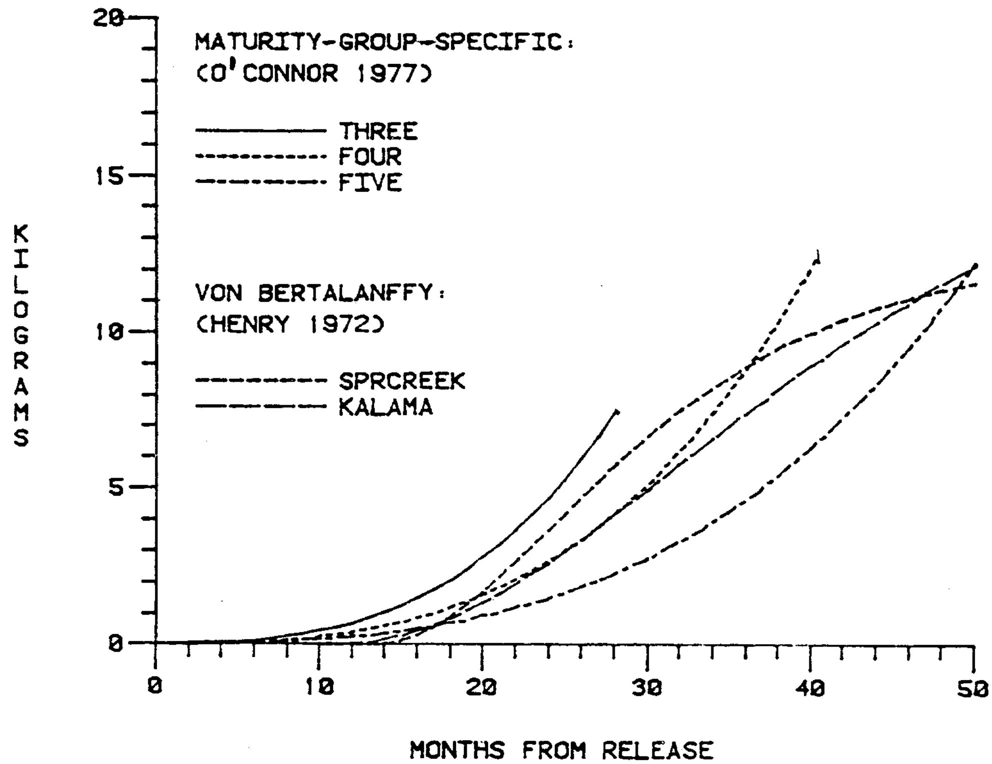

Figure 2. Exponential maturity-group-specific and von Bertalanffy growth models for Columbia River fall chinook salmon.

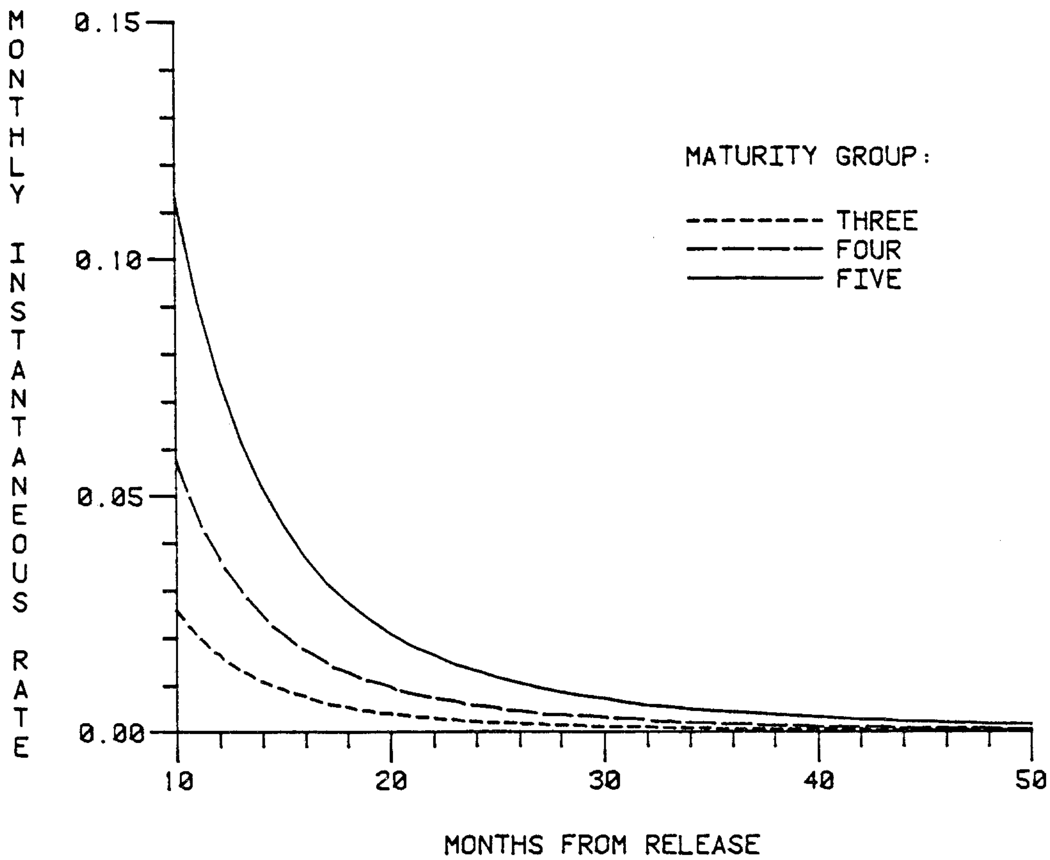

Figure 3. Maturity-group-specific mortality rates for fall chinook salmon, using O'Connor's inverse-weight-proportional model.

where t is time in an interval over which fishing has occurred continuously and N_0 is the population size at the beginning of the interval.

Other authors have postulated constant values for the chinook natural mortality rate. Parker and Kirkness (1956) estimated an instantaneous natural mortality rate of 0.417 from the results of an ocean tagging experiment. Parker (1960) later expanded his analysis and conservatively estimated a range of 0.36 to 0.51 for natural mortality. Ricker (1956) notes that biases in Parker's (1960) assumptions would produce inflated estimates, making them perhaps two or three times too high. Cleaver (1969) and Henry (1972) both estimated a value of 0.45 for the natural mortality rate of Columbia River fall chinook. These estimates pertain to the entire saltwater life history, however. Ricker (1976) estimates that the instantaneous annual natural mortality rate of large salmon (age 2+) in the ocean is approximately 0.10. The point estimate of 0.10 annually, or 0.008333 monthly, is used here in an alternative form of survival model. The usual simple exponential model of survival is employed:

$$N(t) = N_0 \cdot e^{-(F+M)(t-t_0)} \quad ,$$

where F is fishing mortality, M is natural mortality, and N_0 is the number of fish available to the fishery at reference time t_0.

Fishing Mortality:

O'Connor (1977) estimated monthly instantaneous fishing mortality rates for both the 1961 and 1963 broods from the Spring Creek hatchery at 0.055. Fishing mortality was computed over all ocean fisheries and did not account for spatial variation in the distribution of fish. Conditions in ocean troll fisheries have changed considerably since the 1963-1968 period to which these estimates apply.

As an example of more recent instantaneous fishing mortality rates, coded wire tag recoveries from three upper Columbia bright tag groups are examined (Table 2). Virtual population estimation techniques (Gulland 1965; Fry 1949; Derzhavin 1922) can be used to back-calculate the initial population size and instantaneous fishing mortality rates when the final population size, catches, and natural mortality are known. Two greatly simplified models of the spatial distribution of the stocks and of fishing effort are used to place upper and lower bounds on estimated fishing mortality in the Alaska troll fishery. To obtain the lower bound, the fish stocks were assumed to rear entirely in Southeastern Alaskan waters. The stocks would thus be exposed to fishing mortality from the Alaska troll fishery both as immatures and as matures. Tag recoveries outside Alaska are assumed to be composed only of mature fish enroute to the Columbia River. Under these assumptions, an estimate of the total number of fish maturing at a given age which remained at the end of their final fishing season can be obtained by summing escapement; Columbia River harvest; and Oregon, Washington, and British Columbia ocean harvests. The homeward migration is assumed to occur quickly enough so that natural mortality can be ignored. To obtain an upper bound on fishing mortality, fish stocks are assumed to rear jointly in Canadian and Alaskan waters. An estimate of the total number of mature fish remaining at the end of their final fishing season can then be obtained by summing escapement,

Table 2. Estimated recoveries of three 1975-brood upper Columbia River coded wire tag groups, and estimated total recoveries of 1975-brood upper Columbia bright stocks (from Washington Department of Fisheries, 1981).

	Tag Code									
	13/07/13			13/11/01			13/12/02			All 1975 Brood
Age:	3	4	5	3	4	5	3	4	5	
Area:										
Alaska	45	190	80	23	291	225	123	300	122	106,331
British Columbia	295	285	58	188	270	79	562	402	72	108,499
Washington-Oregon	14	45	2	22	33	9	58	48	3	12,538
Columbia River	80	303	30	47	260	54	120	488	23	65,649
Escapement[1]	74	280	28	43	240	50	111	451	21	60,364

[1] Approximated for each tag code and age using 92% of the Columbia River harvest. This figure was derived to represent the entire 1975 brood escapement using methods independent of tag returns by the Washington Department of Fisheries (1981).

Columbia River harvest, and Oregon-Washington ocean harvest. The combined recoveries from the British Columbia and Alaska troll fisheries are then used to estimate fishing mortality.

Virtual population techniques utilize the general catch equation relating catch, C, in a one year interval with final population size N_{t+1}:

$$C = \frac{F}{(F+M)} N_{t+1}[e^{(F+M)}-1] \quad .$$

When M, C, and N_{t+1} are known, F can be determined from this expression with a Newton-Raphson iteration which utilizes its derivative:

$$\frac{d}{dF} = N_{t+1}\left[\frac{F}{(F+M)} \cdot e^{(F+M)} + \frac{M(e^{(F+M)}-1)}{(F+M)^2}\right]$$

The estimation procedure proceeds backwards, using the tag recoveries in Table 2, the twomodels of spatial distribution, and a monthly instantaneous natural mortality rate of 0.0083 (0.10 annually). Starting with the estimate of the number of fish maturing at age 5 which remained at the end of the fishing season, an instantaneous rate of fishing mortality for the 1980 season and the number of fish present at the beginning of the fishing season can be calculated. The number of maturity-group-5 fish which were present at the end of the previous fishing season is then calculated with an exponential survival model which incorporates the instantaneous natural mortality rate. The total number of fish remaining at the end of this previous fishing season is then calculated by summing the number of maturity-group-5 fish and the escapement and south-coastal fishery recoveries of age-4 fish. The back-calculations are continued through three fishing seasons. An average fishing mortality rate for all three fishing seasons is estimated by weighting each season's fishing mortality by the catch during that season. A fishing mortality rate is also computed using estimates of total 1975-brood upper Columbia River bright recoveries obtained from the Washington Department of Fisheries (Table 2). In deriving fishing mortality rates from these data without reference to age, the recoveries of the 1975 brood year over ages 2 to 5 are assumed to represent the recoveries of 4 successive brood years harvested during a single season. The resulting monthly instantaneous fishing mortality rate estimates range from 0.050 to 0.205 (Table 3). Yield per recruit will be evaluated over monthly instantaneous fishing mortalities in the range of 0.02 to 0.40. Detailed yield projections will be made for the range 0.055 to 0.20.

All immature fish are probably not available to the troll fishery. O'Connor (1977) suggests fishing mortality rates on age-2 fish by the factor 0.325 to allow for incomplete recruitment at this age. This value was obtained by assuming age 2 fish were fully recruited to the coastal sport fishery and examining the ratio of age 2 to age 3 fish in the sport catch. When sufficient estimates become available, incomplete recruitment would be better handled as a function of both age and maturity group. In the present configuration of the model, a gear selectivity coefficient of 0.325 is used for age-2 fish. The gear selection coefficient is 1.0 for ages 3, 4, and 5.

Table 3. Weighted means of the virtual population estimates of instantaneous fishing mortality rate at ages 3, 4, and 5 for three coded wire tag groups and for the entire 1975 brood of upper Columbia brights, using two models of spatial distribution of the stocks.

Tag Code	Upper estimate of F^1	Lower estimate of F^2
13/07/13	0.101	0.050
13/11/01	0.137	0.095
13/12/02	0.111	0.056
All 1975 brood upriver brights	0.205	0.078

[1] Assuming stocks rear jointly in Alaska and British Columbia.

[2] Assuming stocks rear only in Alaska and that non-Alaskan recoveries are only mature fish.

Maturity:

In order to compute yield with the approach outlined above, it is necessary to know the proportion of a stock which will return to spawn at each age. O'Connor's (1977) model is the only source of these parameter estimates. The estimates for maturity groups 2 to 5 for the 1961 brood from the Spring Creek Hatchery are 0.0001, 0.05, 0.7, and 0.2499.

Hooking Mortality:

Wright (1970) reviews studies of chinook hooking mortality and concludes that reasonable estimates of the percentage killed lie between 15% and 45%. However, much higher estimates have been reported. Parker and Black (1959) estimated extremely high rates of hooking mortality in a study in which small chinook salmon were held for observation in live tanks on board a vessel for some time after hooking. They estimated an initial 20% mortality from direct injury, followed by an additional 71% mortality ascribed to the after-effects of fatigue. Wright (1970) criticizes the high mortality estimate from live-tank holding experiments, noting that the stress induced by confinement together with hooking stress could have synergistic effects on mortality. However, Ricker (1976) feels that "an overall estimate of 50% seems rather conservative".

Hooking mortality can be incorporated into the survival models described above by applying the fishing mortality rate for legal fish to undersize fish as well, but reducing its value by the proportion of undersize fish which survive hooking encounters. A hooking-mortality model in which hooking mortality is a function of fish length is postulated. The fishing mortality rate on undersize fish can thus be expressed as $F \cdot H(L)$ where $H(L)$ is a linear function of fish length ranging from from 0 to 1 which describes the probability of a fish being killed, given an encounter with fishing gear. Above the size limit, $H(L) = 1$. Since age of entry is the endpoint in computing survival in the present model, two different forms of the survival model can be used with the hooking mortality function. Above the size limit, $H(L) = 1$ and survival reduces to O'Connor's (1977) model. Below the size limit a survival model can be derived from

$$dN = -[M_g(t) + F_t \cdot H(L)] \cdot N\, dt \quad .$$

The function $H(L)$ can be expressed as a function of time. If $H(L)$ is assumed linear with length L, $H(L) = h \cdot L + C$. If L is linear in time, $L(t) = m_g \cdot t + L'_g$, where L'_g is a maturity-group-specific length at release $(f=0)$, and m_g is a maturity-group-specific constant, then

$$H(t) = hm_g t + (hL'_g + C)$$

Substituting this result into the differential equation for survival and integrating (see Appendix 1) gives

$$N(t) = N_0 \cdot e^{-\left\{[K/(am(1-b))] \cdot [(mt+L')^{1-b} - (L')^{1-b}] + Ft[hmt/2+hL'+C]\right\}}$$

The maturity group subscript g is omitted from parameters K_g, a_g, m_g, b_g, and L'_g in the above expression for simplicity.

Estimation of the Relationship of Hooking Mortality and Fish Size:

Size-specific hooking mortality data are required to estimate the parameters of the function $H(L)$. Very little size-specific hooking mortality data for chinook salmon are available in the literature. Mathews (1977) reviewed shaker mortality studies by Wright (1969), and Butler and Loeffel (1972) and estimated that "a 10-15% hooking mortality rate would be reasonable for chinook on the larger end of the shaker range, such as occur on the Fairweather Grounds, and 25-30% for chinook on the small end."

A detailed source of size-specific hooking mortality data were provided by a tagging study conducted by the Alaska Department of Fish and Game in Icy Strait, Southeastern Alaska, during April and May 1981. A description of the study and preliminary results are given in Bethers (1981). The objectives of this study were to compare single and treble hook release mortalities and to investigate general stock distribution patterns. The fish length and severity of hooking wounds were routinely recorded as a part of the tagging operation allowing preliminary estimation of the relationship between hooking mortality and size. More refined estimates of this relationship will be possible after the tag recovery information becomes available.

Using normal commercial trolling methods, 842 fish were captured in the Icy Strait tagging study. The fish were graded by severity of the hooking injury. Grade "A" fish suffered only superficial wounds and showed less than four drops of blood. Grade "B" fish showed significant injury with more bleeding, but with no gill or eye injury, and the wounds were judged probably not fatal. Grade "C" fish showed significant injury, profuse bleeding or gill or eye wounds, and were judged as probable mortalities. Grade "M" fish were dead when examined. Since the fish were destined for use in a tagging study, handling of the fish once alongside the boat was somewhat atypical of a commercial trolling operation. Large fish were boated in a wire basket to which a small electrical potential had been applied. The electrical current effectively subdued the fish allowing hook removal, length measurement, and tag insertion. Because of the careful handling of the hooked fish these results are probably a lower bound on hooking mortality in the commercial fishery.

Of the 842 observations, 826 were caught on either single or treble hooks, and sustained no unusual non-hooking injuries. The few fish caught on double hooks are not considered. The length frequency distribution of all grades of these 826 fish caught on both single and treble hooks is reasonably symmetrical (Figure 4a). However, the length frequency distribution of grades "C" and "M", the probable and known mortalities, is markedly skewed toward larger fish (Figure 4b).

In order to examine the relationship between the proportion killed and length, the fish were accumulated in 100 mm length intervals. The proportion killed in each length interval was estimated by dividing the known and probable mor-

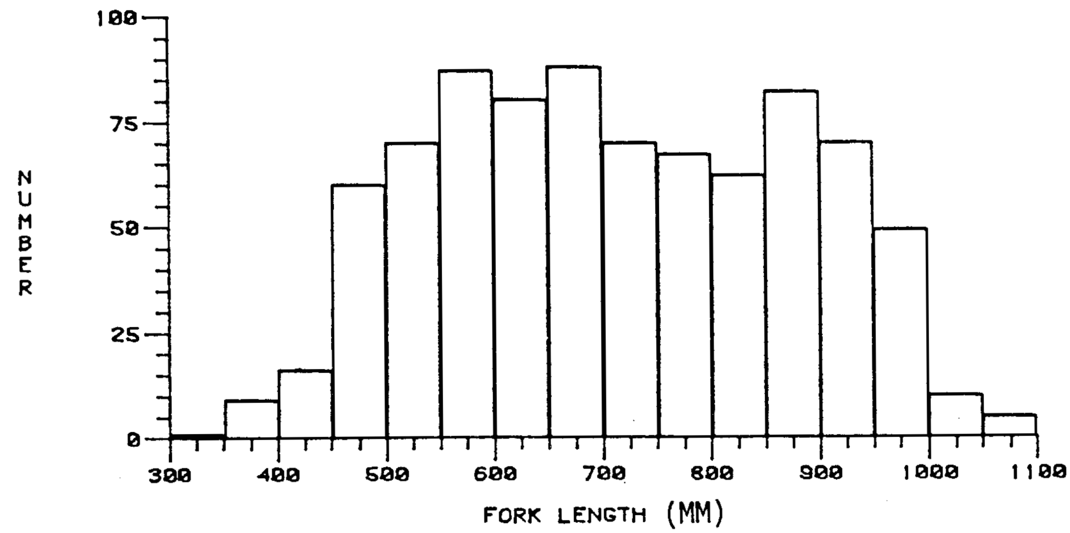

Figure 4a. Length frequency distribution of all grades of chinook salmon captured with single and treble hooks in the Icy Strait tagging study.

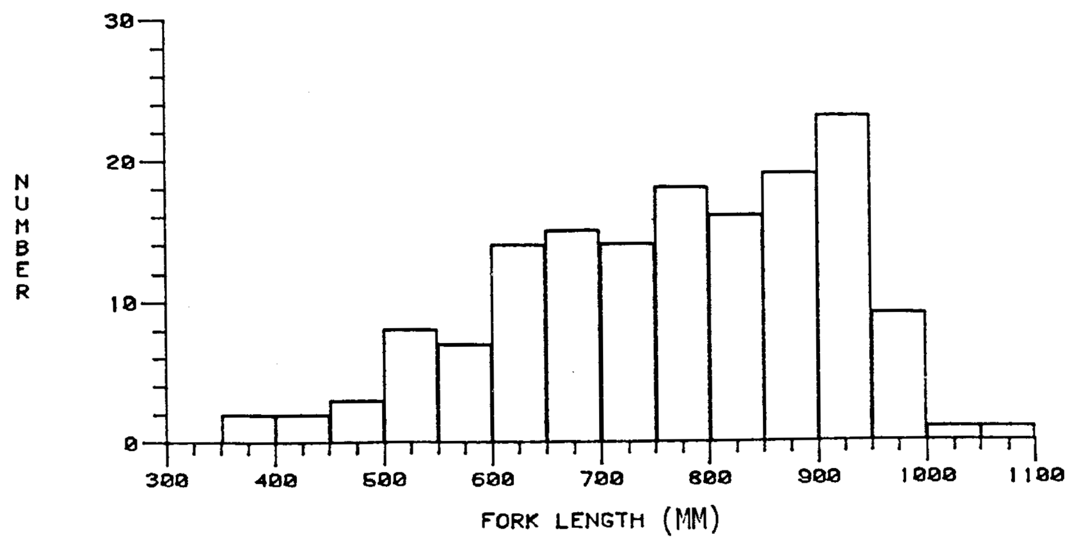

Figure 4b. Length frequency distribution of grades "C" and "M" (known and probable mortalities) of chinook salmon captured with single and treble hooks in the Icy Strait tagging study.

talities (grades "C" and "M") by the total number of fish caught in the interval (grades "A", "B", "C", and "M"):

$$\text{estimated mortality} = \frac{C + M}{A + B + C + M} \quad .$$

Some of the grade "C" fish are known to have survived since some grade "C" tags were recovered in the fishery at a later date (M. Bethers, Alaska Dept. of Fish and Game, pers. comm.). It is assumed that the effect of the survival of some of the grade "C" fish is approximately balanced by mortalities from the "A" and "B" grades. Separate proportions were computed for treble and single hooks since a difference in mortality for the two hook types was hypothesized. The smallest (300-400 mm) and largest (1000-1100 mm) length intervals were excluded because sample sizes were small. The expected number of mortalities was at least 2 in each of the remaining intervals. The resulting proportions show a definite trend toward increasing mortality at larger sizes (Figure 5a). Single-hook mortality appears to be greater than treble-hook mortality. An analysis of covariance of the mortality proportions was performed, using single and treble hook types as treatments and fish length as a covariate. An arcsin transformation of the square root of the proportion killed was used since small proportions were involved at the smaller fish sizes. Mortality proportions were weighted by the sample size in each interval for the analysis of covariance. There was no significant difference ($p > .05$) in the slopes of the two regressions fitted independently (Table 4). There was a very highly significant difference ($p < .005$) in mortality of the two hook types when fish length was accounted for. The resulting regressions fitted through the transformed mortality proportions from the two hook types are shown in Figure 5b. The regressions have equal slopes.

The mortalities resulting from this experiment must be considered an absolute lower bound on mortalities which would be experienced in the fishery. Fish were handled by trained biologists using unusual techniques to subdue the fish in order to minimize handling injury. Under typical commercial fishing conditions hooked fish would be dragged through the water for a longer period of time before being removed from the lines and greater injury would commonly result from hook removal. In addition the mortalities represented by these data are only one portion of total hooking mortality. Additional mortality, not represented in these data, is to be expected after release due to infection of hooking injuries, loss of scales, and failure to recover from hooking stress. Estimates of mortality from these factors may be possible after all tag recoveries have been analyzed.

In order to cover the wide range of hooking mortality estimates present in the literature, three levels of increasing length-related hooking mortality are evaluated in the yield-per-recruit model. The slope of the relationship of hooking mortality with length computed from the Icy Strait tagging study is assumed to hold at all three levels of hooking mortality. The Icy Strait tagging data are used to represent a lower bound on hooking mortality in the commercial fishery, assuming a 50:50 ratio of treble to single hooks. The resulting relationship corresponds to 10% mortality for 20-inch fish (fork length) and 20% mortality for 30-inch fish. As an intermediate level of hooking mortality,

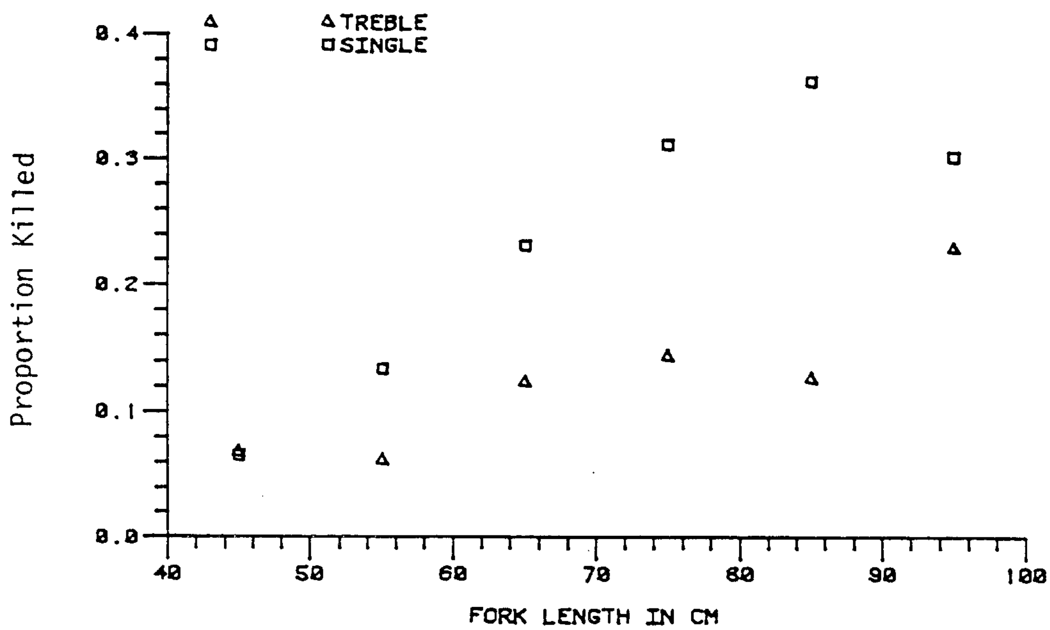

Figure 5a. Proportions of single and treble-hooked fish killed as a function of length in the Icy Strait tagging study.

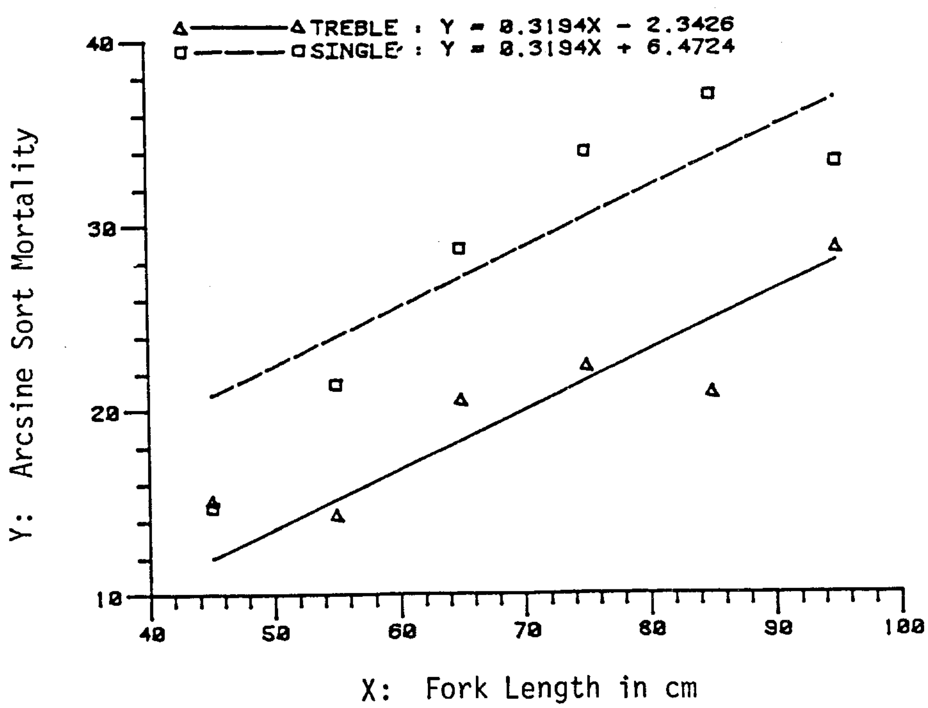

Figure 5b. Arcsine (square root) transformed single and treble hook mortalities and regressions estimated from analysis of covariance.

Table 4. Analysis of covariance of mortality from treble and single hooks with fish length. An arcsine$\sqrt{X}$ transformation is used. Dependent variables are weighted by the number of observations in each 100 mm length interval.

		df	$\sum x^2$	$\sum xy$	$\sum y^2$	Regr. Coeff	Deviations from Regr. df	S.S.	M.S.
	Within								
1	Treble	5	102,452	26,276	8,432	0.256	4	1,693	423.3
2	Single	5	94,252	36,563	18,042	0.388	4	3,858	964.4
3							8	5,551	693.9
4	Pooled(W)	10	196,704	62,840	26,474	0.320	9	6,399	711.0
5			Difference between slopes:				1	848.4	848.4
6	Between(B)	1	706	3,531	17,761				
7	W + B	11	197,409	66,371	44,235		10	21,921	2,192.1
8			Between adjusted means:				1	15,521	15,521.5

Comparison of slopes: $F = \dfrac{848.4}{693.9} = 1.223$, d.f. = 1,8 (N.S.)

Comparison of adjusted means: $F = \dfrac{15,521.5}{711.0} = 21.83$, d.f. = 1,9 ($p < .005$)

Regression model: $Y_{ij} = \alpha_i + \beta X_{ij} + \xi_{ij}$

Parameter estimates: $\beta = 0.320$

$\alpha_{treble} = -2.3426$

$\alpha_{single} = 6.4724$

35% mortality at 20 inches and 45% at 30 inches is used. Mortalities of 60% and 70% at 20 and 30 inches is used as an upper bound on hooking mortality. Constant values of hooking mortality (no variation with length) are also used in order to investigate the sensitivity of the model to this assumption. Two models of a decreasing fish size-hooking mortality relationship are also employed, using the negative slope suggested by Mathews (1977).

The low-level model of negative size-related hooking mortality assumes 20% mortality for 20-inch fork length fish and only 10% mortality for 30-inch fish. An intermediate level of decreasing size-related hooking mortality assumes 45% mortality for a 20-inch fork length fish and only 35% mortality for 30-inch fish.

Ex-vessel Price:

Prices paid to fishermen for chinook salmon vary with fish size, flesh color, and time during the fishing season. Ex-vessel prices are usually at their lowest levels at the beginning of the year and tend to increase slowly through the fishing season. Larger fish are more marketable and fetch higher prices. Three size categories were in effect in the Alaska troll fishery in 1981: "small", less than 9 lbs; "medium", 9 to 11 lbs; and "large", more than 11 lbs. White-fleshed fish bring prices well below those of red-fleshed fish. Because white-fleshed fish are relatively rare in the troll fishery, only red-fleshed prices are considered. Ex-vessel prices at various fish-buying stations were extracted from weekly market summary reports published by the National Marine Fisheries Service in the Fishery Market News for each week of the 1981 Alaska troll salmon season. The average price for all reporting buying stations in Southeastern Alaska was computed for each week. Prices for each size category exhibit increasing linear trends throughout the fishing season (Figure 6). Linear regressions were computed to represent the trends in ex-vessel prices in each size category.

The value of an average fish in each of the three maturity groups over its life history was computed using O'Connor's (1977) growth function and the 1981 Alaska ex-vessel troll prices (Figure 7). Discontinuities in the value function occurred during week 24 for maturity-group-3 fish and during week 36 for maturity-group-5 fish. These discontinuities appear when the medium/large price break is achieved in both cases. Other price-break thresholds are reached before and after the fishing seasons.

Computer Estimation Procedures

A computer program was developed in Fortran to estimate yield per recruit at various combinations of size limits, fishing mortality rates, and hooking mortalities. The model employs a numerical integration procedure to estimate the integral of $N(t) \cdot W(t)$ or $N(t) \cdot W(t) \cdot P(t)$ since closed algebraic expressions for the equations cannot be obtained. The model tracks each maturity group independently and accumulates yield piece-wise over each fishing season interval in which fishing mortality and price are continuous. Discontinuities in the price and fishing mortality functions due to achieving full recruitment to the fishery require partitioning of the fishing seasons into several intervals in some cases. The Fortran implementation of the model is presented in Appendix II.

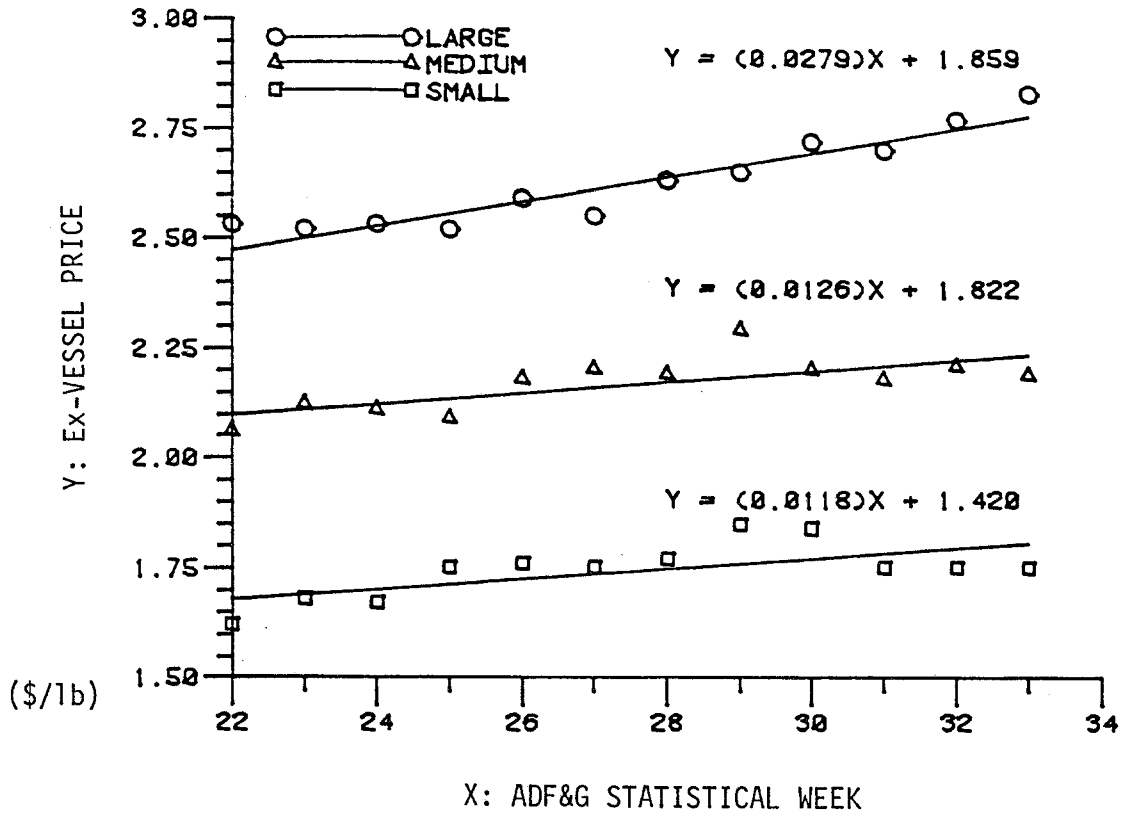

Figure 6. 1981 Alaska ex-vessel chinook salmon prices ($/lb) by size category as a function of ADF&G statistical week. Prices are averaged from all reporting Southeastern Alaskan troll landing ports.

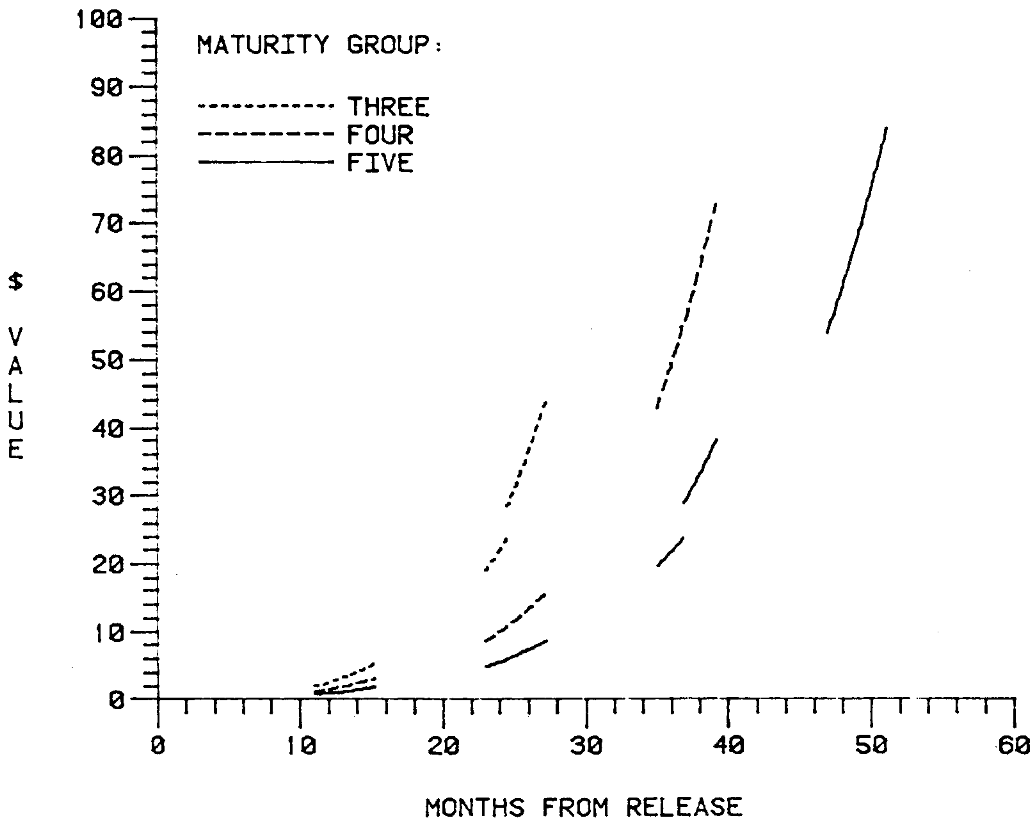

Figure 7. Value of an individual chinook salmon of three maturity groups as estimated from the maturity-group-specific growth functions of O'Connor (1977) and troll ex-vessel prices by size category from the 1981 Alaska troll fishery.

Verification of the Model

To verify the model, the parameter estimates of Beverton and Holt (1957) for North Sea plaice were used. Although Beverton and Holt's model was much simpler in form, their parameter estimates were used to drive all age-structured features of the model. Parameter estimates used and numerical results obtained are given in Appendix III. The resulting yield-per-recruit response surface (Figure 8) is very similar to the contour plot of the surface given by Beverton and Holt (1957, p. 318, Fig. 17.14). Yield-per-recruit values computed by the model were within 0.04% of the values listed by Beverton and Holt (1957).

RESULTS

A complex yield-per-recruit response surface results from modeling simultaneous harvest of all maturity groups, because growth rates vary for each maturity group and fishing seasons are not continuous. For this reason, the behavior of submodels predicting population numbers and biomass as a function of time is examined first, with fixed fishing and hooking mortality rates. Next, the yield-per-recruit response surface is explored under simplified, hypothetical conditions in which each maturity group is harvested independently. Yield and value per recruit for harvesting all maturity groups simultaneously is then computed and optimum size limits are ascertained. Finally, the effects of several gear restrictions and time-area closures are examined.

Trends in Stock Numbers and Biomass with Age

Submodel trends in stock numbers and biomass with age are examined using growth, maturity, and mortality parameter estimates derived from O'Connor's 1963 brood Spring Creek stock. A 28-inch size limit with 50% hooking mortality at all fish sizes is assumed. Population size declines rapidly in the months just following release in all three maturity groups when the weight-related natural mortality function is used (Figure 9). Fish maturing at the later ages have slower growth rates in the model and thus have higher mortality rates. The effect of applying monthly instantaneous fishing mortality rates of 0.10 and 0.20 over a May 15 to September 20 fishing season is also indicated. Fishing mortality causes the population to decline in a stepwise fashion since fishing occurs during only part of the year.

The ratio of biomass to the initial biomass of each maturity group over its life history is shown in Figure 10, using the same growth, maturity and mortality parameter estimates. Biomass of the three release groups declines for a short period just after release, but begins to increase when the growth rate overtakes the mortality rate. Since an exponential growth model with no asymptote has been assumed, biomass continues to increase until the fish leave the ocean. The natural mortality model may give unrealistically high values during early life history. However, the actual chinook yield-per-recruit model begins tracking chinook life history reasonably at age 2. Fishing at a monthly instantaneous rate of 0.1 slows the rate of biomass increase markedly and an instantaneous fishing mortality rate of 0.2 appears to preclude further gains in stock biomass.

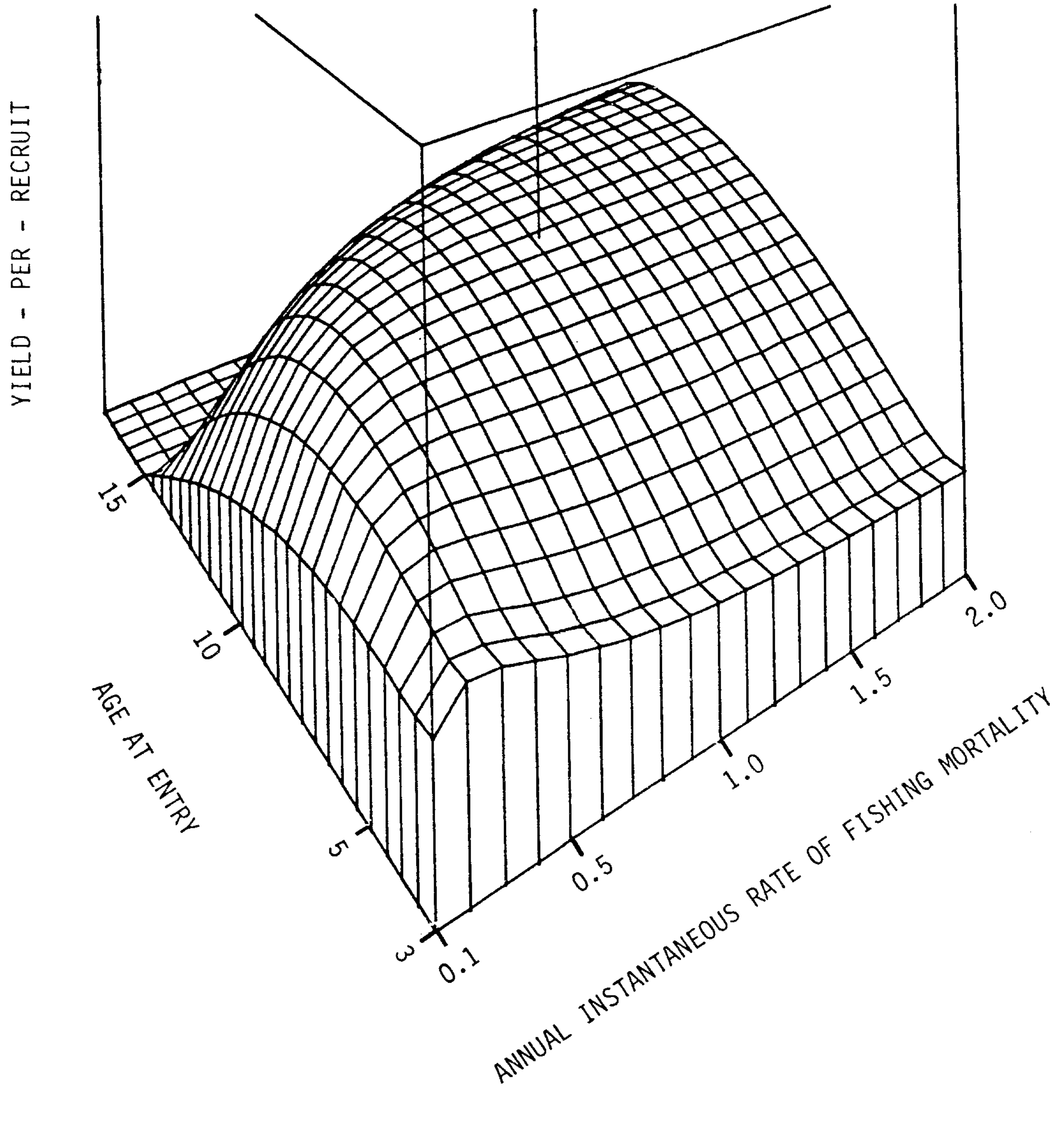

Figure 8. Yield-per-recruit response surface for North Sea plaice, estimated by the yield-per-recruit model with the parameters of Beverton and Holt (1957).

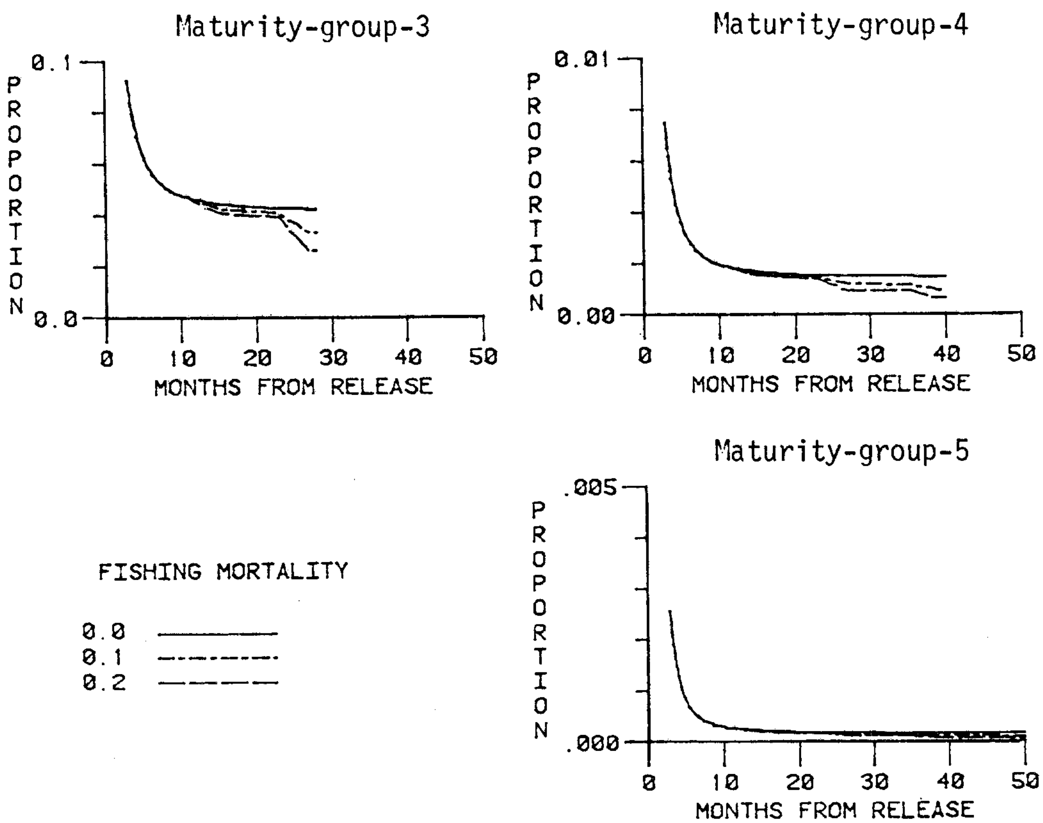

Figure 9. Proportion of original out-migrants surviving with and without fishing mortality for each of the three maturity groups, using O'Connor's exponentially declining model of survival. A 28-inch size limit with 50% hooking mortality is assumed.

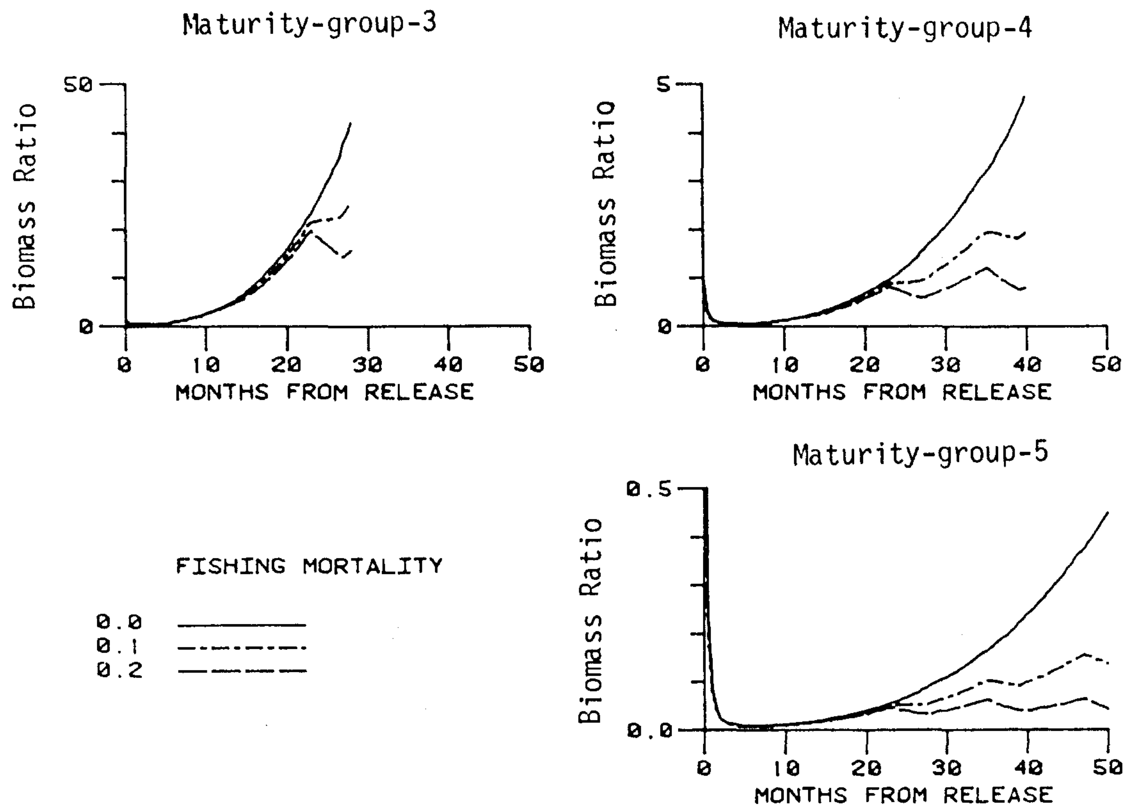

Figure 10. Ratio to original biomass of out-migrants surviving with and without fishing mortality for each of the three maturity groups, using O'Connor's survival and growth models. A 28-inch size limit with 50% hooking mortality is assumed.

Yield-Per-Recruit by Maturity Group

Due to the complexity of the yield surface which results when all maturity groups are harvested simultaneously, yield-per-recruit response surfaces are first computed separately for each maturity group. The minimum size limit is varied from 19 to 33 inches and the monthly instantaneous fishing mortality rate is varied from 0.02 to 0.40. Growth is computed from the maturity-group-specific model. the intermediate size-related hooking mortality function is used, corresponding to 40% hooking mortality at 26.5 inches (total length). For maturity-group-3, the yield-per-recruit response surface (Figure 11) indicates that reducing size limits below 26.5 inches has little effect on yield at any rate of fishing mortality. The response surface slopes steeply downward with size limits larger than 26.5 inches. When the fishing mortality rate is below 0.06, yield is maximized with the smallest size limit examined (19 inches). At these low rates of fishing mortality, fishing must begin at an early age to maximize harvest from the stock before it reaches maturity and leaves the ocean fishing grounds. At fishing mortality rates above 0.10, yield at any fixed fishing mortality rate increases slightly as the size limit is increased from 19 inches to 21.5 inches. In this range growth rate exceeds the combined rates of biomass loss from natural and hooking mortality. With fishing mortality rates above 0.10, yield remains constant from a size limit of 21.5 inches up to a size limit of 26.5 inches. According to the growth model used, fish from maturity-group-3 are 21.5 inches long at the end of their first vulnerable fishing season, 16.5 months after release. At the beginning of the second fishing season, 22 months after release, these fish are 26.5 inches in length. Size limits between 21.5 inches and 26.5 inches have no effect on the yield from this maturity group since these lengths are attained between fishing seasons. Yield declines markedly with size limits above 26.5 inches at all rates of fishing mortality. With these size limits the maturity-group-3 fish are legally retained only in their final summer. With size limits larger than 26.5 inches, significant portions of the population mature without being harvested. Growth over the final fishing season is insufficient to compensate for losses to maturity, hooking, and natural mortality.

The yield-per-recruit response surface from maturity-group-4 shows a distinct ridge maximum at $F = 0.14$ over all sizes examined (Figure 12). This reponse surface is markedly different from the typical yield surfaces for other species (e.g., North Sea plaice, Figure 8), because of the effect of hooking mortality. Hooking mortality causes yield to decline at higher fishing mortality rates for all size limits. The response surface is flat at all fishing mortality rates for size limits from 19 to 22.5 inches. Fish from this maturity group are between their first and second vulnerable fishing seasons in this size range. Between size limits of 22.5 and 28.5 inches the yield response first increases slightly and then decreases to a lower level at any fixed fishing mortality. A global maximum is reached with a size limit of 25 inches at a fishing mortality rate of 0.14. The response surface is flat over all fishing mortality rates for size limits from 28.5 inches to 32.5 inches. In this size range, fish from maturity group 4 are between fishing seasons 2 and 3. Size limits larger than 32.5 inches restrict the harvest of maturity-group-4 fish in their final fishing season, and the yield response surface slopes sharply downward.

Maturity-group-5 fish are only 19.5 inches in length at the start of the second vulnerable fishing season. Yield per recruit is constant up to this size limit,

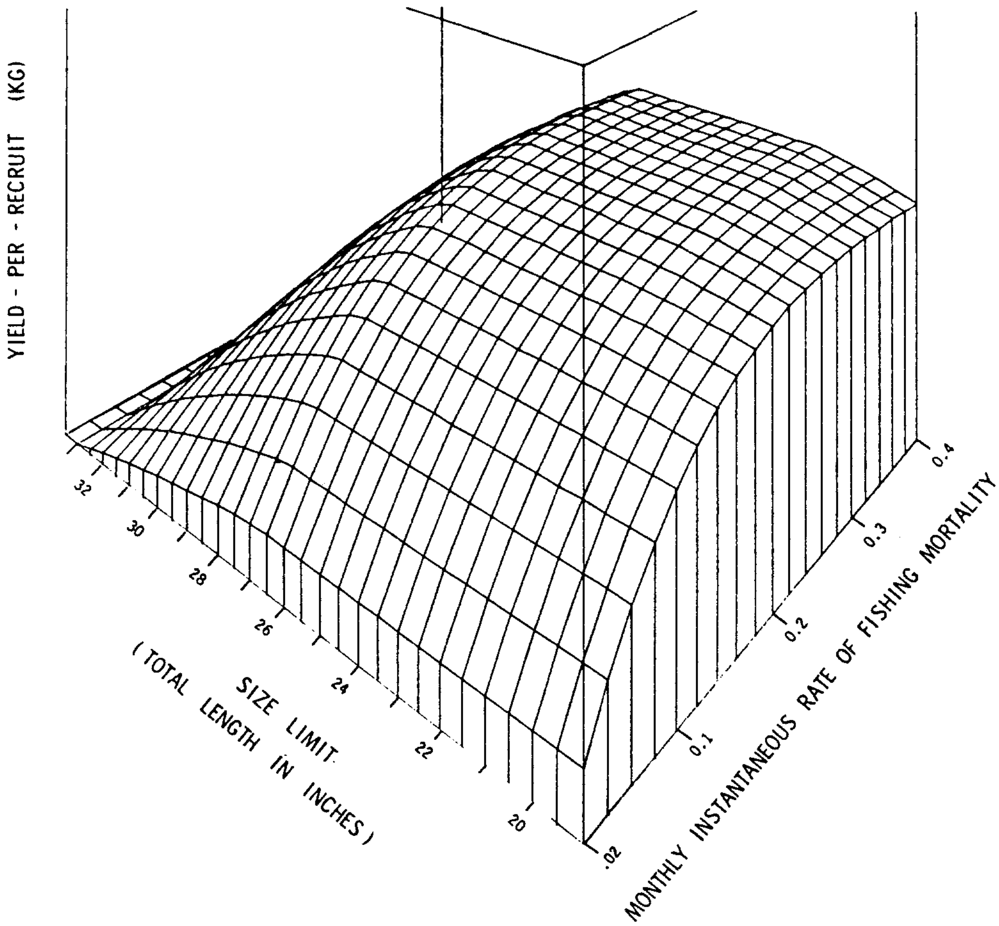

Figure 11. Yield-per-recruit response surface computed with assumptions of independent harvest of maturity-group-3 and intermediate size-related hooking mortality.

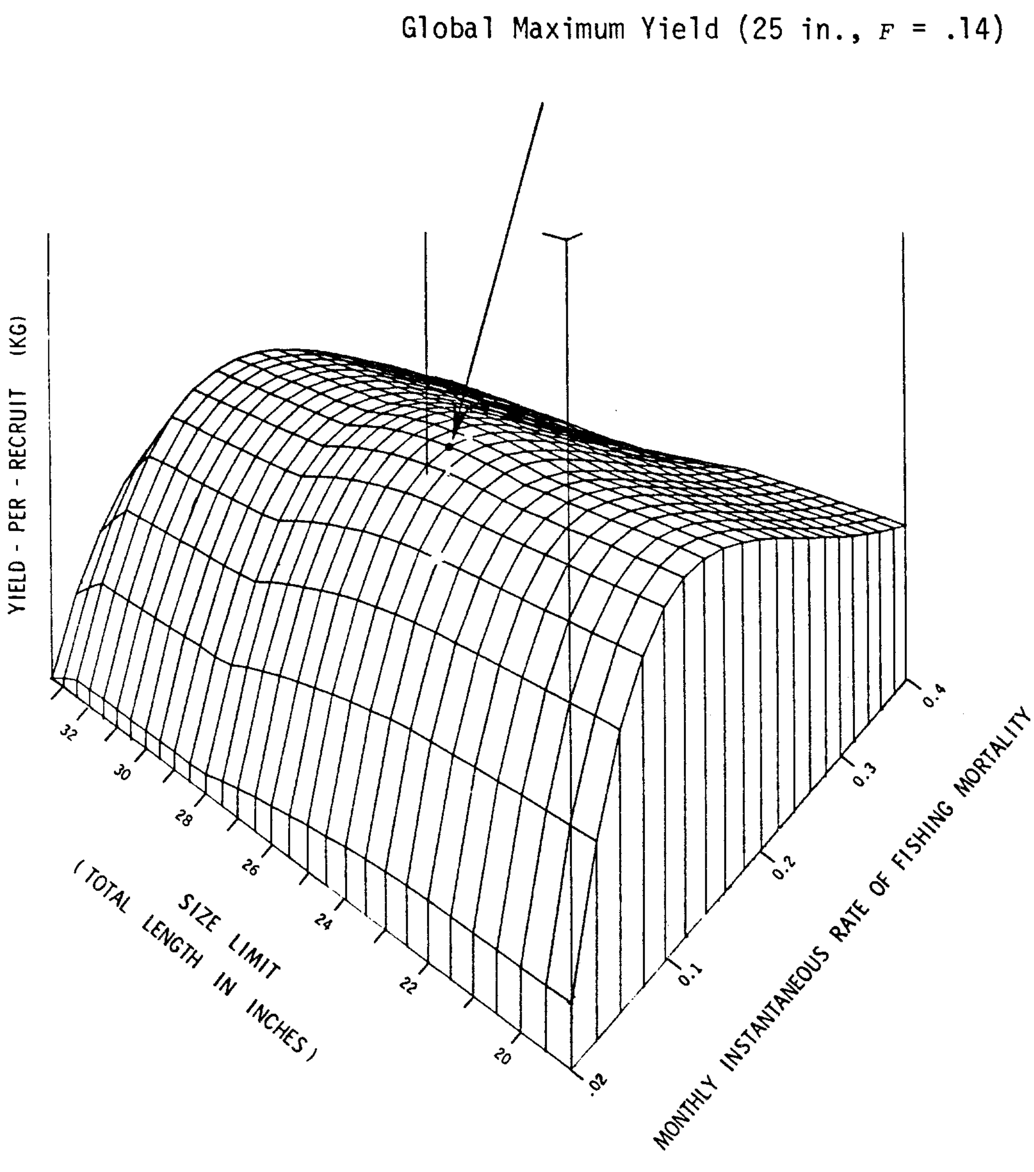

Figure 12. Yield-per-recruit response surface computed with assumptions of independent harvest of maturity-group-4 and intermediate size-related hooking mortality.

at all fishing mortality rates, and then begins to increase with increasing size limits (Figure 13). A pronounced maximum in the yield surface is evident with size limits between 24 and 27 inches at an instantaneous monthly rate of fishing mortality of 0.12. Yield per recruit is constant between 24 and 27 inches since fish from this maturity group are between their second and third vulnerable fishing seasons in this size range. Yield declines sharply with size limits larger than 27.0 inches, the size at which these fish enter the third vulnerable fishing season, even though the fish are not in their final year. The combined effects of biomass losses from natural and hooking mortality are not offset by growth with these large size limits. The yield surface flattens again at the 31.5 inch size of maturity-group-5 fish at the end of the third vulnerable fishing season. The surface would begin declining again at the size at which maturity-group-5 fish enter their final fishing season.

Yield-Per-Recruit for all Maturity Groups

Yield per recruit for the entire release group is computed using the estimates of maturity group proportions at out-migration time. Growth, maturity, and mortality parameters are derived from O'Connor's 1961 brood Spring Creek estimates. The yield-per-recruit response surface computed for all maturity groups with no hooking mortality (Figure 14) is similar in form to that computed for North Sea plaice (Figure 8). There is no global maximum evident on the response surface. The optimum size limit for each level of fishing mortality is indicated by the darkened intersections on the surface. A eumetric fishing curve is fitted by eye to these points on the response surface. The optimum size limit increases from 21.5 inches at a fishing mortality rate of 0.02, to 31.5 inches for fishing mortalities greater than 0.20.

When a low level of hooking mortality is added to the model, the optimum size limits become smaller for all fishing mortality rates and the yield-per-recruit surface begins to slope downward at higher fishing mortalities (Figure 15). This yield surface results from using the maturity-group-specific yield model with the size-related hooking mortality function which was estimated from the Icy Strait tagging study. This relatively low level of hooking mortality corresponds to 15% mortality for 26.5-inch fish (total length). The yield surface now displays a global maximum at a fishing mortality rate of 0.28 and a size limit of 30 inches. Increasing the size limit from 22 inches to 28 inches markedly increases yield, except at very low fishing mortality rates. Size limits between 28 and 32.5 inches have only a small effect on yield. Yield declines with size limits larger than the 32.5-inch size at which the dominant maturity-group-4 enters its final fishing season.

At a moderate level of size-related hooking mortality (40% at 26.5 inches) optimum size limits are further reduced, and the yield-per-recruit surface slopes downward more rapidly at high levels of fishing mortality (Figure 16). The global maximum is now achieved at a fishing mortality rate of 0.14 with a size limit of 25.0 inches. Increasing the size limit from 25 to 28 inches at a fishing mortality rate of 0.14 results in a 5% reduction in yield. Optimum size limits over a broad range of fishing mortalities appear as a slight bulge in the response surface between 25 and 27 inches. Yield-per-recruit does not decline radically until size limits are increased beyond 32.5 inches.

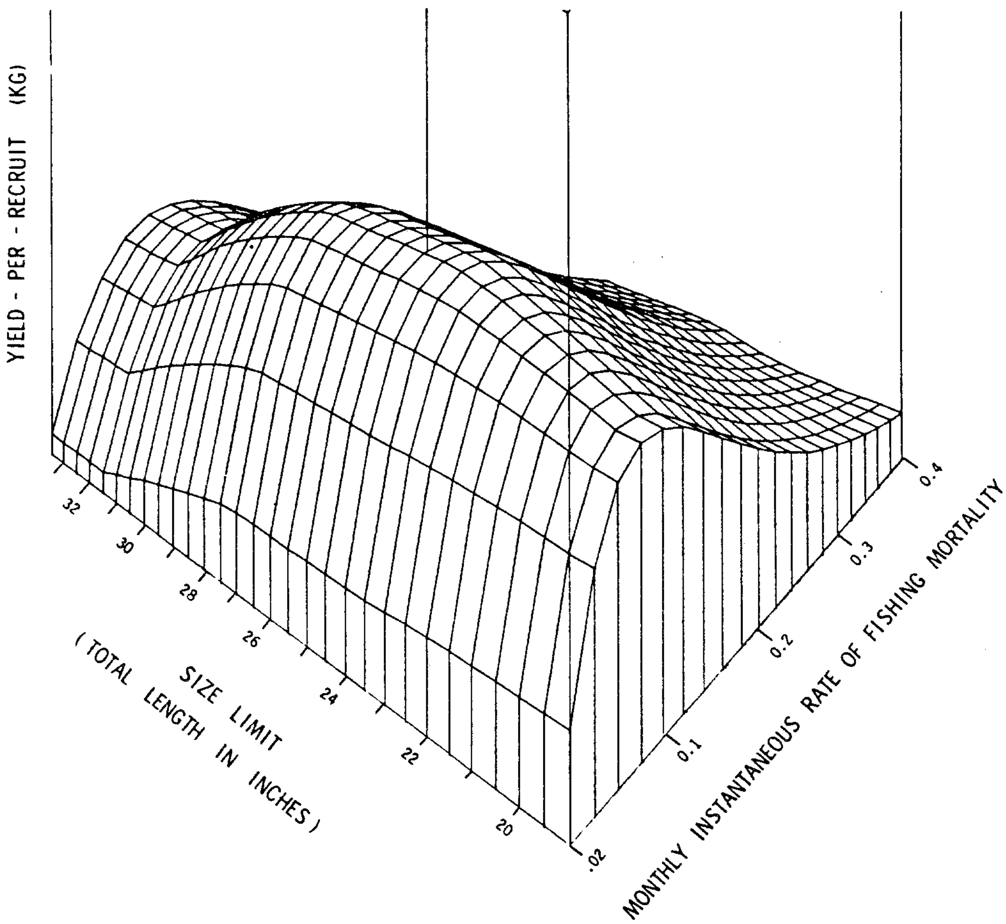

Figure 13. Yield-per-recruit response surface computed with assumptions of independent harvest of maturity-group-5 and intermediate size-related hooking mortality.

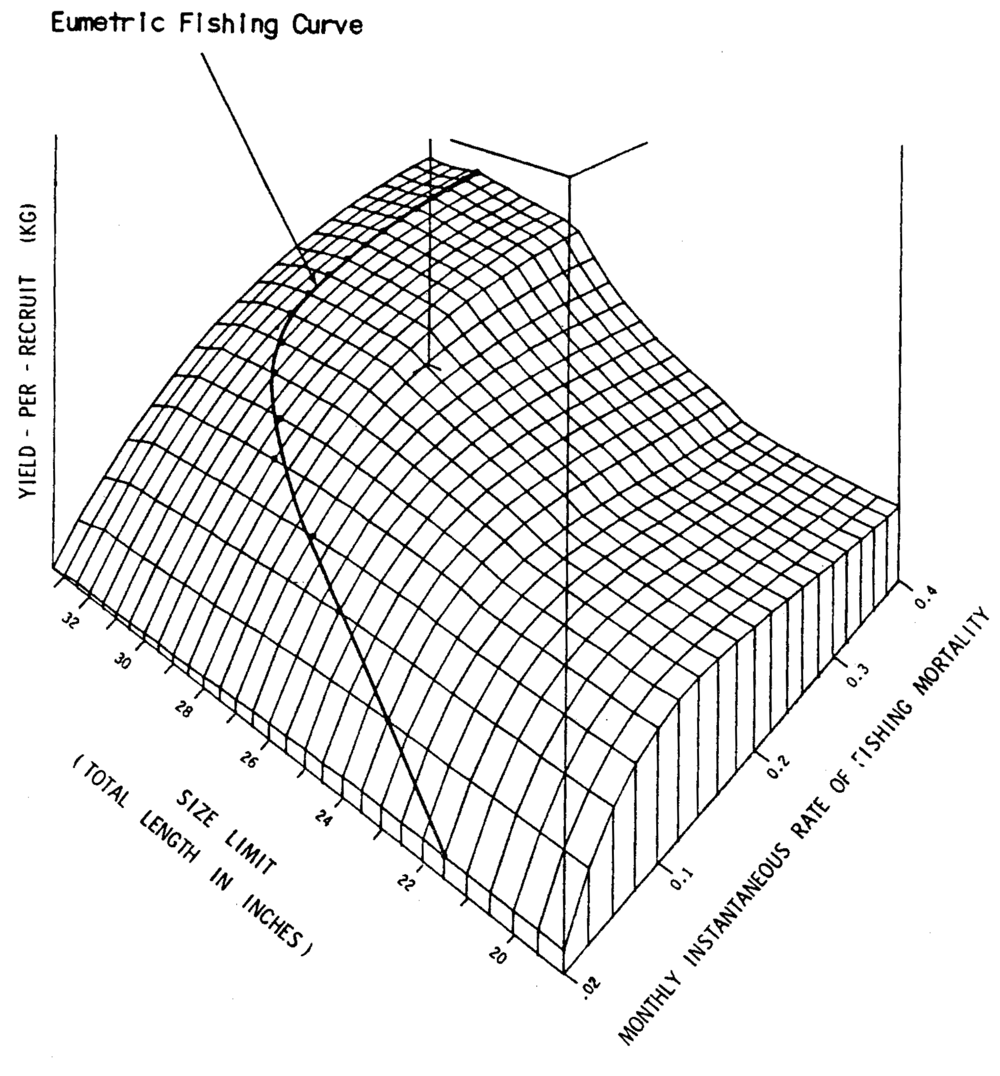

Figure 14. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and instantaneous fishing mortality rate, assuming no hooking mortality.

Global Maximum Yield (30 in., F = .28) = 3.87 Kg per Recruit

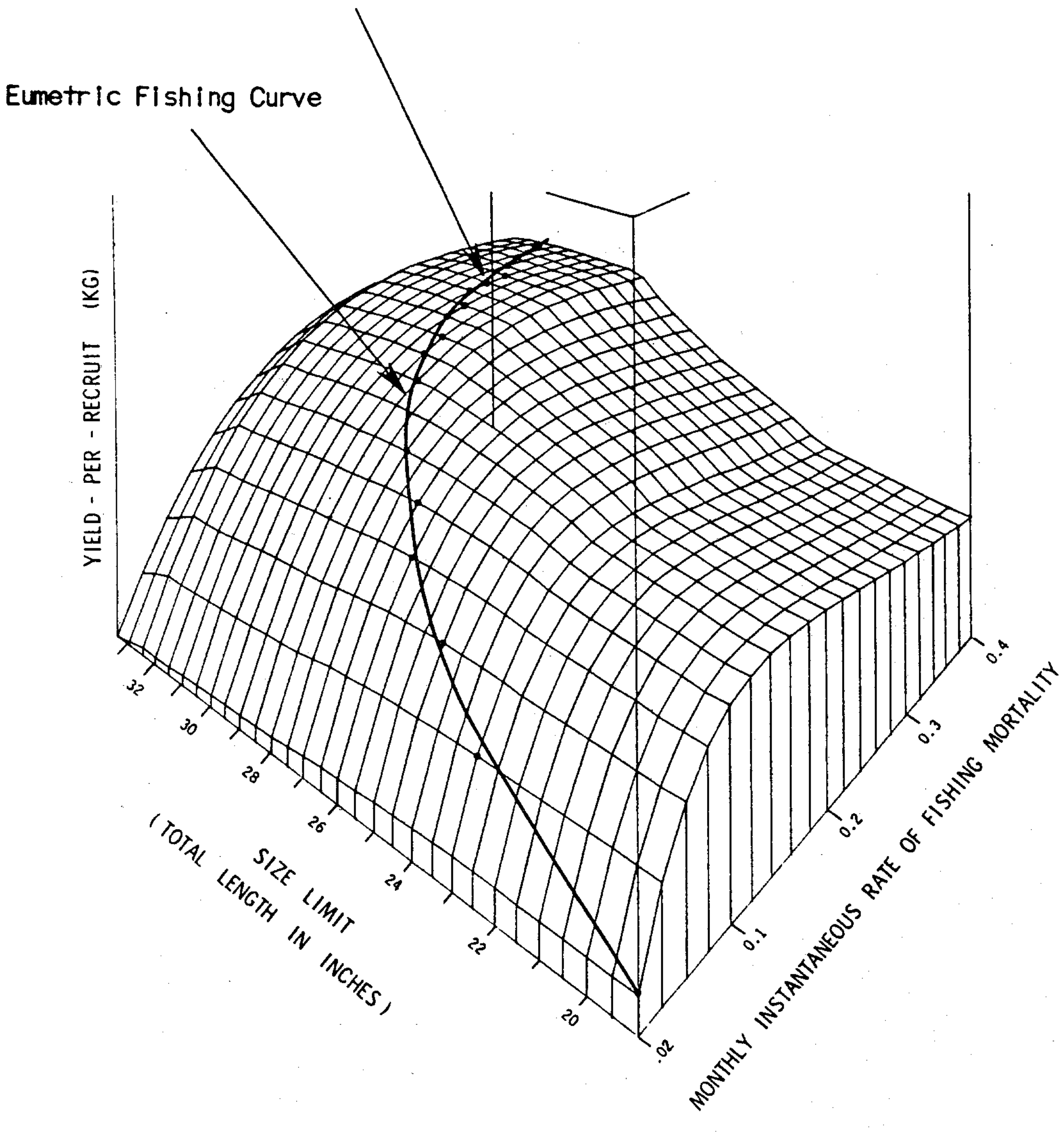

Figure 15. Yield per recruit for all maturity groups of chinook salmon as a function of size limit and instantaneous fishing mortality, assuming low size-related hooking mortality corresponding to 15% mortality for 26.5-inch fish.

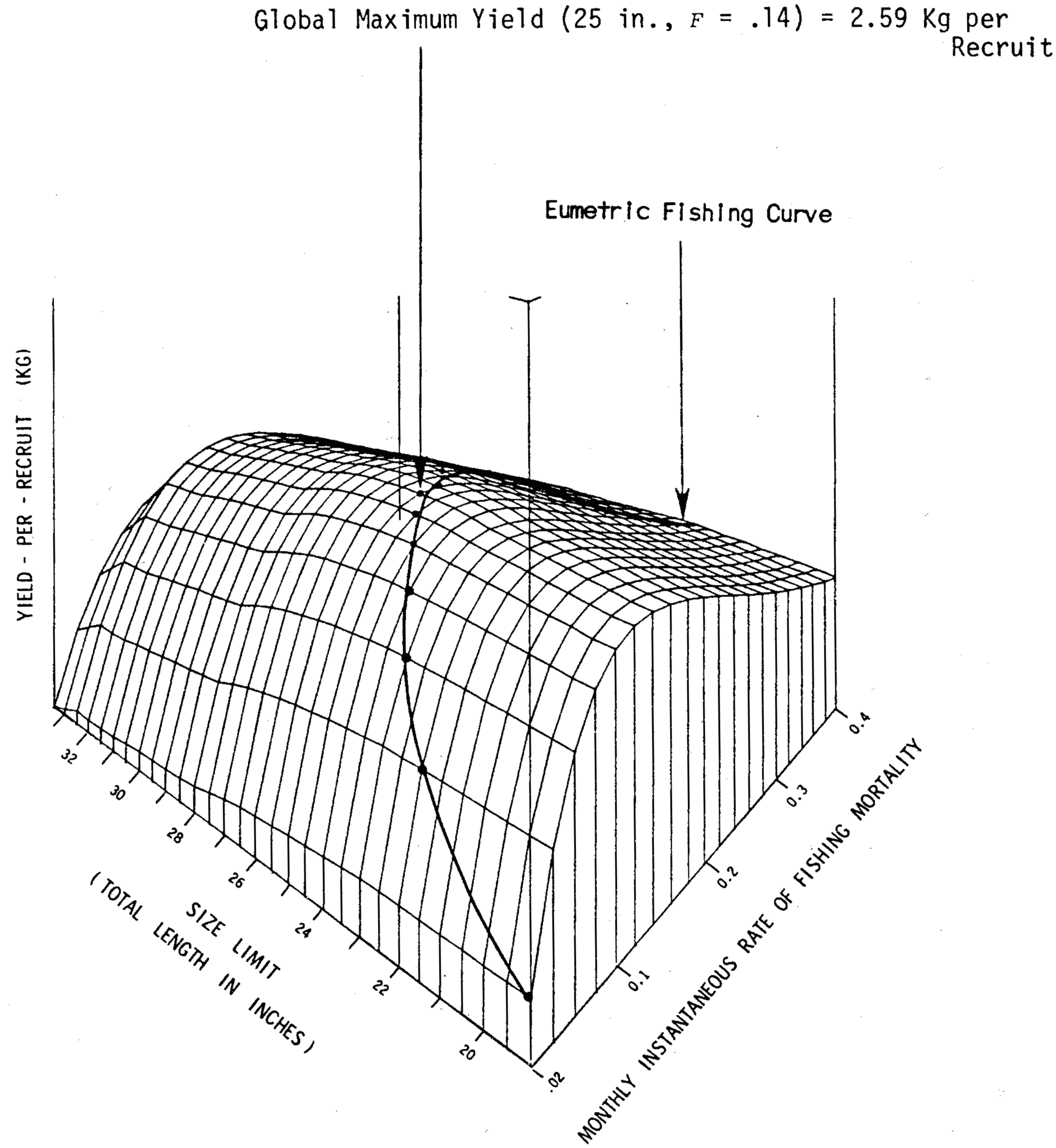

Figure 16. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and instantaneous fishing mortality, assuming moderate size-related hooking mortality corresponding to 40% mortality for 26.5-inch fish.

With severe size-related hooking mortality (65% to 26.5 inches) yield is maximized only with very small size limits (Figure 17). The global maximum yield occurs at a fishing mortality rate of 0.12 with a 20.5-inch size limit. Yield declines rapidly with larger size limits. At a fishing mortality rate of 0.12, yield is reduced 20% when size limits are increased from 20.5 inches to 28.0 inches. Increasing the size limit beyond 28 inches has little further detrimental effect on yield until a 32.5 inch size limit is reached.

Yield computed with the maturity-group-specific model but using a constant 50% hooking mortality at all sizes (Figure 18) appears to be intermediate in form between the yield surface computed using the size-related hooking mortality model at moderate and severe levels of hooking mortality (Figures 16 and 17). No unusual features are evident in the yield response surface. The global maximum yield is achieved at a fishing mortality of 0.12 and a size limit of 23 inches. Yield is reduced 11% by increasing the size limit from 23 inches to 28 inches at this level of hooking mortality.

When hooking mortality is assumed to decrease with fish size and a low level of hooking mortality is used, corresponding to 20% mortality for 20-inch fish (fork length) and 10% mortality for 30-inch fish the response surface of Figure 19 is obtained. This response surface retains the same basic features as when a similar low level of hooking mortality is assumed to increase with fish size (Figure 15), but optimum size limits are increased 1 inch. The global maximum is reached with a size of 30.5 inches at an instantaneous monthly fishing mortality of 0.22; with hooking mortality increasing with fish length the optimum size limit at this fishing mortality was 29.5 inches.

At an intermediate level of decreasing size-related hooking mortality corresponding to 45% mortality for 20-inch fish (fork length) and 35% mortality for 30-inch fish the opposite trend is observed (Figure 20). Optimum size limits are 1 to 1.5 inches smaller than for the corresponding increasing size-related hooking mortality model. The global maximum is reached with a size limit of only 23.5 inches at a fishing mortality of .12; with hooking mortality increasing with fish length the optimum size limit at this fishing mortality was 24.5 inches.

The use of Henry's (1972) von Bertalanffy growth model with a constant monthly instantaneous natural mortality rate of 0.00833 and constant 50% hooking mortality induces some minor alterations in the form of the response surface (Figure 21). Optimum size limits are smaller than with O'Connor's (1977) maturity-group-specific growth models. This effect is due to the asymptotic growth of the von Bertalanffy model which decreases the advantage of delayed capture.

Sensitivity of Yield-Per-Recruit to Hooking Mortality

The sensitivity of yield per recruit to the level of hooking mortality is best illustrated by the response surface of yield per recruit as a function of size limit and hooking mortality with the fishing mortality rate held constant. The response surface computed for $F = 0.055$ is shown in Figure 22. Hooking mortality is assumed to be constant at all fish lengths. Also shown on the response surface is a curve showing the size limits at which yield is maximized for a given value of hooking mortality. The points along this optimum size limit curve, representing pairs of hooking mortalities and corresponding optimum size limits,

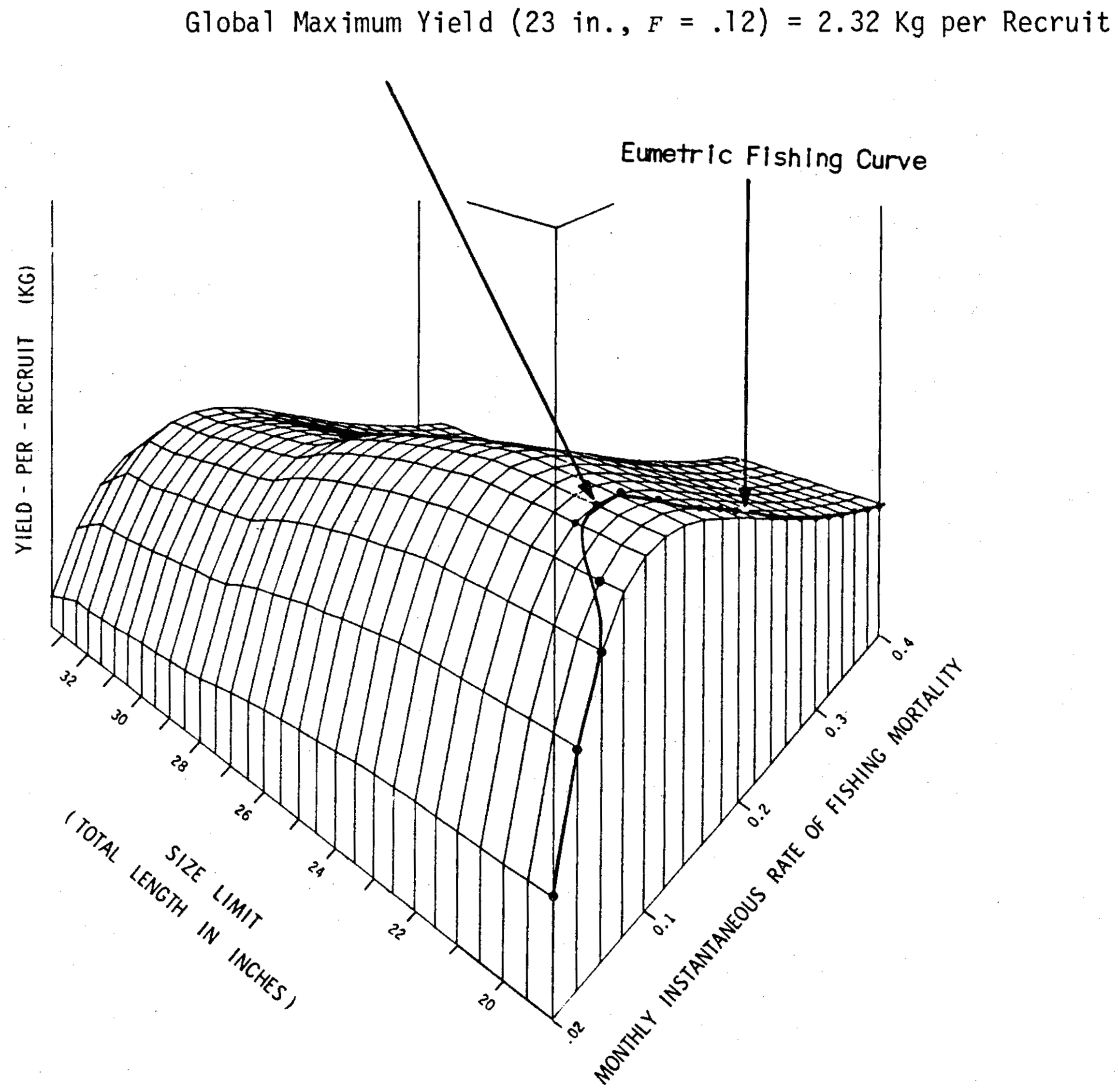

Figure 17. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and instantaneous fishing mortality, assuming severe size-related hooking mortality corresponding to 65% mortality for 26.5-inch fish.

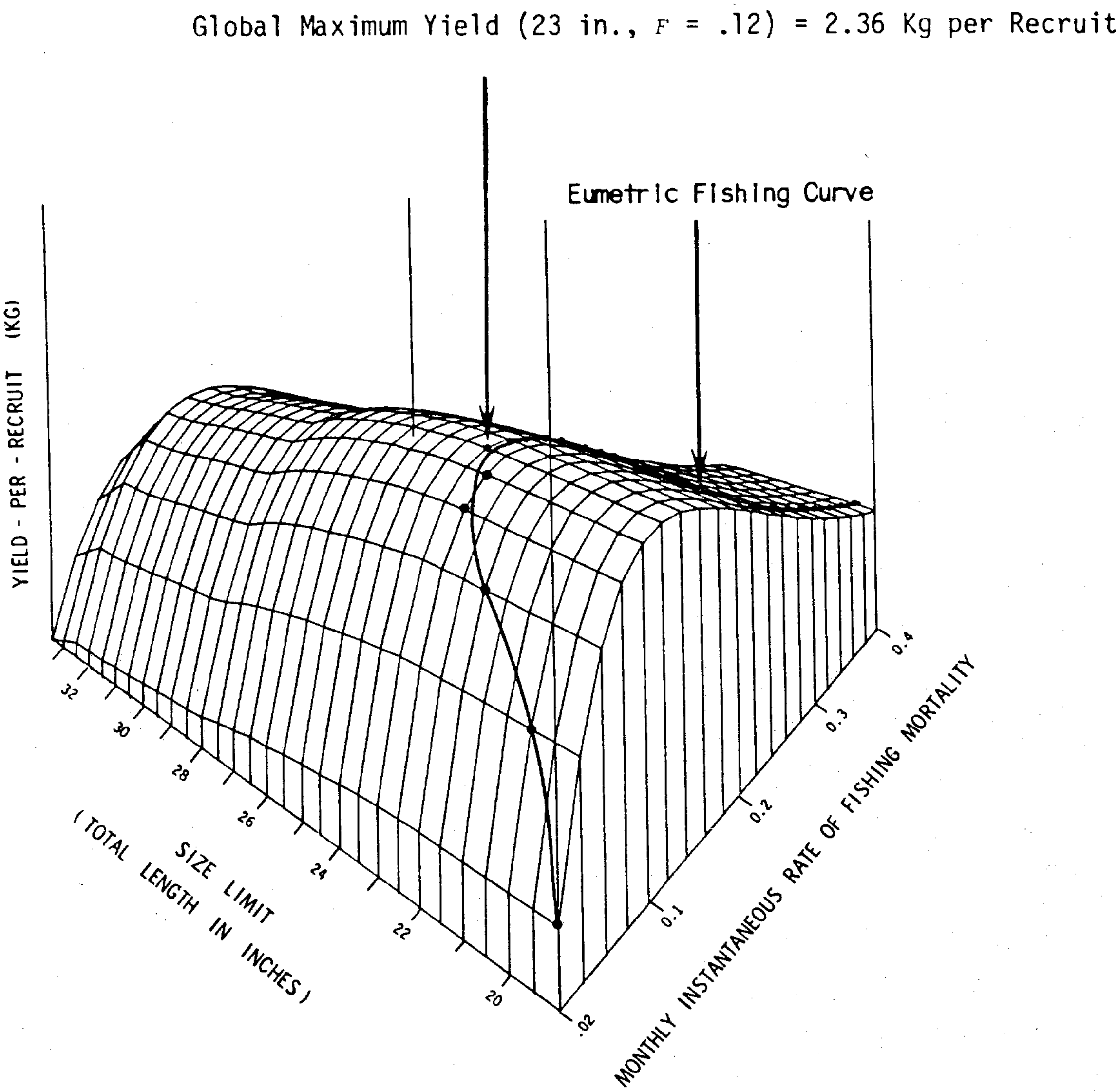

Figure 18. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and instantaneous fishing mortality, assuming a constant 50% hooking mortality for all sizes of sublegal fish.

Global Maximum Yield (30.5 in., F = 0.22) = 3.22 Kg per Recruit

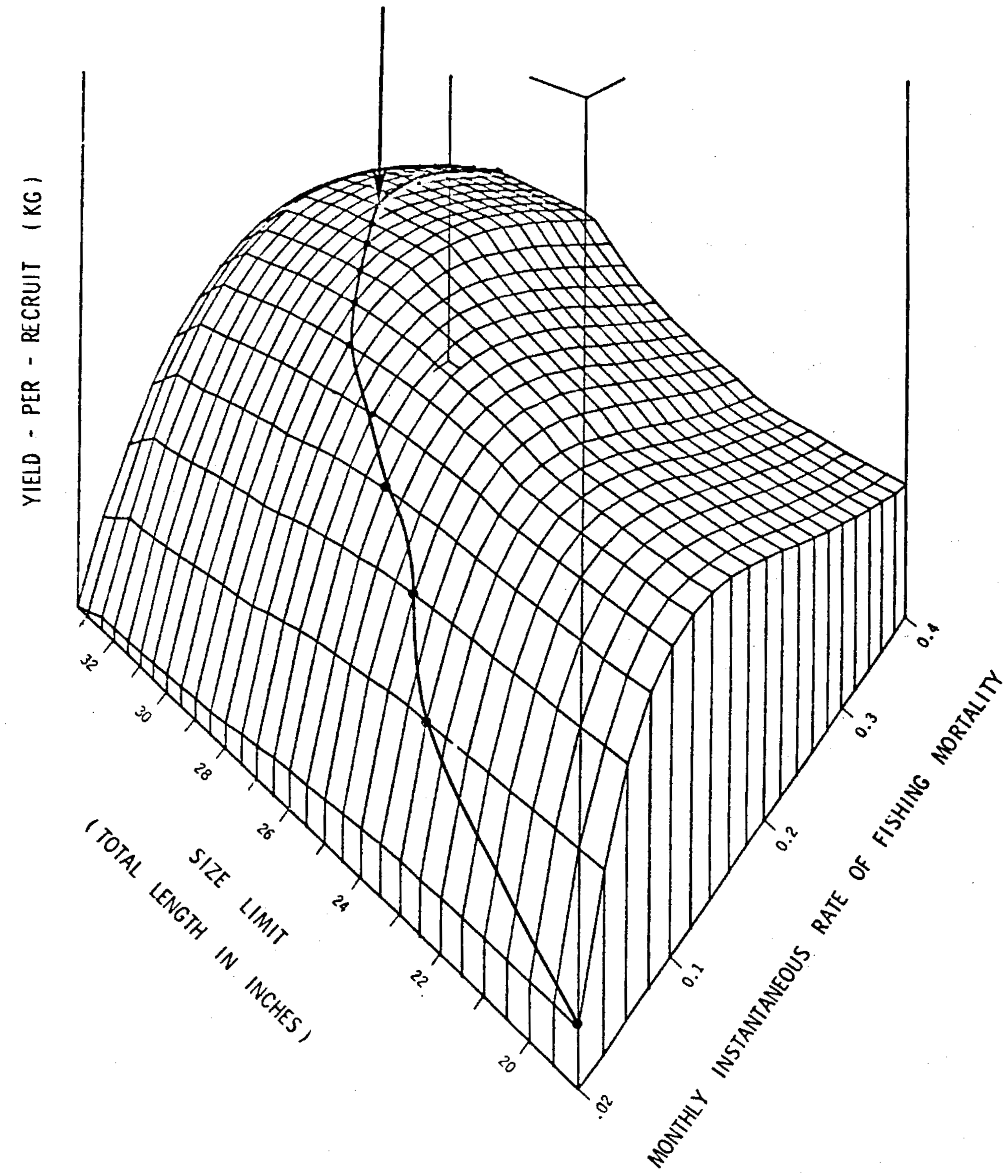

Figure 19. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and instantaneous fishing mortality, assuming low inversely size-related fishing mortality corresponding to 15% mortality for 26.5-inch (total length) fish.

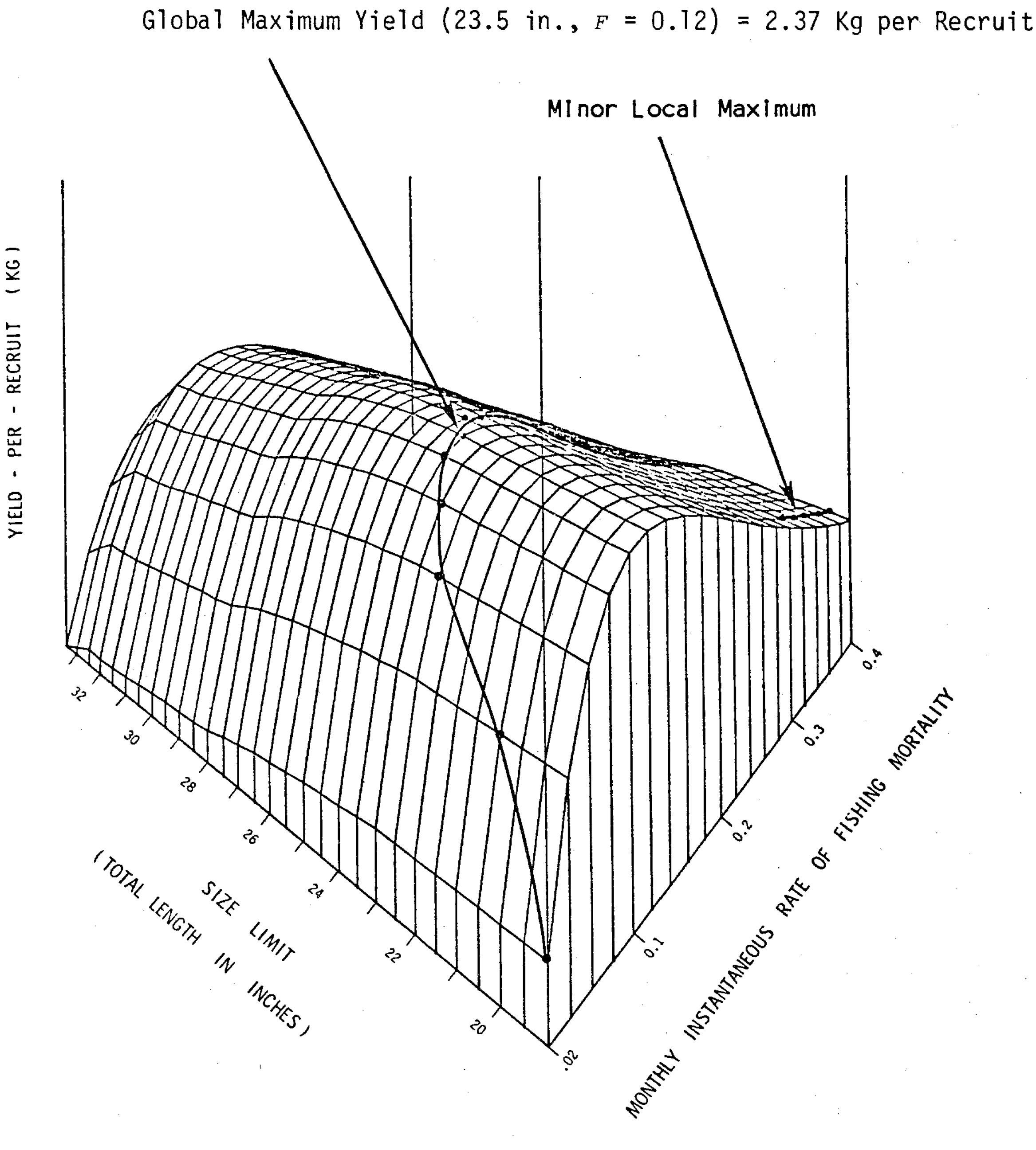

Figure 20. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and instantaneous fishing mortality, assuming intermediate inversely size-related fishing mortality corresponding to 40% mortality for 26.5-inch (total length) fish.

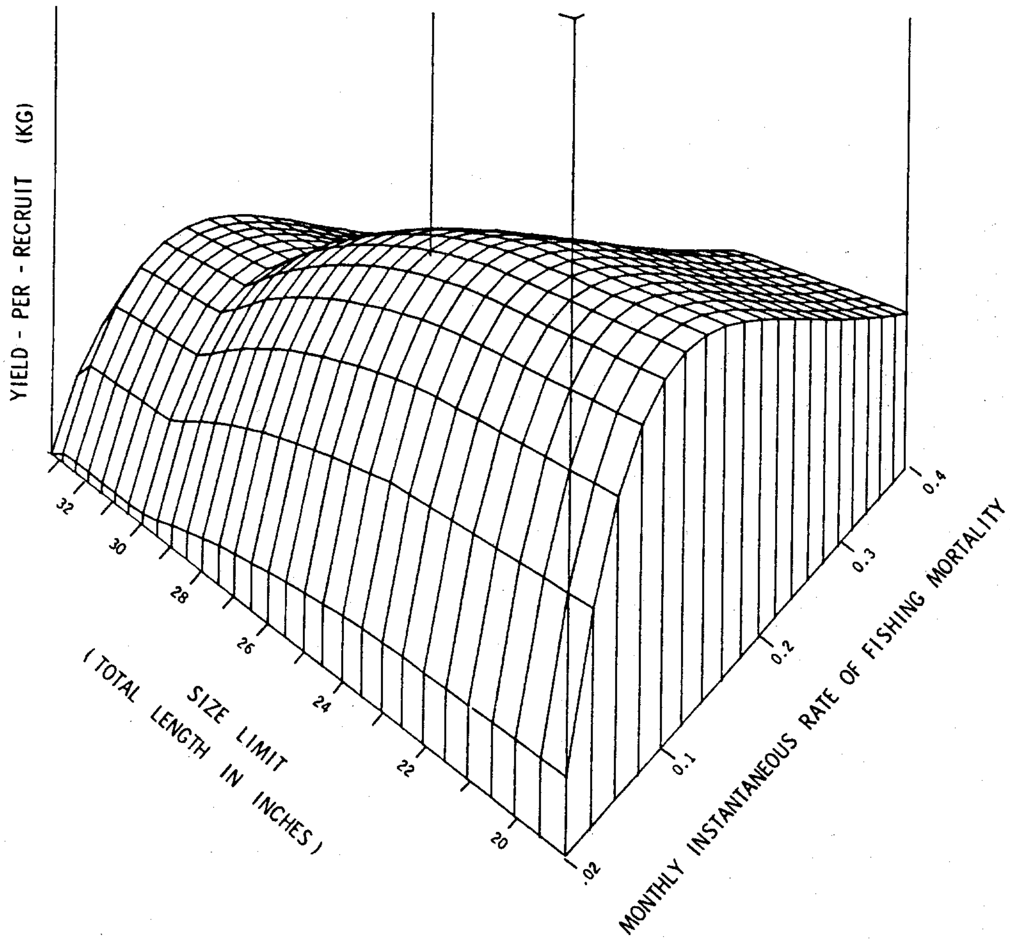

Figure 21. Yield-per-recruit response surface computed using Henry's (1972) von Bertalanffy growth function, a constant 0.00833 monthly instantaneous natural mortality and a constant 50% hooking mortality for all sizes of sublegal fish.

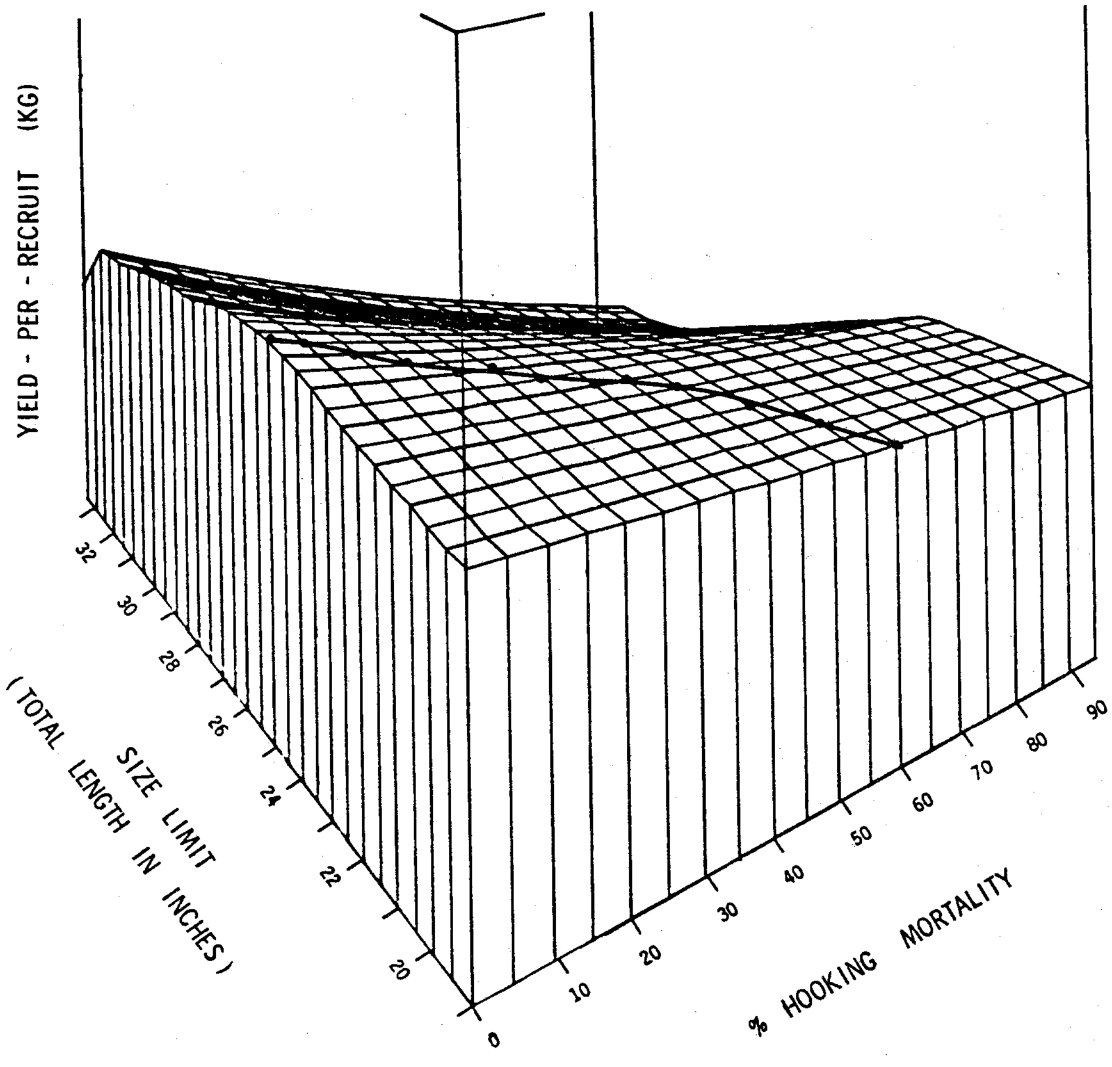

Figure 22. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and hooking mortality with monthly instantaneous fishing mortality held constant at 0.055.

are depicted in 2-dimensional space in Figure 23. This curve slopes downward from an optimum size limit of 25 inches with no hooking mortality to an optimum size limit of 19 inches at 60% hooking mortality. Also shown in Figure 23 are the values of yield per recruit obtained as a function of hooking mortality, using the optimum size limit curve and a constant 28-inch size limit. Yield per recruit with optimum size limits declines steeply with increasing hooking mortalities when hooking mortality is low and appears to approach an asymptote at higher levels of hooking mortality. Yield per recruit with a fixed 28-inch size limit decreases almost linearly as hooking mortality increases. The response surface computed for $F = 0.10$ is shown in Figure 24. The optimum size limit curve (Figure 25) slopes downward in an almost linear fashion from an optimum size limit of 29 inches at 0% hooking mortality to an optimum size limit of 19 inches at 65% hooking mortality. With no hooking mortality and the corresponding 29-inch optimum size limit, yield is 39% higher than when hooking mortality is 60% and the 20.5 inch optimum size limit is used. The constant 28-inch size limit results in a 17% reduction in yield compared to the optimum size limit at 60% hooking mortality and almost no reduction yield from the optimum size limit at 0% hooking mortality.

The yield response surface at $F = 0.20$ (Figure 26) slopes downward more severely than at $F = 0.10$, both with respect to decreasing size limit and increasing hooking mortality. Optimum size limits are somewhat larger at very low levels of hooking mortality, and decline to slightly smaller sizes at higher levels of fishing mortality (Figure 27). At 60% hooking mortality, yield with a 28-inch size limit is reduced 16% below that which would be obtained with the optimum 19-inch size limit for this level of hooking mortality.

Landed Value-Per-Recruit for all Maturity Groups

Since chinook salmon prices increase with size, landed value-per-recruit response surfaces tend to show somewhat larger optimum size limits. The response surface of landed value using the low size-related hooking mortality function (Figure 28) is similar in form to the corresponding yield-per-recruit surface at low hooking mortality (Figure 15), except that the optima are more pronounced. The global maximum occurs at the same 30-inch size limit, but at a slightly lower fishing mortality rate of 0.26. At moderate hooking mortality the landed value global maximum (Figure 29) shifts up to a size limit of 27.5 inches from the 25 inches of the corresponding yield maximum. Other features of the value response surface are similar to the yield response surface. At severe hooking mortality the landed value global maximum (Figure 30) occurs at 23 inches with a fishing mortality rate of 0.10 compared to 20.5 inches at 0.12 for the yield global maximum.

Effects of Gear Restrictions to Reduce Hooking Mortality

The Icy Strait Tagging Study demonstrated that certain types of trolling gear may reduce the mortality of undersize fish which are hooked and must be released. Some types of trolling gear may also be size-selective and thus reduce the number of strikes by small fish. While the latter method in effect alters the age of recruitment to the fishery, either effect can be approximated by examining yield per recruit for reduced levels of hooking mortality, $H(L)$, in model.

For example, the Icy Strait Tagging Study indicates that there would be a 5.9% reduction in hooking mortality if only treble hooks were used in the fishery,

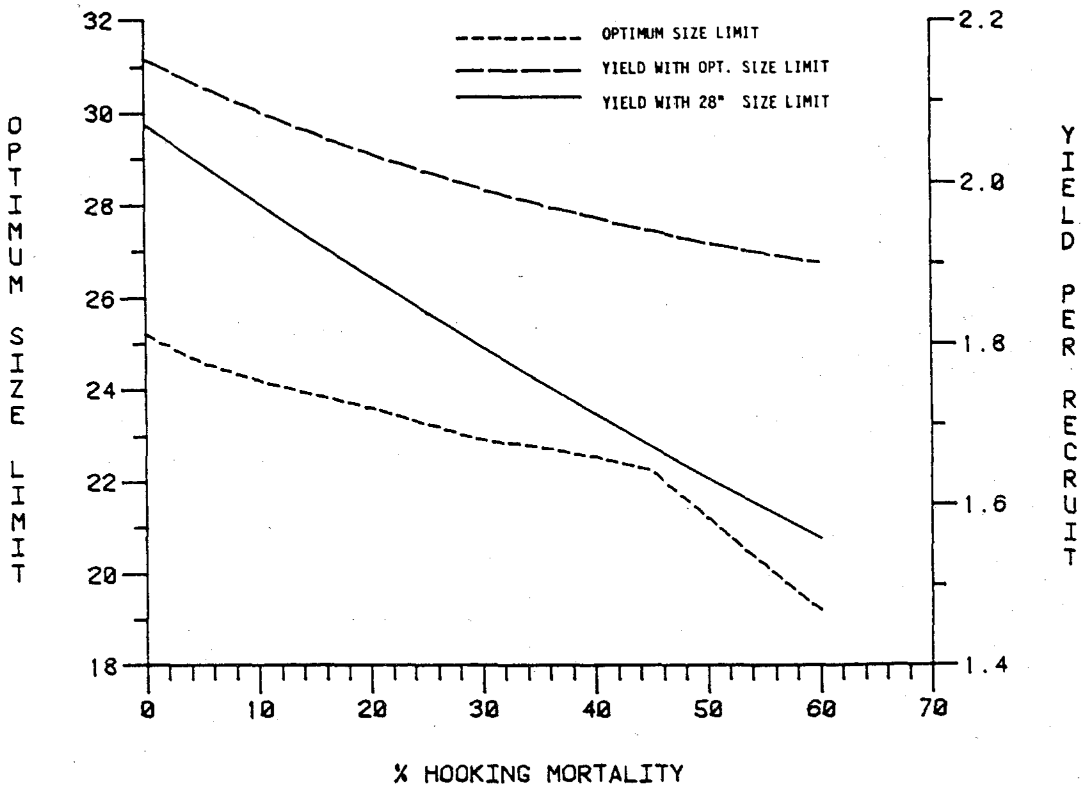

Figure 23. Optimum size limit (left ordinate) and yield per recruit using the optimum size limit and a 28-inch size limit (right ordinate) as functions of hooking mortality with the monthly instantaneous rate of fishing mortality held constant at 0.055. The optimum size limit curve contains the pairs of points lying along the maximum yield line indicated on the response surface in Figure 20. The optimum yield curve is a projection of the maximum yield line of Figure 20 onto the hooking mortality-yield plane. The yield at 28 inches is a projection of the yield values along the 28-inch grid line of Figure 20 onto the hooking mortality-yield plane.

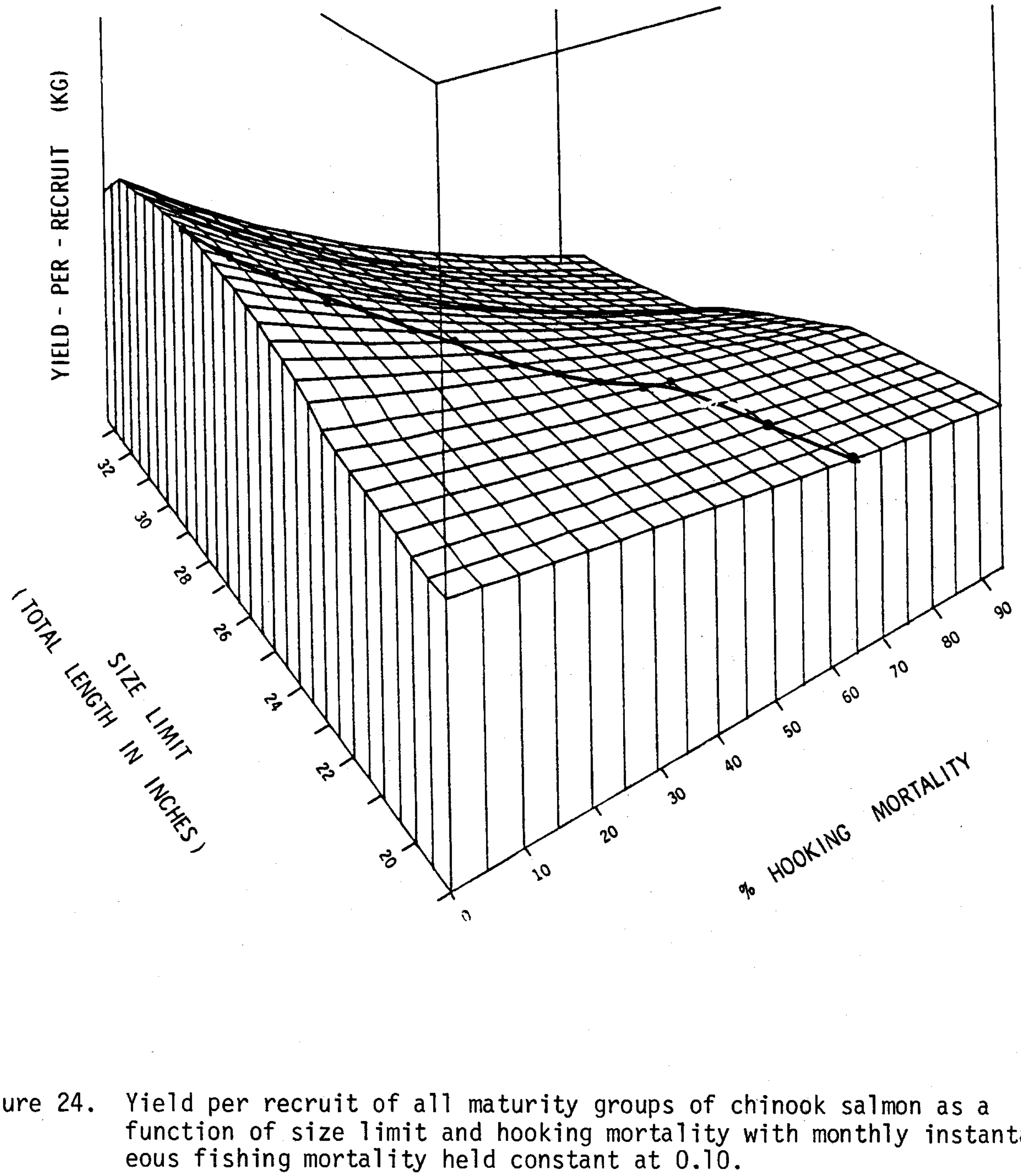

Figure 24. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and hooking mortality with monthly instantaneous fishing mortality held constant at 0.10.

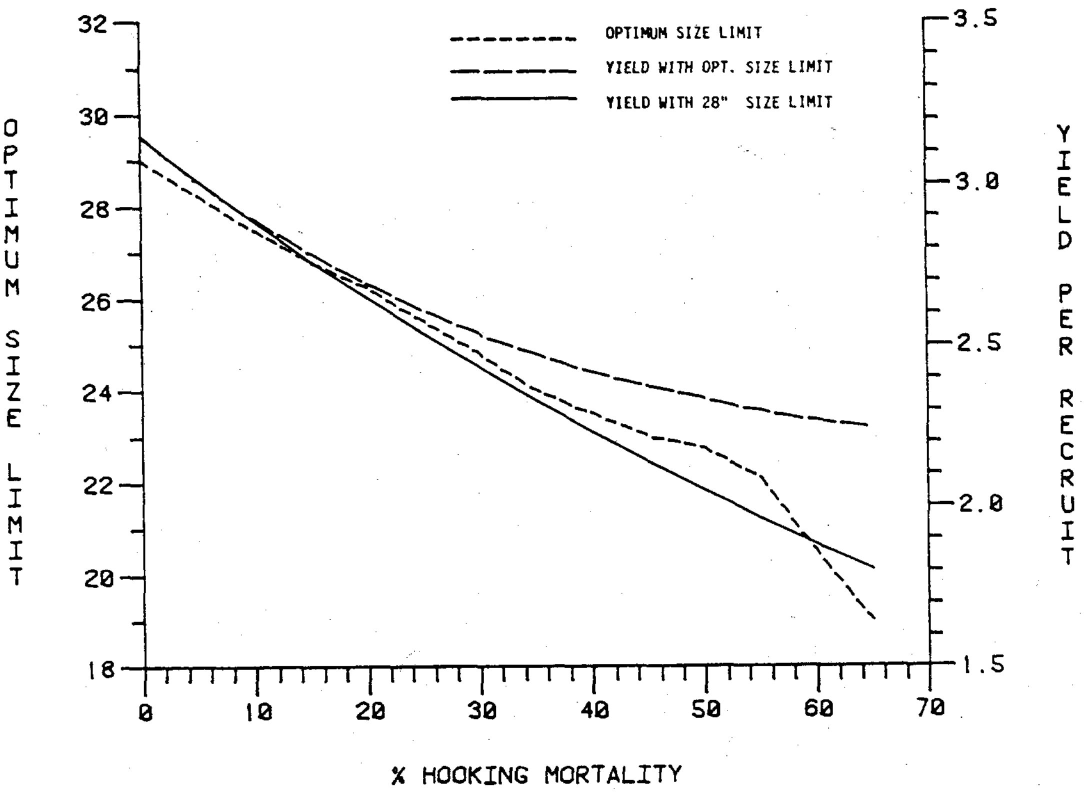

Figure 25. Optimum size limit (left ordinate) and yield per recruit using the optimum size limit and a 28-inch size limit (right ordinate) as functions of hooking mortality with the monthly instantaneous rate of fishing mortality held constant at 0.10. The optimum size limit curve contains the pairs of points lying along the maximum yield line indicated on the response surface in Figure 22. The optimum yield curve is a projection of the maximum yield line of Figure 22 onto the hooking mortality-yield plane. The yield at 28 inches is a projection of the yield values along the 28-inch grid line of Figure 22 onto the hooking mortality-yield plane.

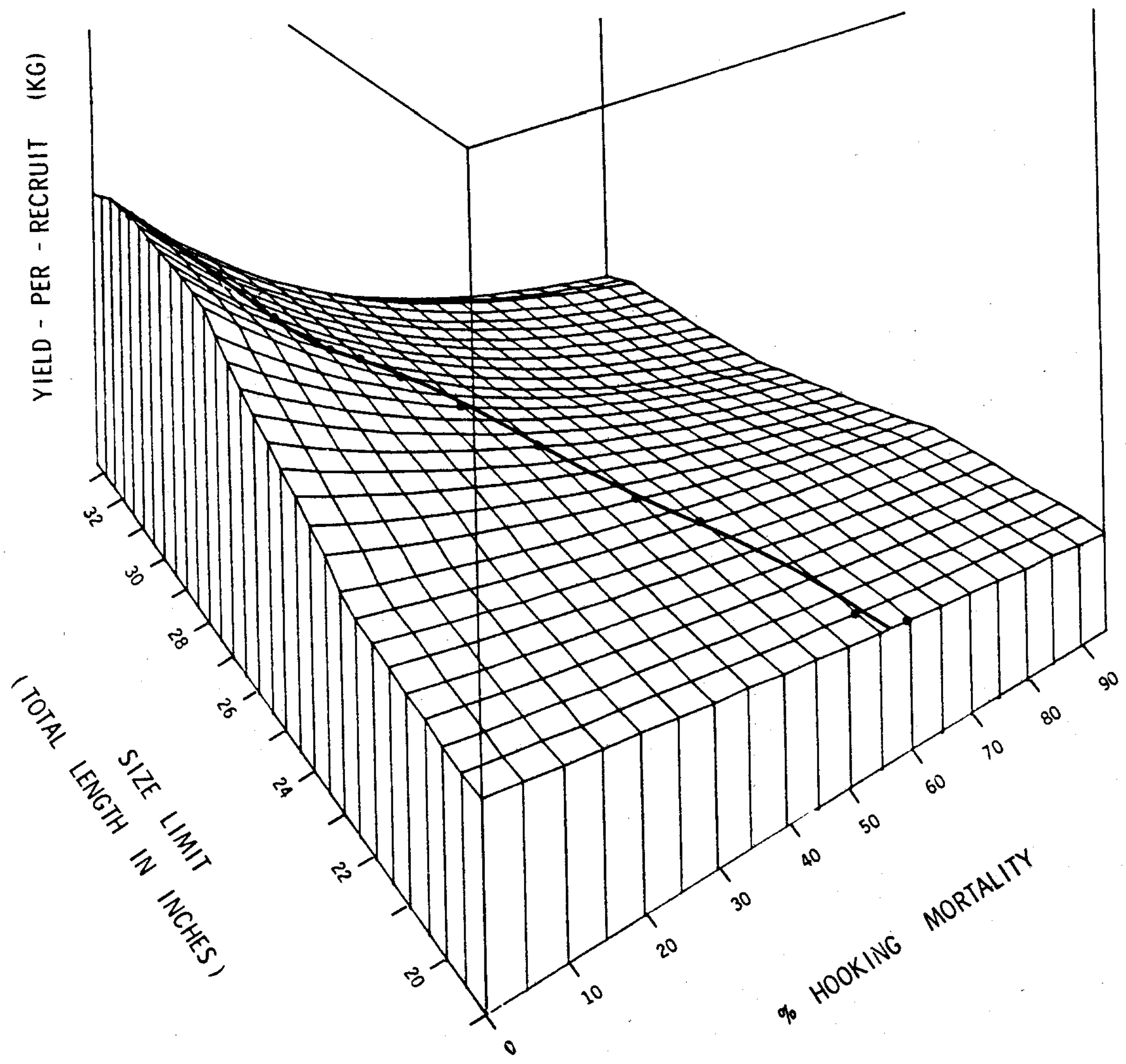

Figure 26. Yield per recruit of all maturity groups of chinook salmon as a function of size limit and hooking mortality with monthly instantaneous fishing mortality held constant at 0.20.

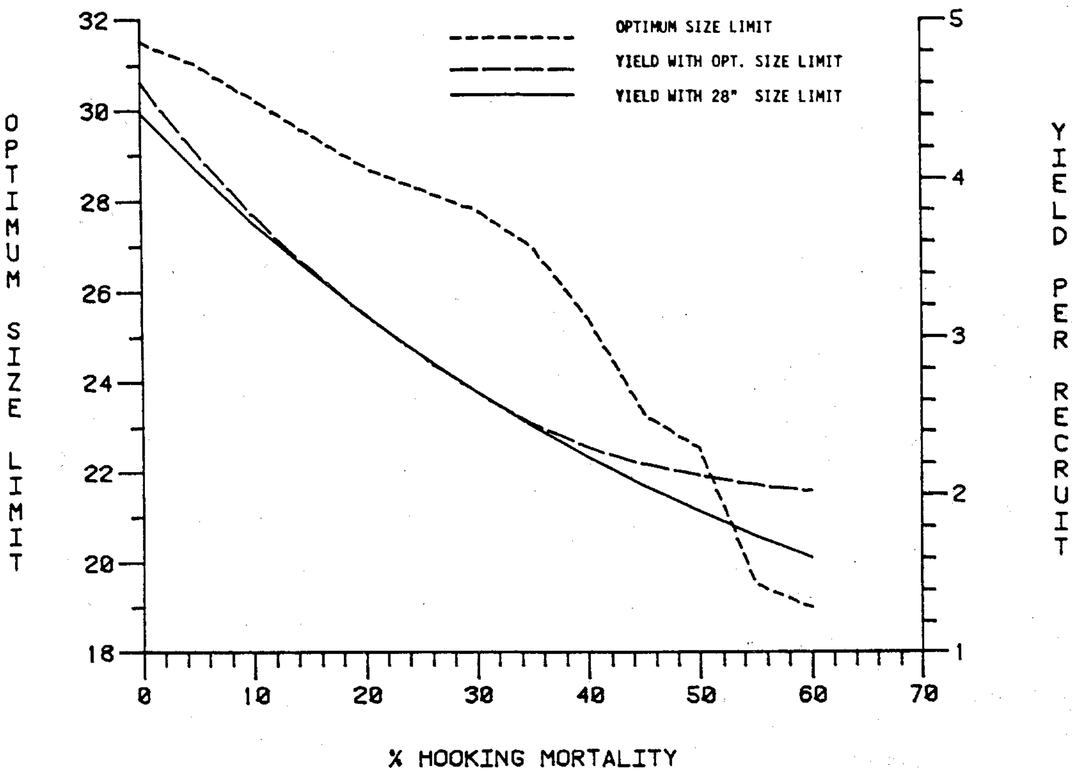

Figure 27. Optimum size limit (left ordinate) and yield per recruit using the optimum size limit and a 28-inch size limit (right ordinate) as functions of hooking mortality with the monthly instantaneous rate of fishing mortality held constant at 0.20. The optimum size limit curve contains the pairs of points lying along the maximum yield line indicated on the response surface in Figure 24. The optimum yield curve is a projection of the maximum yield line of Figure 24 onto the hooking mortality-yield plane. The yield at 28 inches is a projection of the yield values along the 28-inch grid line of Figure 24 onto the hooking mortality-yield plane.

Global Maximum Value (30 in., F = .26) = $10.17 per Recruit

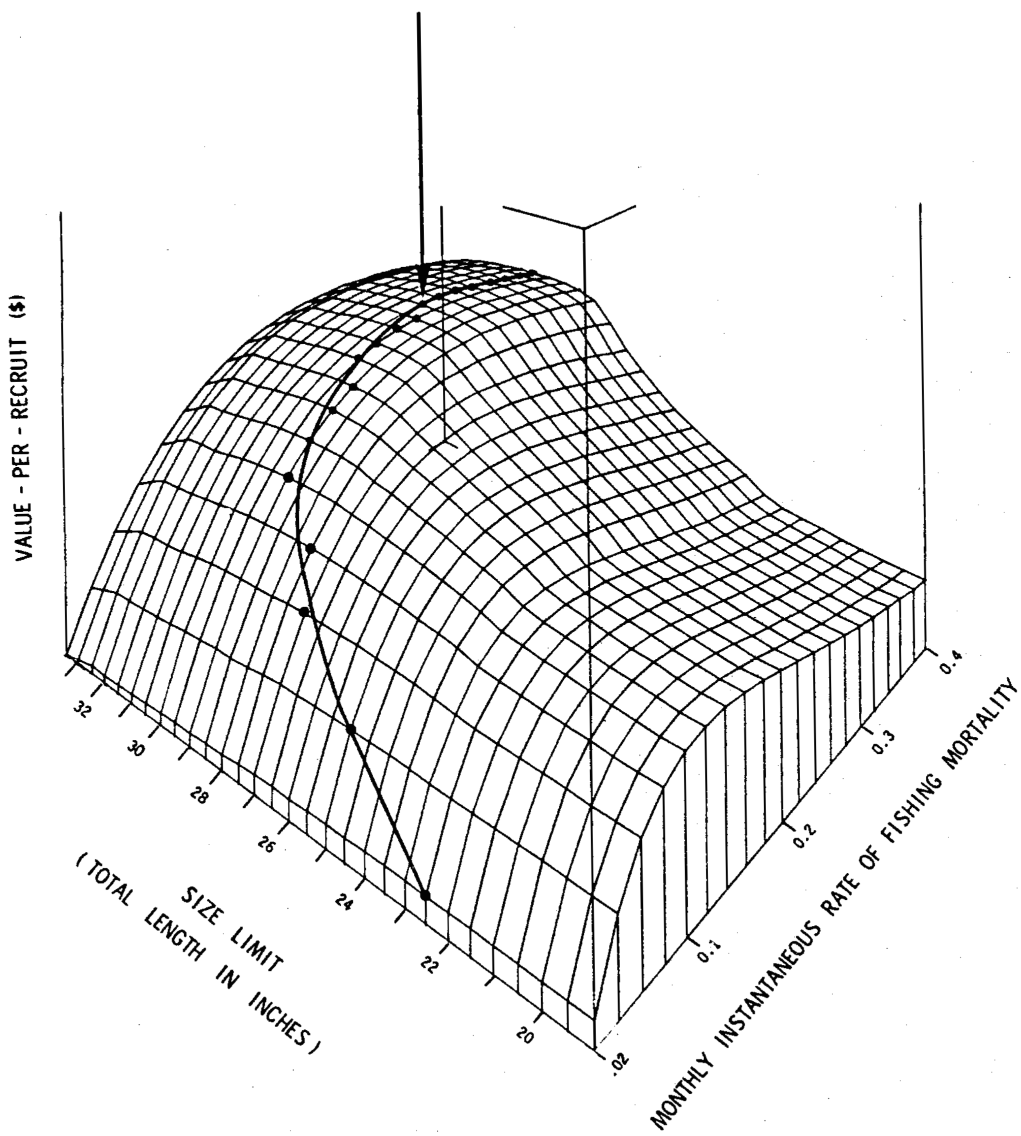

Figure 28. Landed value-per-recruit response surface for all maturity groups of chinook salmon, assuming low size-related hooking mortality corresponding to 15% for 26.5-inch fish.

Global Maximum Value (27.5 in., F = .14) = $6.56 per Recruit

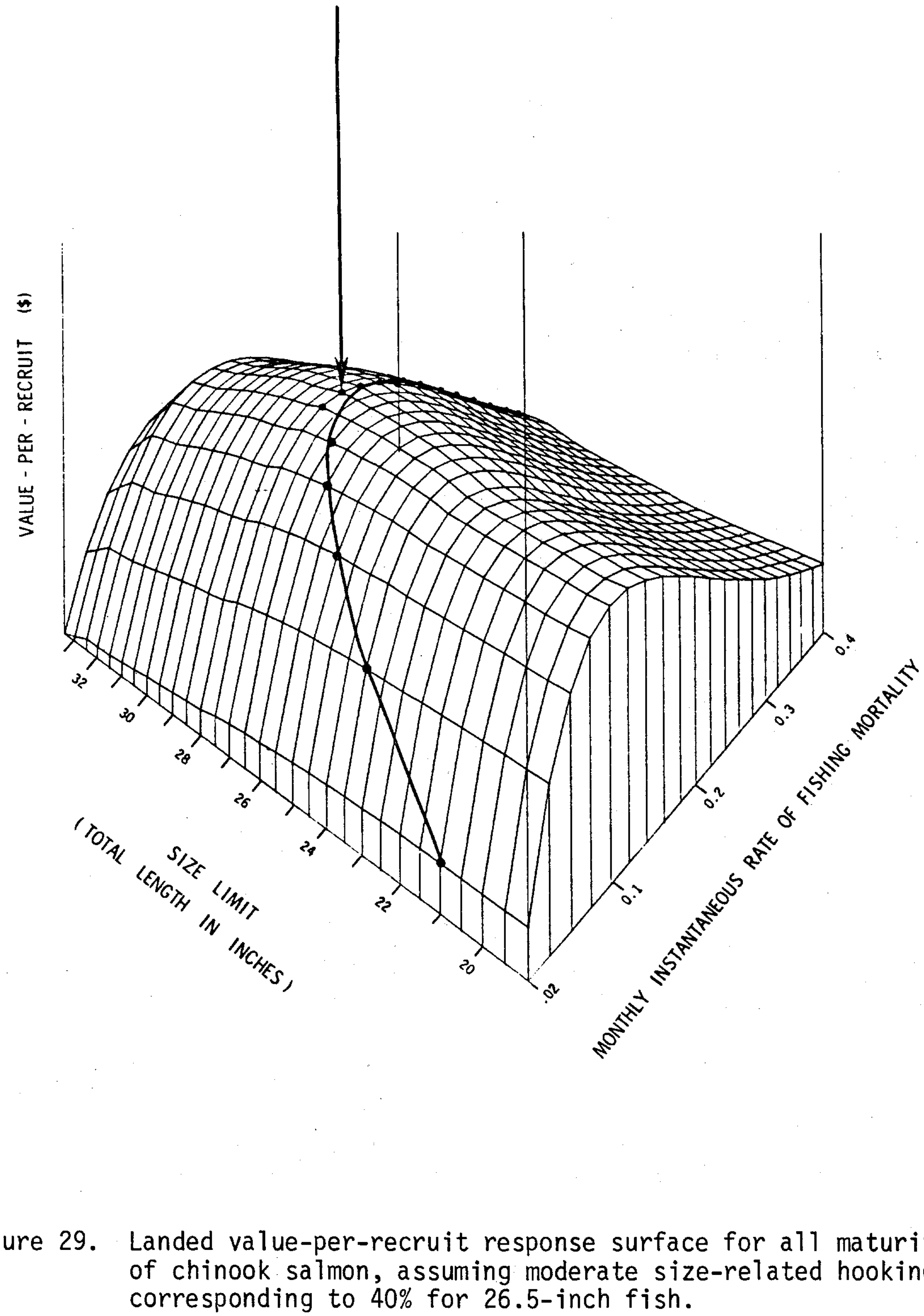

Figure 29. Landed value-per-recruit response surface for all maturity groups of chinook salmon, assuming moderate size-related hooking mortality corresponding to 40% for 26.5-inch fish.

Global Maximum Value (23 in., F = .10) = $5.45 per Recruit

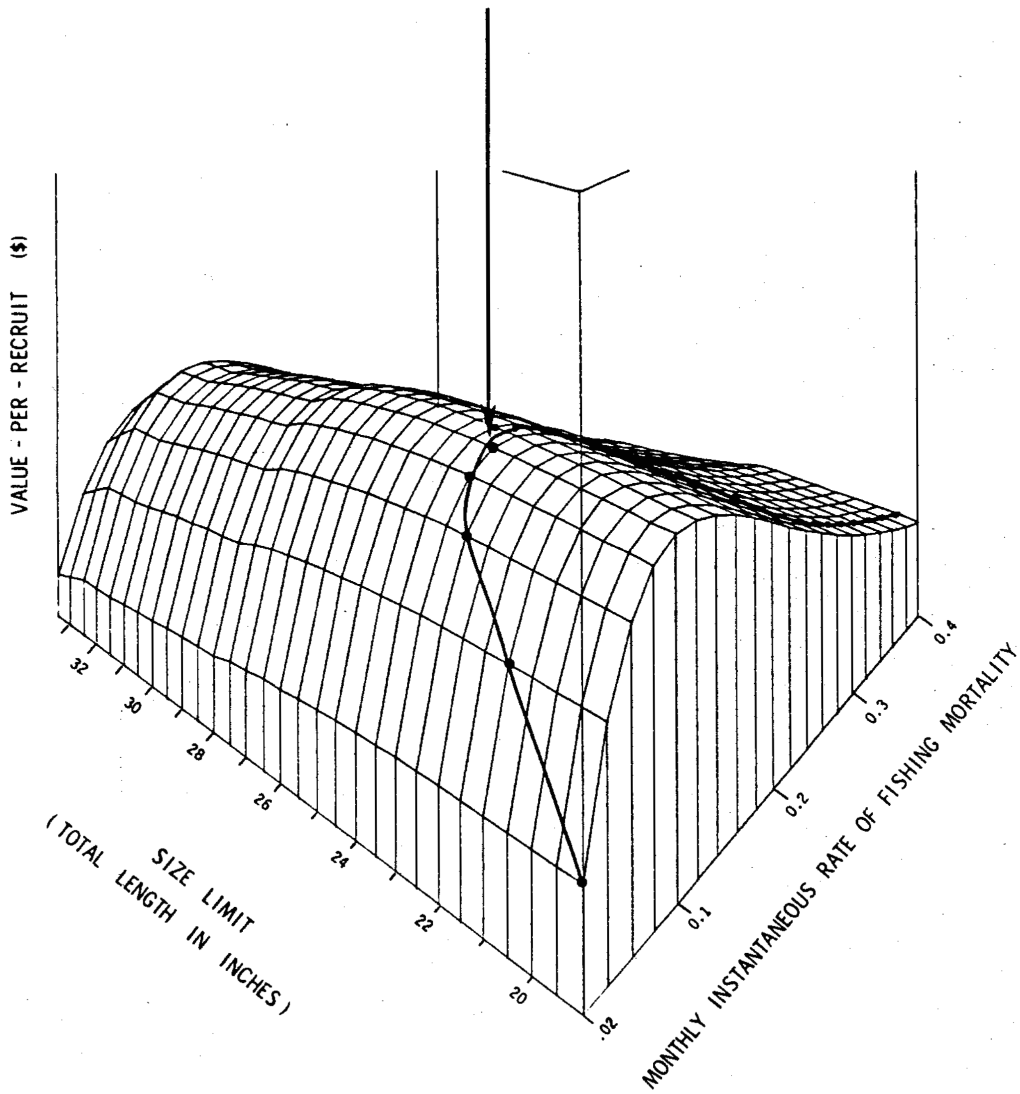

Figure 30. Landed value-per-recruit response surface for all maturity groups of chinook salmon, assuming severe size-related hooking mortality corresponding to 65% for 26.5-inch fish.

compared to a 50:50 ratio of single and treble hooks. The effects of a 5% reduction in hooking mortality on yield are illustrated in Figure 31. Hooking mortality is assumed to be a constant percentage over all fish sizes in these comparisons. With a constant 28-inch size limit, the yield increases are almost constant for all levels of hooking mortality and the results appear as horizontal lines in Figure 31. With a monthly instantaneous fishing mortality rate of 0.20, the increase in yield is approximately 8%. When the fishing mortality rate is 0.10 the increase in yield is only 4%. When optimum size limits for a given level of hooking mortality are used, the percentage gain in yield decreases with increased hooking mortality. At $F = 0.20$, yield increases 10.5% when hooking mortality is only 5%, but yield increases just 2% at 60% hooking mortality. At $F = 0.10$ the percentage gains in yield are lower and decrease more slowly, ranging from 4.5% to 1.1%.

Increases in yield from gear restrictions must be balanced against the negative impacts of the gear restrictions. Most often these negative impacts take the form of reduced CPUE of legal fish and therefore reduced yield. The yield-per-recruit model provides a means of expressing the costs and benefits of gear restrictions in the same units. For example, a gear restriction which reduces hooking mortality from 40% to 35% causes a 6.7% increase in yield when $F = 0.20$ and optimum size limits are used (Figure 31). Thus the gear restriction is only beneficial if it does not decrease the CPUE (and hence yield) of legal fish more than 6.7%. Direct comparison of percentage gains in yield from the gear restriction and percentage decreases in CPUE are possible if the relative size distribution of the catch is not affected by the gear restriction.

Some potential effects of gear restrictions on yield can be evaluated with the yield-per-recruit model, using the results of previous investigations of trolling gear. The present configuration of the model must be assumed to be appropriate for the time period and location of the study. For example, Butler and Loeffel (1972) studied mortality rates of chinook salmon caught with barbed and barbless single hooks. Since these experiments were performed off the Oregon coast between 1959 and 1968, O'Connor's estimates of growth, maturity, and mortality parameters from the 1963-1968 fishing seasons should be applicable for a first approximation. Butler and Loeffel (1972) estimated immediate hooking mortalities from short-term observations of captured fish in on-board holding tanks. Delayed mortality estimates for fish which survived the immediate mortality were derived from tag recoveries. An immediate mortality of 8.0% for barbed hooks was estimated followed by delayed mortality of 7.3% for a total of 15.3% mortality. Using the yield-per-recruit model with the 26-inch size limit which was in effect in 1969, an instantaneous monthly fishing mortality of 0.055, and a 15.0% hooking mortality, yield per recruit is estimated by the model to be 2.0333 kg. For barbless hooks, an immediate mortality of 6.1% followed by a delayed mortality of 6.9% was estimated. Yield per recruit at 13.0% hooking mortality is estimated to be 2.0553 kg, an increase of only 1.1%. However, the CPUE of legal-sized fish using barbless hooks was 5% lower than the CPUE with barbed hooks. Net yield from the fishery would thus be reduced 3.9% by a gear restriction requiring the use of barbless hooks. Using an alternative methodology, Butler and Loeffel estimated that the use of barbless hooks would result in a change in landed value to the fishery ranging from a net loss of $33,500 to a net gain of $4,500. Using their estimates of the 1969 total Oregon catch, the weight distribution of the catch, and the 1969 price structure, it is estimated that this range corresponds

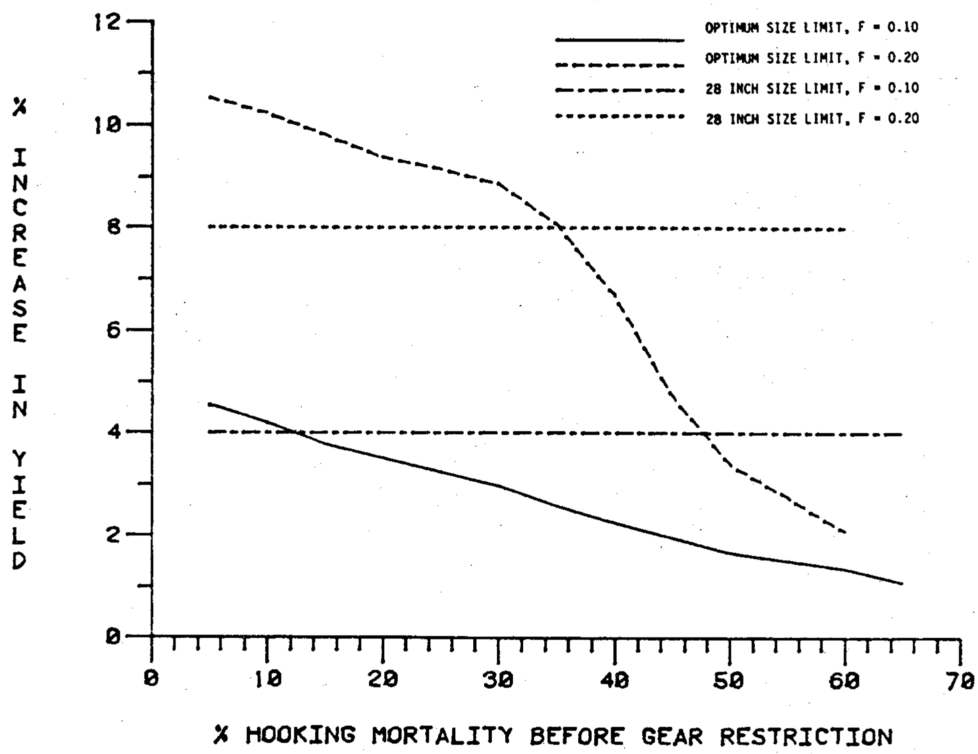

Figure 31. Increase in yield resulting from a 5% reduction in hooking mortality, as a function of hooking mortality prior to the reduction at various combinations of size limits and fishing mortalities.

to a net change in yield ranging from -3.9% to +0.52%. Thus the yield-per-recruit estimate is identical to the lower end of this range.

Boydston (1972) performed an experimental comparison of the CPUE of plugs, spoons, hootchies, and bait in the California troll fishery. Plugs were found to catch only 15% as many shakers as other lure types. However, plugs reduced the CPUE of legal-sized fish approximately 50%. Since the experiments were conducted in 1969, O'Connor's (1977) parameter estimates can again be used in the yield-per-recruit model for a reasonable approximation. Assuming a hooking mortality of 30%, an instantaneous monthly fishing mortality rate of 0.055 and the 26-inch size limit which was in effect at the time of the study, yield per recruit is estimated at 1,9274 kig. Reducing hooking mortality by 85% to 4.5% results in a yield-per-recruit estimate of 2.1111, a 9.5% increase. However, the plugs-only restriction would have reduced CPUE by 50% and net yield to the fishery would have decreased by 40.5%. If F were assumed to be 0.10, net yield would have decreased by 32% and if F were as high as 0.20, net yield would have declined only 12%. The assumption that the gear restriction to plugs only would not change the size distribution of the legal catch is necessary to directly compare CPUE changes to yield changes. This assumption is violated to some degree in this case since size selectivity has been demonstrated for plugs (Milne 1955; Pitre 1970).

Pitre (1970) performed a similar comparison of plugs, spoons, and flasher gear types in the Canadian troll fishery. Plugs caught from 16% to 31% as many shakers as the other gear types and 68% to 86% as many legal chinooks. Plugs actually caught 15% more legal fish than flasher gear in one experiment. Assuming a 75% reduction in hooking mortality from 30% to 7.5%, a 25% reduction in legal CPUE, an initial F of 0.055, and a 26-inch size limit, restriction to plugs only would cause a 17% decrease in net yield. At $F = 0.10$, net yield would decrease 9% and at $F = 0.20$, net yield would increase 8%.

Evaluating the Effects of Time-Area Closures

Parker (1960) recommended that time-area closures in areas with high proportions of immature chinook should be explored as an alternative to size limits for increasing yield per recruit. Little direct data on immature-to-mature ratios has been collected from the fishery to date. However, with the inception of a voluntary logbook program in 1976, a source of undersize chinook catch rate data became available. Records from the Alaska Trollers Association Troll Logbook Program provide the only large sample of direct observations on undersize chinook occurrence for Southeastern Alaskan waters. The logbook records contain relatively precise information on location of capture and the amount of effort expended. Assuming that CPUE computed from the logbook records is approximately proportional to fish density, spatial and temporal variation in shaker distributions can be examined. Projections from logbook records can only be used in conjunction with the current 28-inch size limit.

Funk (1981) reports significant spatial and temporal variation in shaker CPUE computed from the logbook records. Shaker CPUE was highest during late June and early July in most areas. The Clarence Strait and Fairweather Inner Bank logbook areas had higher shaker CPUE than other areas in all three years examined. Similar results were reported in an examination of 1976 and 1977 logbook records by Fried (1977). Thorsteinson (1981) examined shaker sublegal-to-legal ratios and also found substantial spatial and temporal variation. While it is obvious that some benefits would accrue from the closure of areas having high shaker densities, the magnitude of the effects of closures on yield from the fishery have not been determined. The yield-per-recruit model provides a conceptual framework for evaluating the effects of time-area closures.

With the current 28-inch size limit, shakers consist primarily of 2-year-old fish from all maturity groups and 3-year-old fish from maturity groups 4 and 5 (Figure 1). Closure of an area with high shaker density would shift fishing effort into areas where these 2 and 3 year olds are less abundant. The 2 and 3 year olds thus become less fully recruited to the fishery. This effect can be modeled by reducing the gear selectivity coefficients for these age classes, thus reducing their instantaneous fishing mortality rate. The magnitude of this reduction can be estimated from the spatial distribution of shaker CPUE and from the spatial distribution of effort in the fishery.

Average shaker CPUE during the three-year period 1977-1979 for each of 10 logbook fishing areas (see Figure 32) is shown in Table 5. Shaker CPUE is computed in standardized units of catch per hour and is adjusted for the effects of targeting on coho late in the season by methods given in Funk (1981). The Cape Spencer and Fairweather Inner Bank areas are pooled since only one year of data from Cape Spencer contained enough observations to estimate shaker CPUE reliably. Shaker catch per hour was converted to catch per day using the season-average number of hours fished per day of 10.80 from 1977 troll logbooks (Anonymous 1979). The total effort expended in each fishing area (Table 5) is computed from average trip lengths (days fished per landing) by area from port sampling data, and from the total number of landings per area. Only power troll catch and effort is used. The ADF&G statistical areas (Figure 33) corresponding to the areas of Figure 32 are listed in Table 5. Trollers fishing in 1979 tended to report fishing in offshore areas whenever possible in order to avoid additional State tax assessments. This problem only affects the effort estimates for areas 157 and 181 in the present summary scheme. Due to this effort-reporting problem, 50% of the effort reported in area 157 (Fairweather Outer Banks) is applied to area 181 (Fairweather Inner Banks). The estimated numbers of shakers caught in the entire power troll fishery is then computed from the catch-per-day and total days fished for each area.

The effect of an area closure is simulated by assuming that effort would move out of the closed areas into other areas in proportion to the amount of effort already in those areas. The total number of shakers caught is then recomputed using the CPUEs from the remaining open area and the new effort distribution. Given the total number of shakers caught with and without the closure C_1 and C_2, the natural mortality rate M, and the fishing mortality rate F, the magnitude of the gear selectivity coefficient, G, required to represent the reduced recruitment of 2 and 3 year olds with the new effort distribution can be estimated from the catch equation

$$\frac{C_2}{C_1} = \frac{\frac{GF}{(GF+M)}\;[N_o(1 - e^{-(GF+M)t})\,]}{\frac{F}{(F+M)}\;[\,N_o(1 - e^{-(F+M)t})\,]} \quad .$$

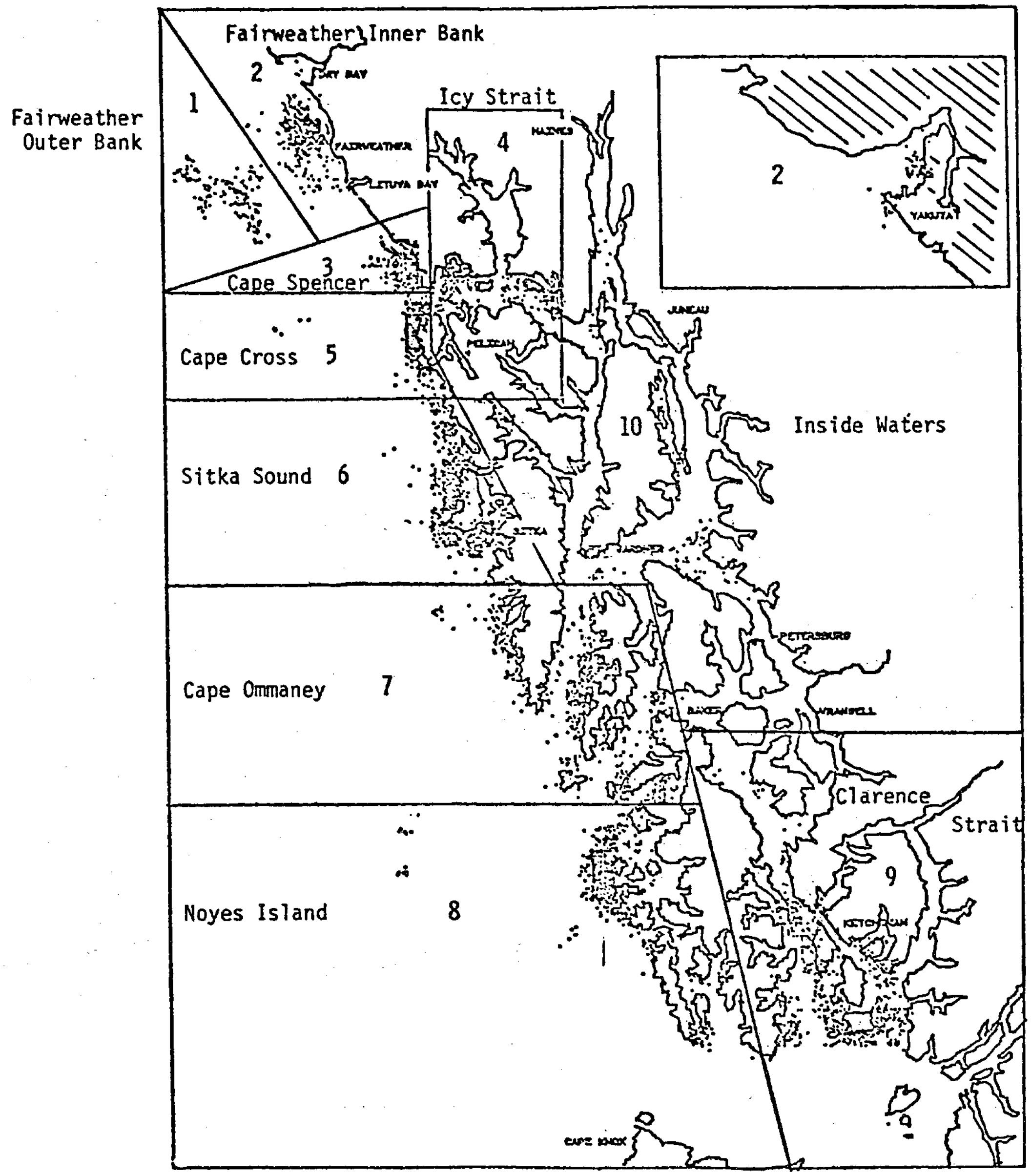

Figure 32. Logbook fishing areas and trolling locations reported in the 1977 troll logbooks. Each dot represents the location of one day of fishing effort.

Table 5. Estimates of power troll effort and shaker catch by area. Shaker catch/hour is derived from 1977-1979 logbook records. Average trip lengths are derived from port sampling data and the numbers of landings are from ADF&G fish ticket summaries.

		Trip Length (Pt. Sampling)		1979 Fish Ticket			
Logbook Area	3 yr. avg. Catch/hour	Pt. Samp. Area	Avg. Days	Areas	Landings	Total Days Fished	Estimated Shaker Catch
1	.03	1	6.184	157;189	159	984	319
2,3	.37	1	6.184	116; 181;183	256	1,584	6,330
4	.28	4	1.877	114	456	856	2,586
5,6	.25	2	4.936	113;154	7,725	38,131	102,954
7	.25	2	4.936	105;109	847	4,181	11,289
8	.17	3	4.936	103; 104;152	2,729	13,470	24,731
9	.52	6	4.639	101; 102;150	681	3,159	17,741
10	.25	4,5	3.010	106;107;108 111;112;115	649	1,953	5,273
Totals:					14,045	67,675	184,642

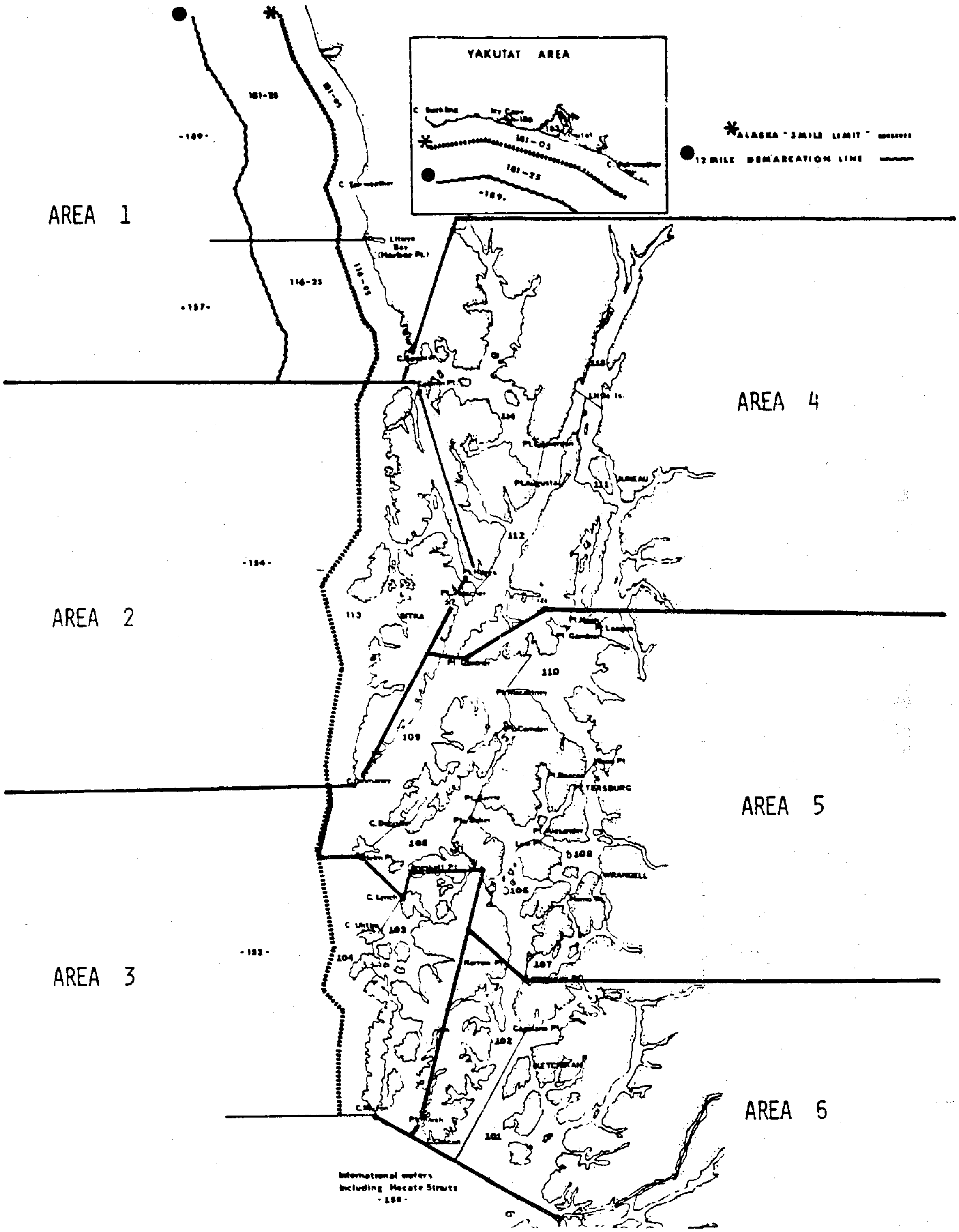

Figure 33. Alaska Department of Fish and Game statistical areas 101 to 189 and port sampling summary areas 1 to 6.

Table 6. Effect of the closure of several high shaker density areas on yield from the power troll fleet.

	ADFG STATISTICAL AREAS CLOSED		
	None	116,181,183	116,181,183 101,102,150
Boat days transferred out of closed areas	0	4,942	8,101
Unaffected boat days	67,675	62,734	59,575
Est. shaker catch	184,642	177,880	167,159
% decrease in shaker catch	---	3.7%	9.5%
Reduction in gear selectivity coefficient:			
at F = 0.060	---	.959	.894
at F = 0.100	---	.955	.885
at F = 0.200	---	.944	.861
Increase in yield as a result of closure:			
at F = 0.060	---	0.7%	1.8%
at F = 0.100	---	1.3%	3.3%
at F = 0.200	---	2.9%	7.1%

$$\frac{d}{dG} = \frac{M}{(GF+M)^2} + \frac{[(GF+M)(1-GFt) - GF] \cdot e^{-(GF+M)t}}{(GF+M)^2} ,$$

Two area closure schemes are evaluated. The current 28-inch size limit is used. Closure of the Fairweather Inner Bank and Cape Spencer areas for the entire season is estimated to reduce the overall shaker harvest by only 3.7%, resulting in a gear selectivity coefficient of 0.944 - 0.959 (Table 6). According to the current configuration of the yield-per-recruit model, these closures would increase the yield from the fishery by 0.7% at a monthly instantaneous fishing mortality rate of 0.06. At a fishing mortality rate of 0.10 yield would be increased 1.3% and at a fishing mortality rate of 0.20 yield would be increased 2.9%. The Clarence Strait area consistently had the highest shaker CPUE in the logbook records for 1977-1979. Closure of this area, in addition to the Fairweather Inner Bank and Cape Spencer areas, would result in a 9.5% reduction in the number of shakers hooked. With the closure of all three of these fishing areas, yield from the fishery would increase 1.8% at a fishing mortality rate of 0.06, 3.3% at a fishing mortality rate of 0.10, and 7.1% at a fishing mortality rate of 0.20.

DISCUSSION

The current 28-inch size limit is intended to protect immature 3-year-old fish while allowing harvest of mature 3 year olds (Natural Resource Consultants 1981). However, the process of choosing an optimum size limit is much more complex than merely choosing the size limit which best protects the dominant maturity group 4 throughout its second vulnerable fishing season. The chinook salmon yield-per-recruit model demonstrates that the optimum size limit is a continuous increasing function of fishing mortality rate and a continuous decreasing function of hooking mortality. Since precise values for neither fishing mortality rate nor hooking mortality are known for the Alaska troll fishery, an exact optimum size limit cannot be recommended at this time. The optimum size limit changes substantially over the ranges of fishing mortalities and hooking mortalities estimated for the fishery. Based on the estimated range of monthly instantaneous fishing mortality rates of 0.055 to 0.20, a May 15 to September 20 fishing season, and a 30% to 50% range of hooking mortality, the results of the model imply that a 21 to 28-inch range of size limits would give optimum yield (Figure 34). With the more probable 0.10 fishing mortality rate and an intermediate 40% hooking mortality, the point estimate of the size limit which optimizes yield is 23.5 inches. For these point estimates, yield-per-recruit would increase 8.4% from the present yield with the 28-inch size limit.

The wide range of optimum size limits recommended from the current configuration of the model results from the relatively wide range of estimates of fishing mortality and hooking mortality rates present in the literature and implied by current troll fishery data. More precise estimates of instantaneous fishing mortality could be derived from a thorough examination of coast-wide coded wire tagging information. Estimates of total tags recovered from a given release, after expansion to correct for sampling fractions, are needed for all ocean fisheries, terminal fisheries, and escapement.

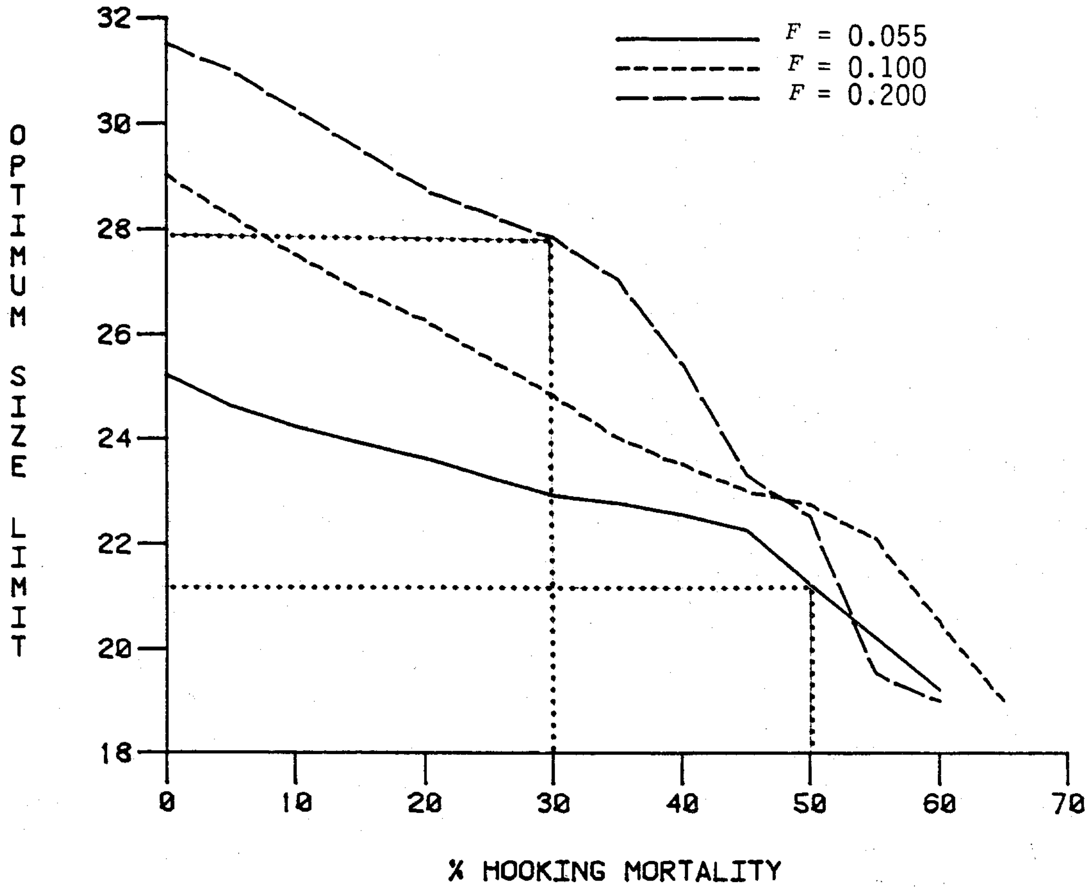

Figure 34. Summary of optimum size limits as a function of hooking mortality at three levels of fishing mortality. Also indicated is the lower bound of optimum size limits computer from 30% hooking mortality at *F* = 0.055, and the upper bound of optimum size limits computed from 50% hooking mortality at *F* = 0.20.

It will be difficult to increase the precision of hooking mortality estimates. A relatively large number of estimates of hooking mortality rates have been made for various experimental and commercial fishing conditions. The uncertainty of the hooking mortality estimate results from attempting to extrapolate from limited observations to the entire fishery in general.

Refined estimates of the instantaneous natural mortality rate are not likely to increase the precision of the optimum size recommendations. Estimates of annual natural mortality rates for age 2+ salmon in the ocean are 1/2 to 1/8 of the estimates of fishing mortality rates. As a result, yield per recruit appears to be relatively insensitive to the level of natural mortality.

Size limits may have an additional positive effect on yield by deterring trollers from fishing in high shaker-density areas. Even if a number of large fish are available for harvest in a given area, the presence of shakers effectively reduces CPUE. Trolling lines must be run more often to remove shakers and to replace bait deteriorated by shaker strikes. As a result, fewer hooks are actively fishing per unit time. A mechanism describing this deterrent effect can easily be incorporated into the yield-per-recruit model. The deterrent effect will effectively shift some proportion of fishing effort from the high shaker density areas to areas where age-2 and 3 fish are less fully recruited. A mechanism similar to that used to compute the effect of a time area closure can be utilized. While it would be difficult to estimate the proportion of effort that would voluntarily shift out of the high shaker density area, the sensitivity of yield per recruit to the deterrent effect could be evaluated.

The model results predict increases in yield of from 1% to 7% if presently-known high shaker density areas were closed. The model configuration assumes that effort would move from the closed areas into the remaining open areas in proportion to the amount of effort previously in the open area. CPUE of legal fish in the remaining open areas is assumed not to change. In reality CPUE in these other open areas would be reduced somewhat due to the increased concentration of fishing gear on the already crowded fishing grounds. Localized depletion of stocks due to concentrations of effort could further reduce CPUE. Closures have other negative impacts which are difficult to quantify. Closure of areas adjacent to small Southeastern Alaskan communities would impact small-boat fishermen who sell their catch each day and who would not be able to range out into the remaining open areas. The ability to fish traditional grounds carries a strong positive value to some fishermen. These values may outweigh the increases in yield resulting from area closures.

Information from the Icy Strait Tagging Study demonstrates a highly significant difference in hooking mortality between treble and single hooks. The lower mortality observed for treble hooks is contrary to the intuition of most fishermen. Treble-hooked fish are often more difficult to release sine several barbs are often embedded in the flesh. However, this difficulty appears to be more than compensated for by the difference in severity of the hooking wounds. Single hooks present a smaller cross-sectional area to the fish and tend to be ingested more deeply, resulting in a higher proportion of gill injuries (M. Bethers, Alaska Dept. of Fish and Game, pers. comm.). Haw (1963) found similar differences in the location and severity of wounds caused by single and treble hooks and noted that the location of the wound appeared to affect survival. The same relationship between hook size and mouth size appears to explain the observed differences in mortality by fish length for both single and treble hooks. Haw (1963) reports an opposite trend with length for increased recoveries of tagged fish. However, he notes that tag-shedding rates were also found to be higher in small fish and that this effect could also explain the observed differences in tag recovery rates.

The yield-per-recruit model demonstrates that unless instantaneous rates of fishing mortality are very high, gear restrictions which utilize the observed differences in hooking mortality and size selectivity of different types of trolling gear are not likely to increase yield from the fishery. Other undesirable effects of imposing gear restrictions are not easy to quantify. Some fishermen have developed an intimate familiarity with certain gear types over a number of years and would find the forced transition to a new gear type difficult. Freedom from regulatory restriction of any kind carries a certain value to many fishermen. Trollers in particular tend to be staunchly independent and may prefer to sacrifice some potential yield to maintain their independence from further regulation.

The sole purpose of a size-limit restriction, or any associated measures to reduce hooking mortality, is to increase yield from the fishery. Size limits have very little effect on problems associated with overharvest. The present size limit does allow maturity-group-2 fish to escape unharvested except for hooking mortality. However, only a very small proportion of chinook salmon mature at age 2. Ricker (1980) points out that this effect, while negligible in terms of conservation of existing stocks, could easily result in longer-term genetic selection for early maturation. Troll size limits are one of several factors suspected to have caused the decline in age and size of chinook salmon in recent decades.

It should be emphasized that yield-per-recruit models cannot be used to set optimum fishing mortality rates. Overall fishing mortality rates should be designed to achieve escapement goals which optimize spawner-recruit relationships. The level of fishing mortality at the global maximum evident on the yield-per-recruit response surface does not represent the optimum long-term management strategy. The yield-per-recruit model ignores the effects of overharvest on future recruitment. Given a fishing mortality rate determined from methods designed to optimize recruitment, the corresponding size limit along the eumetric fishing curve determines the optimum management strategy.

The most serious shortcoming of the current configuration of the model is the assumption that fishing mortality is independent of maturity stage. Fishing mortality was allowed to vary only with age in order to allow for incomplete recruitment. In reality, fishing mortality probably changes with both age and degree of maturity at different rates within each maturity group. Preliminary examination of fishing mortality rates for several coded wire tag recovery groups suggests that fishing mortality is higher for maturing fish at each age. Age and maturity-group-specific fishing mortality rates could be estimated using tag recovery information if the age-specific ratios of immatures to matures in the catch were known.

The yield-per-recruit model provides a conceptual framework for evaluating the effects of size limits, gear restrictions, and time-area closures. With refined estimates of fishing mortality rates by maturity group and age, the yield-per-recruit model could become a more useful tool for troll fishery management planning.

CONCLUSIONS

1. A size limit of 24.0 inches would optimize yield in weight of chinook salmon in the Alaska troll fishery, based on the most likely estimates of fishing and hooking mortalities. Yield would be increased 8.4% over the yield with the current 28-inch limit.

2. A size limit of 26.5 inches would optimize the landed value in dollars of chinook salmon in the Alaska troll fishery, based on the most likely estimates of fishing and hooking mortalities. Landed value would be increased only 1.6% over the landed value with the current 28-inch limit.

3. Unless the instantaneous monthly rate of fishing mortality is greater than 0.10 monthly (for a 4.17 month fishing season), no size limit for chinook salmon should exceed 26 inches.

4. Yield per recruit does not change radically with varying size limits. In the face of uncertain parameter estimates, there is little risk in terms of lost yield to the fishery when size limits are not optimal.

5. Gear saturation resulting from hooked sublegal fish reducing the amount of gear actively fishing was not modeled but could further decrease optimum size limits.

6. Landed value is maximized at larger size limits than yield at corresponding rates of hooking mortality. These differences become more pronounced at high rates of hooking mortality.

7. Shaker mortality estimates in the literature range from 15% to 86%. Values most commonly used by fishery managers are generally 30% to 50%.

8. Including maturity groups other than the dominant age-4 group in a yield analysis makes yield maxima more pronounced on the size limit-fishing mortality yield response surface. The loss of maturity-group-3 fish makes the yield surface decline at larger size limits and the small sublegal sizes of the maturity-group-5 fish causes the surface to decline at smaller size limits.

9. Adding hooking mortality to the yield-per-recruit model causes the yield response surface to decline with increasing fishing mortality. A global maximum appears on the response surface.

10. The yield-per-recruit model was relatively insensitive to the relationship between hooking mortality and fish length over the range of positive and negative slopes of hooking mortality relationships used. Varying the slope of the hooking mortality-fish length relationship changed the optimum size limit by at most 1.5 inches. Optimum size limits are larger for models with decreasing hooking mortality with increasing fish length than for models with increasing hooking mortality with increasing fish length when overall hooking mortality levels are low. However, optimum size limits are smaller for the models with decreasing hooking mortality than for those with increasing hooking mortality when overall hooking mortality is intermediate or high.

11. Most gear restrictions reduce yield. The effect of gear restrictions which reduce hooking mortality must be weighed against the decreases in CPUE of legal fish caused by the gear restriction. Examples from the literature of test fishing with gear which reduce hooking mortality all showed decreased yield when analyzed with the yield-per-recruit model.

12. Gear restrictions which reduce hooking mortality cause the largest increase in yield per recruit at low fishing mortality and hooking mortality rates. The effect of gear restrictions on yield decreases with higher fishing and hooking mortality rates.

13. Better estimates of fishing mortality rates for the Alaska troll fishery would allow more precise estimation of optimum size limits.

14. Closure of high-density shaker areas (inshore waters north of Cape Spencer and the Clarence Strait area) would probably increase the overall yield to the fishery by only 2% to 7%.

15. Gear saturation effects also discourage trollers from fishing in high shaker density areas. Such voluntary effort shifts out of high shaker density areas tend to increase the value of a size limit. However, no data are available with which to estimate the magnitude of this effect.

15. The ADF&G Icy Strait Tagging Study indicates that hooking mortality increases with fish length and that single hooks cause significantly higher mortality than treble hooks. Both effects can be explained by the hypothesis that the relationship between hook size and mouth size controls the depth of swallowing and hence the severity of hooking injuries.

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APPENDIX I

Derivation of Survival Model Incorporating Length-Related Hooking Mortality

DERIVATION OF A SURVIVAL MODEL WITH HOOKING MORTALITY A LINEAR FUNCTION OF FISH LENGTH

A survival model in which the fishing mortality of sublegals varies as a linear function of fish length can be derived from

$$dN = [M_g(t) + F_t \cdot H(L)] \cdot N\ dt \quad ,$$

where, M_g is a maturity-group-specific natural mortality function, F_t is an age-specific instantaneous fishing mortality rate, and $H(L)$ is the hooking mortality function. The subscripts will be omitted from M and F for simplicity. The function $H(L)$ can be expressed as a linear function of time using a linear growth in length model, $L(t) = m \cdot t + L'$, where L' is length at release (time t = 0). If $H(L)$ is assumed linear with length L, $H(L) = h \cdot L + C$. Thus,

$$H(t) = h(m \cdot t + L') + C \quad , \text{ or}$$

$$H(t) = h \cdot m \cdot t + (h \cdot L' + C) \ .$$

Substituting this result into the differential equation for survival gives

$$\frac{dN}{N} = \left\{ M(t) + F[hmt + (hL'+C)\ ] \right\} dt, \text{ and}$$

$$ln\ N = \int -M(t)\ dt - \int Fhmt\ dt - \int F(hL' + C)\ dt,$$

which reduces to

$$N(t) = e^{-\left\{[K/(am(1-b))] \cdot (mt+L')^{1-b} + (Fhmt^2)/2 + Ft(hL'+C)\right\}} \cdot e^{C_0} \ .$$

If $N = N_0$ at release (t=0) ,

$$e^{C_0} = N_0 \cdot e^{[K/(am(1-b))] \cdot (L')^{(1-b)}} \quad , \text{ and}$$

$$N(t) = N_0 \cdot e^{-\left\{[K/(am(1-b))] \cdot [(mt+L')^{1-b} - (L')^{1-b}] + Ft[hmt/2+hL'+C]\right\}} \ .$$

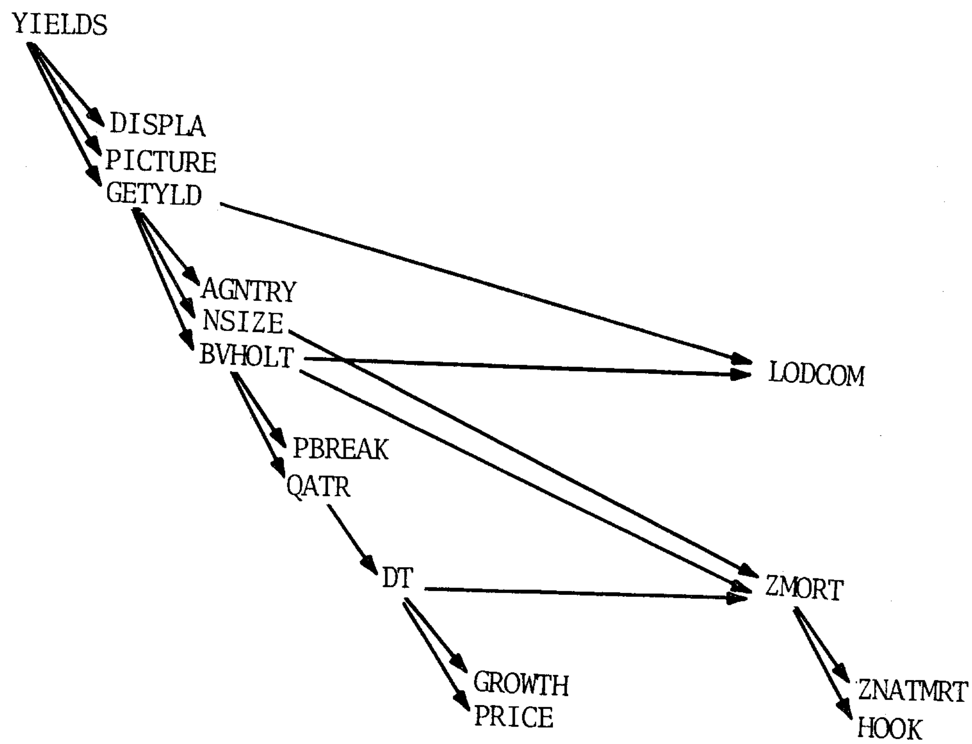
APPENDIX II

Listing of the Fortran program YIELDS which computes yield per recruit for a semelparous species with disjoint fishing seasons, age-related natural mortality, size-related sublegal hooking mortality, and maturity-group-specific growth.

PROGRAM YIELDS

The present configuration of YIELDS is designed to execute on a Honeywell 66/40 running under the GCOS/TSS batch/interactive operating system. Slightly modified versions of the program have been executed on a CDC Cyber 173 under NOS and on various microcomputers running CP/M with Microsoft Fortran compilers.

Calling Hierarchy of Program YIELDS



```
      PROGRAM YIELDS
C
C--Purpose: Compute yield-per-recruit based on modified Beverton-Holt
C--         yield equation. Allows for non-continuous fishing seasons,
C--         semelparous life history with maturation at different ages.
C--         Allows for different growth rates for fish maturing at
C--         different ages.  Allows age-dependent natural mortality to
C--         be specified.  Allows for age-specific fishing mortality.
C--         Allows for sublegal hooking mortality with hooking mortality
C--         a function of size.  Also computes landed value-per-recruit.
C--         Ex-vessel prices are allowed to fluctuated within fishing
C--         seasons and be weight-class specific.
C--         The yield equation is evaluated over a
C--         range of discrete fishing mortality and size limit values to
C--         produce a response surface.  Subroutine PICTURE is called to
C--         display the surface.
C--Definitions:
C--         LMIN - Minimum size limit (varying)
C--         LMIN1 - smallest size limit evaluated (19 inches)
C--         NLEN  - the number of size limits to evaluate
C--         DELTLN - interval between size limits
C--         FRATIO - ratio of fishing mortality to fully recruited
C--                  fishing mortality for each age
C--         F - array storing the age-specific fishing mortalities
C--         F1 - lowest fishing mortality evaluated (0.02)
C--         NF - the number of fishing mortality levels to evaluate
C--         DELTAF - interval between fishing mortality levels
C--         TB - time of beginning of each of the 5 fishing seasons (mo)
C--         TE - time of end of each of the 5 fishing seasons (months)
C--         P  - maturity group proportion
C--         HKMOD - hooking mortality model
C--         NATMOD - natural mortality model
C--         ZNTMRT - level of natural mortality (if NATMOD = 2)
C--         YIELD - array storing the NF by NLEN yield surface
C--         MODGRO - type of growth model (1=vonB,2=mod. exp)
C--         VALMOD - flag for value-per-recruit form (if .true.)
C--Structure:
C--      Main program YIELDS  merely increments F and Tc and drives
C--      FUNCTION GETYLD to compute actual yields.  If flag PLOTIT is
C--      set .true. subroutine PICTURE is called at termination to
C--      display a 3-d representation of the response surface.  A NLEN
C--      by NF table containing the values of YIELD is written to
C--      FORTRAN unit 6 (terminal).
C--      Setting OUTTST .TRUE. turns on a lengthy debug output mode
C--      Growth model parameters are initialized into array GPARMS for
C--      ease in passing.
C
      REAL LMIN,LMIN1
      REAL YIELD(20,30),XPIC(20,30),YPIC(20,30)
```

```
      REAL P(5),F(5),TB(5),TE(5),GPARMS(25),FRATIO(5)
      LOGICAL OUTTST,PRTST,PLOTIT,VALMOD
      COMMON /TEST/ OUTTST,PRTST
      COMMON /HOOKVL/ HKMOD
C--VALMOD-value model -TRUE==> include prices; FALSE==> yield model only
      COMMON /MODELS/ VALMOD,NATMOD,ZNTMRT
      COMMON /IMSLER/ NERR1,NERR2,NCALLS
C
C
      DATA FRATIO /0.0, 0.325, 1.0, 1.0, 1.0/
C
      DATA TB /   0.0,10.0,22.0,34.0,46.0/
C
      DATA TE /9.9999,16.5,28.5,40.5,52.5/
C
      DATA R  /1.0/, P /0.0, 0.0001, 0.05, 0.70, 0.2499 /
C
      DATA F1 /0.02/, LMIN1 /19.0/, NF /20/
C
      DATA NLEN /30/,DELTAF /.02/, DELTLN /0.5/
C
      DATA NERR1 /0/,  NERR2 /0/, NCALLS /0/
C
      DATA NWARN /0/, MODGRO /2/
C
C
      DATA GPARMS /
C
C  AGE =          1          2          3          4          5
C
C  MODEL:
C    1    2
C
C  WINF   A
     &        6.067E-6,  6.067E-6,  3.950E-6,  3.725E-6,   4.727E-6,
C  LINF   B
     &           3.200,     3.200,     3.304,     3.318,      3.263,
C    K    M
     &           3.571,     3.571,     2.542,     2.091,      1.685,
C   TO  LPRIM
     &            8.00,      8.00,      8.00,      8.00,       8.00,
C    B    K
     &          0.0017,    0.0017,     0.011,     0.015,      0.018   /
C
C---------------------------------------------------------------
C
C
      NATMOD = 1
      HKMOD = 3.0
      OUTTST = .FALSE.
      PRTST = .FALSE.
```

```
      PLOTIT = .TRUE.
      VALMOD = .TRUE.
C
      IF ( PLOTIT ) CALL PLOTST
C
C--Convert lengths in inches to centimeters
C
      LMIN1   = LMIN1 * 2.54
      DELTLN = DELTLN * 2.54
C
      WRITE(6,1002) ((lmin1+float(ilen-1)*deltln)/2.54,ilen=1,30)
 1002 Format(40X,'SIZE AT ENTRY (TOTAL LENGTH IN CM)',/,
     &  4X,18F7.1,/,4X,12F7.1,//,4X,'F',/)
C
C--Loop on fishing mortality increment
C
      DO 30 IF = 1,NF
C
C--Compute fishing mortality schedule for all 5 age classes
C
         DO 10 I = 1,5
            F(I) = FRATIO(I) * (F1 + FLOAT(IF-1)*DELTAF)
   10    CONTINUE
C
C--Loop on minimum size increment
C
         DO 20 ILEN = 1,NLEN
C
c--Compute minimum size, total length and then convert to fork length
C
            LMIN = LMIN1 + FLOAT(ILEN-1)*DELTLN
C
            LMIN = (LMIN-5.337)/0.9768
C
C--Compute yield for this minimum size and fishing mortality
C
            YIELD(IF,ILEN) = GETYLD(LMIN,R,P,F,TB,TE,MODGRO,GPARMS)
C
   20    CONTINUE
C
         FX = F1 + FLOAT(IF-1)*DELTAF
C
            WRITE(6,1001) fx,(yield(if,ilen),ilen=1,nlen)
 1001       Format(F4.2,18f7.4,/,1x,3x,12f7.4,/)
C
   30 CONTINUE
C
      CALL DISPLA(' QATR IER = 1  ERRORS$', NERR1)
      CALL DISPLA(' QATR IER = 2  ERRORS$', NERR2)
      CALL DISPLA(' CALLS TO DT$',NCALLS)
C
```

```
      IF ( PLOTIT ) CALL PICTURE(YIELD,XPIC,YPIC,
     &              NF,NLEN,NF,6.,7.,-8.,-6.,10.,0,0,0,2,3,0)
      IF ( PLOTIT ) CALL PLOT(0.,0.,999)
C
C
      STOP
      END
      FUNCIION GETYLD(LMIN,R,P,F,TB,TE,MODGRO,GPARMS)
C
C--     Get yield over all maturity groups and ages for a given
C--     minimum size and fishing mortality schedule.
C
      INTEGER AGE
      REAL LMIN,P(5),F(5),TB(5),TE(5),GPARMS(25),NSIZE
      REAL NSTART,NBEGIN
      LOGICAL OUTTST,PRTST
      COMMON /TEST/ OUTTST,PRTST
C
C-------------------------------------------------------------
C
      GETYLD = 0.0
C
C--Loop on maturity groups
C
      DO 100 MTGRUP = 3,5
C
          CALL LODCOM(D2,D3,I1,I2,GPARMS)
          TMIN = AGNTRY(LMIN,MTGRUP,MODGRO)
C
C--Compute initial numbers
C
          NBEGIN = R * P(MTGRUP)
C
C
C--Loop on ages within maturity groups
C
          DO 200 AGE = 2,MTGRUP
C
C
              NSTART = NBEGIN
C
C--Compute survival of maturity group to end of previous fishing season
C
              IF ( AGE .LT. 3 ) GO TO 250
C
                  IAGE = AGE-1
                  DO 300 J = 2,IAGE
C
                      NSTART = NSTART *
     &                        NSIZE(MTGRUP,TMIN,F(J),TB(J),TE(J-1),TE(J))
C
```

```
C
  300            CONTINUE
C
  250         CONTINUE
C
              GETYLD = GETYLD
     &                  +
     &                 NSTART * BVHOLT(TMIN,F(AGE),TB(AGE),TE(AGE-1),
     &                                  TE(AGE),MTGRUP,MODGRO,GPARMS)
C
  200     CONTINUE
C
  100 CONTINUE
C
      RETURN
      END
      REAL FUNCTION NSIZE(MTGRUP,TMIN,F,TB,OLDTE,TE)
C
C--       Compute proportion of population surviving one complete year.
C--       Assume preseason time interval of length TB - OLDTE with
C--         only natural mortality (M).
C--       Assume fishing season of length TE-TB with F and M operative.
C
      INTEGER MTGRUP
      REAL F,TB,OLDTE,TE
      LOGICAL OUTTST,PRTST,LEGAL
      COMMON /TEST/ OUTTST,PRTST
C
C---------------------------------------------------------
C
      LEGAL = .TRUE.
C--Compute survival to start of fishing season
C
      NSIZE = ZMORT(0.0,TB,OLDTE,MTGRUP,LEGAL)
C
      IF(TMIN .GE. TB) GO TO 100
C
C--Fish of legal size before fishing season
C
          NSIZE = NSIZE * ZMORT(F,TE,TB,MTGRUP,LEGAL)
          GO TO 300
C
  100 IF(TMIN .LE. TE) GO TO 200
C
C--Fish reach legal size after fishing season but are still
C--Hooked at rate F--so reduce fishing mortality by hooking survival
C
         LEGAL = .FALSE.
         NSIZE = NSIZE * ZMORT(F,TE,TB,MTGRUP,LEGAL)
         GO TO 300
C
```

```
  200 CONTINUE
C
C--Fish reach legal size during fishing season
C
C--First compute survival to age-of-entry (TMIN)
C
        LEGAL = .FALSE.
        NSIZE = NSIZE * ZMORT(F,TMIN,TB,MTGRUP,LEGAL)
C
C--Then compute survival after fish reach legal size
C
        LEGAL = .TRUE.
        NSIZE = NSIZE * ZMORT(F,TE,TMIN,MTGRUP,LEGAL)
C
  300 CONTINUE
C
C
      RETURN
      END
      FUNCTION BVHOLT(TMIN,F,TB,OLDTE,TE,MTGRUP,MODGRO,GPARMS)
C
C--      Compute yield per recruit during one fishing season from
c--         one maturity group.  Integrate Beverton-Holt yield equation
c--         from beginning (TE) to end (TB) of one fishing season.
c--         Computes survival from end of previous season (OLDTE) to
c--         beginning of present season (TB).  Checks for fish reaching
c--         legal age during the present fishing season and resets
c--         starting point of yield accumulation if necessary.
c--      If VALMOD was set .TRUE., the quantity integrated is landed
c--         value-per-recruit, not yield.  Regardless of the value of
c--         VALMOD the limits of integration are reset if necessary such
c--         the integral is not evaluated over small-medium and
c--         medium-large price jumps.
c
      REAL GPARMS(25),K,AUX(6)
      LOGICAL OUTTST,PRTST,PBREAK,LEGAL
      EXTERNAL DT
      COMMON /TEST/ OUTTST,PRTST
      DATA EPS /1.0E-3/,NDIM /6/, START /0.0/
C
C-------------------------------------------------------------
C
      CALL LODCOM(F,TB,MTGRUP,MODGRO,GPARMS)
C
C--If fish below legal size during this season, no yield
C
      IF (TMIN .GT. TE) GO TO 300
C
C--Compute survival to start of season
C
      LEGAL = .TRUE.
```

```
      START = ZMORT(0.0,TB,OLDTE,MTGRUP,LEGAL)
C
      TBB = TB
C
      IF ( TMIN .LE. TB) GO TO 200
C
C--Fish reach legal size during fishing season,
C--so compute survival to AGNTRY
C
         LEGAL = .FALSE.
         START = START * ZMORT(F,TMIN,TB,MTGRUP,LEGAL)
         LEGAL = .TRUE.
C
C--Reset starting point of yield accumulation to age legal size reached
C
         TBB = TMIN
C
  200 CONTINUE
C
c--Check for small-medium or medium-large price jump this season
c
      IF ( PBREAK(TE,TBB,TBREAK) ) GO TO 250
C
c--No price jumps, integrate over whole season to compute yield
c
         CALL LODCOM(F,TBB,MTGRUP,MODGRO,GPARMS)
         CALL QATR(TBB,TE,EPS,NDIM,DT,QATVAL,IER,AUX)
         BVHOLT = F * START * QATVAL
         GO TO 400
C
  250 CONTINUE
C
c--Price jump during this season - first evaluate integral up to break:
C
C
         CALL LODCOM(F,TBB,MTGRUP,MODGRO,GPARMS)
         CALL QATR(TBB,TBREAK-0.0001,EPS,NDIM,DT,QATVAL,IER,AUX)
         BVHOLT = F * START * QATVAL
C
c--Now evaluate integral from break to end of season
c--Check for another price break first:
C
         IF ( PBREAK(TE,TBREAK,TBRK2) ) GO TO 280
c
C
            START = START * ZMORT(F,TBREAK,TBB,MTGRUP,LEGAL)
            CALL LODCOM(F,TBREAK,MTGRUP,MODGRO,GPARMS)
            CALL QATR(TBREAK+0.0001,TE,EPS,NDIM,DT,QATVAL,IER,AUX)
            BVHOLT = BVHOLT + ( F * START * QATVAL)
            GO TO 400
C
```

```
  280    CONTINUE
C
C--Second price break - evaluate integral from first to second break
C
C
            START = START * ZMORT(F,TBREAK,TBB,MTGRUP,LEGAL)
            CALL LODCOM(F,TBREAK,MTGRUP,MODGRO,GPARMS)
            CALL QATR(TBREAK+0.0001,TBRK2-0.0001,EPS,NDIM,DT,
     &               QATVAL,IER,AUX)
            BVHOLT = BVHOLT + (F* START * QATVAL)
C
C--Now evaluate integral from second price break to end of season
C
c
            START = START * ZMORT(F,TBRK2,TBREAK,MTGRUP,LEGAL)
            CALL LODCOM(F,TBRK2,MTGRUP,MODGRO,GPARMS)
            CALL QATR(TBRK2+0.0001,TE,EPS,NDIM,DT,QATVAL,IER,AUX)
            BVHOLT = BVHOLT + (F * START * QATVAL)
            GO TO 400
C
  300 CONTINUE
C
C--Fish below legal size, no yield
C
         BVHOLT = 0.0
C
  400 CONTINUE
C
C
      RETURN
      END
      SUBROUTINE LODCOM(F,TB,MTGRUP,MODGRO,GPARMS)
C
C--    Load common block DTARGS for access from DT, GROWTH, AGNTRY,ZMORT
C
      REAL GPARMS(25)
      COMMON /DTARGS/ FX,TBX,MATX,MODGRX,GPX(25)
C
C-------------------------------------------------------
C
C--Transfer arguments to common /DTARGS/ for passing to DT
C
      FX = F
      TBX = TB
      MATX = MTGRUP
      MODGRX = MODGRO
      DO 10 I = 1,25
         GPX(I) = GPARMS(I)
   10 CONTINUE
C
C
```

```
      RETURN
      END
      FUNCTION DT(T)
C
C--      Differential portion of Bev-Holt equation for QATR to
C--      numerically integrate.
C--      T is time from beginning of fishing seaso.
c--      T + TB is time from release
C
      REAL M
      LOGICAL OUTTST,PRTST,LEGAL
      EXTERNAL GROWTH
      COMMON /TEST/ OUTTST,PRTST
      COMMON /DTARGS/ F,TB,MTGRUP,MODGRO,GPARMS(25)
      COMMON /IMSLER/ NERR1,NERR2,NCALLS
C
C-----------------------------------------------------------------
C
      LEGAL = .TRUE.
C
      WEIGHT = GROWTH(T,MTGRUP,MODGRO)
C
      DT = ZMORT(F,T,TB,MTGRUP,LEGAL) * WEIGHT * PRICE(T,WEIGHT)
C
      NCALLS = NCALLS + 1
         If(prtst) WRITE(6,3000) DT
 3000    Format(2x,'DT =',f10.6)
C
      RETURN
      END
      REAL FUNCTION ZMORT(F,T2,T1,MTGRUP,LEGAL)
C
C--       Compute proportion of pop. present at T1 surviving to time T2
C--       using O'Connor's (1977) model with natural mortality as a
C--       declining exponential function of fish weight.
C
      INTEGER MTGRUP
      REAL F,DELTAT,AX(5),BBX(5),MX(5),LPRIMX(5),KX(5),A,BB,M,LPRIM,K
      LOGICAL OUTTST,PRTST,LEGAL,VALMOD
      COMMON /MODELS/ VALMOD,NATMOD,ZNTMRT
      COMMON /TEST/ OUTTST,PRTST
      COMMON /DTARGS/ DUM(2),IDUM(2),GPARMS(25)
C
      EQUIVALENCE (    AX(1),GPARMS( 1) ),
     &            (   BBX(1),GPARMS( 6) ),
     &            (    MX(1),GPARMS(11) ),
     &            (LPRIMX(1),GPARMS(16) ),
     &            (    KX(1),GPARMS(21) )
C
C-----------------------------------------------------------
C
```

```
      ZNATMT(K,M,DELTAT,LPRIM,BB,A) =
C
     &        K * ((M*DELTAT+LPRIM)**(1-BB) - LPRIM**(1-BB))
C              ---------------------------------------------
     &                /( A * M * (1-BB)  )
C
      A     =     AX(MTGRUP)
      BB    =    BBX(MTGRUP)
      M     =     MX(MTGRUP)
      LPRIM = LPRIMX(MTGRUP)
      K     =     KX(MTGRUP)
C
      IF ( NATMOD .EQ. 2 ) GO TO 100
c
c--Natural Mortality as a function of age:
c
      ZMORT =
     &  EXP( -(F*T2*HOOK(LEGAL,T2,M,LPRIM) + ZNATMT(K,M,T2,LPRIM,BB,A)
))
C            ------------------------------------------
     &/ EXP( -(F*T1*HOOK(LEGAL,T1,M,LPRIM) + ZNATMT(K,M,T1,LPRIM,BB,A)
))
C
      GO TO 900
C
  100 CONTINUE
C
C--Constant natural mortality
c
      ZMORT = EXP( -(F*T2*HOOK(LEGAL,T2,M,LPRIM) + ZNTMRT*T2 ) )
C             ------------------------------------------------
     &      / EXP( -(F*T1*HOOK(LEGAL,T1,M,LPRIM) + ZNTMRT*T1 ) )
C
  900 CONTINUE
      RETURN
      END
      REAL FUNCTION HOOK(LEGAL,T,M,LPRIM)
C
C--      Determine hooking mortality if LEGAL is .FALSE.
c--      If LEGAL .TRUE. return with value 1.0 .
C--      Hooking mortality model is determined by the value of HKMOD.
c--      If HKMOD is 1.,2., or 3., a linear model of hooking mortality
c--        as a function of length is used:
c--                          Hooking Mortality at      20 in     30 in
c
c--      HKMOD = 1.0  ==> Severe                        80%       50%
c--      HKMOD = 2.0  ==> Moderate                      60%       30%
c--      HKMOD = 3.0  ==> Low                           40%       10%
c--      HKMOD = any other value ==> Constant hooking mortality equal
c--                                  to the value of HKMOD
c--                                  (proportion killed by
```

```
c--                                          hooking encounter)
      LOGICAL LEGAL
      REAL T,LPRIM,HKMOD,M,H
      COMMON /HOOKVL/ HKMOD
      DATA H / 3.90945E-3 /
C
C-----------------------------------------------------------------------
C
      IF ( .NOT. LEGAL ) GO TO 100
         HOOK = 1.0
         GO TO 500
c
c--Severe hooking mortality
c
  100 IF ( HKMOD .NE. 1.0 ) GO TO 200
         HOOK = (0.5 * H * M * T) + (H * LPRIM) + 0.40140
         GO TO 500
c
c--Moderate hooking mortality
c
  200 IF ( HKMOD .NE. 2.0 ) GO TO 300
         HOOK = (0.5 * H * M * T) + (H * LPRIM) + 0.15140
         GO TO 500
c
c--Low hooking mortality
c
  300 IF ( HKMOD .NE. 3.0 ) GO TO 400
         HOOK = (0.5 * H * M * T) + (H * LPRIM) - 0.10098
         GO TO 500
c
c--Constant hooking mortality
c
  400 CONTINUE
         HOOK = HKMOD
         GO TO 500
  500 CONTINUE
c
c--adjust hook if out of limits of validity
c
      IF ( HOOK .GT. 1.0) HOOK = 1.0
      IF ( HOOK .LT. 0.0) HOOK = 0.0
c
      RETURN
      END
      FUNCTION GROWTH(T,MTGRUP,MODGRO)
C
C--   Compute weight at time T from bertalanffy growth curve,if MODGRO=1
C--   or from O'Connor's non-linear model if MODGRO = 2.
C--   FUNCTION AGNTRY - is similar but computes age at length T
C
      REAL LMIN
```

```
      REAL A(5),BB(5),M(5),LPRIM(5)
      REAL WINF(5),K(5),T0(5),B(5),LINF(5)
      COMMON /DTARGS/ DUM(2),IDUM(2),GPARMS(25)
C
C--MODGRO = 1
C
      EQUIVALENCE ( WINF(1),GPARMS( 1) ),
     &            ( LINF(1),GPARMS( 6) ),
     &            (    K(1),GPARMS(11) ),
     &            (   T0(1),GPARMS(16) ),
     &            (    B(1),GPARMS(21) )
C
C--MODGRO = 2
C
      EQUIVALENCE (    A(1),GPARMS( 1) ),
     &            (   BB(1),GPARMS( 6) ),
     &            (    M(1),GPARMS(11) ),
     &            (LPRIM(1),GPARMS(16) )
C
C-----------------------------------------------------
C
      IF(MODGRO .NE. 1) GO TO 100
         GROWTH = WINF(MTGRUP) *
     &       (1.0 - EXP(-K(MTGRUP)*(T-T0(MTGRUP))))**B(MTGRUP)
         GO TO 200
  100 CONTINUE
         GROWTH = A(MTGRUP) *
     &        (M(MTGRUP)*T + LPRIM(MTGRUP)) ** BB(MTGRUP)
  200 CONTINUE
C
      RETURN
      END
      FUNCIION AGNTRY(LMIN,MTGRUP,MODGRO)
C
C--      Compute age at length LMIN using von Bertalanffy growth model,
c--      if MODGRO = 1, or O'Connor's non linear model if MODGRO = 2.
c
      REAL LMIN
      REAL A(5),BB(5),M(5),LPRIM(5)
      REAL WINF(5),K(5),T0(5),B(5),LINF(5)
      COMMON /DTARGS/ DUM(2),IDUM(2),GPARMS(25)
C
C--MODGRO = 1
C
      EQUIVALENCE ( WINF(1),GPARMS( 1) ),
     &            ( LINF(1),GPARMS( 6) ),
     &            (    K(1),GPARMS(11) ),
     &            (   T0(1),GPARMS(16) ),
     &            (    B(1),GPARMS(21) )
C
C--MODGRO=2
```

```
C
      EQUIVALENCE (     A(1),GPARMS( 1) ),
     &            (    BB(1),GPARMS( 6) ),
     &            (     M(1),GPARMS(11) ),
     &            (LPRIM(1),GPARMS(16) )
C
C-----------------------------------------------------
C
      IF(MODGRO .NE. 1) GO TO 300
         AGNTRY = TO(MTGRUP)-ALOG(1.0-LMIN/LINF(MTGRUP))/K(MTGRUP)
         GO TO 400
 300  CONTINUE
         AGNTRY = (LMIN - LPRIM(MTGRUP))/M(MTGRUP)
 400  CONTINUE
      RETURN
      END
      REAL FUNCTION PRICE(MONTH,WEIGHT)
C
C--       Returns ex-vessel price-per-pound for fish of average
C--       weight "WEIGHT" at time "MONTH" from release
C--       PRICE BREAKS:     < 9 LBS  = SMALL
C--                     9 - 11 LBS = MEDIUM
C--                     >=  11 LBS = LARGE
C
C--       Prices increase linearly with time through troll season
C--       Price regressions based on 1981 troll season prices as
C--       reported in Fishery Market News.  Prices are averaged for all
C--       ports in southeast Alaska.
C
C--       Times are adjusted to reflect release date of June 15
C--       5.5 months are subtracted off of "MONTH" to calibrate to 0.0
C
      REAL MONTH1,MONTH,WEIGHT,WTX
      LOGICAL VALMOD,OUTTST,PRTST
      COMMON /TEST/ OUTTST,PRTST
      COMMON /MODELS/ VALMOD,NATMOD,ZNTMRT
C
C-----------------------------------------------------------------
C
C--If yield model, just return as 1.0
C
      IF(VALMOD) GO TO 45
         PRICE = 1.0
         RETURN
   45 CONTINUE
C
C-- Adjust fish age to time within one fishing season
C
      MONTH1 = MONTH - 6.50
      WTX    = WEIGHT * 2.20462
   50 CONTINUE
```

```
         IF(MONTH1 .LT. 12.0) GO TO 100
         MONTH1 = MONTH1 - 12.0
         GO TO 50
  100 CONTINUE
C
C--Small
C
      IF ( WTX .GE. 9.0 ) GO TO 200
         PRICE = 0.05106 * MONTH1  +  1.420
               If(prtst) WRITE(6,3001) MONTH,MONTH1,WTX,WEIGHT,PRICE
 3001          Format(2X,'Small, MONTH,MONTH1,WTX,WEIGHT,PRICE',5F10.4)
         GO TO 400
C
C--Medium
C
  200 IF ( WTX .GE. 11.0) GO TO 300
         PRICE = 0.05471 * MONTH1  +  1.822
               If(prtst) WRITE(6,3002) MONTH,MONTH1,WTX,WEIGHT,PRICE
 3002          Format(2X,'Medium, MONTH,MONTH1,WTX,WEIGHT,PRICE',5F10.4)
         GO TO 400
C
C--Large
C
  300 CONTINUE
         PRICE = 0.1209 * MONTH1  +  1.859
               If(prtst) WRITE(6,3003) MONTH,MONTH1,WTX,WEIGHT,PRICE
 3003          Format(2X,'Large, MONTH,MONTH1,WTX,WEIGHT,PRICE',5F10.4)
         GO TO 400
  400 CONTINUE
C
      RETURN
c
      END
      LOGICAL FUNCTION PBREAK(TE,TBB,TBREAK)
c
c--     Price Break - Determine if price break
c                        (average weight = 9 or 11 lbs) falls in
c                        this fishing season
c                     If so return .TRUE. and age at time of break
c                        as TBREAK, to be used as limit of integration .
c                        for IMSL routine QATR.
c                     Use either von Bertalanfty growth model (1) or
c                        O'Connor's exponential growth model (2).
      INTEGER MTGRUP,MODGRO
      REAL TE,TBB,TBREAK
      REAL A(5),BB(5),M(5),LPRIM(5)
      REAL WINF(5),K(5),T0(5),B(5),LINF(5)
      LOGICAL VALMOD
      COMMON /MODELS/ VALMOD,NATMOD,ZNTMRT
      COMMON /DTARGS/ F,TB,MTGRUP,MODGRO,GPARMS(25)
C
```

```
C--MODGRO = 1
C
      EQUIVALENCE ( WINF(1),GPARMS( 1) ),
     &            ( LINF(1),GPARMS( 6) ),
     &            (    K(1),GPARMS(11) ),
     &            (   TO(1),GPARMS(16) ),
     &            (    B(1),GPARMS(21) )
C
C--MODGRO=2
C
      EQUIVALENCE (    A(1),GPARMS( 1) ),
     &            (   BB(1),GPARMS( 6) ),
     &            (    M(1),GPARMS(11) ),
     &            (LPRIM(1),GPARMS(16) )
c
c----------------------------------------------------------------------
C
      PBREAK = .FALSE.
      IF ( .NOT. VALMOD) GO TO 900
c
c--compute age at 9 and 11 lbs using appropriate growth model
c
c--pounds to kilograms
c
      W9  =  9.0/2.20462
      W11 = 11.0/2.20462
c
      IF ( MODGRO .NE. 1 ) GO TO 100
C
c--von Bertalanffy
c
         AGE9 = -ALOG(1-EXP( (ALOG( W9)-ALOG(WINF(MTGRUP)))/B(MTGRUP)))/
C               -------------------------------------------------------
     &                                 K(MTGRUP)     +  TO(MTGRUP)
         AGE11= -ALOG(1-EXP( (ALOG(W11)-ALOG(WINF(MTGRUP)))/B(MTGRUP)))/
C               -------------------------------------------------------
     &                                 K(MTGRUP)     +  TO(MTGRUP)
         GO TO 200
c
c--maturity group specific (O'Connor)
c
  100 CONTINUE
C
        AGE9 =(EXP
     &  ((ALOG( W9)-ALOG(A(MTGRUP)))/BB(MTGRUP))-LPRIM(MTGRUP)  )/
C               -------------------------------------------------
     &                                 M(MTGRUP)
        AGE11=(EXP
     &  ((ALOG(W11)-ALOG(A(MTGRUP)))/BB(MTGRUP))-LPRIM(MTGRUP)  )/
C               -------------------------------------------------
     &                                 M(MTGRUP)
```

```
         GO TO 200
C
  200 CONTINUE
C
      IF(AGE9  .LE. TBB .OR. AGE9  .GT. TE) GO TO 300
         PBREAK = .TRUE.
         TBREAK = AGE9
         GO TO 900
  300 IF(AGE11 .LT. TBB .OR. AGE11 .GT. TE) GO TO 900
         PBREAK = .TRUE.
         TBREAK = AGE11
         GO TO 900
  900 CONTINUE
      RETURN
      END
      SUBROUTINE QATR(XL,XU,EPS,NDIM,FCT,Y,IER,AUX)
c
c--   Purpose
c--      To compute an approximation for integral FCT(x), summed
c--      over x from XL to XU.
c--   Description of parameters
c--      XL    - the lower bound of the interval
c--      XU    - the upper bound of the interval
c--      EPS   - the upper bound of the absolute error
c--      NDIM  - the dimension of the auxiliary storage array AUX
c--      FCT   - the name of the external function subprogram used.
c--      Y     - the resulting approximation for the integral value.
c--      IER   - a resulting error parameter
c--      AUX   - an auxiliary storage array with dimension NDIM
c--   Remarks
c--      Error parameter is coded in the following form:
c--      IER = 0  ==> It was possible to reach the required accuracy
c--                   No error.
c-       IER = 1  ==> It was impossible to reach the required accuracy
c--                   because of rounding errors.
c--      IER = 2  ==> It was impossible to check accuracy because NDIM
c--                   is less than 5 or  the required accuracy could
c--                   not be reached within NDIM-1 steps.  NDIM should
c--                   be increased
c--   Method
c--      Evaluation of Y is done by means of trapeziodal rule in
c--      connection with Romberg's Principle.  On return Y contains
c--      the best possible approximation of the integral value and
c--      the vector AUX the upward diagonal of the Romberg scheme.
c
C--   From IBM SSL, with mods, 11/15/81, FCF
c
      DIMENSION AUX(1)
      LOGICAL OUTTST,PRTST
      COMMON /TEST/ OUTTST,PRTST
      COMMON /IMSLER/ NERR1,NERR2,NCALLS
```

```
C
C-----------------------------------------------------------------
C
      AUX(1)=.5*(FCT(XL)+FCT(XU))
      H=XU-XL
      IF(NDIM-1)8,8,1
    1 IF(H)2,10,2
    2 HH=H
      E=EPS/ABS(H)
      DELT2=0.
      P=1.
      JJ=1
      DO 7 I=2,NDIM
      Y=AUX(1)
      DELT1=DELT2
      HD=HH
      HH=.5*HH
      P=.5*P
      X=XL+HH
      SM=0.
      DO 3 J=1,JJ
      SM=SM+FCT(X)
    3 X=X+HD
      AUX(I)=.5*AUX(I-1)+P*SM
      Q=1.
      JI=I-1
      DO 4 J=1,JI
      II=I-J
      Q=Q+Q
      Q=Q+Q
    4 AUX(II)=AUX(II+1)+(AUX(II+1)-AUX(II))/(Q-1.)
      DELT2=ABS(Y-AUX(1))
      IF(I-5)7,5,5
    5 IF(DELT2-E)10,10,6
    6 IF(DELT2-DELT1)7,11,11
    7 JJ=JJ+JJ
    8 IER=2
      WRITE(6,2002) XL,XU
 2002 FORMAT(2X,'ERROR RETURN FROM QATR,  IER = 2, XL,XU = ',2F10.4)
      NERR2 = NERR2 + 1
    9 Y=H*AUX(1)
      RETURN
   10 IER=0
      GO TO 9
   11 IER=1
      WRITE(6,2001) XL,XU
 2001 FORMAT(2X,'ERROR RETURN FROM QATR,  IER = 1, XL,XU = ',2F10.4)
      NERR1 = NERR1 + 1
      Y=H*Y
      RETURN
      END
```

```
      SUBROUTINE DISPLA(IMSG,IVAL)
C
C--     Display alpha message IMSG to terminal followed by integer IVAL
C--     String IMSG is assumed to end in $.
C--     Maximum length of message is 70 char.
C
      INTEGER IVAL
      CHARACTER IMSG*80,AVAL*10,OREC*80
C
C-----------------------------------------------------------------
C
      DO 5 I = 1,80
         CALL CONCAT(OREC,I,' ',1,1)
    5 CONTINUE
      DO 10 I = 1,70
         IF(KOMPCH(IMSG,I,1H$,1,1).EQ.0) GO TO 20
   10 CONTINUE
C
   20 CONTINUE
C
      CALL CONCAT(OREC,2,IMSG,1,I-1)
      IEND = I + 10
      ENCODE(AVAL,2000)IVAL
      CALL CONCAT(OREC,I+1,AVAL,1,10)
      WRITE(6,1000) OREC
 1000 FORMAT(A80)
 2000 FORMAT(I10)
C
      RETURN
      END
```

APPENDIX III

Model Verification

Appendix III - Table 1. Results of model verification by comparing the output from the North Sea plaice configuration of the model to Beverton and Holt's (1957, p. 311 Fig. 17.1) tabulated values of yield-per-recruit for North Sea plaice.

Parameter estimates:

$t_{\rho'}$ = 3.72 years

t_{λ} = 15.0 years

M = 0.10

W_{∞} = 2,867 g

K = 0.095

t_0 = -0.815 years

	Yield-Per-Recruit (g)	
F	Beverton and Holt	Age-structured chinook model
0.10	214.82	214.86
0.20	257.23	257.23
0.30	251.92	251.85
0.40	236.24	236.24
0.50	221.05	220.82
1.00	176.61	176.53
1.50	159.12	159.01

Average difference = 0.037%