A Simulation Model for Sockeye Salmon in the Wood and Nushagak Rivers: A tool for evaluating escapement and harvest levels

by

David G. Evans
James B. Browning
and
Brian G. Bue

Regional Information Report[1] No. 2A00-40

Alaska Department of Fish and Game
Division of Commercial Fisheries
333 Raspberry Road
Anchorage, Alaska 99518

December 2000

[1]The Regional Information Report Series was established in 1987 to provide an information access system for all unpublished divisional reports. These reports frequently serve diverse ad hoc informational purposes or archive basic uninterpreted data. To accommodate timely reporting of recently collected information, reports in this series undergo only limited internal review and may contain preliminary data; this information may be subsequently finalized and published in the formal literature. Consequently, these reports should not be cited without prior approval of the author or the of the Division of Commercial Fisheries.

A Simulation Model for Sockeye Salmon in the Wood and Nushagak Rivers: A tool for evaluating escapement and harvest levels

David G. Evans, James B. Browning and Brian G. Bue
Alaska Department of Fish and Game

Sockeye salmon returning to the Wood and Nushagak Rivers of Bristol Bay, Alaska, are harvested together in the commercial fishery of the Nushagak District. Recent declines in Nushagak River sockeye salmon run strengths have led to much discussion about the best way of harvesting the salmon returning to these two rivers. Until recently, the fishery manager's options under such a scenario have ranged from exploiting one stock optimally in the district, ignoring the effects on the other, to treading the middle ground, such that sub-optimal, but reasonable sustainable yields are obtained from both systems. Beginning in 1996, the manager was provided with a new tool, the Wood River Special Harvest Area (WRSHA), which allowed a degree of stock-specific control over exploitation rates. Nushagak River stocks could theoretically be exploited at an optimum rate in the main district, while any salmon escaping to the Wood River that were in excess of its escapement goal could be harvested in the WRSHA. Introduction of the area was not a cure-all, however, in that it imposed a physical confinement on permit holders. More recently, the Board of Fisheries added a new component, the "Optimum Escapement Goal" (OEG) to the management strategy in response to the low Bristol Bay returns of 1997 and 1998. This action effectively reduced the lower end of the escapement goal range for the Nushagak River from 340,000 to 235,000 sockeye salmon under certain conditions and was designed to provide economic relief to permit holders. With the many different management configurations available, each with their advantages and disadvantages, it became clear that an analysis capable of comparing long-term outcomes of the different strategies was warranted. The purpose of this project was to develop a simulation model that can be used to compare the effect of three different management strategies and to investigate the effect of the OEG under each.

A general overview of the model is provided with more detail given in the Appendices.

The Model

General

The model consists of a number of integrated sub-models, each mimicking a component of the Nushagak District fishery. The general form of a given sub model is based on a theoretical understanding of the biology of the system, while the parameters of the chosen sub model are derived from historical data. An example is the choice of the form of a spawner recruit sub model (e.g. Ricker, Beverton-Holt or Cushing model) and the subsequent estimation of the parameters of the chosen model using return and spawner data collected over many years.

The simulation operates in the following manner. A user chooses a harvest strategy and escapement goals, and a time frame over which the average annual harvest (or other variable) is of interest. The sub models are then allowed to mimic the population and

fishery under the chosen escapement goals and harvest strategy for the chosen time period. At the end of the simulated period, averages of the variables of interest (e.g. average harvest over the period) are calculated and stored. The whole process is repeated many times to account for random fluctuations in returns etc. with the results being stored each time. After the chosen period has been simulated many times, the user examines the results averaged over all simulations to see how the chosen strategy and escapement goal combination has performed. The degree to which results vary from one simulation to the next is also of interest in that it reflects on the likelihood of a particular result in a future time period. The user typically would then repeat the simulation for different goals and harvest strategies.

The sub models are described briefly below. A flow chart describing the model is found in Figure 1. Details of the sub models are presented in the Appendices.

Spawner-Recruit Sub Models

Driving the population dynamics of the sockeye salmon returns in the model are two Ricker spawner recruit relationships, one for each of the Nushagak and Wood Rivers. These relationships are estimated from many years' catch, escapement and age-class data and are used to generate returns from a given number of spawners. Details of the spawner-recruit sub models are provided in Appendix A.

Age-Class Sub Models

A river-specific age-class model is estimated for each of the Nushagak and Wood River sockeye salmon stocks. These models decide how many of the returns generated by the spawner recruit models will mature at each age. The sub model partitions the Wood River return into four age classes, ages 1.2, 1.3, 2.2 and 2.3, while it partitions the Nushagak returns into seven classes, ages 0.2, 0.3, 1.2, 0.4, 1.3, 1.4, and 2.3. Summing across age classes provides annual run sizes for each of the Nushagak and Wood Rivers. Details of the age-class sub models are provided in Appendix B.

Harvest Sub Models

Once the annual runs have been calculated, they are exposed to the harvest strategy chosen by the user at the outset of the simulation. Three harvest strategies are examined.

The first policy is the "Fixed-Wood" policy (FW) where fishery openings are determined by the state of the Wood River escapement only. In essence, the Nushagk River stock is ignored completely under this harvest strategy, and fishing occurs in accordance with the size of the Wood River return.

The second policy is the "Fixed-Wood-Fixed-Nushagak" policy (FWN) in which fishing in the main area of the Nushagak District is controlled by the health of the Nushagak River return, with control of the Wood River return being left to actions in the WRSHA. For example, a low return to the Nushagak River in conjunction with an average or high return to the Wood River would generally mean that a significant proportion of the Wood

River run would be harvested in the WRSHA. On the other hand, a high return to the Nushagak River in conjunction with a low return to the Wood River could result in over-exploitation of the Wood River stocks since fishing in the Nushagak District is controlled by the state of the Nushagak River run only.

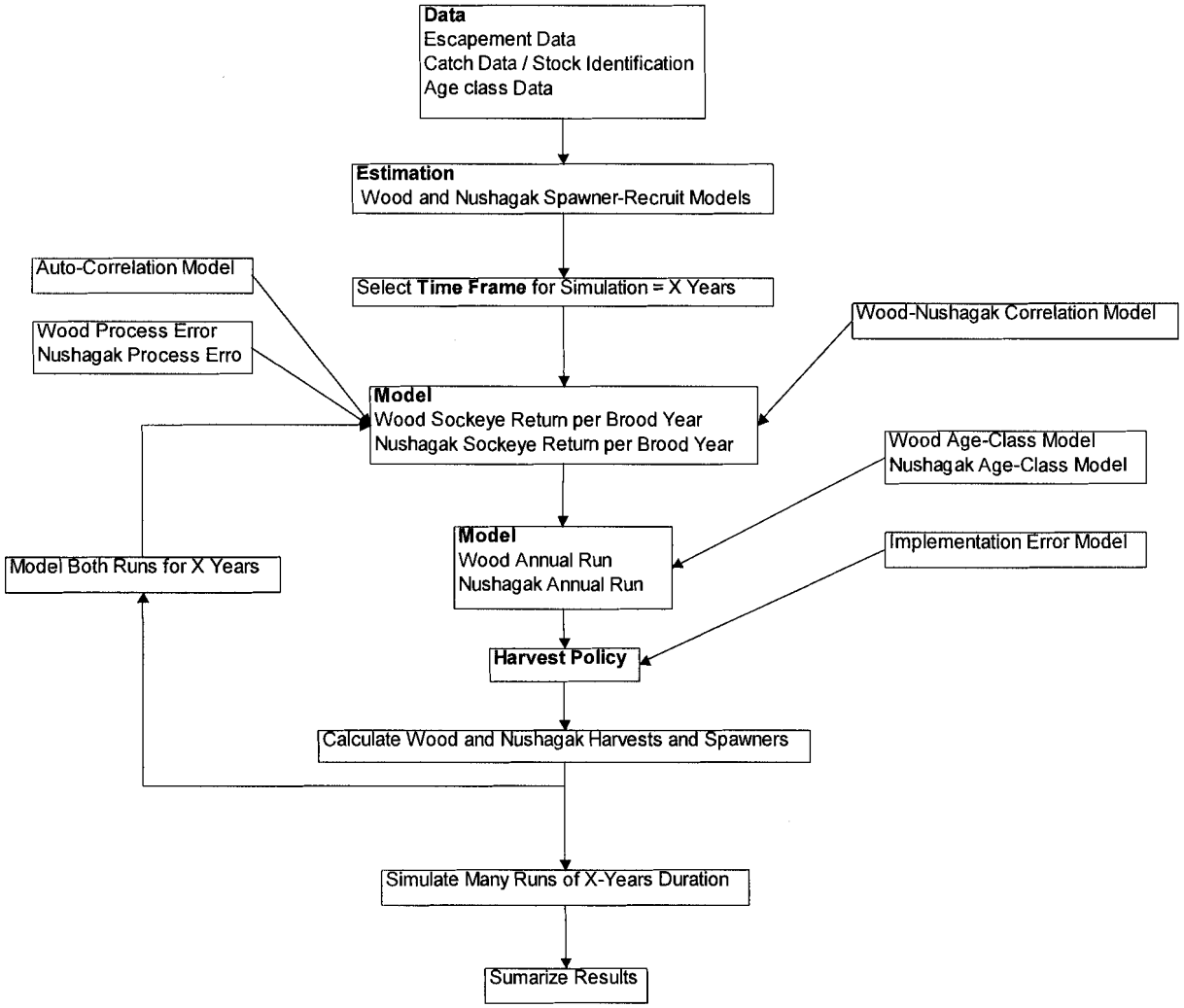


Figure 1. Wood-Nushagak Simulation Model

The third policy is the "Fixed-Nushagak" policy (FN) where fishery openings are determined by the state of the Nushagak River escapement only. In essence, the Wood River stock is ignored completely under this harvest strategy, and fishing occurs in accordance with the size of the Nushagak River return. Details of the harvest strategy sub models are provided in Appendix C.

Operating alongside the chosen harvest policy is a feature that ensures at least some harvest is taken regardless of the size of the run. This component reflects the realistic situation that the size of the run is unknown at the beginning of the season, and that the manager will have allowed some fishing by the time this information is available.

Correlation Sub Models

These sub models allow for correlation in productivity between the Wood and Nushagak River stocks, and correlation of productivity within stocks. The drive for including a correlation between Wood and Nushagak River stocks lies in the idea that large-scale environmental effects likely affect both systems in a similar way. The correlation sub model imposes a link between the two systems and results in a tendency for high returns to the Wood River to occur when there are high returns to the Nushagak River and vice versa. A problem with the sub model is that it is difficult to decide how much correlation to include.

Correlation within each of the Nushagak and Wood River stocks addresses the idea that a high return is more likely to be followed by a high return than a low return, and vice versa. Again, a problem with the model is that it is difficult to decide how much of this auto-correlation to include.

Details of the between-river and within-river correlation sub models are found in Appendices D and E.

Implementation Error Sub Model

The implementation error option concerns the observed tendency for a manager to exceed an escapement goal more often when the run is strong than when it is weak. This behavior has been observed for the Kenai River (Carlson et al. 1999) and also for the Nushagak and Wood Rivers (see Appendix Figure F.1). A modification of the implementation error model developed by Carlson et al. (1999) is used, which adjusts the number of fish allowed into each river according to the relative size of the run and river's escapement goal. Details of the sub model are found in Appendix F.

Accounting for Variability

It is well known that it is practically impossible to predict exactly the number of salmon returning to the Wood and Nushagak Rivers in any given year, or the exact proportion of salmon that will return as age 2.2's or 1.3's, for example. This is because the biology of the system is not perfectly understood. Subtle processes that we cannot hope to model act to nudge outcomes one way or another. While the average effect of these

perturbations around our model predictions is small or zero, it is important to account for them in some way since they control the level of confidence we ultimately have in making predictions from the overall simulation model. Large perturbations around the sub model predictions, for example, would ripple through the simulation and result in harvest varying substantially from one simulated run to another, and subsequently little confidence that the model could predict any one future harvest with accuracy, and vice versa. By injecting the right amount of randomness at the right stages in the sub models, we can estimate the level of confidence with which the simulation predicts a future harvest or run or other variable of interest.

For the recruitment sub model, we account for uncertainty by adding a random component, or 'process error', at appropriate stages within the simulation. We estimate the amount of process error to add by comparing actual returns with those predicted by the sub model. If data points are scattered widely around our predictions, we add a large amount of process error, and vice versa. Practically, the process error added to each simulated return is generated by instructing the computer to take a random number from a statistical distribution with an overall mean of zero, but with spread dictated by the comparison of actual versus predicted returns. For the age-class model, variability in the age composition of the return from a brood year is accounted for by instructing the computer to sample age compositions from a statistical distribution fitted with historical age-class data, and therefore reflecting natural variability.

Model Summaries

Average annual harvest, average run and spawner size, and the chances that the annual harvest is less than a range of values are among some of the numerous quantities we calculated at the end of each simulated period. After simulating many periods, period statistics are averaged over all simulations, along with calculation of the variability of the period statistics across the simulations.

Results and Discussion

The simulation model requires a variety of inputs to function properly, with the quality of these inputs directly affecting the results. The model must be provided with the two spawner-recruit and age-composition models that drive the population dynamics, the amount of correlation to incorporate between and within a river system, minimum harvest levels, and appropriate amounts of stochasticity, or random fluctuation, at all levels of the model. Different inputs necessarily produce different results, and there will undoubtedly be debate regarding which set of inputs is the right set to use. We attempted to accommodate different viewpoints by conducting a sensitivity analysis, where the model was run with a range of inputs.

It was found that the two correlation options had little effect on the model results and that the minimum harvest percentage only affected results to any meaningful degree at values much higher than are believed to occur. We also found little effect of the implementation

error component on annual total harvests. The implementation error model did, however, make it appear that optimum goal for the Wood River was lower than that suggested by the analyses of spawner-recruit data. This is an expected result, since the general effect of the management error component for the Wood River is to add fish over and above a given escapement goal when runs are relatively large. The effect was much less for the Nushagak River. We caution the use of the implementation error model because it depends on assumptions about a manager's behavior. The data used to develop our implementation error model is associated with four different managers, and it is possible that the behavior of any given manager is different from the pooled relationships shown in Figure 4 (Appendix). In summary, implementation error did not affect annual total harvests to any degree for any of the policies. It did affect the apparent optimum escapement goal for the Wood River, but we have reservations about incorporating such a finding in escapement goal policy. The results reported in this study were generated with the implementation error option turned off.

We assessed sensitivity to the spawner recruit sub models by running the model with a variety of Ricker productivity parameters for the Wood and Nushagak Rivers (Table 1). For each harvest policy, we provide the maximum annual total harvest (*i.e.* from the Wood *and* Nushagak Rivers) occurring over the tested Wood and/or Nushagak River escapement levels and the annual total harvest under a Nushagak goal of 340,000 (current lower end of escapement goal range) and the proposed Nushagak OEG of 235,000. The harvest at the OEG escapement level as a percent of the maximum harvest and that occurring at the current lower level of 340,000 is also given for each scenario.

As expected, maximum annual total harvest was affected significantly by the size of the Ricker productivity parameters, and was highest for scenario 5, in which the Wood and Nushagak productivity parameters were highest. Of more interest, however, is the comparison of harvest among policies, and how this changes over the scenarios. Maximum annual total harvests were greatest for the FWN policy under all scenarios considered. The differences in harvest among strategies were small for the situation corresponding to our best estimate of Ricker a parameters (Scenario 1). Differences were, however, much larger for Scenario 2, in which the difference in productivity of the Wood and Nushagak Rivers is at a maximum, and where the exploitation rate for maximum sustainable yield for the Wood River stocks was almost double that of the Nushagak River stocks. This result is not surprising. The FWN harvest policy was conceived because of the idea that the productivity of the Wood and Nushagak Rivers were different, and that an optimum harvest strategy would have to involve a method whereby the two stocks were exploited at different rates. Expectedly small differences in harvests among policies were found for other scenarios for which productivity between stocks was similar.

Maximum Harvests

Plots of annual total harvest versus escapement goals is given for each policy in Figure 2 for the scenario reflecting our best estimate of the Ricker parameters. The vertical bars on the total harvest plot give a measure of the confidence of the predictions of harvest, given the assumption that our Ricker parameter estimates are appropriate. These bars

Table 1. Sensitivity of Simulation Model to Ricker parameters. Results for fitted parameters (scenario 1) are in bold.

Scenario	Ricker a[a]		Policy[b]	Esc at Max Harvest (K)		Harvest Max (K)	'Best' Policy[c]	% Red Among Policy	Harvest		% Red (OEG) from Max Harv	%Red (OEG) from 340K
	Wood	Nush		Wood	Nushagak				340K[d] (K)	OEG[e] (K)		
1	**1.75**	**1.46**	**FW**	**1350**	**NA**	**3494**		**3.0**	**NA**	**NA**	**NA**	**NA**
			FWN	**1350**	**790**	**3603**	X	**0.0**	**3165**	**2875**	**20.2**	**9.2**
			FN	**NA**	**550**	**3303**		**8.3**	**3103**	**2847**	**13.8**	**8.2**
2	2.25	1.00	FW	1100	NA	3968		14.0	NA	NA	NA	NA
			FWN	1150	790	4615	X	0.0	4416	4305	6.7	2.5
			FN	NA	235	2962		35.8	2913	2962	0.0	-1.7
3	1.61	1.61	FW	1250	NA	3355		1.2	NA	NA	NA	NA
			FWN	1350	790	3395	X	0.0	2622	2128	37.3	18.8
			FN	NA	690	3247		4.3	2619	2128	34.5	18.8
4	1.75	1.00	FW	1600	NA	2830		11.7	NA	NA	NA	NA
			FWN	1150	790	3206	X	0.0	2983	2861	10.8	4.1
			FN	NA	340	2504		21.9	2504	2481	0.9	0.9
5	2.25	1.46	FW	1450	NA	4500		10.6	NA	NA	NA	NA
			FWN	1150	790	5035	X	0.0	4737	4531	10.0	4.3
			FN	NA	340	4128		18.0	4128	4076	1.3	1.3
6	1.46	1.75	FW	1150	NA	3155		0.6	NA	NA	NA	NA
			FWN	1350	940	3174	X	0.0	1789	1213	61.8	32.2
			FN	NA	795	3118		1.8	1790	1213	61.1	32.2

a Productivity parameter for Ricker components of model; the best estimates were 1.75 for Wood and 1.46 for Nushagak (Appendix A).

b FW=Fixed Wood Policy; FWN=Fixed Wood, Fixed Nushagak Policy; FN=Fixed Nushagak Policy

c 'Best' means maximum harvest

d For FWN Policy, this is the total harvest at the Nushagak 340K goal (OEG) and the Wood River goal in column 4

e For FWN Policy, this is the total harvest at the Nushagak 235K goal and the Wood River goal in column 4

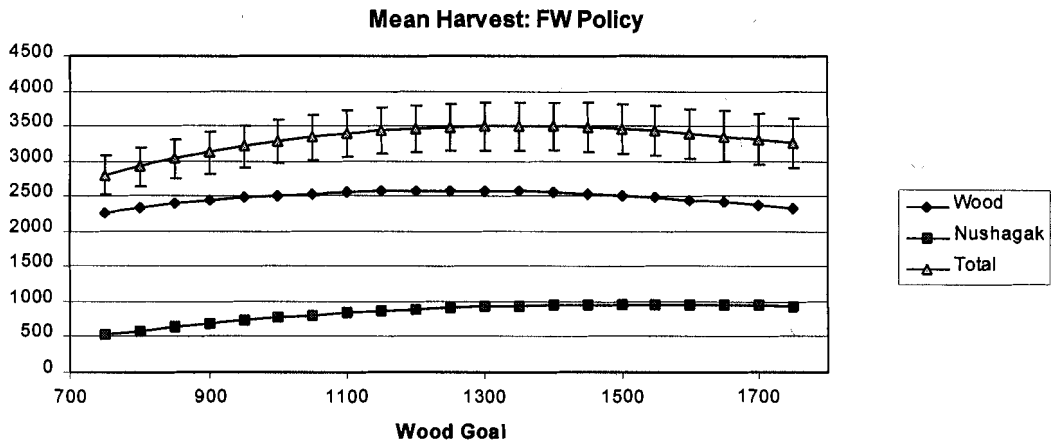
represent the range of a future annual harvest, averaged over any 50-year period, that we are likely (95% sure) to see, and therefore reflect our confidence about the model's ability to give us useful data. Generally, our predictions have a coefficient of variation (CV) of about 5-10% and are therefore usefully precise. A note of caution is warranted here. The model used to generate the results in Figure 2 uses one set of fitted spawner-recruit parameters and process error to account for unmodeled variation around the fitted relationship. We believe our estimates are the best available, but it is possible that the true parameter values differ from those used in the model. The 80% confidence intervals for the Nushagak and Wood River productivity parameters (Ricker *a*) are about {1, 2} and {1.5, 2}, respectively. Our sensitivity analysis encompasses this range of uncertainty (Table 1).

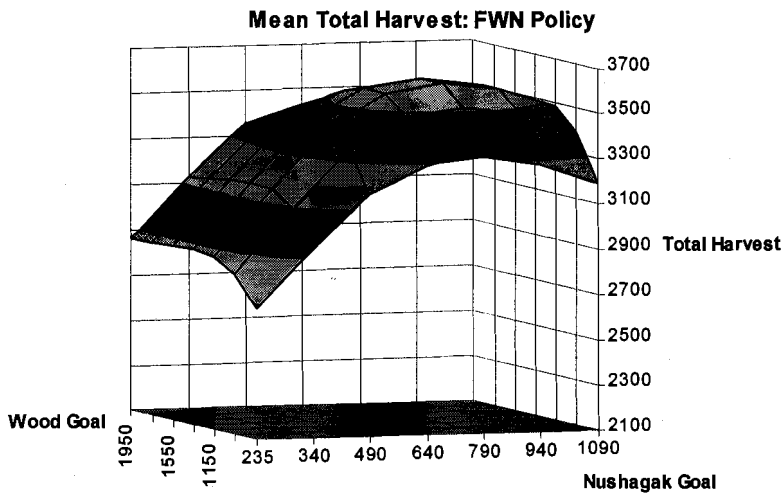
A measure of the risks of poor harvests as affected by escapement goals is given in Figure 3 for the scenario described above. Here the chance that the annual total harvest will fall below a certain value is estimated as a proportion of the number of times out of each 50 year period for which this is true. This calculation is then averaged over all 200 simulations and the result plotted. Plots for the FW and FN policies are similar in shape and show how the risk of poor harvest increases as either too few or too many fish are allowed into the rivers. The plot for the FWN policy is necessarily three-dimensional to allow for interpretation of the effect of the two different escapement goals on the risk variable. Again, however, the saucer shaped plot displays the over and under-escapement traits observed for the FW and FN plots. Suppose a user is interested in the chance the annual total harvest will fall below 2,000,000 salmon over a 50-year period. The plots in Figure 3 indicate that for the escapement goal that maximizes annual total harvest, the risk is in the 10-15% range for the FW policy, and in in the 5-10% for the FN and FWN policy. It is of interest to note that while the FW policy results in a higher maximum annual total harvest than the FN policy, its risk of a poor harvest (defined as under 2,000,000 here) is higher. The FWN policy leads to a higher maximum annual total harvest and the lowest risk of poor harvest, but only marginally so.

Nushagak OEG

The simulation exercise found that annual total harvest at a Nushagak escapement of 235,000 (OEG) was reduced across all policies and scenarios when compared to maximum harvests. This is not at all surprising, but the magnitude of the reduction under some of the scenarios is food for thought. For scenario 6, in which the Nushagak River is more productive than the Wood River, the annual total harvest for the FWN and FN policies under a Nushagak goal of 235,000 is 60% lower than the maximum attainable. Admittedly this scenario may be unlikely, but the reduction is still high (about 35%) when the rivers are considered equally productive (scenario 3).

The annual total harvest at a Nushagak escapement of 235,000 (OEG) was reduced to a lesser degree when compared to the harvest obtained at a Nushagak goal of 340,000. For the fitted Ricker parameter scenario (scenario 1), the reduction for the FWN policy was about 10%. Again, however, the magnitude of the reduction under some of the scenarios is interesting. For scenario 6, described above, the annual total harvest for the FWN and





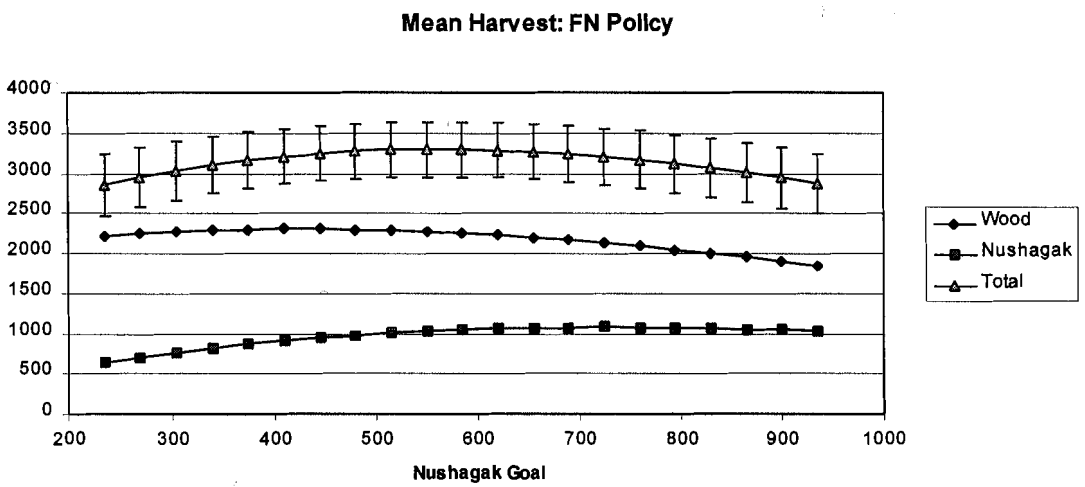
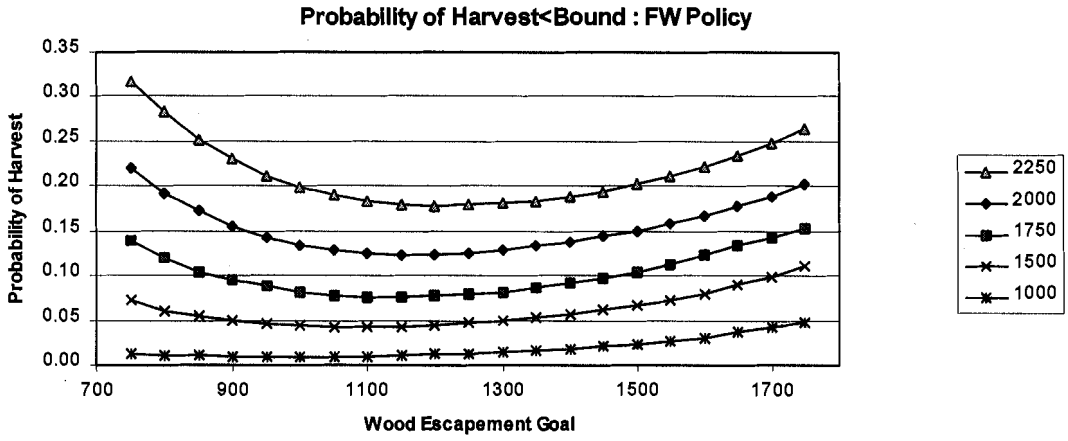
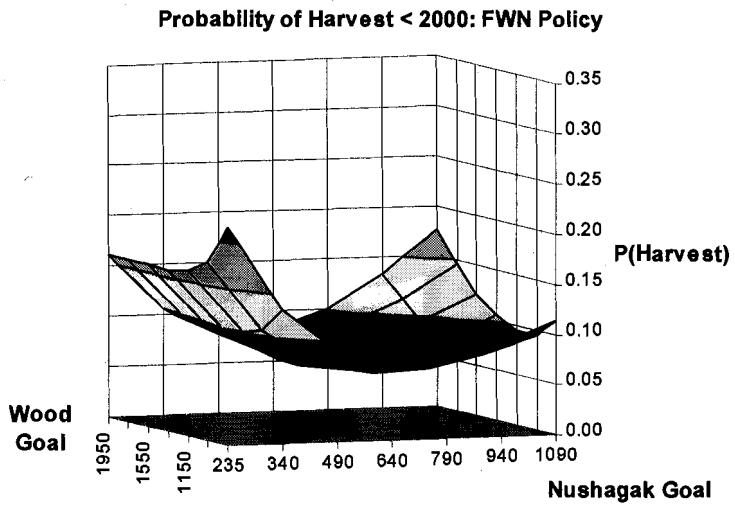


Figure 2. Annual Harvests for Fixed-Wood (FW), Fixed-Wood-Fixed-Nushagak (FWN) and Fixed-Nushagak (FN) policies.





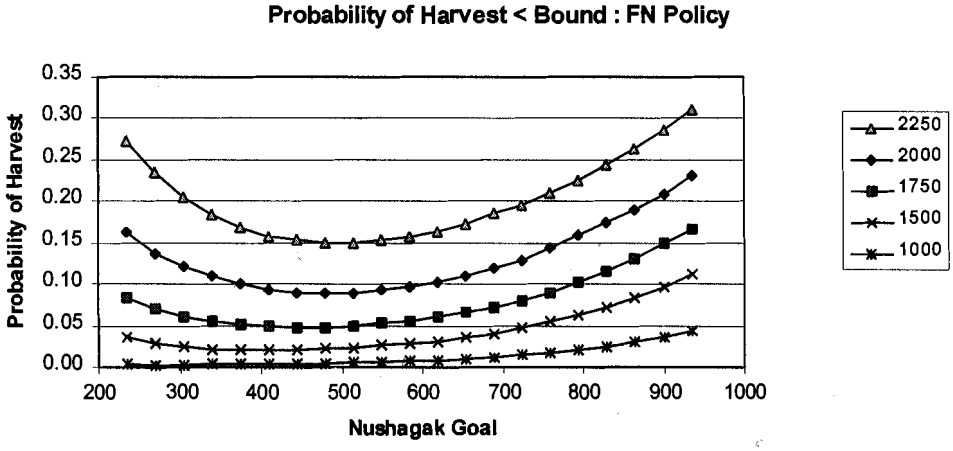


Figure 3. Risk of poor harvest for Fixed-Wood (FW),) Fixed-Wood-Fixed-Nushagak (FWN) and Fixed-Nushagak (FN) policies.

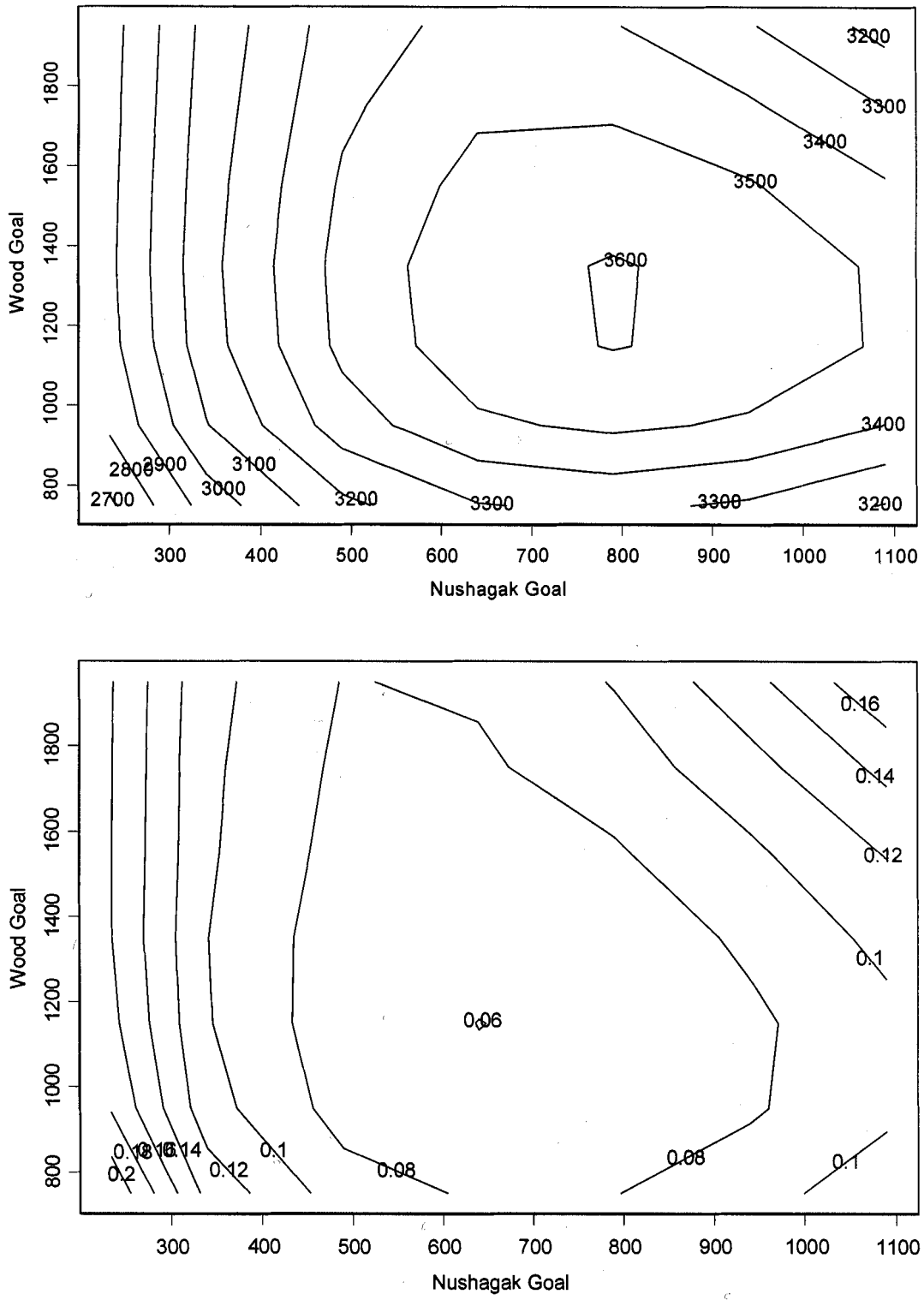


Figure 4. Contour presentations of the Fixed-Wood-Fixed-Nushagak (FWN) plots shown in Figures 2 and 3 (top=harvest, bottom=probability).

FN policies under a Nushagak goal of 235,000 is 32% lower than that obtained at a goal of 340,000, and the reduction is about 19% when the rivers are considered equally productive (scenario 3).

With respect to risk of a poor harvest, Figures 3 shows there to be an accelerating trend in risk as Nushagak escapement goals decline. For example, the risk of a harvest less than 2,000,000 for the FN and FWN policies changes from about 8% at the escapement producing maximum harvest to 10% at the 340,000 escapement level to 16% at the 235,000 level.

Summary

- The FWN policy resulted in the best annual total yields for all scenarios considered.
- The degree to which the FWN policy outperformed the FW or FN policies depended significantly on the choice of Ricker productivity parameters.
- For the fitted Ricker parameters, the FW and FN policies were 3% and 8% inferior, respectively.
- For the fitted Ricker parameter scenario, the % reduction in harvest under the 235,000 (OEG) Nushagak goal compared to the maximum harvest attainable and that at a 340,000 Nushagak goal was 20% and 9%, respectively.
- The risk of poor harvest accelerates with decreasing Nushagak escapement goals.

Acknowledgements

The Wood-Nushagak model originated from the Kenai River model of Carlson et al. (1999), and was modified to account for two river systems, different harvest strategies, correlations within and between rivers and different age-class relations. The implementation error sub model used in the current model is similar to that formulated by Carlson et al. (1999).

Appendices

Notation used in the following Appendices (Common statistical notation is not listed).

u	Nushagak River index
w	Wood River index
R	Number of adult recruits from a given brood year
S	Number of spawners in a brood year
b	Ricker parameter
a	Ricker parameter
ε	$N(0,\sigma^2)$ variable
*	Denotes simulated variable
i	Run year or brood year index
N	Total run of adult sockeye in a given year
j	Age-class index
G	Escapement goal
H	Harvest
E	Exploitation Rate

APPENDIX A: Spawner Recruit Sub Models

Nushagak River

A Ricker model was fitted to the spawner-return data gathered for brood years 1986 through 1995. The beginning of this period, 1986, corresponds to removal of the metal substrate along which the sonar was aimed. Analysis showed that the substrate affected the fish behavior and caused inaccuracies in fish counts. The end of the period, 1995, is the last brood year for which all major age classes have returned or can be estimated by the year 2000. While these data form only part of the Nushagak data series, they were considered the most reliable.

The model fitted was parameterized as follows

$$R = Se^{a(1-S/b)+\varepsilon}$$

where $\hat{a} = 1.46$ and $\hat{b} = 1794$, and $\varepsilon \simeq N(0,0.081)$.

A non linear measurement error technique was used to fit the parameters in order to account for variability in the independent spawner level variable. For comparison, a traditional least squares approach on the linearized Ricker model $\ln(R/S) = a - a/bS + \varepsilon$ yields $\hat{a} = 1.87, \hat{b} = 1229$ and $\varepsilon \simeq N(0,0.12)$.

For brood year i in the simulation, the number of Nushagak River recruits, R_i^*, generated from a spawner level, S_i^*, is given by

$$R_i^* = S_i^* e^{\hat{a}(1-S_i/\hat{b})+\varepsilon_i^*}$$

where ε_i^* is sampled from a $N(0,0.081)$ distribution and reflects process error.

Wood River

A Ricker model was fitted to the spawner-return data gathered for brood years 1973 through 1995. The beginning of this period, 1973, corresponds to a putative shift in productivity for the Wood River, while the end of the period, 1995, is the last brood year for which all major age classes have returned or can be estimated by the year 2000. Estimation and simulation procedures were otherwise identical to those used for the Nushagak River stock. For the Wood River stock, $\hat{a} = 1.75$, $\hat{b} = 3192$, and $\varepsilon \simeq N(0,0.11)$. For comparison with the non linear measurement error technique, a traditional least squares approach on the linearized Ricker model $\ln(R/S) = a - a/bS + \varepsilon$ yields $\hat{a} = 1.94, \hat{b} = 2688$ and $\varepsilon \simeq N(0,0.16)$.

APPENDIX B: Age-Structure Sub Models

Nushagak River

Age structure was modeled using the Dirichlet distribution. This is the multivariate form of the beta distribution, sometimes used to model the Bernoulli parameter defining the probability in a success-failure situation. The Dirichlet distribution generalizes the beta in that it can be used to model more than one yes/no parameter at once. Random numbers generated from both the beta and Dirichlet distributions lie between zero and unity, making them suitable for generation of proportions. A Dirichlet distribution was fitted by maximum likelihood to age-class data collected from Nushagak River returns. For the simulation, a multivariate random vector was sampled from the fitted Dirichlet distribution for each brood year. The resulting vector defined the nature of the age-class return for that brood year. For example, for a given brood year, a Dirichlet random vector for the Nushagak River may consist of {0.06, 0.3, 0.2, 0.05, 0.3, 0.05, 0.04} that corresponds to the Nushagak age classes: ages 0.2, 0.3, 1.2, 0.4, 1.3, 1.4, and 2.3.

The form of the Dirichlet distribution is

$$f(\underline{\theta}|\alpha_1,\ldots,\alpha_K) = \frac{\Gamma(\alpha_1+\ldots+\alpha_K)\theta_1^{\alpha_1-1}\ldots\theta_K^{\alpha_K-1}}{\Gamma(\alpha_1)..\Gamma(\alpha_K)} \quad ; \theta_1,\ldots\ldots,\theta_K \geq 0, \sum_{k=1}^{K}\theta_k = 1$$

and the log likelihood for M observations:

$$\ln(L(\underline{\alpha} \mid \{\underline{\theta}_m\}) = \sum_{m=1}^{M}\left[\ln\Gamma(\alpha_o) - \sum_{k=1}^{K}\ln\Gamma(\alpha_k) + \sum_{k=1}^{K}(\alpha_k - 1)\ln(\theta_{km})\right]$$

with

$$\alpha_o = \sum_{k=1}^{K}\alpha_k$$

Fitted and observed means and variances are shown in Appendix Table B.1.

For each brood year in the simulation, a Dirichlet random variable was generated that determined the proportion of the Ricker-generated Nushagak stock recruitment that would return at each of the seven Nushagak River age classes.

To generate a Nushagak return during year i within the simulation, N_i, returns of the appropriate age classes were summed

$$N_i = \sum_{j=3}^{6} R_{i-j\,j}$$

This is further described in Appendix Table B.2.

Wood River

Age structure for the Wood River stocks was modeled in exactly the same way as those for the Nushagak River, except that only four age classes were modeled (ages 1.2, 1.3, 2.2, and 2.3). The fitted and observed means and variances for the Wood River are shown in Appendix Table B.1. For each brood year in the simulation, a Dirichlet random variable was generated that determined the proportion of the Ricker-generated Wood recruitment that would return at each of the four Wood River age classes.

To generate a Wood return for year i within the simulation, N_i, returns of the appropriate age classes were summed.

$$N_i = \sum_{j=4}^{6} R_{i-j\,j}$$

This is further described in Appendix Table B.2.

Appendix Table B.1. Statistics reflecting fit of Dirichlet distribution to the Wood and Nushagak River age-class data.

	Age Classes							
	0.2	0.3	1.2	0.4	1.3	1.4	2.2	2.3
Nushagak								
Obs Mean	0.034	0.299	0.087	0.040	0.483	0.038		0.020
Theor Mean	0.048	0.264	0.096	0.046	0.467	0.049		0.029
Obs Variance	0.0005	0.0253	0.0034	0.0013	0.0289	0.0011		0.0012
Theor Variance	0.0024	0.0102	0.0046	0.0023	0.0131	0.0025		0.0015
Wood								
Obs Mean			0.442		0.457		0.065	0.035
Theor Mean			0.429		0.452		0.068	0.050
Obs Variance			0.0237		0.0220		0.0050	0.0013
Theor Variance			0.0170		0.0172		0.0044	0.0033

Appendix Table B.2. Calculation of Annual Run (N_i) from Recruits (R_{ij}) components (modified from Carlson et al. 1999)

Year	Returning Recruits				Annual Returns	
	Age 3yr	Age 4yr	Age 5yr	Age 6yr	Nushagak	Wood
7	R_{43}	R_{34}	R_{25}[a]	R_{16}	$N_7=R_{43}+R_{34}+R_{25}+R_{16}$	$N_7=R_{34}+R_{25}+R_{16}$
8	R_{53}	R_{44}	R_{35}	R_{26}	$N_8= R_{53}+R_{44}+R_{35}+R_{26}$	$N_8= R_{44}+R_{35}+R_{26}$
9	R_{63}	R_{54}	R_{45}	R_{36}	$N_9= R_{63}+R_{54}+R_{45}+R_{36}$	$N_9= R_{54}+R_{45}+R_{36}$

a Age 5 fish returning in year 7 originate from brood year 2

APPENDIX C: Harvest Strategy Sub Models

The following algorithms do not incorporate the 'minimum harvest' feature, described earlier. We found it to have little effect on results and have omitted it from the details below in order to clarify descriptions. Three harvest strategies are evaluated in the simulation:

Fixed-Wood (FW) policy

- Control Fishing in Nushagak District to Manage for Wood River Escapement Goal Only
- Wood River SHA Does NOT Exist
- No Attempt to Manage for Nushagak Escapement Goal

Simulated harvest of Wood River fish in the Nushagak District in the ith year, H_{iw}, depends on the return to the Wood River, N_{iw} and the current Wood River goal, G_{iw}. If the Wood River annual run is greater than the Wood River goal then harvest, is calculated as the difference:

$$\text{If } N_{iw} > G_{iw} \quad \text{then} \quad H_{iw} = N_{iw} - G_{iw}$$
$$\text{Otherwise} \quad H_{iw} = 0$$

Simulated harvest of Nushagak River fish in the Nushagak District in the same year is calculated by exposing the annual Nushagak River run to the exploitation rate ($E_{iw} = H_{iw}/N_{iw}$) calculated for the Wood River stock:

$$H_{iu} = E_{iw} N_{iu}$$

Fixed-Wood-Fixed-Nushagak (FWN) policy

- Control Fishing in Nushagak District to Manage for Nushagak River Escapement Goal Only
- Wood River SHA DOES Exist to harvest Wood River run in excess of Wood River escapement goal
- Both Runs Managed for Escapement Goals

Simulated harvest of Nushagak River fish in the Nushagak District in the ith year, H_{iu}, is dependent on the return to the Nushagak River, N_{iu}, and the current Nushagak River goal, G_{iu}. If the Nushagak River annual run is greater than the Nushagak River goal then harvest is calculated as the difference:

$$\begin{array}{lll} \text{If } N_{iu} > G_{iu} & \text{then} & H_{iu} = N_{iu} - G_{iu} \\ \text{Otherwise} & & H_{iu} = 0 \end{array}$$

Simulated harvest of Wood River fish in the same year is calculated by exposing the annual Wood River run to the exploitation rate calculated for the Nushagk River stock ($E_{iu} = H_{iu}/N_{iu}$) and then adding any remaining difference between the Wood River run escaping the Nushagak District fishery and the Wood River goal:

$$H_{iw} = E_{iu} N_{iw} + [(N_{iw} - E_{iu} N_{iw}) - G_{iw}]$$

Fixed-Nushagak (FN) policy

- Control Fishing in Nushagak District to Manage for Nushagak River Escapement Goal Only
- Wood River SHA Does NOT Exist to harvest Wood River run in excess of Wood River escapement goal
- No Attempt to Manage for Wood River Escapement Goal

Simulated harvest of Nushagak River fish in the Nushagak District in the ith year, H_{iu}, is dependent on the return to the Nushagak River, N_{iu}, and the current Nushagak River goal, G_{iu}. Harvest is calculated in a similar manner to that of the Fixed-Wood (FW) policy. If the Nushagak River annual run is greater than the Nushagak River goal then harvest, is calculated as the difference:

$$\begin{array}{lll} \text{If } N_{iu} > G_{iu} & \text{then} & H_{iu} = N_{iu} - G_{iu} \\ \text{Otherwise} & & H_{iu} = 0 \end{array}$$

Simulated harvest of Wood River fish in the Nushagak District in the same year is calculated by exposing the annual run to the Wood River to the exploitation rate $E_{iu} = H_{iu}/N_{iu}$ calculated for the Nushagak River stock:

$$H_{iw} = E_{iu} N_{iw}$$

APPENDIX D: Between-River Correlation Sub Model

Production from the Wood and Nushagak Rivers were correlated in the simulation model by sampling the process error components, e_{iu} and e_{iw} in pairs from a bivariate normal distribution with covariance, $N_2(\underline{0},\Sigma)$, where

$$\Sigma = \begin{bmatrix} \sigma_u^2 & \sigma_{uw} \\ \sigma_{wu} & \sigma_w^2 \end{bmatrix}$$

The entries σ_u^2 and σ_w^2 are estimated after fitting Ricker-Spawner recruit models to the Nushagak and Wood Rivers. An estimate of $\sigma_{wu}=\sigma_{uw}$ is obtained from Peterman et al. (1998).

APPENDIX E: Within-River Correlation Sub Model

Production between adjacent brood years within a system is linked by correlating process errors in adjacent years:

$$\varepsilon_i^{**} = \varepsilon_i^{*} + \rho\varepsilon_{i-1}^{**}$$

where ε_i^{**} is the process error for year i, and $\varepsilon_i^{*} \sim N(0,\sigma^2)$

APPENDIX F: Implementation Error Sub Model

This model is similar to that developed for the Kenai River by Carlson et al. (1999). Implementation error is defined as the ratio of the observed number of spawners to the escapement goal (S/G) and is modeled using the ratio of the escapement goal to the run (G/N) in the observed data:

$$S_i / G_i = \delta(G_i / N_i)^{\gamma} + \varepsilon_i$$

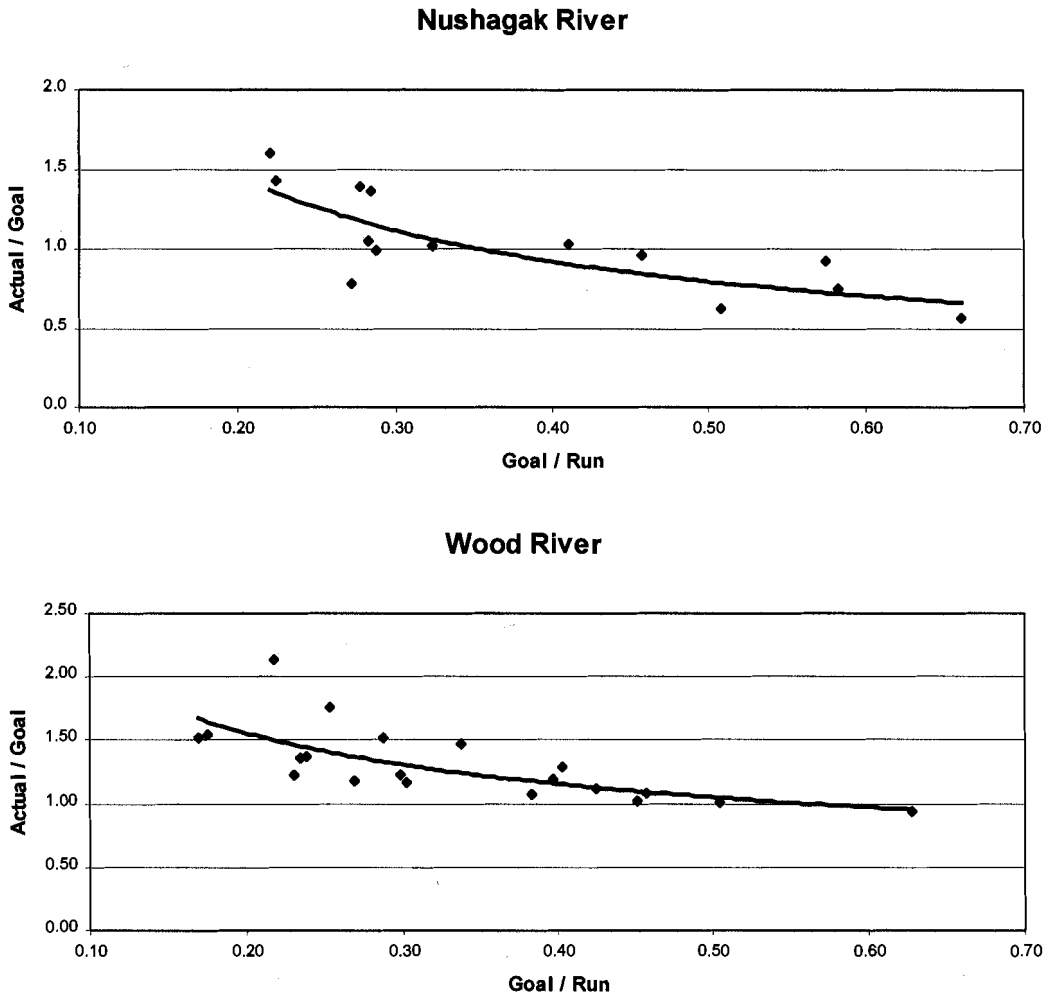
with $\varepsilon_i \sim N(0, \sigma^2)$.

The model addresses the observation that run strength affects the degree to which an escapement differs from the goal, and that the degree to which this happens is related to the relative sizes of the run and the goal. If the run is high relative to the goal ($G/N<<1$), the escapement to goal ratio (S/G) increases. Plots of this tendency are shown in Appendix Figure F1 for the Nushagak and Wood Rivers.

Nonlinear regression analysis was used to estimate δ, γ, and σ for the Nushagak ($\hat{\delta} = 0.5$, $\hat{\gamma} = -0.67$, $\hat{\sigma} = 0.2$, $R^2=0.64$) and Wood ($\hat{\delta} = 0.78$, $\hat{\gamma} = -0.43$, $\hat{\sigma} = 0.21$, R^2) River data ($R^2=0.76$). For each river, the variable $(S_i/G_i)^*$ is generated in the simulations according to:

$$(S/G_i)^* = \hat{\delta}\left(G_i/N_i^*\right)^{-\hat{\gamma}} + \varepsilon_i^*$$

where ε_i^* is sampled from a $N(0, \hat{\sigma})$ distribution and reflects process error. An actual spawner level for the current year within the simulation is then calculated based on the generation of $(S/G_i)^*$.



Appendix Figure F1. Implementation error for the Nushagak and Wood Rivers

Pertinent Articles and References

Carlson, S.R., K.E. Tarbox, and B.G. Bue. 1999. The Kenai sockeye salmon simulation model: a tool for evaluating escapement and harvest levels. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Informational Report No. 2A99-08, Anchorage.

Efron, B. and R. J. Tibshirani. 1993. An introduction to the bootstrap. Chapman and Hall, New York.

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

Hilborn, R., E. K. Pikitch, and R. C. Francis. 1993. Current trends in including risk and uncertainty in stock assessment and harvest decisions. Canadian Journal of Fisheries and Aquatic Sciences 50:874–880.

Hilborn, R. and M. Mangel. 1997. The ecological detective: confronting models with data. Princeton University Press, New Jersey.

Larkin, P. A. 1971. Simulation studies of the Adams River sockeye salmon (*Oncorhynchus nerka*). Journal of the Fisheries Research Board of Canada 28:1493–1502.

Manly, B. F. J. 1994. Randomization and Monte Carlo methods in biology. Chapman and Hall, London.

Neter, J., W. Wasserman, and M. H. Kutner. 1989. Applied linear regression analysis, 2nd edition. Irwin Press, Homewood, Illinois.

Peterman, R.M., Pyper, B.J., Lapointe, F., Adkison, M.D. and C.J. Walters. 1998. Patterns of covariation in survival rates of British Columbian and Alaskan sockeye salmon (Oncorhynchus nerka) stocks. Can. J. Fish. Aquat. Sci. 55:2503-2517.

Punt, A. E. and R. Hilborn. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries 7:35–63.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada, Bulletin 191.

Schmidt, D. C., K.E. Tarbox, S. R. Carlson, G. B. Kyle, J. A. Edmundson, B. E. King, L. K. Brannian, C. O. Swanton, P. A. Nelson, L. G. Coggins, and S. G. Honnold. 1995. Sockeye salmon overescapement, *Exxon Valdez* Oil Spill Restoration Project Final Report (Restoration Project 95258), Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Soldotna, Alaska.

Schmidt, D. C., S. R. Carlson, G. B. Kyle, and B. P. Finney. 1999. Influence of carcass-derived nutrients on sockeye salmon productivity of Karluk Lake, Alaska: importance in the assessment of an escapement goal. North American Journal of Fisheries Management 18:743–763.

Walters, C. J. 1987. Nonstationarity of production relationships in exploited populations. Canadian Journal of Fisheries and Aquatic Sciences 44:156–165.

Welch, D. W. and D. J. Noakes. 1990. Cyclic dominance and optimal escapement of Adams River sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 47:838–849.

The Alaska Department of Fish and Game administers all programs and activities free from discrimination on the basis of sex, color, race, national origin, age, marital status, pregnancy, parenthood, or disability. For information on alternative formats available for this and other department publications, contact the department ADA Coordinator at (voice) 907-465-4120, or (TDD) 907-465-3646. Any person who believes s/he has been discriminated against should write to: ADF&G, P.O. Box 25526, Juneau, AK 99802-5526; or O.E.O.

The Alaska Department of Fish and Game administers all programs and activities free from discrimination based on race, color, national origin, age, sex, religion, marital status, pregnancy, parenthood, or disability. The department administers all programs and activities in compliance with Title VI of the Civil Rights Act of 1964, Section 504 of the Rehabilitation Act of 1973, Title II of the Americans with Disabilities Act of 1990, the Age Discrimination Act of 1975, and Title IX of the Education Amendments of 1972.

If you believe you have been discriminated against in any program, activity, or facility, or if you desire further information please write to ADF&G, P.O. Box 25526, Juneau, AK 99802-5526; U.S. Fish and Wildlife Service, 4040 N. Fairfax Drive, Suite 300 Webb, Arlington, VA 22203 or O.E.O., U.S. Department of the Interior, Washington DC 20240.

For information on alternative formats for this and other department publications, please contact the department ADA Coordinator at (voice) 907-465-6077, (TDD) 907-465-3646, or (FAX) 907-465-6078.