NBSIR 75-745

A Model for Salmon Fishery Regulatory Analysis

Frederick C. Johnson

Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

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Second Interim Report

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PREFACE

The salmon fishery modeling project is a joint State-Federal program for the development of improved techniques for analyzing the economic and biological effects of regulatory changes in the Pacific Coast salmon fisheries. This interim report covers the second segment of the project--the implementation of a multi-species, multi-stock fishery analysis model. This segment of the project was sponsored by the Washington State Department of Fisheries under Service Contract No. 588.

SECTION I. INTRODUCTION

The objective of the fishery modeling project of the Washington State Department of Fisheries and the National Bureau of Standards is to develop improved methodology for the management of the salmon fisheries of the Pacific Coast. The effective management of these fisheries requires an understanding of the biology of the salmon stocks, the economics of the fisheries, and the ecology of the stock-fishery system. Because of the overall complexity of the salmon management problem, a detailed mathematical model of the Pacific Coast salmon fisheries has been developed. The salmon fishery model contains a unified mathematical description of the population dynamics of the various salmon stocks, the physical and economic characteristics of the fisheries, and the interaction between the fisheries and the salmon stocks. The purpose of the model is to evaluate the impact of alternative fishery regulatory policies on the economic performance of the fisheries and on the abundance and long-term stability of the salmon stocks.

A description of the overall design of the fishery model was given in [2]. In order to make this report self-contained, some of the material in [2] has also been included in this report in Section II. Section III discusses the calibration and simulation phases of the model, and a mathematical description of these phases is given in Section IV. The current status of the fishery modeling project is summarized in Section V.

SECTION II. BACKGROUND AND DATA REQUIREMENTS

General Background

The fishery model is a time oriented simulation model based on a monthly time frame. A simulation begins with the initial recruitment of the salmon stocks to the fisheries, continues through the entire ocean life cycle of each stock, and ends with the final escapement of the oldest fish. From initial recruitment to final escapement, the model simulates both the effects of fishing and the biological process of growth, natural mortality, maturation, and migration. The effects of fishing are based on the population size and distribution of the stocks, their length characteristics, the regulations controlling the fisheries, and the historical performance of the fisheries as reflected in catch statistics. The total catch and catch value is obtained for each fishery, and the total escapement is obtained for each stock. This information forms the basis of comparison between alternative fishery regulatory policies.

The fishery model is a steady-state model in which the fishery regulations, effort, and other characteristics are held constant throughout the life of the stocks. Thus, the model emphasizes the major long-term effects of a stable fishery and ignores transitional effects. Although many of the processes in the model have a stochastic component, the nature of these components is not yet well understood, and the model is completely deterministic. Parameter variation techniques can be used to obtain interval bounds on the effects of regulatory changes.

Spawner-recruit relationships are not included in the model because of their highly stochastic nature. Rather, the total annual escapement serves as an index of future production. This is in keeping with the management practice of establishing escapement quotas and adjusting the terminal fisheries to achieve these goals.

The fishery model is concerned with two major entities: salmon stocks and salmon fisheries. A stock is any group of salmon which has been identified for management purposes. Typically, a stock is a particular species further classified by spawning ground location. For example, chinook salmon originating from Puget Sound are completely distinct from chinook salmon originating in the Columbia River. A stock may also be thought of as a group of fish that has been identified by a single mark, such as a coded-wire tag.

The term salmon fishery is somewhat abused since it can refer to a collection of individual fisheries or to a specific fishery. Each fishery in the model is identified by the location of the fishing activity, the type of fishing gear used, the target species of salmon, and the participants in the fishery. Fishery participants are generally distinguished by nationality (U.S. or foreign citizen). This is necessary since different participants can be subject to different sets of regulations.

Data Selection and Model Development

The equations and techniques described in Sections III and IV were selected based on the type of data available for analysis. Consequently, the input data for the model will be described prior to the development of the model itself in order to motivate the material in those sections. The input data for the fishery model consists of three types:

fishery specifications,

stock specifications,

catch data.

The fishery specifications describe the physical and economic characteristics of each salmon fishery, and the stock specifications describe the biological characteristics of each salmon stock. The catch data describe the effects of the stock-fishery interactions.

The following data are used to specify each salmon fishery:

1. area,
2. target species,
3. participant type,
4. gear type,
5. season specifications,
6. induced mortality data,
7. catch values.

The area specifies the location of the fishery, and the target species specifies the species of salmon caught by the fishery. The participant type gives the nationality of the fishery participants, and the gear type identifies the fishing equipment used. The season specifications consist of an opening date and a closing date for the fishing season and the minimum legal length of the catch during the season. A fishery may have more than one season during the year due to changes in minimum length regulations. This is needed, for example, for the Washington troll fishery for coho salmon, which has no size limit in the early summer but has a 16-inch size limit in the late summer and fall.

Induced mortality refers to mortality caused by the act of fishing but which does not generate any catch value. The fishery model considers two types of induced mortality, hooking mortality and cross-species mortality. Hooking mortality is caused by catching sublegal-sized fish. Cross-species mortality occurs in a mixed-species fishery when the season for one species is closed. The induced mortality data specify the starting and ending dates for the mortality, the species affected, and the mortality rate. The induced mortality rate is a function of the catch, i.e., a rate of .1 means that one fish is killed by induced mortality for every 10 fish that are caught.

The catch values for commercial fisheries are ex-vessel prices in dollars per pound. Since the dollar per pound price can change based on the total weight of the fish, the price is specified by weight range. In other words, a fish weighing less than 8 pounds may be worth $0.75 per pound, while a fish larger than 8 pounds may be worth $1.00 per pound. A similar scheme is used for sport fishery values, but in this case, the value is specified as dollars per fish. Since some difference of opinion exists concerning sport fishery values, this technique can be used to represent any particular sport valuation philosophy.

The stock specifications consist of:

1. species,
2. natural mortality rates,
3. growth data,
4. length frequency data,
5. migration paths,
6. substock ratios.

The natural mortality rates of a stock are distinguished by age and maturity and give the fraction of the population which dies due to natural causes in each year.

Growth data are treated somewhat differently in the model than is usual. A common treatment of fish growth utilizes the von Bertalonffy equation (see [1])

$$L(t) = L(t) + (L_x - L_0)(1 - e^{-K(t-t_0)})$$

where $L(t)$ is the length of a fish at time t, t_0 is a base time, $L_0 = L(t_0)$, L_x is the asymptotic length limit, and K is an empirical constant. This equation expresses growth as a function of the three parameters L_0, L_x, and K. Because of seasonal changes in the growth of salmon in the ocean, even annual sets of constants are inadequate. Therefore, there is no real advantage in using such a growth model. Instead, a set of lengths is used to specify growth throughout the year, and these length data are distinguished by age and maturity. Since the model time period is one month, 12 lengths are used for each age and maturity combination.

The length data represent the mean lengths of the members of a fish stock. It is assumed that the lengths of a population are normally distributed. The length frequency data characterize this distribution. Four numbers are specified, σ_0, σ_U, L_0, and L_U. L_0 and L_U are the minimum and maximum mean lengths attained by the stock, and σ_0 and σ_U are the corresponding standard deviations. For each length L, the associated standard deviation $\sigma(L)$ is given by:

$$\sigma(L) = \sigma_0 + \frac{L - L_0}{L_U - L_0} (\sigma_U - \sigma_0).$$

While the stock is the principal salmon entity, a stock must be further categorized into substocks in order to account for major variations in the migration patterns of a stock. All substocks have the same growth and natural mortality characteristics, but differ by migration pattern. The migration data specify the fishing areas over which a substock is distributed, and the migration patterns are distinguished by age and maturity. The substock ratios specify the fraction of the total stock population (at initial recruitment) for each substock. It should be noted that these ratios will change throughout the life of a stock due to the effects of exposure to different fisheries.

The vast majority of the input data to the model consist of catch data. The catch data consist of the number of fish caught, the average length of the fish, and the average weight of the fish. These data are categorized by stock, fishery, age, sex and maturity of the fish, and the time period of the catch. These data are based on historical catch statistics and form the basis for calibrating all parameters in the model.

It may be noted that escapement data have not appeared explicitly in the above description. Escapement is treated by the model as simply another fishery, and the "mortality" for this fishery actually represents the number of fish reaching the spawning grounds. Also, there is no explicit specification of maturation rates for a stock. Since the catch data are distinguished by sex and maturity, it will be seen in Section IV that maturation rates may be derived from these data.

SECTION III. MODEL PROCESSES

The fishery model contains two principal phases--calibration and simulation. The calibration phase is the major portion of the model and is a complex process. After a calibration has been performed, however, the resulting parameters can be used to analyze alternative management policies by multiple executions of the simulation phase. Recalibration is necessary only if new stock, fishery, or catch data become available.

Calibration Phase

The calibration phase of the fishery model calculates all of the fishing mortality rates and the stock maturation rates. The fishing mortality rates are based on the number of fish caught (from the catch data) and the numbers of fish that are of legal (or sublegal) size. Separate rates are computed for each substock/fishery combination. In order to calculate the fishing and maturation rates, several tasks are involved.

The first step of the calibration process is the computation for each stock of the initial number of fish that recruit to the fisheries. A partial estimate of this number is obtained by back calculation using catch data and natural mortality data. At the same time, initial estimates of the maturation rates are obtained. Since the catch data distinguish catch only by stock and not by substock, catch must be allocated to substocks in order to account for differences in migration patterns. Catch allocation is based on the proportional representation of each substock in a catch area. In a similar manner, the induced mortality must be allocated to substocks. The induced mortality allocation differs from catch allocation in that induced mortality is distinguished only by species and not by stock, age, sex, or maturity. Induced mortality is allocated to substock-age-sex-maturity combinations within a species by the model, and this allocation is also based on the proportional representation of the substocks. As the induced mortality is allocated to each substock, it is also back calculated, and final estimates of initial recruitment and maturation rates are obtained.

The final step of the calibration process is the computation of the fishing mortality rates. These rates are obtained by sweeping forward in time and computing the ratio of catch to legal population and/or the ratio of induced mortality to sublegal population.

Simulation Phase

The catch data used in the calibration process reflect a particular set of fishery regulations in force when the data were obtained. Thus, an analysis of a regulatory change first requires a calculation of the effects of the change on the calibrated fishing mortality rates. Generally, a regulatory change will increase or decrease a fishing rate as, for example, when a fishing season is changed. Changes in minimum length regulations, however, do not affect effort but alter the split between the legal and sublegal portions of the stock populations. After the regulatory changes have been converted to rate changes, the simulation phase of the model performs a complete simulation of the stock/fishery system and calculates the catch, catch value, and escapement obtained based on the new rates.

Three types of regulatory changes can be analyzed: season changes, effort changes, and minimum length changes. The effects of new fishery regulations are obtained by first computing scale factors for the calibrated fishing mortality rates and then performing the simulation process. The simulation process treats each salmon substock as an independent entity, and all substocks are processed in an identical fashion.

For each substock population, the simulation begins with the recruitment of young fish to the fisheries. The age of recruitment can vary, but recruitment generally occurs in the second year of life. Based on the calibrated maturation rates for male and female fish, the substock population is decomposed into two groups: a group of fish that will mature during the current year of life, and a group of fish which will not mature during the current year. The mature fish are then subjected to the monthly processes of growth and natural mortality. At the same time, the fish are subjected to fishing mortality. The fishing mortalities that affect the population depend upon the migration path of the population (this determines which fisheries are actively exploiting the population), the length distribution of the population, the types of fishing gear, the regulations controlling the fisheries, and the calibrated fishing rates.

Fishing mortality is either induced mortality and/or catch mortality. The value of the catch is determined by the number of fish caught, the average weight per fish, and the price structure of the fishery which caught the fish. Since escapement is treated as a type of fishery, escapement mortality actually determines the number of fish which arrive on the spawning grounds.

The same procedure is applied to the immature fish. These fish are subject to (possibly) different growth, natural mortality, and migration and, consequently, the effects of the fisheries may be substantially different than was the case with the mature fish. At the end of the calendar year, the remaining immature fish undergo another maturation process, and the entire cycle is repeated for the fish which are now 1 year older. It should be noted that while the effects of the fisheries may change because of the annual changes in the biological characteristics of the population, the physical characteristics of the fisheries remain unchanged. This gives the steady-state nature of the model. Each age and maturation class of every substock passes through a constant set of fisheries which are subject to an unchanging set of regulations throughout the entire life cycle of all substocks.

The annual cycle of maturation, migration, growth, and mortality is continued until all fish have matured and final escapement statistics are obtained. This terminates the processing for a substock. After all stocks have been processed, the total catch in numbers and weight, the catch value, and the induced mortality are known for each fishery/stock combination. In addition, the total escapement is known for each stock. These data are summarized and reported by the model, and this completes the simulation process.

Because of the complex and possibly changing goals of salmon fisheries management, no attempt has been made to compute an overall measure of worth for a fisheries management policy. The model simply computes the effects of a policy; evaluation and comparison of the effects of alternate regulatory policy remain in the hands of the management agency.

SECTION IV. MATHEMATICAL DESCRIPTION OF THE MODEL

Background

The interaction between fishing and a stock is commonly based on the differential equation:

$$\frac{dN}{dt} = -ZN, \tag{1}$$

where $N(t)$ is the population of the stock at time t and Z is the instantaneous total mortality coefficient. Thus, the number of fish alive at any time t is:

$$N(t) = N_0 e^{-Z(t-t_0)}, \tag{2}$$

where $N_0 = N(t_0)$. The mortality coefficient Z can be decomposed into two terms:

$$Z = M + F$$

where M is the coefficient of natural mortality and F is the coefficient of fishing mortality. It can be shown (see [1]) that the number of fish caught in the fishery is:

$$C(t) = \frac{F}{Z} [N_0 - N(t)]. \tag{3}$$

When more than one fishery is active, then:

$$F = \sum_j F_j$$

and,

$$C_j(t) = \frac{F_j}{Z} [N_0 - N(t)],$$

where F_j is the fishing coefficient of the fishery j, and $C_j(t)$ is the corresponding catch.

If we adopt a uniform time interval $\Delta t = 1$ and let $N_i = N(t_0 + i\Delta t)$, then equations (2) and (3) can be written as:

$$N_{i+1} = N_i e^{-Z_i}, \tag{4a}$$

and,

$$C_i = \frac{F_i}{Z_i}(N_i - N_{i+1}), \tag{4b}$$

where the mortality rates M_i and F_i are allowed to vary with i.

When the catch history $\{C_i\}$ is known and estimates for the natural mortality rates are available, then equations 4a and 4b can be used to calculate the initial number of recruits to the fishery by the back-calculation method. Suppose that N_{i+1} is known. Equations 4a and 4b then contain two unknowns, F_i and N_i and may be rewritten as:

$$N_i = N_{i+1} e^{F_i + M_i}, \tag{5a}$$

and,

$$C_i = \frac{F_i}{F_i + M_i} N_{i+1}(e^{F_i + M_i} - 1). \tag{5b}$$

F_i may be obtained from equation (5b) by the Newton-Raphson iterative process, and equation (5a) then gives N_i. The process can now be repeated to obtain F_{i-1}, N_{i-1}, F_{i-2}, N_{i-2}, etc.

Let ℓ be the final time period in which fishing occurs. If escapement, E, occurs after t_ℓ, then the back-calculation processes are initialized by setting $N_{\ell+1} = E$. In the more general case in which all escapement occurs simultaneously with fishing, $N_{\ell+1} = 0$. Equation (5b) cannot be applied in this case, but the problem may be avoided in practice by letting $N_{\ell+1} = 1$ rather than 0.

The catch equations (4a) and (4b) are generally applied using a time interval of 1 year. Since the fishery model uses a time interval of 1 month, an approximation to the catch equations is used in order to avoid the iterative process. If we let

$$e^{-(M_i+F_i)} \quad 1 - M_i - F_i$$

then equations 4a and 4b become

$$N_{i+1} = S_i N_i - F_i N_i, \tag{6a}$$

and,

$$C_i = F_i N_i, \tag{6b}$$

where $S_i = 1 - M_i$. S_i is the survival rate. Equations (6a) and (6b) are the basic catch equations of the model, and the corresponding back-calculation equation is

$$N_i = (N_{i+1} + C_i)/S_i. \tag{7}$$

The Calibration Process

The input data to the model define all of the biological characteristics for each stock except the maturation rates and the initial number of recruits for each substock. This information, together with the fishing rates, is calculated during the calibration process of the model. The description of the calibration process is, as will be seen, an exercise in indexing. In an effort to make the description as meaningful as possible, we introduce the following mnemonic indices:

Parameter	Index
Stock	s
Substock	ss
Time	t
Fishery	f
Age	a
Sex	x
Maturity	m

The range of the stock and substock indices will vary during the different parts of the calibration process. The text will make clear the appropriate range. The time index, t, refers to month, and its upper-bound T is month 12. The age index is in years, and its upper-bound $\bar{a}$ is species-dependent (for coho salmon, $\bar{a} = 3$, and for chinook, $\bar{a} = 5$). The sex index x is either M for male or F for female, and the maturity index m is either I for immature or A for adult. The upper-bound $\bar{f}$ for the fishery index is the total number of salmon fisheries.

We will use C to denote either catch or escapement, and N will be used for population size. Indices will be added to denote the parameters of interest. For example, C (s, a, m, x, f, t) refers to the number of fish caught in fishery f at time t from stock s of age a, maturity m and sex x. The fisheries can be considered to be numbered sequentially over all areas, gears, and participants. Thus, the index f defines these three characteristics for each fishery.

Allocation of Catch to Substock

The catch allocation process consists of two steps; a back calculation to obtain the initial number of recruits for each substock, and a forward calculation to perform catch allocation.

The stock index s is held fixed during the catch allocation process, and the same procedure is followed for each sex. Therefore, we will suppress the stock and sex indices unless explicitly required. Let C(a, m, t) be defined by

$$C(a, m, t) = \sum_f C(a, m, t, f).$$

Since no mature fish are left alive at the end of the year, it follows from equation (7) that for all ages a,

$$N_c(a, M, T) = C(a, M, T)/S(a, M), \tag{8}$$

where S(a, M) is the monthly survival rate, and the subscript c indicates that the population estimate N_c is based on catch data only. Similarly, since there are no immature fish in the final year of life, we have that

$$N_c(\bar{a}, I, 1) = 0. \tag{9}$$

At the end of the year, the following equation holds

$$N_c(a, I, T) = \sum_m N_c(a+1, m, 1)/S(a, I) + C(a, I, T), \tag{10}$$

for a = 1, 2,..., $\bar{a}$ - 1. Equation (10) simply states that both the immature and mature fish of one age are all immature at the preceding age. Equations (8) through (10) are the starting points for the back calculation process given by

$$N_c(a, m, t) = N_c(a, m, t+1)/S(a, m) + C(a, m, t), \tag{11}$$

where a = 1, 2,..., $\bar{a}$, and t = 1, 2,..., T - 1. Let $\mu_c(a, x)$ be the maturation rate for fish of age a and sex x. Then

$$\mu_c(a, x) = \frac{N_c(a, M, x, t_0)}{\sum_m N_c(a, m, x, t_0)}, \tag{12}$$

where the time index t_0 is the first time period of the year ($t_0 = 1$). The maturation rate μ is simply the ratio of mature fish to total population and is a function of age and sex.

Maturation is the only process in the model that is sex dependent. All other biological processes are assumed to be identical for both males and females. Therefore, we introduce the sex ratio α_c, defined by:

$$\alpha_c(a, m, x) = \frac{N_c(a, m, x, t_0)}{\sum_x N_c(a, m, x, t_0)}. \tag{13}$$

This ratio determines the fraction of males and females in a mixed population when sex is not distinguished. From this point on, sex will not be distinguished in the population value N_c, and we define

$$N_c(a, m, t) = \sum_x N_c(a, m, x, t).$$

Let a_0 be the age that stock s recruits to the fisheries. Then $R_c(s) = \sum_m N_c(a_0, m, t_0)$ is the total number of recruits for the stock. $R_c(s)$ is broken down into substock populations by $R_c(ss) = \beta(ss)\ R_c(s)$ where $\sum_{ss} \beta(ss) = 1$. $\beta(ss)$ is the initial fraction of the total stock population that follows the migration pattern of substock ss, and $\beta(ss)$ is specified by input data. The range of ss is over the substocks of stock s only.

We are now able to begin the forward calculation process to allocate catch to substocks. The catch allocation process is based on the population of legal fish subject to a fishery. Let $\lambda(a, m, f, t)$ be the fraction of the population of stock that is of legal size in fishery f at time t. Since all substocks follow the same growth pattern, λ is not substock dependent. The current version of the fishery model assumes that the lengths of the members of a population are normally distributed with mean $L(a, m, t)$ and standard deviation

$\sigma(a, m, t)$. The values of $L(a, m, t)$ are specified by input data, and σ is given by

$$\sigma(a, m, t) = \sigma_0 + \frac{L(a, m, t) - L_0}{L_x - L_0} (\sigma_x - \sigma_0),$$

where L_0 is the minimum fish length, L_x is the maximum fish length, and σ_0 and σ_x are the corresponding standard deviations. L_0, L_x, σ_0, and σ_x are all specified by input data.

Let $\ell(f, t)$ be the regulatory minimum length for fishery f at time t. Then $\lambda(a, m, f, t)$ is given by

$$\lambda(a, m, f, t) = \int_{\ell(f,\ t)}^{\infty} f(L[a, m, t], \sigma[a, m, t]),$$

where $f(L, \sigma)$ is the normal probability density function with mean L and standard deviation σ. Let $P(ss, a, m)$ be the set of fisheries to which substock ss is exposed because of its migration path for age a and maturity m. We extend the definition of λ by defining

$$\lambda(ss, a, m, f, t) = \lambda(a, m, f, t),$$

if f is a member of $P(ss, a, m)$, and

$$\lambda(ss, a, m, f, t) = 0,$$

otherwise. The number of legal fish from substock ss in fishery f is then

$$\lambda(ss, a, m, f, t) * N(ss, a, m, t),$$

which we shall abbreviate as

$$\lambda(ss, f) * N(ss, a, m, t).$$

The catch allocation process now proceeds by processing all substocks simultaneously in the forward computation,

$$N_c(ss, a, m, t+1) = S(a, m) * N_c(ss, a, m, t) - \sum_f C(ss, a, m, f, t), \quad (14)$$

where C(ss, a, m, f, t) is obtained by proportionately allocating the stock catch C(s, a, m, f, t) by the formula

$$C(ss, a, m, f, t) = \frac{\lambda(ss, f) * N_c(ss, a, m, t)}{\sum_{ss} \lambda(ss, f) * N_c(ss, a, m, f)} . \quad (15)$$

The forward calculation process automatically adjusts the substock catch ratios for the effects of previous fishing.

The initial conditions for equation (14) are:

$$N_c(ss, a_0, m, t_0) = R_c(ss) * \sum_x \mu(a_0, x) * \alpha(a_0, m, x).$$

The populations are initialized at the beginning of each following year by

$$N_c(ss, a, m, t_0) = N_c(ss, a-1, I, T+1) * \sum_x \mu(a, x) * \alpha(a, m, x),$$

where,

$$N_c(ss, a, I, T+1) = S(a, I) * N_c(ss, a, I, T) - \sum_f C(ss, a, m, f, T).$$

In other words, the immature fish at the end of 1 year are converted to immature and maturing fish for the next year.

Induced Mortality Allocation

If there were no induced mortality, we could now complete the calibration process by computing fishing mortality rates. When induced mortality exists, however, it must also be allocated to substocks and back-calculated to obtain a complete estimate, R(ss), of the initial number of recruits. Induced mortality is categorized only by species, fishery, and time, and it must be allocated to all substocks of the species. The following development of the induced mortality allocation process is for a fixed species, and the same process is applied to all species. Therefore, a species index will not be indicated. The range of the substock index, ss, is over all substocks of all stocks of the species.

We define the induced mortality, I, caused by fishery f in time t by,

$$I(f, t) = \psi(f, t) \sum_{ss} \sum_{a} \sum_{m} \sum_{x} C(ss, a, m, x, f, t),$$

where the induced mortality rate $\psi(f, t)$ is specified by input data.

The current version of the fishery model considers the induced mortality caused by the catch and release of sublegal-sized fish--the so-called "hooking mortality." Consequently, this type of induced mortality is dependent upon the minimum length regulation, $\ell(f, t)$, and the fraction of the population that is of sublegal length. We also consider the case of cross-species mortality, which occurs when the season is closed for one species. In this case, the total population is sublegal. Let ν be the fraction of a population that is sublegal in fishery f. We define

$$\nu(ss, a, m, f, t) = \int_0^{\overline{\ell}(f, t)} f(L[ss, a, m, t], \sigma[ss, a, m, t]).$$

In most cases, $\nu = 1 - \lambda$, but one difference may arise. The upper integration limit, $\overline{\ell}(f, t)$ is defined as follows. Let g(f), p(f), and sp(f) be the gear type, participant type, and target species of fishery f, and let SP be the species for which induced mortality is being allocated. If sp(f) = SP, then $\overline{\ell}(f, t) = \ell(f, t)$. This is the hooking mortality case. If sp(f) $\neq$ SP, cross-species mortality holds and $\overline{\ell}(f, t)$ is equal to $\ell(f', t)$ if there exists a fishery f' such that g(f') = g(f), p(f') = P(f), and sp(f') = SP. If no such fishery f' exists, then $\overline{\ell}(f, t)$ is infinity (the entire population is sublegal).

The reason for the above definition is best illustrated by an example. Suppose that a non-Indian (participant type) fisherman is active in a troll (gear type) fishery for chinook salmon, and suppose that he catches a coho salmon. If the coho season is closed, he must release the fish no matter what its size, and it is subject to cross-species mortality. However, if the non-Indian, troll season for coho salmon is open, the fisherman will release the fish only if it is less than the minimum length regulation for the coho fishery.

The first step in the induced mortality allocation process is the allocation of I(f, t) to age class. We define

$$Y_c(a, f, t) = \sum_{ss} \sum_{m} \nu(ss, f, t)\, N_c(ss, a, m, t),$$

where we again adopt the convention that $\nu(ss, f, t) = 0$ if f is not in P(ss, a, m). $Y_c(a, f, t)$ is the population of age a that is subject to induced mortality from fishery f in time t. I(f, t) is allocated to age class on a proportional basis,

$$I(a, f, t) = \frac{Y_c(a, f, t)}{\sum_a Y_c(a, f, t)} * I(f, t).$$

We are now ready to allocate the age classified induced mortality I(a, f, t) to the immature and mature substock populations. As with the catch allocation process, this requires a backward calculation in order to account for migration effects. We now introduce the notation $N_I(ss, a, m, t)$ to indicate a population number obtained solely from the back calculation of induced mortality. The total substock population is then

$$N(ss, a, m, t) = N_c(ss, a, m, t) + N_I(ss, a, m, t).$$

The back calculation equations are identical to (8) through (11) with N_c replaced by N_I.

In order to allocate the induced mortality, we need to know the total population D(a, f, t) subject to this mortality. It follows that

$$D(a, f, t) = Y_C(a, f, t) + \sum_{ss} \sum_{m} \nu(ss, f, t) * N_I(ss, a, m, t+1)/S(ss, a, m). \quad (16)$$

The first term in equation (16) represents the contribution from catch data, and the second term is the contribution from back-calculated induced mortality. D(a, f, t) should also include a term for the current induced mortalities $I(a, t) = \sum_f I(a, f, t)$. However, the inclusion of this term would ultimately require the solution of a potentially large set of simultaneous equations. Since $I(a, t) << D(a, f, t)$ (i.e., induced mortality is small relative to population size), the error introduced by ignoring this term is small, and the allocation process is greatly simplified.

Let I(ss, a, m, f, t) be the induced mortality allocated to maturity m of substock ss from fishery f. Then the proportional allocation of I(a, f, t) is

$$I(ss, a, m, f, t) = \frac{\nu(ss, f, t) * [N_C(ss, a, m, t) + N_I(ss, a, m, t+1)/S(s, m)] * I(a, f, t)}{D(a, f, t)} \quad (17)$$

I(ss, a, m, f, t) is then used for the next step of the back-calculation process for N_I.

Upon the completion of the induced mortality allocation and back-calculation process, we have obtained the final values N(ss, a, m, t) of the life histories of the substock populations. As a side effect of including induced mortality, the initial substock ratios β will change. The final values $\overline{\beta}$ are

$$\overline{\beta}(ss) = \frac{\sum_{m} N(ss, a_0, m, t_0)}{\sum_{ss} \sum_{m} N(ss, a_0, m, t_0)} \quad (18a)$$

where the range of the index ss is over the substocks of each stock. In addition, we must compute distinct maturation rates and sex ratios for each substock. Thus:

$$\mu(ss,\ a,\ x) = \frac{N(ss,\ a,\ m,\ x,\ t_0)}{\sum_m N(ss,\ a,\ m,\ x,\ t_0)} \qquad (18b)$$

and

$$\alpha(ss,\ a,\ m,\ x) = \frac{N(ss,\ a,\ m,\ x,\ t_0)}{\sum_x N(ss,\ a,\ m,\ x,\ t_0)}. \qquad (18c)$$

If we had perfect data and ideal fish, we could expect that the maturation rates, sex ratios, and substock ratios would not change from the initial values. Since this is not the case, these values have been permitted to change in the model calibration process in order to achieve internal consistency. The amount of change can be used as a measure of the quality of the input data.

Fishing Mortality Rate Determination

The final step in the calibration process is the calculation of fishing mortality rates. Let ρ be the fishing rate parameter. Since a fishery f may cause both catch mortality and induced mortality, an additional index v must be introduced for ρ (v for catch variety). The range of v is v = CM for catch mortality and v = IM for induced mortality. The generalized form for ρ [from equation (6b)] is then

$$\rho(ss,\ a,\ m,\ t,\ f,\ v) = \frac{C(ss,\ a,\ m,\ f,\ t,\ v)}{\gamma(ss,\ f,\ v) * N(ss,\ a,\ m,\ t)} \qquad (19)$$

where $C(ss, a, m, f, t, v) = C(ss, a, m, f, t)$ and $\gamma(ss, f, v) = \lambda(ss, f, t)$ if v = CM; and $C(ss, a, m, f, t, v) = I(ss, a, m, f, t)$ and $\gamma(ss, f, v) = \nu(ss, f, t)$ if v = IM. The computation of ρ for all index values completes the calibration of the fishery model.

Regulatory Analysis

The detailed form of the linearized catch equations (6a) and (6b) can now be written as

$$N(ss, a, m, t+1) = S(ss, a, m) * N(ss, a, m, t) - \sum_f \sum_v C(ss, a, m, f, t, v), \qquad (20)$$

where

$$C(ss, a, m, f, t, v) = \rho(ss, a, m, f, t, v) * \gamma(ss, f, v) * N(ss, a, m, t). \qquad (21)$$

Equations (20) and (21) together with the calibrated values for β, μ, and σ from equations (18a) through (18c) yield the total catch obtained from the fisheries as a function of the initial recruitment populations. The analysis of regulatory changes is based on these equations with but one more addition--a scale factor in equation (21). We write:

$$C(ss, a, m, t, f, v) = \phi(f, t) * \rho(ss, a, m, t, f, v) * \nu(ss, f, v) * N(ss, a, m, t) \qquad (22)$$

where $\phi(f, t)$ is introduced to account for changes in fishing effort due to regulatory changes ($\phi(f, t)$ is normalized to 1 in the calibration process).

Consider the three types of regulations to be analyzed: minimum length, gear limitation, and season changes. A change in minimum length leaves ϕ unchanged but will alter the catch due to changes in γ. Gear limitation will directly scale the effort parameter ϕ. It should be noted that it is never necessary for the user to know a value of ρ. All that must be specified is the relative change in ρ, e. g., if it is predicted that gear limitation will result in a 25% decrease in effort in fishery f at time t, then $\phi(f, t) = .75$.

A season closure is equivalent to setting the appropriate ϕ equal to zero. The most complex change is a season opening. Since no fishing had occurred at that time in the calibration input data, the corresponding ρ's are zero. In this case, a time period $\bar{t}$ must be specified in which fishing did occur. The fishing effort in the new open period is then specified as a function of the effort in time $\bar{t}$. Again, it is not necessary to know the values of ρ for time $\bar{t}$, only the scale factor must be specified.

Implementation Considerations

It can be seen from the preceding description of the processes of the fishery model that the major implementation problem is the treatment of the large number of indices. An approach based on multi-dimension matrices quickly breaks down due to the large amounts of storage required by the matrix approach. This problem was overcome in the fishery model by the implementation of list processing techniques for storing only the non-zero elements of the matrices. The associated indices are packed into a single computer word to further reduce core storage requirements. The current version of the fishery model can simultaneously analyze 10 stocks, 20 substocks, 30 areas, and 100 fisheries. This represents the current requirements of the Pacific Coast salmon fisheries problem.

SECTION V. PROJECT STATUS

The current segment of the joint fisheries project was primarily concerned with the implementation and validation of a multi-species, multi-stock version of the fishery model. The current version of the model can analyze salmon stocks from any combination of the five species of Pacific Coast salmon. Emphasis has been placed on the interactions between coho and chinook salmon, and the majority of the testing has been with these two species. Detailed testing and validation of the model was undertaken using both artificial test data and real data provided by the Washington State Department of Fisheries. Because of the complexity of the model, more tests have been scheduled for the next segment of the project. As of the current time, however, no known errors exist in the model based on an extensive test and validation period.

Since all fisheries in the model are identified by participant type, the model is capable of analyzing Indian fishery problems. As improved data become available on Indian fishing activity, an analysis of their activity will require only input changes and will not require any structural changes in the model.

The initial emphasis for presenting results from the model has been on the development of tabular formats. A variable report format has been developed for documenting the results of a regulatory analysis by area, participant class, gear, and species. The principal statistics presented are total catch, total weight, catch value, and induced mortality for each of the above categories. In addition, several summary statistics are provided.

Provision has been made in the model for the inclusion of a three-dimensional plotting package. After additional experience is gained in dealing with the output from the model, a decision will be made on whether three-dimensional graphics can be usefully applied. For the current time, the tabular formats have met the needs of the Department of Fisheries.

A great deal of new data have been prepared for analysis by the fishery model. Complete data have been prepared for six stocks of coho salmon and one chinook salmon. The coho stocks are Puget Sound, Willapa Bay, Grays Harbor, Columbia River, Oregon coastal, and southern British Columbia. The chinook salmon stock is Lower Columbia River fall chinook. In addition, complete input data have been prepared for all principal Pacific Coast coho and chinook salmon fisheries. These data will be analyzed and evaluated in the next segment of the fishery modeling project.

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NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 75-745	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

A Model for Salmon Fishery Regulatory Analysis

5. Publication Date July 10, 1975

6. Performing Organization Code

7. AUTHOR(S) Dr. Frederick C. Johnson

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No. 2050571

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

Washington State Dept. of Fisheries
Olympia, Washington 98504

13. Type of Report & Period Covered Second Interim Report

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The salmon fishery modeling project is a joint State-Federal program for the development of improved techniques for analyzing the economic and biological effects of regulatory changes in the Pacific Coast salmon fisheries. This interim report covers the second segment of the project-the implementation of a multi-species, multi-stock fishery analysis model. This segment of the project was sponsored by the Washington State Department of Fisheries under Service Contract No. 588.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Fisheries; Fishery; Fishery Modeling; Mathematical Modeling; Regulatory Analysis; Resource Management; Salmon Fisheries; Salmon Fishery Modeling; Simulation; State of Washington; Washington State; Washington State Fisheries.

18. AVAILABILITY [X] Unlimited

[ ] For Official Distribution. Do Not Release to NTIS

[ ] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13

[X] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
UNCLASSIFIED	32
20. SECURITY CLASS (THIS PAGE)	**22. Price**
UNCLASSIFIED	$3.75

[illegible]