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Run Reconstruction, Spawner-Recruit Analysis, and Escapement Goal Recommendation for Summer Chum Salmon in the East Fork of the Andreafsky River

by

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May 2010

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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The Fishery Manuscript series was established in 1987 by the Division of Sport Fish for the publication of technically oriented results of several years' work undertaken on a project to address common objectives, provide an overview of work undertaken through multiple projects to address specific research or management goal(s), or new and/or highly technical methods, and became a joint divisional series in 2004 with the Division of Commercial Fisheries. Fishery Manuscripts are intended for fishery and other technical professionals. Fishery Manuscripts are available through the Alaska State Library and on the Internet: http://www.sf.adfg.state.ak.us/statewide/divreports/html/intersearch.cfm This publication has undergone editorial and peer review.

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ABSTRACT

Historical abundance of Andreafsky River, Anvik River, and aggregated other upriver stocks of summer chum salmon *Oncorhynchus keta* was reconstructed from mixed stock harvest data and incomplete sonar, weir, counting tower, and aerial survey data of varying precision from 1972 to 2007. The resulting estimates of escapement and harvest of East Fork Andreafsky River chum salmon were fitted to an age-structured Ricker spawner-recruit model. Bayesian statistical methods were employed, which allowed for realistic assessment of uncertainty in the presence of measurement error, serial correlation, and missing data. It is recommended that the existing biological escapement goal of 65,000 to 130,000 be changed to a lower-bound sustainable escapement goal of 40,000 chum salmon counted at the East Fork Andreafsky River weir.

Key words: chum salmon, *Oncorhynchus keta*, Yukon River, Andreafsky River, weir, spawning abundance, age composition, escapement goal, run reconstruction, spawner-recruit analysis, maximum sustained yield, measurement error, serial correlation, missing data, Bayesian statistics, WinBUGS.

INTRODUCTION

The Yukon River is the largest river drainage in Alaska and supports large annual runs of chum salmon *Oncorhynchus keta*. Genetically distinct (Seeb and Crane 1999) early or "summer" and late or "fall" runs of chum salmon occur. Summer chum are smaller and mature more rapidly in fresh water than do fall chum salmon, entering the mouth of the Yukon River early June through mid July. They spawn primarily in tributaries of the lower 500 miles of the Yukon River and in the Tanana River.

Fisheries targeting summer and fall chum salmon are managed separately. For management purposes, the Alaskan portion of the Yukon River is divided into six different fishing districts in the Yukon and Tanana rivers (Figure 1). Commercial and subsistence fishing occur in each district. In addition to the U.S. fisheries, aboriginal, commercial, and domestic salmon fisheries also occur in the Canadian portion of the Yukon River drainage. Management agencies include the Alaska Department of Fish and Game (ADF&G), U.S. Fish and Wildlife Service (USFWS) and the Canadian Department of Fisheries and Oceans (DFO).

Salmon runs in Alaska are managed to achieve escapement goals that are established consistent with the *Policy for the Management of Sustainable Salmon Fisheries* (5 AAC 39.222, 2000) and the *Policy for Statewide Salmon Escapement Goals* (5 AAC 39.223, 2001). Per these policies, unless otherwise directed by regulation, ADF&G will manage Alaska's salmon fisheries to the extent possible for maximum sustained yield (MSY). ADF&G has managed the salmon fisheries in the Yukon Area over the past few decades with the dual goal of maintaining important fisheries while at the same time achieving desired escapements. However, management of the Yukon River salmon fishery is complex due to the inability to determine stock-specific abundance and timing, overlapping runs of multiple species, the increasing efficiency of the fishing fleet, allocation issues, and the immense size of the Yukon River drainage. Salmon fisheries within the Yukon River drainage may harvest stocks that are up to several weeks and over a thousand miles from their spawning grounds. Based on current knowledge, it is not possible to precisely manage for individual stocks in most of the Yukon River area fisheries, and individual stocks may be subjected to varying exploitation rates.

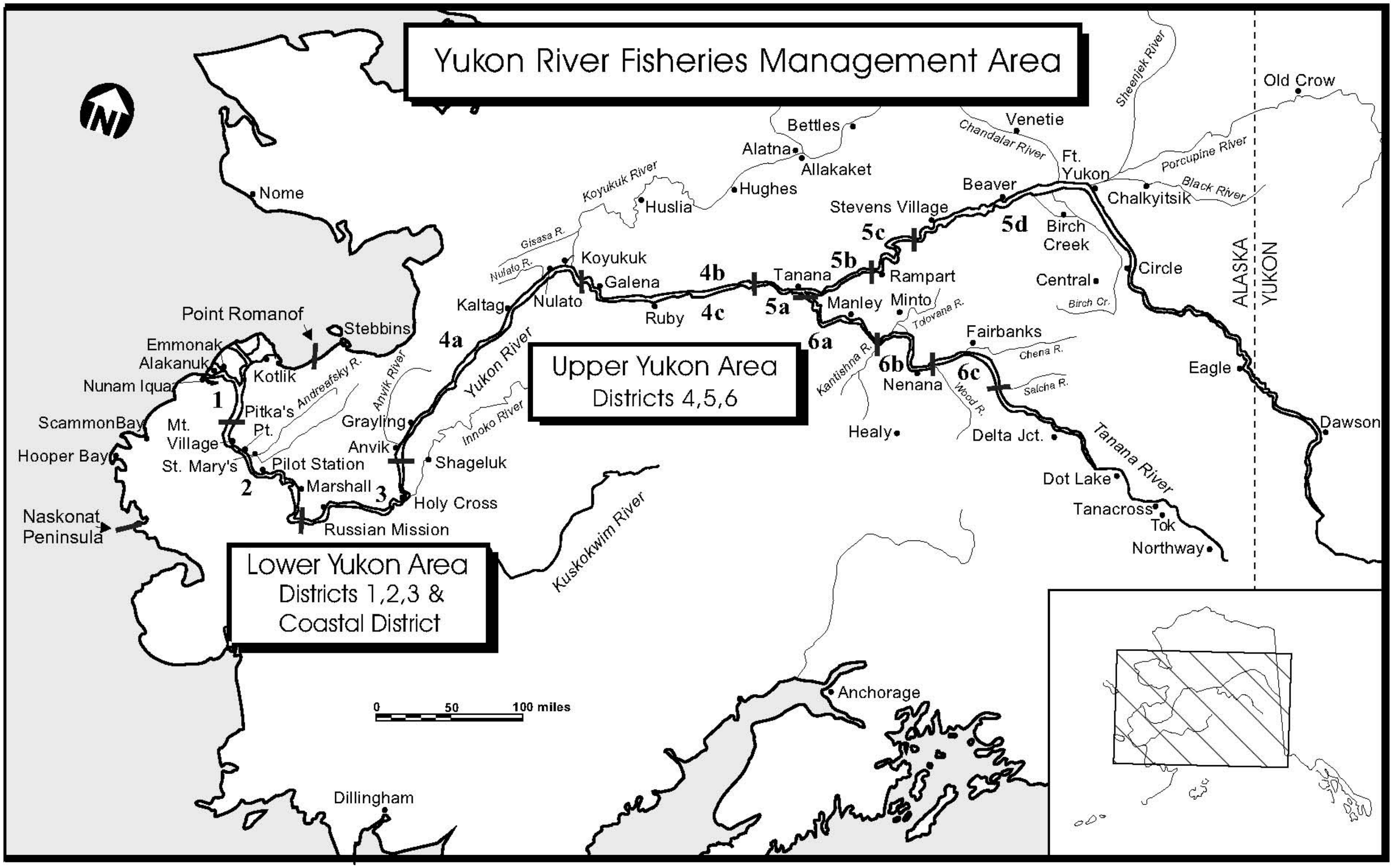

Figure 1.–Fishing districts in the Yukon River drainage.

The Andreafsky River is a large, first-order tributary to the Yukon River. The confluence of the Andreafsky and Yukon Rivers is located 104 miles upstream of the mouth of the Yukon River. The Andreafsky River has two major forks, the East Fork and the West Fork, each supporting a major spawning stock of summer chum salmon.

The Andreafsky River stock of chum salmon is likely the largest spawning stock of summer chum salmon in the lower 200 miles of the Yukon River drainage. Andreafsky River summer chum salmon have been assessed since 1972 with side-scan sonar, counting towers, weirs, and aerial surveys. Use of these individual methodologies, however, has been sporadic, inconsistent in quality and duration, and there have been significant data gaps.

Escapement objectives for Andreafsky River chum salmon population have been in effect for 20 years. Clark (2001) most recently proposed a biological escapement goal (BEG) of 65,000 to 130,000 spawners. Clark reconstructed historical escapements using a series of compound expansions with four main components: (1) an incomplete set of East Fork abundance estimates; (2) expansions developed from paired direct estimates and aerial survey counts; (3) the estimated relationship between East and West Fork abundance developed from expanded aerial survey counts; and (4) the estimated relationship between Andreafsky River expanded estimates and Anvik River escapements.

Currently, several factors warrant a reanalysis of the available information and reconsideration of the escapement goal. Concerns remained about Clark's (2001) approach, including the arbitrary nature of the compound expansions and the failure to consider the resulting uncertainty (unpublished documents submitted to the Alaska Board of Fisheries 2001; DFO *Unpublished*[1]). Newer statistical procedures, capable of accommodating measurement error and with better accounting of uncertainty, are now available. Seven more years of East Fork weir data are also available. Finally, even though the stock has experienced little or no harvest in recent years, the escapement goal has rarely been met.

A sustainable escapement goal (SEG) threshold (lower bound only) is recommended to replace the current BEG range. Andreafsky chum salmon constitute a non-targeted stock, subject to limited active management. Situated low in the Yukon drainage, Andreafsky River chum salmon migrate a relatively short distance upriver, are of lower quality than other summer chum salmon stocks, and contribute relatively small numbers of fish to the total drainagewide harvest. Management of lower Yukon summer chum salmon, including Andreafsky River fish, is based largely on information from the mainstem Yukon River sonar project located at Pilot Station, 20 river miles upstream of the Andreafsky River mouth. For these reasons, a lower-bound SEG, used as a precautionary reference point rather than an active management target, is more sensible than a two-sided BEG range for this stock.

The escapement goal analysis was conducted in two steps. First, incomplete East Fork Andreafsky River chum salmon escapement estimates were analyzed in the context of 3+ decades of other escapement estimates in the West Fork Andreafsky and Anvik rivers, as well as inriver abundance estimates in the Yukon River mainstem at Pilot Station. By considering all such information simultaneously, estimates of East Fork chum salmon abundance were produced

[1] 2002 subcommittee meeting of the Fisheries and Oceans Canada Pacific Scientific Advice Review Committee (PSARC) May 13-14, 2002, Nanaimo, BC.

for years during which direct stock assessments did not occur. By assuming similar harvest rates across stocks within individual reaches, the run reconstruction model allowed estimation of stock-specific annual catch. Second, the resulting estimates of catch rate and abundance, as well as age composition, were analyzed in the framework of an age-structured spawner-recruit model for East Fork Andreafsky River chum salmon.

For both analyses, Markov Chain Monte Carlo (MCMC) methods, which are especially well-suited for modeling complex population and sampling processes, were employed. The MCMC algorithms were implemented in WinBUGS (Lunn et al. 2000), which is a Bayesian software program. This methodology allows for inclusion of the effects of measurement error, serially correlated process errors, and missing data in the analysis; and provides a more realistic assessment of uncertainty than is possible with classical statistical methods.

Bayesian statistical methods employ probability as a language to quantify uncertainty about model parameters. Knowledge existing about the parameters outside the framework of the current analysis is the "prior" probability distribution. The output of the Bayesian analysis is called the "posterior" probability distribution, which is a synthesis of the prior information and the information in the data. See Ericksen and Fleischman (2006), Szarzi et al (2007), and Fleischman and Borba (2009) for other applications of these methods.

METHODS

DATA

Various stock assessment projects for Andreafsky River chum salmon have been conducted since the 1970s (Table 1). Beginning in 1972, aerial surveys were conducted on the east and west forks of the Andreafsky River. Not all surveys produced useful chum salmon counts: Clark (2001) evaluated the surveys and culled out approximately half based on survey timing and subjective ratings of visibility, leaving 10 valid surveys on the East Fork and 13 on the West Fork between 1972 and 1991 (Table 1). On the East Fork, in addition to the aerial surveys, Bendix sonar was deployed 1981-1984, a counting tower was operated 1986-1988, and a weir was installed 1994–2000 and 2002–2007 (Table 1). Summer chum salmon escapement was also monitored, using counting towers and Bendix sonar, on the Anvik River, 214 miles upriver. Finally, single- and split-beam sonar estimates of summer chum salmon passage in the mainstem Yukon at Pilot Station are available from 1995 and 1997–2007. Pilot Station is approximately 20 river miles upstream of the Andreafsky mouth. Fish bound for Anvik and other upriver tributaries[2] pass by Pilot Station.

There are two sources of uncertainty in the escapement estimates. First, there exist numerous missing cells in the matrix of escapement estimates (Table 1). Furthermore, the individual annual estimates are subject to sampling error of varying magnitude. The run reconstruction model, described below, simultaneously incorporates information from all stock assessment projects in the lower Yukon, explicitly considering the missing data as well as the sampling error in the individual estimates.

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[2] Since the mid-1990s, escapement has been monitored in several streams upriver from Anvik: Clear Creek (tower and weir), Gisasa River (weir), Henshaw Creek (weir), Kaltag Creek (tower), Nulato River (tower), and Tozitna River (weir). These data were not used in the current analysis.

Table 1.-Escapement and abundance estimates by sub-drainage, lower Yukon River summer chum salmon, 1972–2007. Assumed sampling error coefficients of variation are listed in parentheses for some projects.

	Andreafsky River escapement			Anvik River	Other Yukon	Anvik + other
Year	East Fork estimates (Bendix, tower, weir)	East Fork index (air survey)	West Fork index (air survey)	Tower, sonar	(No data)	Pilot Station (single- and split-beam sonar)
1972		41,460		457,800 (0.40)		
1973			51,835	249,015 (0.40)		
1974			33,578	411,133 (0.40)		
1975		223,485	235,954	900,967 (0.40)		
1976		105,347	118,420	511,475 (0.40)		
1977		112,722	63,120	358,771 (0.40)		
1978			57,321	307,270 (0.40)		
1979		66,471	43,391	277,712 (0.40)		
1980			114,759	482,181 (0.40)		
1981	147,312 (0.20)	81,555		1,479,582 (0.20)		
1982	181,352 (0.20)			444,581 (0.20)		
1983	110,608 (0.20)			362,912 (0.20)		
1984	70,125 (0.20)			891,028 (0.20)		
1985		66,146	52,750	1,080,243 (0.20)		
1986	167,614 (0.20)	83,931	99,373	1,189,602 (0.20)		
1987	45,221 (0.20)		35,535	455,876 (0.20)		
1988	68,937 (0.20)	43,056	45,432	1,125,449 (0.20)		
1989				636,906 (0.20)		
1990				403,627 (0.20)		
1991		31,886	46,657	847,772 (0.20)		
1992				775,626 (0.20)		
1993				517,409 (0.20)		
1994	200,981 (0.10)			1,147,262 (0.20)		
1995	172,148 (0.10)			1,394,162 (0.20)		3,556,445
1996	108,450 (0.10)			1,017,873 (0.20)		
1997	51,139 (0.10)			619,300 (0.20)		1,415,641
1998	67,591 (0.10)			487,301 (0.20)		826,385
1999	32,229 (0.10)			437,356 (0.20)		973,708
2000	23,500 (0.10)			196,349 (0.20)		456,271
2001				224,058 (0.20)		441,450
2002	44,191 (0.10)			459,058 (0.20)		1,088,463
2003	22,603 (0.10)			256,920 (0.20)		1,168,518
2004	62,878 (0.10)			365,353 (0.20)		1,357,826
2005	20,127 (0.10)			525,391 (0.30)		2,368,216
2006	102,260 (0.10)			992,378 (0.20)		3,767,044
2007	69,642 (0.10)			460,121 (0.20)		1,726,885

Estimates of total annual harvest of Yukon River summer chum salmon were obtained from commercial fish tickets and subsistence surveys, by fishing district and statistical area. Annual estimates of age composition were obtained from fish sampled from the East Fork Andreafsky escapement.

RUN RECONSTRUCTION MODEL

Multiple sources of information were leveraged to reconstruct the runs of Andreafsky, Anvik, and other upriver stocks of Yukon River summer chum salmon. Knowledge of the relative abundance of summer chum salmon stocks, the harvest in specific reaches of the river, and the assumption of similar run timing among stocks enables approximate reconstruction of the abundance, harvest, and escapement of each component stock (Figure 2). Run reconstruction can be carried out deterministically, by assuming that all quantities are known without error. However, it is critical to assess the uncertainty of the resulting estimates, particularly when the output is to be used in a spawner-recruit analysis. The following describes a Bayesian statistical run reconstruction model for lower Yukon River summer chum salmon stocks that, upon fitting to the available data, provides estimates of abundance, catch rate, catch, and escapement by stock, along with realistic assessments of uncertainty. These estimates are then carried forward as input to a separate spawner-recruit model for East Fork Andreafsky chum salmon.

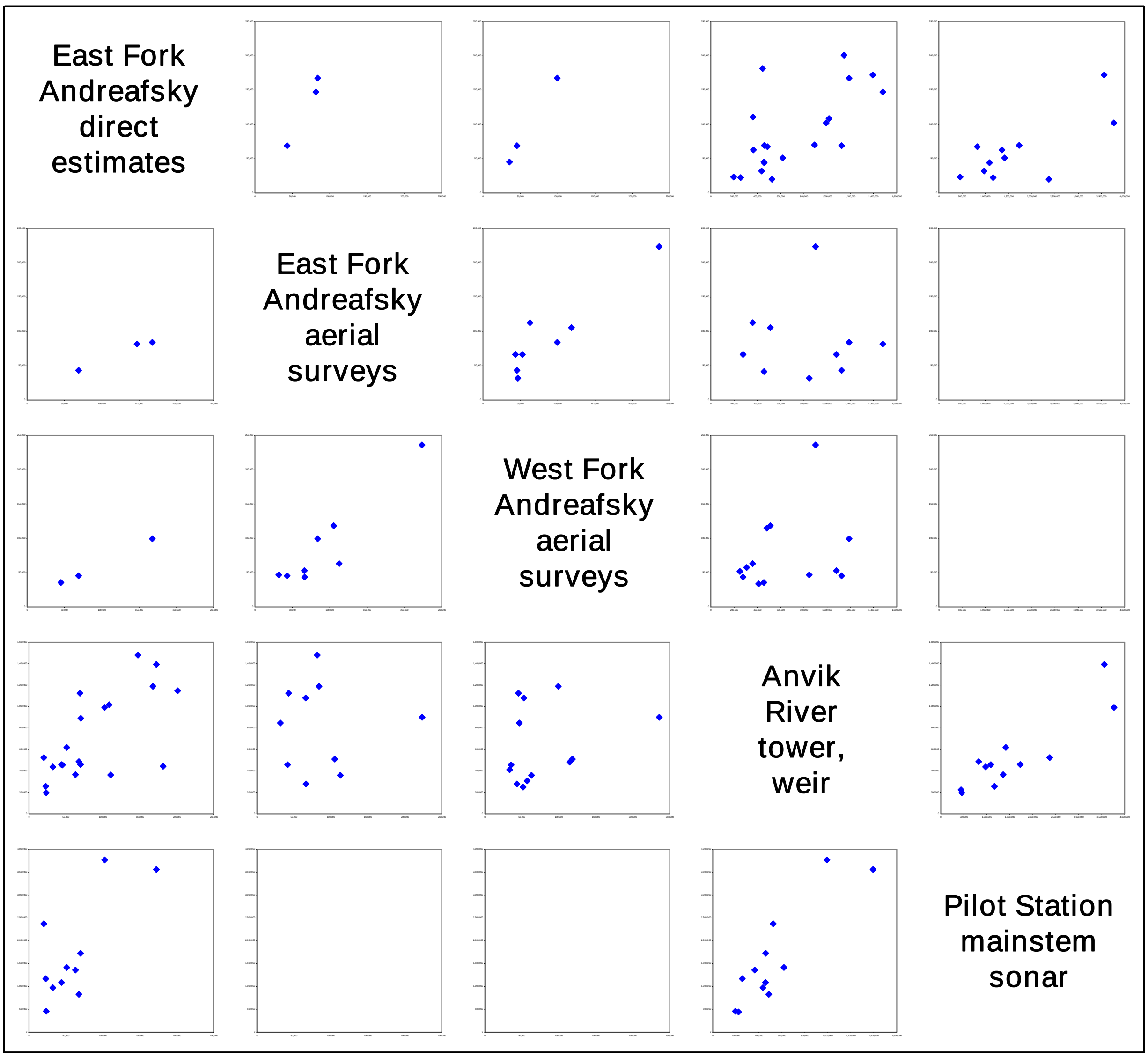

Figure 2.–Scatter plot matrix of summer chum salmon escapement estimates, aerial survey counts, and mainstem abundance estimates in the lower Yukon River, 1972–2007.

Drainagewide summer chum abundance N ("run" size for the entire Yukon River) in year t was hierarchically modeled as a draw from a lognormal distribution, independent across years.

$$\log(N_t) \sim Normal\left(\mu_{\log N}, \sigma^2_{\log N}\right) \tag{1}$$

where $\mu_{\log N}$ is the mean and $\sigma^2_{\log N}$ the standard deviation of the log-transformed abundances, both hyper-parameters to be estimated. Drainagewide abundance consists of four mutually exclusive sub-drainages. Of these, indices or direct estimates of escapement are considered in three: the East and West forks of the Andreafsky as well as the Anvik River. Indirect information is available about abundance of other stocks, collectively, above the Anvik River, by comparison of Anvik River estimates with Pilot Station sonar numbers. Escapement/abundance estimates were generally well-correlated (Figure 2), although the relationship between them occasionally changed over time (Table 1; Figure 2).

The run proportions by stock, and the associated catch, were indirectly modeled by defining three binomial proportions ρ, one for each of three river bifurcations:

River bifurcation[3]	Binomial proportion	Definition = probability of fish choosing
Confluence of Andreafsky and Yukon	ρ_1	Andreafsky (vs other, including Anvik)
Confluence of East and West forks of Andreafsky	ρ_2	East Fork (vs West fork Andreafsky)
Confluence of Anvik and Yukon	ρ_3	Anvik (vs other upriver)

These proportions can then be used to define the four stock components, with stock proportions θ, of interest:

Stock component	Multinomial proportion[4]	RunSize	Interpretation	Equation
East Fork Andreafsky	$\theta_E = \rho_1\,\rho_2$	$N_E = \theta_E N$	Fish choosing Andreafsky and East Fork	(2)
West Fork Andreafsky	$\theta_W = \rho_1\,(1-\rho_2)$	$N_W = \theta_W N$	Fish choosing Andreafsky and not East Fork	(3)
Anvik	$\theta_A = (1-\rho_1)\,\rho_3$	$N_A = \theta_A N$	Fish not choosing Andreafsky and choosing Anvik	(4)
Other upriver stocks	$\theta_O = (1-\rho_1)\,(1-\rho_3)$	$N_O = \theta_O N$	Fish choosing neither Andreafsky nor Anvik	(5)

[3] Consider each bifurcation as a choice made by an upstream migrating fish.
[4] These sum to one.

Each “bifurcation” proportion ρ follows an independent AR(1) binomial logit distribution (Yau and Ma 1999), which permits the bifurcation proportions and therefore the stock proportions to change slowly over time. That is, the observed binomial proportion r for bifurcation b in year t is modeled as

$$\operatorname{logit}(r_{bt}) \sim Normal\left(\operatorname{logit}(\rho_{FITbt}), \sigma^2_{Bt}\right) \tag{6}$$

$$\operatorname{logit}(\rho_{FITbt}) = \operatorname{logit}(\rho_b) + \varphi_b \upsilon_{b,t-1} \tag{7}$$

where the logit function and its inverse are:

$$\operatorname{logit}(x) = \log_e\left(\frac{x}{1-x}\right) \tag{8}$$

$$\operatorname{logistic}(x) = \frac{e^x}{1 - e^x} \tag{9}$$

and ρ_{FITbt} is the fitted proportion[5] for bifurcation b and year t, ρ_b is the overall proportion for bifurcation b, φ_b is the autoregressive lag-1 coefficient for bifurcation b, and the logit residual υ is the difference between the observed logit proportion and the overall value.

$$\upsilon_{bt} = \operatorname{logit}(r_{bt}) - \operatorname{logit}(\rho_b) \tag{10}$$

The bifurcation proportions ρ and r are obtained with the logistic (inverse logit) function (Equation 9), and the proportions θ and q of the total run going to each tributary (stock, sub-drainage) s in year t are obtained with Equations 2–5. The number of summer chum salmon bound for each sub-drainage s in year t is modeled as

$$N_{st} = q_{st} N_t \tag{11}$$

where s = E, W, A, or O; for East Fork, West Fork, Anvik, and other upriver stocks, respectively.

Migrating fish are subject to different harvest rates in each reach of the river. If the Yukon River is divided into three reaches: (1) between the mouths of the Yukon and the Andreafsky, (2) between the mouths of the Andreafsky and the Anvik, and (3) upstream from the mouth of the Anvik (Figure 3), then the inriver run IR at the bottom of reach h and the mixed-stock harvest M within reach h is as follows:

Reach	Inriver Run at Bottom of Reach	Mixed-Stock Harvest by Reach
Reach 1 (Yukon mouth to Andreafsky)	$IR_1 = N = N_E + N_W + N_A + N_O$	$M_1 = \eta_1 IR_1$
Reach 2 (Andreafsky to Anvik mouth)	$IR_2 = (N_A + N_O)(1-\eta_1)$	$M_2 = \eta_2 IR_2$
Reach 3 (Anvik mouth and above)	$IR_3 = N_O (1-\eta_1)(1-\eta_2)$	$M_3 = \eta_3 IR_3$

where η_h is the harvest rate for reach h. Mixed-stock harvest M in reach h is well-estimated, since commercial and subsistence harvest is tallied in such a way that the number of fish harvested in each reach can be obtained. These were modeled as

$$\hat{M}_{h,t} = M_{h,t} e^{\varepsilon_{Mht}} \tag{12}$$

where the $\{\varepsilon_{Mht}\}$ are normally distributed with mean zero and standard deviation $\sigma_M = 0.05$[6].

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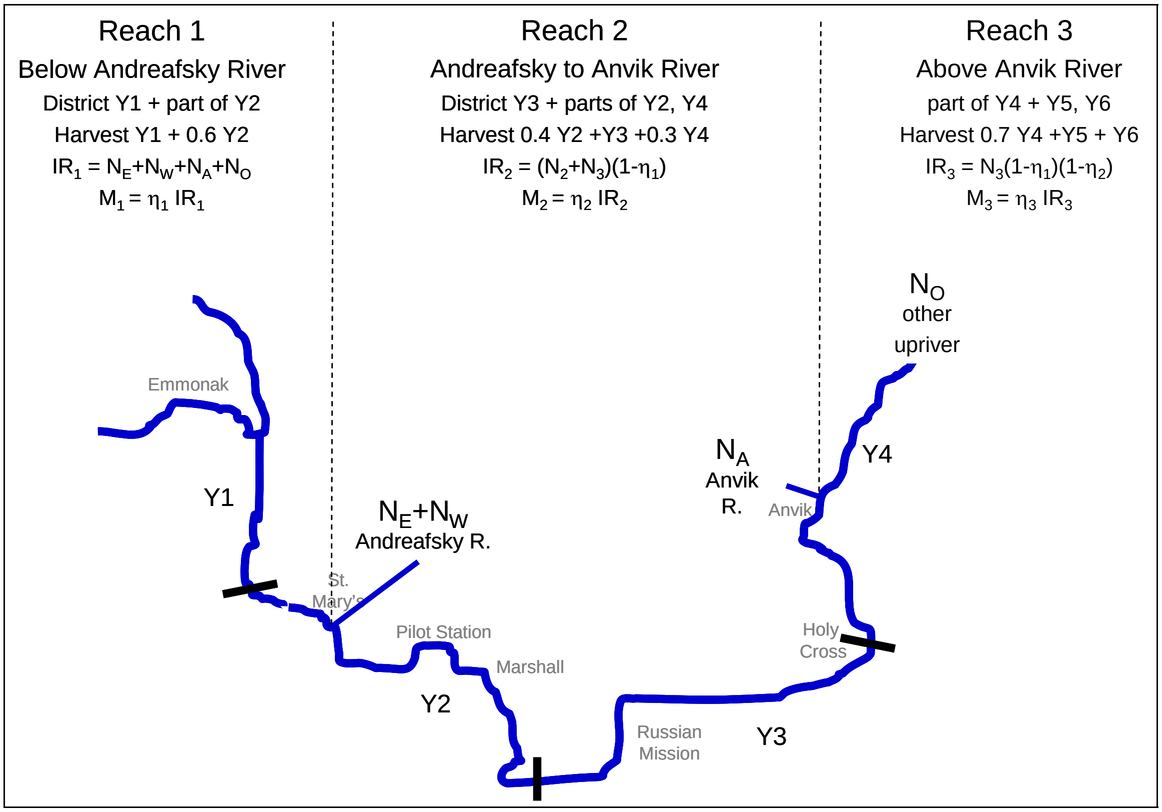
[5] Think of this quantity as the current value of ρ that changes slowly from one year to the next. in a serially correlated manner.

[6] This is approximately equivalent to a CV of 5%. This value was arbitrarily chosen to reflect the fact that inriver harvest is well estimated.



Note: Harvest rates η apply equally to all stocks present in each reach. Inriver returns IR at the bottom of each reach are modeled as the sum of stock specific runs, reduced by the appropriate harvest rates. Mixed-stock harvests M by reach are modeled as the product of inriver returns and reach-specific harvest rates. Harvest data are compiled from commercial fish ticket data in fishing districts Y1-Y6. The river flows from right to left in this figure.

Figure 3.–Three reaches of the lower Yukon River that form the basis for reconstructing summer chum salmon runs *N* to the Andreafsky River, the Anvik River, and other upriver tributaries.

Sonar estimates of summer chum passage at Pilot Station ($\hat{IR}_{PSt}$; 1995, 1997–2007) are modeled as unbiased estimates of mixed-stock inriver abundance passing river-mile 123 subject to lognormal error.

$$\hat{IR}_{PSt} = \left(IR_{2t} - M_{between,t}\right)e^{\varepsilon_{PSt}} \tag{13}$$

where IR_2 is the inriver run passing the mouth of the Andreafsky, $M_{between,t}$ is the mixed stock harvest in year t between the mouth of the Andreafsky and Pilot Station (observed with little or no error), and the $\{\varepsilon_{PSt}\}$ are normally distributed with mean zero and standard deviation σ_{PS}.

Escapement and harvest by stock are as follows:

Stock	Escapement by Stock[7]	Harvest by Stock
East Fork Andreafsky	$S_E = N_E\ (1-\eta_1)$	$H_E = N_E - S_E$
West Fork Andreafsky	$S_W = N_W\ (1-\eta_1)$	$H_W = N_W - S_W$
Anvik	$S_A = N_A\ (1-\eta_1)\ (1-\eta_2)$	$H_A = N_A - S_A$
Other	$S_O = N_O\ (1-\eta_1)\ (1-\eta_2)\ (1-\eta_3)$	$H_O = N_O - S_O$

Stock-specific harvests H are unobserved, but estimates of escapement $\hat{S}$ are observed at the various stock assessment projects in Table 1. These were modeled as

$$\hat{S}_{st} = S_{st} e^{\varepsilon_{Sst}} \tag{14}$$

where the sampling errors $\{\varepsilon_{Sst}\}$ are normally distributed with mean zero and standard deviations $\{\sigma_{Sst}\}$.

Rigorous estimates of sampling error standard deviation were not available for historical escapement estimates. Therefore, a subjective procedure was used, based on professional judgment and experience, to obtain plug-in values of sampling error coefficient of variation (CV). Values of sampling error CV were assigned to stock assessment projects based on relative strengths and weaknesses of the type of project (Fleischman and Borba 2009). For weir projects we assumed a CV of 10%, for Bendix sonar a CV of 20%, and for pre-1981 expanded aerial surveys on the Anvik a CV of 40%. [8]

East and West Fork Andreafsky aerial surveys were modeled as the product of true escapement and a common coefficient of detectability λ, subject to the usual lognormal error,

$$A_{st} = \lambda S_{st} e^{\varepsilon_{Ast}} \tag{15}$$

where the $\{\varepsilon_{Ast}\}$ are normally distributed with mean zero and standard deviation σ_A.

Bayesian analyses require that prior probability distributions be specified for all unknowns in the model. Non-informative priors (chosen to have a minimal effect on the posterior) were used almost exclusively for parameters from both models. For the run reconstruction model, flat priors were used for μ_{logN}, $\{\varphi\}$, $\{\rho\}$ and λ. Diffuse inverse gamma priors were used for σ^2_{logN} and σ^2_B. An informative prior was specified for σ^2_A because the observed relationship between aerial surveys and abundance was "too good to be true" (σ^2_A too small to be believable). An informative prior was also specified for σ^2_{PS}, modified[9] from the posterior distribution for the corresponding quantity from a similar analysis of Yukon fall chum salmon data (Fleischman and Borba 2009).

Markov-chain Monte Carlo samples were drawn from the joint posterior probability distribution of all unknowns in the model. For each of two Markov chains initialized, a 4,000-sample burn-in

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7 This assumes that all stocks are subject to the same harvest rate within a reach. This is a reasonable assumption for Yukon River summer chum salmon, because the run timing of the component stocks is not greatly dissimilar.

8 Fleischman and Borba (2009) in a model of fall chum salmon data, found that the results were not at all sensitive to these assumptions. It is reasonable to assume that the same is true here.

9 The prior for this quantity was arbitrarily set to approximately one half of the value from the fall chum posterior. Estimates of S_{MSY} were not sensitive to changes in this prior.

period was discarded, thinning by a factor of 10 was initiated, and 6,000 additional updates were generated. The resulting total of 12,000 samples was used to estimate the marginal posterior means, standard deviations, and percentiles. The diagnostic tools of WinBUGS assessed mixing and convergence, and no major problems were encountered. Posterior medians for annual East Fork Andreafsky run size $\{N_{Et}\}$ and harvest rate $\{\eta_{1t}\}$, denoted $\{\hat{N}_{t.}\}$ and $\{\hat{\mu}_t\}$, were used as input for the spawner-recruit model described below. Coefficients of variation for $\{\hat{N}_{t.}\}$ and $\{\hat{\mu}_t\}$, were obtained by dividing posterior standard deviations by posterior means. Interval estimates of other model parameters were obtained from the percentiles of the posterior distribution.

SPAWNER-RECRUIT MODEL

A Ricker spawner recruit function (Ricker 1975) was chosen to model the relationship between East Fork Andreafsky chum salmon[10] escapement and recruitment. Under the Ricker model, the total recruitment *R* from brood year *y* is:

$$R = S\,\alpha\,e^{-\beta S}\,e^{\varepsilon_{SR}} \tag{16}$$

where S is the number of spawners, α and β are parameters, and the $\{\varepsilon_{SR}\}$ are normally distributed process errors with variance σ^2_{SR}. Parameter α is the number of recruits per spawner in the absence of density dependence and is a measure of the productivity of a stock. Parameter β is a measure of density dependence; the inverse of β is the number of spawners that produces the theoretical maximum return (S_{MAX}).

Equilibrium spawning abundance, in which the expected return $R = S$, is

$$S_{EQ} = \frac{\ln(\alpha')}{\beta} \tag{17}$$

where $\ln(\alpha)$ is corrected for asymmetric lognormal process error (Hilborn and Walters 1992) as follows:

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma^2_{SR}}{2} \tag{18}$$

Number of spawners leading to maximum sustained yield S_{MSY} is approximately (Hilborn 1985)

$$S_{MSY} \approx S_{EQ}\left(0.5 - 0.07\ln(\alpha')\right). \tag{19}$$

The classical way to estimate the Ricker parameters is to linearize the Ricker relationship by dividing both sides of equation 16 by *S* and taking the natural logarithm, yielding:

$$\ln\left(\frac{R}{S}\right) = \ln(\alpha) - \beta S + \varepsilon \tag{20}$$

This streamlines parameter estimation, because the relationship can now be viewed as a simple linear regression (SLR) of $\ln(R/S)$ on S, in which the intercept is an estimate of $\ln(\alpha)$, the

[10] The run reconstruction model also outputs estimates of N and μ for West Fork Andreafsky River, Anvik River, and other Yukon River summer chum salmon stocks. Using these estimates, similar spawner-recruit analyses could be conducted for these sub-stocks. They are not reported here.

negative slope an estimate of β, and the mean squared error an estimate of the process error variance σ^2_{SR}.

For graphical comparison purposes only, simple linear regression estimates of the Ricker parameters were calculated, using estimates of $\{S,R\}$ from the run reconstruction model (Table 2).[11]

Table 2.–Estimates of run size, harvest rate, harvest, and escapement of East Fork Andreafsky River chum salmon, from run reconstruction of lower Yukon River summer chum salmon 1972–2007, plus East Fork escapement age composition estimates.

Year	Estimated[a] Run Size	CV	Estimated[a] Harvest Rate	CV	Estimated[a] Harvest	CV	Estimated[a] Escapement	CV	Estimated Age Proportions[c] age-3	age-4	age-5	age-6
1972	72,790	0.39	0.17	0.25	12,360	0.39	60,040	0.41				
1973	83,300	0.50	0.32	0.17	26,520	0.43	56,350	0.55				
1974	118,400	0.50	0.41	0.13	48,470	0.45	69,430	0.55				
1975	335,900	0.32	0.19	0.21	63,340	0.31	271,000	0.35				
1976	193,200	0.32	0.21	0.16	40,860	0.30	151,800	0.34				
1977	155,800	0.32	0.24	0.16	37,560	0.30	117,500	0.34				
1978	144,500	0.45	0.29	0.10	42,310	0.41	102,000	0.48				
1979	122,600	0.32	0.33	0.11	39,980	0.31	82,520	0.34				
1980	177,700	0.42	0.27	0.14	47,860	0.37	128,800	0.45				
1981	192,900	0.18	0.20	0.14	39,510	0.23	153,200	0.18				
1982	200,900	0.18	0.22	0.12	44,260	0.20	156,300	0.19	0.02	0.70	0.26	0.02
1983	156,800	0.18	0.34	0.08	53,060	0.19	103,500	0.19	0.01	0.43	0.55	0.01
1984	97,450	0.19	0.22	0.13	21,100	0.22	76,330	0.19	0.04	0.70	0.24	0.02
1985	115,000	0.32	0.17	0.12	18,950	0.31	96,080	0.33	0.02	0.71	0.27	0.00
1986	185,500	0.16	0.20	0.13	36,140	0.21	149,000	0.17	0.00	0.55	0.44	0.02
1987	62,650	0.18	0.26	0.10	16,260	0.20	46,180	0.18	0.01	0.37	0.58	0.05
1988	99,100	0.17	0.29	0.10	28,120	0.21	70,900	0.17	0.01	0.70	0.27	0.02
1989	93,550	0.56	0.32	0.09	29,640	0.51	63,990	0.59	0.02	0.43	0.54	0.01
1990	49,560	0.61	0.21	0.12	10,290	0.52	39,190	0.64	0.01	0.81	0.17	0.00
1991	67,870	0.33	0.16	0.14	10,940	0.34	56,830	0.34	0.00	0.51	0.47	0.01
1992	90,590	0.54	0.18	0.16	16,620	0.47	73,740	0.56	0.00	0.26	0.66	0.08
1993	60,310	0.59	0.12	0.20	7,383	0.49	52,620	0.61	0.01	0.58	0.39	0.02
1994	204,500	0.10	0.04	0.18	8,985	0.20	195,400	0.10	0.00	0.68	0.31	0.01
1995	187,200	0.10	0.07	0.12	13,910	0.15	173,300	0.10	0.01	0.45	0.52	0.02
1996	117,700	0.10	0.08	0.15	9,224	0.18	108,400	0.10	0.00	0.57	0.36	0.06
1997	56,720	0.10	0.09	0.12	4,900	0.16	51,780	0.10	0.00	0.31	0.64	0.06
1998	70,330	0.10	0.06	0.12	4,456	0.15	65,850	0.10	0.00	0.81	0.17	0.02
1999	34,610	0.10	0.05	0.13	1,828	0.16	32,780	0.10	0.01	0.28	0.68	0.03
2000	25,760	0.10	0.10	0.12	2,464	0.16	23,290	0.10	0.00	0.49	0.48	0.03
2001	20,130	0.57	0.07	0.13	1,520	0.51	18,570	0.58	0.00	0.22	0.76	0.02
2002	46,160	0.10	0.04	0.13	1,780	0.16	44,370	0.10	0.01	0.83	0.13	0.03
2003	24,020	0.10	0.04	0.15	902	0.18	23,100	0.10	0.01	0.74	0.25	0.01
2004	63,310	0.10	0.04	0.14	2,291	0.17	61,000	0.10	0.10	0.69	0.20	0.00
2005	22,150	0.10	0.04	0.16	860	0.19	21,270	0.10	0.00	0.90	0.10	0.00
2006	105,900	0.10	0.02	0.14	2,607	0.17	103,300	0.10	0.01	0.27	0.72	0.00
2007	77,000	0.10	0.11	0.13	8,197	0.17	68,710	0.10	0.01	0.67	0.26	0.06

[a] Posterior median.

[b] Posterior standard deviation / posterior mean.

[c] Estimated from fish sampled from the escapement, but used as a surrogate for the entire run.

[11] Recruitment by brood year R first had to be reconstructed from estimates of S, H, and age composition.

The SLR approach requires that the usual assumptions of linear regression analysis be met, including that the independent variable *(S)* be measured without error. Small amounts of measurement error in S have little effect; however measurement error with coefficients of variation exceeding 20% can cause substantial bias in SLR estimates of S_{MSY} (Kehler et al. 2002,Kope 2006), as well as increased uncertainty which is not reflected in the classical estimates. From the run reconstruction model described above, the estimated measurement error CV of the escapement estimates approaches or exceeds 20% in most years and in 7 years exceeds 50%. Another shortcoming of the SLR approach is that it cannot account for serially correlated process error or missing data.

For these reasons Markov Chain Monte Carlo (MCMC) methods were employed to model the spawner-recruit relationship. The Bayesian MCMC analysis considers all the data simultaneously in the context of the following statistical model. Returns of summer chum salmon originating from spawning escapement in brood years y = 1972–2004 are modeled as a Ricker spawner-recruit function with autoregressive lognormal errors with a lag of 1 year (i.e., an AR1 model of serial correlation in residuals)

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi \nu_{y-1} + \varepsilon_{Wy} \tag{21}$$

where α and β are Ricker parameters, ϕ is the lag-1 autoregressive coefficient, $\{\nu_y\}$ are the model residuals

$$\nu_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y\,, \tag{22}$$

and the $\{\varepsilon_{Wy}\}$ are independently and normally distributed process errors with "white noise" variance σ^2_W.

Age proportion vectors[12] $\underline{\boldsymbol{p}}_y = (p_{y4}, p_{y5})$ from brood year y returning at ages 4-5 are drawn from a $Dirichlet(\gamma_4,\gamma_5)$ distribution. The Dirichlet parameters are also expressed in an alternative location/scale form, where

$$D = \sum_a \gamma_a\,; \tag{23}$$

is the (inverse) scale of the $\underline{\boldsymbol{p}}_y$ age proportion vectors, reflecting dispersion of the age proportion vectors among brood years; and (location parameters)

$$\pi_a = \frac{\gamma_a}{D} \tag{24}$$

reflect the overall age proportions.

The abundance N of age-a chum salmon in calendar year t (t = 1972-2007) is the product of the age proportion scalar p and the total return R from brood year $y = t\text{-}a$:

$$N_{ta} = R_{t-a}\, p_{t-a,a} \tag{25}$$

[12] These age proportions are maturity/survival schedules in a given brood year, across calendar years. In contrast, equation 3 describes age proportions in a given calendar year, across brood years.

Total run during calendar year *t* is the sum of abundance at age across ages:

$$N_{t\cdot} = \sum_a N_{ta} \tag{26}$$

Spawning abundance is total abundance minus harvest,

$$S_t = N_{t\cdot} - H_t \tag{27}$$

where H_t is in turn the product of the annual harvest rate and total run:

$$H_t = \mu_t N_{t\cdot}\,. \tag{28}$$

Spawning abundance yielding peak return S_{MAX} is the inverse of the Ricker β parameter. Equilibrium spawning abundance S_{EQ} and spawning abundance leading to maximum sustained yield S_{MSY} are obtained using equations 17–19, except that $\ln(\alpha)$ is corrected for AR(1) serial correlation as well as lognormal process error:

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_W^2}{2(1-\phi^2)}\,. \tag{29}$$

Expected sustained yield at a specified escapement *S* is calculated by subtracting spawning escapement from the expected return, again incorporating corrections for lognormal process error and AR(1) serial correlation:

$$SY = E[R] - S = Se^{\ln(\alpha')-\beta S} - S\,. \tag{30}$$

Probability that a given level of escapement would produce average yields exceeding X% of MSY was obtained by calculating the expected sustained yield (*SY*; Equation 30) at multiple incremental values of *S* (0 to 150,000) for each Monte Carlo sample, then comparing *SY* with *X*% of the value of *MSY* for that sample. The proportion of samples in which *SY* exceeded *0.X MSY* is the desired probability.

Observed data include estimates of annual run size and harvest rate[13] from the run reconstruction model, and multinomial age counts from scales sampled from the escapement. Likelihood functions for the data follow.

Estimated East Fork Andreafsky run size is modeled as:

$$\hat{N}_t = N_{t\cdot} e^{\varepsilon_{Nt}} \tag{31}$$

where the $\{\varepsilon_{Nt}\}$ are normal$(0,\sigma^2_{St})$. Point estimates $\{\hat{N}_t\}$ and variances $\{\sigma^2_{Nt}\}$ were obtained from the run reconstruction model (Table 2).

Similarly, estimated harvest rate of East Fork Andreafsky chum salmon is modeled as:

$$\hat{\mu}_t = \mu_t e^{\varepsilon_{\mu t}} \tag{32}$$

[13] Conventionally, observations of escapement and catch are used as input data for a stock recruit analysis. In this case, there were large positive correlations between the estimates of escapement and catch from the run reconstruction model. Because there is no easy way to specify this covariance structure for the input data to the spawner- recruit model in WinBUGS, run size and harvest rate were specified as stock recruit data instead. Estimates of run size and harvest rate from the run reconstruction model were nearly uncorrelated.

where the $\{\varepsilon_{\mu i}\}$ are normal$(0,\sigma^2_{\mu t})$. Again, point estimates $\{\hat{\mu}_t\}$ and variances $\{\sigma^2_{\mu t}\}$ were obtained from the run reconstruction model (Table 2).

Numbers of fish[14] sampled for scales (n) that were classified as age-a in calendar year t (x_{ta}) are assumed multinomially (r_{ta},n) distributed, with proportion parameters as follows:

$$r_{ta} = \frac{N_{ta}}{N_{t\cdot}} \qquad (33)$$

Non-informative priors (chosen to have a minimal effect on the posterior) were used for most parameters. Initial returns R_{1967}-R_{1971} (those with no linked spawner abundance) were modeled as drawn from a common lognormal distribution with median μ_{logR} and variance σ^2_{logR}. Normal priors with mean zero, very large variances, and constrained to be positive, were used for $\ln(\alpha)$ and β (Millar 2002), as well as for μ_{logR}. The initial model residual v_0 was given a normal prior with mean zero and variance $\sigma^2_W/(1-\phi^2)$. Diffuse conjugate inverse gamma priors were used for σ^2_W and σ^2_{logR}. Annual harvest rates $\{\mu_t\}$ were given beta (0.1,0.1) prior distributions. WinBUGS code and data are provided in Appendix A.

Markov-Chain Monte Carlo samples were drawn from the joint posterior probability distribution of all unknowns in the model. For each of two Markov chains initialized, a 4,000-sample burn-in period was discarded, thinning by a factor of 10 was initiated, and 25,000 additional updates were generated. The resulting total of 50,000 samples was used to estimate the marginal posterior means, standard deviations, and percentiles. The diagnostic tools of WinBUGS assessed mixing and convergence, and no major problems were encountered. Interval estimates were obtained from the percentiles of the posterior distribution.

RESULTS AND DISCUSSION

RUN RECONSTRUCTION

Estimated[15] overall run proportions θ in the four sub-drainages were as follows: East Fork Andreafsky 7% (SE=4%), West Fork Andreafsky 7% (4%), Anvik 44% (10%), and other chum stocks 43% (10%). These run proportions have changed over time. Most notably, the proportion of lower river (Andreafsky and Anvik) stocks has recently declined (Figure 4).

[14]Age data were based on published estimates of annual (1982–2007) escapement age proportions (Table 18 in Clark 2001). The published proportions were multiplied by subjectively chosen total sample sizes (n=50 scales per year, 1982–1993; n=100, 1994-2007). The quantity *n* was increased for recent data because the quantity and quality of age data improved after installation of the weir in 1994. Sample sizes were arbitrarily reduced far below actual values (up to 1,400 annually) because harvested fish were no doubt subject to gillnet size selectivity, and also because the precision of age composition estimates is generally overstated by the assumption of independent multinomial sampling. Estimates of S_{MSY} were not sensitive to choice of total scale sample size. An average of 96.5% of fish were age-4 and -5. Age-3 fish (average 1.2%) were omitted; age-6 fish (average 2.3%) were added to age-5 totals. See Table 2 for age proportion estimates used in this analysis. No reliable age data were available before 1982; these data were set to missing.

[15] The end product of any Bayesian statistical analysis is the posterior probability distribution of model parameters. Point estimates reported here are posterior medians, which have the following interpretation: there is an even (50/50) chance that the true value of the parameter lies above or below the posterior median. The posterior standard deviation is analogous to the standard error of an estimate from a classical (non-Bayesian) statistical analysis. Interval estimates are posterior percentiles.

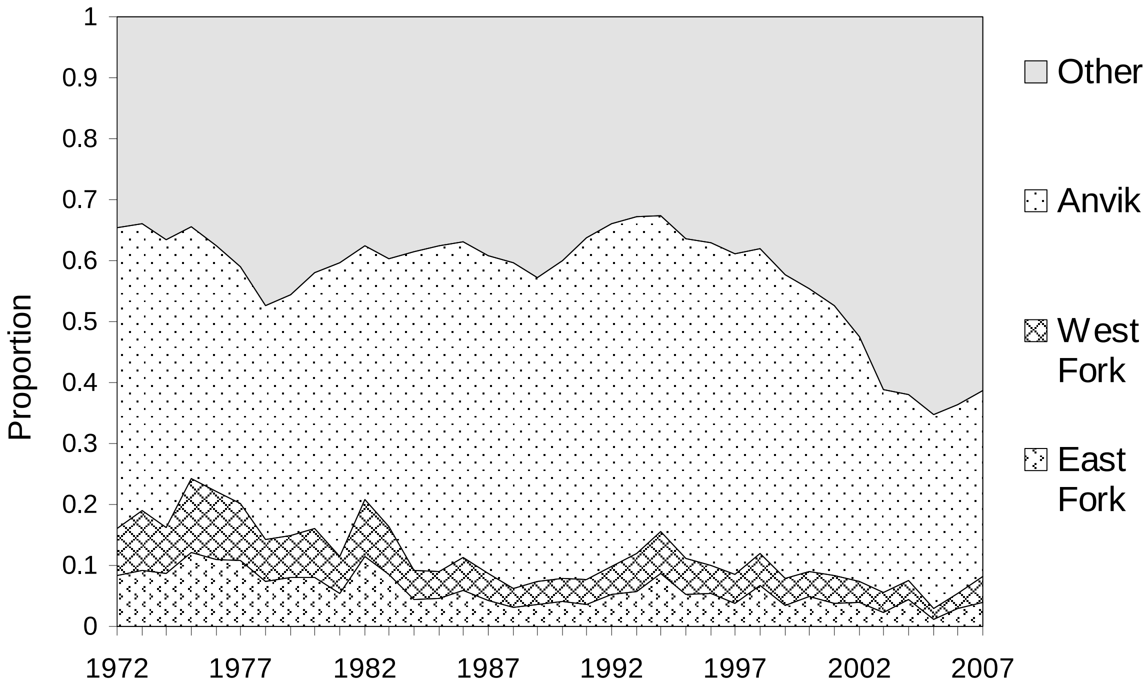

Figure 4.–Estimated proportions of sub-stocks of summer chum salmon in the Yukon River drainage, 1972–2007. East and West forks both refer to the Andreafsky River.

East Fork Andreafsky chum salmon escapement estimates ranged from about 21,000 in 2005 to 271,000 in 1976 (Table 2, Figure 5). There is a great deal of uncertainty about the escapement in years without direct estimates (before 1981 and 1989-1993), with measurement error CVs up to 64% (Table 2). Harvest estimates of East Fork Andreafsky chum salmon ranged from about 900 fish in 2003 to 63,000 in 1975, with CVs from 15% to 52% (Table 2, Figure 5).[16] Precision of harvest estimates parallels that of the escapement estimates (low precision before 1981 and 1989-1993)[17].

The run reconstruction also produced equivalent estimates for Anvik and (aggregated) other upriver stocks[18] (Table 3). Because of the gauntlet nature of the fishery, harvest rates are higher on stocks located further upriver (Figure 6). Aggregated stocks upriver from Anvik probably experienced high harvest rates in the 1970s and 80s, although there is a great deal of uncertainty about exactly how high.[19] Harvest rates on all Yukon summer chum salmon stocks were very low from 1998 to 2006 (Figure 6).

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[16] Many of the escapement and harvest estimates in the 1970s and 1980s are somewhat smaller than those produced by Clark (2001). This difference is partially responsible for the differing escapement goal recommendations of the two analyses.

[17] This is due to the nature of the run reconstruction. Total mixed-stock harvest is well estimated, but estimates of harvest by stock depend on knowledge of the relative abundance of each stock. There is poor information about the relative abundance of the individual stocks before 1981 and 1989-1993.

[18] Potentially, these estimates could serve as input to spawner recruit analyses for these stocks.

[19] We know that harvests were high at that time, but we have little information about run size of upriver stocks before 1995, the first year of mainstem sonar passage estimates.

Table 3.– Estimates of run size and harvest rate of Anvik and other upriver stocks of summer chum salmon, from run reconstruction of lower Yukon River summer chum salmon 1972–2007.

	Anvik River				Other Upriver Stocks			
	Estimated[a]		Estimated[a]		Estimated[a]		Estimated[a]	
Year	Run Size	CV	Harvest Rate	CV	Run Size	CV	Harvest Rate	CV
1972	425,100	0.29	0.22	0.26	279,500	0.45	0.44	0.33
1973	426,700	0.24	0.41	0.17	289,000	0.33	0.73	0.20
1974	645,000	0.22	0.50	0.12	464,900	0.24	0.87	0.13
1975	1,137,000	0.27	0.26	0.22	888,500	0.39	0.56	0.27
1976	702,200	0.24	0.33	0.17	612,400	0.29	0.77	0.19
1977	552,400	0.23	0.36	0.16	557,300	0.26	0.76	0.18
1978	748,400	0.21	0.45	0.10	890,400	0.14	0.93	0.08
1979	605,600	0.20	0.49	0.10	673,300	0.18	0.90	0.11
1980	916,300	0.21	0.44	0.14	873,700	0.23	0.84	0.15
1981	1,727,000	0.15	0.30	0.14	1,408,000	0.27	0.56	0.19
1982	726,700	0.14	0.35	0.12	627,600	0.24	0.79	0.16
1983	801,000	0.13	0.49	0.07	702,800	0.16	0.92	0.09
1984	1,145,000	0.14	0.32	0.12	824,000	0.24	0.75	0.17
1985	1,311,000	0.14	0.26	0.12	891,900	0.22	0.80	0.16
1986	1,642,000	0.14	0.30	0.13	1,134,000	0.27	0.72	0.18
1987	750,600	0.13	0.39	0.10	548,400	0.19	0.85	0.12
1988	1,699,000	0.12	0.42	0.10	1,254,000	0.21	0.83	0.13
1989	1,271,000	0.13	0.46	0.08	1,056,000	0.14	0.93	0.08
1990	628,800	0.13	0.36	0.11	464,800	0.20	0.85	0.13
1991	1,040,000	0.15	0.27	0.14	650,600	0.26	0.74	0.18
1992	976,700	0.15	0.26	0.15	562,100	0.30	0.68	0.21
1993	583,300	0.17	0.18	0.20	329,100	0.39	0.39	0.30
1994	1,228,000	0.18	0.09	0.19	744,700	0.38	0.33	0.34
1995	1,876,000	0.14	0.13	0.12	1,282,000	0.25	0.52	0.22
1996	1,144,000	0.16	0.17	0.15	768,800	0.27	0.75	0.20
1997	772,200	0.13	0.13	0.12	565,200	0.24	0.38	0.20
1998	523,100	0.14	0.10	0.12	389,400	0.24	0.16	0.16
1999	499,300	0.14	0.09	0.12	416,500	0.23	0.13	0.16
2000	241,400	0.14	0.12	0.12	229,100	0.22	0.17	0.14
2001	235,100	0.15	0.10	0.13	245,500	0.21	0.13	0.14
2002	470,100	0.15	0.06	0.12	609,300	0.19	0.09	0.15
2003	339,800	0.16	0.05	0.15	622,600	0.20	0.09	0.17
2004	439,300	0.16	0.05	0.14	886,900	0.20	0.08	0.16
2005	640,900	0.20	0.05	0.16	1,307,000	0.20	0.07	0.17
2006	1,104,000	0.17	0.03	0.14	2,258,000	0.20	0.06	0.17
2007	585,300	0.17	0.12	0.13	1,161,000	0.20	0.28	0.17

[a] Posterior median.

[b] Posterior standard deviation / posterior mean.

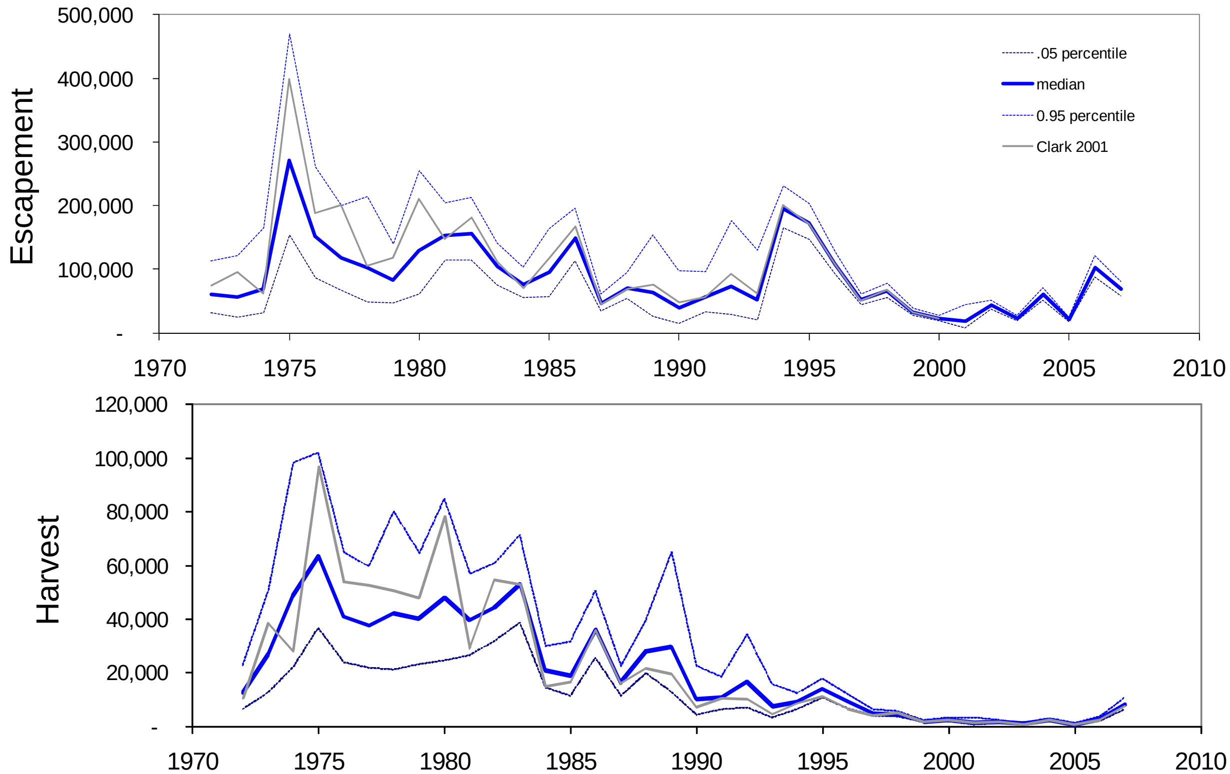

Figure 5.–Estimates of escapement and harvest of East Fork Andreafsky chum salmon from a run reconstruction of lower Yukon summer chum salmon, 1972–2007. Black solid line connects posterior medians, dotted lines bracket 90% credibility intervals; gray solid lines show estimates from Clark (2001) for comparison.

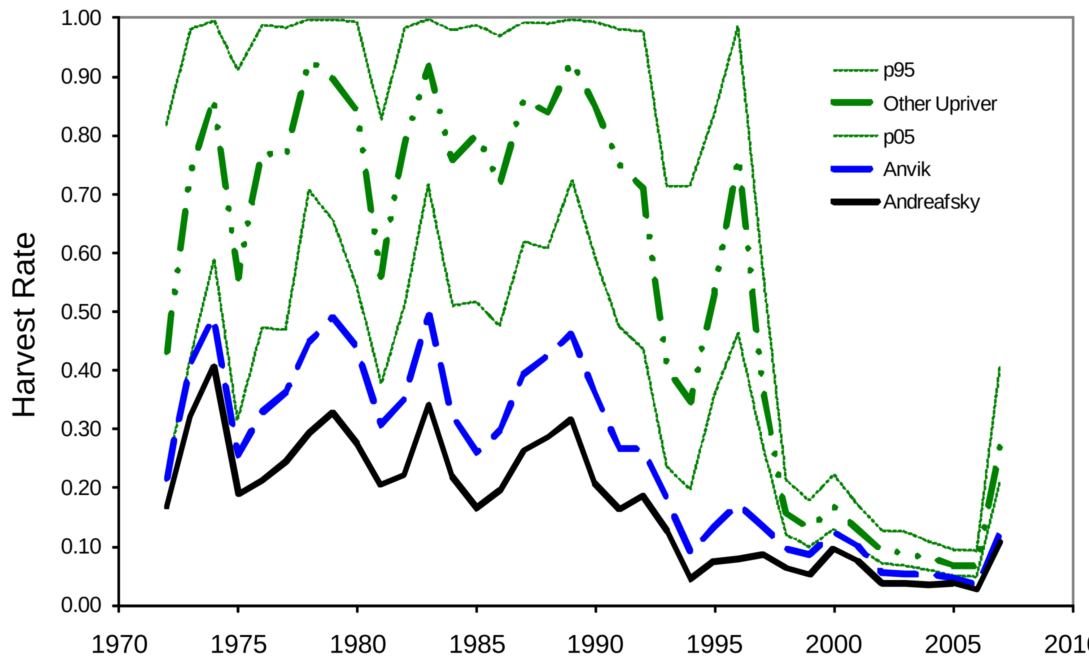

Figure 6.–Estimated harvest rates experienced by Andreafsky, Anvik, and aggregated other upriver stocks, from run reconstruction of lower Yukon summer chum salmon, 1972–2007. Ninety percent credibility intervals are shown for aggregated upriver stocks only.

Reconstructed estimates of total summer chum salmon run size (Yukon River drainagewide abundance; N_t in equation 1) are shown in Figure 7. These are concordant with comparable estimates produced by Shotwell and Adkison (2004), although consistently lower and with wider fluctuations for years prior to 1995.[20]

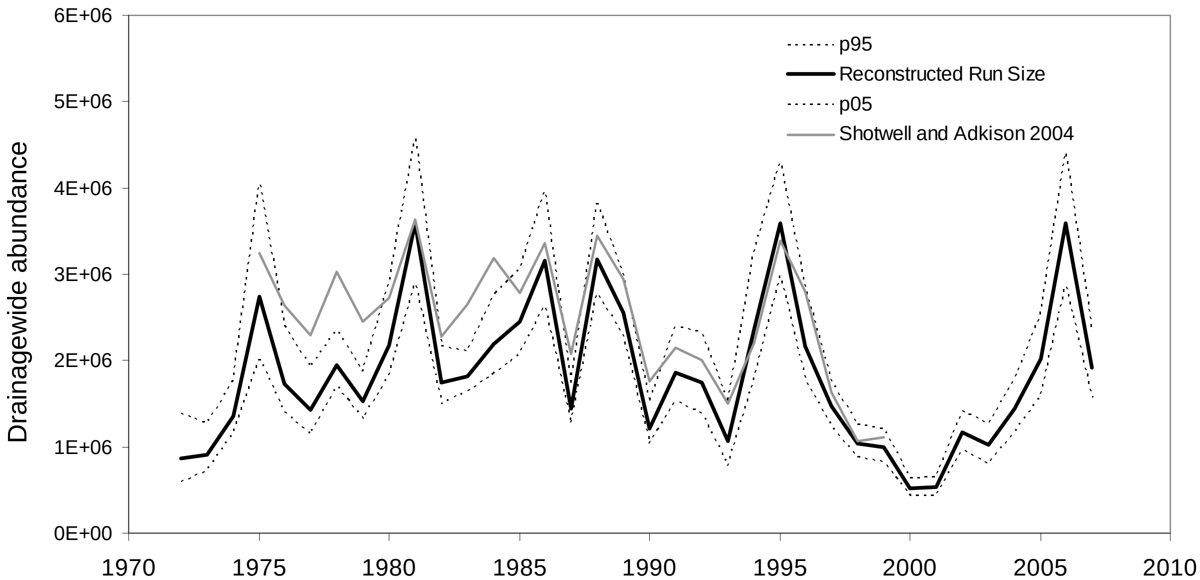

Figure 7.–Estimated total Yukon River drainage summer chum salmon run size, from run reconstruction of lower Yukon summer chum salmon, 1972-2007. Ninety percent credibility intervals are shown for run reconstruction estimates. Estimates of run size for 1975–1999 produced by Shotwell and Adkison (2004) are shown for comparison.

SPAWNER-RECRUIT ANALYSIS

The "point estimate" of the Ricker relationship, constructed from the posterior medians of ln(α) and β, is plotted in Figure 8, with parameter estimates detailed in Table 4. The estimates take into account the measurement error in both *S* and *R*, essentially weighting the individual data pairs depending on how precisely they are estimated[21]. Serial correlation in the relationship, as well as the lack of a complete set of age data, are also taken into consideration.

[20] It is likely that the "other upriver" component is responsible for the discrepancies with Shotwell and Adkison (2004), who included some historical aerial survey data from upriver stocks in their analysis. The current analysis, which is focused on reconstructing the Andreafsky stock, does not utilize upriver aerial surveys. Such data would contain very limited information about Andreafsky abundance because of the demonstrated tendency for the relative abundance of lower and upper river stocks to change over time. Shotwell and Adkison (2004) do not provide geographic breakdowns of abundance.

[21] Data points {S,R} plotted in Figure 8 differ from those of the run reconstruction model because the new estimates are in the context of the spawner-recruit model, which causes individual estimates to "shrink" toward the fitted value of the spawner-recruit relationship for that brood year.

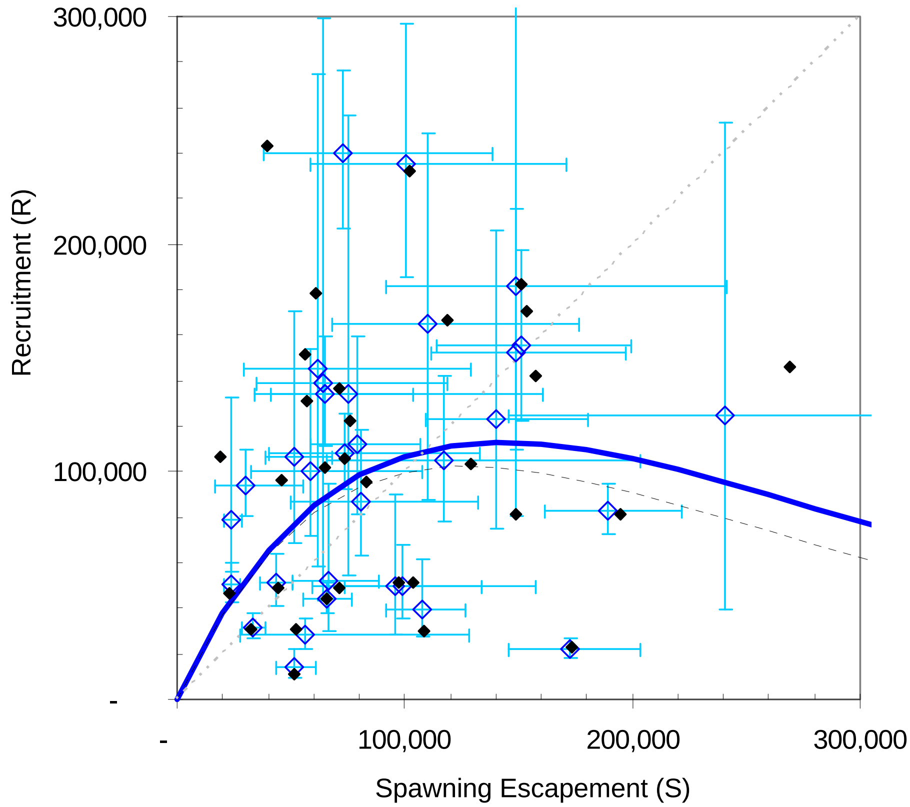

Figure 8.–Scatter plot of recruitment versus escapement estimates, Andreafsky River summer chum salmon, brood years 1972–2003. Posterior medians are plotted as open symbols, 5th and 95th posterior percentiles are bracketed by error bars. Point estimates of S and R from the run reconstruction model are plotted as solid symbols for comparison. Ricker relationships are Bayesian posterior median (solid line) and classical estimate (dashed line). Diagonal dotted line is replacement (R=S) line.

Table 4.–Posterior percentiles from a Bayesian age-structured Ricker spawner-recruit analysis of 1972–2007 Andreafsky River summer chum salmon escapement, harvest, and age data. Quantities are defined in text.

	Percentiles				
	2.5%	**5%**	**median**	**95%**	**97.5%**
ln(0)	0.13	0.22	0.77	1.46	1.64
0	1.1	1.2	2.2	4.3	5.2
0	1.66E-06	2.40E-06	7.06E-06	1.29E-05	1.41E-05
0_W	0.51	0.54	0.69	0.90	0.95
0	0.02	0.08	0.44	0.77	0.83
S_{MAX}	70,910	77,260	141,700	417,400	604,400
S_{EQ}	91,450	99,140	150,400	398,700	580,900
S_{MSY}	39,410	42,200	62,920	156,000	219,800
U_{MSY}	0.21	0.24	0.46	0.70	0.76
D	3	4	6	10	10
0_3	0.52	0.53	0.59	0.65	0.66
0_4	0.34	0.35	0.41	0.47	0.48

It is likely that productivity of the stock is low: there is 95% probability that α is less than 4.3 (Table 4). There is positive serial correlation in productivity ($0.08 < \phi < 0.77$ with 90% probability; for log residuals see Figure 9). The classical point estimate of the Ricker curve, calculated by simple linear regression and ignoring age structure, serial correlation and measurement error, is plotted in Figure 8 for comparison. Apparently, given the minor difference between the two estimated Ricker relationships, serial correlation and measurement error had either small or compensating effects on the estimates for this stock. This is despite the fact that measurement error and serial correlation are both substantial.

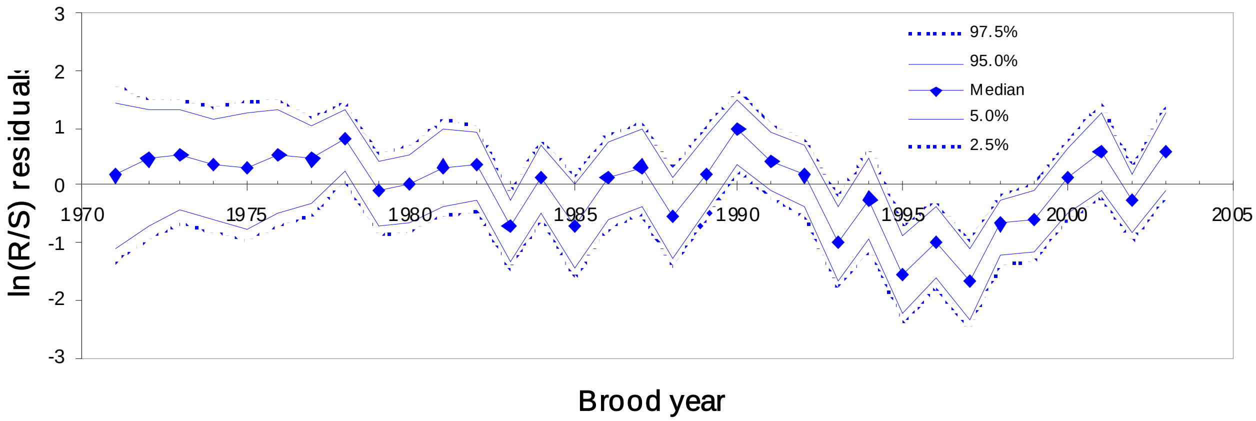

Figure 9.–Residuals (log deviations of R from Ricker spawner-recruit model) for East Fork Andreafsky River summer chum salmon, brood years 1971–2003. Posterior medians and other percentiles are plotted.

The point estimates described above must be considered in the context of the uncertainty about the Ricker relationship. Uncertainty is graphically displayed in Figure 10, which shows Ricker curves generated from ~50 MCMC samples drawn from the posterior distribution of α and β. These represent a sample of Ricker relationships that *could have* generated the observed $\{S,R\}$ data. The slope at the origin varies substantially among the individual curves, reflecting uncertainty about α. The graphical evidence is confirmed by wide 90% interval estimates for α (1.2 – 4.3; Table 4). Poor information about the productivity parameter is typical of stocks with high serial correlation.

Carrying capacity S_{EQ}, represented in Figure 10 by where the curves intersect the replacement line, is subject to similar uncertainty (90% interval 99,000 – 399,000; Table 4), as is the point of maximum recruitment S_{MAX} (77,000 – 417,000), the density-dependent parameter β (2–13 x 10^{-6}) and spawning escapement leading to maximum sustained yield S_{MSY} (42,000 – 156,000). S_{MSY} is equally likely to be above or below 61,920.

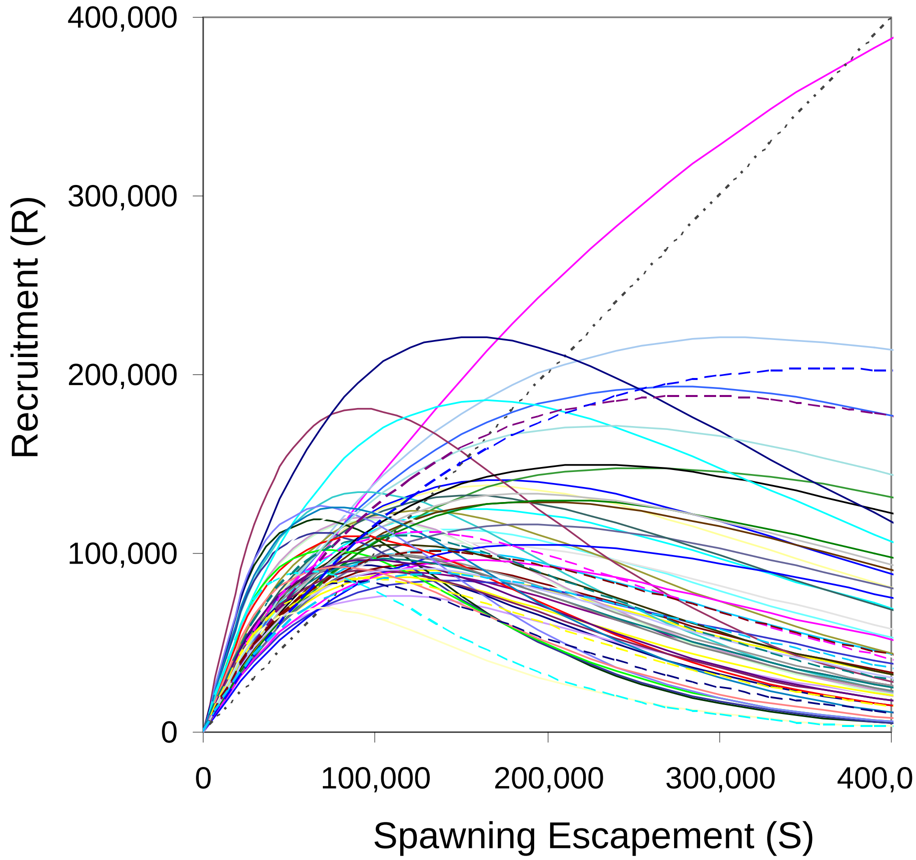

Figure 10.–Ricker relationships represented by ~50 paired values of ln(a) and b sampled from the posterior probability distribution of spawner-recruitment statistics, Andreafsky River summer chum salmon. Curves are a sample of Ricker relationships that could have generated the observed data.

The yield probability profiles in Figure 11 display the probability of achieving near maximal sustained yield (>70%, 80%, and 90% of MSY) for specified levels of escapement. These can be used to evaluate prospective escapement goals. For this stock, there is only weak to moderate certainty about which escapements produce maximal yield[22], yet there is sufficient information to see that the current goal of 65,000-130,000 is too high with respect to maximizing yield performance. The current goal does not effectively bracket the range of escapements with the highest probability of optimal yield; and there is clearly room to move the goal downward (Figure 11).

Although escapements lower than the current escapement goal range have potential for equal or greater yield, the absolute amount of yield is very uncertain (Figure 12; note the extremely wide yield intervals). Perhaps a more important benefit of lowering the goal would be to reduce the potential for unnecessary disruption to subsistence and commercial fisheries. Escapements have been below 65,000 approximately 40% of the time since 1972, even during recent years when fishing has been severely curtailed (Table 2, Figure 13).

---

[22] The steeper the limbs of the probability profile in Figure 11, the more information about what range of escapements produce maximal yield. Compared to other stocks, the probability profile for Andreafsky summer chum is only moderately steep, reflecting fair information about the spawner-recruit relationship.

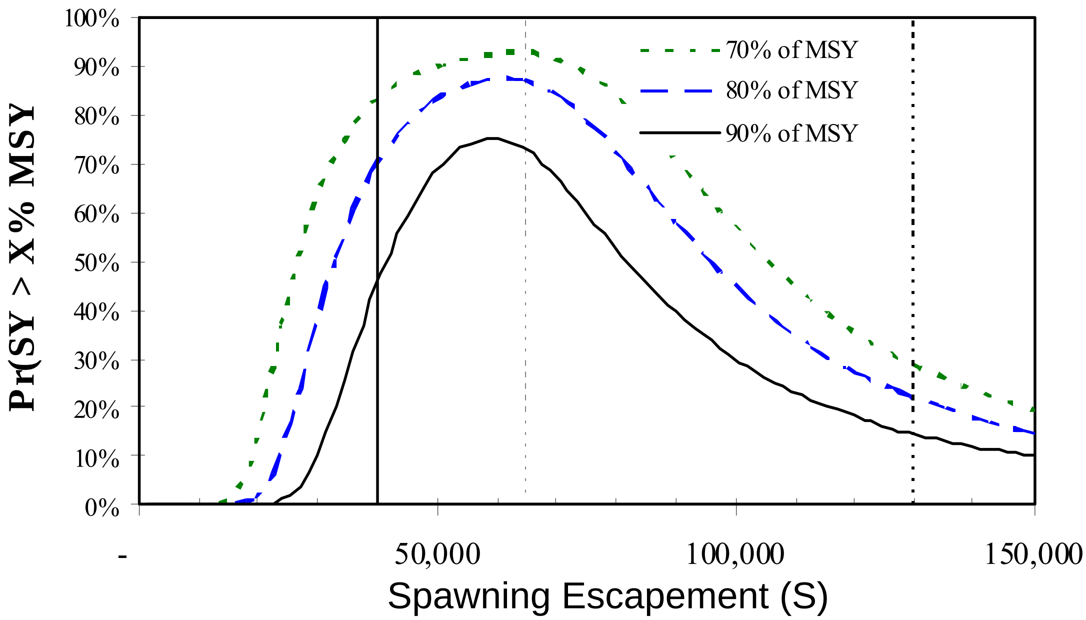

Figure 11.–Probability that a specified spawning abundance will achieve 70%, 80%, and 90% of maximum sustained yield, Andreafsky River summer chum salmon (curved profiles). Vertical lines show current escapement goal range and the proposed lower-bound SEG.

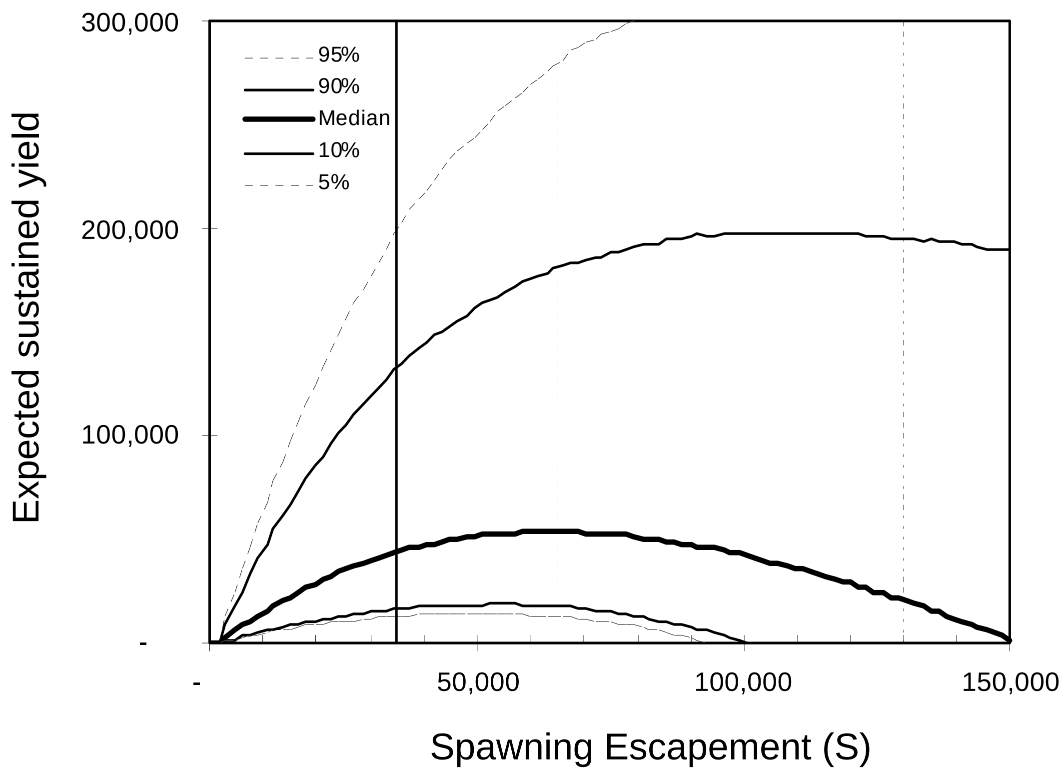

Figure 12.–Bayesian posterior percentiles of expected sustained yield at specified spawning abundances, Andreafsky River summer chum salmon. Vertical lines show current escapement goal range and proposed lower-bound SEG.

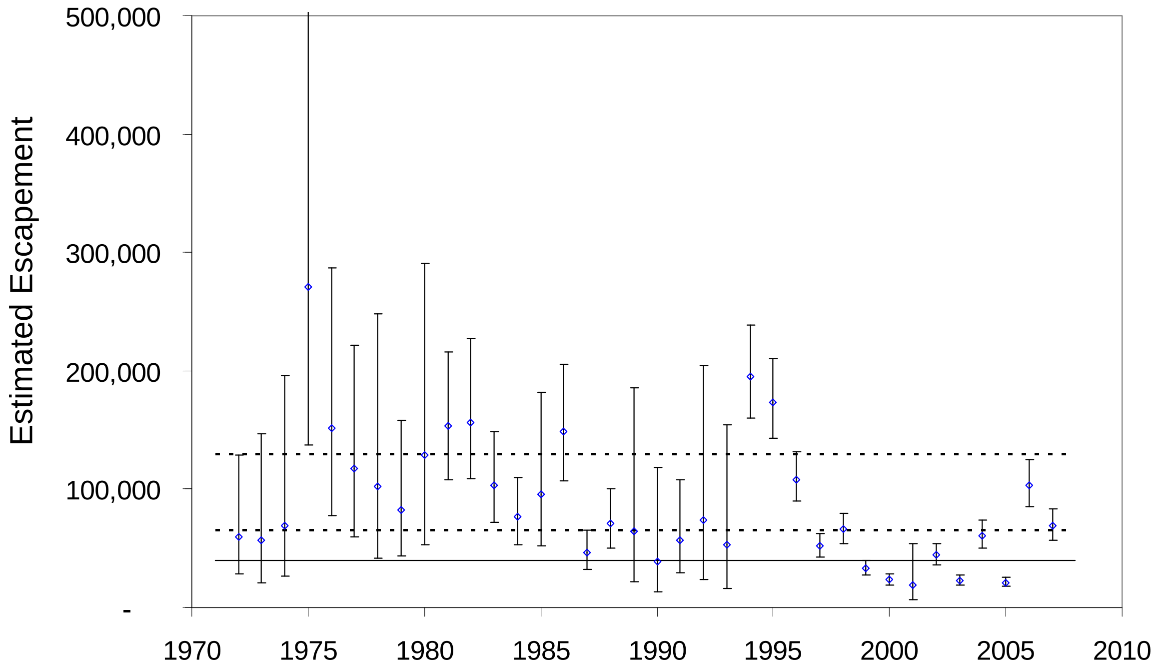

Figure 13.–Historical estimates of escapement and 95% credibility intervals, Andreafsky River summer chum salmon 1972–2007. Horizontal dotted lines bracket the current escapement goal range of 65,000 to 130,000. Horizontal solid line shows proposed lower-bound SEG.

ESCAPEMENT GOAL RECOMMENDATION

A lower bound sustainable escapement goal is recommended for this stock, primarily because it would be difficult or undesirable to hold escapements below the upper bound of a range through inseason management actions. The Andreafsky River is low in the Yukon River drainage and its chum salmon are of relatively low quality, reducing the incentive to single them out for harvest, for instance, by fishing in or near the mouth of the river. Elsewhere in District Y1 and part of Y2, Andreafsky River chum salmon are mixed with other chum salmon stocks, as well as with Chinook salmon. These other stocks are subject to higher harvest rates because they are vulnerable for a longer period as they travel upriver, and thus they must be managed more carefully in the lower river. Therefore, we are unlikely to bring sufficient fishing power in a timely manner to prevent escapement to the Andreafsky River from exceeding an upper limit, and a lower-bound SEG is most appropriate for this stock.

Alaska Department of Fish and Game recommends changing the goal to a lower-bound SEG of 40,000 summer chum salmon enumerated at the East Fork Andreafsky River weir. Escapements of 40,000 have a high probability of achieving near optimal yields, with an 84% probability of achieving 0.7 MSY, a 70% probability of achieving 0.8 MSY, and 47% probability of achieving 0.9 MSY on average (Figure 11).

In summary, Andreafsky River summer chum salmon have low productivity and highly autocorrelated returns. Abundance is probably largely controlled by density-independent factors, such as fluctuating conditions in the freshwater, marine, and estuarine environments. Information garnered from the run reconstruction and spawner-recruit analyses suggests that the current escapement goal could safely be changed to a lower bound SEG of 40,000. The new goal would improve yield potential and reduce disruptions to the lower Yukon summer chum fishery.

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APPENDIX A
WINBUGS CODE AND DATA

Appendix A1.–WinBUGS model code for Bayesian MCMC statistical analysis of Andreafsky River summer chum salmon data, run reconstruction model, 1972-2007. Prior distributions are italicized; sampling distributions of the data are underlined. Notation does not necessarily correspond to report.

WinBUGS code for Run Reconstruction Model

```
model{
 mu.log.N ~ dnorm(0,1.0E-4)I(0,)
 tau.N ~ dgamma(1,10)
 q.AirSurv ~ dunif(0,1)
 tau.AirSurv ~ dgamma(4,1)    # Air survey relationship "too good to be true"
 tau.log.Pilot ~ dgamma(24,0.48)   # sigma.PS = 0.15 (approx 2x as precise as fall chum)
 sigma.Pilot <- 1 / sqrt(tau.log.Pilot)
 for (b in 1:3) {
  phi[b] ~ dnorm(0,1.0E-4)I(-1,1)
  tau.white[b] ~ dgamma(0.01,0.01)
  logit.resid.0[b] ~ dnorm(0,tau.red[b])I(-3,3)
  pi[b] ~ dunif(0,1)
  }
 sigma.log.N <- 1 / sqrt(tau.N)
 mu.N <- exp(mu.log.N + sigma.log.N * sigma.log.N / 2)
 sigma.AirSurv <- 1 / sqrt(tau.AirSurv)

#  Annual total runs drawn from common lognormal distribution;
 for (y in 1:Y) {
    N[y] <- exp(log.N[y])
    log.N[y] ~ dnorm(mu.log.N,tau.N)
    }

# AR(1) logit proportions at river bifurcations {b=1,2,3}.
   # b=1: Andreafsky vs (other including Anvik)
   # b=2: East vs West Fork Andreafsky
   # b=3: Anvik vs other upriver
 for (b in 1:3) {
  logit.pi[b] <- log(pi[b]/(1-pi[b]))
  logit.p[b,1]                 <- logit.pi[b] + phi[b] * logit.resid.0[b]
  for (y in 2:Y) {    logit.p[b,y] <- logit.pi[b] + phi[b] * logit.resid[b,y-1] }
  for (y in 1:Y) {
    logit.resid[b,y] <- logit.p.obs[b,y] - logit.pi[b]
    logit.p.obs[b,y] ~ dnorm(logit.p[b,y],tau.white[b])
    p[b,y] <- exp(logit.p.obs[b,y]) / (1 + exp(logit.p.obs[b,y]))
    }
  }
 for (b in 1:3) {
  tau.red[b] <- tau.white[b] * (1-phi[b]*phi[b])
  sigma.white[b] <- 1 / sqrt(tau.white[b])
  sigma.red[b] <- 1 / sqrt(tau.red[b])
  }
```

-continued-

```
# IR = Inriver return at the bottom of each of three reaches
  for (y in 1:Y) {
    N.Andreafsky[y] <- p[1,y] * N[y]
    N.Anvik[y] <- (1-p[1,y]) * p[3,y] * N[y]
    N.other[y] <- (1-p[1,y]) * (1-p[3,y]) * N[y]
    IR[y,1] <- N.Andreafsky[y] + N.Anvik[y] + N.other[y]
    IR[y,2] <-                          (N.Anvik[y] + N.other[y]) * (1 - mu[y,1])
    IR[y,3] <-                                              N.other[y]  * (1 - mu[y,1])  * (1 - mu[y,2])
    }
  for (reach in 1:3) {
    for (y in 1:Y) {
         mu[y,reach] ~ dunif(0,1)
          H[y,reach] <- mu[y,reach] * IR[y,reach]
          log.H[y,reach] <- log(H[y,reach])
      H.hat[y,reach] ~ dlnorm(log.H[y,reach],400)
      }
         }

# Multinomial sub-stock proportions, overall and by year
  theta.Andreafsky <- pi[1]
  theta.Efork <- pi[1] * pi[2]
  theta.Wfork <- pi[1] * (1-pi[2])
  theta.Anvik <- (1-pi[1]) * pi[3]
  theta.other <- (1-pi[1]) * (1-pi[3])
  for (y in 1:Y) {
    q.Andreafsky[y] <- p[1,y]
    q.Efork[y] <- p[1,y] * p[2,y]
    q.Wfork[y] <- p[1,y] * (1-p[2,y])
    q.Anvik[y] <- (1-p[1,y]) * p[3,y]
    q.other[y] <- (1-p[1,y]) * (1-p[3,y])
    }

# Observed estimates and indices of escapement by substock/method;
#  Pilot Station sonar assumed to be an unbiased estimator of passage
  for (y in 1:Y) {
      N.EF[y] <- p[2,y] * N.Andreafsky[y]
      S.EF[y] <- N.EF[y] * (1 - mu[y,1])
      H.EF[y] <- N.EF[y] - S.EF[y]
      mu.EF[y] <- H.EF[y] / N.EF[y]
      log.S.EF[y] <- log(S.EF[y])
      log.Shat.EF[y] ~ dnorm(log.S.EF[y],tau.log.S.EF[y])
      S.hat.EF[y] <- exp(log.Shat.EF[y])

      log.Sq.EF[y] <- log(S.EF[y]) + log(q.AirSurv)
      log.AirSurv.EF[y] ~ dnorm(log.Sq.EF[y],tau.AirSurv)
      AirSurv.EF[y] <- exp(log.AirSurv.EF[y])
```

-continued-

```
    N.WF[y] <- (1-p[2,y]) * N.Andreafsky[y]
    S.WF[y] <- N.WF[y] * (1 - mu[y,1])
    H.WF[y] <- N.WF[y] - S.WF[y]
    mu.WF[y] <- H.WF[y] / N.WF[y]
    log.Sq.WF[y] <- log(S.WF[y]) + log(q.AirSurv)
    log.AirSurv.WF[y] ~ dnorm(log.Sq.WF[y],tau.AirSurv)
 AirSurv.WF[y] <- exp(log.AirSurv.WF[y])

    S.Anvik[y] <- N.Anvik[y] * (1 - mu[y,1]) * (1 - mu[y,2])
    H.Anvik[y] <- N.Anvik[y] - S.Anvik[y]
    mu.Anvik[y] <- H.Anvik[y] / N.Anvik[y]
    log.S.Anvik[y] <- log(S.Anvik[y])
    log.Shat.Anvik[y] ~ dnorm(log.S.Anvik[y],tau.log.S.Anvik[y])
    S.hat.Anvik[y] <- exp(log.Shat.Anvik[y])

    S.other[y] <- IR[y,3] * (1-mu[y,3])
    H.other[y] <- N.other[y] - S.other[y]
    mu.other[y] <- H.other[y] / N.other[y]

    N.Pilot[y] <- max(IR[y,2] - H.statarea33425[y],1)
    log.Pilot[y] <- log(N.Pilot[y])
    log.Pilot.hat[y] ~ dnorm(log.Pilot[y],tau.log.Pilot)
    Pilot.hat[y] <- exp(log.Pilot.hat[y])

    Anvik.to.Pilot[y] <- S.Anvik[y] / N.Pilot[y]

# Measurement error coefficients of variation converted to precisions;
    tau.log.S.EF[y] <- 1 / cv.S.EF[y] / cv.S.EF[y]
    tau.log.S.Anvik[y] <- 1 / cv.S.Anvik[y] / cv.S.Anvik[y]
    }
 }
```

Appendix A2.–WinBUGS model code for Bayesian MCMC statistical analysis of Andreafsky River summer chum salmon data, age-structured spawner recruit model, 1972–2007. Prior distributions are italicized; sampling distributions of the data are underlined. Notation does not necessarily correspond to report.

WinBUGS code for Age-structured Spawner Recruit Model

```
model {
#  RICKER STOCK-RECRUIT RELATIONSHIP WITH AR1 ERRORS;
#  R[y] IS THE TOTAL RETURN FROM BROOD YEAR y
#  THERE ARE A TOTAL OF Y+A-1 = 36 + 2 - 1 = 37 BROOD YRS REPRESENTED IN DATA
#  THE FIRST a.max = 5 DO NOT HAVE CORRESPONDING SPAWNING ABUNDANCES
#  THE REMAINING Y-a.min = 32 DO (BROOD YEARS A+a.min=6 - 37)
 for (y in A+a.min:Y+A-1) {
  log.R[y] ~ dt(log.R.mean2[y],tau.white,500)
  R[y] <- exp(log.R[y])
  log.R.mean1[y] <- log(S[y-a.max]) + lnalpha - beta * S[y-a.max]
  log.resid[y] <- log(R[y]) - log.R.mean1[y]
  }
 log.R.mean2[A+a.min] <- log.R.mean1[A+a.min] + phi * log.resid.0
 for (y in A+a.min+1:Y+A-1) {
  log.R.mean2[y] <- log.R.mean1[y] + phi * log.resid[y-1]
  }
 lnalpha ~ dnorm(0,1.0E-6)I(0,)
 beta ~ dnorm(0,1.0E-1)I(0,)
 phi ~ dnorm(0,1.0E-4)I(-1,1)
 tau.white ~ dgamma(0.01,0.01)
 log.resid.0 ~ dnorm(0,tau.red)I(-3,3)
 alpha <- exp(lnalpha)
 tau.red <- tau.white * (1-phi*phi)
 sigma.white <- 1 / sqrt(tau.white)
 sigma.red <- 1 / sqrt(tau.red)
 lnalpha.c <- lnalpha + (sigma.white * sigma.white / 2 / (1-phi*phi) )
 S.max <- 1 / beta
 S.eq <- lnalpha.c * S.max
 S.msy <- S.eq * (0.5 - 0.07*lnalpha.c)
 U.msy <- lnalpha.c * (0.5 - 0.07*lnalpha.c)

# BROOD YEAR RETURNS W/O SR LINK DRAWN FROM COMMON LOGNORMAL DISTN
 mean.log.R ~ dnorm(0,1.0E-4)I(0,)
 tau.R ~ dgamma(1,10)          #TO MINIMIZE SHRINKAGE
 for (y in 1:a.max) {
  log.R.lag[y] ~ dt(mean.log.R,tau.R,500)
  R.lag[y] <- exp(log.R.lag[y])
  }

# GENERATE Y+A-1 = 37 MATURITY SCHEDULES, ONE PER BROOD YEAR
 D.scale ~ dunif(0,1)
 D.sum <- 1 / (D.scale * D.scale)
 pi[1] ~ dbeta(1,1)
 pi[2] <- 1 - pi[1]
 for (a in 1:A) {
  gamma[a] <- D.sum * pi[a]
```

-continued-

```
  for (y in 1:Y+A-1) {
    g[y,a] ~ dgamma(gamma[a],1)
    p[y,a] <- g[y,a]/sum(g[y,])
   }
  }
for (a in 2:A) {
  sibratio[a] <- pi[a] / pi[a-1]
  }

# ASSIGN PRODUCT OF P AND R TO ALL CELLS IN N MATRIX
# y SUBSCRIPT INDEXES BROOD YEAR
# y=1 IS THE BROOD YEAR OF THE OLDEST FISH IN YEAR 1 (upper right cell)
# y=37 IS THE BROOD YEAR OF THE YOUNGEST FISH IN YEAR Y (lower left cell)

# FIRST DO INITIAL CELLS WITHOUT SR LINK (o's and x's IN MATRIX ABOVE)
for (y in 2:a.max)  {  N.ta[y-1,1] <- p[y,1] * R.lag[y]  }    # COLUMN 1
for (y in 1:a.max)  {  N.ta[y   ,2] <- p[y,2] * R.lag[y]  }    # COLUMN A=2

# THEN DO CELLS DESCENDING WITH SR LINK (y's IN MATRIX)
for (y in a.max+1:Y+1)   {  N.ta[y-1,1] <- p[y,1] * R[y]  }
for (y in a.max+1:Y)       {  N.ta[y  ,2] <- p[y,2] * R[y]  }

# MULTINOMIAL SCALE SAMPLING ON TOTAL ANNUAL RETURN N
# INDEX t IS CALENDAR YEAR
for (t in 1:Y) {
  N[t] <- sum(N.ta[t,1:A])
  for (a in 1:A) {
    q[t,a] <- N.ta[t,a] / N[t]
    }
  n[t] <- sum(x[t,1:A])
  x[t,1:A] ~ dmulti(q[t,],n[t])
  }

# RUN SIZE AND HARVEST RATE ESTIMATED
# MU^ AND N^ ARE DATA
for (y in 1:Y) {
  log.N[y] <- log(N[y])
  tau.log.N[y] <- 1 / N.cv[y] / N.cv[y]
  N.hat[y] ~ dlnorm(log.N[y],tau.log.N[y])
  mu.H[y] ~ dbeta(0.1,0.1)
  log.mu[y] <- log(mu.H[y])
  tau.log.mu[y] <- 1 / mu.cv[y] / mu.cv[y]
  mu.hat[y] ~ dlnorm(log.mu[y],tau.log.mu[y])
  H[y] <- mu.H[y] * N[y]
  S[y] <- max(N[y] - H[y],1)
  }
```

-continued-

```
 # GENERATE FITTED VALUES OF R FOR GRAPHICS;
for (i in 1:25) {
  S.star.1[i] <- 15000*i
  R.fit[i] <- S.star.1[i] * exp(lnalpha - beta * S.star.1[i])
  }
# CALCULATE SUSTAINED YIELD AT REGULAR INTERVALS OF S;
# FIND PROBABILITY THAT EACH VALUE OF S WILL RESULT IN YIELDS WITHIN x% OF MSC;
R.msy <- S.msy * exp(lnalpha - beta * S.msy)*exp(sigma.red*sigma.red/2)
MSY <- R.msy - S.msy
for (i in 1:100) {
  S.star.2[i] <- 1500*i
  R.fit2[i] <- S.star.2[i] * exp(lnalpha - beta * S.star.2[i])*exp(sigma.red*sigma.red/2)
  SY[i] <- R.fit2[i] - S.star.2[i]
  I90[i] <- step(SY[i] - 0.9 * MSY)
  I80[i] <- step(SY[i] - 0.8 * MSY)
  I70[i] <- step(SY[i] - 0.7 * MSY)
  }
}
```

Appendix A3.–WinBUGS data objects for Bayesian analysis of Andreafsky River summer chum salmon data, run reconstruction model, 1972–2007.

Data for Run Reconstruction Model

```
log.Shat.EF[] log.AirSurv.EF[] log.AirSurv.WF[] log.Shat.Anvik[]
log.Pilot.hat[] cv.S.EF[] cv.S.Anvik[]
   NA 10.63    NA 13.03    NA 0.2   0.4
   NA    NA 10.86 12.43    NA 0.2   0.4
   NA    NA 10.42 12.93    NA 0.2   0.4
   NA 12.32 12.37 13.71    NA 0.2   0.4
   NA 11.57 11.68 13.15    NA 0.2   0.4
   NA 11.63 11.05 12.79    NA 0.2   0.4
   NA    NA 10.96 12.64    NA 0.2   0.4
   NA 11.10 10.68 12.53    NA 0.2   0.4
   NA    NA 11.65 13.09    NA 0.2   0.4
11.90 11.31    NA 14.21    NA 0.2   0.2
12.11    NA    NA 13.00    NA 0.2   0.2
11.61    NA    NA 12.80    NA 0.2   0.2
11.16    NA    NA 13.70    NA 0.2   0.2
   NA 11.10 10.87 13.89    NA 0.2   0.2
12.03 11.34 11.51 13.99    NA 0.2   0.2
10.72    NA 10.48 13.03    NA 0.2   0.2
11.14 10.67 10.72 13.93    NA 0.2   0.2
   NA    NA    NA 13.36    NA 0.2   0.2
   NA    NA    NA 12.91    NA 0.2   0.2
   NA 10.37 10.75 13.65    NA 0.2   0.2
   NA    NA    NA 13.56    NA 0.2   0.2
   NA    NA    NA 13.16    NA 0.2   0.2
12.21    NA    NA 13.95    NA 0.1   0.2
12.06    NA    NA 14.15 15.08 0.1   0.2
11.59    NA    NA 13.83    NA 0.1   0.2
10.84    NA    NA 13.34 14.16 0.1   0.2
11.12    NA    NA 13.10 13.62 0.1   0.2
10.38    NA    NA 12.99 13.79 0.1   0.2
10.06    NA    NA 12.19 13.03 0.1   0.2
   NA    NA    NA 12.32 13.00 0.1   0.2
10.70    NA    NA 13.04 13.90 0.1   0.2
10.03    NA    NA 12.46 13.97 0.1   0.2
11.05    NA    NA 12.81 14.12 0.1   0.2
 9.91    NA    NA 13.17 14.68 0.1   0.3
11.54    NA    NA 13.81 15.14 0.1   0.2
11.15    NA    NA 13.04 14.36 0.1   0.2
END
```

-continued-

```
list( Y=36,
H.hat = structure(.Data =c(
148361,         34919,  60394,
291571,         64916,  90033,
555749,         94042,  167912,
519627,         135599,         266958,
369496,         151866,         266404,
345262,         130357,         219074,
571989,         258084,         419748,
501990,         206766,         267075,
597767,         290033,         348102,
734846,         313445,         349651,
386641,         176878,         271687,
619711,         232017,         293919,
474916,         206544,         351795,
405124,         211048,         476851,
618971,         282972,         470140,
376403,         170469,         251455,
906617,         408448,         505065,
809362,         343836,         481323,
250545,         169302,         223501,
300445,         174688,         306480,
318614,         116997,         236737,
130391,         48836,  68772,
103741,         85682,  182783,
266137,         185005,         494022,
169905,         179402,         445497,
127084,         64691,  137229,
65934,  29693,  22699,
52561,  30675,  18273,
49772,  12491,  10095,
39624,  11992,  6997,
45023,  20008,  21758,
38428,  14908,  21929,
52178,  21343,  23212,
78570,  14899,  27418,
87926,  27151,  69784,
203715,         31108
),.Dim=c(36,3)),
H.statarea33425=c(5031,12183,14978,18314,17860,18297,36209,28492,46837,53187,
29171,62738,48029,27612,41527,22787,60114,54640,30529,36566,
25839,10374,4039,15340,9558,1669,5233,4467,2839,3814,
5915,1641,7404,3332,4658,12587)
)
```

Appendix A4.–WinBUGS data objects for Bayesian analysis of Andreafsky River summer chum salmon data, age-structured spawner recruit model, 1972–2007.

Data for Age-structured Spawner Recruit Model

```
list( Y=36, A=2, a.min=4, a.max=5,
x = structure(.Data =c(
0,0,
0,0,
0,0,
0,0,
0,0,
0,0,
0,0,
0,0,
0,0,
0,0,
37,13,
19,31,
36,13,
37,13,
31,19,
14,35,
35,14,
23,26,
47,3,
26,25,
12,38,
30,20,
69,31,
45,55,
58,42,
28,73,
84,16,
27,72,
53,47,
20,80,
85,15,
76,24,
77,20,
93,7,
27,72,
72,27
),.Dim = c(36,2))
)
```

-continued-

mu.hat[]	mu.cv[]	N.hat[]	N.cv[]
0.171	0.25	72790	0.39
0.322	0.17	83300	0.50
0.410	0.13	118400	0.50
0.190	0.21	335900	0.32
0.214	0.16	193200	0.32
0.243	0.16	155800	0.32
0.294	0.10	144500	0.45
0.329	0.11	122600	0.32
0.274	0.14	177700	0.42
0.205	0.14	192900	0.18
0.222	0.12	200900	0.18
0.340	0.08	156800	0.18
0.217	0.13	97450	0.19
0.165	0.12	115000	0.32
0.196	0.13	185500	0.16
0.261	0.10	62650	0.18
0.285	0.10	99100	0.17
0.317	0.09	93550	0.56
0.208	0.12	49560	0.61
0.162	0.14	67870	0.33
0.183	0.16	90590	0.54
0.123	0.20	60310	0.59
0.044	0.18	204500	0.10
0.074	0.12	187200	0.10
0.079	0.15	117700	0.10
0.086	0.12	56720	0.10
0.063	0.12	70330	0.10
0.053	0.13	34610	0.10
0.096	0.12	25760	0.10
0.075	0.13	20130	0.57
0.039	0.13	46160	0.10
0.038	0.15	24020	0.10
0.036	0.14	63310	0.10
0.039	0.16	22150	0.10
0.025	0.14	105900	0.10
0.106	0.13	77000	0.10

END