North American Journal of Fisheries Management 21:533–547, 2001

The Harvest Rate Model for Klamath River Fall Chinook Salmon, with Management Applications and Comments on Model Development and Documentation

MICHAEL H. PRAGER*

Center for Coastal Fisheries and Habitat Research,
National Oceanic and Atmospheric Administration,
101 Pivers Island Road, Beaufort, North Carolina 28516, USA

MICHAEL S. MOHR

Santa Cruz Laboratory, Southwest Fisheries Science Center,
National Marine Fisheries Service, National Oceanic and Atmospheric Administration,
110 Shaffer Road, Santa Cruz, California 95060, USA

Abstract.—The fall run of chinook salmon *Oncorhynchus tshawytscha* in the California portion of the Klamath River supports important ocean and river fisheries. At the start of each annual management season, the Klamath Harvest Rate Model (KHRM) is used to propose preliminary harvest levels that are subsequently used as the basis of negotiations on harvest allocation and fishing season structure. Until recently, the KHRM existed only as a computer spreadsheet file without written documentation, from which optimal harvest levels (the highest levels attainable within current management policy) were found by repeated manual adjustment of trial values, a tedious and error-prone procedure. We provide formal treatment of the KHRM by setting forth the equations that define it and providing the analytical solution to its optimization. We then give three examples of its use in managing the stock, ranging from routine use to incorporation into simulation studies. Introduction of spreadsheets and similar simplified programming tools has encouraged the implementation of computer models that are not clearly defined mathematically. That approach forces users to decipher programming code to grasp model structure and raises the question whether model structure was carefully thought out. Written development of theory properly precedes and provides a foundation for any implementation. Explicit development of theory is critical to foster mathematical insight and consequent progress in model development. Documentation of theory is particularly important for models that are used in setting public policy since it allows them to undergo peer and stakeholder review, which increases accountability and public trust.

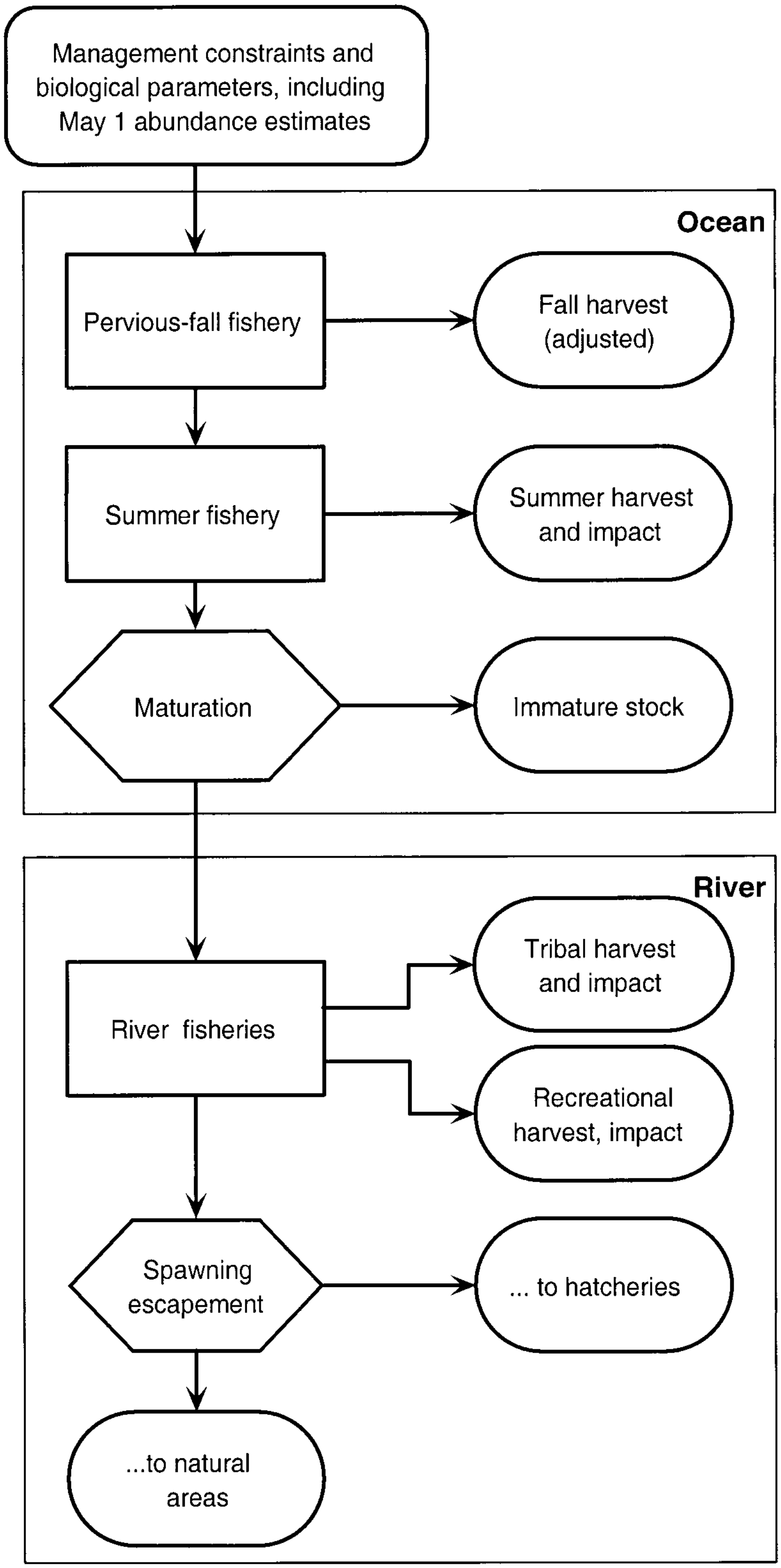
The fall run of chinook salmon *Oncorhynchus tshawytscha* in the Klamath River supports important fisheries along the northern Pacific coast of the United States, particularly off California and in the Klamath River system itself. The stock is managed by the Pacific Fishery Management Council (PFMC) under advice given by the Klamath Fishery Management Council. An overview of the fisheries is given by Pierce (1991a, 1991b) and an overview of management by Pierce (1998).

The Klamath Harvest Rate Model (KHRM) is a simple, time-aggregated model that is used each year to project the maximum harvests available in three segments (ocean, river-tribal, and river-recreational) of the fishery. Such projections are conditional on present management policy, which follows concepts developed for this fishery in the 1980s (Hankin and Healey 1986; KRTT 1986). We designate such projected maximum harvests as optimal because they are the largest available under the specified conditions. They may not be optimal in other senses, however; for example, they do not directly consider sustainability, although sustainability is a basis of the underlying management policy.

Each year, the KHRM is used early in the management process to provide estimates of anticipated harvests and a general outline of management for that year. That information allows extended discussions on harvest allocation and the time–space structure of the fishing season, discussions that are aided by repeated application of a more complex space- and time-disaggregated model, the Klamath Ocean Harvest Model (KOHM). The KOHM provides more detailed projections of harvest than the KHRM but is more difficult to apply and lacks an algorithm for op-

* Corresponding author: Mike.Prager@noaa.gov

Received December 13, 1999; accepted December 18, 2000


Management constraints and
biological parameters, including
May 1 abundance estimates
Ocean
Pervious-fall fishery
Fall harvest
(adjusted)
Summer fishery
Summer harvest
and impact
Maturation
Immature stock
River
River fisheries
Tribal harvest
and impact
Recreational
harvest, impact
Spawning
escapement
... to hatcheries
...to natural
areas

timizing harvest, thus the two models are complementary.

Until recently, the KHRM existed only as a computer spreadsheet, and in that form it had two major shortcomings: (1) the theory behind the KHRM was completely undocumented and (2) solution of the model for optimal harvest required a time-consuming process of trial and error by humans. In this paper we remove both shortcomings by separating the underlying mathematical model from its implementation. We provide the equations that form the model itself and give their analytical solution for optimal harvest. In doing so, we give the KHRM the theoretical foundation that it apparently has lacked until now.

Following the mathematical exposition, we present three examples of the KHRM's use. The first demonstrates the model's use in the annual management setting. In the second, the KHRM serves as the core of a simulation study to examine the effects of opening the fishery when it would otherwise be closed. In the third example, the KHRM is used in a Monte Carlo study to estimate the probability of achieving a management goal under uncertainty. The two simulation studies would not have been possible without the analytical solution described here.

We close by discussing documentation of fishery models. In particular, we emphasize the difference between a model and its implementation and stress that implementing a model, in a spreadsheet or otherwise, does not constitute documentation. Indeed, implementing a model without documenting the underlying theory is extremely poor practice and raises questions of correctness, completeness, and professionalism. Finally, we offer suggestions for the documentation of management models in the hope of stimulating discussion among fishery managers and scientists about the increasing number of undocumented models in our field, which do not reflect well on our profession.

Structure of the KHRM

The KHRM is a simple box model with only two boxes: the ocean and the river (Figure 1). The model begins in the ocean with a preseason population whose size has been estimated previously. Ocean harvest and related mortalities are then applied to this population; a certain fraction of the remaining stock is presumed to become mature and migrate to the river, where river mortalities, including harvest, occur. Finally, river survivors spawn, some in hatcheries and some in natural areas. Current management focuses on fish that spawn in natural areas, and the KHRM is used to project their abundance in numbers of fish. With the solution developed below, the KHRM can be used to project the highest harvests that are consistent with a specific goal for the number of fish spawning in natural areas.

Management Background

Present management of this stock calls for taking the maximum possible harvest of adults (ages 3–5) subject to the following constraints: (1) removals must not reduce the spawning escapement below a predetermined minimum number of spawners in natural areas (i.e., outside hatcheries), a number termed the ''spawner floor''; (2) removals must not reduce the spawning escapement below a certain proportion of the escapement projected in the absence of fishing, a proportion we call the maximum ''spawner reduction rate''; and (3) harvests in the three fishery segments (which we call ''fisheries'' for brevity) must be in accordance with predetermined harvest-sharing agreements. Those agreements presently allocate portions of the landings to (1) the ocean fishery, (2) the fishery conducted in the Klamath River by the Yurok and Hoopa tribes, and (3) a nontribal river-recreational fishery. These management constraints are incorporated into the KHRM, where they shape the model's projections of spawning escapement and harvest.

Notation

The mathematical symbols that appear in the KHRM are summarized in Table 1. Depending on context, symbols have no, one, or two subscripts. When two subscripts are used, the first indicates the fishery segment and the second the age of the fish. When one subscript is used, it indicates the fishery segment, and the quantity in question is either age independent (if a rate) or a sum across ages (if a number of fish). When no subscript is used, the corresponding quantity is a sum across

←

FIGURE 1.—Conceptual structure of the Klamath Harvest Rate Model used for management of Klamath River fall chinook salmon. The implemented model includes an algorithm for finding optimal harvest, so that its computational flow is different from that shown here.

TABLE 1.—Symbols used in the Klamath Harvest Rate Model.

Symbol	Description
a	Subscript denoting age, $a \in \{3, 4, 5\}$
i	Subscript denoting fishery segment, $i \in \{f, o, \omega, t, r, \rho\}$
f	Ocean segment, previous fall
o	Ocean segment, summer
ω	Both ocean segments
t	River segment, tribal
r	River segment, recreational
ρ	Both river segments
c	Fully recruited (age-4) contact rate; proportion
C	Number of fish contacted (hooked) by fishery
d	Dropoff mortality rate; proportion
D	Dropoff deaths; number of fish
E	Projected spawning escapement in all areas; number of fish
E_n	Projected spawning escapement in natural areas only; number of fish
$E_n^{\perp}$	Spawner floor (minimum escapement in natural areas [constraint])
E_n^*	Target spawning escapement in natural areas (goal)
E_n^0	Projected spawning escapement in natural areas without fishing
ϕ	Spawner reduction rate (reduction in the number of spawners relative to that without fishing)
g	Proportion of spawning that occurs in natural areas
H	Number of fish harvested (landed) by fishery
I	Impact (number of fish killed by fishery)
l	Proportion of fish of legal size
m	Proportion of mature fish
N	Number of fish in the ocean on May 1, (before the summer ocean fishery begins)
N'	Number of fish in the river before river fisheries begin (''river run'' or ''ocean escapement'')
π_t	Proportion of total harvest taken by tribal fisheries
π_r	Proportion of nontribal harvest taken by river-recreational fishery
s	Shaker (catch-and-release) mortality rate; proportion
S	Shaker deaths; number of fish
v	Vulnerability to gear; proportion

all segments and ages. Uppercase letters are generally used for numbers of fish, lowercase letters for subscripts, proportions, and rates. Throughout the paper, rates are simple proportions.

Known and Unknown Quantities

The variables in Table 1 are of three types: constraints, biological parameters, and unknowns. Constraints are the spawner floor, $E_n^{\perp}$; the proportion of total harvest allocated to the tribes, π_t; and the proportion of nontribal harvest allocated to the river-recreational segment, π_r. The values of these constraints are set by management policy, which at present includes the legally mandated value $\pi_t = 0.5$. Two other constraints may also be applied: a maximum spawner reduction rate, $\phi_{\max}$ (where $\phi_{\max} < 1$), which limits the exploitation rate at large stock sizes; and a minimum spawner reduction rate, $\phi_{\min}$ (where $0 \leq \phi_{\min} < \phi_{\max}$), which when nonzero allows a small amount of fishing even when the spawner floor cannot be achieved.

Present management policy includes a maximum spawner reduction rate of 0.67, which corresponds to 33% of the spawning in natural areas that would be expected from the same population in the absence of fishing. A minimum spawner reduction rate greater than zero, sometimes called a ''de minimis'' fishery, is under study but is not part of current policy. Thus, fishing pressure is presently reduced to zero if necessary to come as close as possible to the spawner floor target.

The biological parameters in Table 1 are such quantities as proportion mature at age, proportion of legal size at age, and segment-specific dropoff mortality rates. In using the KHRM, external estimates or assumed values are used for biological parameters, which are presumed to be known without error. Although the KHRM is deterministic, we show later how it can be used in a stochastic simulation to examine the effects of uncertainties in biological parameters.

The unknowns in Table 1 are the allowable age-4 (the age considered fully recruited) ocean contact rate, c_o (defined below); the tribal harvest quota, H_t; and the river-recreational harvest quota, H_r. Current management methods dictate this structure because the ocean fishery is managed by effort limitation (achieved through season and area closures), which more or less directly sets c_o, while the river fisheries (tribal and recreational) are managed by quotas, which directly set H_t and H_r. For any set of river harvest quotas $\{H_t, H_r\}$, there is a corresponding set of river contact rates $\{c_t, c_r\}$, and the two measures can be used equivalently to describe harvest intensity.

In our initial description of the KHRM, we use river contact rates rather than quotas for simplicity of presentation, and we assume that all three contact rates are known. Although not the usual starting point for annual management, this sequence allows a logical presentation (similar to that of Figure 1) of the underlying model and describes the method of projecting escapement given specific contact rates. In a later section, a method of solving for the ocean contact rate and two river quotas, given the constraints and biological parameters, is developed. The latter sequence is the one more often used in management.

Ocean Impacts

The KHRM sequentially models the ocean, tribal, and river-recreational segments of the fishery throughout a fishing season, which is considered to start on May 1. Catch taken in the ocean fishery during the previous fall is not modeled in detail but is added to summer ocean catch when evaluating the harvest-sharing agreements. Typically, fall catch has been converted to summer-equivalent catch before being used in the KHRM. The conversion to summer-equivalent catch is made by multiplying fall ocean harvest by assumed winter survival rates (0.5, 0.8, and 0.8 for ages 2, 3, and 4, respectively). This conversion is intended to approximate the number of fish landed that otherwise would have survived until May 1.

Computations for the summer ocean fishery start with estimates of ocean population sizes at age, N_a, on May 1. These estimates are derived externally to the KHRM from a linear ''sibling regression'' that predicts N_a from the escapement (river run) of fish of age $a - 1$ observed in the preceding year. In fitting the regression, estimates from cohort analyses (catch-at-age analyses using methods similar to those of Pope [1972]) of historical cohorts are used for N_a, and estimates made from various observational data are used for escapement of fish of age $a - 1$ (J. Barnes, U.S. Fish and Wildlife Service, personal communication). As in the KHRM, ages 3, 4, and 5 are represented.

The first quantity modeled within the KHRM itself is the number of fish of age a contacted by the summer ocean fishery, $C_{o,a}$. Here ''contacted'' means caught and successfully retrieved, although it is assumed that fish believed by fishermen to be of sublegal size are shaken from the hook after retrieval and not retained. The number contacted at age is defined as the product of preseason ocean abundance at age, the fully recruited (age-4) ocean contact rate, and age-specific vulnerability:

$$C_{o,a} = N_a c_o v_{o,a}. \tag{1}$$

The product $c_o v_{o,a}$ forms an age-specific contact rate, and since $v_{o,4} \equiv 1$, we refer to c_o as the age-4 contact rate.

The next quantities modeled are age-specific summer ocean harvest deaths $H_{o,a}$ and shaker (catch-and-release) deaths $S_{o,a}$. These depend on age-specific proportions l_a of fish of legal size:

$$H_{o,a} = C_{o,a} l_a, \tag{2}$$

and

$$S_{o,a} = C_{o,a}(1 - l_a)s_a. \tag{3}$$

Equations (2) and (3) assume that fishermen accurately observe when a fish is undersized and only then shake it from the hook.

A third type of mortality, dropoff mortality, may occur when a fish that has been hooked is later lost. Per PFMC practice, dropoff mortality is computed as a specified multiple, $d(d \ll 1.0)$, of the number of fish contacted (STT 1994). Thus, dropoff deaths in the summer ocean fishery are modeled as

$$D_{o,a} = C_{o,a} d_o. \tag{4}$$

The main causes of dropoff mortality are gear-inflicted wounds and losses to California sea lions *Zalophus californianus.*

Total summer ocean impacts at age are defined as the sum of ocean harvest, shaker, and dropoff deaths:

$$I_{o,a} = H_{o,a} + S_{o,a} + D_{o,a}. \tag{5}$$

Total summer ocean harvest is obtained by summing across ages:

$$H_o = \sum_{a=3}^{5} H_{o,a}, \tag{6}$$

with similar expressions being used for the other summer ocean totals, S_o, D_o, and I_o.

At this point, summer-equivalent catches from the previous fall are added to correct the totals for computing harvest-sharing proportions:

$$H_{\omega,a} = H_{o,a} + H_{f,a}. \tag{7}$$

River Impacts

Pacific salmonids reenter fresh water only when mature and attempting a spawning migration. For that reason, models of population dynamics in rivers assume that all individuals are spawners.

Following the ocean fishery, the number of fish at age remaining in the ocean is considered to be $N_a - I_{o,a}$. The resulting age-specific river run of spawners is that number times the proportion that is mature:

$$N'_a = (N_a - I_{o,a})m_a. \tag{8}$$

In the KHRM, the two river segments, tribal (t) and recreational (r), are treated as independent rather than competing sources of mortality. The number of fish at age contacted by each of these segments is the product of the number of fish in the river, the contact rate, and the river vulnerability rate:

$$C_{i,a} = N'_a c_i v_{i,a}, \qquad i \in \{t, r\}, \tag{9}$$

where, as in the ocean fishery, $v_{i,4} \equiv 1$.

All adult chinook salmon caught by the tribes are kept, and all those caught by the recreational fishery are assumed to exceed the sportfishing minimum size limit; thus, shaker mortalities are presumed to be negligible in the river fisheries. It follows that number of fish harvested is identical to number of fish contacted:

$$H_{i,a} = C_{i,a}, \qquad i \in \{t, r\}. \tag{10}$$

In each river fishery, number of deaths at age attributable to dropoff is assumed to be

$$D_{i,a} = C_{i,a}d_i, \qquad i \in \{t, r\}. \tag{11}$$

which is analogous to equation (4). Impacts at age are then defined as the sum of harvest and dropoff deaths:

$$I_{i,a} = H_{i,a} + D_{i,a}, \qquad i \in \{t, r\}. \tag{12}$$

As in the ocean fishery, the model considers total harvests, dropoff deaths, and impacts to be simple sums:

$$H_i = \sum_{a=3}^{5} H_{i,a}, \qquad i \in \{t, r\},$$

with similar expressions applying to D_i and I_i.

Spawning Escapement

Spawning escapement is computed as river run less the impacts of river fisheries:

$$E = \sum_{a=3}^{5} N'_a - I_\rho, \tag{13}$$

where the impacts of river fisheries are given by

$$I_\rho = H_t + D_t + H_r + D_r. \tag{14}$$

In the Klamath River system, some portion of total spawning escapement returns to hatcheries; thus, total spawning escapement, E, exceeds ''natural'' spawning escapement, E_n. An age-aggregated estimate of the proportion of spawners in natural areas, g, is used to project spawning escapement to natural areas as a function of total spawning escapement:

$$E_n = gE. \tag{15}$$

The method by which g is estimated for use in equation (15) is external to the KHRM and is described in a later section.

Summary of the Model

Equations (1) through (15) define how, from a proposed set of contact rates, the KHRM projects escapement in natural areas, thus indicating whether that set of contact rates allows an escapement goal to be met. By evaluating the KHRM again with all contact rates set to zero, the spawner reduction rate, ϕ, is projected as

$$\phi = 1 - E_n/E_n^0,$$

where E_n^0 is the projected escapement in natural areas under no fishing. Comparing ϕ with $\phi_{\min}$ and $\phi_{\max}$ indicates whether those limits on spawner reduction rate are met. Finally, the projected harvest ratios, π_t and π_r, which are computed from the projections of H_ω, H_t, and H_r, indicate whether harvest-sharing agreements are met. Thus, the KHRM allows one to evaluate whether a set of contact rates meets all presently established management constraints.

The preceding description of the KHRM closely follows the model structure embedded in the original spreadsheet file, with several minor corrections. The model structure itself, however, provides no way other than trial and error to find those contact rates yielding optimal harvests. To find those rates, a solution algorithm must be coupled with the KHRM model structure.

Solution Algorithm

Through manipulation of equations (1) through (15), optimal harvest rates can be found directly. The first step is to realize that, as a consequence of the harvest-sharing agreements, a specific ocean contact rate is consistent with one (and only one) tribal harvest and one (and only one) river-recreational harvest. In other words, this is a problem in one, not three, unknowns. This relationship was not exploited in the original spreadsheet file, which treated the three harvests as independent; its discovery was made possible by documenting and analyzing the model equations.

Because of the fixed sharing proportions, it is possible, given an ocean contact rate, to compute the corresponding ocean, tribal, and river-recreational impacts. Then, from equations (13) to (15), one can project the ensuing spawning escapement in natural areas, E_n, and the corresponding spawner reduction rate. If the starting population size is large enough, the ocean contact rate can be adjusted to make E_n equal to any desired escapement target E_n^*. That target will normally be the lowest escapement that fulfills the management constraints, which by definition corresponds to taking optimal harvests. Thus the problem of finding optimal harvests has been reduced to that of finding the ocean contact rate corresponding to the smallest allowable E_n^*. We now explain how that is done.

Formulating the Solution

From equations (8), (13), and (15), escapement to natural areas can be expressed in terms of ocean abundance on May 1, maturity at age, and fishery-segment impacts as

$$E_n = g\left[\sum_{a=3}^{5} (N_a - I_{o,a})m_a - I_\rho\right]. \qquad (16)$$

For fixed $\{N_a\}$, $\{m_a\}$, and g, the KHRM implies that E_n is a linear function of the ocean contact rate, c_o. We demonstrate this by showing that both ocean impacts I_o and total river impacts I_ρ are linearly related to the number of ocean contacts, C_o, which is proportional to c_o by equation (1). As described earlier, impacts are the sum of harvested fish, shaker mortalities, and dropoff mortalities:

$$I_{o,a} = C_{o,a}[l_a + (1 - l_a)s_a + d_o]. \qquad (17)$$

From equations (10) and (12), river impacts can be expressed in terms of river harvests and dropoff rates as

$$I_\rho = H_t(1 + d_t) + H_r(1 + d_r). \qquad (18)$$

But as defined by the harvest-sharing agreements, the river harvests, H_t and H_r, are determined by the ocean harvest, H_ω, and thereby by ocean contacts, $C_{o,a}$. Let H represent total harvest over all segments, so that: $H \equiv H_\omega + H_t + H_r$. As defined in Table 1, the sharing agreements provide that

$$H_t = H\pi_t, \qquad (19a)$$

$$H_r = H(1 - \pi_t)\pi_r, \quad \text{and} \qquad (19b)$$

$$H_\omega = H(1 - \pi_t)(1 - \pi_r). \qquad (19c)$$

On solving equation (19c) for H and substituting the result into equations (19a) and (19b), we find that equation (18) reduces to

$$I_\rho = \kappa H_\omega = \kappa \sum_{a=3}^{5} (C_{o,a} l_a + H_{f,a}), \qquad (20)$$

H_ω being given by equations (7) and (2), and

$$\kappa = \frac{\pi_t(1 + d_t)}{(1 - \pi_t)(1 - \pi_r)} + \frac{\pi_r(1 + d_r)}{(1 - \pi_r)}. \qquad (21)$$

Finally, substituting equations (17) and (20) into equation (16) and applying equation (1) shows that, under the sharing agreements, projected escapement to natural areas is a linear function of the age-4 ocean contact rate:

$$E_n = \beta_0 - \beta_1 c_o, \qquad (22a)$$

where

$$\beta_0 = g \sum_{a=3}^{5} (N_a m_a - \kappa H_{f,a}) \quad \text{and} \qquad (22b)$$

$$\beta_1 = g \sum_{a=3}^{5} N_a v_{o,a}[(l_a + (1 - l_a)s_a + d_o)m_a + \kappa l_a]. \qquad (22c)$$

Thus, given a target E_n^* for escapement in natural areas, the KHRM projects that the age-4 ocean contact rate c_o^* that will yield that target is

$$c_o^* = \frac{\beta_0 - E_n^*}{\beta_1}. \qquad (23)$$

Here, β_0 and β_1 are known quantities in that they depend entirely on constraints and biological parameters considered as known in the model, which means that the trial-and-error approach used formerly is unnecessary. Given π_t, π_r, the biological parameters, and the escapement target, one can directly compute the corresponding contact rates, harvests, and impacts.

It may not be obvious from the above how the escapement target for natural areas, E_n^*, is set in practice. It is done through a comparison between

E_n^0, the projected escapement in natural areas without fishing, and $E_n^\perp$, the spawner floor. That comparison is used in the following set of decision rules, in which the notation $\phi(E_n^\perp)$ means the spawner reduction rate that would be achieved by using the spawner floor, $E_n^\perp$, as the spawner target, E_n^*:

1. When $E_n^0 \le E_n^\perp$ and
   a. $\phi_{\min} = 0$, then $E_n^* = E_n^0$ (the fishery is closed);
   b. $\phi_{\min} > 0$, then $E_n^* = (1 - \phi_{\min})\ E_n^0$ (a de minimis fishery takes place).
2. When $E_n^0 > E_n^\perp$ and
   a. $\phi(E_n^\perp) \le \phi_{\max}$, then $E_n^* = E_n^\perp$ (the fishery is governed by the spawner floor);
   b. $\phi(E_n^\perp) > \phi_{\max}$, then $E_n^* = (1 - \phi_{\max})\ E_n^0$ (the fishery is governed by the maximum spawner reduction rate).

TABLE 2.—Harvest projections from the Klamath Harvest Rate Model (KHRM) and Klamath Ocean Harvest Model (KOHM; a more detailed complementary model) for Klamath River fall chinook salmon in the 2000 fishing year. See Table 1 for symbol definitions.

Harvest variable	Projection (number of fish)	
	KHRM	KOHM
$H_{\omega,3}$	18,555	19,480
$H_{\omega,4}$	4,738	4,310
$H_{\omega,5}$	224	203
H_{ω}	23,517	23,993
H_r	4,150	4,234
Nontribal harvest	27,667	28,227
H_t	27,667	28,227
Total harvest	55,335	56,454
Harvest rates		
$H_{o,3}/N_3$	10.6%	11.1%
$H_{o,4}/N_4$	15.1%	13.7%
$H_{o,5}/N_5$	15.0%	13.1%

Examples of Management Application

We give three examples of the KHRM's use in management. The first demonstrates the model's routine use in annual deliberations on season structure; the two remaining examples, which are slightly longer, illustrate the KHRM's use in simulation studies of management questions.

Example 1. Year 2000 Fishing Season

At the start of management deliberations for the 2000 fishing season, the KHRM was applied as described above. Its projections indicated that in the coming season the major management constraint would be meeting the spawner floor (case 2a above). Also as a result of the application of the KHRM, approximate harvests and harvest rates in the different segments were known at the start of the management process. That information was the basis of subsequent discussions about season structure and allocation in the ocean fishery, during which many proposals were evaluated with the more complex Klamath Ocean Harvest Model (KOHM). The projections from the KOHM based on final season structure and management parameters were close to the initial projections of the KHRM (Table 2) made more than two months earlier. This example illustrates the pivotal role of the KHRM in management and its close agreement with the more realistic model used to evaluate the ocean fishery.

Example 2. Evaluation of a De Minimis Fishery

Under current management policy, the fishery is completely closed when abundance is insufficient to attain the spawner floor, in other words, now the minimum spawner reduction rate, $\phi_{\min}$, = 0. The authors recently undertook a simulation study to examine the effects of a possible policy change to $\phi_{\min} > 0$, that is, a de minimis fishery in years when closure would otherwise be imposed. The values of $\phi_{\min}$ examined were 0% to 20% in steps of 5%.

The simulation study, presented here in highly condensed form, used the KHRM as its core. In Figure 2, KHRM elements are shown with heavy borders; added elements are a recruitment submodel (left portion of Figure 2), application of natural mortality between years (right portion of Figure 2), and introduction of random errors. The model reflects only the naturally spawning component of the stock.

Recruitment was generated from a Ricker (1954) recruitment model with an added stochastic component. Stock and recruitment estimates provided by Alan Baracco (California Department of Fish and Game, personal communication) were updated by the authors from unpublished reports of the PFMC and the Klamath River Technical Advisory Team. Parameters of the recruitment function were estimated by standard regression techniques that relate the natural logarithm of recruits per spawner to parent stock size. The resulting model with estimated parameters was

$$\log_e(R/P) = 2.106 - 0.0233P, \qquad (24)$$

where R is recruitment in thousands of age-3 fish on May 1 and P is parent spawning stock in thousands of 3-year-old equivalents. Each age-4 fish was considered equivalent to 1.55 3-year-olds and

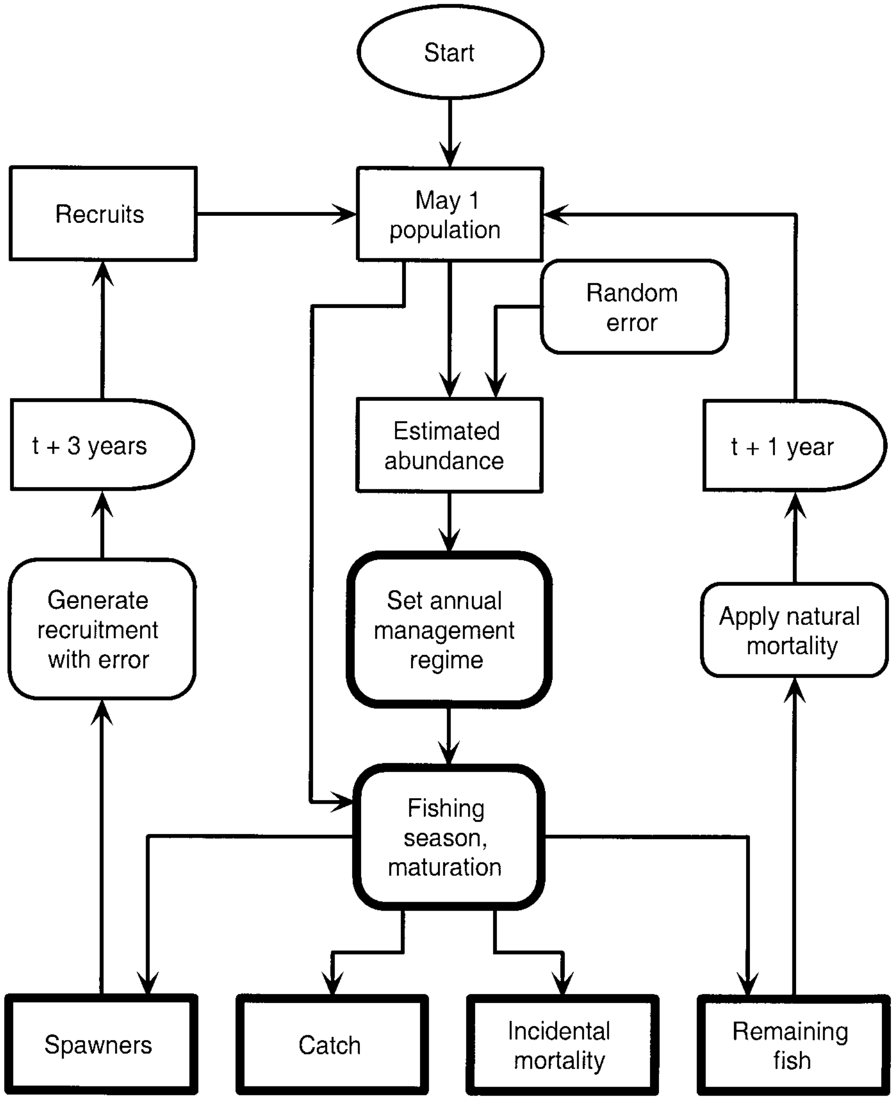


FIGURE 2.—Overview of the logic flow of simulations of Klamath River fall chinook salmon to examine a possible de minimis fishery. Rectangles represent numbers of fish, rounded rectangles processes, and "D" shapes time delays. Shapes with heavy borders indicate step that are internal to the Klamath Harvest Rate Model.

each age-5 fish to 1.99 3-year-olds; these constants were based on average relative weight at age, a measure that is closely correlated with individual fecundity in many fish species. Normally distributed random errors (mean, zero; SD derived from the regression analysis) were added to the right-hand side of equation (24) to generate projected recruitment during simulations.

Estimated abundance on May 1, the other quantity modeled as uncertain, was considered unbiased in terms of its median but subject to lognormal random error. Four levels of random error were used, covering a wide range; the coefficients of variation (CV = 100 SD/mean) were zero (indicating no imprecision), 25%, 50%, and 75%.

The simulations used starting population sizes similar to those recently observed; the results were insensitive to that assumption, however, probably because of the 3,000-year length of each simulation, which was selected to minimize any such transient effects. One such simulation was run for each combination of the CV of estimated abundance on May 1 and level of de minimis fishery; thus, the results reflect $4 \times 5 = 20$ simulations.

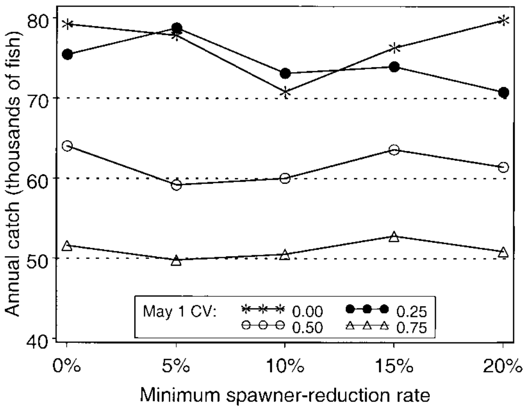


FIGURE 3.—Results from a simulation study on Klamath River fall chinook salmon, showing the total average annual catch as a function of a de minimis fishery instituted in place of total closure. A minimum spawner reduction rate (ϕ_{min}) = 0 is equivalent to closure; the magnitude of the de minimis fishery increases with ϕ_{min}. The May 1 coefficient variation (CV) describes the uncertainty in preseason estimates of abundance, $\{N_a\}$.

Statistics were recorded on annual catch in each fishery segment, magnitude of annual spawning escapement in natural areas, and number of years in each simulation with each fishery outcome: closed, limited by ϕ_{min}, limited by spawner floor, or limited by ϕ_{max}.

Average catch was found to be insensitive to the introduction of a de minimis fishery. Indeed, the major factor affecting catch was the precision of preseason abundance estimates (Figure 3). Within the values examined, CVs of 50% or more reduced average catch as much as 35% compared with the catches available under CVs of zero or 25%. This suggests that better estimation of abundances on May 1 could allow higher catches in the fishery.

Like average catch, the following quantities were essentially unaffected by a de minimis fishery in the simulations: year-to-year variability of catch, average spawning escapement in natural areas, and average proportion of catch taken by the tribes. We projected that without a de minimis fishery, complete closures would occur in about 8–18% of years, depending on the precision of preseason abundance estimates. Use of the de minimis fishery would by definition preclude such closures.

Example 3. Probability of Attaining Spawner Floor

Frequently, the limiting management concern in this fishery is attaining sufficient escapement to satisfy the Fishery Management Plan, that is, attaining $E_n \geq E_n^{\perp}$, the spawner floor of 35,000 fish. To put this in a wider context, uncertainties in nature, science, and management may determine that in any fishery a spawning target E_n^* is not met in a given year, even when it is met on average. Indeed, if realized escapement is distributed symmetrically about a target, the target will be missed in 50% of years. Under the PFMC's framework plan for ocean salmon fisheries, failure to meet the spawner floor 3 years in a row would cause the stock to be defined as overfished, a highly undesirable outcome. To make that outcome less likely, one could use $E_n^{\perp}$ = 35,000 fish as a limit reference point (FAO 1993) and establish a higher target reference point, $E_n^* > E_n^{\perp}$. To evaluate that approach, we used the KHRM as the basis of a Monte Carlo simulation to estimate the probability of achieving $E_n^{\perp}$ in the year 2000 as a function of the value chosen for E_n^*.

Overview of Monte Carlo simulation.—The parameters of the KHRM considered most uncertain are the estimates of preseason abundance $\{N_a\}$, $a = \{3, 4, 5\}$, and the proportion of spawning escapement in natural areas, g. We assumed that $\{N_a\}$ and g were random variables with distributions described below but that the values used in management (here termed ''PFMC projections'') for the year 2000 would be those developed through normal management procedures.

Several other assumptions were used in the simulation. Simulated harvest levels were obtained by applying the KHRM to values for 2000 (over a range of target escapement values $E_n^* \geq E_n^{\perp}$) and were assumed to be taken precisely. We drew 50,000 sets of random realizations of $\{N_a\}$ and g from their distributions, and for each we computed the realized spawning escapement E_n for each value of E_n^* examined. This allowed us to compile an empirical estimate of the probability, as a function of E_n^*, that $E_n \geq E_n^{\perp}$. That probability was estimated as the fraction of trials based on a particular value of E_n^* in which $E_n \geq E_n^{\perp}$.

The range considered for E_n^* was $E_n^{\perp}$ to $E_n^{\perp}$ + 32,536. The value 32,536 was the limiting case because on average it allows no nontribal summer harvest and a tribal harvest of 100 fish, which is needed for parity with the previous fall's nontribal ocean harvest of 100 fish.

Distributions of stochastic quantities.—Preseason estimates of $\{N_a\}$ are made each year from age-specific, zero-intercept linear ''sibling regressions'' of historical N_a on the river run of the same cohort, N'_{a-1}, observed the previous fall. Data from brood years 1979–1995 are used, and as the data

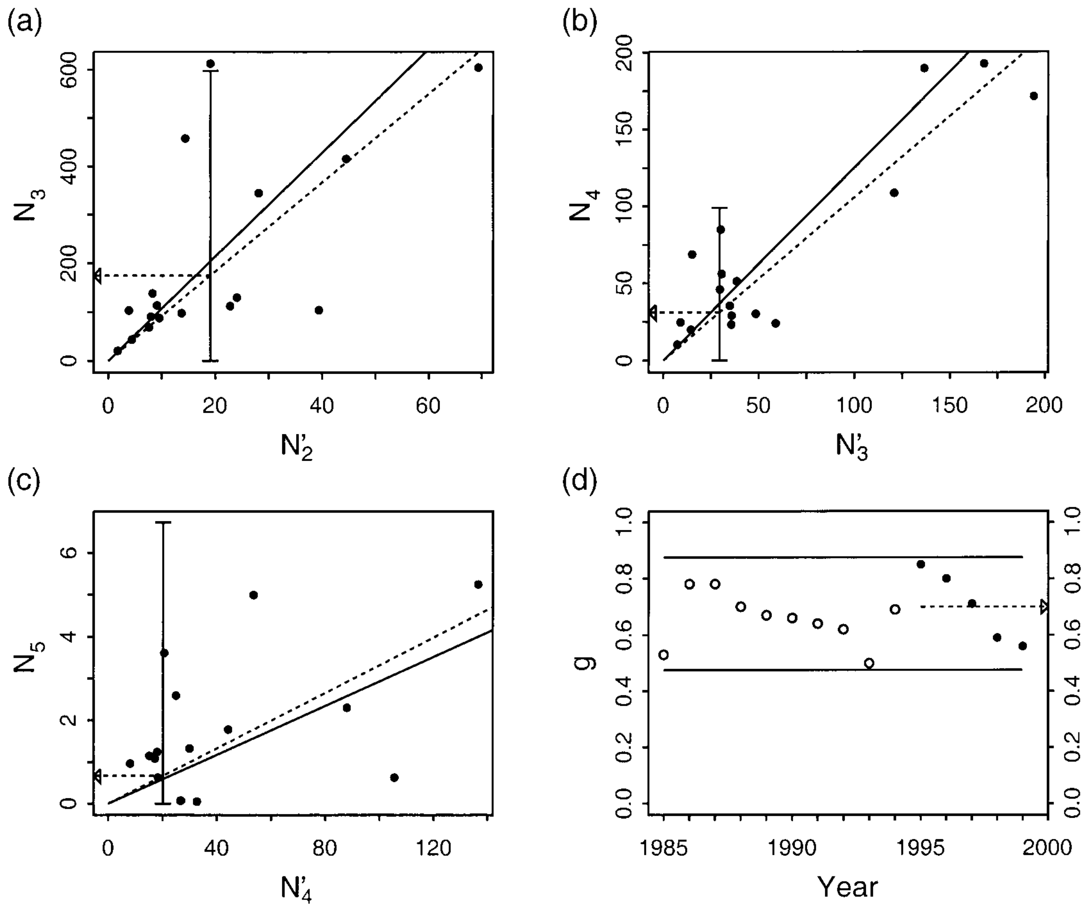


FIGURE 4.—Stochastic quantities in a Monte Carlo simulation of Klamath River fall chinook salmon, shown with Pacific Fishery Management Council (PFMC) projections (see text) for 2000. Panels **(a)**–**(c)** show sibling regressions estimating age-specific abundances on May 1 from the same cohort's river run in the previous fall. In each panel, the oblique dashed line is the existing regression; the oblique solid line is the new regression; the horizontal dashed line is the PFMC projection; and the vertical line with caps is the range of values (from a lognormal distribution) used in the simulation. Panel **(d)** shows the distribution of *g*, the projected proportion of spawning in natural areas. The PFMC projection is the average of the last 5 years' observations (solid circles, dashed line). Solid horizontal lines mark the limits of the uniform distribution estimated from all data and used in the simulation.

are widely scattered (Figure 4a-c), uncertainty in the estimates of $\{N_a\}$ is large. We estimated distributions of N_a for simulation by fitting new sibling regressions that kept the linear structure of present models but assumed that the variation in $\{N_a\}$ is lognormally, rather than normally, distributed. The new model for estimating abundance at each age was then

$$N_a = \beta_a N'_{a-1} \exp(\lambda_a), \tag{25}$$

where N_a and N'_{a-1} are the abundances of the same cohort on May 1 and in the preceding fall, respectively (Table 1); β_a is an age-specific constant, and λ_a is a random error that is distributed normally with zero mean and constant variance. The value of β_a and the variance of λ_a were estimated for each age by maximum likelihood. Simulated values of $\{N_a\}$ from equation (25) were truncated at the 95th percentile to avoid unrealistically large values.

The proportion of adults spawning in natural areas, *g*, is routinely estimated as a moving average of the five most recent observed proportions. For the simulation, we obtained realizations of *g* from a uniform distribution described by a minimum-variance unbiased estimator (Johnson et al. 1995) applied to all data on *g* (Figure 4d). The uniform density reflects our belief, based on observed val-

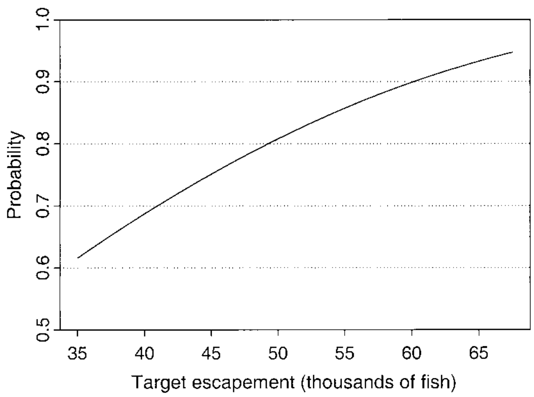


FIGURE 5.—Probability of attaining the escapement floor (35,000 fish spawning in natural areas) for Klamath River fall chinook salmon as a function of the escapement target used for management. Probabilities were estimated by Monte Carlo simulations based on the Klamath Harvest Rate Model.

ues of g, that in the study year (2000) no particular value in the estimated distribution was any more likely to occur than any other.

Results of Monte Carlo simulations.—With target escapement set to the floor of 35,000 fish, the probability of attaining the floor was estimated at about 0.62, rather than 0.50 as expected (Figure 5). This result is due to differences between the sibling regressions used in current PFMC projections and the new regressions fitted here. The new regressions provide larger estimates of the number of returning age-3 and age-4 fish than present regressions (Figure 4a-c), and those two ages make up the bulk of the spawning population. If the new regressions are considered true (as they are in the simulation), the present projection method underestimates N_a on average, and as a result the spawner floor is attained more often than expected.

With target escapement set higher than the floor, the estimated probability of attaining the floor increases steadily as the target escapement level is increased (Figure 5). At the highest target examined, the probability of attaining the floor is about 0.96, indicating that given the assumed stochasticity in g and $\{N_a\}$, it is not possible to guarantee meeting the floor every year. Nonetheless, establishment of a target escapement E_n^* greater than the spawner floor can indeed provide a higher probability of attaining the floor.

The old and new sibling regressions differ only in the error structure assumed, yet they lead to different conclusions. Although the multiplicative error structure of the new regressions seems more plausible, it is still unknown whether the new regressions will lead to more accurate conclusions. Because of that uncertainty, we believe the preceding analysis provides reasonable estimates of the improvements in the probability of achieving the spawner floor by increasing target escapement but less certain estimates of the corresponding probabilities on an absolute scale. The uncertainty may be inherent in the use of sibling regressions, which assume constant proportions of fish maturing at age and which for semelparous species are sensitive to violation of that assumption. For example, given a constant population size, a higher rate of maturity at age 2 in a given year would result in a larger river run of age-2 fish but a smaller remaining ocean stock to provide age-3 fish. That would contradict the usual interpretation of equation (25), in which it is assumed that a larger river run will lead to a larger ocean stock of the next higher age the next year.

Discussion

The availability of rapid solutions to the KHRM under different management scenarios has had several practical benefits. The most obvious is that a tedious trial-and-error process has been eliminated from an already demanding management procedure that is usually conducted under severe time constraints. A further benefit is increased ability to use last-minute data corrections that become available during the management procedure. Resource users have exercised the improved KHRM (as implemented in a Fortran computer program [Prager and Mohr 1997]) to explore management alternatives, and this has increased confidence in the model.

The availability of a direct solution makes possible simulation studies of likely short- and long-term effects of different management strategies, as described above. Finally, explication of the theory behind the KHRM has corrected a serious epistemological deficiency in management of the stock.

Mathematical and Statistical Aspects of the KHRM

In documenting the KHRM, we made several minor changes, either for mathematical consistency or to incorporate management practices previously ignored by the model. In accordance with PFMC assumptions in past assessments, a term for ocean dropoff mortality was added. Parameterization of dropoff mortality in the river fisheries was also made consistent with its treatment in the ocean fishery (the values of the dropoff rates were adjusted slightly to make the old and new formulations equivalent). We also resolved inconsistencies in the treatment of fall ocean harvest.

Further improvements could be made to the KHRM, as they could to any management model. For example, the ocean fishery, which is presented here as a single component, is actually composed of a commercial troll fishery and a recreational hook-and-line fishery, with the latter taking about 15% of the summer ocean catch. This distinction has never been elaborated in the KHRM because the resulting errors are considered insignificant.

The solution described here for optimal harvests depends on linearity of the population model, but it could be adapted for use with a nonlinear model. The algorithm proceeds in two stages: first, three unknowns (c_o, H_t, and H_r) are reduced to one; second, the single unknown (c_o) is found. Because the present model is completely linear, a simple analytical expression exists at each stage. Under a nonlinear population model, it might be difficult or impossible to obtain an analytical expression at the second stage, but in that case the computations could be done numerically, such as by bisection (Gill et al. 1981). Thus, the ability to find a systematically computable solution is aided by, but does not depend on, linearity of the model.

As in many models of Pacific salmonids, the KHRM uses ad hoc methods to compute dropoff mortality D (defined as the number of fish that are hooked but lost and die from the encounter). In both ocean and river, D is not computed from the number of fish hooked but from the number contacted (hooked and retrieved). To do otherwise would require estimating the total fraction of fish hooked but not retrieved, a problem that is not yet solved. Lawson and Sampson (1996), in a review of gear-related mortalities in salmon fisheries, characterized such noncatch mortalities as ''neither directly observable nor measurable.'' Nevertheless, any estimates of dropoff mortality developed in the future could readily be incorporated into the KHRM.

A major limitation of the KHRM is uncertainty about g, the fraction of this stock's spawning that occurs in natural areas. As part of each year's monitoring efforts, returns to hatcheries are recorded and a primary estimate of g is made by subtraction from estimated total spawning escapement and division; however, the estimate is not available in time for use in the KHRM. The value used in the KHRM is the average of primary estimates for the preceding 5 years. Primary estimates of g vary from year to year depending on the relative strengths of hatchery and ''natural'' stocks, among other factors, and this variation directly affects estimation of E_n, the projected escapement to natural areas, from equation (15). At present, this appears to be an irreducible source of error in using the KHRM (or any other model) to project natural escapement; in our third example, however, we demonstrated how this uncertainty and its implications for management can be accounted for by simulation, along with the other major source of uncertainty, preseason estimates of abundance.

Models, Implementations, Documentation, and Tools

Guiding this work was the principle that a model's theory and its implementation are distinct and nonequivalent entities. A model's theory defines its assumptions, limitations, and other properties. In contrast, an implementation (computer program) is a reflection, possibly imperfect, of a particular mathematical model.

A related principle is that any model used in fishery management requires formal documentation. By this we mean that the theory underlying a model should be set forth mathematically and clearly explained. Such documentation should not be confused with instructions for operating the computer program that implements the model.

Good modeling practice requires developing and documenting the underlying mathematical theory before implementation is attempted. If that had been done for the KHRM, it is quite possible that the correct model rank and the analytical solution would have been discovered previously. We share the sentiments of a reviewer of this paper, who stated that ''[i]t is troubling . . . that spreadsheet implementation preceded the mathematical development of the model. This is a poorly disciplined approach.'' We are perhaps more optimistic than the reviewer in assuming that some mathematical development, albeit undocumented, was undertaken by the spreadsheet's original (and anonymous) authors.

In espousing the importance of documentation, we have been told by some colleagues that computer spreadsheets are ''self-documenting.'' We reject that assertion emphatically. In a sense, of course, any computer program documents itself: if the program's implementation is correct, given sufficient effort and knowledge, one can eventually extract the underlying mathematical relationships from the program code. However, such an exercise is tedious, lengthy, and uncertain. For example, it took several man-weeks to extract the KHRM, which is a relatively simple model, from its spreadsheet implementation, and even then much explanation was absent. Clearly, a computer program does not constitute sufficient documentation of a mathematical model.

We find it curious that the claim of self-documentation is often made for spreadsheets but rarely for other types of computer program. Based on several experiences extracting model equations from spreadsheets, our opinion is that they are far less easily deconstructed than programs in languages with loop structures and names for all variables. Lacking a loop structure, a spreadsheet may have, for example, 100 times as many formulas as a program written in a conventional language (if the same formula is repeated for five age-classes and 20 years). We find that this makes spreadsheets much more difficult to check for errors than conventional programs and thus less suitable for management analyses of natural resources. Not all modeling practitioners will agree with this opinion, but we encourage our colleagues to consider these factors: the difficulty of using structured programming techniques in spreadsheets; the ease of introducing hidden errors when, for example, the range of ages in a model is increased; and the difficulty or impossibility of printing a spreadsheet's underlying source code so that it can be reviewed by another party.

That one must deconstruct computer programs to evaluate certain fishery management models indicates a professional shortcoming in our field. For a model's implementation to precede its theoretical development is a highly undesirable sequence, and one that stymies true progress. Unfortunately, that sequence has been encouraged by the ease with which spreadsheets can be used for numerical work, although we neither reject spreadsheets as tools nor place the blame primarily on them. Regardless of the tools used by the modeler, we believe that models should be based on mathematical expression of biological thought and that without exception computer programs for fisheries work should be based on such models, properly documented.

Documentation, Management, and Public Trust

The worthwhile goal of model documentation is not always easily achieved, but it should always be pursued. Full documentation and peer review build public trust, facilitate independent replication of analyses, and stimulate progress in the development of better models. These observations would seem commonplace, but advocacy of model documentation is not a prominent part of the fisheries canon. Indeed, the word ''documentation'' cannot be found in the index of many volumes partly or completely concerned with fisheries modeling (e.g., Lackey and Nielsen 1980; Everhart and Youngs 1981; Gulland 1988; Hilborn and Walters 1992) or modeling in general (Law and Kelton 1982; Gilchrist 1984); there is no chapter on documentation in a recent symposium volume dedicated to fisheries modeling (Edwards and Megrey 1989); and a recent review of U.S. fish stock assessments (Committee on Fish Stock Assessment Methods 1998) does not include better documentation of models among its many constructive suggestions.

Models can be used for ad hoc and exploratory analyses as well as in formal management processes. Clearly, higher standards of documentation are needed when models are used in the management of public resources. In such cases, we suggest the following guidelines: (1) a model used in fishery management should be clearly defined mathematically, so that management analyses are unambiguous and can be replicated by others; (2) mathematical definition of the model should be accompanied by a clear explanation of the model's objectives and methods in words; (3) implementation of the model (i.e., as a computer program) should be in a form that facilitates checking, modification, and peer review; and (4) an implementation should be accompanied by its own documentation describing the use of the program and explaining any departures from the mathematical model. We hope the preceding guidelines will stimulate discussion among fishery scientists and managers and encourage more careful documentation of fishery models and the software that implements them.

Acknowledgments

The authors gratefully acknowledge the assistance of Alan Baracco of the California Department of Fish and Game, as well as that of the Klamath River Technical Advisory Team. Constructive comments on improving this work were provided by C. Griswold, D. Hankin, J. Hoenig, S. Ralston, P. Spencer, D. Vaughan, and three anonymous reviewers. A Fortran computer program implementing the KHRM is available from the authors.

References

Committee on Fish Stock Assessment Methods, Ocean Studies Board, National Research Council. 1998.

Improving fish stock assessments. National Academy Press, Washington, D.C.

Edwards, E. F., and B. A. Megrey, editors. 1989. Mathematical analysis of fish stock dynamics. American Fisheries Society, Symposium 6, Bethesda, Maryland.

Everhart, W. H., and W. D. Youngs. 1981. Principles of fishery science. Cornell University Press, Ithaca, New York.

FAO (Food and Agriculture Organization of the United Nations). 1993. Reference points for fisheries management: their potential application to straddling and highly migratory resources. FAO Fisheries Circular 864, Rome.

Gilchrist, W. 1984. Statistical modeling. John Wiley & Sons, Chichester, UK.

Gill, P. E., W. Murray, and M. H. Wright. 1981. Practical optimization. Academic Press, London.

Gulland, J. A., editor. 1988. Fish population dynamics, 2nd edition. John Wiley & Sons, Chichester, UK.

Hankin, D. G., and M. C. Healey. 1986. Dependence of exploitation rates for maximum yield and stock collapse on age and sex structure of chinook salmon (*Oncorhynchus tshawytscha*) stocks. Canadian Journal of Fisheries and Aquatic Sciences 43:1746–1759.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment. Chapman and Hall, New York.

Johnson, N. L., S. Kotz, and N. Balakrishnan. 1995. Continuous univariate distributions, volume 2, 2nd edition. John Wiley & Sons, New York.

KRTT (Klamath River Technical Team). 1986. Recommended spawning escapement policy for Klamath River fall-run chinook. Technical Report to Klamath Fishery Management Council. Available from Yreka Fish and Wildlife Office, U.S. Fish and Wildlife Service, 1829 S. Oregon Street, Yreka, California 96097.

Lackey, R. T., and L. A. Nielsen. 1980. Fisheries management. Blackwell Scientific Publications, Oxford, UK.

Law, A. M., and W. D. Kelton. 1982. Simulation modeling and analysis. McGraw-Hill, New York.

Lawson, P. W., and D. B. Sampson. 1996. Gear-related mortality in selective fisheries for ocean salmon. North American Journal of Fisheries Management 15:512–520.

Pierce, R. M. 1991a. The Klamath River fishery: early history. Pages 37–45 *in* A. Lufkin, editor. California's salmon and steelhead. University of California Press, Berkeley.

Pierce, R. M. 1991b. The lower Klamath fishery: recent times. Pages 142–150 *in* A. Lufkin, editor. California's salmon and steelhead. University of California Press, Berkeley.

Pierce, R. M. 1998. Klamath salmon: understanding allocation. Pamphlet published by Klamath River Basin Fisheries Task Force and U.S. Fish and Wildlife Service. Available from Yreka Fish and Wildlife Office, U.S. Fish and Wildlife Service, 1829 S. Oregon Street, Yreka, California 96097.

Pope, J. G. 1972. An investigation of the accuracy of virtual population analysis using cohort analysis. International Commission for Northwest Atlantic Fisheries, Bulletin number 9:65–74, Dartmouth, Nova Scotia.

Prager, M. H., and M. S. Mohr. 1997. An improved implementation of the Harvest Rate Model for Klamath River chinook salmon. U.S. Department of Commerce, National Marine Fisheries Service, Southwest Fisheries Science Center, Administrative Report T-97-01, Tiburon, California. Available from the authors.

Ricker, W. E. 1954. Stock and recruitment. Journal of the Fisheries Research Board of Canada 11:559–623.

STT (Salmon Technical Team). 1994. Nonlanded mortality of chinook and coho salmon in Pacific Fishery Management Council ocean recreational and commercial salmon fisheries. Technical Report to Pacific Fishery Management Council. Available from Pacific Fishery Management Council. Available from Pacific Fishery Management Council, 2130 Southwest Fifth Avenue, Suite 224, Portland, Oregon 97201.