Fishery Manuscript Series No. 11-01

Run Reconstruction and Escapement Goals for Alsek River Sockeye Salmon

by

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January 2011

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

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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

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January 2011

Development and publication of this manuscript were partially funded by the Southeast Alaska Anadromous Salmon Research grant, NOAA Award No. NA08NMF4050519.

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This document should be cited as:
Eggers, D. M., and D. R. Bernard. 2011. Run reconstruction and escapement goals for Alsek River sockeye salmon. Alaska Department of Fish and Game, Fishery Manuscript Series No. 11-01, Anchorage.

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ABSTRACT

Escapement goal analyses for stocks of sockeye salmon in the transboundary Alsek River and in one of its tributaries, the Klukshu River, are described. Data and estimates for harvest, in-river run size, harvest rates, relative age composition, and escapements for calendar years 1976 through 2008 are provided. Bayesian statistical analysis was used to address measurement error in estimated escapements, missing information on stock-specific harvests, missing data on relative age composition of some harvests, measurement error in estimates of relative age composition, process error, and the possibility of autocorrelation in that process error. Optimum yield profiles and overfishing profiles showed that escapements to the Alsek River distributed evenly across the range of 24,000 to 33,500 adults (ages 4–6) have a 90% to 96% chance of attaining optimum yield (a sustained yield ≥90% of maximum). A modified analysis showed that escapements to the Klukshu River spread evenly across the range 7,500 to 11,000 have a 79% to 90% chance of attaining optimum yield. The analysis also showed the upper range of the current goal for the Klukshu stock (7,500 to 15,000) to be too high to regularly attain optimum yield.

Key words: sockeye salmon, Alsek River, Klukshu River, escapement goal, optimum yield profiles, overfishing profiles, uncertainty, BEG, harvest rates.

INTRODUCTION

The Klukshu River is a tributary of the Tatshenshini River which in turn is a tributary of the Alsek River. The Alsek River originates in Canada and flows through the United States terminating in the Gulf of Alaska, east of Yakutat (Figure 1). Alsek River salmon stocks contribute to U.S. commercial and subsistence fisheries located near Dry Bay. No commercial fishery exists in the Canadian portion of the Alsek River drainage, although both aboriginal (Indian food) and recreational (sport) fisheries occur in the Tatshenshini River and some of its headwater tributaries. Management of salmon returning to the Alsek River drainage has been under the auspices of the Pacific Salmon Commission (PSC) since the signing of the U.S.-Canada Pacific Salmon Treaty in 1985. A consistent and long-term escapement enumeration program for sockeye salmon (*Oncorhynchus nerka*) has been conducted at a weir located on the Klukshu River just upstream of its confluence with the Tatshenshini River since 1976 by personnel of the Canadian Department of Fisheries and Oceans (CDFO).

In the mid-1980s, the U. S. set an interim escapement goal of 33,000 sockeye salmon for the Alsek River drainage and at the time assumed the portion of the overall escapement that spawned in the Klukshu River system was 37% based upon an Alaska Department of Fish and Game (ADF&G) mark-recapture study (McBride and Bernard 1984). Thus the intent was an escapement goal of about 12,000 sockeye salmon in the Klukshu River. At about the same time, the CDFO set an interim escapement goal for the Alsek River drainage of 58,000 sockeye salmon. Professional judgements by staff of CDFO were that about 60% of the overall Alsek River drainage sockeye salmon population spawned in the Klukshu River system and hence intent was an escapement goal of about 35,000 sockeye salmon in the Klukshu River.

Other than continuing the collection of data, little technical progress has been made since the signing of the U.S.-Canada Pacific Salmon Treaty to assist in defining an escapement goal for Klukshu River system sockeye salmon that is acceptable to both countries. This view is reflected in Annex IV of the Pacific Salmon Treaty Fishing Annexes and Related Agreements agreed to by the United States and Canada in June 1999. Specifically, Paragraph 3(c)(i) of the June 1999 agreement states: “Consistent with paragraph 2 above, the Parties will develop and implement cooperative abundance-based management programs for Alsek River Chinook, sockeye and coho salmon, including MSY escapement and management goals for Chinook and sockeye salmon.”

In response to this direction, Clark and Etherton (2000) undertook an escapement goal review for Klukshu River sockeye salmon. Their review was the result of a stock-recruit analysis on reconstructed Klukshu sockeye salmon returns by age (1976–1992 brood years) assuming that 37% of U.S. marine and Dry Bay catch were of Klukshu River origin, consistent with the 1983 estimated proportion of Klukshu River run (escapement + Canadian catch) to mark-recapture estimated in-river run (McBride and Bernard 1984). Based on the Clark and Etherton (2000) analysis, an escapement goal of 7,500 to 15,000 spawners into the Klukshu River was adopted by the Transboundary Technical Committee (TTC) of the PSC, CDFO, and ADF&G in 2000 and has been the management target for the Alsek River sockeye salmon fishery since 2001 (Transboundary Technical Committee 2008).

Annex IV of the 2008 Pacific Salmon Treaty Bilateral Agreement directs the parties to continue to develop and implement abundance based management programs for Alsek River sockeye salmon. Specifically Chapter 1, Paragraph 3(c)(i) of Annex IV of the Pacific Salmon Treaty Bilateral Agreement adopted in 2008 states: "The Parties will continue to develop and implement cooperative abundance-based management programs for Alsek River sockeye salmon including agreed above border spawning escapement and management goals for Chinook and sockeye salmon. The Parties agree to develop joint technical reports and submit it through the various Parties' review mechanisms. The aim is to identify and establish a revised bilaterally agreed to maximum sustained yield (MSY) escapement goal for Alsek Chinook and sockeye salmon prior to the 2014 fishing season that will be used until another agreed goal is developed."

In the spirit of this direction, the intent is to use available data from both countries to provide a technical estimate of the annual average escapement levels that are most likely to produce MSY in fisheries of both countries. The specific intent of this report is to provide a technical recommendation concerning an appropriate escapement goal for this stock of sockeye salmon in the hope that both countries will reach a consensus agreement on an appropriate management target that can be used by the Pacific Salmon Commission and its technical committees in annual evaluations of fishery management.

This report documents available data concerning abundance and age composition of Alsek River sockeye salmon exploited in U. S. and Canadian fisheries. The objectives of this report are to 1) develop estimates (and variances) of the sizes of the annual runs, annual spawning abundances, and brood-year production for the aggregate stock of sockeye salmon in the Alsek River, and 2) use these statistics to determine escapement goals that are likely to produce MSY or nearly MSY from the Alsek River sockeye salmon stock. This work is both an expansion and update of the earlier work by Clark and Etherton (2000) to determine an escapement goal for sockeye salmon in the Klukshu River. Escapement goals from the analysis in Clark and Etherton (2000) have been expanded to the entire drainage of the Alsek River and the Klukshu River escapement goal updated with 11 years of additional data, including seven additional years of complete Alsek River run assessments.

STOCK ASSESSMENT DATA

ALSEK RIVER RUN COMPONENTS

The Alsek River sockeye salmon run consists of several enumerated components described in Clark and Etherton (2000), and includes the Dry Bay and marine commercial fishery catch, and the U.S. subsistence use and sport harvest which occurs in Dry Bay. The in-river run is defined as the run above the Dry Bay and marine fisheries, and consists of the Klukshu escapement, the non-Klukshu escapement, and the Canadian food fishery and sport fishery harvests.

Dry Bay Harvests

Sockeye salmon are harvested in commercial and subsistence set gillnet fisheries below the border in the U.S. portion of the Alsek River (fishing district 182-30) and in U.S. surf waters near the terminus of the Alsek River (fishing district 182-31). Harvests in the commercial fishery are enumerated from fish tickets (sales receipts issued to fishermen from processors when their catches are sold). Commercial harvests are considered a census with no sampling error. Harvests in the subsistence fishery are enumerated from catch reports returned to ADF&G for permits issued to fishery participants and are assumed to have only moderate precision (coefficient of variation is believed to be less than 30%, but more than 10%). However, because the annual harvests in the subsistence fishery are very small in comparison to the commercial harvests (Table 1), overall catch of sockeye salmon in the U.S. Alsek fishery is known precisely on an annual basis.

Klukshu River Escapement and Canadian Harvests

Numeric escapement information for sockeye salmon spawning in the Klukshu River is annually obtained by staff of the CDFO with the aid of a weir constructed across the lower portion of the Klukshu River. Counts of sockeye salmon as they pass the Klukshu River weir have been made each year since 1976. Some fishing occurs upstream of the weir; staff of CDFO annually estimate these catches. Further, some sockeye salmon are removed as brood stock and subsequently used for small scale enhancement activities; staff of CDFO enumerates these removals. The CDFO provides estimates of the number of sockeye salmon that spawn each year by subtracting from the weir counts the estimated upstream catches and brood stock removals (Table 2). These annual estimates provide a continuous database of monitored annual escapements that represent reliable estimates of the number of sockeye salmon spawning in the Klukshu River system. There is some degree of uncertainty in the annual Klukshu sockeye salmon escapement estimates due to the uncertainty in the fishery catch above the weir, which are subtracted. In most years (particularly since 1980); however, removals are relatively small in comparison to weir counts so the escapement estimates, in many cases, nearly represent a complete census and sampling error is relatively low.

The run of sockeye salmon at the Klukshu weir is very protracted, beginning in late June and continuing through late October. Inspection of daily weir counts, 1976–2008, shows a very consistent temporal pattern of weir counts between years. CDFO keeps track of the weir counts of sockeye salmon through August 15th (historical average of 19%) and thereafter (historical average of 81%) each year in an effort to monitor early segments of the escapement versus later segments of the escapement (Table 1). There is little evidence, however, of a bi-modal run that conforms to the August 15th date demarking CDFO's "early-" and "late-runs," though the run at the weir increases and remains high from mid-August through mid-September.

Sockeye salmon of Klukshu River system origin are harvested in Canadian aboriginal and sport fisheries. The sport fishery takes place in the Klukshu River below the weir and in portions of the Tatshenshini River near its confluence with the Klukshu River. Because of the location of the sport fishery, staffs of the CDFO estimate that 90% of the sockeye salmon annually harvested in the Alsek drainage sport fishery are of Klukshu origin. The Canadian aboriginal fishery historically took place above the Klukshu River weir, but starting in 1989, a portion of the harvest took place in the Klukshu River below the weir. These harvests are monitored by staff of CDFO and the harvests both above and below the weir are estimated on an annual basis and assumed to be completely of Klukshu River system origin.

In-river Run

Mark-recapture programs were conducted on the Alsek River to assess total escapement of sockeye salmon upstream of the marine and Dry Bay fisheries in 1983 (McBride and Bernard 1984), and 2000–2004 (Smith et al. 2007). In 2005 and 2006, genetic stock identification was used to assess the Klukshu River component of the in-river run and used to expand the Klukshu River run total to in-river run (Transboundary Technical Committee 2008). These estimates of Alsek River in-river runs are presented with standard errors in Table 1.

Relative Age Composition

Relative age composition was estimated annually for the following three groups of sockeye salmon: commercial harvest from U. S. waters, live salmon through the weir on the Klukshu River, and harvest in Canadian food fisheries. Scales were collected from each sampled fish, and age was determined later from those scales by respective agencies. Note that sockeye salmon were described with both freshwater and ocean ages. Samples of freshwater and ocean ages were appropriately pooled to get total age. Tallies of samples by age of salmon for the Canadian food fishery, 1976–1982, the U.S. Commercial fishery, 1982–1996, and the Klukshu weir, 1982–1996, can be found in Clark and Etherton (2000). Tallies of samples by age for the U.S. Commercial catch, 1997–2008 were obtained from the Integrated Fisheries Database (IFDB) sponsored by ADF&G. Tallies of samples by age from live fish at the Klukshu weir after 1996 were provided by CDFO. These tallies are also given in Appendix A1 and A2. Average age over years for each of these groups is plotted in Figure 2. Note that average ages in samples from the U.S commercial fishery and from live fish sampled at the Klukshu weir were similar in years of overlap (1986 to 2008). Relative age composition in a calendar year (cy) was treated as a vector of proportions that sum to 1 with each proportion representing age a. The proportion for each age was estimated for harvest ($\hat{x}.h_{cy,a}$) in U. S. fisheries and for the in-river run ($\hat{x}.irr_{cy,a}$) as follows:

$$\hat{x}.h_{cy,a} = \frac{h_{cy,a}}{h_{cy}}, \qquad \text{and} \qquad \hat{x}.irr_{cy,a} = \frac{w_{cy,a}}{w_{cy}}.$$

STATISTICAL METHODS

Bayesian statistical analysis of the information described above was used to reconstruct runs and to determine optimum escapement goals for the Alsek Sockeye stock because 1) information on relative age composition is missing for some years, 2) estimates of spawning abundance contain considerable measurement error, and 3) such an analysis provides an expression of the uncertainty associated with the chosen escapement goal. This approach follows closely that used by Bernard and Jones (2010) in analysis of Alsek River Chinook salmon stock productivity. This expression of uncertainty is in the form of posterior probability distributions for parameters and variables given the observations of the Alsek stock made since 1976. Some observations (estimates and data) are considered known without error while others were considered to be stochastic with assumed or estimated levels of measurement error. Rates, parameters, and variables defining states are considered to be unknown, but with an uncertainty expressible through probability distributions.

A two-stage approach was used; first a Bayesian run reconstruction model was used to estimate the posterior distributions of the historical run components (Alsek in-river run, Klukshu in-river run, and U.S. catch). In the second stage, a Bayesian stock-recruit model was used to estimate desired reference points, where the posterior distributions of the reconstructed components of the Alsek run (expressed as log normal posteriors with respective mean and variance) were provided as input to the Baysean simulations. The program WinBUGS[1] version 1.4.2 (Lunn et al. 2000) was used to determine these posterior probability distributions (see Appendix B1, B2, and B3 for listings of the code).

RUN RECONSTRUCTION MODEL

A Bayesian statistical method was used to estimate the historical runs of Alsek River sockeye salmon. The model explicitly considered the effects of measurement error of estimated run components and missing observations in years without full assessment of the Alsek River runs. Markov Chain Monte Carlo (MCMC; c.f., Gelman et al. 1995) methods were used to fit the run reconstruction model. This methodology reduces bias caused by measurement error, and provides a more realistic assessment of uncertainty than is possible with other statistical methods.

The Alsek River total run of sockeye salmon (N_{cy}) consists of the Dry Bay commercial/subsistence catch (H_{cy}), and the in-river run above the Dry Bay fisheries (IR_{cy}):

$$N_{cy} = H_{cy} + IR_{cy} \ . \tag{1}$$

The in-river run consists of the escapement (S_{cy}) and Canadian food fishery and sport harvests (C_{cy}):

$$IR_{cy} = S_{cy} + C_{cy} \ . \tag{2}$$

The Alsek River sockeye salmon run consists of the Klukshu run (NK_{cy}) and the non-Klukshu run. The Klukshu in-river run (KIR_{cy}) consists of the Klukshu River escapement (kS_{cy}) taken to be the Klukshu weir count, less the estimated Canadian harvests above the weir, and Canadian harvest. Note that a small portion of the Canadian harvest occurs below the Klukshu weir. Clark

[1] © Medical Research Council, Imperial College, London, U. K. 2007.

and Etherton (2000) suggested that the non-Klukshu component of these catches is small, so that the Canadian harvests are treated as being entirely of Klukshu origin:

$$KIR_{cy} = kS_{cy} + C_{cy}\ . \tag{3}$$

Multiple sources of information were considered to reconstruct the runs of Alsek River sockeye salmon. Observed data modeled with lognormal measurement errors include the Dry Bay commercial catch, the Klukshu in-river runs, and the Alsek in-river run. Because of the small magnitude of the U.S. subsistence and personal use catch, it was considered as a known quantity without measurement error.

Estimated Dry Bay commercial/subsistence catch was modeled as:

$$\hat{H}_{cy} = H_{cy}\exp(\varepsilon_C)\ ,\ \varepsilon_C \sim \mathrm{N}(0,\sigma_c^2)\ , \tag{4}$$

where σ_c^2 is the variance assumed known from coefficients of variation typical of catch enumeration (coefficient of variation—CV = 0.03).

The estimated Klukshu in-river run was modeled as:

$$\hat{KIR}_{cy} = KIR_{cy}\exp(\varepsilon_W)\ ,\ \varepsilon_W \sim \mathrm{N}(0,\sigma_W^2)\ , \tag{5}$$

where σ_W^2 is the variance assumed known from coefficients of variation typical of weir counts (CV = 0.06). Although some of the Klukshu in-river run consists of catch below the Klukshu weir, these are generally small and measurement errors typical of weir counts apply to the estimated Klukshu in-river run.

The estimated Alsek in-river run was modeled as:

$$\hat{IR}_{cy} = IR_{cy}\exp(\varepsilon_{IRcy})\ ,\ \varepsilon_{IRcy} \sim \mathrm{N}(0,\sigma_{IRcy}^2)\ , \tag{6}$$

where σ_{IRcy}^2 is the estimated variance of assessments of the in-river run (Table 1).

Complete assessment of the Alsek River total runs were available for years where assessments of the in-river run were conducted either by mark-recapture or expansions of estimated Klukshu River run from genetic stock identification (GSI) estimated stock composition of the Dry Bay catch (Table 1). For other years, the Alsek sockeye salmon run was modeled as expansion of the Dry Bay commercial fishery catch and the exploitation rate (UH_{cy}) estimated from gillnet catchability (q_{cy}) and observed fishing effort (E_{cy}):

$$UH_{cy} = 1 - \exp(-q_{cy}E_{cy})\ , \tag{7}$$

$$H_{cy} = UH_{cy} * N_{cy} = \left(UH_{cy}/\left(1 - UH_{cy}\right)\right) * IR_{cy}\ . \tag{8}$$

In addition, the Alsek sockeye salmon run was also modeled as expansion of the observed Klukshu in-river run and the estimated Klukshu proportion of the Alsek Run (p_{cy}):

$$KIR_{cy} = p_{cy} * N_{cy}\ . \tag{9}$$

Bayesian analyses require that prior distributions be specified for all unknowns in the model. Non-informative priors (i.e., chosen to have a minimal effect on the posterior distributions) were used throughout. Normal priors with mean zero, large variances, and constrained to be positive (i.e., log transformed) were used for the mean (ln*IR*) and a diffuse inverse gamma prior was used for σ_{IR}^2. Dry Bay commercial/subsistence fishery catchabilities (q_{cy}) and the Klukshu in-river run proportion (p_{cy}) were given diffuse beta prior distributions. The exact prior distributions used in simulations are presented in Table 3. Likelihood distributions for estimated parameters $\left(\hat{IR}_{cy}\Big|_{cy \neq 1981, 2000-2006}; \hat{p}_{cy}, \hat{q}_{cy}\Big|_{cy_{1976-2008}}\right)$ are also provided in Table 3.

Three versions of the Bayesian run reconstructions were examined: 1) expansion of the Klukshu in-river run for years when total Alsek runs were not assessed from the estimated Klukshu in-river run proportion, 2) expansion of U.S. fishery catch for years when total Alsek runs were not assessed from observed fishing effort and the estimated catchability coefficient, and 3) combined expansion of Klukshu in-river run and U.S. fishery catch. Note that the Klukshu in-river run expansion was the approach used by Clark and Etherton (2000) in the earlier assessment of Klukshu sockeye salmon runs and in the assessment of Alsek Chinook salmon runs by Bernard and Jones (2010).

As a diagnostic check, and to provide initial parameter values in the WinBUGS simulations, more traditional run reconstructions based on maximum likelihood estimation (MLE) were conducted. Three traditional run reconstruction models were used: 1) the MLE Klukshu expansion model based on the expansion of Klukshu in-river run and estimated Klukshu in-river run, 2) the MLE U.S. fishery catch expansion model based on observed fishing effort and estimated catchability, and 3) the MLE combined expansion model based on combined expansion Klukshu in-river run and U.S. catch effort. In the MLE Klukshu expansion model, the Klukshu in-river run ($\hat{KIR}$) is:

$$\hat{KIR} = pN \,. \tag{10}$$

Again, *N* is known for years with complete assessment of the Alsek run and estimated for other years. Run reconstruction parameters estimated by MLE (here, the likelihoods were maximized using EXCEL solver in a spreadsheet version of the run reconstruction) include *p* and *N* for years without assessed Alsek runs:

$$L(p, N_{cy} | data) = \prod_{cy=1}^{33}\left[\left(\frac{1}{\sigma\sqrt{2\pi}}\right)\exp-\left(\frac{\ln\left(\frac{KIR_{cy}}{\hat{KIR}_{cy}}\right)}{2\sigma^2}\right)\right]. \tag{11}$$

In the MLE U.S. catch expansion model the estimated U.S. catch is:

$$UH_{cy} = 1 - \exp(-qE_{cy}) \ \text{ and} \tag{12}$$

$$\hat{H}_{cy} = UH_{cy} * N_{cy} \,. \tag{13}$$

Again, *N* is known for years with complete assessment of the Alsek run and estimated for other years. Run reconstruction parameters estimated by MLE include *q* and *N* for years without assessed Alsek runs:

$$L(q, N_{cy} | data) = \prod_{cy=1}^{33} \left[\left(\frac{1}{\sigma\sqrt{2\pi}} \right) \exp - \left(\frac{\ln\left(\frac{H_{cy}}{\hat{H}_{cy}} \right)}{2\sigma^2} \right) \right], \quad (14)$$

In the MLE combined expansion model the U.S. Catch and Klukshu in-river run were estimated as in equations (10) and (13), respectively; however, the likelihoods were combined:

$$L(q, p, N_{cy} | data) = \prod \left[\left(\frac{1}{\sigma\sqrt{2\pi}} \right) \exp - \left(\frac{\ln\left(\frac{KIR_{cy}}{\hat{KIR}_{cy}} \right)}{2\sigma^2} \right) \right] \prod_{cy=1}^{33} \left[\left(\frac{1}{\sigma\sqrt{2\pi}} \right) \exp - \left(\frac{\ln\left(\frac{H_{cy}}{\hat{H}_{cy}} \right)}{2\sigma^2} \right) \right]. \quad (15)$$

ALSEK SOCKEYE STOCK-RECRUIT MODEL

Our Bayesian analysis was based on a time-linked model of escapement, harvest, harvest rates, production, and rates of survival/maturation. Production as a function of spawning escapement was modeled for brood years 1976–2001 as an exponential process (i.e., the Ricker model, Hilborn and Walters 1992) with the possibility of an autoregressive process error having a lag of 1 brood year. From Noakes et al. (1987):

$$\ln(\tilde{P}_{by}) = \ln(S_{by}) + (1-\phi)\ln(\alpha) + \phi\ln(P_{by-1}/S_{by-1}) - \beta(S_{by} - \phi S_{by-1}) \text{ and} \quad (16)$$

$$\ln(P_{by}) = \ln(\tilde{P}_{by}) + \varepsilon_{by}, \quad (17)$$

where $\ln(\alpha)$ represents intrinsic productivity of the stock, β scales for density-dependant survival, ϕ discounts random process error in the production of brood year *by* for the process error in brood year $by - 1$, and ε_{by} represents independent and identically distributed ("white" noise) process error ~ $norm(0, \sigma^2)$. Production for brood years 1970 through 1975, which contributed to harvests and escapements from 1976–1981, was modeled as following a common lognormal distribution (Table 4). Production from those early brood years was modeled differently because no estimates of escapement were available to seed Equation 16 (i.e., provides initial values for R_{by-1}, S_{by-1}). Escapement in 1975 was also modeled as following a lognormal distribution (Table 4) to provide information required to begin the autoregressive model (Equation 16) at 1976.

Production P_{by} for all brood years was allocated in the model to annual runs N_{cy} by age in the next generation as:

$$N_{cy,a} = P_{by}\theta_{by,a} \big|_{cy=by+a}, \quad (18)$$

where $\theta_{by,a}$ is the fraction of brood year *by* that survive and mature to become members of the run in calendar year $cy = by + a$. The $\{\theta_{by,a}\}$ vectors were drawn from a common Dirichlet distribution such that the usual parameters (labeled as D) were written in terms of location (overall age proportions $\{p\}$) and scale ($\omega = \sqrt{D_4 + D_5 + D_6}$)[2]. Here the multivariate Dirichlet

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[2] Initial runs with WinBUGS incorporated ages 3–6; however, these runs failed because salmon ages 0.2 and 1.1 (3-year olds) were often missing in samples, and when present were considerably less than the other age groups. Over the years sampled, 3-year olds combined

distribution was re-parameterized as three independent gamma distributions enabling simulations to reflect brood year survival fractions that sum to one. Details of the re-parameterization are presented in Table 5.

The in-river run size by age was the age-specific commercial/subsistence harvest by age ($H_{cy,a}$, including the U.S. commercial and subsistence harvest) subtracted from the age-specific run size:

$$IR_{cy,a} = N_{cy,a} - H_{cy,a} . \tag{19}$$

Values of $\theta_{by,a}$ were conditioned on observations of harvest (H_{cy}), on observed numbers of sampled fish by age ($h_{cy,a}$, h_{cy}, $w_{cy,a}$, and w_{cy}), and on observed estimates of in-river run size ($\hat{N}_{cy}$) in the following manner:

$$(h_{cy,4}, h_{cy,5}, h_{cy,6}) \sim multinomial(x.h_{cy,4}, x.h_{cy,5}, x.h_{cy,6}, h_{cy}) \text{, where } x.h_{cy,a} = H_{cy,a} / H_{cy} , \tag{20}$$

$$(w_{y,4}, w_{cy,5}, w_{cy,6}) \sim multinomial(x.irr_{cy,4}, x.irr_{cy,5}, x.irr_{cy,6}, w_{cy}) \text{, where } x.irr_{cy,a} = IR_{cy,a} / IR_{cy} , \tag{21}$$

$$\hat{H}_{cy} \sim lognormal(\mu^h_{cy}, \lambda^2_{h\text{-}cy}) \text{, and} \tag{22}$$

$$\widehat{IR}_{cy} \sim lognormal(\mu^i_{cy}, \lambda^2_{i\text{-}cy}) , \tag{23}$$

where; $\lambda^2_{h-cy} \leftarrow \ln[cvH^2(\hat{H}_{cy}) + 1]$; $\mu^h_{cy} = \ln(cvIR_{cy}) - \lambda^2_{i-cy}/2$; and $\mu^i_{cy} = \ln(IR_{cy}) - \lambda^2_{i-cy}/2$ and $\lambda^2_{i-cy} \leftarrow \ln[cvIR^2(\widehat{IR}_{cy}) + 1]$ (relationships from Evans et al. 1993). Equation 23 represents measurement error in estimated size of the in-river run. Equation 22 represents measurement error in estimated size of the commercial/subsistence harvest. Equation 21 represents measurement error from sampling to estimate relative age composition of the in-river run. Data used in Equation 21 came from sampling the harvest by the Canadian sport fishery from 1976 through 1981[3] and from sampling live fish at the Klukshu weir from 1982 through 2008, with 1999 missing. Equation 20 represents measurement error from sampling to estimate relative age compositions of the harvest in U.S. fisheries. Data used in Equation 20 after 1982 came from sampling the commercial harvest, with years 1976 through 1981 considered as missing. Size of the in-river run in a calendar year in the model was a matter of summing over age:

$$IR_{cy} = \sum_{a=4}^{6} IR_{cy,a} . \tag{24}$$

Spawning abundance (escapement) was the in-river run size minus the observed harvest in Canadian fisheries:

$$S_{cy} = IR_{cy} - C_{cy} , \tag{25}$$

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annually averaged 0.7 % of the marine harvest and were virtually absent from the in-river run. Salmon aged 3 were therefore ignored in the analysis making $h_{cy,4} + h_{cy,5} + h_{cy,6} \equiv h_{cy}$; $w_{cy,4} + w_{cy,5} + w_{cy,6} \equiv w_{cy}$; $p_{cy,4} + p_{cy,5} + p_{cy,6} = 1$; $q_{cy,4} + q_{cy,5} + q_{cy,6} = 1$; and the stock appears slightly less (<1%) productive than it really is.

3 Because of the overlap in average ages apparent in Figure 2, samples from the Canadian sport fishery were considered representative of the relative age composition of the in-river run before installation of the weir on the Klukshu River.

where C_{cy} is considered known. Dry Bay commercial/subsistence fishery annual harvest rates U_{cy} were calculated as:

$$U_{cy} = \frac{H_{cy}}{H_{cy} + IR_{cy}}. \quad (26)$$

Spawning abundance associated with carrying capacity S_{EQ} and maximum sustained yield S_{MSY} were calculated as:

$$S_{EQ} = \frac{\ln(\alpha')}{\beta}, \text{ and} \quad (27)$$

$$S_{MSY} = S_{EQ}[0.5 - 0.07\ln(\alpha')], \quad (28)$$

$$\text{with } \ln(\alpha') = \ln(\alpha) + \frac{\sigma^2}{2(1-\phi^2)}. \quad (29)$$

Equation 29 is the correction in the expectation of production from log-normally distributed process error (Hilborn and Walters 1992) when that error contains an autoregressive process error with lag 1 brood year. Equation 28 is an algebraic approximation for S_{MSY} from Hilborn (1985).

MCMC Simulations

Samples from posterior probability distributions were generated with MCMC methods (see Gilks et al. 1996) with the program WinBUGS. Samples consisted of 2 chains each containing 29,000 updates (samples). The updates were thinned by 5 to reduce the autocorrelation. Each chain was initialized with a different set of starting values. The first 500 simulations in each chain (representing a "burn-in" period) were omitted before calculating posterior percentiles. See Appendix B1 for the code, data, and initializing values for the run reconstruction model, and see Appendix B2 for the Alsek stock-recruit model.

Optimum Yield and Overfishing Profiles

Results from simulations were displayed as posterior probability distributions and as optimum yield (OY) profiles as developed by S. J. Fleischman (ADF&G Fishery Scientist; see Ericksen and Fleischman 2006; Szarzi et al. 2007) where OY is a sustained yield that is at or near MSY, say OY ≥ 90% of MSY. For each MCMC sample, there is a range of escapements that meet the criterion above for OY as determined from the Ricker parameters. For each sample, an array of binary numbers was maintained with each element in the array corresponding to a level of escapement; one if the escapement corresponding to that element was within the optimum range for that sample, and zero otherwise. The mean of binary numbers across all MCMC samples at the same escapement represented the probability that OY would be realized at that escapement. A plot of these probabilities across elements (escapements) produced an OY profile (Figure 6, top panel) with which to determine an escapement goal range expected to produce OY. Each OY profile incorporates uncertainty due to measurement error in observations, from process error, and from missing data.

For an escapement goal threshold designed to avoid recruitment overfishing, binary numbers had a value of one for escapements within or above optimum ranges in an MCMC sample. The mean of all binary numbers was subtracted from one for each escapement to get an overfishing (OF) profile over all escapements (Figure 6, bottom panel). Like OY profiles, OF profiles incorporate uncertainty from measurement and process errors and from missing data.

KLUKSHU STOCK-RECRUIT MODEL

Optimum yield and overfishing profiles were also derived for sockeye salmon spawned in the Klukshu River. The in-river run of Klukshu sockeye salmon (KIR_{cy}) is continuously monitored as the sum of the Klukshu escapement (kS_{cy}) and the Canadian harvest (C_{cy}). The remainder of the Klukshu run is the Klukshu portion of the Dry Bay commercial/subsistence catch (kH_{cy}). In the simulations this was estimated by expanding the Klukshu in-river run by the estimated calendar year applying the estimated Dry Bay commercial/subsistence exploitation rate on the Alsek stock as a whole (UH_{cy}):

$$kH_{cy} = UH_{cy} * KIR_{cy} . \quad (30)$$

Relative age composition for the Klukshu sockeye salmon stock in the U. S. harvest was calculated as:

$$x.h_{cy,a} = \frac{kH_{cy,a}}{kH_{cy}} . \quad (31)$$

Relative age composition for the Klukshu sockeye salmon stock in-river run was calculated as:

$$x.irr_{cy,a} = \frac{IRK_{cy,a}}{IRK_{cy}} . \quad (32)$$

Changes in equations to shift emphasis of the analysis from the Alsek stock to the Kluskshu stock generated corresponding changes in the statements of the WinBUGS program listed in Appendix B2. Appendix B3 contains alternative statements and the locations for their substitution in Appendix B1. As with the Alsek stock-recruit model, samples from posterior probability distributions were generated with MCMC methods.

RESULTS

ALSEK RIVER SOCKEYE SALMON RUN RECONSTRUCTION

The Alsek sockeye salmon run reconstruction model simulations resulted in posterior distributions for the Alsek run components which include: U.S. fishery catch (H_{cy}), Alsek in-river run (IR_{cy}), and Klukshu in-river run (KIR_{cy}); as well as posterior distributions for model parameters, U.S. fishery catchability (q_{cy}), and the Klukshu proportion of the Alsek Run (p_{cy}). The mean and standard deviations for each of these variables, for the years 1976–2008 are provided in Table 6.

The Bayesian run reconstruction relies on the relationship between indicators of relative abundance of the Alsek stock (i.e., the catch per unit fishing effort [CPUE]observed in the U.S. fishery and the Klukshu stock in-river run) which are assessed annually, and the total Alsek River sockeye salmon run which was assessed for eight years. There is a fairly high correlation among these indicators (pairwise correlation coefficients are 0.502, 0.690, and 0.744 for U.S. fishery CPUE versus Klukshu in-river run, U.S. fishery CPUE versus Alsek in-river run, and Alsek in-river run versus Klukshu in-river run, respectively) of Alsek sockeye salmon run strength (Figure 3). This high correlation enables a reasonable and fairly precise reconstruction of the historical Alsek River sockeye salmon escapement and total run (Figure 4).

The reconstructed Alsek total runs using the Bayesian combined expansion model and the Bayesian U.S. Fishery catch expansion model were virtually identical, with the runs and precision slightly higher in the combined expansion model (Figure 4). The reconstructed runs with the Bayesian Klukshu expansion model during the period 1976–1999, were inconsistent with the other models being higher and more variable (Figure 4). The Bayesian combined expansion model was considered the best model, and resultant posterior distributions (Table 6) from that expansion were used in the Alsek and Klukshu sockeye salmon stock-recruit analyses.

The Alsek River sockeye salmon runs were relatively stable during the periods 1976–2002, 2005–2007; high during 2003–2004; and the lowest for the 2008 run. The 2008 runs of sockeye salmon were poor throughout all of Southeast Alaska (Eggers et al. 2008). Note the uncertainty in the estimated Alsek sockeye salmon runs is much higher for years without assessment of the in-river run (Figure 5).

The estimated Klukshu in-river run proportion ($\hat{p}$) from the MLE Klukshu in-river run expansion was 0.136; the estimated catchability coefficient ($\hat{q}$) from the MLE U.S. fishery expansion was 0.00081; and the estimated catchability and Klukshu proportions from the MLE combined expansion were 0.00077 and 0.231, respectively. The estimated catchability and Klukshu proportion for the combined expansion model were almost identical to the average posterior means of these parameters in the combined Bayesian run reconstruction (Table 6). Each of these models fit the observed Alsek run in the years the run was assessed (Figure 4); however, the MLE Klukshu expansion model estimates were much higher than those from the Bayesian run reconstruction model for years prior to 2000. The U.S. fishery expansion model, the combined model, and the Bayesian run reconstruction model were very consistent over the entire period, 1976–2008 (Figure 4).

ALSEK RIVER SOCKEYE SALMON STOCK ESCAPEMENT GOALS

The Alsek sockeye salmon stock-recruit model simulations resulted in posterior distributions for age 4–age 6 production (P_{by}) and parent escapement (S_{by}). The means and standard deviation of these posterior distributions by brood year are presented in Table 7. These posterior distributions incorporated measurement error associated with estimates of age composition of the U.S. catch and in-river run for age composition as well as the uncertainty in the reconstructed components of the Alsek run. A plot of the mean production versus the mean escapement with the central 90 percent of the posterior distributions demonstrates a moderate amount of uncertainty in the estimates of production from parent escapement for the Alsek sockeye salmon stock (Figure 6).

Means from posterior distributions of Alsek River in-river run (variables) in the stock-recruit model simulations and means of posterior distributions from the run reconstruction (observations or input to stock-recruit model) tracked well (Figure 7). Descriptive statistics for Alsek River run components (means and standard deviations by age) from the posterior distributions of the stock-recruit model are found in Appendix A. Included in Appendix A is the U.S. fishery harvest by age (Appendix A3), the Alsek River sockeye salmon total run by age (appendix A4), and the

Alsek River sockeye salmon in-river run (Appendix A5). Descriptive statistics for the aggregated Alsek River sockeye salmon in-river run and escapement are in Appendix A6.

The Alsek sockeye salmon stock-recruit model simulations resulted in posterior distributions for parameters of the Ricker stock-recruit model with the means, standard deviation, median, and central 95th percentiles of these posterior distributions as reported in Table 8. The plots of the explicit posterior distributions for stock-recruit model parameters are presented in Figure 8. Parameters were relatively well defined in the simulations, although there is some uncertainty. Fifty likely stock-recruit relationships given the data in Figure 9 (upper panel) demonstrate the uncertainty in the stock production relationship for the Alsek The stock-recruit relationship is reasonably well defined by the simulations as seen from the percentile envelope of the posterior distribution of the predicted production from the Ricker stock-recruit model (Figure 9; lower panel).

Simulations resulted in a posterior distribution for the variable S_{MSY} with a mean of 73,320 and a median of 69,830 adults for the Alsek stock. The median value of MSY from its posterior distribution is 39,220 adults. The expected value for the average of spawning escapements from the stock-recruit model over years 1976–2008 (49,600 adults) compares favorably the 1976–2008 mean of the calendar year posterior distribution from the run reconstruction model simulations (51,800 adults). The average escapement is below the mean (73,300 adults) of the posterior distribution for carrying capacity (the variable S_{EQ}), consistent with the exploitation history of the stock. The average total harvest rate (U.S. fishery + Canadian food and sport fishery) on this stock is 37%. The posterior distribution for the parameter ϕ (mean of 0.293) indicates some probability of negligibly positive autocorrelation in process error.

Optimum yield profiles for the Alsek stock are given in Figure 10 (upper panel). For convenience OY was defined as a sustained yield that was at least 60%, 70%, 80%, or 90% of MSY. A range of 24,000 to 33,500 spawners was used to demonstrate how to establish a specific goal. The probability of achieving OY if escapements are kept within this range is 90% to 96%, given that OY is defined as at least 90% of MSY. The probability of achieving OY was capped at 96% because there was no escapement that was bracketed by optimum ranges in all MCMC samples. The probability of achieving a less stringent (80% of MSY) standard for OY at this range reaches near certainty at 97% to 100%. For the 60% and 70% MSY standard, the range of 24,000 to 33,500 spawners was within the optimum ranges in virtually all simulations. Overfishing profiles for the Alsek stock show that an escapement of 24,000 spawners runs a 10% risk of recruitment overfishing if OY is based on ≥90% of MSY (Figure 10; lower panel). As expected, that risk is less (3%) when OY is at least 80% of MSY and virtually nil under less stringent standards for OY.

A biological escapement goal range of 24,000 to 33,500 spawners per year is recommended for the Alsek River sockeye salmon stock. The number of spawners is assessed either by direct assessment of the in-river run, or by combined expansion of Klukshu weir count and U.S. river fishery performance. This range of escapement is expected to produce yields close to MSY (≥90% of MSY) with a high probability (90% to 96%). This range carries with it a reasonable expectation of MSY and was estimated with explicit consideration of uncertainties in the data (measurement error) and in the productivity of the resource (process error). This range meets the common standard of OY used by ADF&G (≥90% of MSY), and meets the requirements for a Biological Escapement Goal (BEG) under the State of Alaska's Sustainable Salmon Fishery Policy (5 AAC 39.222).

KLUKSHU RIVER SOCKEYE SALMON STOCK ESCAPEMENT GOALS

The Klukshu stock-recruit model is very similar to the Alsek stock-recruit model except: 1) the Klukshu portion of the U.S. fishery harvest is estimated by applying the overall survival from simulated U.S. fishery harvest rate to the estimated Klukshu in-river run, and 2) the Klukshu escapement is relatively precisely estimated with weir counts available for all years.

The Klukshu sockeye salmon stock-recruit model simulations resulted in posterior distributions for the Klukshu total run (Figure 11; lower panel), and its components: U.S. fishery catch of Klukshu origin fish (kH_{cy}), Klukshu escapement (kS_{cy}) (Figure 11; upper panel), and Klukshu in-river run (KIR_{cy}).

The Klukshu sockeye salmon stock-recruit model simulations resulted in posterior distributions for age 4–age 6 production (P_{by}) and parent escapement (S_{by}). The means and standard deviation of these posterior distributions by brood year are presented in Table 9. These posterior distributions incorporate measurement error associated with estimates of age composition of the U.S. catch and the in-river run, as well as the uncertainty in reconstructed components of the Alsek run. A plot of the mean production versus the mean escapement with the central 90 percent of the posterior distributions demonstrates a moderate amount of uncertainty in the estimates of production from parent escapement for the Klukshu sockeye salmon stock (Figure 12).

The Klukshu sockeye salmon stock-recruit model simulations resulted in posterior distributions for parameters of the Ricker stock-recruit model. The means, standard deviation, median, and central 95^{th} percentiles of these posterior distributions are presented in Table 9. The plots of the explicit posterior distributions for stock-recruit model parameters are presented in Figure 13. Parameters were relatively well defined in the Klukshu stock-recruit model simulations (Figure 13). There is some uncertainty in the stock production relationship for the Klukshu stock (Figure 14; upper panel). The stock-recruit relationship is reasonably well defined by the simulations as seen from the percentile envelope of the posterior distribution of the predicted production from the Ricker stock-recruit model (Figure 14; lower panel).

Simulations resulted in a posterior distribution for the variable S_{MSY} with a mean of 9,727 and a median of 9,102 adults for the Klukshu stock. The median value of MSY from its posterior distribution is 15,980 adults. The expected value for the average of spawning escapements from the Klukshu stock-recruit model over years 1976–2008 (14,250) compares favorably to the 1976–2008 mean of the calendar year posterior distribution from the run reconstruction model simulations (14,283 adults). The average escapement is well below the mean (24,250 adults) of the posterior distribution for carrying capacity (the variable S_{EQ}), consistent with the exploitation history of the stock. The average U.S. fishery annual harvest on this stock is 27.2% across the years.

Optimum yield profiles for the Klukshu stock are given in Figure 15 (upper panel). For convenience OY was defined as a sustained yield that was at least 60%, 70%, 80%, or 90% of MSY. A range of 7,500 to 11,000 spawners was used to demonstrate how to establish a specific goal. The probability of achieving OY if escapements are kept within this range is 79% to 90%, given that OY is defined as at least 90% of MSY. The probability of achieving OY was capped at 90% because there was no escapement that was bracketed by optimum ranges in all MCMC samples. The probability of achieving a less stringent (80% of MSY) standard for OY at this range reaches near certainty at 95% to 96%. Overfishing profiles for the Klukshu stock show that an escapement of 7,500 adults runs a 15% risk of recruitment overfishing if OY is based on ≥90% of MSY (Figure 15 - lower panel). As expected that risk is less (4.7%) when OY is at least 80% of MSY and virtually nil under less stringent standards for OY.

A biological escapement goal range of 7,500 to 11,000 spawners per year is recommended for the Klukshu River sockeye salmon stock. The number of spawners is enumerated by Klukshu weir count. This range of escapement is expected to produce yields close to MSY (≥90% of MSY) with a high probability (≥90%). This range carries with it a reasonable expectation of MSY and was estimated with explicit consideration of uncertainties in the data (measurement error) and in the productivity of the resource (process error). This range meets the common standard of OY used by ADF&G (≥90% of MSY), and meets the requirements for a Biological Escapement Goal (BEG) under the State of Alaska's Sustainable Salmon Fishery Policy (5 AAC 39.222).

DISCUSSION

Assessment of Alsek River sockeye salmon runs, on which determination of stock productivity and biological escapement goals depends, is of inconsistent quality. The Bayesian run reconstruction models detailed above estimate the Alsek River sockeye salmon runs for years without assessment on in-river run (assessed 1984, 2000–2006) based on relationships among relative abundance indicators assessed annually and the absolute abundance assessed more infrequently. The Bayesian run reconstruction provides reconstructed posterior distributions of abundance and reflects uncertainty in the assessed abundance as well as uncertainty in the coherence between relative abundance indicators and absolute abundance. The reconstructed Alsek River sockeye salmon abundance is fairly precise with total run posterior distribution CVs for years of assessed runs ranging from 5% to 12% and CVs for years where runs are not completely assessed ranging from 14% to 23%. CV's for in-river run posterior distributions were higher and ranged from 7% to 13% for assessed runs, and 23% to 27% for incompletely assessed runs.

The Bayesian stock-recruit analysis considers the uncertainty in reconstructed catch and escapement, as well as sampling error in estimating provided reasonable estimates of uncertainty reflected in the posterior distributions of production, stock-recruit parameters, and yield expected under possible escapement goals, as well as risk of overfishing under possible escapement goals. In spite of limited stock assessment data, the Bayesian run reconstruction and stock-recruit models provided reasonable reconstructions of total runs and stock productivity. The stock exhibited strong density dependence with expected yields from possible escapement goals well defined.

Although the same observations were used to develop escapement goals for the Alsek and for the Klukshu stocks, circumstances differed in some fundamental ways between the two analyses. Annual escapement to the Alsek River was known with considerable measurement error, while escapement to the Klukshu River was known with near certainty. In contrast harvest of the Alsek stock in U. S. waters was known with near certainty, while harvest of the Klukshu stock was not. Because of the lack of explicit knowledge of the stock specific harvest from the Klukshu stock, there was strong autocorrelation in process error ($\phi = 0.575$), and greater uncertainty in the stock-recruit relationship (Figure 14). Note the analysis for the Alsek stock based on the same data showed a much lower autocorrelation (ϕ = 0.242), and a much more precise stock-recruit relationship. This divergence in results arose because the autocorrelation in the analysis for the Klukshu stock is not environmentally driven, but is an artifact of not having year-specific information on stock-specific harvests. Our remedy to this missing information tends to artificially smooth out variation in harvest allocation across calendar years and subsequently in estimated production by brood year. Not addressing autocorrelation within process error, even autocorrelation as artifact, will make a stock look more productive than it really is ($\ln(\hat{\alpha}) > \ln(\alpha)$ from Kope 2006). This observation is consistent with results here, in that the expected value of $\ln(\alpha)$ from simulations with the autoregressive model for the Klukshu stock was 1.656 whereas the expected value from the model uncorrected for autocorrelation (i.e., simple Ricker) was 1.918. Similarly for the Alsek stock the $\ln(\alpha)$ from the autoregressive and simple Ricker was 1.363 and 1.46, respectively. There was considerably more uncertainty in yields expected from potential escapement goals for the Klukshu stock (Figure 15) compared to that for the Alsek stock (Figure 11).

The proposed escapement goals for the Klukshu stock are very similar to those proposed by Clark and Etherton (2000). That study had a more limited data set and particular a very limited assessment (one year) of Alsek total runs. They addressed uncertainty in assessments by assuming this stock represented a constant 100%, 37% and 0% of U. S. harvest, resulting in estimates for S_{MSY} of 11,313, 9,361, and 7,806 adults, respectively. The mean of the posterior distribution for the Klukshu S_{MSY} in our analysis is 9,727 adults. The recommended escapement goal in Clark and Etherton (2000) was based on the 37% Klukshu stock fraction of the Alsek run. Essentially we adopted a similar approach as Clark and Etherton in allocation of U.S. catch to the Klukshu stock, by applying the U.S. fishery harvest rate estimated for Alsek stock to the Klukshu stock. However, the analysis benefitted from 11 additional years of stock assessment data including seven additional years of paired assessments of the Alsek and Klukshu runs. The main difference between the earlier analysis and ours is that we modeled possible autocorrelation, and provided a realistic assessment of uncertainty in the stock assessment and stock productivity, including explicit estimate of the uncertainty in yield relative to MSY for the proposed escapement goals.

CDFO tracks escapement at the Klukshu weir prior to 16 August, and thereafter, as early-run and late-run stocks. It is not known, however, if there are biologically separate early-run and late-run stocks in the Klukshu system. In addition, it is not possible, due to the lack of stock-specific catch data, to estimate escapement goals for early-run and late-run stocks within the Klukshu drainage. In view of the protracted overall run-timing and the substantial time period that “early-run” fish pass the Klukshu weir (from mid-June to mid-August), it would be prudent to continue to manage fisheries so that exploitation occurs as evenly as possible over the entire Alsek sockeye salmon run.

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TABLES AND FIGURES

Table 1.–Alsek River sockeye salmon run components, including U.S. commercial harvest, U.S. subsistence harvest, in-river run, harvest in Canadian food and recreational fisheries, and Klukshu River escapement.

				Alsek In-River Run			
Year	Dry Bay Commercial Catch	Dry Bay Fishing Effort (Boat Days)	U.S. Subsistence and Sport Catch	Magnitude	Standard Error	Canadian Food and Recreational Fishery Catch	Klukshu Escapement
1976	19,741	550	51			4,600	7,941
1977	40,780	882	113			11,850	15,441
1978	50,580	929	95			8,500	19,017
1979	41,449	1,110	35			7,750	7,051
1980	25,522	773	41			1,500	10,850
1981	23,641	588	50	55,662	5,218	2,808	18,448
1982	27,443	552	75			5,755	28,899
1983	18,293	487	25			3,282	18,017
1984	14,326	429	90			2,889	10,227
1985	5,792	277	95			1,461	17,259
1986	24,791	517	241			2,221	22,936
1987	11,393	388	173			1,541	9,346
1988	6,286	324	148			1,926	7,737
1989	13,513	378	131			2,225	21,636
1990	17,013	374	144			2,706	24,607
1991	17,542	530	104			2,414	17,645
1992	19,298	372	37			3,174	18,269
1993	20,043	372	96			2,690	14,921
1994	19,639	403	47			2,006	13,892
1995	33,112	879	167			2,427	19,817
1996	15,182	419	67			1,361	7,891
1997	25,879	611	273			520	11,303
1998	15,007	358	158			585	13,580
1999	11,441	319	152			554	5,101
2000	9,522	307	146	37,887	4,334	745	5,422
2001	13,995	234	72	31,164	2,401	1,177	9,329
2002	16,918	270	232	95,427	11,837	2,255	23,587
2003	39,698	271	176	103,507	8,730	2,795	32,120
2004	18,030	280	122	83,703	13,215	2,122	13,721
2005	7,572	171	63	64,665	(10,300)[a]	594	3,167
2006	9,842	248	272	48,923	(7,800)[a]	1,327	12,890
2007	19,791	311	72			10	8,479
2008	2,815	171	117			0	2,741

[a] Standard error calculated on highest CV's observed in mark–recapture experiments.

Table 2.–Klukshu River weir counts of sockeye salmon and estimated annual escapements.

Year	Sockeye Weir Count			Annual Harvest	
	Early [a]	Late [b]	Total	Above Weir	Escapement
1976	181	11,510	11,691	3,750	7,941
1977	8,931	17,860	26,791	11,350	15,441
1978	2,508	24,359	26,867	7,850	19,017
1979	977	11,334	12,311	5,260	7,051
1980	1,008	10,742	11,750	900	10,850
1981	997	19,351	20,348	1,900	18,448
1982	7,758	25,941	33,699	4,800	28,899
1983	6,047	14,445	20,492	2,475	18,017
1984	2,769	9,958	12,727	2,500	10,227
1985	539	18,081	18,620	1,361	17,259
1986	416	24,434	24,850	1,914	22,936
1987	3,269	7,235	10,504	1,158	9,346
1988	585	8,756	9,341	1,604	7,737
1989	3,400	20,142	23,542	1,906	21,636
1990	1,316	24,679	25,995	1,388	24,607
1991	1,924	17,053	18,977	1,332	17,645
1992	11,339	8,428	19,767	1,498	18,269
1993	5,369	11,371	16,740	1,819	14,921
1994	3,247	11,791	15,038	1,146	13,892
1995	2,289	18,407	20,696	879	19,817
1996	1,502	6,818	8,320	429	7,891
1997	6,565	4,931	11,496	193	11,303
1998	597	12,994	13,591	11	13,580
1999	371	5,010	5,381	280	5,101
2000	237	5,314	5,551	129	5,422
2001	908	9,382	10,290	961	9,329
2002	11,904	13,807	25,711	2,124	23,587
2003	3,084	31,278	34,362	2,242	32,120
2004	3,464	11,884	15,348	1,627	13,721
2005	994	2,379	3,373	206	3,167
2006	247	13,208	13,455	565	12,890
2007	2,725	6,231	8,956	477	8,479
2008	43	2,698	2,741	0	2,741

[a] Counts before August 15.
[b] Counts after August 15.

Table 3.–Likelihood and prior probability distributions used in simulations involving the Bayesian model of run reconstruction of the Alsek River sockeye salmon. Note that when expressing that a variable follows the normal distribution, the WinBUGS ver. 1.4.2 program uses the precision which is the reciprocal of the variance.

Quantity	Constraints	Comments
$\ln(IR_{cy}) \sim norm(\ln(\mu_{IR}), \tau_{IR})$		Likelihood
$\ln(\mu_{IR}) \sim norm(0,0.001)$	Positive	Non-informative prior
$\tau_{IR} \sim gamma(0.001,0.001)$	None	Non-informative prior
$q_{c}y \sim beta(B1_1, B1_2)$		Likelihood
$Q \sim beta(0.1,0.1)$	None	Non-informative prior
$B1.scale \sim Uniform(0,1)$	None	Non-informative prior
$B1_1 = Q / B1.scale^2$, $B1_2 = (1 - Q) / B1.scale^2$		Calculation
$p_{cy} \sim beta(B2_1, B2_2)$		Likelihood
$P \sim beta(0.1,0.1)$	None	Non-informative prior
$B2.scale \sim Uniform(0, 1)$	None	Non-informative prior
$B2_1 = P / B2.scale^2$, $B2_2 = (1 - P) / B2.scale^2$		Calculation

Table 4.–Prior probability distributions used in simulations involving the Bayesian model of the population and stock-recruit dynamics of the Alsek River sockeye salmon stock 1976 through 2008. Note that when expressing that a variable follows the normal probability distribution, the WinBUGS ver. 1.4.2 program uses the precision which is the reciprocal of the variance.

Prior probability distributions	Constraints	Comments
$\ln\alpha \sim norm(1.58,0.01)$	$0 \rightarrow 4$	Non-informative prior for Ricker productivity parameter.
$\phi \sim norm(0,0.00001)$	$-0.99 \rightarrow 0.99$	Non-informative prior for autoregressive lag-1 coefficient.
$\tau = 1 / \sigma^2 \sim gamma(0.01,0.01)$	None	Non-informative prior for inverse variance of "white noise" process error in Ricker production.
$\overline{lnP} \sim norm(0,0.0001)$	$0 \rightarrow$	Non-informative hyper-prior for mean of hierarchical lognormal production (by 1970 –1975).
$\tau_{lnP} = 1/Var(lnP) \sim gamma(0.001,0.001)$	None	Non-informative hyper-prior for inverse variance of hierarchical lognormal production (*by* 1970 –1975).
$lnS_o \sim norm(0,0.0001)$	$4 \rightarrow 14$	Non-informative prior for lognormal escapement in 1975.

Table 5.–Algorithm based on re-parameterization of the Dirichlet used to determine the stochastic fraction ($\theta_{by,a}$) of a brood year's production returning as adults of age a. Fractions vary from brood year to brood year within a simulation and from simulation to simulation.

Variable	Relationship	Non-Informative Prior Distribution	Comments
Deviation in Maturation rate.	$\nabla t_4 = t_4$ $\nabla t_5 = t_5(1-\nabla t_4)$ $\nabla t_6 = (1-\nabla t_5 - \nabla t_6)$	$t_a \sim beta(1,1)\big\|_{a=4,5}$	Expected rates of survival/maturation (t_a) modeled by these relationships and two prior distributions
Expected brood year specific maturation rates.	$\gamma_a = \frac{\nabla t_a}{\omega^2}\Big\|_{a=4,5,6}$	$\omega \sim uniform(0,1)$	Brood year deviations from expected rates of maturation for 4-, 5-, and 6- year olds within a simulation modeled with this and next relationship.
Brood year specific deviation in maturation rates.	$\theta_{by,a} = \frac{D_{by,a}}{D_{by,4} + D_{by,5} + D_{by,6}}\Big\|_{a=4,5,6}$	$D_{by,a} \sim gamma(\gamma_a,1)\big\|_{a=4,5,6}$	

Table 6.–Means and standard deviations of posterior distribution of estimated parameters in Alsek River sockeye salmon run reconstruction.

	Alsek In-River Run (IR_{cy})		U.S.Fishery Harvests(H_{cy})		Klukshu In-River Run(KIR_{cy})		U.S.Fishery Catchability (q_{cy})		Klukshu Proportion (p_{cy})	
Year	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD .
1976	44,180	11,210	19,800	592	12,610	752	7.03E-04	1.48E-04	0.203	0.036
1977	51,010	13,330	40,950	1,221	25,880	1,532	6.94E-04	1.34E-04	0.287	0.043
1978	52,120	13,870	50,700	1,518	27,490	1,632	7.59E-04	1.44E-04	0.272	0.039
1979	41,990	11,580	41,520	1,246	14,900	892	6.44E-04	1.26E-04	0.182	0.027
1980	41,390	11,160	25,590	766	12,330	732	6.51E-04	1.35E-04	0.189	0.032
1981	50,650	12,930	23,730	711	21,200	1,252	6.83E-04	1.42E-04	0.293	0.051
1982	62,850	15,270	27,580	826	34,150	2,018	6.86E-04	1.35E-04	0.388	0.064
1983	54,730	4,807	18,360	549	21,240	1,263	5.98E-04	4.79E-05	0.292	0.026
1984	45,200	11,500	14,430	429	13,160	783	6.76E-04	1.44E-04	0.228	0.043
1985	45,460	10,970	5,916	178	18,490	1,095	4.64E-04	1.02E-04	0.375	0.077
1986	57,180	14,410	25,060	749	25,040	1,485	7.33E-04	1.49E-04	0.313	0.054
1987	41,990	10,150	11,580	347	10,940	655	6.57E-04	1.41E-04	0.211	0.041
1988	36,010	9,671	6,454	193	9,681	577	5.39E-04	1.29E-04	0.239	0.053
1989	55,210	13,670	13,680	411	23,580	1,402	6.13E-04	1.29E-04	0.355	0.067
1990	60,680	13,910	17,190	517	27,040	1,607	6.93E-04	1.37E-04	0.358	0.063
1991	47,770	11,820	17,690	531	19,960	1,180	6.21E-04	1.30E-04	0.314	0.057
1992	58,410	13,310	19,330	575	21,410	1,260	7.98E-04	1.52E-04	0.283	0.048
1993	57,530	13,220	20,130	600	17,660	1,053	8.38E-04	1.63E-04	0.234	0.041
1994	52,410	11,970	19,670	590	15,950	949	8.20E-04	1.57E-04	0.227	0.038
1995	46,710	12,330	33,350	1,001	22,200	1,316	6.38E-04	1.25E-04	0.284	0.044
1996	43,220	10,320	15,250	456	9,335	559	7.52E-04	1.55E-04	0.165	0.030
1997	45,990	11,520	26,140	786	11,920	715	7.66E-04	1.52E-04	0.169	0.028
1998	50,290	11,620	15,170	454	14,220	850	7.66E-04	1.52E-04	0.224	0.040
1999	42,300	10,050	11,580	347	5,722	343	7.92E-04	1.67E-04	0.110	0.021
2000	37,720	3,912	9,669	291	6,231	374	7.50E-04	7.18E-05	0.132	0.013
2001	32,780	2,439	13,930	417	10,540	624	1.52E-03	1.02E-04	0.226	0.018
2002	85,290	9,405	17,170	516	25,870	1,536	6.86E-04	7.14E-05	0.255	0.028
2003	101,000	8,032	39,640	1,190	34,970	2,064	1.23E-03	8.81E-05	0.249	0.020
2004	73,790	9,569	18,140	543	15,970	950	7.96E-04	9.45E-05	0.176	0.021
2005	57,510	7,660	7,637	229	3,817	230	7.40E-04	9.35E-05	0.059	0.008
2006	49,390	6,414	10,110	302	14,240	845	7.62E-04	9.18E-05	0.242	0.029
2007	57,250	13,370	19,800	595	8,589	513	9.93E-04	1.95E-04	0.115	0.020
2008	29,130	7,975	2,940	88	2,777	166	5.99E-04	1.49E-04	0.092	0.022
1976–2008 average	51,792		19,997		16,943		7.47E-04		0.235	

Table 7.–Estimated mean and standard deviation of posterior distribution of production (P_{by}) of sockeye salmon (age 4–age 6) by brood year and estimated mean and standard deviation of the posterior distribution of spawning abundance (S_{by}) of their parents for the Alsek River stock, 1976–2008.

Brood Year (*by*)	P_{by}	SD(P_{by})	S_{by}	SD(S_{by})
1976	64,350	9,431	28,549	7,740
1977	95,470	12,420	41,440	10,990
1978	84,630	5,415	48,820	12,750
1979	63,210	9,929	34,220	9,706
1980	52,320	7,817	40,540	10,870
1981	68,580	8,907	46,480	10,430
1982	65,030	7,748	55,560	12,010
1983	52,640	7,625	52,110	4,835
1984	55,080	7,611	43,970	10,410
1985	84,290	10,420	49,750	9,081
1986	64,680	8,851	48,190	10,460
1987	84,350	10,220	46,440	8,937
1988	68,350	8,367	44,170	9,127
1989	61,520	7,238	47,870	10,250
1990	96,970	12,340	54,820	10,260
1991	62,760	8,579	48,500	10,610
1992	70,530	8,653	55,270	10,790
1993	69,820	9,258	52,310	10,050
1994	52,630	8,424	50,230	10,350
1995	47,250	5,100	44,040	11,650
1996	53,790	2,807	47,080	10,030
1997	92,700	7,817	45,220	9,182
1998	141,000	7,716	50,500	9,354
1999	91,030	8,482	44,660	8,456
2000	66,130	6,649	38,270	3,878
2001	50,010	4,644	32,300	2,453
2002	85,000	10,980	76,800	8,154
2003	38,510	8,881	97,150	7,855
2004	60,190	18,650	70,080	8,742
2005	68,800	23,790	57,800	7,149
2006	70,740	24,770	48,870	5,995
2007	71,390	25,440	53,850	11,000
2008	70,600	25,690	39,330	9,813

Table 8.–Means, SDs, medians, and percentiles of posterior probability distributions for parameters and variables in Bayesian stock-recruit analysis for the Alsek and Klukshu stocks of sockeye salmon. Notation is defined in text.

					Percentiles	
Stock	Parameter	Mean	SD	Median	2.50%	97.50%
Alsek	S_{EQ}	73,320	22,070	69,830	58,290	106,600
	S_{MSY}	29,710	9,150	28,190	22,060	45,830
	U_{MSY}	0.544	0.099	0.551	0.330	0.716
	MSY	39,220	56,190	35,800	17,810	61,640
	β	0.0000194	0.0000059	0.0000193	0.0000081	0.0000311
	$\ln\alpha$	1.303	0.324	1.308	0.652	1.914
	$\ln\alpha'$	1.363	0.331	1.360	0.735	1.982
	ϕ	0.242	0.257	0.2152	0.215	0.798
	σ^2	0.293	0.052	0.207	0.288	0.411
Klukshu	S_{EO}	25,810	12,300	23,840	14,270	49,070
	S_{MSY}	9,727	4,366	9,102	6,085	16,800
	U_{MSY}	0.6165	0.1222	0.6243	0.3478	0.8443
	MSY	24,080	69,300	15,980	3,875	75,330
	β	0.000067	0.000018	0.000067	0.000032	0.000102
	$\ln\alpha$	1.295	0.4791	1.316	0.2911	2.194
	$\ln\alpha'$	1.656	0.5287	1.613	0.782	2.81
	ϕ	0.5749	0.1879	0.5817	0.1907	0.9051
	σ^2	0.6048	0.09083	0.5949	0.4561	0.8113

Table 9.–Estimated mean and standard deviation of posterior distribution of production (P_{by}) of sockeye salmon (age 4–age 6) by brood year and estimated mean and standard deviation of the posterior distribution of spawning abundance (S_{by}) of their parents for the Klukshu River stock, 1976–2008.

Brood Year(*by*)	P_{by}	SD(P_{by})	S_{by}	SD(S_{by})
1976	53,360	26,280	8,043	750
1977	58,560	7,845	14,010	1,522
1978	40,740	3,033	18,940	1,621
1979	23,250	3,444	7,185	883
1980	20,130	1,408	10,860	742
1981	32,930	3,268	18,350	1,244
1982	21,290	2,233	27,980	1,941
1983	13,500	1,254	18,280	1,274
1984	26,390	2,848	10,370	782
1985	43,510	3,437	17,090	1,079
1986	32,430	4,160	22,140	1,427
1987	36,940	3,987	9,568	654
1988	25,980	2,898	7,948	580
1989	24,730	3,837	21,130	1,376
1990	53,560	8,501	24,090	1,563
1991	21,260	4,580	17,610	1,172
1992	23,830	4,215	18,270	1,238
1993	22,180	2,295	14,940	1,031
1994	9,104	1,494	14,030	958
1995	8,590	855	19,520	1,292
1996	18,560	1,347	8,175	569
1997	31,680	1,855	11,320	700
1998	57,290	4,279	13,570	840
1999	21,850	1,433	5,266	345
2000	5,774	344	5,533	373
2001	13,350	885	9,366	611
2002	17,030	1,563	23,500	1,473
2003	3,282	315	32,190	2,080
2004	7,164	4,833	13,700	937
2005	6,917	7,217	3,353	235
2006	17,780	18,280	12,700	829
2007	18,590	18,440	8,650	512
2008	10,220	10,570	2,844	169

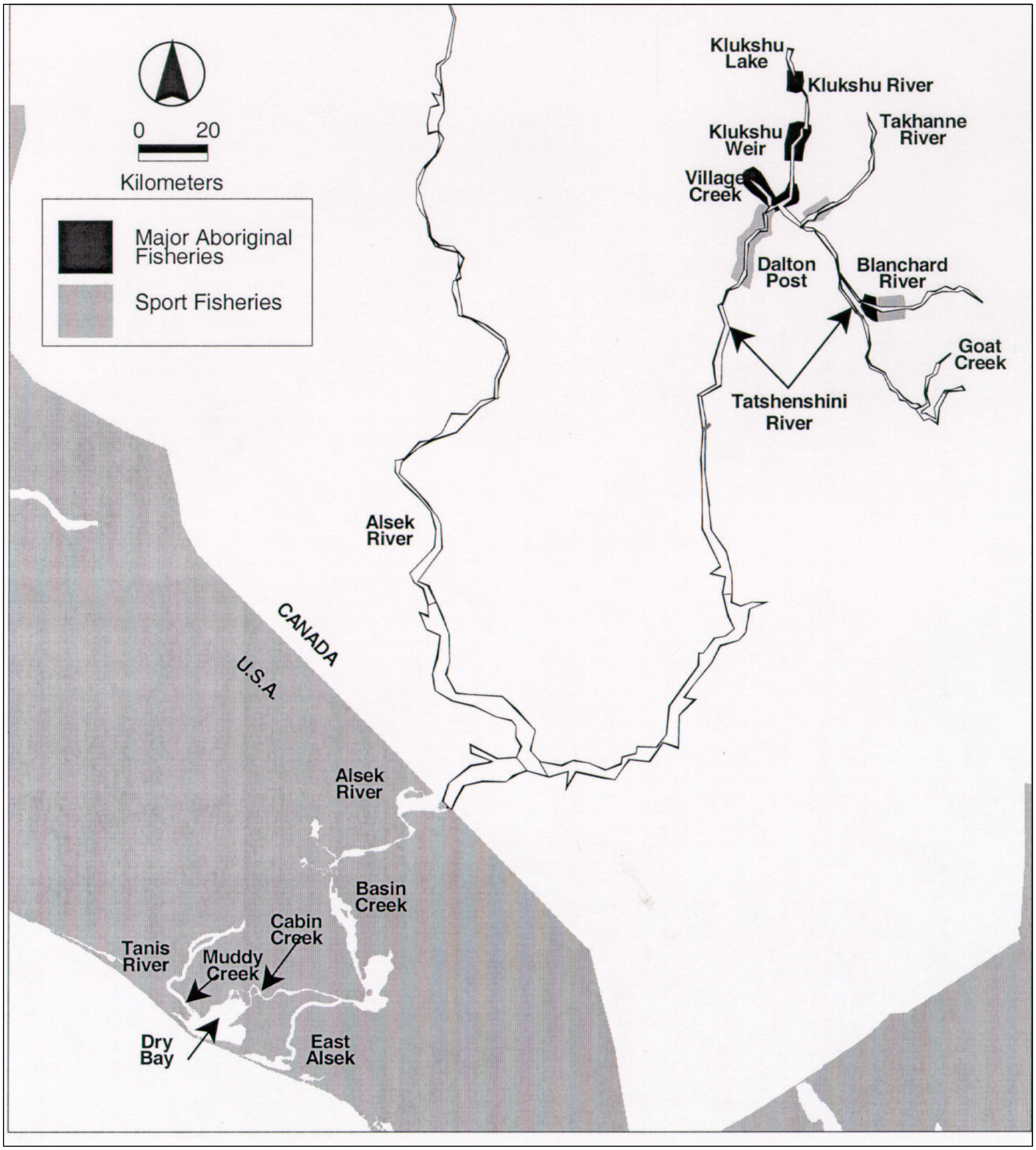


Figure 1.–Alsek River and principal U.S. and Canadian fishing areas.

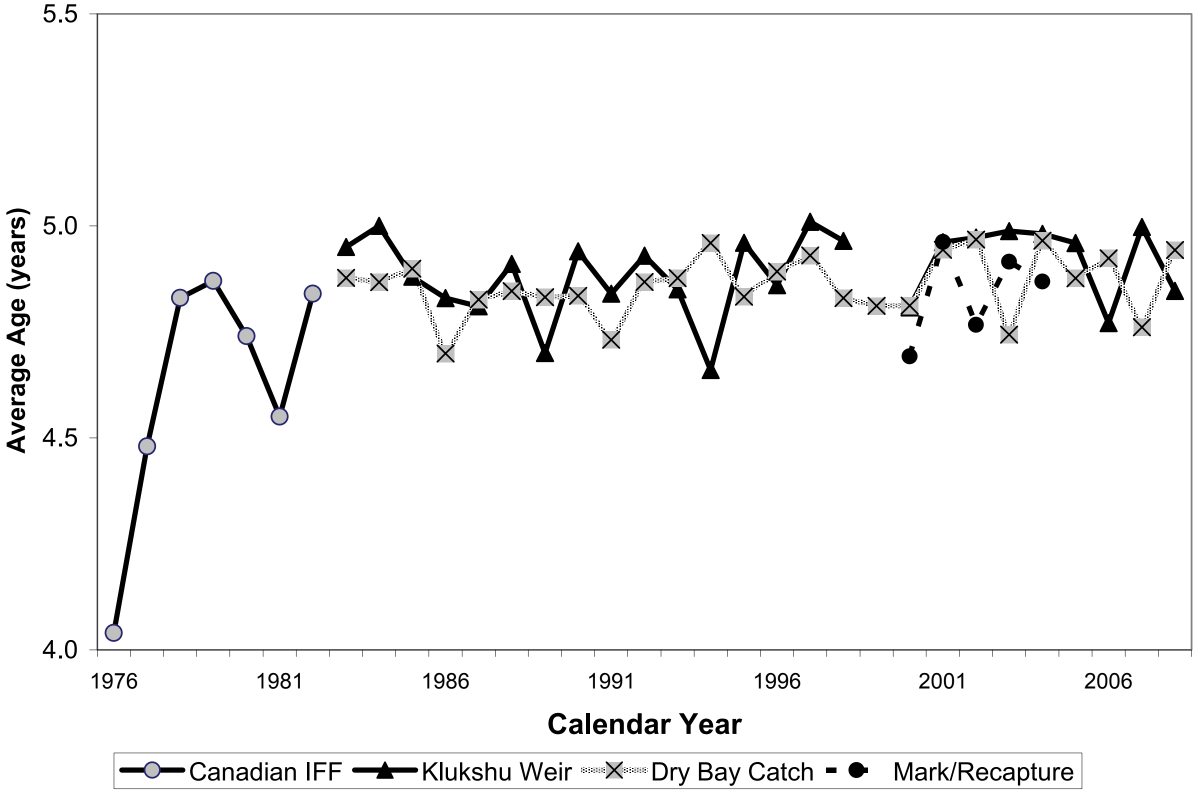


Figure 2.–Average age from different samples taken by year from the different segments of the annual run of sockeye salmon to the Alsek River.

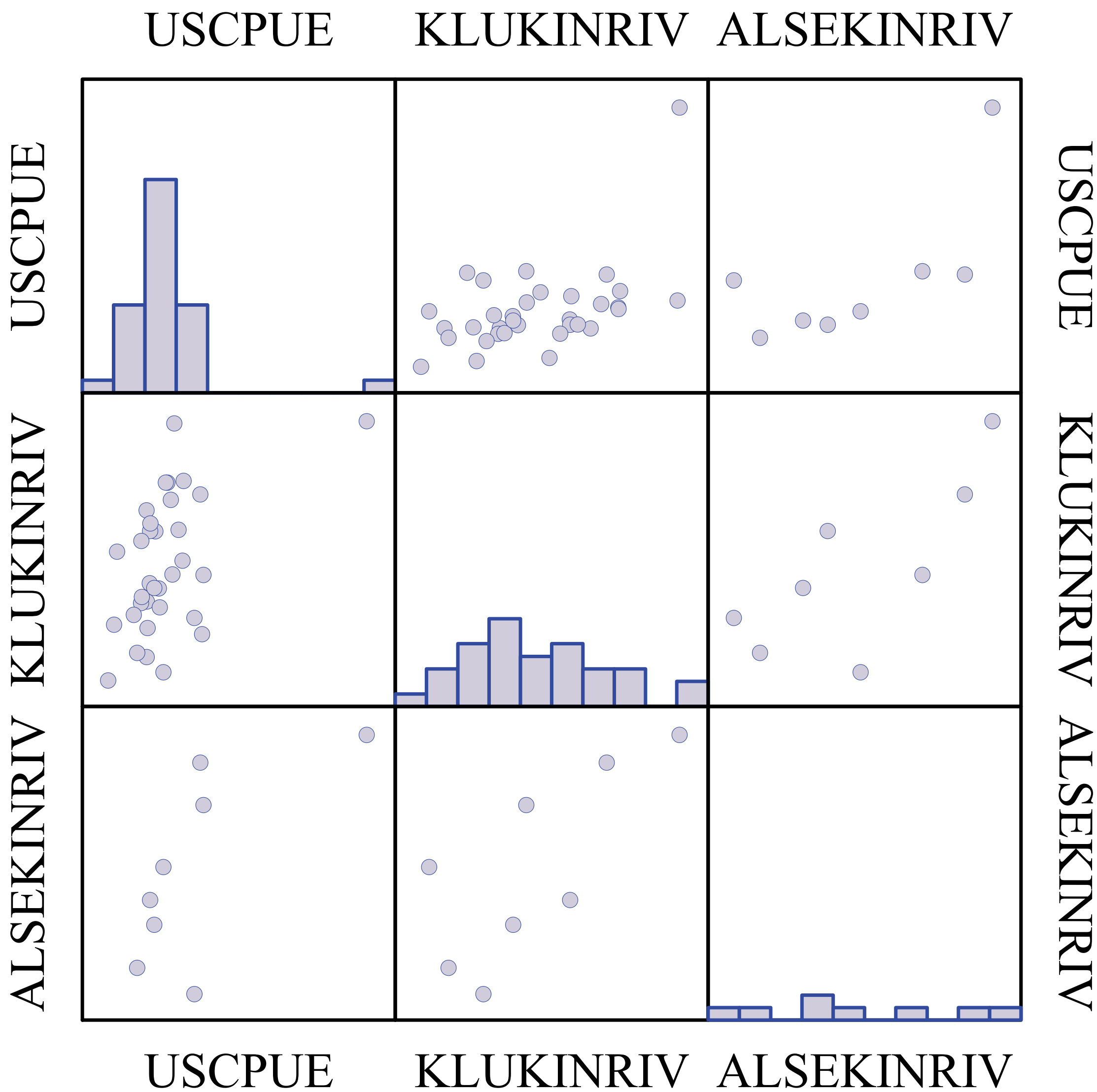


Figure 3.–Possible bivariate scatter plots among the three indicators of the Alsek River sockeye salmon run, catch-per-unit-fishing-effort in the U.S. fishery (USCPUE), the Klukshu stock in-river run (KLUKINRIV) and the Alsek stock in-river run (ALSEKINRIV); together with the frequency distribution of these statistics.

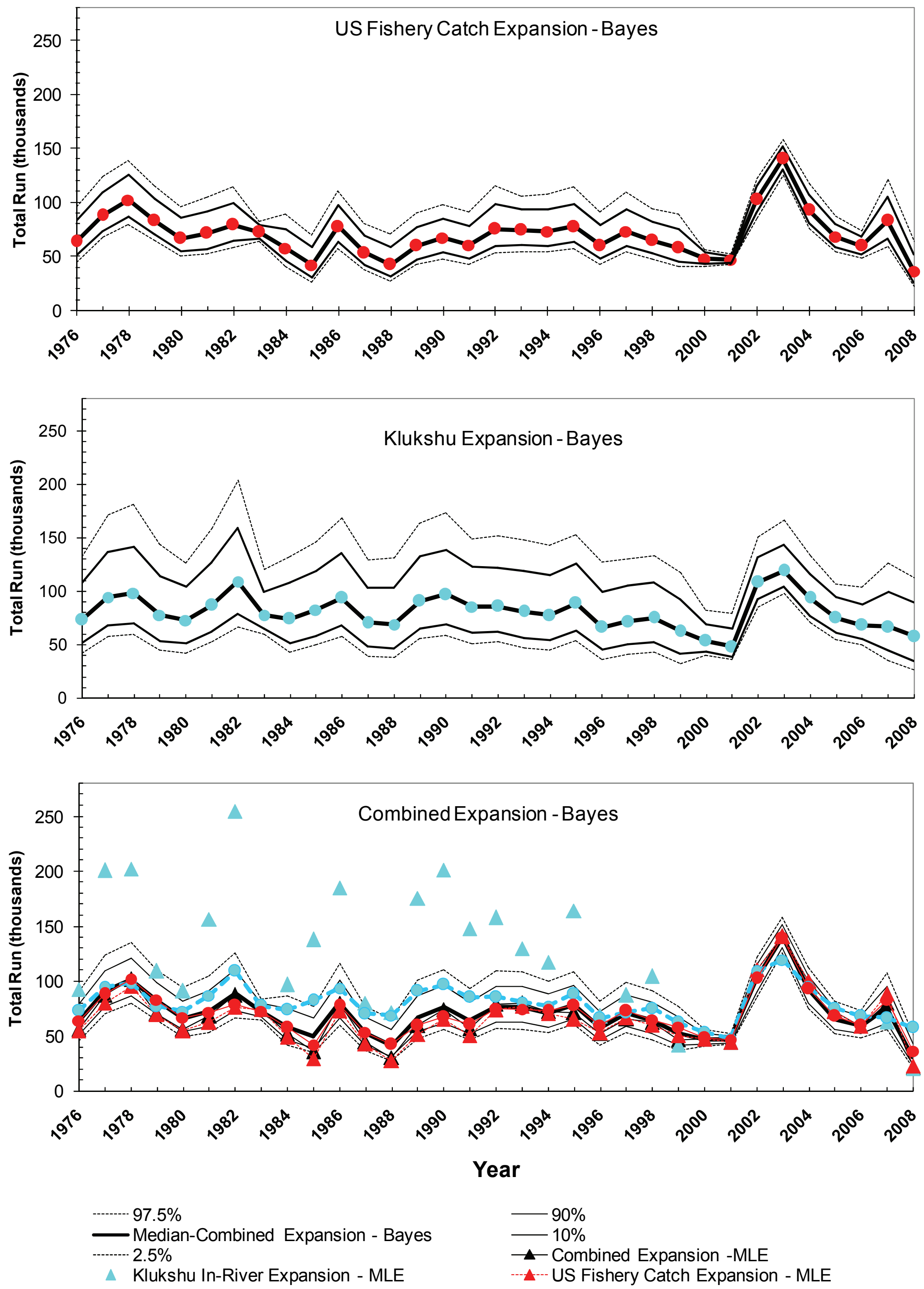


Figure 4.–Median, 97.5%, 90%, 10% and 2.5% credible intervals for Alsek River sockeye salmon based on Bayesian combined expansion (lower panel), Bayes Klukshu in-river run expansion (middle panel), and Bayes U.S. fishery catch expansion (upper panel) over the period 1976 to 2008. Also shown are run reconstructions based on traditional MLE estimation based on Klukshu in-river run (constant expansion factor), effort expansion of U.S. catch and effort (constant catchability), and a combined expansion Klukshu in-river run and U.S. catch (constant parameters). See text for details of MLE estimation.

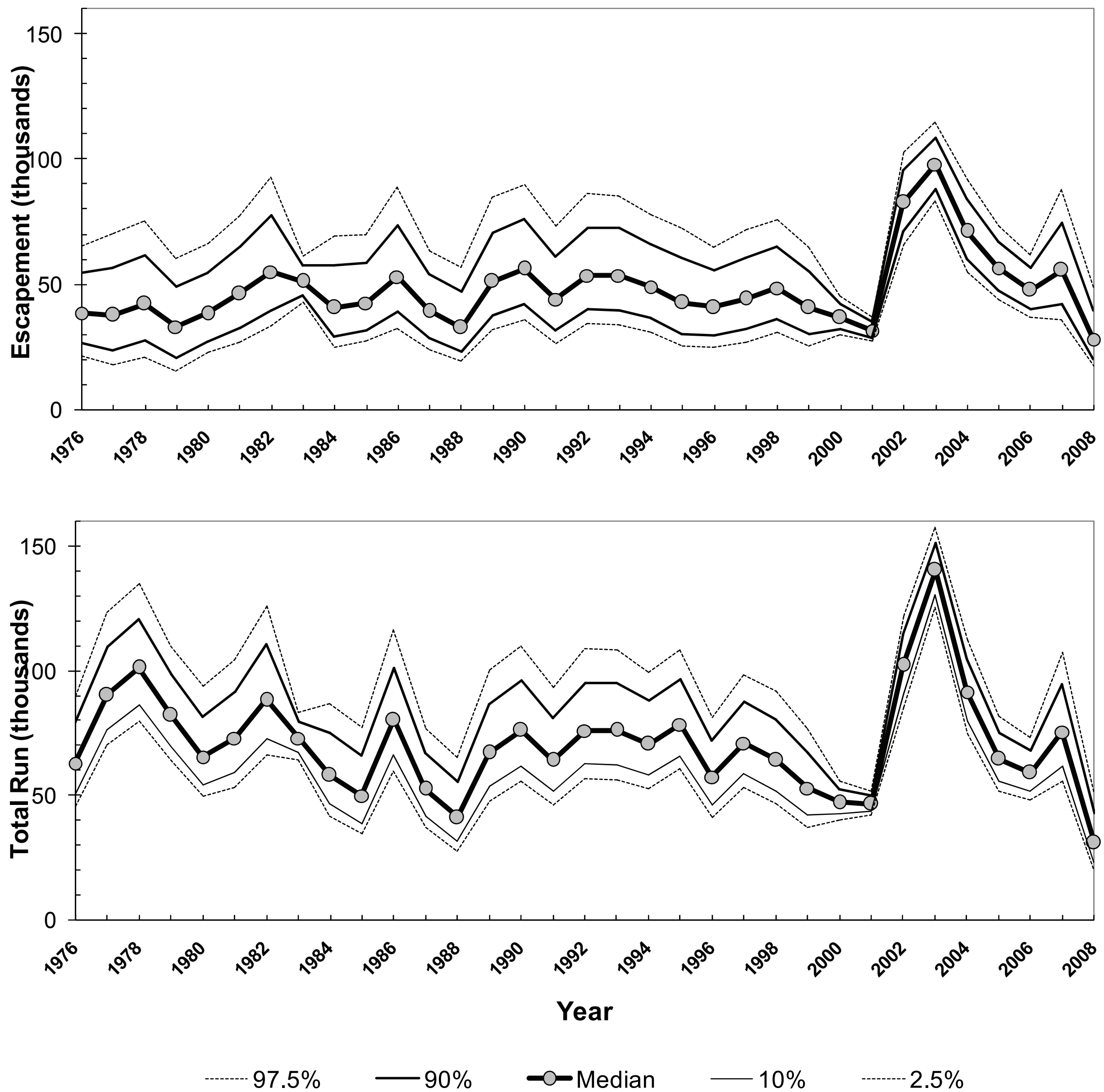


Figure 5.–Median, 97.5%, 90%, 10% and 2.5% credible intervals for Alsek River sockeye salmon total runs (lower panel) and escapement (upper panel) over the period 1976 to 2008 based on Bayesian combined Klukshu in-river run and U.S. fishery catch expansion run reconstruction model.

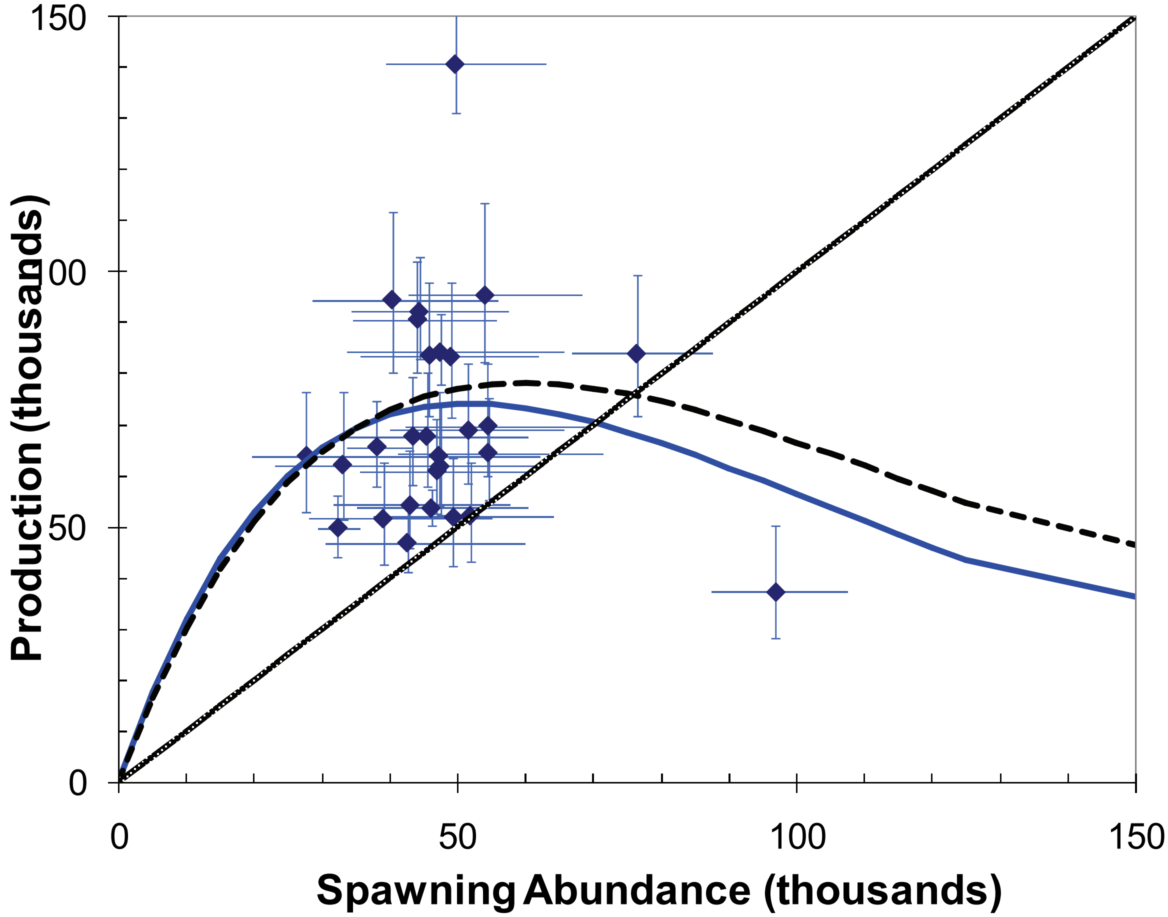


Figure 6.–Scatter plot of estimated production $\hat{P}_{by}$ against estimated spawning abundance $\hat{S}_{by}$ of sockeye salmon of all ages (age 4–6) in the Alsek River stock for brood years 1976–2008. Posterior means are plotted as closed symbols, 10th and 90th posterior percentiles are bracketed by error bars. Ricker relationships are Bayesian posterior median (blue solid line) and autoregressive Ricker (dashed black line) fit using MLE to production estimated from the traditional MLE combined expansion model run reconstruction.

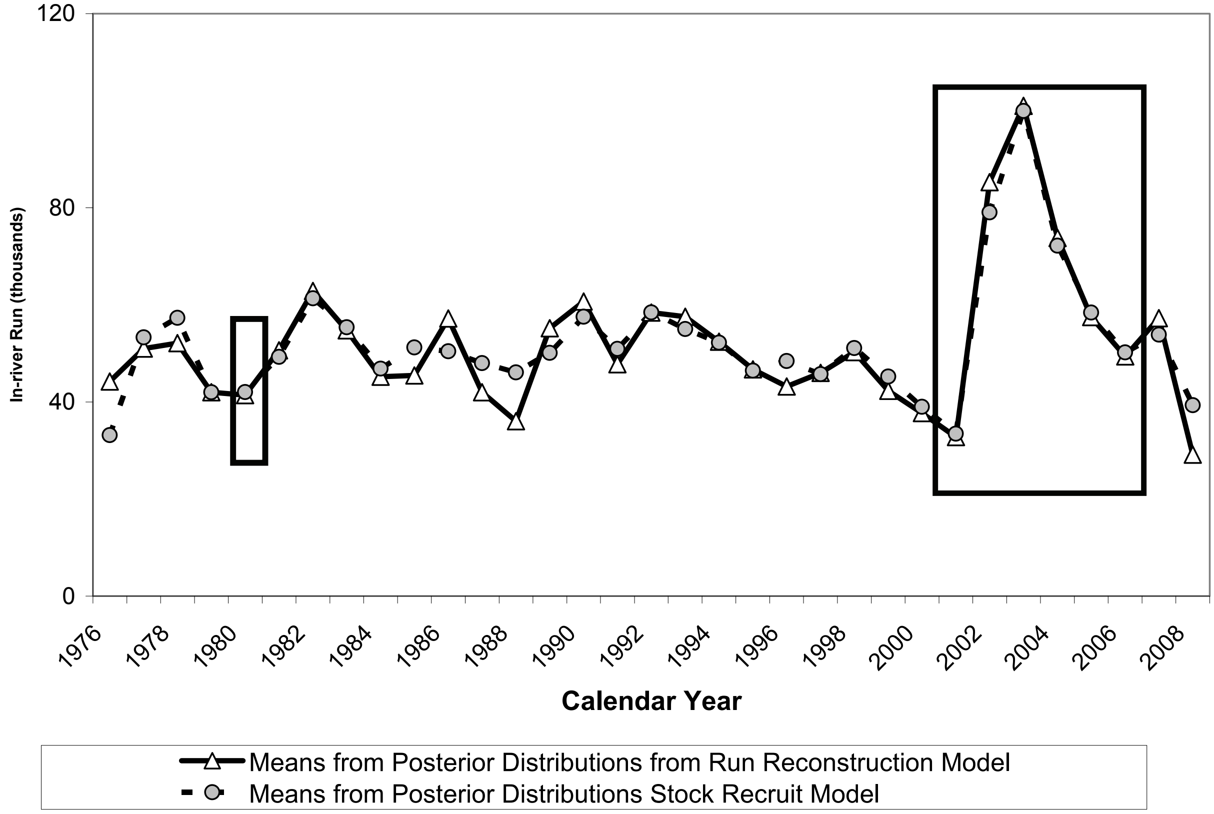


Figure 7.–Estimated size of the in-river run to the Alsek stock of sockeye salmon based on the run reconstruction model against the means of the in-river run from the posterior distribution of the in-river run from the stock-recruit model. The boxed comparisons represent years with assessed in-river runs.

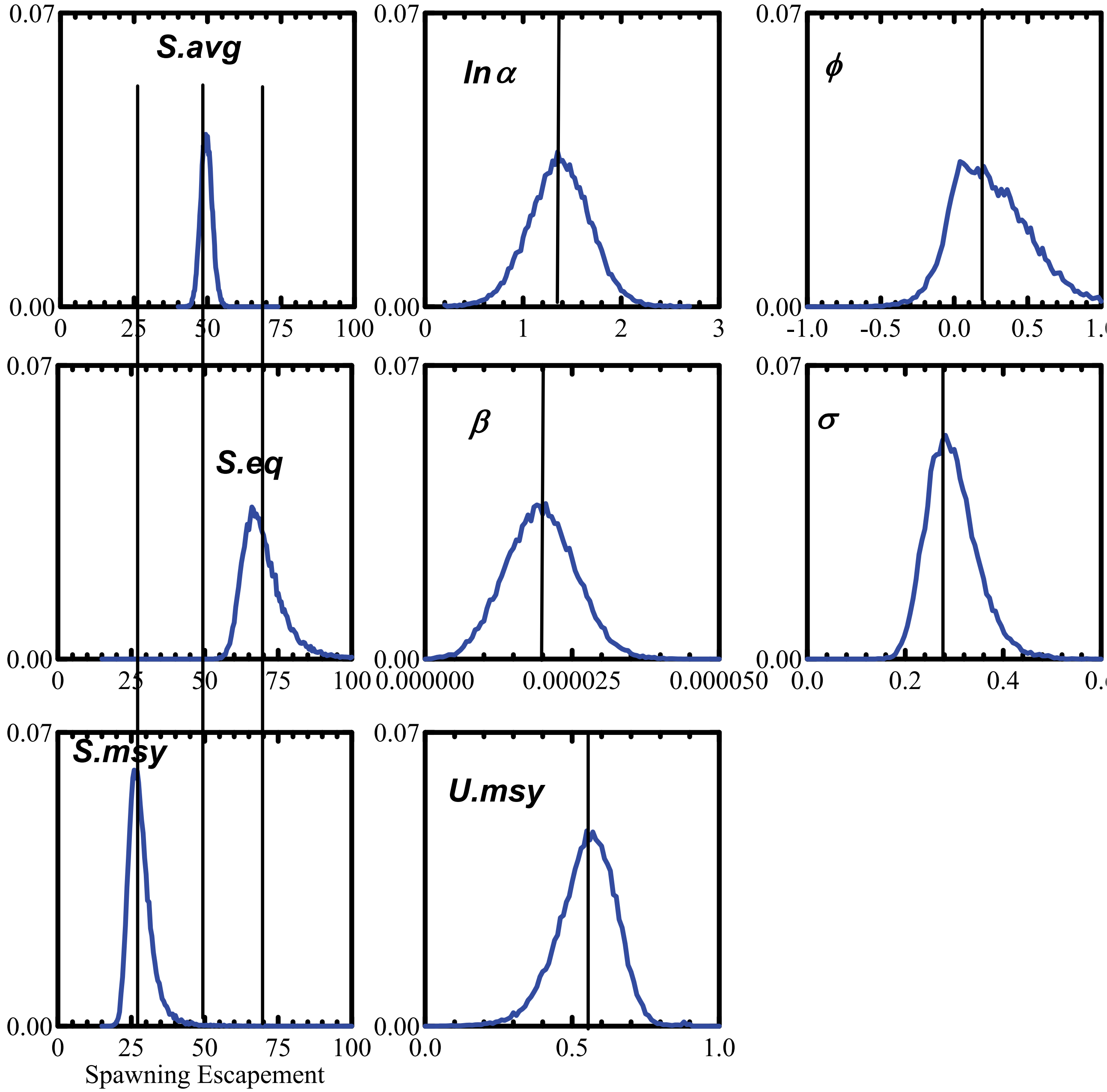
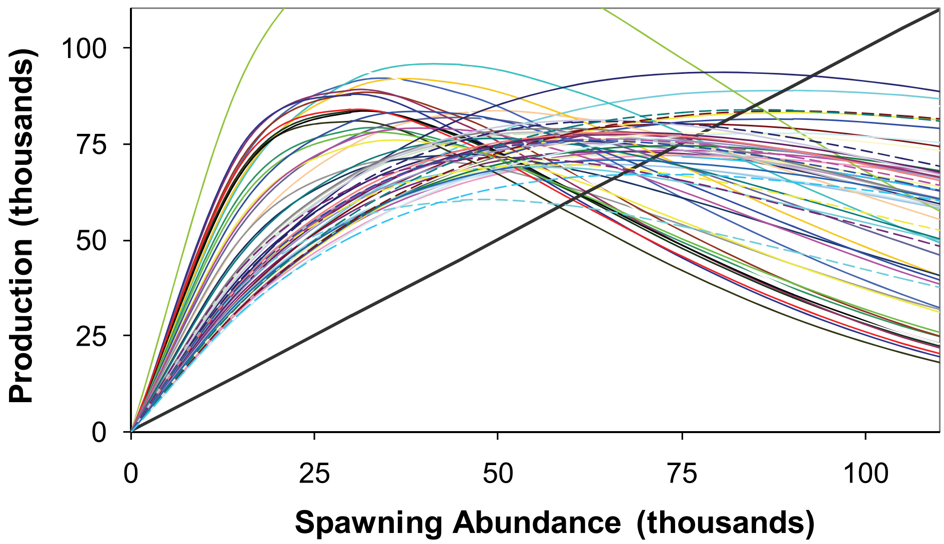


Figure 8.–Posterior probability distributions for parameters and some variables from the Alsek stock-recruit model. Solid vertical lines correspond to expected (mean) values in each probability distribution as specified. The line through S.avg is average of the estimated spawning abundance $\hat{S}cy$ over the data. Notation is defined in the text.



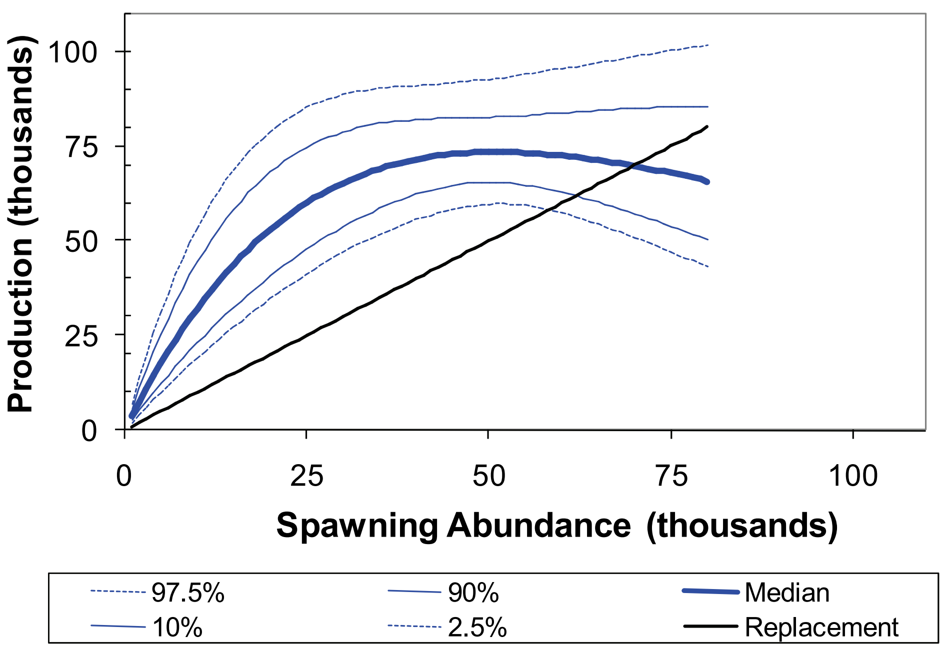


Figure 9.–Estimated production $\hat{P}_{by}$ against estimated spawning abundance $\hat{S}_{by}$ of sockeye salmon of all ages (age 4–6) in the Alsek River stock for brood years 1976–2008. Upper panel: Ricker relationships represented by 50 paired values of ln(α) and β sampled from the posterior probability distribution of stock-recruitment statistics. Curves can be interpreted as a sampling of Ricker relationships that could have generated the observed data. Lower panel: percentile envelope of the posterior distribution of the predicted production from the Ricker stock-recruit model.

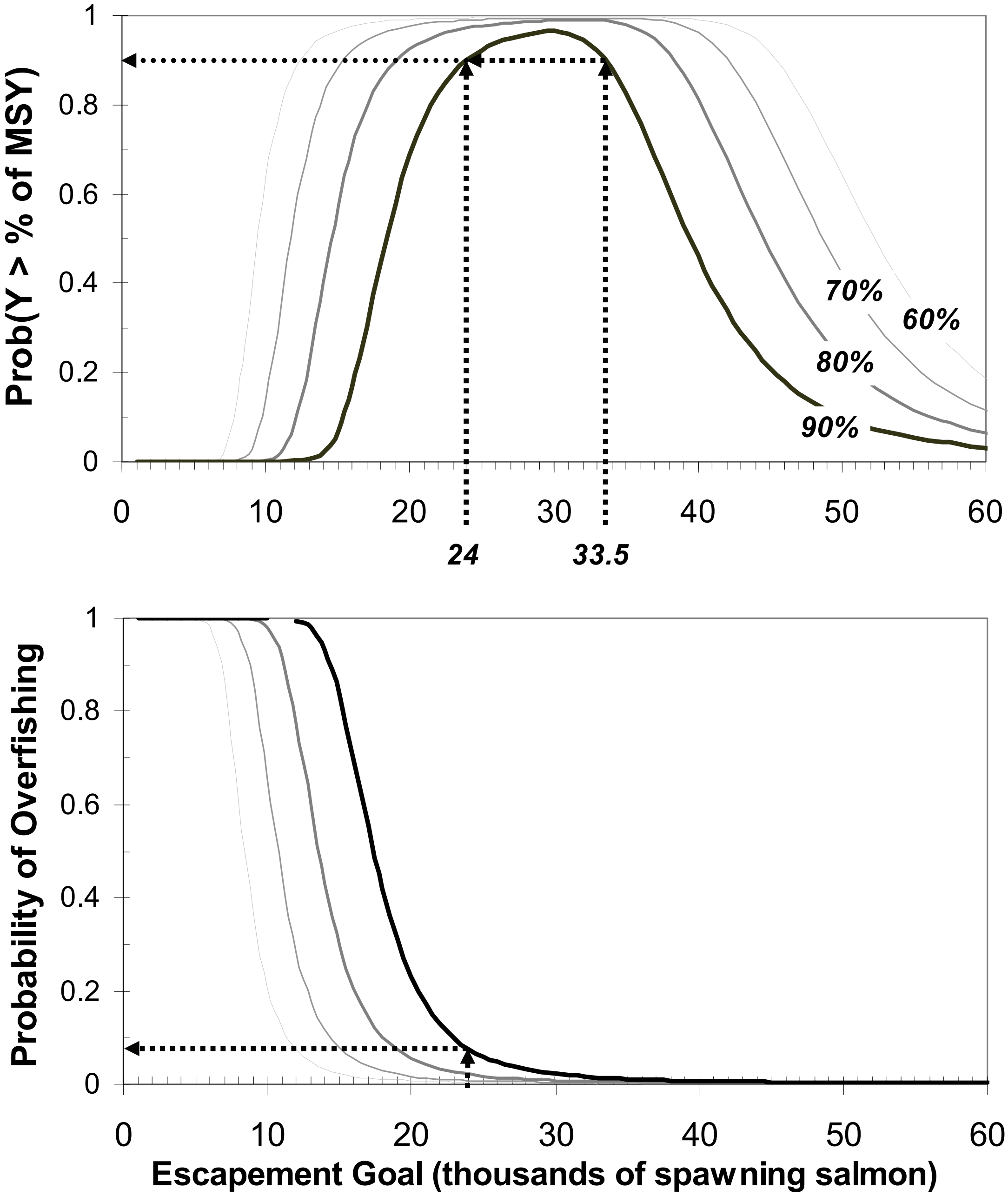


Figure 10.–Upper Panel: optimum yield (OY) profiles defined as probability of at least Y percent of maximum sustained yield (MSY) at potential escapement goals for the Alsek River stock. Shown are profiles for 60%, 70%, 80% and 90% of MSY. Dashed lines on the 90% OY profile connect the range of escapements (24 to 33.5 thousand) that provide 90% percent of MSY with probability 0.9. Lower panel: overfishing (OF) profiles defined as the probability of having less than Y percent of optimum yield through recruitment overfishing at that escapement level. Shown are profiles corresponding to 60%, 70%, 80%, and 90% of MSY.

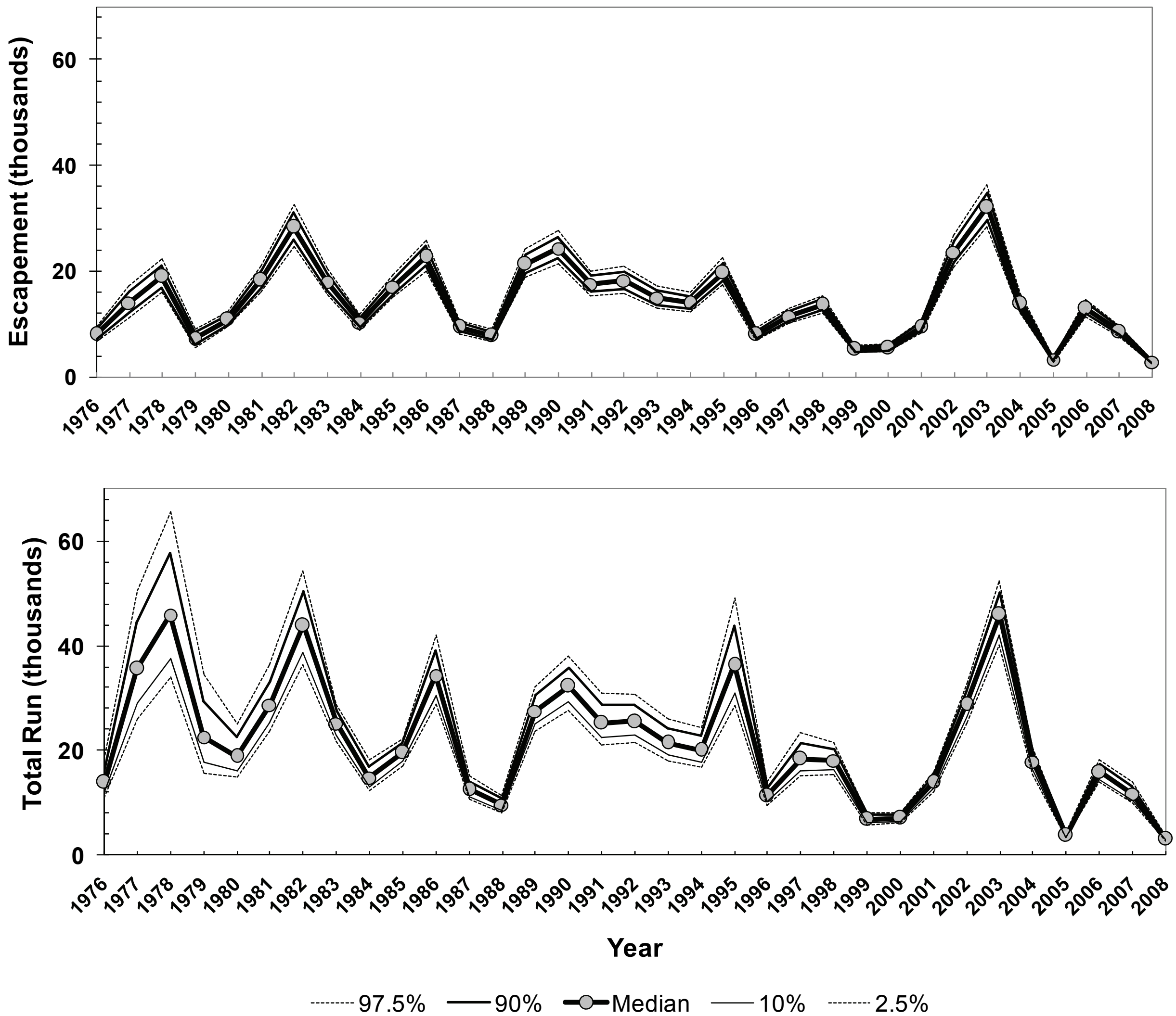


Figure 11.–Median, 97.5%, 90%, 10% and 2.5% confidence intervals for Klukshu River sockeye salmon total runs (lower panel) and escapement (upper panel) over the period 1976 to 2008 based on the Bayesian Klukshu stock-recruit model.

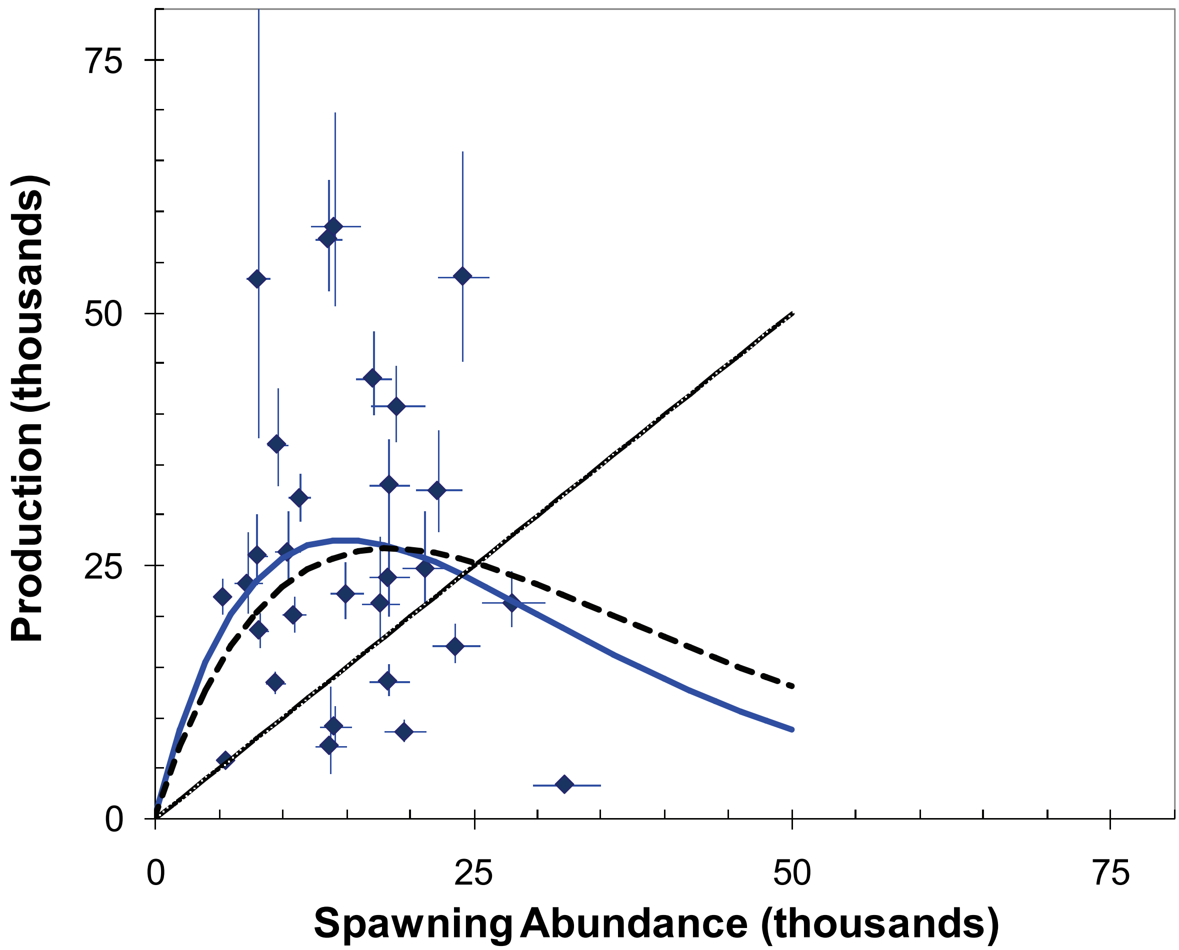


Figure 12.–Scatter plot of estimated production $\hat{P}_{by}$ plotted against estimated spawning abundance $\hat{S}_{by}$ of sockeye salmon of all ages (age 4–6) in the Klukshu River stock for brood years 1976–2008. Posterior means are plotted as closed symbols, 10th and 90th posterior percentiles are bracketed by error bars. Ricker relationships are Bayesian posterior median (blue solid line) and autoregressive Ricker (dashed black line) fit using MLE to production estimated from the traditional MLE combined expansion model run reconstruction.

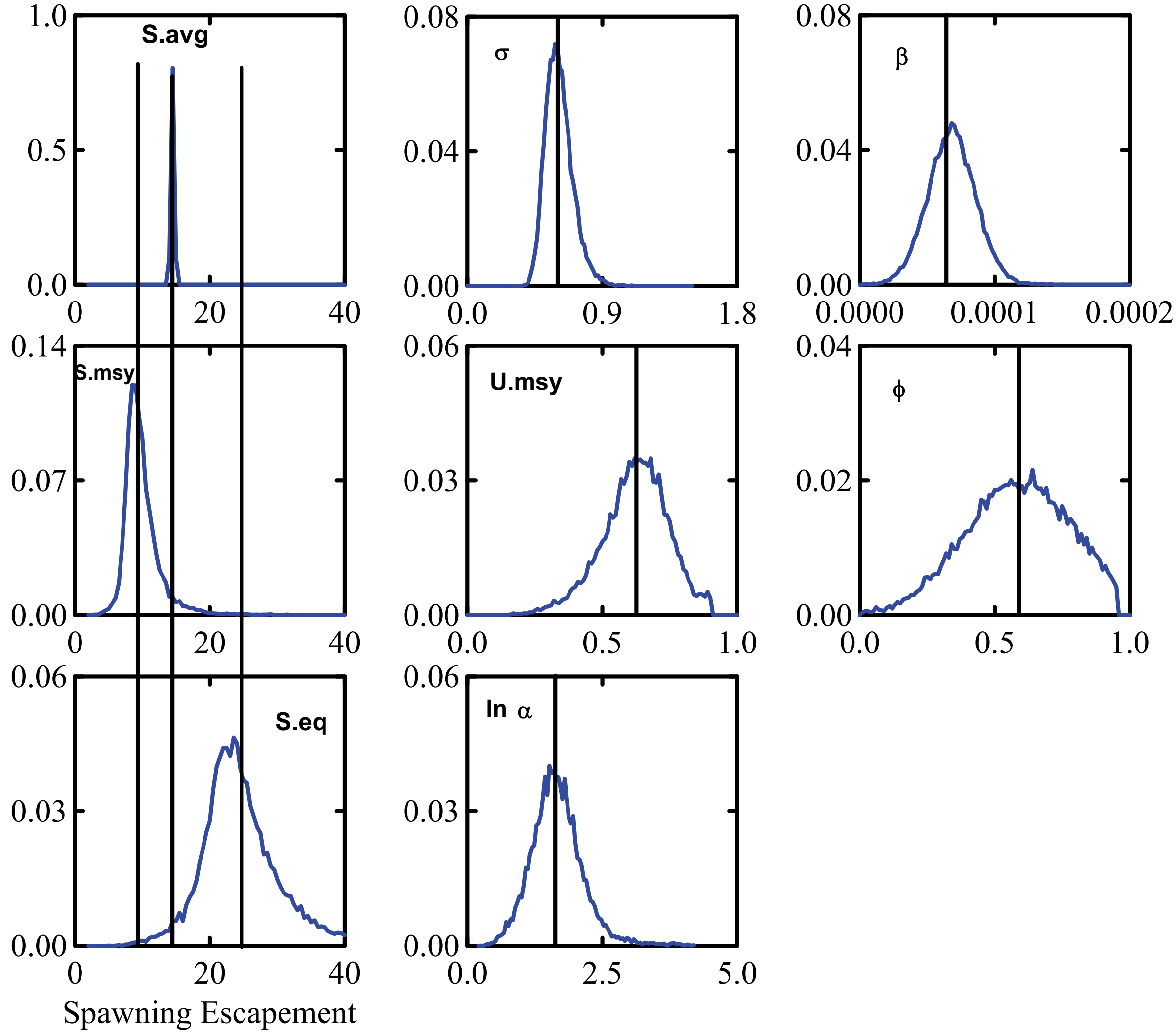


Figure 13.–Posterior probability distributions for parameters and some variables in the stock-recruitment relationship for the Klukshu River stock. Solid vertical lines correspond to expected (mean) values in each probability distribution as specified. The line through *S.avg* is the average of the estimated spawning abundance $\hat{S}cy$ over the data. Notation is defined in the text.

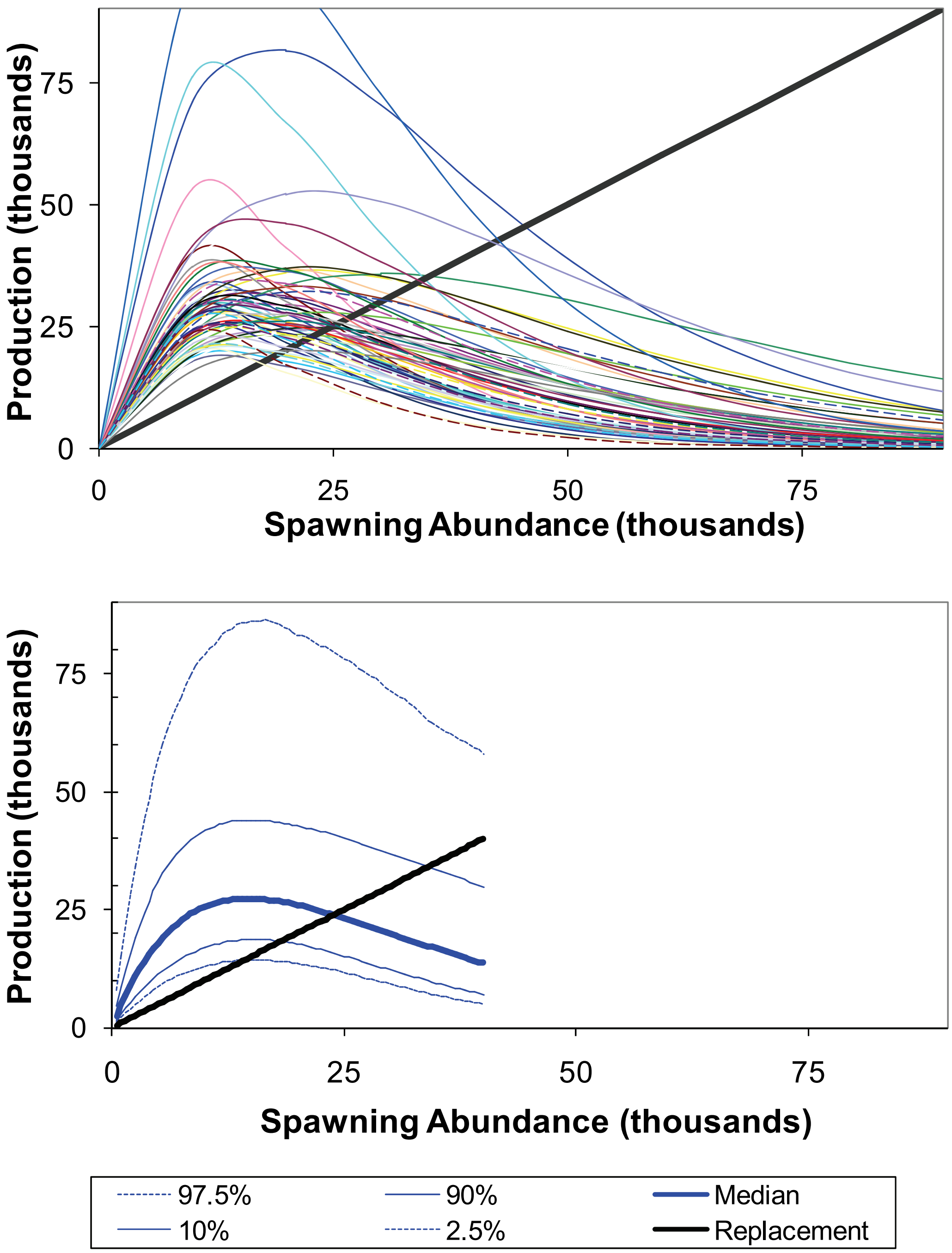


Figure 14.–Estimated production $\hat{P}_{by}$ against estimated spawning abundance $\hat{S}_{by}$ of sockeye salmon of all ages (age 4–6) in the Klukshu River stock for brood years 1976–2008. Upper panel: Ricker relationships represented by ~50 paired values of ln(α) and β sampled from the posterior probability distribution of stock-recruitment statistics. Curves can be interpreted as a sampling of Ricker relationships that could have generated the observed data. Lower panel: percentile envelope of the posterior distribution of the predicted production from the Ricker stock-recruit model.

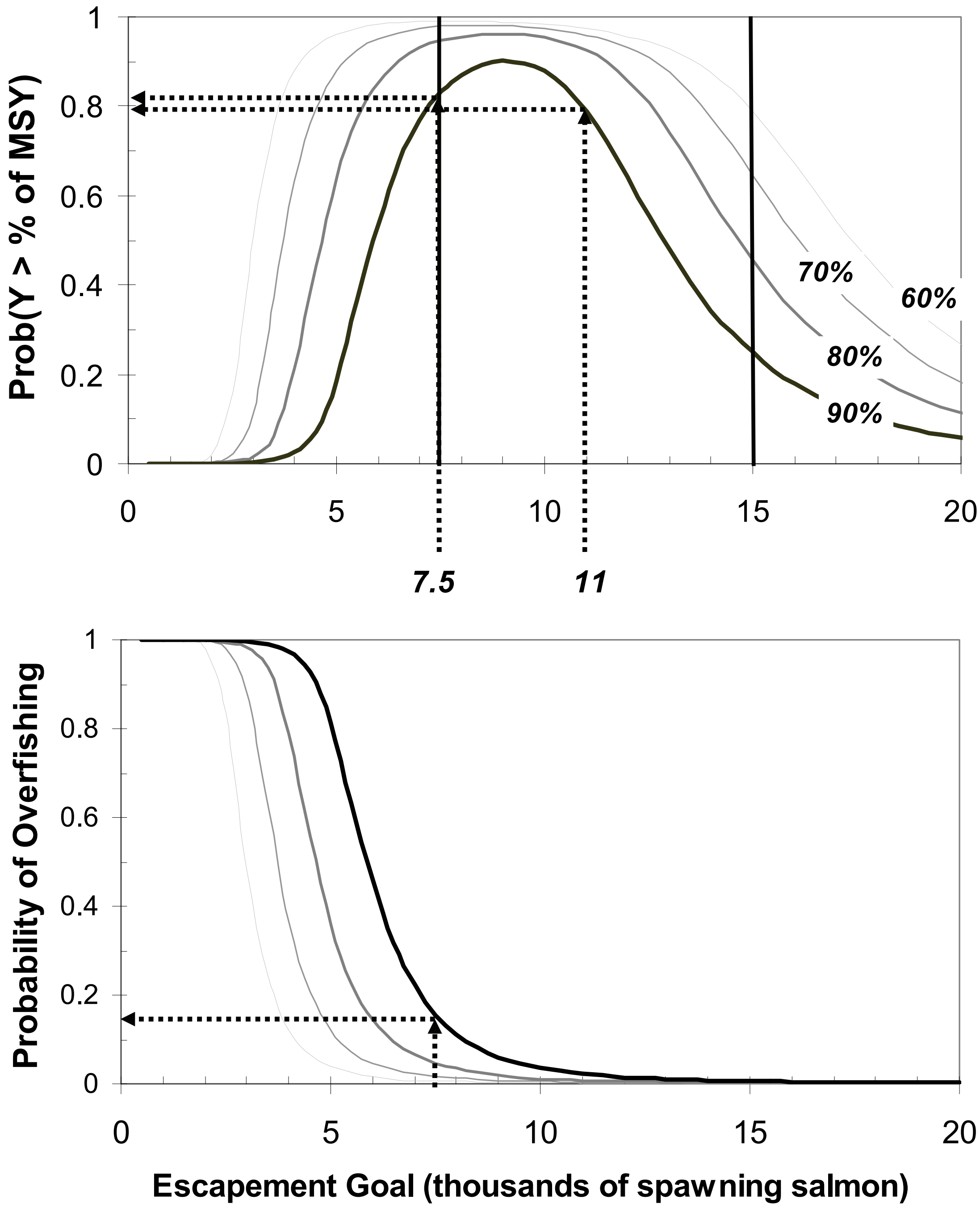


Figure 15.–Upper Panel: optimum yield (OY) profiles defined as probability of at least Y percent of maximum sustained yield (MSY) at potential escapement goals for the Klukshu River stock. Shown are profiles for 60%, 70%, 80% and 90% of MSY. Dashed vertical lines on the 90% OY profile connect the range of escapements (7.5 to 11 thousand) that provide 90% percent of MSY with probability 0.87. Solid vertical lines show escapement goal (7,500 to 15,000) proposed by Clark and Etherton (2000). Lower panel: overfishing (OF) profiles defined as the probability of having less than Y percent of optimum yield through recruitment overfishing at that escapement level. Shown are profiles corresponding to 60%, 70%, 80%, and 90% of MSY.

APPENDIX A: STATISTICS

Appendix A1.–Number of sockeye salmon by age in samples from the U.S. Commercial fishery in Dry Bay, 1982–2008. Samples missing for 1976–1981.

	Age Composition of Marine Fishery Sockeye Harvests				Sample	Sample
Year	Age 3	Age 4	Age 5	Age 6	Size	Source
1976	ND	ND	ND	ND	ND	ND
1977	ND	ND	ND	ND	ND	ND
1978	ND	ND	ND	ND	ND	ND
1979	ND	ND	ND	ND	ND	ND
1980	ND	ND	ND	ND	ND	ND
1981	ND	ND	ND	ND	ND	ND
1982	11	277	1,155	109	1,552	Marine Fishery
1983	25	229	1,741	12	2,007	Marine Fishery
1984	9	211	1,634	38	1,892	Marine Fishery
1985	23	475	960	63	1,521	Marine Fishery
1986	22	372	1,123	130	1,647	Marine Fishery
1987	8	295	1,293	57	1,653	Marine Fishery
1988	13	236	1,052	37	1,338	Marine Fishery
1989	10	140	557	37	744	Marine Fishery
1990	7	190	378	39	614	Marine Fishery
1991	1	101	342	39	483	Marine Fishery
1992	4	80	413	24	521	Marine Fishery
1993	0	80	355	60	495	Marine Fishery
1994	1	97	334	23	455	Marine Fishery
1995	3	79	522	18	622	Marine Fishery
1996	2	52	441	20	515	Marine Fishery
1997	4	100	420	16	540	Marine Fishery
1998	2	101	397	9	509	Marine Fishery
1999	2	122	375	27	526	Marine Fishery
2000	1	59	365	35	460	Marine Fishery
2001	0	48	383	33	464	Marine Fishery
2002	3	135	368	9	515	Marine Fishery
2003	0	28	447	11	486	Marine Fishery
2004	1	74	413	14	502	Marine Fishery
2005	2	67	452	29	550	Marine Fishery
2006	4	155	383	27	569	Marine Fishery
2007	0	65	578	27	670	Marine Fishery
2008	2	237	266	19	524	Marine Fishery

Appendix A2.–Number of sockeye salmon by age in samples from live fish taken at the weir in the Klukshu River, 1982–2008. Samples from Canadian in-river food fishery (IFF) used for 1976–1981. Sample missing for 1999.

	Age Composition of Canadian Sockeye Harvests and Escapement:					
Year	Age 3	Age 4	Age 5	Age 6	Sample Size	Sample Source
1976	22	384	40	0	446	IFF
1977	2	93	80	4	178	IFF
1978	0	18	69	3	90	IFF
1979	0	38	120	16	174	IFF
1980	0	19	53	0	72	IFF
1981	2	100	130	0	233	IFF
1982	0	28	136	2	166	IFF
1983	0	22	423	0	445	Weir
1984	0	3	148	3	154	Weir
1985	0	29	171	4	204	Weir
1986	0	95	428	5	528	Weir
1987	0	81	322	4	407	Weir
1988	0	78	373	34	485	Weir
1989	0	210	489	0	699	Weir
1990	0	41	647	0	688	Weir
1991	0	84	405	5	494	Weir
1992	0	56	637	7	700	Weir
1993	0	128	610	15	753	Weir
1994	0	151	276	4	431	Weir
1995	0	27	650	0	677	Weir
1996	7	46	290	11	354	Weir
1997	0	40	900	49	989	Weir
1998	0	5	136	0	141	Weir
1999	ND	ND	ND	ND	ND	ND
2000	0	35	116	5	156	Weir
2001	0	41	841	7	889	Weir
2002	0	38	954	10	1,002	Weir
2003	0	14	550	7	571	Weir
2004	0	16	555	5	576	Weir
2005	0	37	568	12	617	Weir
2006	0	143	432	9	584	Weir
2007	0	10	748	8	766	Weir
2008	0	40	206	2	248	Weir

Appendix A3.–Mean and standard deviation for posterior distributions for annual harvests of sockeye salmon by age in U.S. fisheries on the Alsek stock, 1976–2008.

		$H_{cy,a}$			$SD(H_{cy,a})$		
cy	H_{cy}	Age 4	Age 5	Age 6	Age 4	Age 5	Age 6
1976	19,850	3,383	14,780	1,686	3,359	3,931	2,490
1977	41,030	5,372	35,120	535	5,138	5,319	610
1978	50,730	4,260	45,120	1,343	3,921	4,463	1,599
1979	41,480	4,448	34,330	2,700	4,059	5,146	2,912
1980	25,610	3,712	20,670	1,228	3,313	4,219	2,588
1981	23,760	3,744	18,800	1,216	3,425	4,044	2,396
1982	27,560	4,958	20,680	1,923	308	687	187
1983	18,370	2,125	16,130	110	147	504	32
1984	14,440	1,618	12,530	296	116	392	48
1985	5,919	1,874	3,798	248	90	136	31
1986	25,030	5,726	17,320	1,983	311	593	178
1987	11,590	2,080	9,115	392	126	298	53
1988	6,458	1,145	5,129	185	75	168	30
1989	13,710	2,613	10,400	696	212	382	112
1990	17,220	5,383	10,720	1,115	361	465	176
1991	17,700	3,722	12,590	1,388	347	527	221
1992	19,330	3,015	15,460	853	319	576	174
1993	20,110	3,269	14,460	2,379	345	591	297
1994	19,690	4,200	14,540	948	392	595	201
1995	33,390	4,298	28,090	995	459	978	231
1996	15,250	1,569	13,110	575	208	455	122
1997	26,150	4,870	20,480	799	463	770	192
1998	15,180	3,029	11,880	272	281	454	89
1999	11,590	2,683	8,308	594	227	333	112
2000	9,676	1,256	7,713	708	155	295	118
2001	13,960	1,486	11,520	957	205	426	165
2002	17,190	4,528	12,340	319	362	508	101
2003	39,570	2,312	36,380	882	427	1,193	254
2004	18,150	2,678	14,960	513	297	542	133
2005	7,640	940	6,309	391	109	227	71
2006	10,110	2,781	6,875	458	206	284	90
2007	19,800	1,939	17,070	793	235	582	150
2008	2,941	1,332	1,505	104	75	78	23

Appendix A4.–Mean and standard deviation for posterior distributions for annual total run of sockeye salmon by age for the Alsek stock, 1976–2008.

cy	N_{cy}	$N_{cy,a}$			$SD(N_{cy,a})$		
		Age 4	Age 5	Age 6	Age 4	Age 5	Age 6
1976	52,700	32,980	18,020	1,168	8,108	3,965	1,701
1977	94,070	32,330	60,230	1,519	8,144	7,418	866
1978	108,000	14,810	89,940	3,244	4,992	11,430	2,096
1979	83,340	13,340	63,520	6,476	4,775	8,728	3,290
1980	67,680	13,890	52,250	1,206	4,704	9,840	1,702
1981	72,750	24,250	47,160	972	5,980	7,268	1,515
1982	88,650	14,890	70,640	3,115	2,538	9,927	715
1983	73,830	5,062	68,530	235	655	4,602	123
1984	61,250	3,335	56,690	1,219	863	10,020	522
1985	57,160	9,334	46,440	1,387	1,797	7,812	482
1986	75,620	14,700	58,350	2,573	2,042	8,583	325
1987	59,950	11,460	47,400	1,093	1,960	7,179	323
1988	52,840	8,650	40,910	3,290	1,649	7,083	794
1989	63,560	17,430	45,410	581	3,063	7,020	190
1990	74,410	8,831	64,450	897	873	9,502	281
1991	68,390	12,260	54,080	2,043	1,963	8,593	369
1992	77,750	7,726	68,460	1,564	1,098	9,852	327
1993	75,150	12,540	59,040	3,564	1,877	8,195	471
1994	72,130	22,170	48,340	1,617	3,733	6,806	367
1995	79,950	6,213	72,720	791	752	11,280	279
1996	64,080	8,031	53,810	2,242	1,575	8,332	576
1997	71,830	6,794	62,000	3,030	669	8,328	574
1998	66,200	5,350	60,330	512	1,012	8,810	291
1999	56,690	9,223	44,790	2,671	3,827	8,280	1,836
2000	48,710	9,614	36,830	2,268	1,469	3,188	596
2001	47,460	3,087	43,110	1,268	335	2,362	197
2002	96,140	7,722	87,320	1,106	697	7,744	273
2003	139,400	5,186	132,000	2,197	839	7,648	537
2004	90,260	4,959	84,100	1,202	665	8,434	324
2005	66,080	4,592	59,840	1,652	718	6,573	367
2006	60,330	14,890	44,040	1,391	1,703	4,550	313
2007	73,670	2,776	69,510	1,387	381	10,800	278
2008	42,170	7,701	33,870	600	1,778	8,087	260

Appendix A5.–Mean and standard deviation for posterior distributions for annual in-river run of sockeye salmon by age for the Alsek stock, 1976–2008.

cy	IR_{cy}	$IR_{cy,a}$			$SD(IR_{cy,a})$		
		Age 4	Age 5	Age 6	Age 4	Age 5	Age 6
1976	32,850	29,590	3,240	20	6,936	917	46
1977	53,050	26,960	25,110	984	5,841	5,722	505
1978	57,260	10,550	44,810	1,901	3,001	10,420	1,057
1979	41,860	8,892	29,190	3,777	2,388	7,091	1,252
1980	42,070	10,180	31,580	308	3,187	8,785	417
1981	48,990	20,500	28,360	123	4,527	6,333	180
1982	61,090	9,936	49,960	1,193	2,520	9,908	696
1983	55,460	2,937	52,390	128	640	4,577	113
1984	46,800	1,717	44,160	923	859	10,010	518
1985	51,240	7,461	42,640	1,139	1,794	7,811	478
1986	50,590	8,971	41,030	590	2,019	8,570	273
1987	48,360	9,378	38,290	701	1,956	7,176	319
1988	46,390	7,505	35,780	3,105	1,646	7,084	794
1989	49,850	14,820	35,010	23	3,054	7,014	57
1990	57,200	3,447	53,730	19	796	9,490	57
1991	50,690	8,538	41,490	655	1,930	8,590	300
1992	58,420	4,711	53,000	711	1,053	9,845	277
1993	55,030	9,274	44,580	1,185	1,846	8,182	367
1994	52,440	17,970	33,800	670	3,712	6,795	319
1995	46,560	1,914	44,630	15	598	11,260	47
1996	48,830	6,462	40,700	1,667	1,562	8,321	550
1997	45,680	1,924	41,520	2,231	492	8,308	538
1998	51,020	2,320	48,450	251	975	8,799	260
1999	45,110	6,547	36,480	2,083	3,808	8,277	1,816
2000	39,030	8,358	29,120	1,561	1,461	3,177	580
2001	33,500	1,600	31,590	311	268	2,325	110
2002	78,960	3,194	74,980	786	600	7,731	252
2003	99,780	2,874	95,590	1,316	722	7,541	448
2004	72,100	2,280	69,140	689	599	8,413	284
2005	58,440	3,652	53,530	1,261	707	6,569	355
2006	50,210	12,110	37,170	933	1,691	4,545	300
2007	53,870	838	52,440	594	305	10,780	229
2008	39,230	6,368	32,370	495	1,777	8,087	256

Appendix A6.–Descriptive statistics for posterior probability distributions for in-river run (*IRcy*) and spawning escapement (*Scy*) for sockeye salmon to the Alsek River.

	In-river run size (IR_{cy})					Spawning escapement (S_{cy})				
				Percentiles					Percentiles	
cy	Mean	SD	Median	2.50%	97.50%	Mean	SD	Median	2.50%	97.50%
1976	33,140	7,740	32,180	20,730	50,760	28,540	7,740	27,580	16,130	46,160
1977	53,290	10,990	52,190	35,170	78,010	41,440	10,990	40,340	23,320	66,160
1978	57,320	12,750	55,960	36,460	85,910	48,820	12,750	47,460	27,960	77,410
1979	41,970	9,706	40,750	26,430	64,160	34,220	9,706	33,000	18,680	56,410
1980	42,040	10,870	40,570	25,110	67,190	40,540	10,870	39,070	23,610	65,690
1981	49,290	10,430	48,270	31,760	72,560	46,480	10,430	45,460	28,950	69,750
1982	61,320	12,010	60,280	40,830	87,760	55,560	12,010	54,530	35,080	82,010
1983	55,390	4,835	55,150	46,600	65,480	52,110	4,835	51,870	43,310	62,200
1984	46,860	10,410	45,730	29,870	70,230	43,970	10,410	42,840	26,980	67,340
1985	51,210	9,081	50,450	35,470	70,960	49,750	9,081	48,990	34,010	69,500
1986	50,410	10,460	49,420	33,020	73,550	48,190	10,460	47,200	30,800	71,320
1987	47,980	8,937	47,320	32,490	67,370	46,440	8,937	45,780	30,950	65,830
1988	46,100	9,127	45,300	30,450	65,830	44,170	9,127	43,370	28,520	63,900
1989	50,090	10,250	49,100	32,950	72,580	47,870	10,250	46,870	30,720	70,360
1990	57,520	10,260	56,600	40,100	80,320	54,820	10,260	53,900	37,390	77,610
1991	50,910	10,610	49,870	33,140	74,360	48,500	10,610	47,450	30,720	71,940
1992	58,440	10,790	57,580	39,890	81,790	55,270	10,790	54,410	36,720	78,620
1993	55,000	10,050	54,210	37,630	76,790	52,310	10,050	51,520	34,940	74,100
1994	52,240	10,350	51,340	34,700	75,160	50,230	10,350	49,330	32,700	73,160
1995	46,470	11,650	44,970	28,000	73,290	44,040	11,650	42,550	25,580	70,860
1996	48,450	10,030	47,480	31,760	70,740	47,080	10,030	46,120	30,400	69,380
1997	45,740	9,182	44,890	30,110	65,890	45,220	9,182	44,370	29,590	65,370
1998	51,090	9,354	50,250	35,110	71,590	50,500	9,354	49,670	34,530	71,010
1999	45,210	8,456	44,520	30,710	63,640	44,660	8,456	43,970	30,160	63,090
2000	39,020	3,878	38,820	31,980	47,190	38,270	3,878	38,070	31,240	46,440
2001	33,480	2,453	33,400	28,940	38,530	32,300	2,453	32,230	27,770	37,350
2002	79,050	8,154	78,640	64,320	96,170	76,800	8,154	76,390	62,060	93,910
2003	99,950	7,855	99,620	85,190	116,000	97,150	7,855	96,820	82,390	113,200
2004	72,200	8,742	71,730	56,450	90,530	70,080	8,742	69,600	54,330	88,410
2005	58,390	7,149	57,960	45,480	73,720	57,800	7,149	57,370	44,890	73,120
2006	50,200	5,995	49,890	39,460	62,790	48,870	5,995	48,560	38,130	61,460
2007	53,860	11,000	52,750	35,500	78,470	53,850	11,000	52,740	35,490	78,460
2008	39,330	9,813	38,080	23,370	61,790	39,330	9,813	38,080	23,370	61,790

APPENDIX B: MODEL STATEMENTS

Appendix B1.–Program written in WinBUGS v.1.4.2, describing the run reconstruction of the Alsek River stock of sockeye salmon across calendar years 1976–2008. Variables, parameters, and observations (nodes) follow the nomenclature in the text. Italicized lines involve stochastic elements to represent either prior probability distributions or probability distributions involved with sampling error in estimates. Text on a line after '#' is a comment. Lines are numbered for convenience. Lines 62–102 represent data, NA represent missing data, and lines 103 to the end are initial values for two chains.

```
1   Alsek River Sockeye Run Reconstruct
2   Two Stage Analysis  --  Stage 1
3
4   model {
5           #InRiver Alsek Run (Total Run less marine and US sub/PU catch)
6           mean.log.IR ~ dnorm(0,1.0E-4)I(0,) #non-informative prior
7           tau.IR ~ dgamma(0.001,0.001)  #non-informative prior
8           sigma.log.IR <- 1/sqrt(tau.IR)
9
10
11     #Hierarchical marine harvest catchability
12          Q ~ dbeta(.1,.1)  #non-informative prior
13          B1.scale ~ dunif(0,1)  #non-informative prior
14     B1.sum <- 1/B1.scale/B1.scale
15          B1[1] <- Q*B1.sum
16          B1[2] <- B1.sum - B1[1]
17
18          #Hierarchical Klukshu fraction
19          P ~ dbeta(.1,.1)  #non-informative prior
20          B2.scale ~ dunif(0,1)  #non-informative prior
21     B2.sum <- 1/B2.scale/B2.scale
22          B2[1] <- P*B2.sum
23          B2[2] <- B2.sum - B2[1]
24          Pi <- 1 / P                                 # expansion factor
25
26          for (y in 1:33)  {
27      #InRiver run lognormally distributed, estimated with lognormal errors
28          log.IR[y] ~ dnorm(mean.log.IR,tau.IR)  #likelihood distribution
29      tau.IR.hat[y] <- 1/IR.cv[y]/IR.cv[y]
30           IR[y] <- exp(log.IR[y])
31          log.IR.hat[y] ~ dnorm(log.IR[y],tau.IR.hat[y])  #likelihood distribution
32
33      #Gillnet marine harvest as function of total run size and effort
34            q[y] ~ dbeta(B1[1],B1[2])   #likelihood distribution
35      F[y] <- q[y] * boatdays[y]
36          UH[y] <- 1 - exp(-F[y])
37           H[y] <- max(((UH[y]/(1-UH[y])) * (IR[y])),1)
38            log.H[y] <- log(H[y])
39            tau.log.H[y] <- 1/H.cv/H.cv
40            log.H.hat[y] ~ dnorm(log.H[y], tau.log.H[y])  #likelihood distribution
41
```

-continued-

```
              #Klukshu escapement as fraction of InRiver Run
              p[y] ~ dbeta(B2[1],B2[2])   #likelihood distribution
            N[y] <- max(IR[y] + H[y] , 1)
            k[y]<- N[y] * p[y]
            log.k[y] <- log(k[y])
            tau.log.k[y] <-1/k.cv/k.cv
            log.k.hat[y] ~dnorm(log.k[y],tau.log.k[y])  #likelihood distribution
             S[y] <- IR[y] - C[y]
            #Klukshu run components
            #marine and lower river harvest rate
            LRU[y] <- max(((H[y])/N[y]),0)
            #marine and lower river Klukshu catch
            kLRC[y] <- max((LRU[y]/(1-LRU[y]))* k[y],1)
            #Klukshu escapement
            KS[y] <- max(k[y]-C[y],1)
            KlukRun[y]<-KS[y]+kLRC[y]

              }
  }
data:
list(
H.cv = 0.03,  k.cv = 0.06,
boatdays = c(
550, 882, 929,1110, 773, 588, 552, 487, 429, 277,
517, 388, 324, 378, 374, 530, 372, 372, 403, 879,
419, 611, 358, 319, 307, 234, 270, 271, 280, 171,
248, 311, 171),
log.H.hat = c(
 9.8930, 10.6187, 10.8332, 10.6331, 10.1489,
10.0729, 10.2226,  9.8156,  9.5761,  8.6805,
10.1279,  9.3558,  8.7694,  9.5211,  9.7502,
 9.7783,  9.8697,  9.9104,  9.8877, 10.4127,
 9.6323, 10.1717,  9.6267,  9.3582,  9.1766,
 9.5516,  9.7498, 10.5935,  9.8065,  8.9405,
 9.2217, 9.8966, 7.9834
),
log.IR.hat = c(
NA,NA,NA,NA,NA,NA,NA,10.9271,
NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,NA,NA,NA,NA,NA,
10.5225,10.3085,11.4422,11.5200,11.3094,11.0768,10.7980,
NA,NA),

IR.cv = c(
.3, .3, .3, .3, .3, .3, .3,
0.094,
.3, .3, .3, .3, .3, .3, .3, .3,
.3, .3, .3, .3, .3, .3, .3, .3,
```

-continued-

```
0.114, 0.077, 0.124,0.084,0.158,0.16,0.16,
.3, .3),
log.k.hat = c(
 9.4368, 10.1636, 10.2226,  9.6025, 9.4133,  9.9644, 10.4532,
 9.9664,  9.4816,  9.8373, 10.1329, 9.2953,  9.1761, 10.0777,
10.2151,  9.9064,  9.9732,  9.7763, 9.6739, 10.0098,  9.1326,
 9.3778,  9.5585,  8.6403,  8.7270, 9.2597, 10.1598,  10.4607,
 9.6705,  8.2324,  9.5622,  9.0465, 7.9161),
C = c(
4600,11850, 8500, 7750, 1500, 2808, 5755, 3282, 2889, 1461,
2221, 1541, 1926, 2225, 2706, 2414, 3174, 2690, 2006, 2427,
1361,  520,  585,  554,  745, 1177, 2255, 2795, 2122,  594,
1327,   10,    0 )
)
initial values:
INITIAL Conditions Chain 1

list(B1.scale = 0.25, B2.scale = 0.5, Q=0.002, P = 0.2,
mean.log.IR = 11.,tau.IR = 3,

log.IR = c(
11.7976,12.3380,12.4100,12.4069,12.0679,11.9548,12.0111,
NA,
11.7929, 11.2600, 11.8972, 11.4705, 11.2780, 11.5974,
11.6372, 11.8421, 11.6071, 11.5777, 11.6128, 12.2883,
11.5198, 11.8868, 11.4788, 11.2085,
NA,NA,NA,NA,NA,NA,NA,
11.3217, 10.5293),

q = c(
0.00075,0.00067,0.00071,0.00071,0.00072,0.00070,0.00066,
0.00067,0.00071,0.00053,0.00073,0.00068,0.00058,0.00064,
0.00070,0.00065,0.00078,0.00083,0.00080,0.00064,0.00076,
0.00079,0.00078,0.00078,0.00075,0.00121,0.00068,0.00108,
0.00076,0.00069,0.00074,0.00091,0.000580),

p = c(
0.33210,0.50880,0.51440,0.43400,0.36520,0.45300,0.54410,
0.44560,0.33120,0.48090,0.46480,0.29040,0.31140,0.46720,
0.47250,0.46210,0.38370,0.32900,0.31760,0.50120,0.23590,
0.29650,0.31240,0.14530,0.17130,0.28310,0.30740,0.33080,
0.21200,0.06339,0.29670,0.14960,0.10230)
)

INITIAL Conditions Chain 2
list(B1.scale = 0.15, B2.scale = 0.5, Q=0.0005, P = 0.3,
mean.log.IR = 11.,tau.IR = 3,
log.IR = c(
```

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```
11.7976,12.3380,12.4100,12.4069,12.0679,11.9548,12.0111,
NA,
11.7929,11.2600,11.8972,11.4705,11.2780,11.5974,11.6372,
11.8421,11.6071,11.5777,11.6128,12.2883,11.5198,11.8868,
11.4788,11.2085,
NA,NA,NA,NA,NA,NA,NA,
11.3217,10.5293),

q = c(
0.00075,0.00067,0.00071,0.00071,0.00072,0.00070,0.00066,
0.00067,0.00071,0.00053,0.00073,0.00068,0.00058,0.00064,
0.00070,0.00065,0.00078,0.00083,0.00080,0.00064,0.00076,
0.00079,0.00078,0.00078,0.00075,0.00121,0.00068,0.00108,
0.00076,0.00069,0.00074,0.00091,0.000580),

p = c(
0.33210,0.50880,0.51440,0.43400,0.36520,0.45300,0.54410,
0.44560,0.33120,0.48090,0.46480,0.29040,0.31140,0.46720,
0.47250,0.46210,0.38370,0.32900,0.31760,0.50120,0.23590,
0.29650,0.31240,0.14530,0.17130,0.28310,0.30740,0.33080,
0.21200,0.06339,0.29670,0.14960,0.10230)
)
```

Appendix B2.–Program written in WinBUGS v.1.4.2 describing the stock-recruit analysis of the Alsek River stock of sockeye salmon across calendar years 1976–2008. Variables, parameters, and observations (nodes) follow the nomenclature in the text. Italicized lines involve stochastic elements to represent either prior probability distributions or probability distributions involved with sampling error in estimates. Text on a line after '#' is a comment. Lines are numbered for convenience. Lines 203–312 represent data, NA represent missing data, and lines 318 to the end are initial values for two chains.

```
   Alsek Sockeye Stock Recruit Analysis
   Two Stage Analysis  --  Stage 2
1  model {
2
3  #stock recruit analysis,   with stochastic age composition
4   lnalpha ~ dnorm(1.58,.01)I(0,4)        #Non-informative Prior
5    beta ~ dnorm(0,0.001)I(0,)             #Non-informative Prior
6    phi ~dunif(-.99,.99)                                  #Non-Informative Prior
7    tau ~ dgamma(0.01,0.01)            #Non-informative Prior
8    ln.Pr.mean ~dnorm(0,0.0001)I(0,)    #Non-informative Prior
9    ln.S.0.mean ~ dnorm(0,0.0001)I(4,14)    #Non-informative Prior
10   tau.Pr ~ dgamma(0.01,0.01)              #Non-informative Prior
11   tau.S ~  dgamma(0.01,0.01)              #Non-informative Prior
12   ln.S.0 ~ dnorm(ln.S.0.mean,tau.S)I(4,14)    #Non-informative Prior
13
14   #generate initial escapements, BY 70 - 75
15   for ( y in 1:6)  {
16     d.ln.Pr[y] ~ dnorm(ln.Pr.mean, tau.S)I(1,)   #Non-informative Prior
17     d.Pr[y] <- exp(d.ln.Pr[y])
18      }
19
20   S.0 <- exp(ln.S.0)
21
22 #---estimated return,  Autoregressive Ricker, linear regression implementation - Noakes
23
24   ln.Pr.pred[1] <- log(S[1])+(1-phi)*lnalpha+phi*(d.ln.Pr[6]-ln.S.0)-beta*S[1]+phi*beta*S.0
25
26   ln.Pr[1] ~ dnorm(ln.Pr.pred[1],tau)I(0,)       #Non-informative Prior
27   Pr[1] <- exp(ln.Pr[1])
28
29   for (y in 2:33)  {
30
31            ln.Pr.pred[y] <- log(S[y])+(1-phi)*lnalpha+phi*log(Pr[y-1]/S[y-1]) -
32                        beta*S[y]+phi*beta*S[y-1]
33    ln.Pr[y] ~ dnorm(ln.Pr.pred[y],tau)I(0,) #Non-informative Prior
34            Pr[y] <- exp(ln.Pr[y])
35  }
36
37  #Generate maturation/survival rates BYs 70-02
38
39  d.t1~ dbeta(1,1)        #Non-informative Prior
```

-continued-

```
d.t2 ~ dbeta(1,1)        #Non-informative Prior


d.t[1] <- d.t1
d.t[2] <- d.t2 *(1-d.t[1])
d.t[3] <- 1-d.t[1]-d.t[2]


d.scale ~ dunif(0,1) #Non-informative Prior
d.sum <- 1/d.scale/d.scale

for ( a in 1:3) {matur[a] <- d.sum*d.t[a] }

for (y in 1:36) {

  for (a in 1:3) { d.theta[y,a] ~ dgamma(matur[a],1)  }  #Non-informative prior
  sum.d.theta[y]<-sum(d.theta[y,])
  for (a in 1:3) {theta[y,a] <- d.theta[y,a]/sum.d.theta[y]}
  }

#----------------Aportion to runs CYs 76 - 08
# CY 76 - 79, BY 70 - 75
  for (y in 1:4) {
    for (a in 1:3) {Run.a[y,a]<- d.Pr[y+3-a]*theta[y+3-a,a] }
  }

# CY 80  BY 74-76

  Run.a[5,1]<- Pr[1] * theta[7,1]
  Run.a[5,2]<- d.Pr[6] * theta[6,2]
  Run.a[5,3]<- d.Pr[5] * theta[5,3]

#CY 81 BY 75 - 77

  Run.a[6,1]<- Pr[2] * theta[8,1]
  Run.a[6,2]<- Pr[1] * theta[7,2]
  Run.a[6,3]<- d.Pr[6] * theta[6,3]

#CY 82 - 02

for (y in 7:33) {

  for (a in 1:3) {Run.a[y,a] <- Pr[y-3-a]* theta[y+3-a,a]  }
  }

#--------------Apply relative age composition

  for (y in 1:33) {
```

-continued-

```
        for (a in 1:3)  {

                        U.H.a[y,a] ~dbeta(1,1)  #Non-informative prior

                        d.H.a[y,a] <- Run.a[y,a] * U.H.a[y,a]
                        }

        d.H.[y]<- sum(d.H.a[y,1:3])

        for(a in 1:3) {
                        H.a[y,a]<- (d.H.a[y,a]/d.H.[y]) *(H[y])

                        hq[y,a] <- H.a[y,a]/(H[y])   #-----lower river harvest age composition

                        IR.a[y,a] <- max(Run.a[y,a] - H.a[y,a],1)

                        }
        IR[y] <- sum(IR.a[y,1:3])

        for (a in 1:3) {irrq[y,a] <- IR.a[y,a]/IR[y]   }      #---in-river run age composition

#----measurement in relative age composition

        n.h[y] <- sum(x.h[y,1:3])
        n.irr[y]<-sum(x.irr[y,1:3])

        x.h[y,1:3] ~ dmulti(hq[y, ],n.h[y])       #-----stochastic errors from sampling
        x.irr[y,1:3] ~ dmulti(irrq[y, ], n.irr[y])     #-----stochastic errors from sampling

 # data: IR,H,k, input as stochastic (mean, cv);C,  as fixed
 #InRiver run lognormally distributed, estimated with lognormal errors
        var.IR[y] <-log(IR.cv[y] *IR.cv[y]+1)
         mu.IR[y] <- max(log(IR[y] - var.IR[y]/2),1)
         tau.IR[y] <- 1/IR.cv[y] / IR.cv[y]
        IR.hat[y] ~ dlnorm(mu.IR[y], tau.IR[y]) #input  from Run Reconstruction

 #Dry Bay commercial/subsistence catch lognormally distributed,
  #estimated with lognormal errors
         log.H[y]~dnorm(0,1.0E-4)I(0,)
         H[y] <- exp(log.H[y])
    var.H[y] <-log(H.cv[y] *H.cv[y]+1)
         mu.H[y] <- max(log(H[y] - var.H[y]/2),1)
         tau.H[y] <- 1/H.cv[y] / H.cv[y]
        H.hat[y] ~ dlnorm(mu.H[y], tau.H[y]) #input  from RunReconstruction

#Klukshu in-river run lognormally distributed, estimated with lognormal errors
    log.k[y]~dnorm(0,1.0E-4)I(0,)
         k[y] <- exp(log.k[y])
```

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```
    var.k[y] <-log(k.cv[y] *k.cv[y]+1)
        mu.k[y] <- max(log(k[y] - var.k[y]/2),1)
        tau.k[y] <- 1/k.cv[y] / k.cv[y]
       k.hat[y] ~ dlnorm(mu.k[y], tau.k[y])  #input  from RunReconstruction

   S[y] <- max(IR[y] - C[y],1)
       N[y] <- max(IR[y] + H[y],1)

       #Klukshu run components

       kS[y]<-k[y]-C[y]

       #marine and lower river harvest rate
       LRU[y] <- max((H[y]/N[y]),0)
       #marine and lower river Klukshu catch

       kLRC[y] <- max((LRU[y]/(1-LRU[y]))* k[y],1)

       }

#------Reference points from Stock Recruit Analysis

S.avg <- sum(S[1:33])/33
sigma.SR <- 1/sqrt(tau)
alpha <- exp(lnalpha)
lnalpha.c <- min(lnalpha +(sigma.SR*sigma.SR/2)/(1-phi*phi),4)
S.eq <- lnalpha.c/beta
S.msy <- S.eq * (0.5 - 0.07 *lnalpha.c)
U.msy <- lnalpha.c*(0.5 - 0.07 *lnalpha.c)
Pr.msy <- S.msy*exp(lnalpha.c-beta*S.msy)
msy <- Pr.msy - S.msy

#------OY  profiles

for (i in 1:80) {

       S.star[i] <- 1000 * i
       Pr.star[i] <- S.star[i] * exp(lnalpha.c - beta * S.star[i])
       SY[i] <- Pr.star[i] - S.star[i]

       OY90[i] <- step(SY[i] - 0.9* msy)
       OY80[i] <- step(SY[i] - 0.8* msy)
       OY70[i] <- step(SY[i] - 0.7* msy)
       OY60[i] <- step(SY[i] - 0.6* msy)

       }

#------OF  profiles
```

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```
OF90[1] <- 0
OF80[1] <- 0
OF70[1] <- 0
OF60[1] <- 0


for (i in 2:80) {
        OF90[i] <- max(OY90[i], OF90[i-1])
        OF80[i] <- max(OY80[i], OF80[i-1])
        OF70[i] <- max(OY70[i], OF70[i-1])
        OF60[i] <- max(OY60[i], OF60[i-1])
        }

        }
data:
list(
IR.hat = c(
 44180,51010,52120,41990,41390,50650,62850,54730,45200,
 45460,57180,41990,36010,55210,60680,47770,58410,57530,
 52410,46710,43220,45990,50290,42300,37720,32780,85290,
101000,73790,57510,49390,57250,29130
),
IR.cv = c(
0.2537,0.2613,0.2661,0.2758,0.2696,0.2553,0.2430,0.0878,0.2544,
0.2413,0.2520,0.2417,0.2686,0.2476,0.2292,0.2474,0.2279,0.2298,
0.2284,0.2640,0.2388,0.2505,0.2311,0.2376,0.1037,0.0744,0.1103,
0.0795,0.1297,0.1332,0.1299,0.2335,0.2738
),
H.hat = c(
19800,40950,50700,41520,25590,23730,27580,18360,14430,
 5916,25060,11580, 6454,13680,17190,17690,19330,20130,
19670,33350,15250,26140,15170,11580, 9669,13930,17170,
39640,18140, 7637,10110,19800, 2940
),
H.cv = c(
0.0299,0.0298,0.0299,0.0300,0.0299,0.0300,0.0299,0.0299,0.0298,
0.0300,0.0299,0.0300,0.0299,0.0300,0.0301,0.0300,0.0298,0.0298,
0.0300,0.0300,0.0299,0.0301,0.0299,0.0299,0.0301,0.0299,0.0301,
0.0300,0.0299,0.0299,0.0299,0.0300,0.0300
),
k.hat = c(
12610,25880,27490,14900,12330,21200,34150,21240,13160,
18490,25040,10940, 9681,23580,27040,19960,21410,17660,
15950,22200, 9335,11920,14220, 5722, 6231,10540,25870,
34970,15970, 3817,14240, 8589, 2777
),
k.cv =c(
0.0597,0.0592,0.0594,0.0598,0.0593,0.0591,0.0591,0.0595,0.0595,
```

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```
0.0592,0.0593,0.0599,0.0595,0.0595,0.0594,0.0591,0.0589,0.0596,
0.0595,0.0593,0.0599,0.0600,0.0598,0.0599,0.0600,0.0592,0.0594,
0.0590,0.0595,0.0602,0.0593,0.0598,0.0598
),
C = c(
4600,11850,8500,7750,1500,2808,5755,3282,2889,
1461, 2221,1541,1926,2225,2706,2414,3174,2690,
2006, 2427,1361, 520, 585, 554, 745,1177,2255,
2795, 2122, 594,1327, 10, 0
),
x.h = structure(.Data = c(
0,      0,      0,
0,      0,      0,
0,      0,      0,
0,      0,      0,
0,      0,      0,
0,      0,      0,
277,    1155,   109,
229,    1741,   12,
211,    1634,   38,
475,    960,    63,
372,    1123,   130,
295,    1293,   57,
236,    1052,   37,
140,    557,    37,
190,    378,    39,
101,    342,    39,
80,     413,    24,
80,     355,    60,
97,     334,    23,
79,     522,    18,
52,     441,    20,
100,    420,    16,
101,    397,    9,
122,    375,    27,
59,     365,    35,
48,     383,    33,
135,    368,    9,
28,     447,    11,
74,     413,    14,
67,     452,    29,
155,    383,    27,
65,     578,    27,
237,    266,    19),.Dim=c(33,3)),

x.irr = structure(.Data = c(
384,    40,     0,
93,     80,     4,
```

-continued-

```
18,     69,     3,
38,     120,    16,
19,     53,     0,
100,    130,    0,
28,     136,    2,
22,     423,    0,
3,      148,    3,
29,     171,    4,
95,     428,    5,
81,     322,    4,
78,     373,    34,
210,    489,    0,
41,     647,    0,
84,     405,    5,
56,     637,    7,
128,    610,    15,
151,    276,    4,
27,     650,    0,
46,     290,    11,
40,     900,    49,
5,      136,    0,
0,      0,      0,
35,     116,    5,
41,     841,    7,
38,     954,    10,
14,     550,    7,
16,     555,    5,
37,     568,    12,
143,    432,    9,
10,     748,    8,
40,     206,    2),.Dim=c(33,3)),
)

initial values:
Initial values chain one

list(lnalpha = 1.0, beta = 0.000012,  ln.Pr.mean = 11.2, ln.S.0 = 10.7,
tau.Pr = 5, tau.S = 5, d.scale = 01, d.t1 = .2, d.t2 = .8,tau = 5,
ln.S.0.mean = 10.7, phi = .2,

ln.Pr = c(
11.14,10.99,11.58,11.28,11.01,10.70,11.20,10.98,10.57,10.88,
11.37,10.99,11.37,11.18,11.08,11.49,10.94,11.11,11.13,10.83,
10.77,10.99,11.51,11.92,11.47,11.13,11.14,11.14,11.14,11.14,
11.14,11.14,11.14
),
log.k = c(
8.9798, 9.6448,9.8531,8.8609,9.2919, 9.8227,10.2716,9.7991, 9.2328,
```

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```
9.7561,10.0405,9.1427,8.9538,9.9821,10.1108, 9.7782,9.8130, 9.6105,
9.5391, 9.8943,8.9735,9.3328,9.5164, 8.5372, 8.5982,9.1409,10.0685,
10.3772,9.5267,8.0605,9.4642,9.0453, 7.9161
),
log.H = c(
 9.890453,10.615947,10.831312,10.632219,10.147296,10.070738,10.219866,
 9.814274, 9.569831, 8.664233,10.118236, 9.340754, 8.746080, 9.511407,
 9.741733, 9.772353, 9.867757, 9.905635, 9.885273,10.407651, 9.627866,
10.161187, 9.616272, 9.344959, 9.161360, 9.546455, 9.736133,10.589056,
 9.799792, 8.932213, 9.194414, 9.892983, 7.942718),
d.ln.Pr = c(11.14,11.14,11.14,11.14,11.14,11.14),
d.theta = structure(.Data = c(
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23,
1.46,      8.29,     0.23) ,.Dim=c(36,3)),
```

-continued-

```

U.H.a = structure(.Data = c(
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2,
0.2,        0.2,        0.2),.Dim=c(33,3))
)

Initial values chain two
list(lnalpha = 2.0, beta = 0.000022, ln.Pr.mean = 11.2, ln.S.0 = 10.7,
tau.Pr = 5, tau.S = 5, d.scale = 01, d.t1 = .2, d.t2 = .8,tau = 5,
ln.S.0.mean = 10.7, phi = .4,
ln.Pr = c(
11.14,10.99,11.58,11.28,11.01,10.70,11.20,10.98,10.57,10.88,
11.37,10.99,11.37,11.18,11.08,11.49,10.94,11.11,11.13,10.83,
10.77,10.99,11.51,11.92,11.47,11.13,11.14,11.14,11.14,11.14,
11.14,11.14,11.14
),
log.k = c(
```

-continued-

```
 8.9798, 9.6448,9.8531,8.8609,9.2919, 9.8227,10.2716,9.7991, 9.2328,
 9.7561,10.0405,9.1427,8.9538,9.9821,10.1108, 9.7782,9.8130, 9.6105,
 9.5391, 9.8943,8.9735,9.3328,9.5164, 8.5372, 8.5982,9.1409,10.0685,
10.3772, 9.5267,8.0605,9.4642,9.0453, 7.9161
),
log.H = c(
 9.890453,10.615947,10.831312,10.632219,10.147296,10.070738,10.219866,
 9.814274, 9.569831, 8.664233,10.118236, 9.340754, 8.746080, 9.511407,
 9.741733, 9.772353, 9.867757, 9.905635, 9.885273,10.407651, 9.627866,
10.161187, 9.616272, 9.344959, 9.161360, 9.546455, 9.736133,10.589056,
 .799792,  8.932213, 9.194414, 9.892983, 7.942718
),
d.ln.Pr = c(11.14,11.14,11.14,11.14,11.14,11.14),
d.theta = structure(.Data = c(
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
1.46,     8.29,     0.23,
```

-continued-

```
1.46,        8.29,      0.23,
1.46,        8.29,      0.23) ,.Dim=c(36,3)),
U.H.a = structure(.Data = c(
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2,
0.2,         0.2,       0.2),.Dim=c(33,3))
)
```

Appendix B3.–Alternative statements to the program described in Appendix B2 that create optimum yield and overfishing profiles for the Klukshu stock of sockeye salmon.

<table>
<tr><th>Alternative statements</th><th>Line location for substitutions within program listed in Appendix B2.</th></tr>
<tr><td>

```
#--------------Apply relative age composition

  for (y in 1:33) {
    for (a in 1:3)  {

        U.H.a[y,a] ~dbeta(1,1)  #Non-informative prior

         k.H.a[y,a] <- Run.a[y,a] * U.H.a[y,a]
                                  }

    Run[y] <-sum(Run.a[y,1:3])
    d.Hk[y]<- max(Run[y] - k[y],1)
     k.H[y] <- sum(k.H.a[y,1:3])

    for(a in 1:3) {

     hq[y,a] <- k.H.a[y,a]/k.H[y]  #-----lower river harvest age composition
     d.Hk.a[y,a] <- hq[y,a]*d.Hk[y]

     IRk.a[y,a] <- max(Run.a[y,a] - d.Hk.a[y,a],1)   #---escapement age composition
                        }

     IRk[y] <- sum(IRk.a[y,1:3])
     krat[y] <- (H[y])/d.Hk[y]

     IR[y] <- (k[y]+d.Hk[y])*krat[y]

     for (a in 1:3) {irrq[y,a] <- IRk.a[y,a]/IRk[y]   }       #---in-river run age composition
```

</td><td>Substitution for lines 85–108.</td></tr>
<tr><td>

```
#kluksu escapement
    S[y] <- max(k[y] - C[y],1)
    N[y] <- max(IR[y] + H[y],1)

#marine and lower river harvest rate
    LRU[y] <- max(((H [y])/N[y]),0)

#marine and lower river Klukshu catch

     kLRC[y] <- max((LRU[y]/(1-LRU[y]))* k[y],1)

#Klukshu run components
     KlukRun[y]<- max((S[y] + C[y] +kLRC[y]),1)
```

</td><td>Substitution for lines 140–151.</td></tr>
</table>