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The Kenai Sockeye Salmon Simulation Model: A Tool for Evaluating Escapement and Harvest Levels

By

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PREFACE

This paper was developed for distribution at a series of public meetings held prior to the 1999 Alaska Board of Fisheries meeting on Upper Cook Inlet salmon proposals.. The purpose of these public meetings was to provide information on an interactive fisheries simulation model used as one of the tools by the Alaska Department of Fish and Game in evaluating and modifying the Kenai River sockeye salmon biological escapement goal. The model was made available to the general public on the Alaska Department of Fish and Game's Internet website, and was distributed to interested individuals, upon request, on computer diskettes. Department staff also used the model during the Alaska Board of Fisheries meeting in Soldotna, Alaska, 16-28 February 1999, to explore potential effects of setting different optimal escapement goals on future Kenai River sockeye salmon production.

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The Kenai Simulation Model was developed to examine the potential effects of various harvest policies on the Kenai River sockeye salmon population. The model simulates sockeye salmon production using a spawner-recruit relationship, modifies the simulated production for year of return using an age-structure sub-model, estimates annual returns by summing across age groups, and estimates resulting catches and escapements under user-specified harvest strategies. An implementation error sub-model based on actual fisheries management performance for the past 19 years is also available to further refine the harvest model. All sub-models were developed using escapement, catch, and age data from the 1968–1998 Kenai River sockeye salmon returns and incorporate observed variation. Monte Carlo methods were used to simulate variation.

The body of this document presents a general overview of the model with more in depth descriptions of the sub-model components described in the Appendices. Flow charts for the models can be found in Figures 1 and 2. Finally, a list of pertinent articles and references which influenced this work is attached.

Spawner-Recruit Sub-Model

A brood-year interaction model was used to quantify the spawner-recruit relationship. The model incorporates spawner abundance from the previous brood year to help predict recruitment from the current brood year. This type of model helps explain observed cyclic dominance in annual runs of sockeye salmon to the Kenai River. An indepth discussion of the sub-model is provided in Appendix A.

A potential biological mechanism explaining brood-year interaction comes from the work on juvenile sockeye salmon rearing in the large lake systems of the Kenai drainage. These studies examined the effects of large escapements of sockeye salmon into the Kenai River on both the salmon population and lake limnology. It was found that seasonal variability of the dominant copepod, *Cyclops columbianus*, coupled with variation in salmon escapement, provides a high degree of predictability of fall juvenile sockeye salmon recruitment in Skilak and Kenai lakes. Cropping by juvenile sockeye salmon of a cohort of *Cyclops* is hypothesized to be an important factor affecting the recruitment of juvenile sockeye salmon from the subsequent year class.

Age Structure Sub-Model

An age-structure model was used to modify the production from each simulated brood year to reflect the actual return. The Kenai River sockeye salmon return is composed of 3 through 7 year-old fish with over 98% of the return being 4, 5, and 6 year olds. An examination of age at return data for the 1968–1992 brood years indicated that on average, 70% of the return from a brood year are 5 year-old fish. We also found that on average, 62% of the 4 and 6 year-old returns were 6 years old. This information along with the observed variation about these estimates was used to allocate the simulated production between return years. An in-depth discussion of this model can be found in Appendix B.

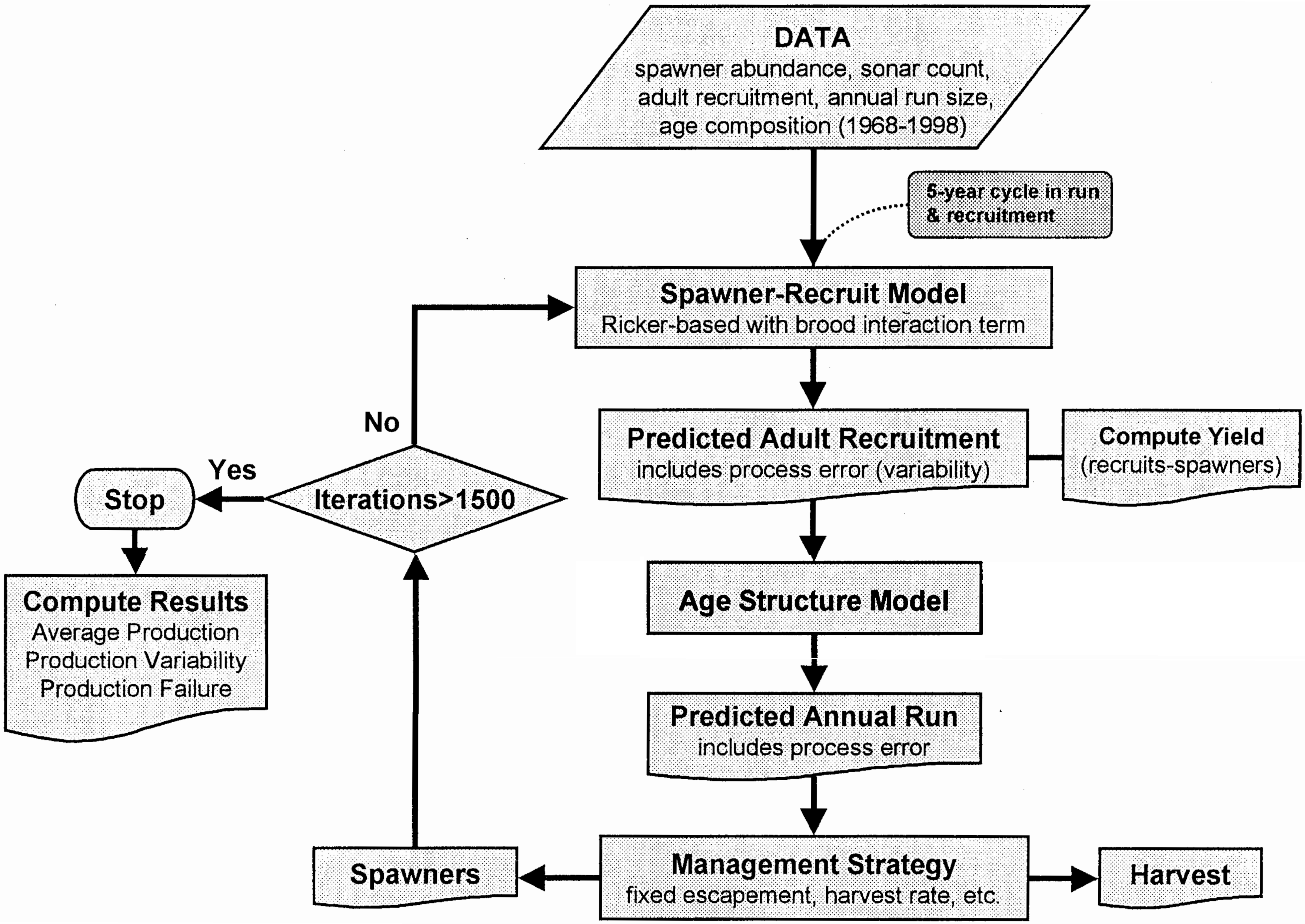
Harvest Strategy Sub-Model

Four harvest strategies can be evaluated interactively in the simulation. The first is a fixed escapement goal policy where all fish in excess of the escapement goal are harvested. The second is a fixed harvest rate policy where a constant proportion of the run is harvested. The third utilizes a floor policy where a harvest rate is applied to all returns above a minimum escapement level; and the fourth is a floor–ceiling policy where no harvest is allowed below a minimum escapement, all fish above a maximum escapement are harvested, and a harvest rate is applied between the minimum and maximum escapements. Model details are presented in Appendix C.

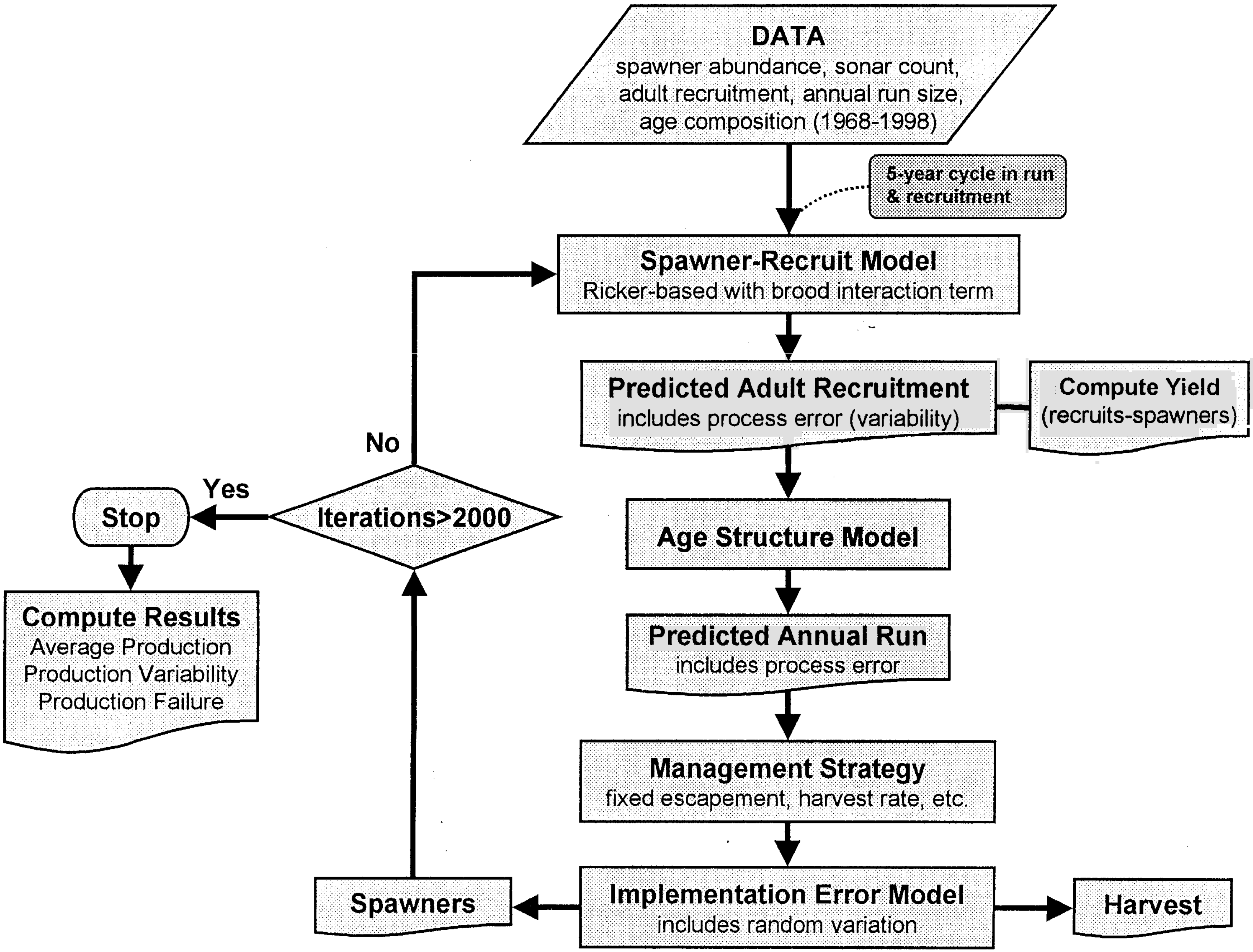
Implementation Error Sub-Model

An examination of the sockeye salmon escapement data for the Kenai River shows that the number of spawners has exceeded the biological escapement goal range for 10 of the last 18 years. We have defined this discrepancy, the ratio of actual spawners to the biological escapement goal, to be implementation error. We have also found that this error is related to the degree of difference between the escapement goal and the total run of sockeye salmon; generally, the larger the difference, the greater the implementation error. The implementation error model was developed using Kenai River sockeye salmon data from the past 18 seasons, the period when current management techniques were in place. We used the model in the simulation analysis to modify the predicted number of spawners. Details of this model are described in Appendix D.

Kenai River Sockeye Salmon Simulation Model



Kenai Sockeye Simulation Model – implementation error



Notation used in the spawner-recruit analyses and simulation of Kenai River sockeye salmon. Common statistical notation is not listed.

i	run year or brood year index
j	age-class index
R	number of adult recruits from a given brood year
N	total run of adult sockeye in a given year
S	number of spawners
G	escapement goal
H	harvest
Y	yield
HR	harvest rate
F	floor or minimum escapement goal
T	ceiling or maximum escapement goal
msy	maximum sustainable yield
ε	random normal variate
mse	regression analysis mean squared error
s	square-root of mse
ln	natural logarithm
exp	exponent (base e)
var	estimated sample variance
sd	estimated sample standard deviation (square-root of var)
IE	implementation error

APPENDIX A. Brood Interaction Spawner-Recruit Model

The full brood interaction model is

$$R_i = S_i^{\gamma} \exp[\alpha - \beta_1 S_i - \beta_2 S_{i-1} - \beta S_i S_{i-1} + v] \quad , \qquad \text{(A1)}$$

which includes spawners from the previous year (S_{i-1}) and a statistical interaction term ($S_i S_{i-1}$). The reduced, 3-parameter brood interaction model,

$$R_i = S_i^{\gamma} \exp[\alpha - \beta S_i S_{i-1} + v] \quad , \qquad \text{(A2)}$$

is the result of concurrence among several variable selection procedures used in regression analysis, including best subsets, Mallow's C_p, and stepwise regression. The regression equation is

$$\hat{R}_i = S_i^{g} \exp[a - b S_i S_{i-1}] \quad , \qquad \text{(A3)}$$

where $a = 1.55$, $g = 1.07$, and $b = 8.70\text{E-}07$ ($P < 0.0001$). However, γ does not differ significantly from 1.0 ($P = 0.73$). Therefore, an alternative reduced model is

$$R_i = S_i \exp[\alpha - \beta S_i S_{i-1} + v] \quad , \qquad \text{(A4)}$$

which is the 2-parameter brood interaction model. The regression equation is

$$\hat{R}_i = S_i \exp[a - b S_i S_{i-1}] \quad , \qquad \text{(A5)}$$

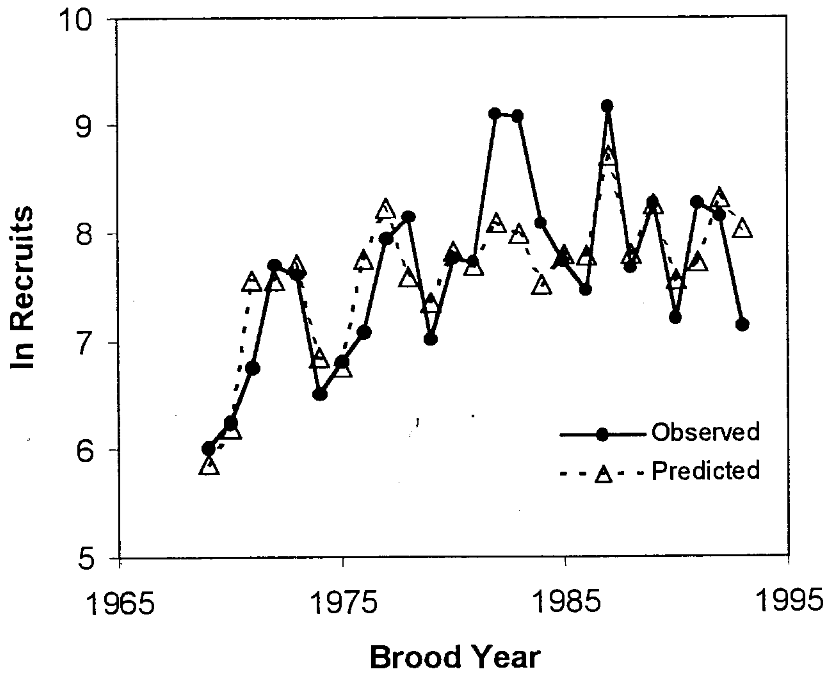
where $a = 1.91$ and $b = 7.55\text{E-}07$ ($P = 0.036$).

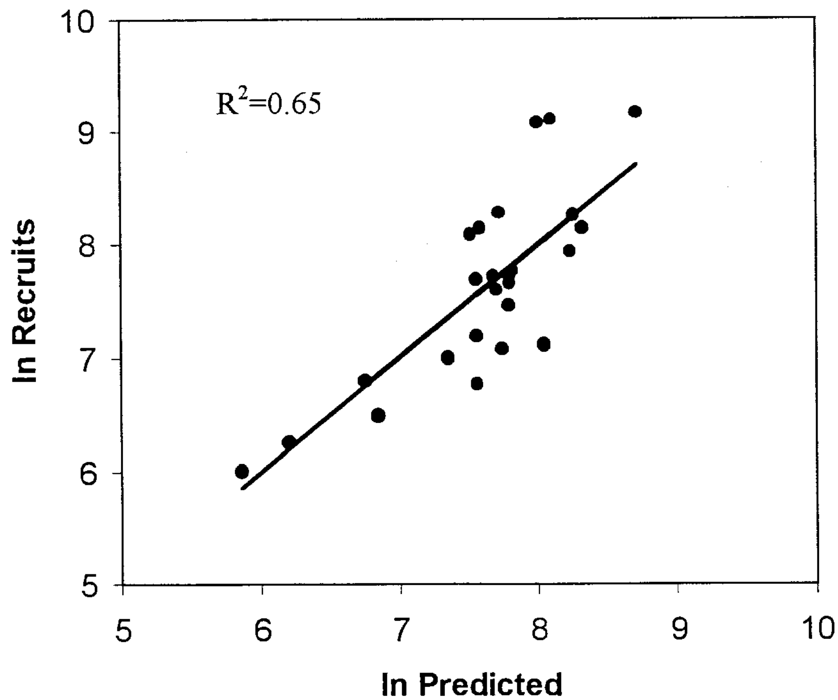
The computation of predicted recruitment in the simulation model uses equation A5, the 2-parameter reduced regression equation. The prediction includes *mse* from the regression analysis to reflect variability or process error. Predicted recruitment in the i^{th} simulation year is therefore

$$\hat{R}_i = S_i \exp[a - b S_i S_{i-1} + s(\varepsilon)] \quad , \qquad \text{(A6)}$$

noting that the number of spawners S is predicted for each iteration (see Appendix C).

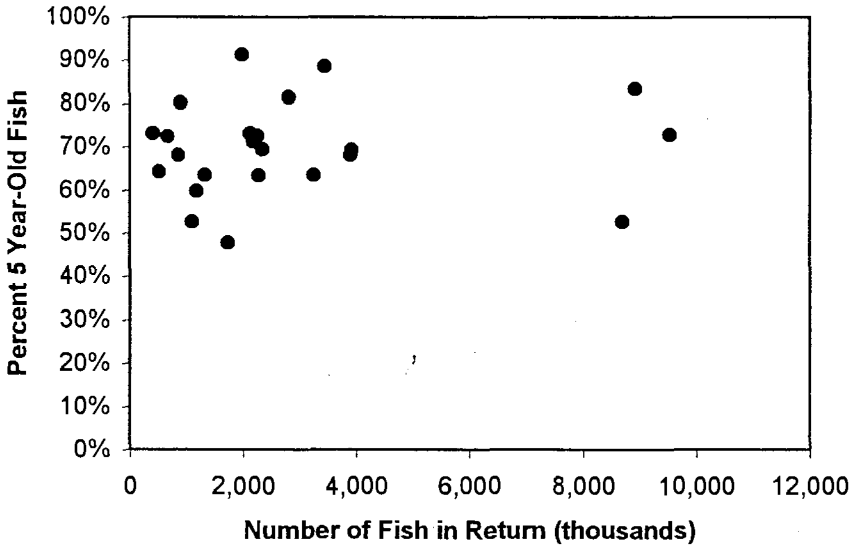
The following Figures illustrate the ability of the brood-year interaction model to predict past recruitment to the Kenai River.





APPENDIX B. Age-Structure Model

An examination of the Kenai River sockeye salmon brood year data for the 1968–1992 brood years indicated that on average 70% of the brood year returns are 5 year-old fish. There does not appear to be a relationship between the percent of 5 year-old fish and the size of the recruitment.



We also found that on average, 62% of the 4 and 6 year-old returns were 6 years old and this percentage did not appear to be related to the total number of 4 and 6 year-old recruits. Because there was no detectable relationship between the percent contribution of an age class and the recruitment we assumed that an age class could be simulated using the mean percent contribution.

The observed proportions were first transformed using natural logarithms to normalize the distribution as well as constrain the estimates to values greater than or equal to zero. The mean transformed proportion ($\bar{x}$) and corresponding standard deviation were calculated for the proportion of 5 year-olds in the total recruitment and for the proportion of 6 year-olds in the 6 and 4 year-old recruitment.

The algorithm used to simulate the age structured recruitment was,

$$\begin{aligned} \hat{R}_{i5} &= \hat{R}_i \exp[\bar{x}_5 + sd_5(\varepsilon)] \\ \hat{R}_{i6} &= (\hat{R}_i - \hat{R}_{i5}) \exp[\bar{x}_6 + sd_6(\varepsilon)] \\ \hat{R}_{i4} &= \hat{R}_i - \hat{R}_{i5} - \hat{R}_{i6} \end{aligned} \qquad \text{(B1)}$$

The predicted run in simulation year *i* is composed of 4, 5, and 6 year-old recruits,

$$\hat{N}_i = \sum_{j=4}^{6} \hat{R}_{i-j,j} \quad , \qquad \text{(B2)}$$

where the brood year of the recruits is *i-j* and *j* indicates the age at recruitment. Equation B2 is depicted below.

Simulation Year	Spawners	Recruits	Annual Run Components			
			Age-4	Age-5	Age-6	Total Run
1	S_1	R_1				
2	S_2	R_2				
3	S_3	R_3				
4						
5			R_{14}			
6			R_{24}	R_{15}		
7			R_{34}	R_{25}	R_{16}	$R_{34}+R_{25}+R_{16}$
8				R_{35}	R_{26}	
9					R_{36}	

APPENDIX C. Harvest Strategy Model

Four harvest strategies can be evaluated interactively in the simulation: (1) fixed escapement goal, where the number of fish exceeding G are harvested; (2) fixed harvest rate, HR, where a constant proportion of the run is harvested; (3) floor, F, where a fixed harvest rate is applied above a minimum allowable escapement; and (4) floor–ceiling, $F–T$, where a fixed harvest rate is applied above the floor, until the maximum allowed escapement is achieved.

For a fixed escapement goal $\hat{S}_i = G$ is constant, unless $G > \hat{N}_i$; therefore, predicted harvest in the simulation is

$$\hat{H}_i = \max\{0, \hat{N}_i - G\} \quad . \tag{C1}$$

For a fixed harvest rate

$$\hat{H}_i = HR(\hat{N}_i) \quad . \tag{C2}$$

For the floor option

$$\hat{H}_i = \max\{0, HR(\hat{N}_i) - F\} \quad . \tag{C3}$$

For the floor–ceiling strategy

$$\hat{H}_i = \max\{0, HR(\hat{N}_i) - F, \ \hat{N}_i - T\} \quad . \tag{C4}$$

Under perfect implementation $\hat{S}_i = \hat{N}_i - \hat{H}_i$ defines the escapement goal G_i.

Appendix D. Implementation Error Model

This appendix only applies to the simulation analysis with implementation error. Implementation error (*IE*) is defined as the ratio of the observed number of spawners to the escapement goal:

$$IE_i = {S_i}/{G_i} \quad . \tag{D1}$$

The statistical model relates implementation error to the ratio of the escapement goal to the run (*G*/*N*) in the observed data:

$$IE_i = \delta(G_i/N_i)^{\gamma}\exp(v) \quad . \tag{D2}$$

This approach relates implementation error to the relative escapement goal and is based on our observation that historically implementation error has decreased as the goal approached the run size. We also recognized that certain constraints were necessary for this model to be useful in the simulation. First, the number of spawners cannot exceed the run, so when $G_i/N_i = 1$, *IE* cannot be greater than 1. Second, some harvest will always take place regardless of how small the run is. The first index of sockeye salmon run strength to the Kenai River has been available on July 10, the date of the first offshore test fishing report. The percent of the total harvest taken prior to July 10 for the years 1980 to 1998 has averaged 11%. We used this as the minimum annual harvest proportion in the simulation. The implementation error model was further constrained such that when $G_i = 0.89(N_i)$, $S_i = G_i$. When $G_i > 0.89(N_i)$, the simulation algorithm sets $S_i = 0.89(N_i)$. The constrained implementation error model is

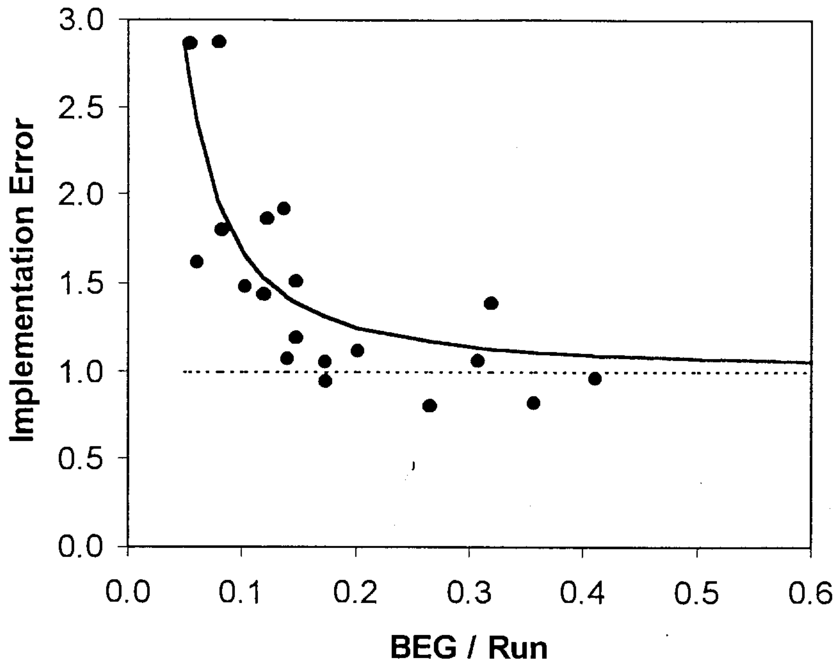
$$IE_i = \delta(G_i/N_i)^{\gamma}\exp(v) + k \quad . \tag{D3}$$

Nonlinear regression analysis was used to estimate δ and γ by varying the constant *k* to satisfy the above constraint. Data collected from 1980 to 1998 were used in the analysis to reflect the period of currently available management tools. The regression equation is

$$\hat{IE}_i = d(G_i/N_i)^{g} + k \quad , \tag{D4}$$

where $d = 0.0243$, $g = -1.45$, and $k = 0.97$ ($R^2 = 0.61$).

The following figure illustrates the fit of the model to the actual data.



Equation D4 is used to adjust the predicted number of spawners and the regression *mse* is included to reflect variability in implementation error:

$$\hat{S}_i = G_i\left[d\left(G_i/\hat{N}_i\right)\right]\exp[s(\varepsilon)] + k \quad , \tag{D5}$$

where G_i is defined by the management strategy (see Appendix C).

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