Special Publication No. 07-12

Escapement Goal Review for Kenai River Late-Run Sockeye Salmon: Report to the Alaska Board of Fisheries, January 2005

contributors

John H. Clark,

Douglas M. Eggers,

and

Jim A. Edmundson

June 2007

Alaska Department of Fish and Game **Divisions of Sport Fish and Commercial Fisheries**

Symbols and Abbreviations

The following symbols and abbreviations, and others approved for the Système International d'Unités (SI), are used without definition in the following reports by the Divisions of Sport Fish and of Commercial Fisheries: Fishery Manuscripts, Fishery Data Series Reports, Fishery Management Reports, and Special Publications. All others, including deviations from definitions listed below, are noted in the text at first mention, as well as in the titles or footnotes of tables, and in figure or figure captions.

Weights and measures (metric)	
centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm
Weights and measures (English)	
cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd
Time and temperature	
day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s
Physics and chemistry	
all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General	
Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat. or long.
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Measures (fisheries)	
fork length	FL
mideye-to-fork	MEF
mideye-to-tail-fork	METF
standard length	SL
total length	TL
Mathematics, statistics	
all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

SPECIAL PUBLICATION NO. 07-12

ESCAPEMENT GOAL REVIEW FOR KENAI RIVER LATE-RUN SOCKEYE SALMON: REPORT TO THE ALASKA BOARD OF FISHERIES, JANUARY 2005

contributors
John H. Clark,
Douglas M. Eggers,
and
Jim A. Edmundson
Division of Commercial Fisheries

Alaska Department of Fish and Game
Division of Sport Fish, Research and Technical Services
333 Raspberry Road, Anchorage, Alaska, 99518-1565

June 2007

The Division of Sport Fish Special Publications series was established in 1991 for the publication of techniques and procedures manuals, informational pamphlets, special subject reports to decision-making bodies, symposia and workshop proceedings, application software documentation, in-house lectures, and other documents that do not fit in another publication series of the Division of Sport Fish. Since 2004, the Division of Commercial Fisheries has also used the same Special Publication series. Special Publications are intended for fishery and other technical professionals. Special Publications are available through the Alaska State Library and on the Internet: http://www.sf.adfg.state.ak.us/statewide/divreports/html/intersearch.cfm. This publication has undergone editorial and peer review.

John H. Clark
and
Douglas M. Eggers
Alaska Department of Fish and Game, Division of Commercial Fisheries,
P.O. Box 25526, Juneau, Alaska 99802-5526, USA

Jim A. Edmundson
Alaska Department of Fish and Game, Division of Commercial Fisheries
333 Raspberry Road, Anchorage, Alaska 99518-1599, USA

This document should be cited as:
Clark, J. H., D. M. Eggers, and J. A. Edmundson. 2007. Escapement goal review for Kenai River late-run sockeye salmon: Report to the Alaska Board of Fisheries, January 2005. Alaska Department of Fish and Game, Special Publication No. 07-12, Anchorage.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ABSTRACT

The current escapement goal range of 500,000-800,000 spawners for the Kenai River late-run sockeye salmon stock was adopted by the Alaska Department of Fish and Game in 1999. However, considerable uncertainty is associated with stock-recruit analysis and modeling for this stock. Various stock-recruit analyses using the available data were conducted and led to very different end results. Based on adjacent year interactions, an alternative stock-recruit relationship was developed by including spawning escapements (*S*) in year *i* and in year *i*-1, i.e., using a multiplicative term ($S_i \times S_{i-1}$), to predict recruitment of sockeye salmon in the Kenai River. This simple brood-interaction model had the best statistical fit to the available spawner-recruit data. Simulations of the brood-interaction model show a policy of alternating escapement goals, rather than a constant escapement goal policy, maximizes sustained yield. However, implementation of such a management scheme to achieve maximum sustained yield would severely disrupt the existing fisheries. From a biological perspective, there is good reason to believe in a brood interaction effect, but little reason to believe the effect is multiplicative. Thus the brood interaction model is suspect. We are unable to define an escapement goal range using the existing data that can be scientifically demonstrated as the range expected to produce maximum sustained yield, e.g., a biological escapement goal range (BEG). On the other hand, escapements as currently measured by sonar, whether they are in actuality total escapements or are instead indices of total escapement, in the range of 500,000-800,000 all provided demonstrable harvestable surpluses and the escapement goal of 500,000-800,000 fully fits criteria associated with a sustainable escapement goal (SEG). Therefore, we recommend the late-run Kenai River sockeye salmon escapement goal range of 500,000-800,000 be designated as a sustainable escapement goal. This report was originally provided to the Alaska Board of Fisheries in January 2005. This version of the report reflects a subsequent peer review and revisions to clarify some of the text and figures; however, most aspects of the report remain unchanged from the original provided to the Alaska Board of Fisheries.

Key words: BEG, biological escapement goal, brood interaction, Kenai River, maximum sustained yield, MSY, recruits, recruits per spawner, Ricker model, sustainable escapement goal, SEG, Skilak Lake, simulations, sockeye salmon, *Oncorhynchus nerka*, spawner-recruit models.

EXECUTIVE SUMMARY

The current escapement goal range of 500,000-800,000 spawners for the Kenai River late-run sockeye salmon stock was adopted by Alaska Department of Fish and Game (ADF&G) in 1999. Over the past 36 years, estimated escapements have ranged from about 50,000 to 1.3 million sockeye salmon. Estimates of recruits from these levels of escapement ranged from a low of about 2 recruits per spawner to a high of about 16 recruits per spawner. These stock-recruit data have been extensively modeled in historic reports and again in this report in an effort to identify an appropriate escapement goal. However, considerable uncertainty is associated with stock-recruit analysis and modeling for this stock.

First, by accepted standards, scientifically determining maximum sustained yield escapement levels from brood-year information requires that "large" escapements have frequently failed to replace themselves. Such failure is the working definition for large escapements. With 31 years of recruit estimates available for the Kenai stock, no such failure has been observed, thus indicating that the observed escapements in the data set have been "small" relative to carrying capacity. When escapements are small, ability to estimate the production curve for a stock against a background of environmental "noise" is problematic because little of the curve has been exposed to observation.

Second, there is substantial uncertainty in the set of escapement and recruit estimates for this stock because of unknown precision and potential bias in both the annual set of catch apportionments and in the annual set of escapement estimates. Assumptions associated with annual catch apportionments are known to be violated; for instance, total escapements by age for all sockeye salmon stocks caught in Upper Cook Inlet are not annually monitored. The assumption that all sockeye salmon that escape into the Kenai River swim through the sonar beams at mile 19.5 is also likely not true; thus the escapement estimates are probably biased low. As a result of these basic data issues, the stock-recruit data itself is suspect, likely biased and has unknown precision. As a result, we cannot adequately separate measurement error from environmental noise with this set of stock-recruit data.

Various stock-recruit analyses using the available data were conducted and led to very different end results. For example, analysis of these data using a typical Ricker curve approach indicated that the escapement level expected to produce maximum sustained yield (MSY) was about 1.3 million fish. Two past escapements of this magnitude (about 1.3 million) produced return per spawner rates of about 3 and 7. For a variety of technical reasons, the MSY escapement level predicted from the Ricker model of 1.3 million spawners is suspect.

Limnological studies conducted in this system have demonstrated that abundances of rearing sockeye juveniles in one year influences growth and survival of juveniles in the next year through grazing effects on zooplankton populations. Based on adjacent year interactions, an alternative stock-recruit relationship was developed by including spawning escapements (S) in year i and in year i-1, i.e., using a multiplicative term ($S_i \times S_{i-1}$), to predict recruitment of sockeye salmon in the Kenai River. This simple brood-interaction model had the best statistical fit to the available spawner-recruit data. Simulations of the brood-interaction model show that a policy of alternating escapement goals, rather than a constant escapement goal policy, maximizes sustained yield. That is, a pattern of very high escapements in year i-1 (e.g., 1.3 million) followed by very low escapements in year i (e.g. 100,000) are predicted to provide substantially more potential yield than are escapements in the range of 500,000-800,000. However, implementation of such a management scheme to achieve maximum sustained yield would severely disrupt the existing fisheries.

From a biological perspective, there is good reason to believe in a brood interaction effect, but little reason to believe the effect is multiplicative. Thus like the Ricker model, the brood interaction model is suspect. We are unable to define an escapement goal range using the existing data that can be scientifically demonstrated as the range expected to produce maximum sustained yield, e.g., a biological escapement goal range or BEG. On the other hand, escapements as currently measured by sonar, whether they are in actuality total escapements or are instead indices of total escapement, in the range of 500,000-800,000 all provided demonstrable harvestable surpluses and the escapement goal of 500,000-800,000 fully fits criteria associated with a sustainable escapement goal (SEG). Therefore, we recommend the late-run Kenai River sockeye salmon escapement goal range of 500,000-800,000 be designated as an SEG.

This report was originally provided to the Alaska Board of Fisheries (BOF) in January 2005. This version of the report reflects a subsequent peer review and revisions to clarify some of the text and figures; however, most aspects of the report remain unchanged from the original provided to the Alaska Board of Fisheries.

INTRODUCTION

The Kenai River late-run sockeye salmon *Oncorhynchus nerka* run is typically the largest of four major sockeye salmon runs (Figure 1) in upper Cook Inlet (UCI); the other three are the Kasilof, Susitna, and Crescent rivers. Since 1976, estimated total UCI sockeye salmon runs have ranged from 1.8 to 12.1 million, while estimated Kenai sockeye salmon runs have ranged from 654,000 to 8.6 million (Tobias and Willette 2004a, 2004b). Kenai River late-run sockeye salmon rear as juveniles in Hidden, Kenai, Skilak, and Russian lakes, but the majority (~90%) rear in glacially turbid Kenai and Skilak lakes (DeCino et al. 2004). As adults, they spawn in several tributaries flowing into these lakes, as well as in the mainstem Kenai River between Kenai and Skilak lakes, and in an approximately 6 km segment of the Kenai River below Skilak Lake (Figure 1).

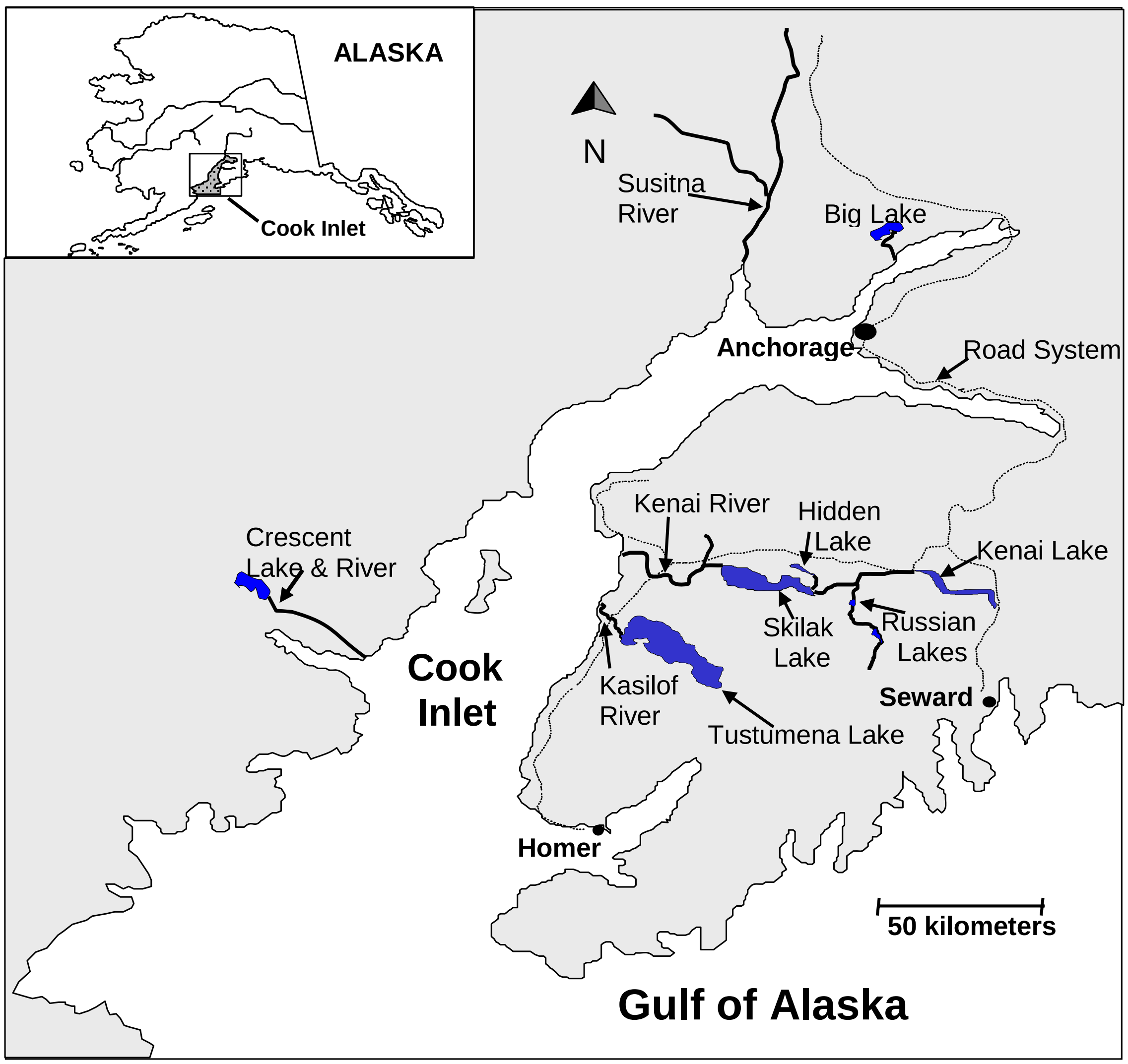

Figure 1.–Locations of the Kenai River and three other major sockeye salmon producing watersheds (Crescent, Susitna, and Kasilof rivers) in the upper Cook Inlet region.

Kenai sockeye salmon are harvested in mixed-stock gillnet fisheries in Cook Inlet. Management of these sockeye salmon runs is based upon achieving spawning escapements for each river within a specific escapement goal range. The current escapement goal range for Kenai River late-run sockeye salmon was adopted by ADF&G in 1999. The escapement goal range was based upon analyses conducted by the UCI Escapement Goal Interdivisional Review Team (hereafter referred to as the team). In 2001, the team again reviewed the goal for this stock and found no compelling evidence that changing the goal range would result in higher yields (Bue and Hasbrouck *Unpublished*). The escapement goal range established in 1999 was based upon a Markov yield analysis and a brood-interaction simulation model in which returns per spawner were a function of spawner abundance in the brood year and the previous year (Carlson et al. 1999). The spawner abundance that provided the greatest potential to achieve MSY was estimated to be 553,000 from the yield table and 731,000 from the brood-interaction model assuming a constant escapement goal policy (Fried 1999). The escapement goal range was established from tables of the risk of future yields <1 million sockeye salmon estimated from the brood-interaction simulation model assuming a constant escapement goal policy (Carlson et al. 1999). Simulation results indicated that escapements maintained within a range of 500,000-800,000 spawners sustained high yields and had a low probability (about 5%) of producing poor runs with annual harvests less than 1 million sockeye salmon (Fried 1999).

ADF&G reviews escapement goals for UCI salmon stocks on a schedule corresponding to the Alaska Board of Fisheries (BOF) triennial cycle for considering area regulatory proposals. This report documents a review of the escapement goal for Kenai River late-run sockeye salmon. The review was based upon the Policy for the Management of Sustainable Salmon Fisheries (SSFP; 5 AAC 39.222) and the Policy for Statewide Salmon Escapement Goals (EGP; 5 AAC 39.223). The BOF adopted these policies into regulation during winter 2000-2001 to ensure that the state's salmon stocks are conserved, managed, and developed using the sustained yield principle. These policies state that escapement goals be a range with a lower and upper bound, rather than a single point estimate. Three important terms defined in the SSFP are:

> ***Biological Escapement Goal* (BEG)**: means the escapement that provides the greatest potential for maximum sustained yield (MSY); BEG will be the primary management objective for the escapement unless an optimal escapement or inriver run goal has been adopted; BEG will be developed from the best available biological information, and should be scientifically defensible on the basis of available biological information; BEG will be determined by the department and will be expressed as a range based on factors such as salmon stock productivity and data uncertainty; the department will seek to maintain evenly distributed salmon escapements within the bounds of a BEG;
>
> ***Maximum Sustained Yield* (MSY)**: means the greatest average annual yield from a salmon stock; in practice, MSY is achieved when a level of escapement is maintained within a specific range on an annual basis, regardless of annual run strength; and
>
> ***Sustainable Escapement Goal* (SEG)**: means a level of escapement, indicated by an index or an escapement estimate, that is known to provide for sustained yield over a 5 to 10 year period, used in situations where a BEG cannot be estimated due to the absence of a stock specific catch estimate.

This report was originally provided to the Alaska Board of Fisheries in January 2005. This version of the report reflects a subsequent peer review and revisions to clarify some of the text and figures; however, most aspects of the report remain unchanged from the original provided to the Alaska Board of Fisheries.

METHODS

DATA AVAILABLE TO DEFINE ESCAPEMENT GOALS

The escapement goal for Kenai River late-run sockeye salmon has been based upon the number of wild sockeye salmon estimated to spawn within the watershed. The number of wild sockeye salmon spawning within the watershed has been estimated from the total sonar counts of sockeye salmon escapement minus (1) the number of sockeye salmon harvested in recreational fisheries upstream of the sonar, and (2) the number of hatchery-origin sockeye salmon enumerated at a weir on Hidden Creek (Tobias and Willette 2004b). Since 1968, sonars have been operated on the Kenai River at river mile 19.5 during July and early August each year to estimate numbers of sockeye salmon escaping into the Kenai River (Westerman and Willette 2003). Sonar technology has been used because high glacial turbidity precludes visual enumeration of migrating salmon in this river. However, these annual sonar counts of sockeye salmon have unknown precision and bias. The sonar counts of passage have not been verified with other escapement estimation methodologies. While sonar is used to count fish that swim through the sonar beams located along both banks of the river, the entire river is not ensonified. Sockeye salmon pass upstream without being counted if they swim over the top of the bottom-oriented sonar beam or if they pass upstream in the center of the river between the two beams. There is no doubt that the counting process employed leads to an enumeration program that undercounts true escapement. However, what is not known is whether the bias is significant, if the bias changes across the season, or if the bias is variable on an annual basis. Any negative bias in the escapement program means that current estimates of the return per spawner rates that are currently used by ADF&G are too high.

Prior to 1978, uplooking transducer arrays were used to enumerate salmon. Since 1978, side-looking sonars were used to enumerate salmon. Fish wheel catches have been used to apportion sonar counts to species when the fraction of other species in catches exceeded 5%. This has typically occurred only in early August during even-numbered years when pink salmon *O. gorbuscha* were most abundant. The number of sockeye salmon harvested in recreational fisheries upstream of the sonar has been estimated annually using a statewide harvest survey (Mills 1979-1980, 1981, 1982-1994; Howe et al. 1995, 1996, 2001 a-d) and creel surveys conducted during the fishery (King 1995, 1997). Prior to 1999, the number of hatchery-origin sockeye salmon passing the weir on Hidden Creek was estimated from the ratio of hatchery to wild smolt by brood year (Tobias and Willette 2004b). After 1999, the number of hatchery-origin sockeye salmon passing this weir was estimated from recovery of otolith thermal marked salmon.

The vast majority of sockeye returning to the Kenai River are caught in mixed stock fisheries (Fox and Shields 2004). A weighted age-composition apportionment method has been used to estimate harvests of Kenai River late-run sockeye salmon in commercial gillnet fisheries in UCI (Tobias and Tarbox 1999). This method is based upon the assumption that age-specific exploitation rates were equal among stocks in the gillnet fishery (Bernard 1983) and is dependent upon accurate and precise escapement measures for all contributing stocks to the fishery. The age-composition catch apportionment method as used utilizes four data sources: (1) commercial harvests, (2) escapements into major UCI river systems, (3) age composition of harvests, and (4) age composition of escapements.

Beginning in 1979, side-looking sonars were used to enumerate sockeye salmon, and fish wheels were used to collect scale samples on four major river systems in UCI (Westerman and Willette 2003). Prior to 1979, uplooking sonar arrays were used on the Kasilof River, and peak ground-based survey counts on 23 streams were used to index escapements in the Susitna drainage. The age-composition of sockeye salmon harvests has been estimated annually using a systematic sampling design stratified by time and area (Tobias and Willette 2004a). A minimum sample (n=403) of readable scales has been used to estimate the age composition of sockeye salmon in each stratum within 5% of the true proportion 90% of the time (Thompson 1987). These various data sources have been used to construct brood tables for late-run Kenai River sockeye salmon beginning with brood year 1968 (Tarbox et al. 1983), but the most consistent methods have been applied since brood year 1979 (Tobias and Willette 2004b). Two other methods have been used to estimate the stock composition of commercial harvests in UCI. In the mid 1980s, scale pattern analyses were conducted (Waltemyer et al. 1996). In the 1990s, genetic methods were used (Seeb et al. 2000). Due to budget reductions, the independent catch apportionment programs were dropped.

Most annual catch apportionments have been based upon the weighted age-composition method. These catch apportionment are based on the assumption that we know total escapement of sockeye returning to UCI by stock and age; and that the harvest by age class for an individual stock is the same as that stock's portion of the total escapement on an age class by age class basis. The precision of these estimates is questionable and the estimates are undoubtedly biased. Sockeye salmon that originate from rivers where escapement is not measured or where total escapement is undercounted are misclassified through this approach. We do not know if the bias is substantial, if it varies across years, or if the historical recruit estimates are unsound. Most fish included in recruitment estimates for the Kenai River stock of sockeye salmon come from these potentially biased catch apportionment estimates.

EVALUATION OF SPAWNER-RECRUIT MODELS

We initially conducted two sets of analyses to examine the fit of six spawner-recruit models to the Kenai River late-run sockeye salmon data (Appendix A1), with recruits being returning adults. In the first set, we fit the six models to the data from brood years 1969-1999, because these data were used in earlier spawner-recruit analyses for this system (Carlson et al. 1999). In the second set, we fit the six models to the data from brood years 1979-1999, because consistent methods were used to estimate four major sockeye salmon escapements during this period. In both sets of analyses, we first fit a general Ricker model that provides for depensation at low stock size and compensation at high stock size (Reisch et al. 1985; Hilborn and Walters 1992; Quinn and Deriso 1999), i.e.

$$R_t = S_t^{\gamma} \exp\left(\alpha - \beta S_t + \varepsilon_t\right), \qquad (1)$$

where R_t is recruits, S_t is wild spawners, α is a density-independent parameter, γ and β are density-dependent parameters, and t indicates the brood year. In all of the models, density-independent survival is given by ε_t, which is assumed to be a random variable with a mean of zero and a constant variance σ^2.

When $\gamma<1$, the spawner-recruit curve is dome shaped like the Ricker model (Quinn and Deriso 1999). Depensation is indicated if γ is significantly greater than 1.0. Hilborn and Walters (1992) suggest that γ should be 2.0 or larger for strong depensatory effects.

The classic Ricker model (Ricker 1954, 1975) is a special case when $\beta<0$ and $\gamma=1$, i.e.

$$R_t = S_t \exp(\alpha - \beta S_t + \varepsilon_t). \tag{2}$$

The Cushing model (Cushing 1971, 1973) is a special case when $\beta=0$ and $\gamma>0$, i.e.

$$R_t = \alpha S_t^{\gamma} + \varepsilon_t. \tag{3}$$

However, the Cushing model is not used much in practice, because it predicts infinite recruitment for infinite spawning stock (Quinn and Deriso 1999). The case when $\gamma\leq0$ does not correspond to a valid spawner-recruit model, because it does not go through the origin (Quinn and Deriso 1999).

Several authors have examined density-dependent models that include interaction terms between brood-year spawners and prior year spawners with lags from 1-3 years (Ward and Larkin 1964; Larkin 1971; Collie and Walters 1987; Welch and Noakes 1990). However, Myers et al. (1997) examined data from 34 sockeye salmon stocks and found no evidence for brood interactions at lags exceeding one year. We fit the Kenai River late-run sockeye salmon data to a modified Ricker model used by many of these investigators with only a 1-year lag, i.e.

$$R_t = S_t \exp(\alpha - \beta_1 S_t - \beta_2 S_{t-1} + \varepsilon_t), \tag{4}$$

where S_{t-1} is spawners from the previous year.

We then developed a general Ricker model with brood-interaction that also included a statistical interaction (multiplicative) term between brood-year spawners and spawners from the previous year, i.e.,

$$R_t = S_t^{\gamma} \exp[\alpha - \beta_1 S_t - \beta_2 S_{t-1} - \beta_3 S_t S_{t-1} + \varepsilon_t]. \tag{5}$$

A stepwise multiple regression procedure was then applied to develop the most parsimonious brood-interaction model. The *F* and *t* statistics were used to select variables for inclusion in the model. A variable was retained in the model if $P\leq0.10$, considered significant if $P\leq0.05$, and marginally significant if $0.05<P\leq0.10$. To provide for comparisons of fit among models, the coefficient of determination was calculated by regressing observed on predicted recruits (natural logarithm transformed). Akaike's Information Criteria (AIC) (Akaike 1973) was used to compare goodness of fit among models. Data from brood year 1968 was omitted from these analyses to provide for a reasonable comparison of goodness of fit among models. Finally, we applied a jackknife procedure to examine the robustness of the fit of the classic Ricker, Cushing, and simple brood-interaction models to the data. Individual observations were omitted from the regression analyses in a stepwise procedure, and model parameters and significance levels were estimated (Quinn and Deriso 1999).

We then used a more standard likelihood based process for model selection among another set of models having common process error structure (Hilborn and Mangel 1997). The following hierarchal set of spawner-recruit models was considered:

Linear Model: $$R_i = S_i \exp(\alpha + \varepsilon), \tag{6}$$

Classic Ricker: $$R_i = S_i \exp(\alpha - \beta_1 S_i + \varepsilon), \tag{7}$$

Autoregressive Ricker: $$R_i = S_i \exp(\alpha - \beta_1 S_i + \phi \varepsilon_{i-1}), \tag{8}$$

Ricker with brood year interaction (main effects only): $$R_i = S_i \exp(\alpha - \beta_1 S_i - \beta_2 S_{i-1} + \varepsilon), \tag{9}$$

Ricker with brood year interaction terms (full model): $$R_i = S_i \exp(\alpha - \beta_1 S_i - \beta_2 S_{i-1} - \beta S_i S_{i-1} + \varepsilon), \tag{10}$$

Ricker with brood year interaction term (interaction only): $$R_i = S_i \exp(\alpha - \beta S_i S_{i-1} + \varepsilon,) \tag{11}$$

where, S_i is escapement in brood year i, R_i is the recruits in brood year i , α, β, β_1 , β_2 are model parameters, and ε is the log normal error term.

Note that the linear model, classic Ricker, main effects brood-year interaction, and full brood-year interaction are a hierarchal set of models and the fit can be evaluated using the likelihood ratio test (Hilborn and Mangel 1997). These models were fit using the method of maximum likelihood using log normal error structure:

$$L(R/Model) = \prod \left[\left(\frac{1}{\sigma\sqrt{2\pi}} \right) \exp - \left(\frac{\ln\left(\frac{R_i}{\hat{R}_i}\right)}{2\sigma^2} \right) \right].$$

Model parameters were selected that minimized the negative log likelihood (i.e., –ln(L)). Model fits were evaluated based on the likelihood ratio test for the hierarchal models (i.e., linear, standard Ricker, brood-year interaction main effects only and brood-year interaction full model. The autoregressive and brood-year interaction only models are not strictly hierarchal and the AIC was therefore used to assess goodness of fit.

EVALUATION OF EARLIER METHODS TO EVALUATE ESCAPEMENT GOALS

The current escapement goal range was based upon a brood-interaction simulation model (Carlson et al. 1999) and Markov yield analysis so we applied these two methods to (1) the original spawner-recruit data set used in 1999, (2) an updated data set, and (3) a reduced data set as previously described. We ran three sets of simulations using brood-interaction model parameters obtained from three different regression analyses of these data sets. Each set consisted of 26 simulations of the population dynamics of the stock over 1,000 generations. In each simulation, the number of spawners was constant, i.e. a constant escapement goal policy was assumed. The number of spawners was incremented by 50,000 spawners to produce each set of 26 simulations (total range 100,000-1,350,000 spawners as observed). The first set of simulations was conducted using model parameters obtained from analysis of the 1969-1993 spawner-recruit data, i.e. the data used in the original analysis that established the current escapement goal range. This was done to provide for comparison of the original and updated analyses. The second set of simulations was conducted using model parameters obtained from analysis of the 1969-1999 spawner-recruit data, i.e. the data used in earlier analyses updated with the most recent return data. The third set of simulations was conducted using model parameters obtained from analysis of the 1979-1999 spawner-recruit data, i.e. the data obtained using consistent methods to estimate sockeye salmon escapements in four major UCI river systems.

The current escapement goal range (500,000-800,000 spawners) was based upon simulation results which indicated that escapements maintained within this range sustained high yields and had a low probability (about once every 20 years) of producing poor yields less than 1 million sockeye salmon (Fried 1999). This corresponded to a <6% risk level in the simulation. As in the original analysis, we estimated mean yield, the coefficient of variation of yields, and the probabilities of yields <1 million sockeye salmon. Simulation results were presented in a table, and escapement goal ranges corresponding to a <6% risk (about once every 20 years) of a yield <1 million sockeye salmon, and 90-100% of the number of spawners estimated to maximize yield (assuming a constant escapement goal policy) were indicated for comparison.

We also conducted a Markov yield analysis (Hilborn and Walters 1992) to further evaluate the escapement goal range using the three data sets previously described. As in the original 1999 analysis, the yield table was constructed by partitioning the data into overlapping intervals of 200,000 spawners. The mean number of spawners, mean return, mean return per spawner, mean yield, and the range of yields was calculated for each interval of spawner abundance.

EVALUATION OF AN ALTERNATE-YEAR ESCAPEMENT GOAL POLICY

Because the structure of the brood-interaction model shows that a policy of alternating escapement goals maximizes yield, we modified the original brood-interaction simulation model (Carlson et al. 1999) to simulate the effects of alternating spawner abundances in successive years on yields. The parameters used in the simulation model were obtained from analysis of the 1979-1999 spawner-recruit data. The model simulated the population dynamics of the stock given alternating numbers of spawners in the brood year and in the previous year over 1,000 generations. The number of spawners was incremented by 100,000 to produce a set of 91 simulations (total range 100,000-1,300,000 spawners as observed). Mean yields and probabilities of future yields <1 million sockeye salmon were estimated from the simulations and summarized in tabular form. We also summarized the actual mean yields in a similar tabular format for comparison.

RESULTS

Based upon the data available for the 36 years, 1969-2004, estimated escapements of sockeye salmon in the Kenai River have ranged from about 50,000 to about 1.3 million fish (Figure 2). Estimates of recruits from these spawning escapements range from a low of about 2 recruits per spawner to a high of about 16 recruits per spawner (Figure 2). The highest estimated escapement level occurred in 1987 and produced recruits at the rate of about 7 to 1, while a similar escapement in 1989 produced recruits at a rate of about 3 to 1. The highest estimate of recruits (about 9.5 million sockeye salmon) from any escapement in the entire data set of 31 brood year recruits came from the 1987 escapement of about 1.3 million fish.

A serious technical issue associated with analysis of stock-recruit data for the Kenai River stock of sockeye salmon is lack of information associated with large escapements. By accepted scientific standards (see CTC 1999 for example), scientifically determining salmon escapement levels that provide for maximum sustained yield from brood year information require that large escapements have frequently failed to replace themselves. Such failure is the working definition for "large" escapements. In more than 30 years of collecting data on Kenai River sockeye salmon, no such failure has been observed for any brood year regardless of its estimated size. Such a one-sided result suggests that observed escapements have been "small" relative to carrying capacity for the stock, based on the working definitions of "large" and "small". Relatively small escapements are not surprising given that the fisheries on this stock have on average removed about 80% of the return. When escapements are small, ability to estimate the production curve for a stock against background environmental "noise" is problematic because little of the curve has been exposed. This serious technical concern coupled with the stock-recruit data precision and bias issue earlier discussed in this report can lead to technical misinformation and problems if ignored as stock-recruit analysis proceeds. Such problems include spurious results, poor model fits, great uncertainty in estimated parameters, and nonsensical consequences due to the models chosen based simply on statistical fit of an imprecise and biased set of data without informative large escapements.

In this report, we have proceeded with stock-recruit analysis and model fitting. However, the readers are cautioned that results provided are based upon the assumption that the stock-recruit data collected for Kenai sockeye are without error, which is clearly not the case; and as if the lack of information concerning large escapements creates no technical problems, which it certainly does. Multiple stock-recruit models are presented and statistical tests are used to choose which models best fit the data. We fully realize that the lack of information from large escapements means much of the analysis is speculative concerning maximum sustained yield escapement levels. Further, we fully realize that the precision and bias issues inherent in this stock-recruit data set means that alternate stock-recruit data sets could be developed and if similarly analyzed could easily lead to quite different inferences concerning an appropriate escapement goal.

EVALUATION OF SPAWNER-RECRUITMENT MODELS

Using the 1969-1999 data, the Ricker and Cushing models did not adequately describe the spawner-recruit relationship for Kenai River late-run sockeye salmon. In the general Ricker model, the density-dependent parameter (β) was not significantly different from zero, and γ was not different from one (Table 1). In the classic Ricker model, β was also not significantly different from zero (P=0.105) when brood year 1968 was excluded to compare goodness of fit

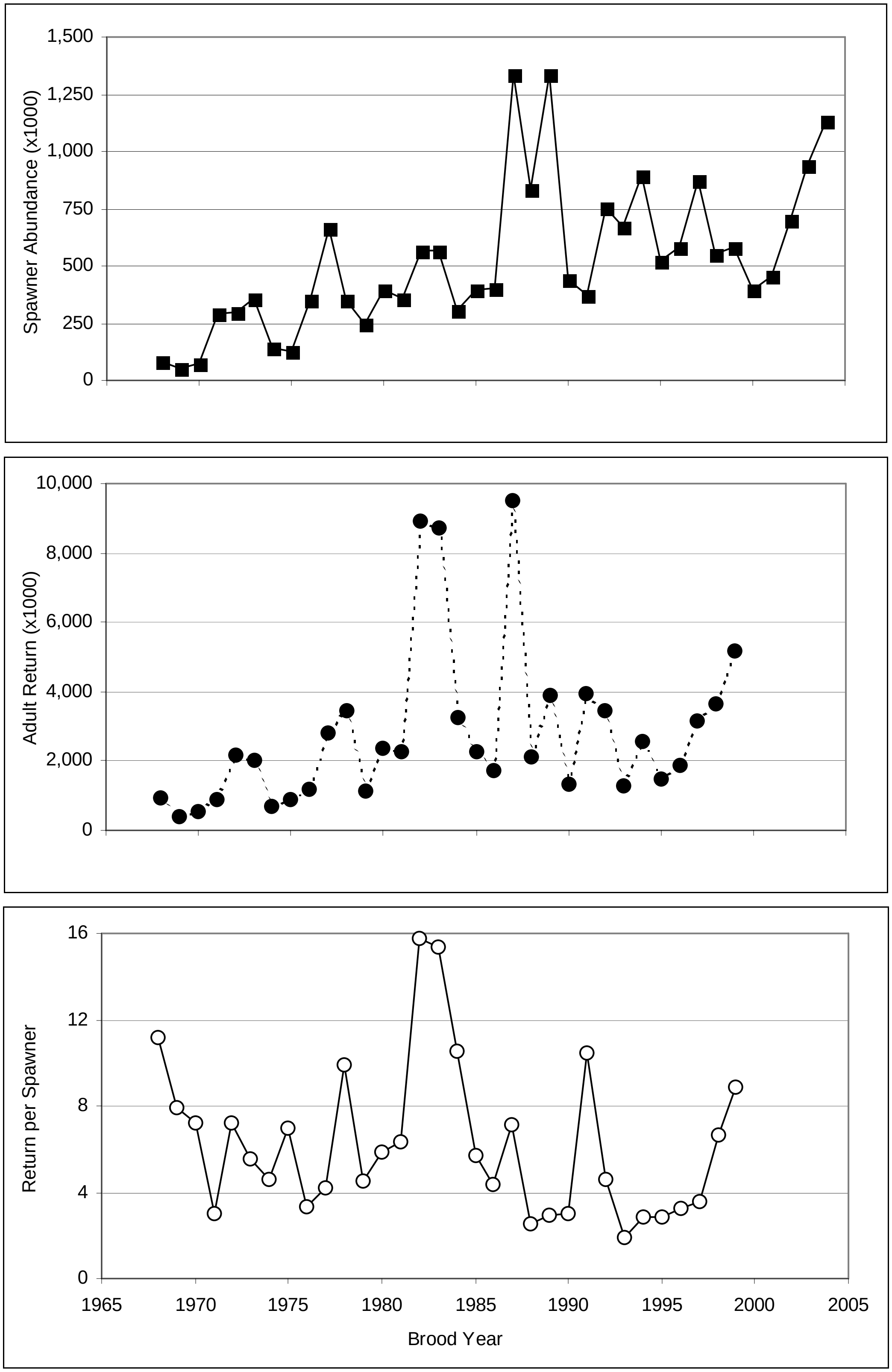

Figure 2.–Time series of spawner abundance, adult returns, and returns per spawner for Kenai River late-run sockeye salmon, 1968-2004.

Table 1.–Summary of spawner-recruit models evaluated for Kenai River late-run sockeye salmon (brood years 1969-1999). Significance levels indicated for γ test whether the parameter was different from one.

Model	Parameter	Estimate	*P*-value	R^2	AIC[a]	Residual white noise test
General Ricker model			<0.001	0.567	51.42	0.416
	α	2.34	0.113			
	β	3.33E-04	0.627			
	γ	0.92	0.771			
Classic Ricker model			0.105	0.567	49.42	0.457
	α	1.92	<0.001			
	β	5.10E-04	0.105			
Cushing model			<0.001	0.564	49.60	0.334
	α	2.92	<0.001			
	γ	0.79	0.116			
Classic Ricker model			0.106	0.595	49.39	0.471
with brood interaction	α	2.04	<0.001			
	β_1	2.86E-04	0.407			
	β_2	4.65E-04	0.170			
General Ricker model			<0.001	0.618	47.53	0.633
with brood interaction	α	1.69	0.092			
	β_3	9.02E-07	0.055			
	γ	1.04	0.818			
Simple brood			0.012	0.618	45.50	0.608
interaction model	α	1.91	<0.001			
	β_3	8.27E-07	0.012			

[a] AIC = Akaike's Information Criteria.

among models. However, when all observations were included, the β parameter in the classic Ricker model was significantly different, albeit marginally, from zero (*P*=0.059). The density-dependent parameter (γ) in the Cushing model was not significantly different from one (Table 1) when brood year 1968 was excluded from the analysis. However, when all observations were included, the γ parameter in the Cushing model was significantly different from one (*P*=0.051). Finally, the density-dependent parameters in the classic Ricker model with a single brood-interaction term were not significantly different from zero (Table 1).

A stepwise regression procedure revealed a brood-interaction model that may describe the spawner-recruit relationship for Kenai River late-run sockeye salmon (Table 1). All of the independent variables in a 3-parameter model were significantly different from zero, but γ was not different from one. A simplified 2-parameter brood-interaction model best statistically described the spawner-recruit relationship for this stock. The improved fit of the simple-brood interaction model over the classic Ricker and Cushing models was due primarily to brood years 1988-1990, which followed the largest spawner abundances observed in the system for brood years 1987 and 1989.

To examine this further, we applied a jackknife procedure to evaluate the goodness of fit of these three models. The results indicated that the simple brood-interaction model remained significant in all cases where individual observations were omitted from the analysis, while the Cushing and classic Ricker models were not significant (P>0.050) in 69% and 81% of the cases, respectively (Table 2). We then fit these three models to the data omitting brood years 1988-1990. The significance levels for the density-dependent parameters in the models were P=0.224 for the classic Ricker, P=0.162 for the Cushing, and P=0.189 for the simple brood-interaction models.

Using the 1979-1999 data, the Ricker and Cushing models again did not statistically fit the spawner-recruit data for Kenai River late-run sockeye salmon (Table 3). In the classic Ricker model with a single brood-interaction term, the first density-dependent parameter (β_1) was not significantly different from zero, but β_2 was different from zero (P=0.034). As before, a stepwise regression procedure revealed a simplified 2-parameter brood-interaction model that best statistically fit the spawner-recruit data for this stock. The model parameters were very similar to those obtained in the analyses using the full dataset. We then fit the classic Ricker, Cushing, and simple brood-interaction models to this dataset omitting brood years 1988-1990. The significance levels for the density-dependent parameters in the models were P=0.452 for the classic Ricker, P=0.392 for the Cushing, and P=0.083 for the simple brood-interaction models.

Using a more standard (likelihood based) model selection process, the classic Ricker produced a significant improvement (P=0.035) in fit over the linear, the brood-year interaction main effects only and brood-interaction full model (Table 4). The brood-interaction main effects model was a marginal improvement (P=0.052) over the classic Ricker; and the brood-interaction full model was not a significant improvement (P= 0.18) over the brood-interaction main effects only model. The brood-interaction only model had an identical fit to the brood-interaction full model; however, this model would be considered the best statistical fit based on fewer parameters and AIC. Inspection of the autocorrelation function of the residuals from the Ricker model indicated a marginally significant lag-1 autocorrelation, which suggested a first order auto-regressive model should be examined. An autoregressive model fit to the data resulted in slightly better fit than the classic Ricker model (Table 4); however the AIC was almost identical to the Ricker indicating no significant improvement with the auto-regressive Ricker model. Because of the large number of years of spawner recruit data, there were significant differences in fit among the models. The brood-interaction term only model had the best fit based on the fewer number of parameters and lowest AIC. Most of the improvement in fit was due to the data for the 1987-1991 brood years, where the brood-interaction models had better fit than the classic Ricker. The principal difference among the brood-interaction models was the better fit to the 1990 brood year data for the brood-interaction models with the interaction term. Given that there was weak evidence for the brood year interaction based on model fit, there were enormous differences in the estimated escapement to produce maximum sustained yield (MSY) among the various models (Table 4). The classic Ricker and brood-interaction main effects term only models had similar MSY escapement levels (about 1.3 million), whereas the autoregressive Ricker had a very high MSY escapement level (6.3 million).

Table 2.–Results from a jackknife procedure used to evaluate the goodness of the fit of the classic Ricker, Cushing, and simple brood-interaction models to the Kenai River late-run sockeye salmon data, brood years 1969-1999.

Year	Classic Ricker Model		Cushing Model		Brood Interaction Model	
Omitted	β	*P*	γ	*P*	β	*P*
1968	-5.10E-04	0.105	0.79	0.116	-	-
1969	-5.61E-04	0.082	0.74	0.070	-8.07E-07	0.018
1970	-5.75E-04	0.074	0.74	0.061	-8.19E-07	0.017
1971	-6.30E-04	0.040	0.75	0.040	-9.22E-07	0.005
1972	-5.69E-04	0.070	0.76	0.057	-8.15E-07	0.016
1973	-5.82E-04	0.064	0.76	0.055	-8.35E-07	0.014
1974	-6.25E-04	0.049	0.73	0.039	-8.63E-07	0.011
1975	-5.75E-04	0.072	0.76	0.062	-8.22E-07	0.016
1976	-6.07E-04	0.050	0.75	0.049	-8.98E-07	0.007
1977	-5.72E-04	0.068	0.76	0.060	-8.34E-07	0.013
1978	-5.55E-04	0.072	0.76	0.053	-8.13E-07	0.014
1979	-6.08E-04	0.054	0.75	0.048	-8.57E-07	0.012
1980	-5.79E-04	0.065	0.76	0.055	-8.32E-07	0.014
1981	-5.77E-04	0.066	0.76	0.055	-8.24E-07	0.015
1982	-6.07E-04	0.036	0.73	0.022	-7.89E-07	0.011
1983	-6.07E-04	0.037	0.73	0.023	-8.40E-07	0.007
1984	-5.46E-04	0.076	0.76	0.057	-7.98E-07	0.015
1985	-5.81E-04	0.064	0.76	0.055	-8.33E-07	0.014
1986	-5.89E-04	0.059	0.76	0.054	-8.45E-07	0.012
1987	-8.62E-04	0.013	0.71	0.028	-8.79E-07	0.009
1988	-5.12E-04	0.099	0.78	0.081	-8.00E-07	0.041
1989	-5.33E-04	0.132	0.78	0.092	-8.71E-07	0.027
1990	-5.91E-04	0.054	0.76	0.054	-7.88E-07	0.020
1991	-5.57E-04	0.069	0.76	0.050	-7.96E-07	0.016
1992	-5.79E-04	0.067	0.76	0.058	-8.28E-07	0.014
1993	-5.24E-04	0.076	0.78	0.073	-7.52E-07	0.019
1994	-5.22E-04	0.099	0.78	0.079	-7.79E-07	0.021
1995	-5.74E-04	0.060	0.77	0.059	-7.93E-07	0.017
1996	-5.67E-04	0.066	0.77	0.062	-8.26E-07	0.013
1997	-5.55E-04	0.082	0.77	0.069	-8.08E-07	0.017
1998	-5.85E-04	0.061	0.75	0.049	-8.58E-07	0.011
1999	-5.96E-04	0.053	0.74	0.040	-8.34E-07	0.012

Notes: Statistical tests indicated whether β was different from zero or γ was different from one. Significance levels (*P*) greater than 0.050 are shaded

Table 3.–Summary of spawner-recruit models evaluated for Kenai River late-run sockeye salmon (brood years 1979-1999).

Model	Parameter	Estimate	*P*-value	R^2	AIC[a]	Residual white noise test
General Ricker model			0.173	0.177	41.10	0.444
	α	5.21	0.436			
	β	2.78E-04	0.879			
	γ	0.41	0.628			
Classic Ricker model			0.202	0.168	39.24	0.459
	α	2.00	<0.001			
	β	5.79E-04	0.202			
Cushing model			0.058	0.176	38.99	0.465
	α	4.25	0.033			
	γ	0.59	0.174			
Classic Ricker model			0.045	0.356	35.96	0.140
with brood interaction	α	2.43	<0.001			
	β_1	3.72E-04	0.372			
	β_2	9.17E-04	0.034			
General Ricker model			0.014	0.376	35.28	0.223
with brood interaction	α	0.32	0.893			
	β_3	1.44E-06	0.027			
	γ	1.30	0.458			
Simple brood			0.011	0.376	33.80	0.381
interaction model	α	2.07	<0.001			
	β_3	1.10E-06	0.011			

Notes: Significance levels indicated for γ test whether the parameter was different from one.

[a] AIC = Akaike's Information Criteria.

Table 4.–Goodness of fit criteria (Akaike's Information Criteria [AIC]), negative log-likelihood and likelihood ratio for various stock-recruit models and estimated escapement to produce maximum sustained yield (MSY).

Model	Number of parameters	Negative log-likelihood	Likelihood ratio	*P*-value	Likelihood ratio test comments	Escapement at MSY (thousands)	Bias correction	AIC
Linear	1	25.10						27.10
Classic Ricker	2	22.88	4.433	0.0353	relative to linear	1,333	yes	26.88
Autoregresive Ricker	3	20.60	4.567			6,327	no	26.60
Brood-interaction main effects	3	20.99	3.791	0.0515	relative to Classic Ricker	1,229	no	26.99
Brood-interaction Full model	4	20.10	1.780	0.1822	relative to brood-interaction main effects	663	no	28.10
Brood-interaction only	2	20.10	1.780			752	no	24.10

Notes: Estimates of escapement at MSY listed for brood interaction models based upon constant escapement levels for comparative purposes.

APPLICATION OF EARLIER METHODS TO EVALUATE ESCAPEMENT GOALS

Applying the same criteria (<6% risk of a yield <1 million sockeye salmon) used to establish the current escapement goal, simulations of the brood-interaction model using parameters from analysis of the 1969-1999 data indicated a goal range of 500,000-750,000 spawners, while simulations using parameters from analysis of the 1979-1999 data indicated a goal range of 400,000-750,000 spawners (Table 5). Applying a 90-100% of spawners to maximize yield criteria, the ranges were slightly broader in the first two cases, but not the third.

Using a Markov yield analysis, as in the original 1999 analysis, the highest mean yields were obtained within a range of 400,000-700,000 spawners using both the 1969-1999 and 1979-1999 data sets (Tables 6-8). Spawner abundances below 300,000 salmon never produced yields exceeding 865,000. The highest yields were produced from spawner abundances of 566,000, 567,000, and 1,333,000 sockeye salmon (brood years 1982, 1983, and 1987). When spawner abundances exceeded 800,000, yields ranged from 1,281,000-8,197,000. In the updated data sets, two year classes have been added to this interval (Tables 7-8), but their yields were below the mean (1,654,000 and 2,264,000).

Table 5.–Simulation results from a brood-interaction model for Kenai River late-run sockeye salmon assuming a constant escapement goal policy.

Number of Spawners[a]	1969-1993 data set Mean Yield[a]	Yield CV[b] (%)	P<1000[c]	1969-1999 data set Mean Yield[a]	Yield CV[b] (%)	P<1000[c]	1979-1999 data set Mean Yield[a]	Yield CV[b] (%)	P<1000[c]
100	709	61	0.850	698	59	0.858	847	58	0.713
150	1,042	55	0.556	1,026	54	0.563	1,241	54	0.425
200	1,362	53	0.353	1,339	52	0.355	1,613	53	0.239
250	1,665	53	0.223	1,634	51	0.225	1,957	53	0.140
300	1,948	53	0.142	1,906	51	0.146	2,266	53	0.090
350	2,207	53	0.097	2,153	51	0.100	2,536	53	0.065
400	2,439	53	0.072	2,371	52	0.074	2,762	53	0.053
450	2,642	53	0.060	2,558	52	0.063	2,944	54	0.043
500	2,814	53	0.053	2,712	52	0.056	3,078	54	0.040
550	2,954	54	0.048	2,832	53	0.050	3,164	55	0.039
600	3,061	54	0.044	2,918	53	0.050	3,203	55	0.041
650	3,134	55	0.043	2,969	54	0.050	3,196	56	0.044
700	3,174	55	0.045	2,985	54	0.051	3,146	57	0.052
750	3,182	56	0.049	2,968	55	0.058	3,055	58	0.059
800	3,158	57	0.055	2,920	56	0.064	2,927	59	0.072
850	3,104	58	0.060	2,842	57	0.071	2,768	61	0.091
900	3,022	59	0.070	2,737	59	0.085	2,581	63	0.123
950	2,914	60	0.075	2,607	60	0.106	2,372	65	0.156
1,000	2,782	62	0.096	2,457	62	0.134	2,147	68	0.207
1,050	2,631	63	0.124	2,288	64	0.169	1,911	72	0.270
1,100	2,462	66	0.150	2,104	67	0.212	1,673	77	0.346
1,150	2,278	68	0.190	1,909	70	0.262	1,446	83	0.421
1,200	2,083	71	0.238	1,710	75	0.326	1,236	92	0.493
1,250	1,883	75	0.288	1,513	80	0.397	1,059	102	0.577
1,300	1,684	80	0.351	1,325	86	0.461	921	116	0.644
1,350	1,493	85	0.418	1,153	94	0.526	829	132	0.703

Notes: Model parameters were obtained from regression analyses conducted using brood years 1969-1993, 1969-1999, and 1979-1999 data. Solid brackets indicate ranges corresponding to the original criteria (<6% risk of a yield <1 million salmon) that were used to establish the escapement goal range. Dashed brackets indicate ranges corresponding to 90-100% of spawners to maximize yield (assuming a constant escapement goal policy).

[a] × 1,000.

[b] Coefficient of variation.

[c] Probability of a yield less than 1 million.

Table 6.–Markov yield table for Kenai River late-run sockeye salmon constructed using data from brood years 1968-1993. Highest mean yields are indicated in bold.

Escapement		Mean	Mean	Return per	Yield[a]	
Interval[a]	n	Spawners[a]	Returns[a]	Spawner	Mean	Range
0-200	5	96	681	7.6	585	358-834
100-300	4	202	883	4.8	681	521-865
200-400	11	340	2,257	6.6	1,917	573-3,550
300-500	11	367	2,357	6.6	1,990	834-3,550
400-600	**4**	**491**	**5,175**	**9.7**	**4,685**	**895-8,394**
500-700	**5**	**642**	**5,029**	**8.4**	**4,388**	**571-8,364**
600-800	3	695	2,507	3.6	1,811	571-2,716
700-900	2	796	2,794	3.6	1,999	1,281-2,716
>800	3	1,169	5,183	4.2	4,014	1,281-8,197

[a] × 1,000.

Table 7.–Markov yield table for Kenai River late-run sockeye salmon constructed using data from brood years 1968-1999. Highest mean yields indicated in bold.

Escapement		Mean	Mean	Return-per-	Yield[a]	
Interval[a]	n	Spawners[a]	Returns[a]	Spawner	Mean	Range
0-200	5	96	681	7.6	585	358-834
100-300	4	202	883	4.8	681	521-865
200-400	11	340	2,257	6.6	1,917	573-3,550
300-500	11	367	2,357	6.6	1,990	834-3,550
400-600	**8**	**526**	**4,111**	**7.5**	**3,586**	**895-8,364**
500-700	**8**	**588**	**4,239**	**7.4**	**3,652**	**617-8,364**
600-800	3	695	2,522	3.6	1,827	617-2,716
700-900	4	839	2,818	3.4	1,979	1,281-2,716
>800	5	1,054	4,247	3.8	3,192	1,281-8,197

[a] × 1,000.

Table 8.–Markov yield table for Kenai River late-run sockeye salmon constructed using data from brood years 1979-1999. Highest mean yields indicated in bold.

Escapement		Mean	Mean	Return-per-	Yield[a]	
Interval[a]	n	Spawners[a]	Returns[a]	Spawner	Mean	Range
100-300	1	246	1,111	4.5	865	865-865
200-400	6	347	2,525	7.2	2,177	865-3,550
300-500	7	383	2,444	6.6	2,062	895-3,550
400-600	**8**	**526**	**4,111**	**7.5**	**3,586**	**895-8,364**
500-700	**7**	**577**	**4,443**	**7.8**	**3,867**	**617-8,364**
600-800	2	711	2,378	3.3	1,667	617-2,716
700-900	4	839	2,818	3.4	1,979	1,281-2,716
>800	5	1,054	4,247	3.8	3,192	1,281-8,197

[a] × 1,000.

EVALUATION OF AN ALTERNATE-YEAR ESCAPEMENT GOAL POLICY

The brood-interaction model shows that an alternate-year escapement goal policy maximizes yield (Figure 3). We calculated average yields using a brood-interaction simulation model with alternating spawner abundances in successive years. Average yields in the simulation were greatest when spawner abundance was 1,300,000 in the brood year and 100,000 in the previous year (Table 9). But, actual stock productivity under this scenario is very uncertain, since we have never observed any returns with this combination of spawner abundances. The greatest observed range of alternating spawner abundances was about 400,000 and 1,300,000. Our simulation indicated that an alternating escapement goal policy over this range of spawner abundances would produce the highest average yields (3,352,000). Average yields within the current goal range were lower (2,866,000-3,182,000). Also, the risk of yields <1 million sockeye salmon given this scenario was elevated to 19% versus 7-12% for the current goal range (assuming an alternating escapement goal policy) (Table 10).

DISCUSSION

EVALUATION OF COMPETING MODELS

Analysis of the data using a typical Ricker approach, as is fairly standard practice for salmon escapement goal analysis throughout Alaska, indicates the escapement level expected to produce maximum sustained yield is about 1.3 million fish (Table 4). Harvestable surplus expected with a range of escapements from 500,000-800,000 is considerably less according to a typical Ricker approach to analysis. Problems with this analysis, however, include the fact that no observational data are available at high levels of escapement; or in other words, escapements high enough to have density dependence strong enough to produce a number of recruits less than the parental escapement. Without such observations, the escapement level that produces maximum sustained yield from stock-recruit analysis is speculative at best. Lack of observational data at high levels of escapement inserts considerable uncertainty in stock-recruit analysis (Hilborn and Walters 1992); and as a result, often leads to nonsensical decision-making in escapement goal management.

A simple brood-interaction model best fit the spawner-recruit data for the Kenai River late-run sockeye salmon stock. This model resulted in the highest R^2 (Tables 1 and 3) lowest AIC (Tables 1 and 3), and smallest likelihood ratio (Table 4) compared to the other models evaluated. It has been hypothesized that the brood interaction likely results from food limitation and subsequent mortality of fry immediately following emergence and during the first winter (Edmundson et al. 2003). Large fry populations from the previous brood year cause reduced copepod (zooplankton) density the following spring limiting food resources available for fry from the subsequent brood. The effect of fry grazing on copepod biomass the following spring is caused by the two-year lifecycle of the dominant copepod species in this system. However, these limnological data provide no clear indication as to whether the interaction effect of one fry cohort on another is additive, multiplicative, exponential or of some other mathematical form. The mathematical model that was developed by Carlson et al. (1999) and repeated in our analysis herein reduced the independent variable to a multiplicative interaction term or in other words, the product of escapement in year i (S_i) and the escapement in year i-1 (S_{i-1}).

Although the statistical fit of the brood-interaction model is better than the simpler approach of using just escapement in year i versus recruitment, solution for an estimate of the escapement

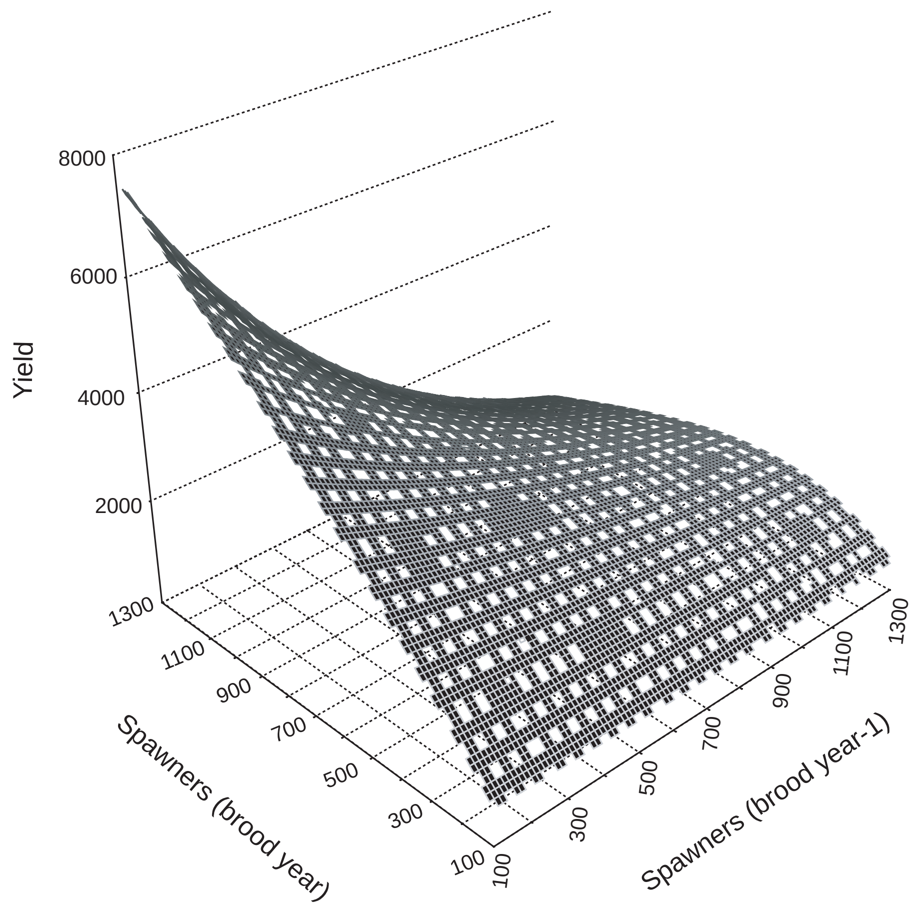

Figure 3.–Yields (×1,000) predicted from the brood-interaction spawner-recruit model for Kenai River late-run sockeye salmon using parameters obtained from fitting the 1979-1999 data.

Table 9.–Mean yields (×1,000) estimated from the brood-interaction model for Kenai River late-run sockeye salmon with alternating spawner escapements (×1,000) in the brood year and the previous year.

Spawners	Spawners (brood year -1)												
(brood year)	100	200	300	400	500	600	700	800	900	1,000	1,100	1,200	1,300
100	777												
200	1,128	1,541											
300	1,562	1,852	2,215										
400	1,925	2,178	2,484	2,693									
500	2,258	2,504	2,660	2,809	2,946								
600	2,683	2,749	2,880	3,000	3,024	2,866							
700	2,931	3,088	3,093	3,037	3,089	3,182	2,933						
800	3,282	3,273	3,157	3,114	3,182	3,002	2,947	2,866					
900	3,611	3,515	3,421	3,342	3,147	2,944	2,759	2,578	2,536				
1,000	3,917	3,791	3,540	3,450	3,114	2,864	2,692	2,602	2,210	1,980			
1,100	4,251	3,904	3,643	3,440	3,276	2,910	2,594	2,340	2,160	1,741	1,635		
1,200	4,720	4,060	3,701	3,466	3,146	2,819	2,440	2,090	1,826	1,564	1,327	1,089	
1,300	4,889	4,316	3,912	3,352	3,039	2,738	2,241	2,029	1,704	1,358	1,086	915	701

Table 10.–Probabilities of yields of <1million sockeye salmon estimated from a modified brood-interaction simulation model for Kenai River late-run sockeye salmon with alternating spawner abundances (×1,000) in the brood year and the previous year.

Spawners	Spawners (brood year -1)												
(brood year)	100	200	300	400	500	600	700	800	900	1,000	1,100	1,200	1,300
100	75												
200	55	31											
300	43	25	16										
400	42	21	14	10									
500	40	21	13	9	7								
600	41	23	12	8	8	11							
700	40	22	14	12	8	9	11						
800	38	21	15	10	11	12	12	12					
900	40	23	14	11	12	13	16	16	17				
1,000	40	22	15	14	16	16	18	19	25	29			
1,100	40	26	17	15	15	16	20	22	27	35	43		
1,200	41	26	16	16	17	18	23	28	34	42	51	57	
1,300	42	26	20	19	19	21	26	34	41	48	60	65	74

level that produces maximum sustained yield had previously been achieved by simply taking the square root of the term $S_i \times S_{i-1}$. This is a flaw in prior analysis. There is supportive biological information that confirms an interaction across brood years. In other words, escapement strength in year i-1 influences the level of recruitment that can be expected from escapements in year i. Biologically, this means that the level of recruitment that can be expected from a given escapement is conditioned on escapement in the prior year (Figure 3). Multiplication of the two escapements followed by taking the square root of the product hides much of the real biological effect. The biology implies a three dimension approach, and reducing the problem to two dimensions obscures predicted yields.

The brood-interaction model suggests that an alternate-year escapement goal policy maximizes yield (Figure 3). Simulation results show that a very high escapement in year *i*-1 followed by very low escapement in year *i* or visa versa provide for more potential sustained yield than do escapements in the range of 500,000-800,000 fish (Table 9). However, in order to implement a regulatory strategy to achieve maximum sustained yield as predicted from the brood interaction model, the fishery would have to be managed for little fishing in one year, followed by very heavy fishing the next, followed by little fishing the third year, and so on. Fried (1999) concluded that the department was unable to effectively control sockeye salmon escapement into the Kenai River given available regulatory and management tools at that time, so implementation of an alternate-year escapement goal policy would not be successful without substantial changes to the regulatory structure of the commercial fishery. Such an alternating escapement goal policy management approach would likely bankrupt fishermen and processors alike and might very well lead to collapse of the commercial fishing industry in UCI.

A precautionary approach should be taken regarding change to the escapement goal range for Kenai sockeye salmon because of declining productivity in Skilak Lake. Euphotic zone depth, copepod biomass and the average size of fry in the fall have decreased markedly over the past decade (Figure 4). This decline is correlated with the decline in the summer ice balance in the Kenai Mountains (Edmundson et al. 2003). Since glaciers across Alaska are melting due to global warming and the rate of melting has accelerated (Arendt et al. 2002), this trend of declining productivity may continue. These changes may indicate that productivity of the stock is not stationary. Application of stock-recruit analysis to escapement goal setting has an inherent stock productivity stability assumption; quite simply the assumption is that the past is representative of the future. If productivity of the stock is changing, an escapement goal derived from historic data would be applicable to the past, but may not be directly applicable to the future. Ongoing limnological monitoring and improved salmon stock assessment will help reveal how this ecosystem responds under these changing conditions of lower productivity and may be helpful to understanding how best to take historical information into account in escapement goal setting.

By definition, a BEG is the department's best expression of the escapement level that will lead to maximum sustained production and sustained salmon fishing. The brood-interaction model has the best statistical fit of the models investigated, but predicts maximum sustained production is achieved with a two year pattern of low and high escapements that would undoubtedly be highly disruptive to the fisheries of Upper Cook Inlet. Other models investigated such as the Ricker model predict maximum sustained production can be achieved with annual escapements of about 1.3 million sockeye salmon in the Kenai River. However, this result is inconsistent with other biological data, the model fits are poor, and other analyses demonstrate increased risks of

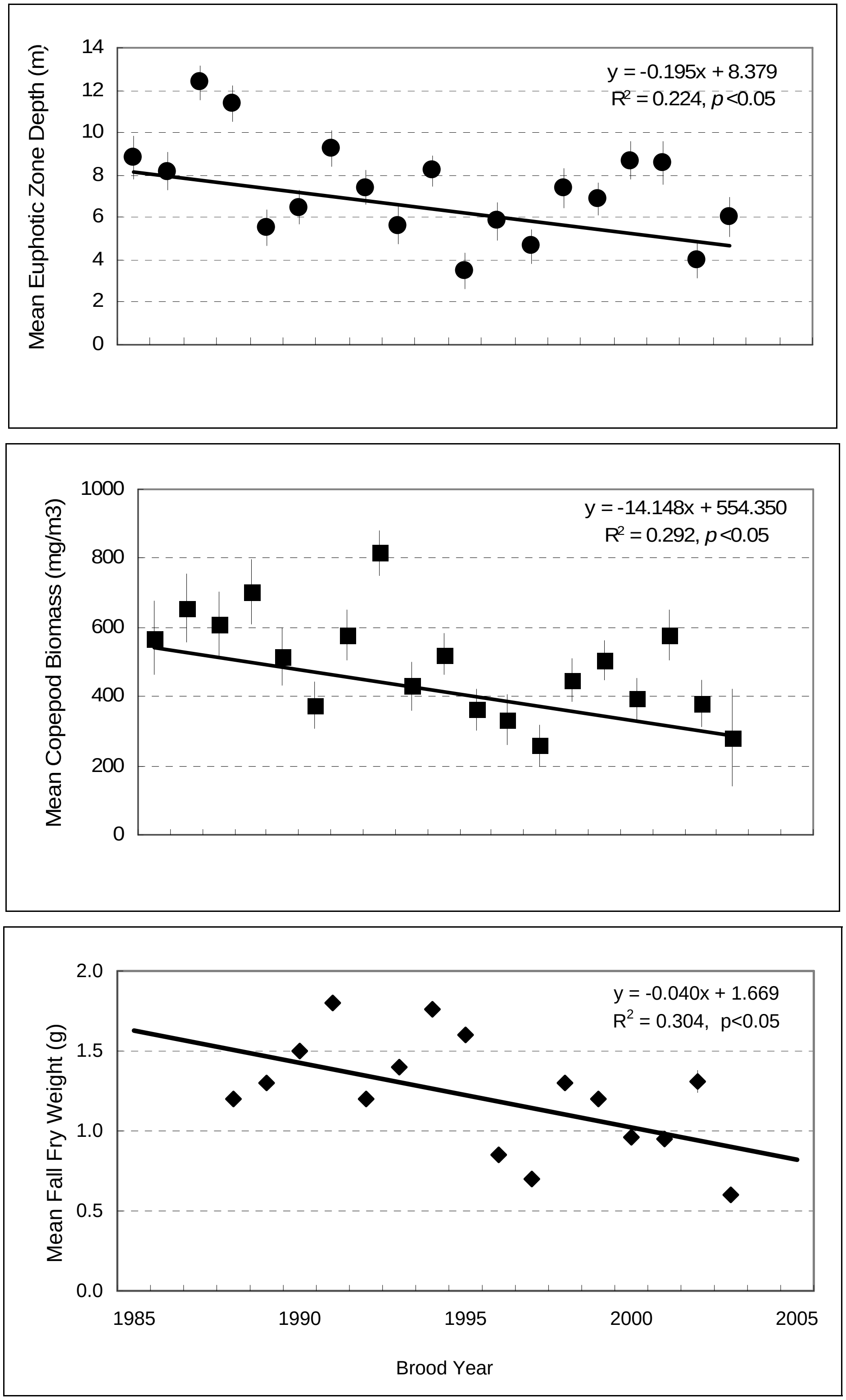

Figure 4.-Time series of mean euphotic zone depth, mean total copepod biomass and mean fall fry weight in Skilak Lake. Vertical bars indicate the standard error of the mean.

consistent yields under such a harvest policy. Lack of observed recruit per spawner values less than one and potential bias and precision issues associated with the historic escapement and recruit estimates further clouds the scientific determination of an escapement goal range that would reliably produce maximum sustained yield from the stock of sockeye salmon that spawns in the Kenai River system of Upper Cook Inlet.

CONCLUSIONS AND RECOMMENDATIONS

In summary, there have been several different stock-recruit relationships developed for the Kenai River late-run stock of sockeye salmon. For example, the Ricker model indicates a BEG type goal should be about 1.3 million fish, not 500,000-800,000. The brood-interaction model indicates maximum production is achieved with alternating very large and small escapements, not escapements in the range of 500,000-800,000. The lack of observations at high escapement levels means quite literally that both of these stock-recruit models are largely conjecture and fail to provide scientifically credible support for definition of a biological escapement goal for the Kenai River stock of sockeye salmon.

A SEG is defined in policy as a level of escapement, indicated as an index or an escapement estimate that is known to provide for sustained yield over a 5 to 10 year period. Escapements of late-run sockeye in the Kenai River have been counted by sonar since the 1970's in a consistent fashion. While we are not entirely certain if these counts represent total escapement for the stock, they certainly, at a minimum, represent an index of escapement. Sonar estimates of escapement in the years 1977, 1982, 1983, 1992, 1993, 1995, 1996, and 1998 were all within the current escapement goal range and all eight provided surplus yield from the Kenai stock of sockeye salmon. Thus, the escapement goal range of 500,000-800,000 fully fits the criteria associated with a SEG. However, a wide variety of other escapement goal ranges would also fully meet the criteria associated with definition of a SEG. At this time, we recommend designating the escapement goal range for the late-run Kenai River stock of sockeye salmon as a SEG of from 500,000-800,000 fish.

REFERENCES CITED

Bue, B. G., and J. J. Hasbrouck. *Unpublished*. Escapement goal review of salmon stocks of Upper Cook Inlet. Alaska Department of Fish and Game, Report to the Alaska Board of Fisheries, November 2001 (and February 2002), Anchorage.

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267-281 [*In*]: Petranand, B. N., and F. Csaki, editors. International Symposium on Information theory, second edition. Akademiai Kiadi, Budapest, Hungary.

Arendt, A. A., K. A. Echelmeyer, W. D. Harrison, C. S. Lingle, and V. B. Valentine. 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. Science 297:382-386.

Bernard, D. R. 1983. Variance and bias of catch allocations that use the age composition of escapements. Alaska Department of Fish and Game, Division of Commercial Fisheries, Informational Leaflet No. 227, Anchorage.

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 Information Report 2A99-08, Anchorage.

Collie, J. S., and C. J. Walters. 1987. Alternative recruitment models of Adams River sockeye salmon, *Oncorhynchus nerka*. Canadian Journal of Fisheries and Aquatic Sciences 44:1551-1561.

CTC (Chinook Technical Committee). 1999. Maximum sustained yield of biologically sustained escapement goals for selected Chinook stocks used by the Pacific Salmon Commission's Joint Technical Committee for escapement assessment, Volume 1. Pacific Salmon Commission Joint Technical Committee Report No. TCCHINOOK (99)-3, Vancouver, British Columbia, Canada.

Cushing, D. H. 1971. Dependence of recruitment on parent stock in different groups of fishes. Journal du conseil / Counseil international pour l'exploration de la mer (International Council for the Exploration of the Sea) 33:340-362, Charlottenlund, Denmark.

Cushing, D. H. 1973. Dependence of recruitment on parent stock. Journal of the Fisheries Research Board of Canada 30:1965-1976.

DeCino, R. D., T. M. Willette, and J. A. Edmundson. 2004. Juvenile sockeye salmon population estimates in Skilak and Kenai Lakes, Alaska by use of split-beam hydroacoustic techniques in September 2003. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A04-07, Anchorage.

Edmundson, J. A., T. M. Willette, J. M. Edmundson, D. C. Schmidt, S. R. Carlson, B. G. Bue, and K. E. Tarbox. 2003. Sockeye salmon overescapement (Kenai River component). Alaska Department of Fish and Game, Division of Commercial Fisheries, Exxon Valdez Oil Spill Restoration Project 96258A-1 Final Report, Anchorage.

Fox, J., and P. Shields. 2004. Upper Cook Inlet commercial fisheries annual management report, 2003. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A04-18, Anchorage.

Fried, S. M. 1999. Upper Cook Inlet Pacific salmon biological escapement goal review: department findings and recommendations to the Alaska Board of Fisheries. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A99-05, Anchorage.

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

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

Howe, A. L., G. Fidler, A. E. Bingham, and M. J. Mills. 1996. Harvest, catch, and participation in Alaska sport fisheries during 1995. Alaska Department of Fish and Game, Fishery Data Series No. 96-32, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds96-32.pdf

Howe, A. L., G. Fidler, and M. J. Mills. 1995. Harvest, catch, and participation in Alaska sport fisheries during 1994. Alaska Department of Fish and Game, Fishery Data Series No. 95-24, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds95-24.pdf

Howe, A. L., R. J. Walker, C. Olnes, K. Sundet, and A. E. Bingham. 2001a. Revised Edition. Harvest, catch, and participation in Alaska sport fisheries during 1996. Alaska Department of Fish and Game, Fishery Data Series No. 97-29 (revised), Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds97-29(revised).pdf

Howe, A. L., R. J. Walker, C. Olnes, K. Sundet, and A. E. Bingham. 2001b. Revised Edition. Harvest, catch, and participation in Alaska sport fisheries during 1997. Alaska Department of Fish and Game, Fishery Data Series No. 98-25 (revised), Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds98-25(revised).pdf

Howe, A. L., R. J. Walker, C. Olnes, K. Sundet, and A. E. Bingham. 2001c. Revised Edition. Participation, catch, and harvest in Alaska sport fisheries during 1998. Alaska Department of Fish and Game, Fishery Data Series No. 99-41 (revised), Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds99-41(revised).pdf

Howe, A. L., R. J. Walker, C. Olnes, K. Sundet, and A. E. Bingham. 2001d. Participation, catch, and harvest in Alaska sport fisheries during 1999. Alaska Department of Fish and Game, Fishery Data Series No. 01-8, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds01-08.pdf

REFERENCES CITED (Continued)

King, M. A. 1995. Fishery surveys during the recreational fishery for late-run sockeye salmon in the Kenai River, 1994. Alaska Department of Fish and Game, Fishery Data Series No. 95-28, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds95-28.pdf

King, M. A. 1997. Fishery surveys during the recreational fishery for late-run sockeye salmon to the Kenai River, 1995. Alaska Department of Fish and Game, Fishery Data Series No. 97-4, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds97-04.pdf

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.

Mills, M. J. 1979. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game, Federal Aid in Fish Restoration, Annual Performance Report 1978-1979, Project F-9-11, 20 (SW-I-A), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-9-11(20)SW-I-A.pdf

Mills, M. J. 1980. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game. Federal Aid in Fish Restoration, Annual Performance Report, 1979-1980, Project F-9-12, 21 (SW-I-A), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-9-12(21)SW-I-A.pdf

Mills, M. J. 1981. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game, Federal Aid in Fish Restoration, Annual Performance Report 1980-1981, Project F-9-13, 22 (SW-I-A), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-9-13(22a)SW-I-A.pdf

Mills, M. J. 1982. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game, Federal Aid in Fish Restoration, Annual Performance Report 1981-1982, Project F-9-14, 23 (SW-I-A), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-9-14(23)SW-I-A.pdf

Mills, M. J. 1983. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game, Federal Aid in Fish Restoration, Annual Performance Report 1982-1983, Project F-9-15, 24 (SW-I-A), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-9-15(24)SW-I-A.pdf

Mills, M. J. 1984. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game, Federal Aid in Fish Restoration, Annual Performance Report 1983-1984, Project F-9-16, 25 (SW-I-A), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-9-16(25)SW-I-A.pdf

Mills, M. J. 1985. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game, Federal Aid in Fish Restoration, Annual Performance Report 1984-1985, Project F-9-17, 26 (SW-I-A), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-9-17(26)SW-I-A.pdf

Mills, M. J. 1986. Alaska statewide sport fish harvest studies. Alaska Department of Fish and Game, Federal Aid in Fish Restoration, Annual Performance Report 1985-1986, Project F-10-1, 27 (RT-2), Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/FREDf-10-1(27)RT-2.pdf

Mills, M. J. 1987. Alaska statewide sport fisheries harvest report, 1986. Alaska Department of Fish and Game, Fishery Data Series No. 2, Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds-002.pdf

Mills, M. J. 1988. Alaska statewide sport fisheries harvest report, 1987. Alaska Department of Fish and Game, Fishery Data Series No. 52, Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds-052.pdf

Mills, M. J. 1989. Alaska statewide sport fisheries harvest report, 1988. Alaska Department of Fish and Game, Fishery Data Series No. 122, Juneau. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds-122.pdf

Mills, M. J. 1990. Harvest and participation in Alaska sport fisheries during 1989. Alaska Department of Fish and Game, Fishery Data Series No. 90-44, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds90-44.pdf

Mills, M. J. 1991. Harvest, catch, and participation in Alaska sport fisheries during 1990. Alaska Department of Fish and Game, Fishery Data Series No. 91-58, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds91-58.pdf

Mills, M. J. 1992. Harvest, catch, and participation in Alaska sport fisheries during 1991. Alaska Department of Fish and Game, Fishery Data Series No. 92-40, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds92-40.pdf

Mills, M. J. 1993. Harvest, catch, and participation in Alaska sport fisheries during 1992. Alaska Department of Fish and Game, Fishery Data Series No. 93-42, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds93-42.pdf

Mills, M. J. 1994. Harvest, catch, and participation in Alaska sport fisheries during 1993. Alaska Department of Fish and Game, Fishery Data Series No. 94-28, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds94-28.pdf

Myers, R. A., M. J. Bradford, J. M. Bridson, and G. Mertz. 1997. Estimating delayed density-dependent mortality in sockeye salmon (*Oncorhynchus nerka*): a meta-analysis approach. Canadian Journal of Fisheries and Aquatic Sciences 54:2449-2462.

Quinn, T. J., II, and R. Deriso. 1999. Quantitative fish dynamics. Oxford University Press, New York.

Reisch, R. L., R. B. Deriso, D. Ruppert, and R. J. Carroll. 1985. An investigation of the population dynamics of Atlantic menhaden (*Brevoortia tyrannus*). Canadian Journal of Fisheries and Aquatic Sciences 42:147-157.

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

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191:382.

Seeb, L. W., C. Habicht, W. D. Templin, K. E. Tarbox, R. Z. Davis, L. K. Brannian, and J. E. Seeb. 2000. Genetic diversity of sockeye salmon of Cook Inlet, Alaska, and its application to management of populations affected by the Exxon Valdez oil spill. Transactions of the American Fisheries Society 129(6):1223-1249.

Tarbox, K. E., B. E. King, and D. L. Waltemyer. 1983. Cook Inlet sockeye salmon studies. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anadromous Fish Conservation Act Project Report No AFC-62, Anchorage.

Thompson, S. K. 1987. Sample size for estimating multinomial proportions. The American Statistician 41(1):42-46.

Tobias, T., and K. E. Tarbox. 1999. An estimate of total return of sockeye salmon to upper Cook Inlet, Alaska 1976-1998. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A99-11, Anchorage.

Tobias, T., and T. M. Willette. 2004a. Abundance, age, sex and size of Chinook, sockeye, coho and chum salmon returning to Upper Cook Inlet, Alaska, in 2003. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A04-10, Anchorage.

Tobias, T., and T. M. Willette. 2004b. An estimate of total return of sockeye salmon to upper Cook Inlet. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A04-11, Anchorage.

Waltemyer, D. L., B. G. Bue, and K. E. Tarbox. 1996. Evaluation of scale pattern analysis for upper Cook Inlet sockeye salmon stocks. Alaska Department of Fish and Game, Alaska Fishery Research Bulletin. 3(2):69-80, Juneau.

Ward, F. J., and P. A. Larkin. 1964. Cyclic dominance in Adams River sockeye salmon. International Pacific Salmon Fisheries Commission Progress Report 11:166.

Westerman, D., and T. M. Willette. 2003. Upper Cook Inlet salmon escapement studies, 2003. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 2A04-03, Anchorage.

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

APPENDIX A. KENAI RIVER LATE-RUN SOCKEYE SALMON SPAWNER-RECRUIT DATA

Appendix A1.–Kenai River late-run sockeye salmon spawner-recruit data.

Brood Year (BrYr)	Spawners BrYr	Spawners BrYr-1	Total Return	Return per Spawner
1969	51,850	82,180	409,481	7.9
1970	72,400	51,850	519,828	7.2
1971	289,270	72,400	862,669	3.0
1972	301,950	289,270	2,185,543	7.2
1973	358,070	301,950	1,995,399	5.6
1974	144,470	358,070	665,130	4.6
1975	128,500	144,470	895,207	7.0
1976	353,161	128,500	1,186,922	3.4
1977	663,627	353,161	2,810,690	4.2
1978	349,828	663,627	3,450,735	9.9
1979	245,850	349,828	1,110,592	4.5
1980	397,557	245,850	2,345,553	5.9
1981	359,344	397,557	2,267,624	6.3
1982	566,034	359,344	8,929,594	15.8
1983	566,652	566,034	8,697,304	15.3
1984	309,514	566,652	3,251,505	10.5
1985	396,032	309,514	2,245,906	5.7
1986	400,302	396,032	1,740,938	4.3
1987	1,333,136	400,302	9,530,501	7.1
1988	838,851	1,333,136	2,119,694	2.5
1989	1,333,687	838,851	3,898,327	2.9
1990	439,052	1,333,687	1,333,864	3.0
1991	376,149	439,052	3,926,048	10.4
1992	752,239	376,149	3,468,728	4.6
1993	669,758	752,239	1,287,000	1.9
1994	894,646	669,758	2,549,000	2.8
1995	520,778	894,646	1,490,000	2.9
1996	578,927	520,778	1,887,000	3.3
1997	872,041	578,927	3,136,000	3.6
1998	551,891	872,041	3,654,000	6.6
1999	582,907	551,891	5,159,000	8.9
2000	393,154	582,000		
2001	457,760	393,154		
2002	700,549	457,760		
2003	938,398	700,549		
2004	1,136,875	938,398		