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TITLE: A MODEL FOR DETERMINING OPTIMAL HARVEST IN A COMMERCIAL PACIFIC SALMON FISHERY

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Background and Introduction

The commercial Pacific salmon fishing industry, like most other fisheries, has been the subject of public policy initiatives for several decades. Following the period of laissez faire in the late 19th and early 20th century, both North American governments began a series of efforts to regulate even the seemingly most minute aspects of the fish harvesting process, e.g., the mesh size of nets. The motivations behind these regulatory initiatives have been ascribed to fears of species extinction.

The development of the specialized field of natural resource economics and questions raised about the efficiency of historical regulatory measures brought the increasing attention of economists. After Scott Gordon began the systematic analysis of common property resource exploitation, what fishery managers knew from practical experience became theoretically clear: that common property resources absorbed too much labor and capital. The root cause of this phenomenon was the market signals produced by common property resource exploitation. Canada's well known attempt to patch up the market failure through entry limitation is the subject of separate study by several economists. It is not generally regarded as a resounding success.

More recently, governments have viewed the salmon fishery as a somewhat unique investment opportunity. The United States, Canada, Russia, and Japan have all, more or less simultaneously, embarked on programs for enhancing, by a variety of means, the natural reproductive and growth processes of Pacific salmon. Moreover, recent deliberations at Law of the Sea conferences promise to heighten the interest of national governments in making the investment outlays necessary to enhance salmon fisheries. The adoption of Canada's abstention principle will help to assure that each nation can expect to reap the net returns of such investments.

These public policy initiatives served as part of the motivation for the research reported in this paper. It was apparent that a gap exists between the efforts of economists to model fish harvesting as an economic endeavor and the efforts of biologists to model the effects of the exercise of this endeavor on fish stocks. To put it simply, economists used crude biological models and biologists used crude economic models. Yet both groups influenced public policy. The influence of economists is apparent in Canada's License Limitation Programme for the west coast salmon fishery, while the influence of biologists is apparent in fishery regulatory measures; e.g., area closures, gear restrictions, etc. A fruitful line of inquiry appeared to be the development and combination of the best modeling efforts of both groups.

The remainder of this paper contains a description of a computer simulation model employed as a format for conducting bioeconomic analysis of a Pacific Coast salmon fishery. Results of exercise of the model follow its description.

Model Development

The structure of the computer simulation model is general in that it could be applied to any Pacific coast salmon fishery. For this study, parameter estimates were obtained from observed data for the Skeena River fishery located in northern British Columbia. The model relies on the two key relationships-- the harvest production function and the biological growth function. From this it is immediately clear that one of the unique features of the model is that it incorporates both within-season (intraseasonal) and between-season (interseasonal) relationships. The model simulates fifty years of fishing activity proceeding through time in weekly increments.
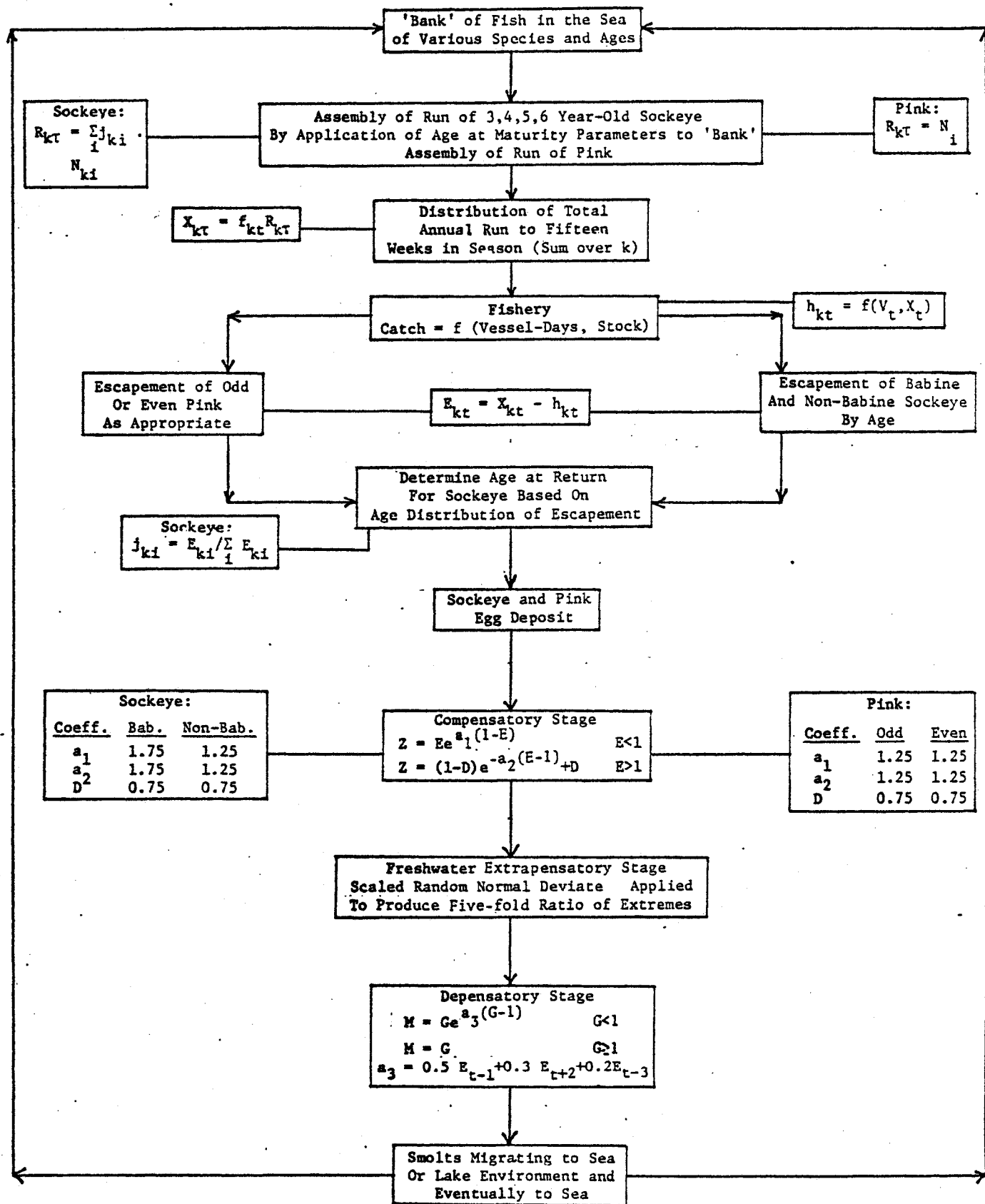
Figure 1 presents a schematic diagram outlining the general structure of the simulation model. The functional relationships employed in the various routines are also shown together with the parameter values employed in them. The general structure of the biological model is similar to simulation models used by biologists to analyze salmon population dynamics. The major departure from such models is embodied in the harvesting sector. Whereas biologists typically assume that the fishery harvests a constant proportion of the recruitment, this model features a more complex harvesting sector which allows the technological nature of the harvesting process together with output prices and input costs to jointly determine the size of the harvest. What is attempted in this model is the merging of more sophisticated economic and biological models than have heretofore been constructed. The remainder of the model's description will follow the schematic diagram of Figure 1.

The values of certain variables and coefficients which are generally endogenous to the model must be initialized in order to permit the model to function in the first six years of the simulation experiments. The biomass of sockeye and pink salmon as well as the proportions of sockeye maturing at various ages are the endogenous variables in this model requiring initialization.

Intraseasonal Relationships

The annual cycle of the model begins with the formation of the run of salmon which originates from the biomass of age-race combinations on the ocean feeding grounds. For sockeye, which exhibit a variable age at return, a means must be developed for ascribing a particular age at maturity to individual sockeye. One method of handling this problem, developed by Larkin, links the determination of age at maturity to inheritance.[1] Simply stated, this hypothesis holds that five-year-old spawners will produce progeny which will mature at age five, four-year-old spawners will produce progeny which will mature at age four, and so on. Following Larkin it is assumed that by natural selection the age composition of the sockeye biomass would stabilize in the absence of a fishery.[2] This reflects

Figure 1
SCHEMATIC DIAGRAM OF SIMULATION MODEL

'Bank' of Fish in the Sea of Various Species and Ages

Sockeye:
$$R_{k\tau} = \sum_i j_{ki} \cdot N_{ki}$$

Assembly of Run of 3,4,5,6 Year-Old Sockeye
By Application of Age at Maturity Parameters to 'Bank'
Assembly of Run of Pink

Pink:
$$R_{k\tau} = N_i$$

$$X_{k\tau} = f_{kt} R_{k\tau}$$

Distribution of Total Annual Run to Fifteen Weeks in Season (Sum over k)

Fishery
Catch = f (Vessel-Days, Stock)

$$h_{kt} = f(V_t, X_t)$$

Escapement of Odd Or Even Pink As Appropriate

$$E_{kt} = X_{kt} - h_{kt}$$

Escapement of Babine And Non-Babine Sockeye By Age

Determine Age at Return For Sockeye Based On Age Distribution of Escapement

Sockeye:
$$j_{ki} = E_{ki} / \sum_i E_{ki}$$

Sockeye and Pink Egg Deposit

Sockeye:

Coeff.	Bab.	Non-Bab.
a_1	1.75	1.25
a_2	1.75	1.25
D	0.75	0.75

Compensatory Stage
$$Z = Ee^{a_1(1-E)} \qquad E<1$$
$$Z = (1-D)e^{-a_2(E-1)}+D \qquad E>1$$

Pink:

Coeff.	Odd	Even
a_1	1.25	1.25
a_2	1.25	1.25
D	0.75	0.75

Freshwater Extrapensatory Stage
Scaled Random Normal Deviate Applied
To Produce Five-fold Ratio of Extremes

Depensatory Stage
$$M = Ge^{a_3(G-1)} \qquad G<1$$
$$M = G \qquad G\geq 1$$
$$a_3 = 0.5\, E_{t-1} + 0.3\, E_{t+2} + 0.2 E_{t-3}$$

Smolts Migrating to Sea Or Lake Environment and Eventually to Sea

the assumption that the greater fecundity of older fish compensates for their lesser survival to maturity. With this assumption, the age composition of the progeny of a brood can be related to the age composition of the parent escapement. For any season, τ, and sockeye race, k, the proportion maturing at various ages is expressed as:

$$(1) \quad j_{ki} = \frac{E_{ki}}{\sum_i E_{ki}} \quad ,$$

where j_{ki} refers to the proportion of race k maturing at various ages i(i=3,6). The variable E symbolizes escapement. For the first four years the proportions j_{ki} are initialized since there is no record of escapement upon which to calculate the maturity coefficients endogenously. Thereafter, the j_{ki} are determined according to (1).

Unlike the sockeye salmon, pink salmon have a fixed life cycle length and return to the natal stream two years after having been spawned. Thus, the size of the pink salmon run is determinable directly from the age structure of the pink salmon biomass on the ocean feeding grounds (i.e., the age-species-race accounting routine) within the model.

Given the above, total sockeye recruitment for season τ is determined according to the following relation:

$$(2) \quad R_{k\tau} = \sum_i j_{ki} N_{ki} \quad , \qquad k = 1,2; \ i = 3,\ldots,6.$$

$R_{k\tau}$ is total recruitment for season τ and N_{ki} is the sockeye biomass. For purposes of application of this model to the Skeena River, the two sockeye races resident in that river are designated k = 1,2. As noted above, determination of the pink salmon run is more direct. Thus,

$$(3) \quad R_{k\tau} = N_i \quad , \qquad k = 3,4, \ i = 2.$$

The pink salmon stocks of the Skeena River are designated k = 3,4. $R_{k\tau}$ and N_i are defined as for (2). Given (2) and (3), total recruitment in τ is

$$(4) \quad R_\tau = \sum_k R_{k\tau}, \qquad k = 1,\ldots,4.$$

Unlike continuous time models in which recruitment is instantaneous, this discrete time model assumes that total recruitment for a season is distributed over time throughout the season. Thus

$$(5) \qquad X_{kt} = f_{kt} R_{k\tau} \ , \qquad t = 1,\ldots,15.$$

X_{kt} is the stock of race k present in the fishery during t. The coefficients f_{kt} are given values estimated from observed time distributions for the Skeena River.

Most models of commercial fisheries assume the mass encounter fishing technology which postulates that the catch is proportional to the physical contact between fish and fishing gear. In the mass encounter technology, the catch per unit effort, i.e., the fraction of a fish stock which is caught by a defined unit of the fishing effort, is a constant. The catch per unit effort is sometimes referred to as the catchability coefficient.

In the salmon fishery a variable catch per unit effort more accurately describes the actual technology. For example, the increasing concentration of fish as they near the mouths of rivers creates congestion problems for the vessels. In addition, the operation of the fishing gear is affected by the size of the run. Gillnets used in the Skeena River begin to sink when they contain more than approximately 200 fish. It is reasonable to assume that this threshold would be reached sooner, the greater the run size.[3] These production phenomena are frequently labelled gear externalities and gear saturation effects, respectively. To reflect their effects the production function developed below hypothesizes a variable catchability coefficient. Given the above definition, the catchability coefficient is

$$(6) \qquad q_t^i \equiv \frac{h_t^i}{X_t}$$

where q_t^i is the catchability coefficient of vessel i fishing during interval t, h_t^i is the total harvest of vessel i in period t and X_t is the stock of fish available for capture during t.[4] Given the above definition, the harvest during t of vessel i is

$$(7) \qquad h_t^i = q_t^i X_t \ .$$

With n vessels fishing simultaneously, the total harvest during t is given by

$$(8) \qquad h_t = \sum_{i=1}^{n} q_t^i X_t \ .$$

Equation (8) can be re-expressed as:

$$(9) \qquad h_t = q_t \, V_t X_t$$

where q_t is the catchability coefficient for the fleet, V_t is the number of vessels fishing simultaneously and h_t and X_t are as defined above.

To complete the development of the production function, it is necessary to specify the variables to which q_t is functionally related. The spatial organization of vessels during the harvest of a salmon run is such that vessels are stationed in what may be assumed to be a grid pattern across the mouth of a river or inlet forming a gauntlet of fishing gear through which the salmon must pass on their spawning migrations. The productive efficiency of an individual vessel is affected both by the number of other vessels fishing simultaneously (crowding externality) and by the size of the run which the gear will encounter during that time interval (gear saturation). Thus, the catchability coefficient is hypothesized to be functionally related to the number of vessels fishing and the run size or,

$$(10) \qquad q_t = q_t(V_t, X_t)$$

where all variables are defined as above. When (10) is substituted into (9) the total harvest in time interval t is

$$(11) \qquad h_t = q_t(V_t, X_t) V_t \cdot X_t \ .$$

Our hypothesis is that the specific functional form of (10) is Cobb-Douglas, but, unlike most specifications of the Cobb-Douglas production function, the exponents δ_1 and δ_2 are hypothesized to be negative. Given these postulates, (10) becomes

$$(12) \qquad q(V_t, X_t) = AV_t^{\delta_1} X_t^{\delta_2} , \qquad -1 < \delta_1 < 0, \ -1 < \delta_2 < 0 \ .$$

The sign restrictions on δ_1 and δ_2 reflect the effects of the crowding and gear externalities described above.[5] When (12) is substituted into (11), the fishery production function is obtained. Thus

$$(13) \qquad h_t = AV_t^{\delta_1+1} X_t^{\delta_2+1} \ .$$

While the result (13) could have been postulated at the outset as the production function of the salmon fishery, its derivation from (6) links the more general formulation using a variable catchability coefficient to the more customary proportionality assumption.

The harvesting sector employs the harvest production function developed above as its core relationship. This function requires as input a value for stock size present in the fishery during each week, x_t, and a value for vessel-days of fishing each week, V_t, in order to determine the salmon harvest, h_t. Depending upon the fleet hiring assumption (weekly or seasonal), a different algorithm is required for determination of the optimal fleet size.

The determination of the optimal number of vessel-days of fishing for weekly fleet hiring is carried out by a fleet dispatch algorithm which employs the production function to calculate the total harvest for the endogenously determined stock size present in the fishery during a given t and numerous trial values of vessel-days of fishing. For each iteration the harvest is allocated to species and races on the basis of the proportion of the total run contributed by each race. Gross revenues can then be calculated with given output prices. Costs can also be calculated by applying exogenously determined input costs. Net returns are then calculated and employed in a linear comparison to determine whether they have increased, decreased, or remained constant from the previous iteration. This process continues until the maximum net returns have been determined for each of fifteen weeks in the season. Figure 2 contains a flow diagram of the logic of this algorithm.

The annual fleet hiring assumption requires a modification of the fleet control algorithm described above. Figure 3 presents a schematic diagram of this algorithm.

The modified algorithm begins by initializing a set of 50 (50-year simulation) values for the annual fleet size (vessel-days). These values are initial estimates of the optimal fleet size as defined for the simulation model, i.e., that fleet size which maximizes current net returns. The assumption that the fleet is procured once annually prior to the commencement of the season requires the sole owner to undertake a two-part decision making procedure for determining the optimal seasonal and weekly fleet size. Due to the fluctuating size of the run present each week, the sole owner will not necessarily wish to operate all the vessels he has available each week. He must choose that annual fleet size which results in that combination of operating and idle vessels (if any) which mazimizes net returns summed over the entire season.

The procedure for programming this constrained maximization problem is to regard the initial value for the seasonal fleet size as a binding constraint on the maximum number of vessels which could be deployed in any one week. The full season is run with precisely the same fleet control algorithm described in the previous section. If the constraint $V_t \leq V_\tau$ prevents the net return maximizing fleet size from being deployed during any week, the flow of logic is redirected so that the initial guess at the optimal annual fleet size, V_τ, is
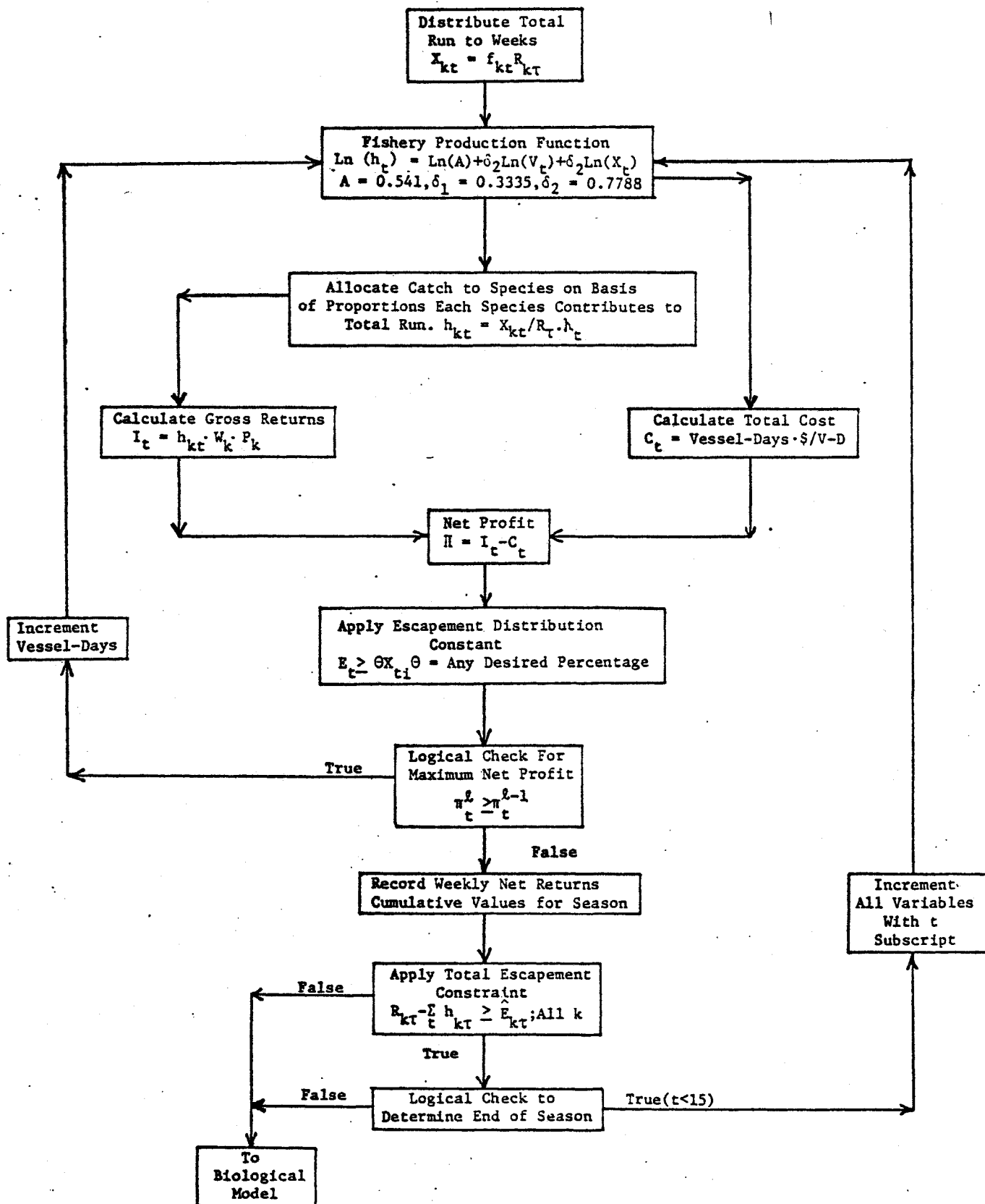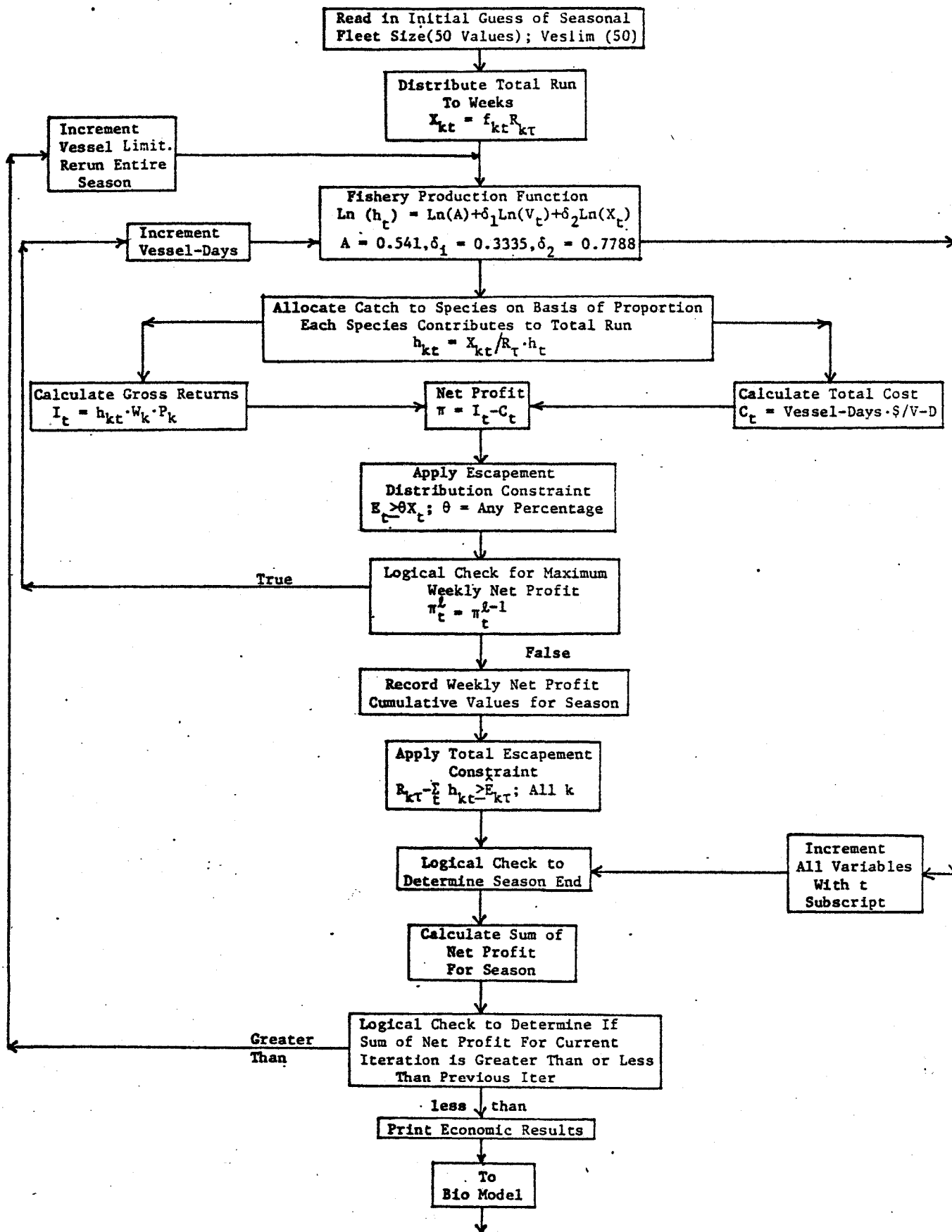
Figure 2

DETAIL OF HARVESTING TECHNOLOGY
CASE I

$$\boxed{\begin{array}{c} \textbf{Distribute Total} \\ \textbf{Run to Weeks} \\ X_{kt} = f_{kt} R_{k\tau} \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Fishery Production Function} \\ Ln\ (h_t) = Ln(A) + \delta_2 Ln(V_t) + \delta_2 Ln(X_t) \\ A = 0.541, \delta_1 = 0.3335, \delta_2 = 0.7788 \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Allocate Catch to Species on Basis} \\ \textbf{of Proportions Each Species Contributes to} \\ \textbf{Total Run.}\ h_{kt} = X_{kt}/R_\tau \cdot h_t \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Calculate Gross Returns} \\ I_t = h_{kt} \cdot W_k \cdot P_k \end{array}} \qquad \boxed{\begin{array}{c} \textbf{Calculate Total Cost} \\ C_t = \text{Vessel-Days} \cdot \$/V\text{--}D \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Net Profit} \\ \Pi = I_t - C_t \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Increment} \\ \textbf{Vessel-Days} \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Apply Escapement Distribution} \\ \textbf{Constant} \\ E_t \geq \theta X_{ti}\ \theta = \text{Any Desired Percentage} \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Logical Check For} \\ \textbf{Maximum Net Profit} \\ \pi_t^\ell \geq \pi_t^{\ell-1} \end{array}}$$

True

False

$$\boxed{\begin{array}{c} \textbf{Record Weekly Net Returns} \\ \textbf{Cumulative Values for Season} \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Increment} \\ \textbf{All Variables} \\ \textbf{With t} \\ \textbf{Subscript} \end{array}}$$

$$\boxed{\begin{array}{c} \textbf{Apply Total Escapement} \\ \textbf{Constraint} \\ R_{k\tau} - \sum_t h_{k\tau} \geq \hat{E}_{k\tau}; \text{All k} \end{array}}$$

False

True

$$\boxed{\begin{array}{c} \textbf{Logical Check to} \\ \textbf{Determine End of Season} \end{array}}$$

False ← | → **True(t<15)**

$$\boxed{\begin{array}{c} \textbf{To} \\ \textbf{Biological} \\ \textbf{Model} \end{array}}$$

Figure 3
DETAIL OF HARVESTING TECHNOLOGY
CASE II

Read in Initial Guess of Seasonal
Fleet Size(50 Values); Veslim (50)

Distribute Total Run
To Weeks
$X_{kt} = f_{kt}R_{k\tau}$

Increment
Vessel Limit.
Rerun Entire
Season

Fishery Production Function
$Ln (h_t) = Ln(A)+\delta_1 Ln(V_t)+\delta_2 Ln(X_t)$
$A = 0.541, \delta_1 = 0.3335, \delta_2 = 0.7788$

Increment
Vessel-Days

Allocate Catch to Species on Basis of Proportion
Each Species Contributes to Total Run
$h_{kt} = X_{kt}/R_\tau \cdot h_t$

Calculate Gross Returns
$I_t = h_{kt} \cdot W_k \cdot P_k$

Net Profit
$\pi = I_t - C_t$

Calculate Total Cost
$C_t = $ Vessel-Days $\cdot \$/V-D$

Apply Escapement
Distribution Constraint
$E_t \geq \theta X_t$; $\theta = $ Any Percentage

Logical Check for Maximum
Weekly Net Profit
$\pi_t^\ell = \pi_t^{\ell-1}$

True

False

Record Weekly Net Profit
Cumulative Values for Season

Apply Total Escapement
Constraint
$R_{k\tau} - \sum_t h_{kt} \geq E_{k\tau}$; All k

Logical Check to
Determine Season End

Increment
All Variables
With t
Subscript

Calculate Sum of
Net Profit
For Season

Logical Check to Determine If
Sum of Net Profit For Current
Iteration is Greater Than or Less
Than Previous Iter

Greater
Than

less ↓ than

Print Economic Results

To
Bio Model

increased. With the new value for V_τ, the model runs through the same season (same total recruitment) once again. After completing this iteration a comparison is made between

$$(\sum_t \Pi_t)_i \text{ and } (\sum_t \Pi_t)_{i+1}$$

(where Π is profit and i refers to an iteration number). If

$$(\sum_t \Pi_t)_{i+1} > (\sum_t \Pi_t)_i,$$

V_τ is incremented once again with a new comparison to be made. Otherwise, the net profit maximizing fleet size for the season and its week-by-week utilization has been determined.

For purposes of writing the objective function for the fishery it is necessary to assume that the fishery is managed by a sole owner who has right of access and right to exclude others. This assumption transforms the common property fishery into a defined management unit. Institutionally, the sole owner could be a private fishing corporation in which the fishermen are employees or a government body hiring the services of fishermen. The objective functions can now be developed.

Gross revenues resulting from fishing activities for each intraseasonal time interval are

$$(14) \quad I_t = \sum_k h_{kt} \cdot W_k \cdot p_k .$$

The variable h_{kt}, harvest of race k at t, is expressed in numbers of fish and the price parameter p_k is expressed in cents per pound. The W_k are average weights per individual fish. Since it has been assumed that costs are constant with respect to vessel-days,

$$(15) \quad C_t = bV_t , \quad c'(V_t) = b .$$

Net profit in t, Π_t, then is

$$(16) \qquad \Pi_t = I_t - C_t$$

which, when summed over the entire season is

$$(17) \qquad \Pi_\tau = \sum_t \Pi_t = \sum_t (I_t - C_t) \quad .$$

The sole owner with perpetual tenure, who within the season acts to maximize the value of current net profits, also wishes to correct for this myopia by using self-imposed escapement constraints to find that harvesting policy which results in the largest value of his asset, the fishery. Thus, during the season (17) is maximized subject to the production function, (18), and a harvest no greater than actual recruitment for the season, (19):

$$(18) \qquad h_t = A V_t^{\delta_1 + 1} X_t^{\delta_2 + 1}$$

$$(19) \qquad \sum_t h_t \leq R_\tau \quad .$$

However, the sole owner recognizes that maximization of current net returns has implications for future seasons' fishing activity. Therefore, the sole owner imposes the additional constraints, (20) and (21), experimenting with various values

$$(20) \qquad R_{k\tau} - \sum_t h_{kt} \geq \hat{E}_{k\tau}$$

$$(21) \qquad E_t \geq \Theta X_t \quad ,$$

of $\hat{E}$, and Θ so as to find those values which result in the largest discounted present value of the net profit stream. Thus, experiments are performed so as to maximize

$$(22) \quad \sum_{\tau} \Pi_{\tau} \, a^{\tau-1} \quad , \quad a = \frac{1}{1+r}$$

subject to (18) through (21).

Interseasonal Relationships

The biological growth model employed in the model utilizes a disaggregated approach to salmon population dynamics. This more complete approach involves segregating the life cycle into a series of stages. Based on research published in the biological literature, it is possible to attribute different types of mortality phenomena to different life stages and, of course, to the flow regimes of particular river systems. In particular, research has been conducted on Skeena River salmon stocks (especially sockeye) which has been used to develop simulation models of their population dynamics. The biological model employed is patterned after the models of Larkin and McDonald[6] and Larkin and Hourston.[7]

Upon completion of the harvesting activity in each season, the accumulated escapement by race enters the biological phase of the model, the first stage of which is the egg deposition stage. The age distribution of the sockeye escapement affects the size of the egg deposition since more mature fish are of larger size and produce more eggs per individual. Additionally, males form a larger percentage of the younger fish. To account for these phenomena, the egg deposition associated with each sockeye age group is adjusted by an egg production factor. The factors are chosen so that the sum of the products of the proportions of sockeye maturing at various ages and the egg production factors equals unity. This reflects the equilibrium condition that the race must be just capable of reproducing itself.

In contrast to sockeye, pink salmon do not exhibit a variable age at return. While there is definitely a size-distribution of returning pink and while the number of eggs produced will vary positively with the size of the female, for practical purposes it will be assumed that each female deposits the same quantity of eggs on average.

The stages of life through which the new brood must pass on the path to adulthood--alevin, fry and smolt--are all subject to various types of mortality--compensatory, depensatory and extrapensatory. The sequence in which these mortality types affect the various life stages may vary with both the race and the freshwater environment. It is generally thought that compensation occurs among salmon in the egg stage. The competition among adults for a limited supply of good spawning sites and the competition among eggs for oxygen are thought to be strong reasons to suspect compensation at this stage, given freshwater environmental conditions. For sockeye, which spend at least one year in the freshwater stage, the limited rearing capacity of this environment is a further reason to suspect compensation to occur during the juvenile stages.

To simulate compensatory mortality, two equations are employed--one applying to brood densities greater than one unit and the other applying to brood densities less than one unit. Brood size in numbers is converted to density--relative magnitudes--before application of natural mortality. The two-equation approach is utilized to avoid the unusually high compensation implied by the Ricker equation for density dependent predation (applied to brood densities less than one unit) given below:

$$(23) \quad Z = Ee^{a_1(1-E)} \quad , \quad E < 1.0$$

where Z refers to the production of progeny from E adults and a_1 is the compensation coefficient. For brood densities greater than one unit, the modified Ricker equation employed is

$$(24) \quad Z = (1-D)e^{-a_2(E-1)} + D \quad , \quad E > 1.0 \quad .$$

Here D is the asymptote of brood units beyond which there is no compensation. Z and E have the same definitions as above. This sequence and procedure for implementing compensation applies to both the sockeye and pink species.

Fluctuations in the quality of the freshwater and marine environments can have a substantial effect on salmon stocks. These fluctuations have been observed historically in wide swings in the size of the returning adult run. The magnitude of such environmental effects is unrelated to the size of the biomass and for this reason is termed extrapensatory mortality.

To simulate these effects, a procedure developed by Ricker and refined by Larkin and Hourston is employed. This procedure involves the application of scaled random normal deviates. The value of the deviates produced by this procedure are augmented in absolute value by 1.0 and are used as multipliers if the sign of the deviate is positive and as divisors if the sign is negative. To achieve an order of magnitude ratio of extremes for environmental fluctuation, scaling factors are applied before the deviate is augmented in absolute value. In this model the extrapensatory natural mortality routine is applied after the compensatory natural mortality stage in order to simulate the biomass fluctuations caused by freshwater environmental variation. There is no marine extrapensatory natural mortality in this model.

The final stage of mortality in the biological model is critical for creation of cycles in the size of the spawning population. The mechanism employed to apply depensatory mortality must generate an increasing rate of mortality for smaller fry populations. The rationale behind this type of mortality phenomenon is to simulate, for example, the situation in which a predator takes a larger proportion of a small population than of a larger one. Another type of

biological situation in which depensation operates is that in which mortality is a function of the density of prey in previous years.[8] Larkin and Hourston hypothesized that predators prospered on eggs and fry produced by previous broods and that the most appropriate single index of the availability of this food supply was the size of the spawning escapement which produced it.[9] Thus the value of the coefficient of depensation was made a function of the previous three years' spawning escapements whose influence on the value of the coefficient was hypothesized to decline with the 'age' of the spawning escapement. Larkin and McDonald also followed this same procedure.[10]

Smolt production is expressed as follows when the fry population is less than one stock unit:

$$(25) \qquad M = G_e^{a_3(G-1)}, \qquad G \leq 1.0 .$$

In (25) M is the number of smolts produced in brood units, G is the number of fry remaining after the extrapensatory influence, and a_3 is the coefficient of depensation. When $G \geq 1.0$, the alternative relation (26) is invoked:

$$(26) \qquad M = G, \qquad G \geq 1.0 .$$

For both the Babine and non-Babine sockeye races, the value of the coefficient of depensation is expressed as a function of the size of the previous three years' spawning escapements. Thus,

$$(27) \qquad a_3 = 0.5 \, E_{\tau-1} + 0.3 \, E_{\tau-2} + 0.2 \, E_{\tau-3} .$$

The output of the depensatory mortality routine is a smolt population which will grow to maturity and return as spawning adults in subsequent years. In the natural situation some of these smolts will migrate to freshwater rearing grounds for several years while others will proceed directly to the ocean feeding grounds. To simulate this variability in life history, an accounting routine has been developed. This routine advances the biological system one year at the close of the mortality routine. As the salmon 'mature' through this process they eventually become subject to the formation of the run routine described above. This closes the biological life cycle and completes the description of the structure and operation of the full computer simulation model.

Results and Policy Implications

An optimal escapement policy emerged from the trial-and-error process of repeated simulation experiments using different levels of minimum annual specified escapement for both the weekly fleet hiring (Case I) and annual fleet hiring (Case II) formulations. The escapement policy which maximized the present value of net profits using a discount rate of 10% per annum turned out to be approximately the same for both cases, i.e., 300,000 sockeye and 400,000 pink. However, we found that, while the decision process of the Case II sole owner had exhausted all the opportunities for optimal allocation of available effort throughout the season, the net profits of the Case I regime were increased by the application of a constraint on the weekly escapement. Thus, the escapement policy which maximized the present value of net profits for the Case I model was a minimum specified escapement of 300,000 sockeye and 400,000 pink in addition to a minimum weekly escapement of 30% of the stock available for harvest during that week.

Specification of lower bound escapement constraints does not prevent the model from finding an interior solution consistent with the objective function. Thus, actual escapement exceeded the specified minimum by 266,000 fish for Case II and 274,000 fish for Case I (the excess of actual over desired escapement is based on the mean actual escapement for the two models). Based on comparisons of actual escapement for the two simulations with results from the actual fishery, in addition to other evidence from the simulation results, it was concluded that escapement policy in the real-world fishery has probably been more liberal than economic optima would indicate.

The implications of this finding for management of the actual fishery can be interpreted fairly directly. Given that historical escapement of sockeye and pink has averaged approximately 639,000 and 682,000 fish, respectively, while mean simulated escapement is 396,000 and 578,000 sockeye and pink, respectively, it appears that both sockeye and pink harvest could have been increased. Using the average fish prices and weights employed in the simulation model, the gross annual value of reducing mean escapement (by increasing the harvest) in the actual fishery to the mean simulated levels would be approximately $1.035 million.

A comparison of the optimal simulation results for Case I and II assumptions pointed to several contrasts between those results which have important policy and/or management implications. The marked contrast between within-season fleet utilization patterns under the two cases is one of the most obvious comparisons. The differential fleet utilization patterns result in differential within-season harvesting patterns which affect the intensity of overall exploitation of the stocks as well as the exploitation of the races which make up the stocks.

The policy and management implications of these findings are significant. If one views establishment of clearly defined property rights to fish in a river system as a means of improving the performance of the harvesting industry, it is clear that the method of establishing sole ownership and attendant institutional

rules will require careful attention. Establishment of sole ownership of the fishery by a private firm required to rent its capital equipment on a yearly basis would result in an underutilization of the Skeena River fishery in the sense that under different organizational rules a larger fleet could be utilized at certain periods during the season. Conversely, at other times during the season the fleet size would be larger than that dictated by a set of more flexible institutional rules. The result of these excesses and deficiencies of harvesting capacity is lesser present value of net profits under the Case II regime than under the Case I regime as shown by the simulation results. Were society to auction rights to the fishery, the discounted sum of net profits approximates the price a private owner would be willing to pay for the right of sole access. It is clearly in society's interest to establish institutional rules which maximize the present value of net profits of the fishery. Accordingly, it appears that a sole owner who would rent vessels on a weekly basis could optimize the fishery by adjusting the fleet capacity as dictated by the stock available for harvest.

Moreover, in addition to the reduced present value of net profits which results from use of Case II assumptions, society must reckon the additional net returns which the vessels could generate were they not sitting idle during the early and late weeks of the season.

While the optimal organization for the fishery in terms of the maximization of net profits appears to be a variant of the Case I sole ownership rules, this also implies a fleet size which fluctuates markedly from week to week within the season and from season to season. If part of the management strategy is to maintain relatively stable and continuous employment in the fishery, the Case I sole ownership regime as described here appears to do little to achieve this result. However, as described below, coast-wide application of Case I fleet hiring rules might mitigate the apparent difficulty which results from application of the Case I regime to a single salmon fishery.

In this model, management of the Skeena River fishery has been considered largely in isolation from other coastal salmon fisheries. Consider for a moment the establishment of sole ownership in all such fisheries with the Fisheries and Marine Service acting as a sole owner who licenses vessels to exploit the various fisheries. If the timing of the discrete fisheries is such that some peak while others wane, it is clear that the Case I regime need not result in wide fluctuations of employment of vessels coastwide. This adds new scope to the determination of optimal fleet capacity. It is easy to see how the model developed in this research could be repeated for all fisheries coastwide and linked through response functions which would allocate vessels to various fisheries according to their comparative marginal net returns in the different fisheries. Coastwise a set of sole owners has within it a given fleet of vessels which they desire to dispatch to the appropriate fishery much as the owner of a fleet of taxis desires to place them optimally with respect to potential fares. Within the season the fleet size is given but vessels may be retired or constructed from season to season. The timing and size of the various runs will then determine both the size of the fleet and the degree to which it is fully utilized at any point in the season.

It was concluded from all the simulation results that the fleet size which optimized the exploitation of the fishery would have to fluctuate both within the season and from season to season, irrespective of the fleet procurement rules which prevailed. Given this conclusion, some difficulty was experienced in specifying the reduction in present fleet size in the real world fishery required to achieve optimality. A rationale was developed which resulted in an order of magnitude estimate of the extent of present excess harvesting capacity. Depending upon the fleet procurement rules prevailing, it was concluded that the maximum number of vessel-days which would be optimally employed in the Skeena River during any season would be 14% less for Case II and 52% less for Case I than the maximum number of vessel-days actually employed in any one year over the period 1971-1975. This is indicative of significant excess harvesting capacity.

The final observation which can be supported by the simulation results is that, given the structure of the model and the price and cost estimates utilized in the various simulations, it does not appear that a rational sole owner following the profit motive would exploit the stock to a point approaching extinction in a virtually unconstrained fishery. From this it would appear that official management activity in the fishery, given the establishment of sole ownership, could not be justified on stock maintenance grounds. This clearly strengthens the case for measuring optimality by the economist's, not the biologist's, measure.

Footnotes

1. P. A. Larkin and A. S. Hourston, "A Model for Simulation of the Population Biology of Pacific Salmon," Journal of the Fisheries Research Board of Canada, XXI, No. 5, (1964).

2. Larkin and Hourston, "A Model for Simulation."

3. R. F. A. Roberts, "A Commercial Fisheries Production Function For the Skeena River Gillnet Sockeye Salmon Fishery," unpublished Master's thesis, University of British Columbia, 1974.

4. A problem of terminology can easily develop here. Total recruitment for the season in an anticipatory sense is given by the Ricker curve. However, strictly speaking, fish are not recruited until they are within the range of the relevant gear. Thus, for salmon fisheries, recruitment takes place throughout the season as fish enter the range of the gear. Thus, the stock of fish available during any subseasonal time period are the recruits for that period.

5. Note that in equation (12), $q(V_t, X_t)$ is the catchability coefficient and, given the form assumed there, $\partial q/\partial V_t = \delta_1 A V_t^{\delta_1 - 1} X_t^{\delta_2}$. This is not the same as $\partial h/\partial V_t$ where h is given by (13); i.e., $\partial h/\partial V_t = (\delta_1 + 1) A V_t^{\delta_1} X_t^{\delta_2 + 1}$.

6. P. A. Larkin and J. G. McDonald, "Factors in the Population Biology of the Sockeye Salmon of the Skeena River," Journal of Animal Ecology, XXXVII, (1968), p. 251.

7. Larkin and Hourston, "A Model for Simulation," p. 1254.

8. Larkin and Hourston, "A Model for Simulation," p. 1254.

9. Ibid.

10. Larkin and McDonald, "Factors," p. 251.