Fishery Manuscript Series No. 09-08

Escapement Estimation, Spawner-Recruit Analysis, and Escapement Goal Recommendation for Fall Chum Salmon in the Yukon River Drainage

by

Steven J. Fleischman

and

Bonnie M. Borba

December 2009

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

Symbols and Abbreviations

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

Weights and measures (metric)	
centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)	
cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature	
day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry	
all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

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

Measures (fisheries)	
fork length	FL
mideye to fork	MEF
mideye to tail fork	METF
standard length	SL
total length	TL

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

FISHERY MANUSCRIPT SERIES NO. 09-08

ESCAPEMENT ESTIMATION, SPAWNER-RECRUIT ANALYSIS, AND ESCAPEMENT GOAL RECOMMENDATION FOR FALL CHUM SALMON IN THE YUKON RIVER DRAINAGE

by

Steven J. Fleischman
Division of Sport Fish, Anchorage

and

Bonnie M. Borba
Division of Commercial Fisheries, Fairbanks

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

December 2009

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.

Steven J. Fleischman
Alaska Department of Fish and Game, Division of Sport Fish, RTS
333 Raspberry Road, Anchorage, AK 99518, USA

Bonnie M. Borba
Alaska Department of Fish and Game, Division of Commercial Fisheries, AYK Region
1300 College Road, Fairbanks, AK 99701-1599

This document should be cited as:
Fleischman, S. J. and B. M. Borba. 2009. Escapement estimation, spawner-recruit analysis, and escapement goal recommendation for fall chum salmon in the Yukon River drainage. Alaska Department of Fish and Game, Fishery Manuscript Series No. 09-08, Anchorage.

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF APPENDICES

Appendix **Page**

ABSTRACT

Historical escapement and run size of fall chum salmon *Oncorhynchus keta* was reconstructed from incomplete sonar, weir, counting tower, mark-recapture, aerial survey, and foot survey data of varying precision from 1974 to 2007. The resulting estimates of drainagewide escapement 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 drainagewide biological escapement goal of 300,000 to 600,000 be newly designated as a sustainable escapement goal, but that the upper and lower bounds not be changed.

Key words: chum salmon, *Oncorhynchus keta*, Yukon River, 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. Fall chum are larger and mature more slowly in fresh water than summer chum salmon, entering the mouth of the Yukon River mid July through early September. They also migrate further upstream, spawning in spring-fed streams that usually remain ice-free in the winter. Major fall chum salmon spawning areas include the Tanana, Chandalar, and Porcupine River systems, and various streams in Yukon Territory, Canada.

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, subsistence, and personal use fishing occurs 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) 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.

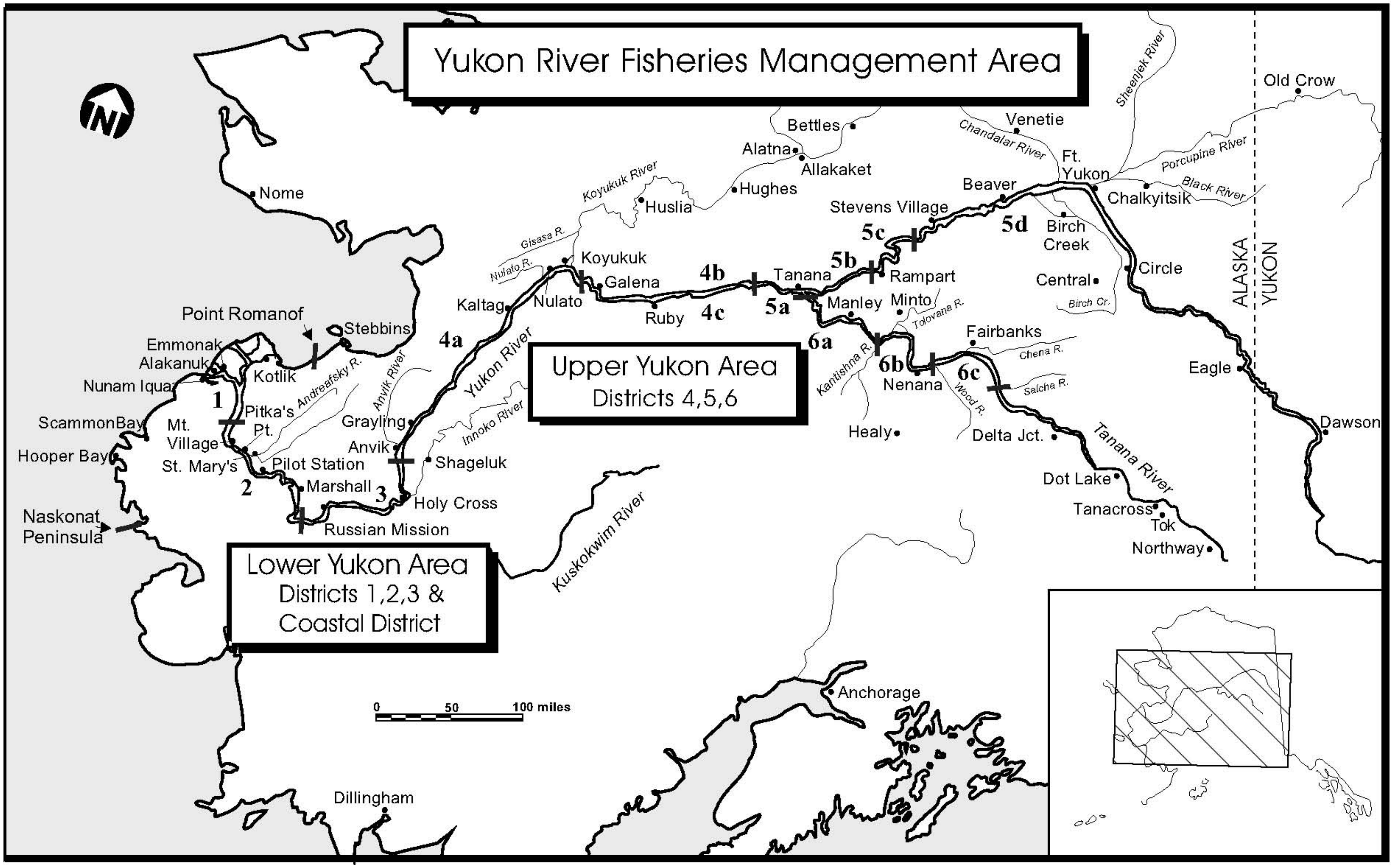

Figure 1.-Fishing districts in the Yukon River drainage.

ADF&G has conducted assessments of fall chum salmon escapement in the Yukon River for more than three decades. Between 1979 and 1987 escapement goals were established for five primary tributary spawning areas including: Toklat, Delta, Sheenjek, Fishing Branch Rivers and the Canadian mainstem stocks. However, because of the size of the Yukon River drainage, knowledge of whether or not escapement goals have been achieved typically is not available until long after the major fisheries have been completed. Therefore, although tributary escapement assessments serve as a measure of management performance and an estimation of fish distribution within the drainage, they are not useful for the inseason prosecution of fisheries.

Yukon River drainagewide escapement objectives were first developed in 1993 to help guide inseason fisheries management, soon after a sonar assessment project near Pilot Station began providing mainstem fish passage estimates. Pilot Station sonar (river mile 123) is located relatively low in the drainage compared to the destination of most spawning stocks (700 to 1,700 river miles inland) and thus is able to provide timely information on abundance. The initial version of a drainagewide escapement goal was based on an arbitrary doubling of the Toklat, Delta, Sheenjek, and Fishing Branch river assessments, to expand for areas not monitored (Bergstrom et. al. 1996). Better coverage of fall chum salmon stocks was achieved upon the establishment of projects on the Chandalar and Upper Tanana River in 1995, and on the Kantishna River in 1999. From 1999 to 2007, drainagewide assessment of fall chum salmon in the Yukon River was nearly complete, with escapement estimates obtained annually for each of the primary component stocks. Stock assessments on the Kantishna and Upper Tanana rivers were discontinued after the 2007 season due to budget constraints.

Eggers (2001) used the best data available at the time[1] to reconstruct historical fall chum salmon runs and develop recommendations for individual-tributary and drainagewide escapement goals. Eggers (2001) estimated that an escapement of approximately 500,000 fall chum salmon drainagewide would maximize sustained yield. A management plan was eventually adopted with a drainagewide optimal escapement goal of 300,000-600,000, which was designed to preserve subsistence opportunity during years of low abundance. Yet, concerns remained about data quality (measurement error), particularly where expansions were developed for historical reconstructions, and the attendant possibility of bias in assessments of optimal escapement (unpublished documents submitted to the Alaska Board of Fisheries 2001; DFO *Unpublished*[2]) The current analysis, which includes thirteen years of data from the Upper Tanana and Chandalar Rivers and nine years of data from the Kantishna River drainage, was conducted in two steps.[3] First, incomplete data on fall chum salmon abundance in scattered tributaries over 3+ decades were analyzed in a framework that allowed estimation of annual, drainagewide escapement, while also realistically assessing the uncertainty in those estimates. Second, the resulting escapement estimates, as well as age composition and harvest estimates, were analyzed in the framework of an age-structured spawner-recruit model.

For both analyses Markov Chain Monte Carlo (MCMC) methods, which are especially well-suited for modeling complex population and sampling processes, were employed. MCMC

---

1 Five years (1995–1999) of Upper Tanana and Chandalar data were available for Eggers (2001) analysis.

2 2002 subcommittee meeting of the Fisheries and Oceans Canada Pacific Scientific Advice Review Committee (PSARC) May 13-14, 2002, Nanaimo, BC.

3 The output from the first step of the analysis (drainagewide escapement estimates) is required as input for the second step.

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 experimental design 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. For similar analyses see Ericksen and Fleischman (2006), Szarzi et al. (2007), and Fleischman and Evenson (*In prep*).

METHODS

DATA

Various stock assessment projects for Yukon fall chum salmon have been conducted since the 1970s (Table 1). The number and quality of those assessment projects have generally increased over the years. In 1974, foot surveys were initiated on the Toklat and Delta rivers, as well as aerial surveys on the Sheenjek and Fishing Branch rivers. Mark-recapture experiments began on the upper mainstem in 1980, Bendix sonar replaced aerial surveys on the Sheenjek in 1981, and a weir replaced aerial surveys on the Fishing Branch in 1985. In 1995, split-beam sonar was first installed on the Chandalar River, and a mark-recapture project was initiated on the Upper Tanana River, including the Delta River. Another mark-recapture project was initiated on the Kantishna River (including the Toklat) in 1999. Finally, single- and split-beam sonar estimates of fall chum passage in the mainstem Yukon at Pilot Station are available starting in 1995. Data through 2007 were included in the current analysis.

The monitored sub-drainages listed in Table 1 support perhaps 95% of Yukon fall chum salmon escapement[4]. Nevertheless, there exist numerous missing cells in the resulting matrix of escapement estimates, especially during the first two decades of escapement monitoring. Furthermore, the individual annual estimates are subject to sampling error of varying magnitude. The drainagewide escapement model, described below, simultaneously incorporates information from all monitored sub-drainages, explicitly considering the missing data as well as the sampling error in the individual estimates.

Estimates of total annual harvest of Yukon River fall chum salmon were obtained from commercial fish tickets and subsistence surveys, summed across fishing districts and statistical areas (Eggers 2001, revised and updated with more recent data). Annual estimates of age composition were obtained from lower river test gillnets and in some instances, lower river commercial catch (Eggers 2001, revised and updated with more recent data).

[4] The Koyukuk River is the only large tributary that has not been consistently monitored for fall chum abundance in the recent past. Limited data from 1990, 1996, and 1997 indicate that Koyukuk fish comprise approximately 5% of the Yukon drainage total.

Table 1.-Escapement and abundance estimates by sub-drainage, Yukon River fall chum salmon, 1974-2007. Sampling error coefficients of variations in parentheses.

	Tanana River escapement				Upper tributaries escapement			Upper mainstem escapement	Mainstem abundance
Year	Toklat River (single foot survey)	Kantishna including Toklat (mark-recapture)	Delta River (multiple foot surveys)	Upper Tanana including Delta	Chandalar River (split-beam DIDSON sonar)	Sheenjek River (air survey, Bendix sonar)	Fishing Branch (air survey, weir)	Canada (mark-recapture)	Pilot Station (single-beam, split beam, DIDSON sonar)
1974	41,798 (0.20)		5,915 (0.15)			117,921 (0.40)	31,525 (0.10)		
1975	92,265 (0.20)		3,734 (0.15)			227,935 (0.40)	353,282 (0.10)		
1976	52,891 (0.20)		6,312 (0.15)			34,649 (0.40)	36,584 (0.40)		
1977	34,887 (0.20)		16,876 (0.15)			59,878 (0.40)	88,400 (0.40)		
1978	37,001 (0.20)		11,136 (0.15)			42,661 (0.40)	40,800 (0.40)		
1979	158,336 (0.20)		8,355 (0.15)			120,129 (0.40)	119,898 (0.40)		
1980	26,346 (0.30)		5,137 (0.15)			38,093 (0.40)	55,268 (0.40)	22,912 (0.20)	
1981	15,623 (0.20)		23,508 (0.15)			102,137 (0.30)	57,386 (0.45)	47,066 (0.30)	
1982	3,624 (0.20)		4,235 (0.15)			43,042 (0.30)	15,901 (0.40)	31,958 (0.20)	
1983	21,869 (0.20)		7,705 (0.15)			64,989 (0.30)	27,200 (0.40)	90,875 (0.20)	
1984	16,758 (0.20)		12,411 (0.15)			36,173 (0.30)	15,150 (0.40)	56,633 (0.30)	
1985	22,750 (0.20)		17,276 (0.15)			179,727 (0.30)	56,016 (0.10)	62,010 (0.20)	
1986	17,976 (0.20)		6,703 (0.15)			84,207 (0.25)	31,723 (0.10)	87,940 (0.20)	
1987	22,117 (0.20)		21,180 (0.15)			153,267 (0.25)	48,956 (0.10)	80,776 (0.20)	
1988	13,436 (0.20)		18,024 (0.15)			45,206 (0.25)	23,597 (0.10)	36,786 (0.20)	
1989	30,421 (0.20)		21,342 (0.15)			99,116 (0.25)	43,834 (0.10)	35,750 (0.20)	
1990	34,739 (0.20)		8,992 (0.15)			77,750 (0.25)	35,000 (0.40)	51,735 (0.20)	
1991	13,347 (0.20)		32,905 (0.15)			86,496 (0.20)	37,733 (0.10)	78,461 (0.20)	
1992	14,070 (0.20)		8,893 (0.15)			78,808 (0.20)	22,517 (0.10)	49,082 (0.20)	
1993	27,838 (0.20)		19,857 (0.15)			42,922 (0.20)	28,707 (0.10)	29,743 (0.20)	
1994	76,057 (0.20)		23,777 (0.15)			150,565 (0.20)	65,247 (0.10)	98,358 (0.20)	
1995	54,513 (0.30)		20,587 (0.20)	172,109 (0.19)	280,999 (0.15)	241,855 (0.20)	51,971 (0.20)	158,092 (0.20)	1,053,245 (0.05)
1996	18,264 (0.20)		19,758 (0.15)	98,337 (0.26)	208,170 (0.15)	246,889 (0.20)	77,278 (0.10)	122,429 (0.20)	
1997	14,511 (0.20)		7,705 (0.15)	61,140 (0.29)	199,874 (0.15)	80,423 (0.20)	26,959 (0.10)	85,439 (0.20)	506,621 (0.05)
1998	15,605 (0.20)		7,804 (0.15)	51,660 (0.19)	75,811 (0.15)	33,058 (0.20)	13,564 (0.10)	46,305 (0.20)	372,927 (0.04)
1999	4,551 (0.20)	27,199 (0.20)	16,534 (0.15)	87,286(0.33)	88,662 (0.15)	14,229 (0.20)	12,904 (0.10)	58,682 (0.20)	379,493 (0.06)
2000	8,911 (0.20)	21,450 (0.21)	3,001 (0.15)	34,533(0.22)	65,894 (0.15)	30,084 (0.30)	9,182 (0.30)	53,742 (0.20)	247,935 (0.06)
2001	6,007 (0.30)	22,992 (0.14)	8,103 (0.15)	94,350 (0.33)	110,971 (0.15)	53,932 (0.20)	21,669 (0.10)	33,851 (0.20)	376,182 (0.04)
2002	28,519 (0.20)	56,665 (0.11)	11,992 (0.15)	107,832 (0.18)	89,580 (0.15)	31,642 (0.20)	13,563 (0.10)	98,695 (0.20)	326,858 (0.06)
2003	21,492 (0.25)	87,359 (0.14)	22,582 (0.15)	177,339 (0.08)	214,416 (0.15)	44,047 (0.25)	29,519 (0.10)	142,683 (0.20)	889,778 (0.04)
2004	35,480 (0.20)	76,163 (0.09)	25,073 (0.15)	112,775 (0.15)	136,703 (0.15)	37,878 (0.20)	20,274 (0.10)	154,080 (0.20)	594,060 (0.04)
2005	17,779 (0.30)	107,719 (0.11)	28,132 (0.15)	271,301 (0.12)	496,484 (0.15)	561,863 (0.20)	121,413 (0.10)	437,733 (0.20)	1,813,589 (0.04)
2006		71,135 (0.10)	14,055 (0.15)	155,542 (0.16)	245,090 (0.15)	160,178 (0.20)	30,849 (0.10)	211,193 (0.20)	790,563 (0.05)
2007		81,843 (0.09)	18,610 (0.15)	292,720 (0.12)	228,056 (0.10)	65,435 (0.20)	33,752 (0.10)	226,626 (0.20)	684,011 (0.04)

DRAINAGEWIDE ESCAPEMENT MODEL

Drainagewide spawning escapement S (for all monitored sub-drainages) in year t was modeled hierarchically as lognormally distributed, independent across years.

$$\log(S_t) \sim Normal(\mu_{\log S}, \sigma^2_{\log S}) \tag{1}$$

where μ_{logS} was the mean and σ_{logS} the standard deviation of the log-transformed escapements. Drainagewide escapement consists of the summed escapement from eight mutually exclusive sub-drainages. Of these, direct estimates of the escapement were available in the Delta, Toklat, upper mainstem, Chandalar, Sheenjek, and Fishing Branch rivers; and indirect estimates (by subtraction) were available for the other two (Upper Tanana exclusive of Delta, and upper Kantishna exclusive of Toklat). Escapement estimates were generally well-correlated among sub-drainages (Figure 2). In pairs of sub-drainages that were poorly correlated, at least one of the sub-drainages was Delta or Toklat, which contribute the fewest fish on average. This fits the pattern of a Dirichlet distribution[5], in which the smallest proportions are the most variable relative to one another. Therefore the proportions of the total escapement going to tributary (sub-drainage) s in year t were modeled as

$$S_{st} = q_{st} S_t \tag{2}$$

$$\underline{q}_t \sim Dirichlet(\underline{o}) \tag{3}$$

where $\underline{\boldsymbol{q}}_{\boldsymbol{t}}$ is the vector of tributary proportions $\{q_{1t}, q_{2t}, \ldots, q_{8t}\}$ for year t and $\underline{\boldsymbol{o}}$ is the vector of Dirichlet parameters $\{o_1, o_2, \ldots, o_8\}$. The overall proportions[6] of the escapement, by sub-stock, were as follows:

$$\theta_s = \frac{o_s}{\sum_s o_s} \tag{4}$$

Stock assessment projects such as weirs can occasionally provide near-perfect (negligible sampling error) passage estimates when conditions are ideal. However this is rare. Weirs can be overtopped or leak fish during high water, and all other stock assessment projects have inherent sampling error. Unfortunately, few rigorous estimates of sampling error were available for historical escapement estimates. Therefore, where standard errors were not available a subjective procedure was used, based on professional judgment and experience, to obtain plug-in values of sampling error coefficient of variation (CV). Initially, values of sampling error CV were assigned to stock assessment projects based on relative strengths and weaknesses of the

---

[5] The Dirichlet distribution can be illustrated with a simple example. Imagine a very large number (say 1 million) marbles in a bin. There are five colors, and they are mixed randomly in equal proportions. If you draw marbles from the bin, the number of marbles of each color would be multinomially distributed and the proportions of marbles of each color would be approximately Dirichlet distributed. For instance if you drew 10 marbles from the bin, you would expect to get about 20% (2 marbles) of each color, but you rarely would get exactly those results. In fact, the actual proportions would be quite variable. If you drew 10 marbles over and over again, it wouldn't be unusual to draw 4 or 5 (40-50%) marbles of the same color. But if you drew 100 marbles, the color proportions would tend to be closer to the expected 20% each. With 1000 marbles per draw (replenishing the bin and remixing each time), they would be even closer. The sets of proportions that result from drawing 10 marbles over and over again would have an approximate Dirichlet distribution with parameters {2, 2, 2, 2, 2}, the sets of proportions from 100-marble draws would have an approximate Dirichlet distribution with parameters {20, 20, 20, 20, 20}, and so on. Thus the variability of the proportions decreases as the sum of the Dirichlet parameters increases.

[6] This model assumes no trends in these proportions over time.

type of project. For weir projects a CV of 10% was assumed, DIDSON sonar 10%, split-beam sonar 15%, Bendix sonar 20%, multiple foot surveys 15%, single foot surveys 20%, mark-recapture 20%, and aerial surveys 40%. Then the history of each project was reviewed and some annual CVs revised up or down depending on circumstances for that year (e.g. CV revised upward when weir was installed late or removed early and the count was expanded for the missed time; Table 1).[7]

Individual annual estimates of sub-drainage escapement were modeled as

$$\hat{S}_{st} = S_{st} e^{\varepsilon_{Sst}} \tag{5}$$

where the $\{\varepsilon_{Sst}\}$ were normally distributed with mean zero and standard deviations $\{\sigma_{Sst}\}$. The individual standard deviations $\{\sigma_{Sst}\}$ were the imputed CVs described above.

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 drainagewide escapement model, a normal prior with mean zero, large variance, and constrained to be positive, was used for μ_{logS}; and a diffuse conjugate inverse gamma prior for σ^2_{logS}. Diffuse gamma priors were used for the Dirichlet parameters $\{o_1, o_2, \ldots, o_8\}$.

Markov-chain Monte Carlo samples were drawn from the joint posterior probability distribution of all unknowns in the model. For each of three Markov chains initialized, a 4,000-sample burn-in period was discarded, and 16,000 additional updates were generated. The resulting total of 48,000 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 drainagewide spawning escapement $\{S_t\}$, denoted $\{\hat{S}_t\}$, were used as input for the spawner recruit model described below. Coefficients of variation for $\{\hat{S}_t\}$ were obtained by dividing $\{S_t\}$ posterior standard deviations by the posterior means.

SPAWNER-RECRUIT MODEL

A Ricker spawner recruit function (Ricker 1975) was used to model the relationship between drainagewide escapement and recruitment. Under the Ricker model, recruitment R from brood year y is:

$$R_y = S_y \, \alpha \, e^{-\beta S_y} \, e^{\varepsilon_{SR}} \tag{6}$$

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}).

[7] Ultimately, the results of the final analysis were not sensitive to these assumptions. When the subjective sampling CVs were increased by a factor of 1.5, the effect on the escapement estimates and their SEs was negligible.

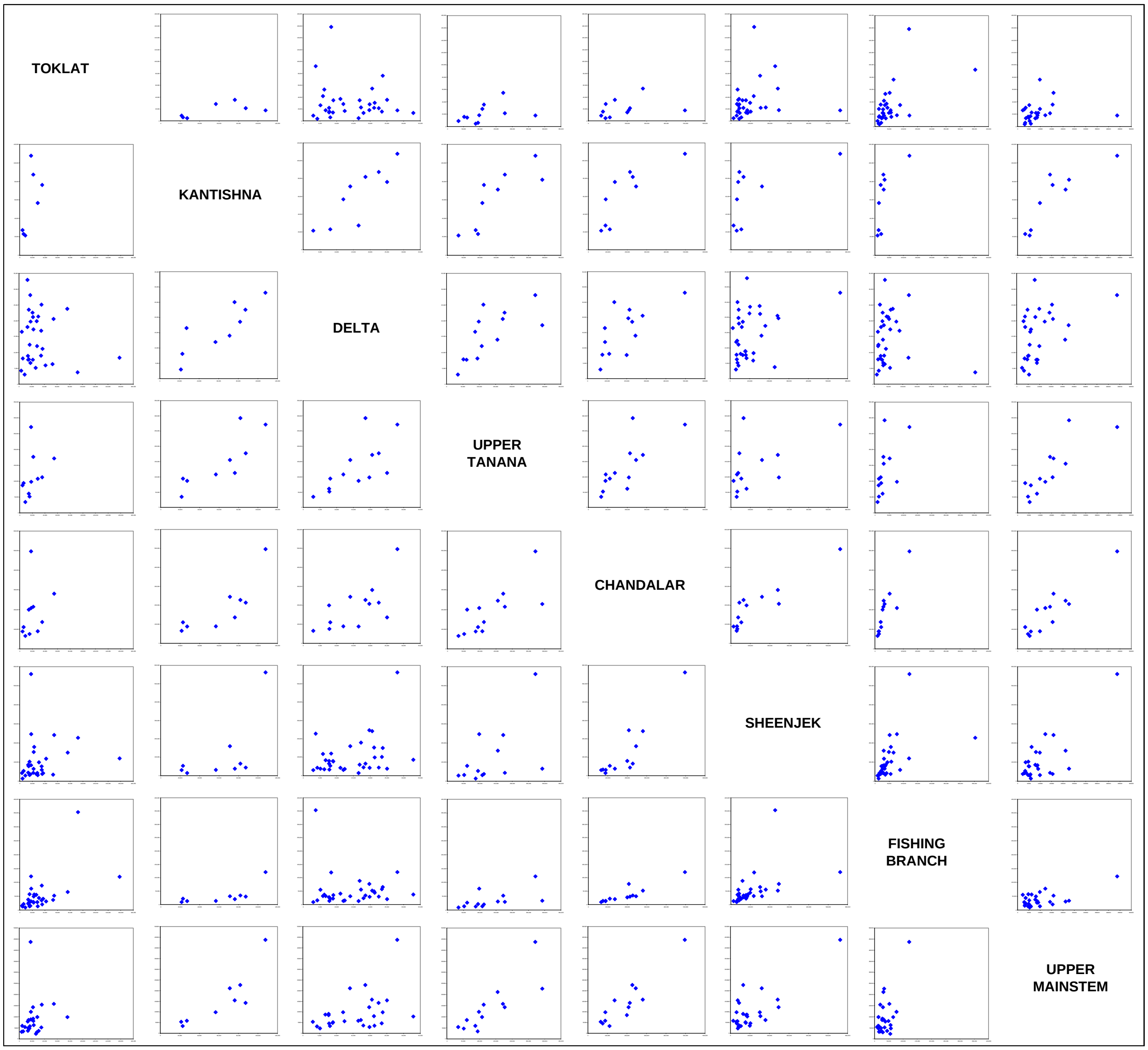

Figure 2.-Scatter plot matrix of fall chum salmon escapement estimates by sub-drainage in the Yukon River, 1974-2007.

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

$$S_{EQ} = \frac{\ln(\alpha')}{\beta} \tag{7}$$

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

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_{SR}^2}{2} \tag{8}$$

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

$$S_{MSY} \approx S_{EQ}(0.5 - 0.07\ln(\alpha')). \tag{9}$$

The classical way to estimate the Ricker parameters is to linearize the Ricker relationship by dividing both sides of equation 6 by S and taking the natural logarithm, yielding:

$$\ln\left(\frac{R_y}{S_y}\right) = \ln(\alpha) - \beta S_y + \varepsilon_y \tag{10}$$

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

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 that is not reflected in the classical estimates. From the drainagewide escapement model described above, the measurement error CV of the escapement estimates approaches or exceeds 20% in most years (Table 2). Another shortcoming of the SLR approach is that it cannot account for serially correlated process errors or incomplete brood years.

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 fall chum salmon originating from spawning escapement in brood years y = 1974 - 2004 are modeled as a Ricker stock-recruit function with autoregressive lognormal errors with a lag of 1 year (i.e., model residuals are subject to AR(1) serial correlation)

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi \nu_{y-1} + \varepsilon_{Wy} \tag{11}$$

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

$$\nu_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y, \tag{12}$$

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

Table 2.-Point estimates, coefficients of variation, 95% interval bounds of drainagewide escapement, harvest, and age composition estimates for Yukon River fall chum salmon 1974–2007.

			95% interval			Estimated age proportions[a]			
Year	Estimated escapement[b]	CV[c]	Lower[d]	Upper[e]	Estimated harvest	age-3	age-4	age-5	age-6
1974	587,400	0.25	378,900	973,700	478,875				
1975	2,068,000	0.22	1,415,000	3,218,000	473,062				
1976	491,300	0.24	316,900	793,300	339,043				
1977	663,100	0.25	421,600	1,094,000	447,918	0.095	0.851	0.053	0.001
1978	502,000	0.26	318,000	826,700	434,030	0.199	0.660	0.139	0.002
1979	1,245,000	0.25	785,600	2,014,000	615,377	0.073	0.878	0.049	0.000
1980	314,800	0.22	211,200	485,400	488,373	0.137	0.782	0.082	0.000
1981	529,900	0.20	368,600	797,300	683,391	0.018	0.871	0.111	0.000
1982	229,700	0.21	157,300	343,400	373,519	0.074	0.600	0.318	0.008
1983	483,400	0.19	336,900	714,800	525,485	0.010	0.882	0.104	0.005
1984	331,800	0.20	230,200	489,800	412,323	0.067	0.531	0.402	0.000
1985	661,500	0.18	478,900	958,000	515,481	0.010	0.810	0.177	0.003
1986	500,800	0.18	359,400	724,800	318,028	0.018	0.577	0.401	0.005
1987	675,000	0.17	490,700	952,800	406,143	0.007	0.827	0.158	0.008
1988	327,500	0.18	238,100	475,900	353,685	0.069	0.601	0.329	0.001
1989	504,900	0.18	370,900	729,300	545,166	0.000	0.832	0.166	0.002
1990	468,800	0.19	334,500	681,300	352,007	0.017	0.596	0.376	0.012
1991	556,400	0.17	412,800	789,400	439,096	0.040	0.599	0.358	0.003
1992	384,600	0.17	284,100	547,100	148,846	0.006	0.370	0.615	0.009
1993	353,000	0.17	259,200	500,100	91,015	0.002	0.638	0.343	0.017
1994	895,800	0.16	670,200	1,248,000	169,225	0.004	0.617	0.368	0.012
1995	1,006,000	0.09	849,600	1,195,000	461,147	0.005	0.697	0.285	0.014
1996	813,000	0.09	685,300	969,900	260,923	0.007	0.616	0.348	0.029
1997	502,400	0.09	419,500	605,600	170,059	0.007	0.679	0.296	0.018
1998	258,600	0.09	220,200	308,400	70,820	0.007	0.675	0.307	0.012
1999	271,800	0.09	228,300	326,900	131,175	0.001	0.635	0.356	0.008
2000	217,700	0.09	183,300	259,000	28,543	0.013	0.692	0.288	0.007
2001	320,600	0.09	269,900	384,300	44,976	0.002	0.640	0.358	0.001
2002	388,200	0.07	336,200	448,900	27,411	0.068	0.634	0.278	0.020
2003	689,700	0.07	606,100	783,900	79,529	0.011	0.910	0.075	0.004
2004	525,400	0.07	458,400	603,200	76,296	0.222	0.484	0.284	0.011
2005	1,823,000	0.07	1,575,000	2,112,000	290,183	0.000	0.944	0.051	0.006
2006	834,100	0.08	722,800	968,800	270,471	0.021	0.388	0.590	0.000
2007	884,400	0.06	781,900	1,000,000	194,786	0.000	0.759	0.211	0.030

[a] No data for years 1974–1976.
[b] Bayesian posterior median.
[c] Posterior standard deviation/posterior mean.
[d] 2.5th percentile of posterior distribution.
[e] 97.5th percentile of posterior distribution.

Age proportion vectors[8] $\underline{\boldsymbol{p}}_{\boldsymbol{y}}$ = (p_{y3}, p_{y4}, p_{y5}) from brood year y returning at ages *3-5* are drawn from a $Dirichlet(\gamma_3, \gamma_4, \gamma_5)$ distribution. The Dirichlet parameters are also expressed in an alternative location/scale form, where

$$D = \sum_a \gamma_a \; ; \tag{13}$$

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

$$\pi_a = \frac{\gamma_a}{D} . \tag{14}$$

reflect the overall age proportions. The abundance N of age-a fall chum salmon in calendar year t (t = 1974-2007) is the product of the age proportion scalar p and the total return R from brood year $y = t\text{-}a$:

$$N_{ta} = R_{t-a} \, p_{t-a,a} \tag{15}$$

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

$$N_{t\cdot} = \sum_a N_{ta} \tag{16}$$

Spawning abundance is total run minus harvest,

$$S_t = N_{t\cdot} - H_t \tag{17}$$

where H_t is the product of the annual exploitation rate and total run:

$$H_t = \mu_t N_{t\cdot} . \tag{18}$$

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 7–9, except that ln(α) is corrected for lognormal process error with AR(1) serial correlation[9]:

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_W^2}{2(1-\phi^2)} . \tag{19}$$

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:

$$SY = E[R] - S = Se^{\ln(\alpha') - \beta S} - S . \tag{20}$$

---

[8] These age proportions are maturity/survival schedules in a given brood year, across calendar years. In contrast, equation 23 describes age proportions in a given calendar year, across brood years.

[9] In this case the correction is based on the total "red noise" variance of the AR(1) process. For instance, see Chatfield (1989: page 36).

Probability that a given level of escapement would produce average yields exceeding X% of MSY is obtained by calculating the expected sustained yield (Equation 20) at multiple incremental values of S (0 to 1,500,000) 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 included sonar estimates of inriver passage, estimates of spawning abundance from the drainagewide escapement model, estimates of harvest, and age counts determined from scale samples. Sampling distributions for the data are as follows.

Sonar estimates of mainstem fall chum salmon passage at Pilot Station ($\hat{N}_{PSt}$; 1995, 1997–2007) are modeled as

$$\hat{N}_{PSt} = \theta\left(N_{t\cdot} - H_{below,t}\right)e^{\varepsilon_{PSt}} \quad (21)$$

where θ is a factor of detectability[10] for fall chum salmon at Pilot Station, $H_{below,t}$ is the harvest in year t below (downstream from) Pilot Station (observed with little or no error), and ε_{PSt} are normal $(0, \sigma^2_{PS})$.

Estimated harvest (1974–2007) is modeled as

$$\hat{H}_t = H_t e^{\varepsilon_{Ht}} \quad (22)$$

where the $\{\varepsilon_{Ht}\}$ are assumed normal (0, 0.01).[11]

Numbers of fish sampled for scales (n) that were classified as age-a in calendar year t (x_{ta}) are assumed to be multinomially (q_{ta},n) distributed, with proportion parameters as follows[12]:

$$q_{ta} = \frac{N_{ta}}{N_{t\cdot}} \quad (23)$$

Estimated spawning abundance is modeled as:

$$\hat{S}_t = S_t e^{\varepsilon_{St}} \quad (24)$$

where the $\{\varepsilon_{St}\}$ are normal $(0, \sigma^2_{St})$. Point estimates and variances were obtained from the drainagewide escapement model (Table 2).

Non-informative priors (chosen to have a minimal effect on the posterior) were used for most parameters. Initial returns R_{1969}-R_{1973} (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 Pilot Station sonar detectability factor θ was given a uniform(0,1) prior, and the initial model residual v_0 was given a normal prior with mean zero and variance $\sigma^2_{SR}/(1-\phi^2)$.[13] Diffuse conjugate inverse gamma priors were used for σ^2_W, σ^2_{PS}, and

[10] In the real world (as opposed to the model), the quantity θ would be better described as a conversion factor. See Results and Discussion.

[11] This is approximately equivalent to a CV of 10%. This value was arbitrarily chosen to reflect the fact that inriver harvest is well estimated. Results of the analysis were not sensitive to this assumption.

[12] Simulation experiments have shown that SRA results are not sensitive to typical variations in the precision of age composition estimates. Nevertheless, sample sizes for scale ages were artificially lowered to 100 scales per year to reflect possible biases in age composition estimates and the fact that individual scale ages were not obtained strictly independently, as is assumed for a multinomial distribution.

[13] This prior reflects the uncertainty surrounding a single unknown residual, given the presence of AR(1) serial correlation.

σ^2_{logR}. Diffuse gamma priors were used for the Dirichlet parameters (γ_3,γ_4,γ_5). Annual exploitation rates $\{\mu_t\}$ were given beta (0.1,0.1) prior distributions. WinBUGS code and data are provided in Appendix A.

As with the drainagewide escapement model, 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 10,000 additional updates were generated. The resulting 20,000 samples were used to estimate the marginal posterior means, standard deviations, and percentiles. The diagnostic tools of WinBUGS were used to assess mixing and convergence, and no major problems were encountered. Interval estimates were obtained from the percentiles of the posterior distribution.

RESULTS AND DISCUSSION

DRAINAGEWIDE ESCAPEMENT

Estimated[14] escapement proportions in the eight sub-drainages were as follows: Toklat 5.0% (SE=0.5%), other Kantishna 6.6% (1.1%), Delta 2.9% (0.3%), other Upper Tanana 18.5% (1.6%), Chandalar 29.7% (1.8%), Sheenjek 14.6% (1.0%), Fishing Branch 7.1% (0.6%), and Canadian mainstem 15.4% (1.1%). Escapement estimates ranged from 218,000 in 2000 to 2,068,000 in 1975, with measurement error CVs from 6% to 26% (Table 2; Figure 3).[15] These values were used as input into the spawner-recruit model (results from which are described below).

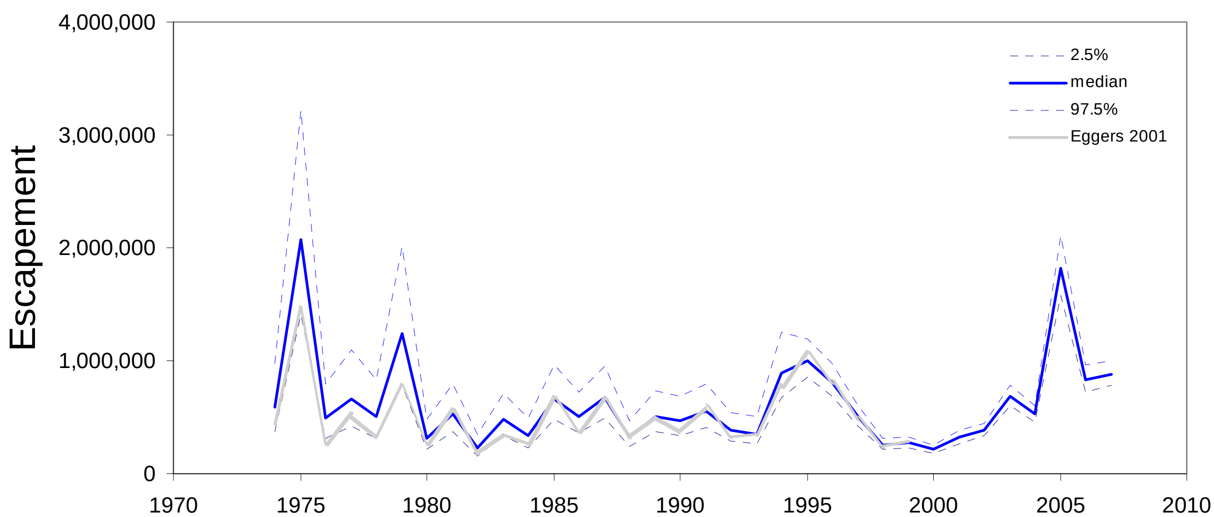

Figure 3.-Estimates and 95% interval bounds of spawning escapement from drainagewide escapement model fitted to Yukon River fall chum salmon data, 1974–2007. Comparable estimates produced by Eggers (2001) are shown for comparison.

---

[14] 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.

[15] Escapement estimates were very similar to those produced by Eggers (2001), except for the 1970s, when they were somewhat larger.

Spawner-Recruit Analysis

The "point estimate" of the Ricker relationship, constructed from the posterior medians of α and β, is plotted in Figure 4.[16] Productivity of Yukon River drainage fall chum salmon is very low; there is 95% probability that α is less than 3.7 (Table 3). Serial correlation in productivity is substantial ($0.18 < \phi < 0.82$ with 90% probability, Table 3). Log residuals illustrate the recent dramatic swings in productivity; there was a 5-fold decline in productivity between the 1991 and 1996 brood years and a 15-fold increase in productivity between 1996 and 2001 (Figure 5). S_{MSY} is equally likely to be above or below 672,000 (Table 3). These estimates take into account the missing data and measurement error in both S and R, differentially weighting the individual data pairs in Figure 4 depending on how precisely they were estimated. Serial correlation in the relationship is also factored in.[17]

The estimates described above must be considered in the context of very large uncertainty about the Ricker relationship. This is graphically displayed in Figure 6, 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, and they are very diverse. The slope at the origin (α) varies substantially among the individual curves; as does the point of maximum recruitment S_{MAX}, which is the inverse of the density-dependent parameter β. Carrying capacity S_{EQ}, represented by where the curves intersect the replacement line, is also highly variable. The graphical evidence is confirmed by extremely wide 90% interval estimates for $ln(\alpha)$ (0.33–1.30), β (1.8–12.4 x 10^{-7}), S_{MAX} (810,000–5,582,000), and S_{EQ} (934,400–5,073,000; Table 3). Spawning escapement leading to maximum sustained yield S_{MSY} is similarly uncertain (90% interval 396,000–2,065,000; Table 3).[18]

The yield probability profiles in Figure 7 display the probability of achieving near maximal SY (>70%, 80%, and 90% of MSY) for specified levels of escapement. For this stock, there are only modest levels of certainty about which escapements produce maximal yield.[19] Yet the information at hand can still be used to evaluate prospective escapement goals. The current goal has low probability (13-64%) of achieving the highest standards for yield (90% of MSY). There is higher probability (54-87%) of achieving more relaxed, but still high, yield standards (70% of MSY). Larger yields, relative to MSY, could probably be attained from escapements greater than the current escapement goal range.

---

[16] Estimates of S plotted in Figure 4 differ from those of drainagewide escapement model because the new estimates are in the context of the spawner-recruit (SR) model, which allows individual estimates to "shrink" toward the fitted value of the SR model for that brood year.

[17] The effects of serial correlation and measurement error on spawner-recruit analysis are dataset-specific. The classical point estimate of the Ricker curve, calculated by simple linear regression (SLR) from brood year 1974–2002 data, is plotted as a dashed line in Figure 4. This is the naive analysis, ignoring age structure, serial correlation and measurement error. The classical SLR point estimate of S_{MSY} is 518,000, much smaller than the corresponding value from the full analysis (posterior median 672,000). Another Bayesian model (not shown) fit to the Yukon fall chum salmon data, without age structure or measurement error but including serial correlation, yielded an S_{MSY} posterior median of 746,000. Thus, for the Yukon fall chum dataset, the incorporation of serial correlation in the model had a large positive effect on the estimate of S_{MSY} (746K vs 518K), and the incorporation of measurement error in the model had a smaller negative effect (672K vs 746K). I.e., *for this data set*, serial correlation caused a large negative bias in the estimate, whereas measurement error caused a smaller positive bias.

[18] The corresponding 90% confidence interval for S_{MSY} from the naive classical SLR analysis is much narrower (385K to 850K), illustrating the potential for the SLR method to drastically understate uncertainty.

[19] The steeper the limbs of the probability profile in Figure 7, the more information about what range of escapements produce maximal yield. Compared to other stocks, the probability profile for Yukon fall chum is not very steep, reflecting substantial uncertainty about the spawner-recruit relationship.

Figure 8 displays the absolute amount of expected yield as a function of escapement. This function is relatively flat and subject to a great deal of uncertainty, and the amount of uncertainty increases with increasing escapement. Specifically, the difference in expected yield between the current escapement goal midpoint (450,000) and the point where expected yield is maximized (apx. 700,000) is 45,000 fish. This is equivalent to a 9% gain in yield, but the true gain is very uncertain, with an 80% interval of -17% to 480%. There is greater than 25% probability that expected yield would decline from such a change.

Table 3.-Posterior percentiles from a Bayesian age-structured Ricker spawner-recruit analysis of 1974–2007 Yukon River fall chum salmon escapement, harvest, and age data. Quantities are defined in text.

	Percentiles				
	2.5%	**5%**	**median**	**95%**	**97.5%**
$ln(\alpha)$	0.23	0.33	0.80	1.30	1.43
α	1.3	1.4	2.22	3.7	4.2
β	1.13E-07	1.79E-07	6.17E-07	1.24E-06	1.40E-06
σ_{SR}	0.39	0.41	0.52	0.67	0.70
ϕ	0.10	0.18	0.52	0.82	0.87
S_{MSY}	365,000	395,800	671,600	2,065,000	3,155,000
S_{MAX}	716,500	810,100	1,622,000	5,582,000	8,886,000
S_{EQ}	862,600	934,400	1,566,000	5,073,000	7,957,000
D	11	11	18	26	28
π_3	0.024	0.026	0.037	0.052	0.055
π_4	0.653	0.661	0.698	0.731	0.737
π_5	0.227	0.233	0.265	0.299	0.306
q	0.80	0.82	0.91	0.99	0.99
$1/q$	1.01	1.02	1.10	1.22	1.25
σ_{PS}	0.14	0.15	0.21	0.32	0.35

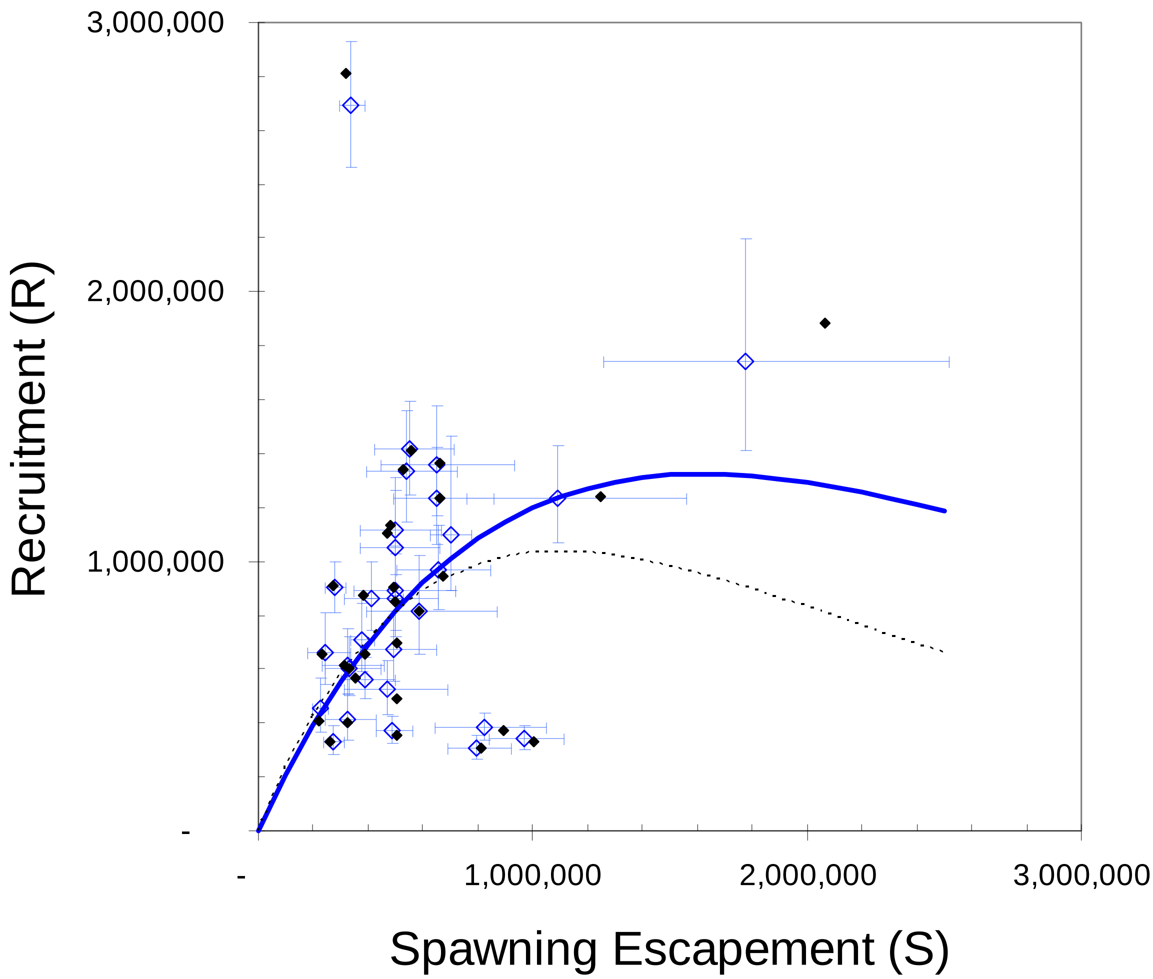

Figure 4.-Scatter plot of recruitment (R) versus escapement (S) from Bayesian spawner-recruit model fitted to Yukon River fall chum salmon data, brood years 1974-2004. Posterior medians are plotted as open symbols, with 10th and 90th posterior percentiles bracketed by error bars. Posterior medians of S and R from the drainagewide escapement model are plotted as solid symbols for comparison. Ricker relationships (curved lines) are constructed from Bayesian posterior medians (solid line) and classical point estimates (dashed line) of α and β.

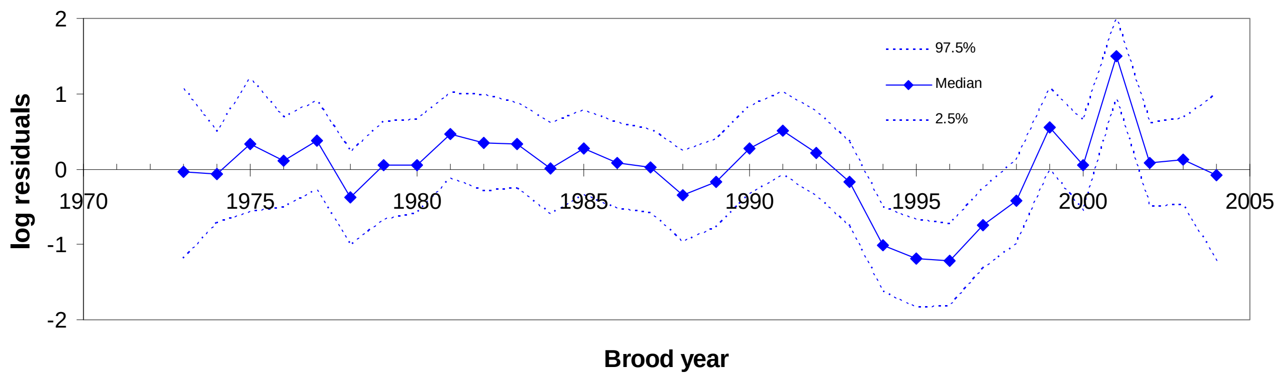

Figure 5.- Residuals (log deviations of R from Ricker spawner-recruit model) for Yukon River fall chum salmon, brood years 1974-2004. Posterior medians and other percentiles are plotted.

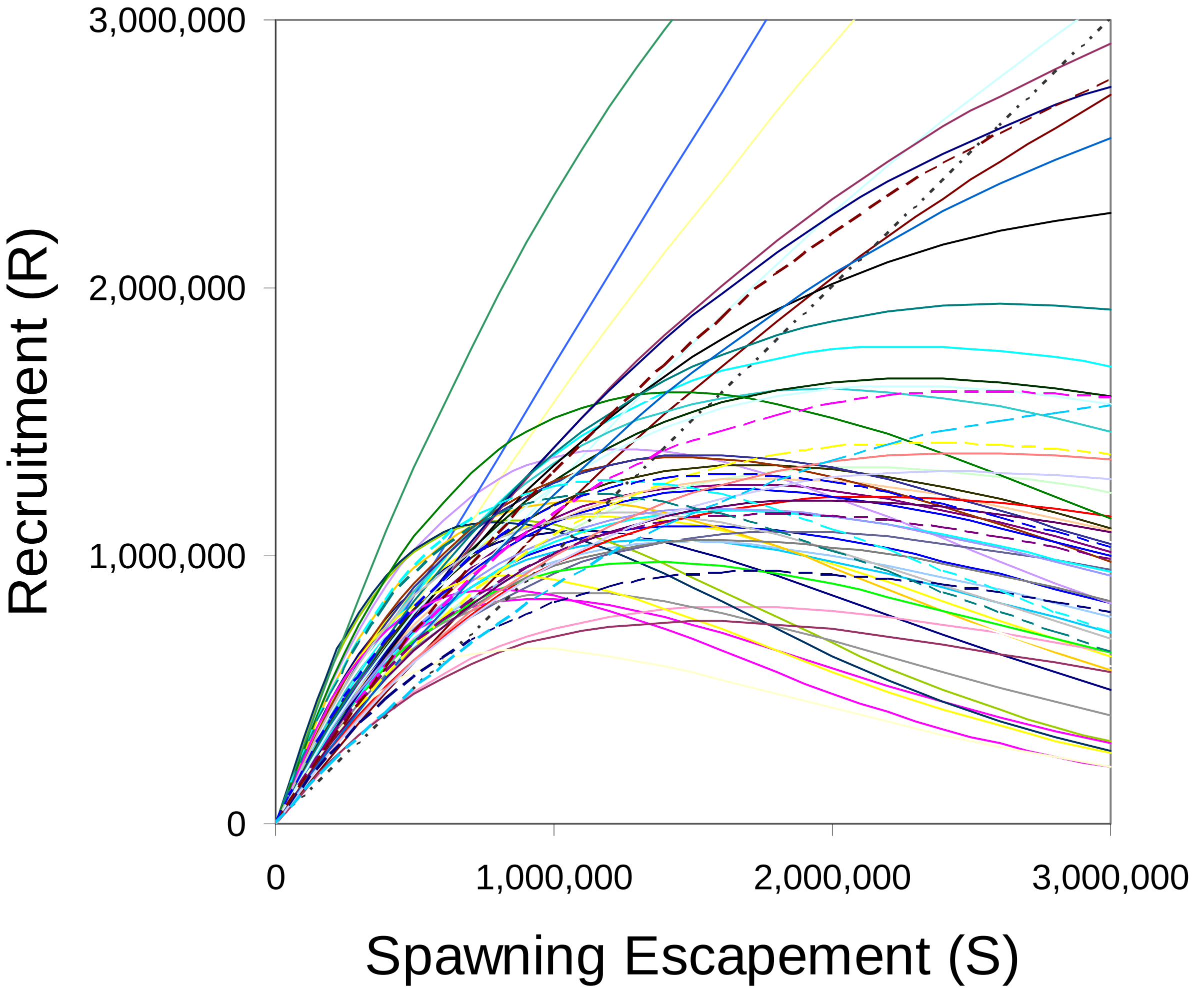

Figure 6.-Ricker relationships represented by ~50 paired values of ln(α) and β sampled from the posterior probability distribution of stock-recruitment statistics, Yukon River fall chum salmon. Curves are a sample of Ricker relationships that could have generated the observed data.

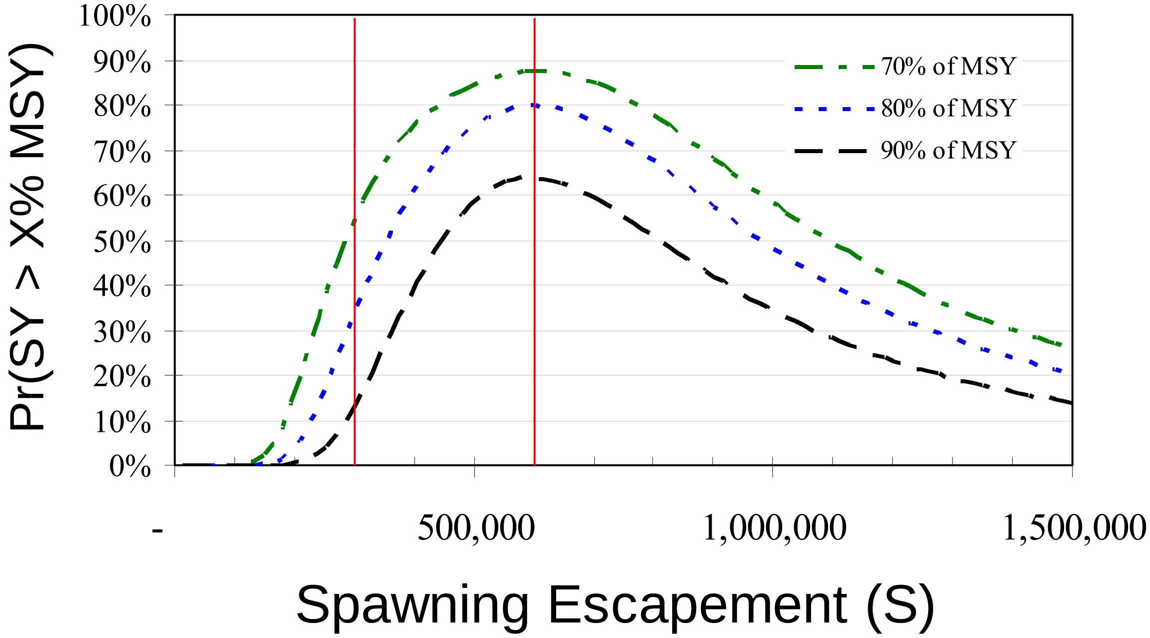

Figure 7.-Probability that a specified spawning escapement will result in sustained yield exceeding 70%, 80%, and 90% of maximum sustained yield, Yukon River fall chum salmon . Vertical lines bracket the current escapement goal range.

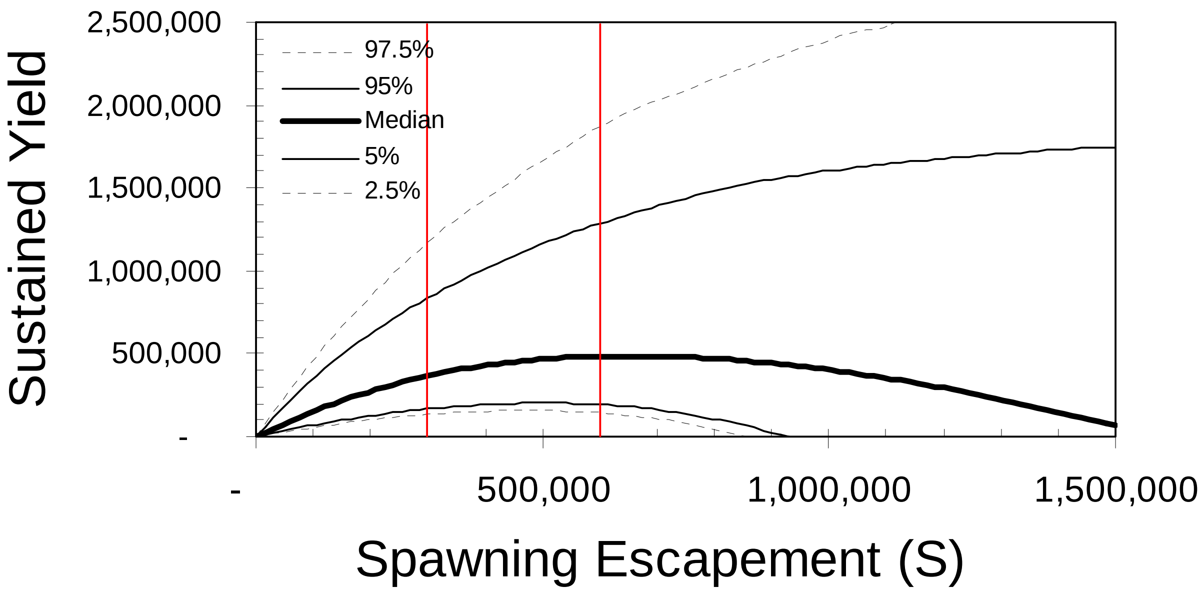

Figure 8.-Bayesian posterior percentiles of expected sustained yield at specified spawning escapements, Yukon River fall chum salmon. Vertical lines bracket the current escapement goal range.

ESCAPEMENT GOAL RECOMMENDATION

In summary, Yukon River fall chum salmon, considered over the entire drainage, have low productivity and highly autocorrelated returns that are probably largely the result of fluctuating conditions in the marine and estuarine environments. These factors limit our ability to quantify the spawner recruit relationship and determine optimal levels of escapement.[20] Information garnered from the stock-recruit analysis suggests that the current escapement goal may be somewhat lower than what would be required to maximize average yield (Figure 6). However, the uncertainty associated with estimating maximum sustained yield coupled with limited run assessment information makes in-season management for MSY extremely difficult in a practical sense.

The Department does not recommend changing the goal at this time, for several reasons:

- The expected gain in yield from raising the goal is modest and uncertain. Beyond about 500,000 spawners, the small and uncertain increases in expected yield are partially offset by increased probability of low yields. Thus there may be little or nothing to gain from increasing the current escapement goal range.[21]
- Given the nature of the fishery, with multiple sub-stocks and user groups located along 1,000 miles of river, there are many constraints on management. Moreover, with the exception of Pilot Station sonar at river-mile 123, there are few real-time indices of abundance with which to guide inseason management of the fishery. Some harvest occurs during small runs and insufficient harvest occurs during large runs to keep the escapement below the upper end of the goal. It is unlikely that raising the goal would translate to better management performance with respect to the complex demands of this fishery. ADF&G is currently participating in an effort to investigate ways to better optimize management within existing constraints, striking an appropriate balance between maximizing subsistence and commercial harvest opportunities while continuing to safeguard preservation of the stock.[22]
- The prominence of subsistence fisheries in the region translates to somewhat different priorities, in that reliable opportunities for harvest assume greater importance than strict maximization of expected yield. Raising the goal would clearly result in more frequent fishery closures. For example, there have been six years since 1974 during which the estimated escapement has been between 300K and 400K (Table 2; Figure 9).

Given the weak evidence in support of raising the goal, the prospect of better information on the immediate horizon, and the potential disruption to local fisheries, raising the goal does not seem prudent at this time. The escapement goal should be re-evaluated after the 2010 season, when the return from the 2005 brood year will be largely complete. In the interim, the current

---

[20] They also make management of the stock more difficult.

[21] Furthermore, at the time of this writing (fall 2009), it appears that the 2009 fall chum run is unexpectedly small. The 2009 run includes 4-year-olds from the 2005. There has been only one other escapement as large as 2005, and it was decades ago. Thus the return from the 2005 escapement will have considerable impact on the outcome of the spawner recruit analysis. If 5-year-olds in 2010 are also weak, it will mean that density dependence is stronger than the current analysis indicates and probably result in a downward revision of the estimate of S_{MSY}. This would further weaken the case for raising the goal.

[22] Arctic Yukon Kuskokwim Sustainable Salmon Initiative (http://www.aykssi.org/) expert panel appointed March 2009 and charged with evaluating "*escapement goals that support effective harvest policies for AYK salmon stocks*".

escapement goal should be denoted an SEG rather than a BEG, because it may not meet the stated BEG requirements of providing the greatest potential for maximum sustained yield.

In the future, it is likely that additional tributary escapement monitoring projects will be discontinued, making the associated tributary escapement goals obsolete. Estimated passage at the mainstem sonar, with stock contributions determined by genetic analysis, may become the basis for fishery management. Pilot Station sonar estimates agree reasonably well with reconstructed inriver run strength[23] (Figure 10). Estimates of harvest and age composition will still be required to reconstruct returns by brood year.

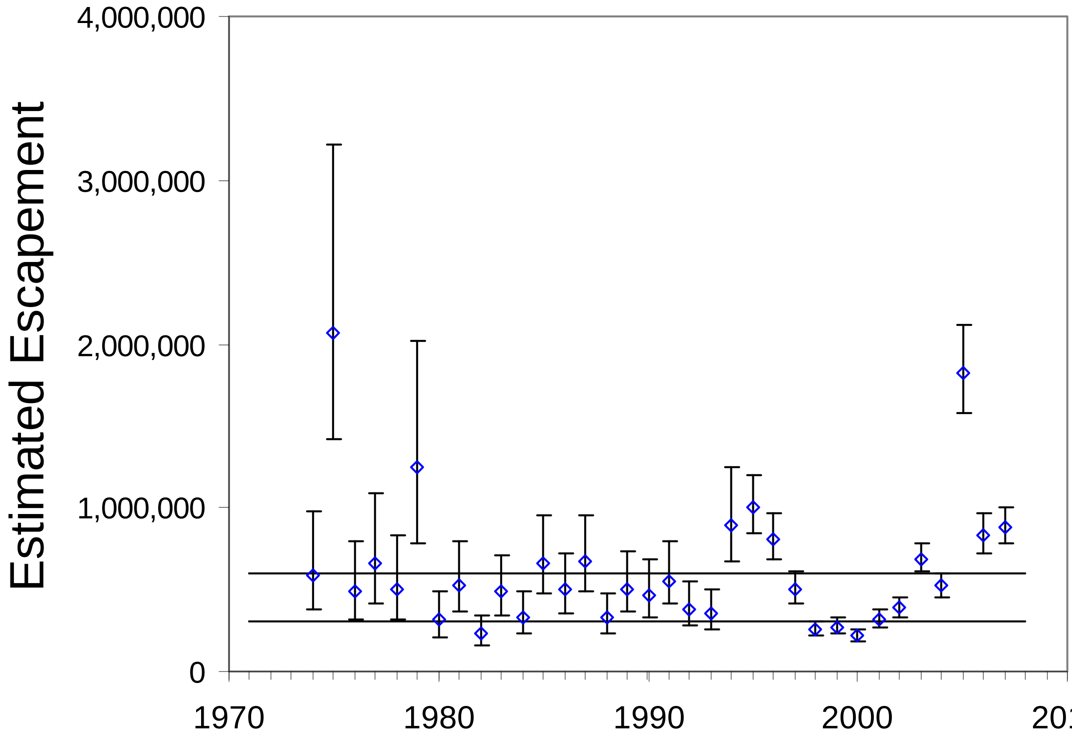

Figure 9- Historical estimates of escapement and 95% credibility intervals, Yukon River fall chum salmon, 1974-2007. Horizontal lines bracket the current escapement goal range.

[23] Use of Pilot Station sonar estimates for evaluation of run strength relative to escapement goal would require a conversion factor of 1 / q = 1.1 (SE=0.06; one sonar fish is worth about 1.1 fish in the escapement, although upstream harvest would still have to be projected). This doesn't necessarily mean that the sonar estimates are biased low, only that there is approximately 10% disagreement between the sonar and the collective escapement and harvest assessment projects. This disagreement, along with the imprecision in the relationship depicted in Figure 10, would have to be considered when using the sonar numbers inseason.

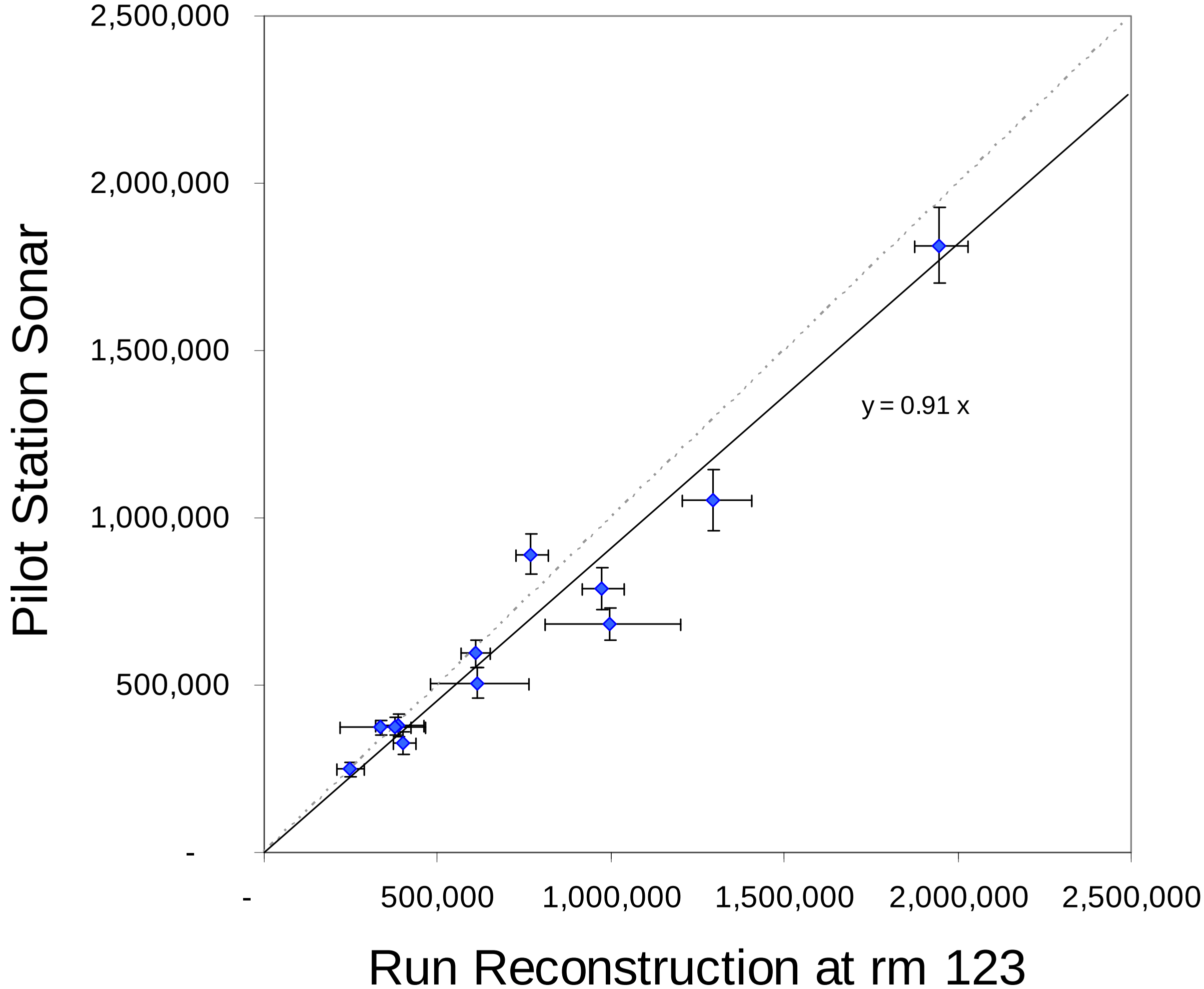

Figure 10.- Fall chum salmon passage estimates at Pilot Station sonar (river mile 123) versus reconstructed inriver run from Bayesian spawner-recruit model (total run minus harvest below rm 123), 1995, 1997-2007. Error bars represent 90% intervals.

ACKNOWLEDGEMENTS

Doug Eggers' work provided the foundation upon which the current analysis was built. Discussions with AYK Escapement Goal Committee members Matt Evenson, Dan Bergstrom, Eric Volk, and others were very helpful. Critical review of this document was provided by Bob Clark, Fred Bue, Toshihide Hamazaki, and Xinxian Zhang. Data presented in this report were collected over the decades by uncountable dedicated ADF&G staff.

REFERENCES CITED

Bergstrom, D. J., K. C. Schultz, R. R. Holder, B. M. Borba, G. J. Sandone, L. H. Barton, and D. J. Schneiderhan. 1996. Annual management report Yukon Area, 1994. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 3A96-18, Anchorage.

Chatfield, C. 1989. The analysis of time series: Fourth edition. An introduction. Chapman and Hall, London.

Eggers, D. E. 2001. Biological escapement goals for Yukon River fall chum salmon. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 3A01-10, Anchorage.

Ericksen, R. P., and S. J. Fleischman. 2006. Optimal production of coho salmon from the Chilkat River. Alaska Department of Fish and Game, Fishery Manuscript No. 06-06, Anchorage.

Fleischman, S. J., and D. Evenson. In prep. Run reconstruction, spawner-recruit analysis, and escapement goal recommendation for summer chum salmon in the East Fork of the Andreafsky River. Alaska Department of Fish and Game, Fishery Manuscript , Anchorage.

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

Hilborn, R. 1985. Simplified calculation of optimum spawning stock size from Ricker's stock recruitment curve. Canadian Journal of Fisheries and Aquatic Sciences 42: 1833-1834.

Kehler D. G., Myers, R. A., and C. A. Field. 2002. Measurement error and bias in the maximum reproductive rate for the Ricker model. Canadian Journal of Fisheries and Aquatic Sciences 59: 854-864.

Kope R. 2006. Cumulative effects of multiple sources of bias in estimating spawner–recruit parameters with application to harvested stocks of Chinook salmon (*Oncorhynchus tshawytscha*). Fisheries Research 82: 101-110.

Lunn, D.J., A. Thomas, N. Best, and D. Spiegelhalter. 2000. WinBUGS - a Bayesian modeling framework: concepts, structure, and extensibility. Statistics and Computing 10:325--337.

Millar, R. 2002. Reference priors for Bayesian fisheries models. Canadian Journal of Fisheries and Aquatic Sciences 59:1492-1502.

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

Seeb, L. W. and P. A. Crane. 1999. Allozymes and Mitochondrial DNA Discriminate Asian and North American Populations of Chum Salmon in Mixed-Stock Fisheries along the South Coast of the Alaska Peninsula. Transactions of the American Fisheries Society.128: 88-103.

Szarzi, N. J., S. J. Fleischman, R. A. Clark and C. M. Kerkvliet. 2007. Stock status and recommended escapement goal for Anchor River Chinook Salmon. Alaska Department of Fish and Game, Fishery Manuscript No. 07-05, Anchorage.

APPENDIX A
WINBUGS CODE AND DATA

Appendix A1.–WinBUGS model code for Bayesian MCMC statistical analysis of Yukon River fall chum salmon data, drainagewide escapement model, 1974-2007. Prior distributions are italicized; sampling distributions of the data are underlined.

WinBUGS code for Drainagewide Escapement Model

```
model{
 mu.log.Stotal ~ dnorm(0,1.0E-4)I(0,)
 tau.Stotal ~ dgamma(0.001,0.001)
 sigma.log.Stotal <- 1 / sqrt(tau.Stotal)
 mu.Stotal <- exp(mu.log.Stotal + sigma.log.Stotal*sigma.log.Stotal/2)

 #  Annual overall escapements drawn from common lognormal distribution;
 for (y in 1:34) {
    Stotal[y] <- exp(log.Stotal[y])
    log.Stotal[y] ~ dnorm(mu.log.Stotal,tau.Stotal)
    }

 # Dirichlet proportions among substocks:  Toklat, other Kantishna, Delta, other Upper Tanana,
 # Chandalar, Sheenjek, Fishing Branch, Canadian mainstem;
 for (t in 1:8) {
  gamma[t] ~ dgamma(0.001,0.001)
  pi[t] <- gamma[t] / D
  }
 D <- sum(gamma[])
 for (y in 1:34) {
  for (t in 1:8) {
    g[y,t] ~ dgamma(gamma[t],1)
    }
  }

# Observed escapements by substock;
 for (y in 1:34) {
  for (t in 1:10) {
    tau.logShat[y,t] <- 1 / sigma.logShat[y,t] / sigma.logShat[y,t]
    }
  }
 for (y in 1:34) {
  for (t in 1:8) {
    p[y,t] <- g[y,t] / sum(g[y,])
    S[y,t] <- p[y,t] * Stotal[y]
    log.S[y,t] <- log(S[y,t])
    log.Shat[y,t] ~ dnorm(log.S[y,t],tau.logShat[y,t])
    S.hat[y,t] <- exp(log.Shat[y,t])
    }
# Observed Kantishna escapement (=Toklat and other Kantishna combined);
  S.Kantishna[y] <- S[y,1] + S[y,2]
  log.S.Kantishna[y] <- log(S.Kantishna[y])
  log.Shat[y,9] ~ dnorm(log.S.Kantishna[y],tau.logShat[y,9])
  Shat.Kantishna[y] <- exp(log.Shat[y,9])
```

-continued-

```
# Observed Upper Tanana escapement (=Delta and other Upper Tanana combined);
    S.UpperTan[y] <- S[y,3] + S[y,4]
    log.S.UpperTan[y] <- log(S.UpperTan[y])
    log.Shat[y,10] ~ dnorm(log.S.UpperTan[y],tau.logShat[y,10])
    Shat.UpperTan[y] <- exp(log.Shat[y,10])
    }

# Calculate Subtotals
  for (y in 1:34) {
    S.Tanana[y] <- S.Kantishna[y] + S.UpperTan[y]
    S.UYTribs[y] <- S[y,5]+S[y,6]+S[y,7]
    p.nonTanana[y] <- 1 - S.Tanana[y] / Stotal[y]
    }

  pi.Kantishna <- pi[1]+pi[2]
  pi.UpperTan <- pi[3]+pi[4]
  pi.Tanana <- pi.Kantishna + pi.UpperTan
  pi.nonTanana <- 1 - pi.Tanana
  pi.UYTribs <- pi[5]+pi[6]+pi[7]

}
```

Appendix A2.–WinBUGS model code for Bayesian MCMC statistical analysis of Yukon River fall chum salmon data, age-structured spawner recruit model, 1974-2007. Prior distributions are italicized; sampling distributions of the data are underlined.

WinBUGS code for Age-structured Spawner Recruit 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 = 34 + 3 - 1 = 36 BROOD YRS REPRESENTED IN DATA
#  THE FIRST a.max = 5 DO NOT HAVE CORRESPONDING SPAWNING ABUNDANCES
#  THE REMAINING Y-a.min = 31 DO (BROOD YEARS A+a.min=6 - 36)

 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)

# 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(0.1,0.1)
 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])
  }

# DIRICHLET MATURITY SCHEDULES, ONE PER BROOD YEAR
D <- sum(gamma[])
for (a in 1:A) {
 gamma[a] ~ dgamma(0.001,0.001)
 pi[a] <- gamma[a] / D
 for (y in 1:Y+A-1) {
    g[y,a] ~ dgamma(gamma[a],0.1)
    p[y,a] <- g[y,a]/sum(g[y,])
  }
 }
```

-continued-

```
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

# FIRST DO INITIAL CELLS WITHOUT SR LINK (o's and x's IN MATRIX ABOVE)
for (y in 3:a.max)  {  N.ta[y-2,1] <- p[y,1] * R.lag[y]  }    # COLUMN 1
for (y in 2:a.max)  {  N.ta[y-1,2] <- p[y,2] * R.lag[y]  }    # COLUMN 2
for (y in 1:a.max)  {  N.ta[y   ,3] <- p[y,3] * R.lag[y]  }    # COLUMN A=3

# THEN DO CELLS DESCENDING WITH SR LINK (y's IN MATRIX)
for (y in a.max+1:Y+2)   {  N.ta[y-2,1] <- p[y,1] * R[y]  }
for (y in a.max+1:Y+1)   {  N.ta[y-1,2] <- p[y,2] * R[y]  }
for (y in a.max+1:Y)     {  N.ta[y  ,3] <- p[y,3] * 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])
  }

# SMALL HARVEST BELOW SONAR IS ASSUMED KNOWN
# HARVEST ABOVE SONAR IS ESTIMATED, AND CAN BE LARGE
theta ~ dunif(0,1)
tau.log.PS ~ dgamma(0.1,0.1)
sigma.log.PS <- 1 / sqrt(tau.log.PS)
for (y in 1:Y) {
  Pilot.Station[y] <- max(N[y] - Hhat.belowPilot[y],1)
  log.qPS[y] <- log(theta * Pilot.Station[y])
  PS.hat[y] ~ dlnorm(log.qPS[y],tau.log.PS)
  S[y] <- max(Pilot.Station[y] - H.above[y],1)
  log.S[y] <- log(S[y])
  tau.log.S[y] <- 1 / S.cv[y] / S.cv[y]
  S.hat[y] ~ dlnorm(log.S[y],tau.log.S[y])
  mu.Habove[y] ~ dbeta(0.1,0.1)
  H.above[y] <- mu.Habove[y] * Pilot.Station[y]
  log.Ha[y] <- log(H.above[y])
  tau.log.Ha[y] <- 1 / Ha.cv[y] / Ha.cv[y]
  Hhat.above[y] ~ dlnorm(log.Ha[y],tau.log.Ha[y])
  }
inverse.theta <- 1 / theta
```

-continued-

```
# GENERATE FITTED VALUES OF R EVERY 1000 SPAWNING FISH FOR GRAPHICS;
for (i in 1:25) {
  S.star.1[i] <- 100000*i
  R.fit[i] <- S.star.1[i] * exp(lnalpha - beta * S.star.1[i])
  }
# CALCULATE SUSTAINED YIELD AT REGULAR INTERVALS OF S;
# FIND THE PROBABILITY THAT EACH VALUE OF S WILL RESULT IN YIELDS WITHIN 10% 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] <- 15000*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)
  }
SY700 <- 700000 * exp(lnalpha - beta * 700000)*exp(sigma.red*sigma.red/2) - 700000
SY450 <- 450000 * exp(lnalpha - beta * 450000)*exp(sigma.red*sigma.red/2) - 450000
delta.SY <- SY700 - SY450
}
```

Appendix A3.–WinBUGS data objects for Bayesian analysis of Yukon River fall chum salmon data, drainagewide escapement model, 1974-2007.

Data for Drainagewide Escapement Model

```
list(
log.Shat = structure(.Data =c(
10.64,NA,8.69,NA,NA,11.68,10.36,NA,NA,NA,
11.43,NA,8.23,NA,NA,12.34,12.78,NA,NA,NA,
10.88,NA,8.75,NA,NA,10.45,10.51,NA,NA,NA,
10.46,NA,9.73,NA,NA,11.00,11.39,NA,NA,NA,
10.52,NA,9.32,NA,NA,10.66,10.62,NA,NA,NA,
11.97,NA,9.03,NA,NA,11.70,11.69,NA,NA,NA,
10.18,NA,8.54,NA,NA,10.55,10.92,10.04,NA,NA,
9.66,NA,10.07,NA,NA,11.53,10.96,10.76,NA,NA,
8.20,NA,8.35,NA,NA,10.67,9.67,10.37,NA,NA,
9.99,NA,8.95,NA,NA,11.08,10.21,11.42,NA,NA,
9.73,NA,9.43,NA,NA,10.50,9.63,10.94,NA,NA,
10.03,NA,9.76,NA,NA,12.10,10.93,11.04,NA,NA,
9.80,NA,8.81,NA,NA,11.34,10.36,11.38,NA,NA,
10.00,NA,9.96,NA,NA,11.94,10.80,11.30,NA,NA,
9.51,NA,9.80,NA,NA,10.72,10.07,10.51,NA,NA,
10.32,NA,9.97,NA,NA,11.50,10.69,10.48,NA,NA,
10.46,NA,9.10,NA,NA,11.26,10.46,10.85,NA,NA,
9.50,NA,10.40,NA,NA,11.37,10.54,11.27,NA,NA,
9.55,NA,9.09,NA,NA,11.27,10.02,10.80,NA,NA,
10.23,NA,9.90,NA,NA,10.67,10.26,10.30,NA,NA,
11.24,NA,10.08,NA,NA,11.92,11.09,11.50,NA,NA,
10.91,NA,9.93,NA,12.55,12.40,10.86,11.97,NA,12.06,
9.81,NA,9.89,NA,12.25,12.42,11.26,11.72,NA,11.50,
9.58,NA,8.95,NA,12.21,11.30,10.20,11.36,NA,11.02,
9.66,NA,8.96,NA,11.24,10.41,9.52,10.74,NA,10.85,
8.42,NA,9.71,NA,11.39,9.56,9.47,10.98,10.21,11.38,
9.10,NA,8.01,NA,11.10,10.31,9.13,10.89,9.97,10.45,
8.70,NA,9.00,NA,11.62,10.90,9.98,10.43,10.04,11.45,
10.26,NA,9.39,NA,11.40,10.36,9.52,11.50,10.94,11.59,
9.98,NA,10.02,NA,12.28,10.69,10.29,11.87,11.38,12.09,
10.48,NA,10.13,NA,11.83,10.54,9.92,11.95,11.24,11.63,
9.79,NA,10.24,NA,13.12,13.24,11.71,12.99,11.59,12.51,
NA,NA,9.55,NA,12.41,11.98,10.34,12.26,11.17,11.95,
NA,NA,9.83,NA,12.34,11.09,10.43,12.33,11.31,12.59
),.Dim=c(34,10)),
```

-continued-

```
sigma.logShat = structure(.Data =c(
0.20,  0.99,  0.15,  0.99,  0.99,  0.40,  0.10,  0.99,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.40,  0.10,  0.99,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.40,  0.40,  0.99,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.40,  0.40,  0.99,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.40,  0.40,  0.99,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.40,  0.40,  0.99,  0.99,  0.99,
0.30,  0.99,  0.15,  0.99,  0.99,  0.40,  0.40,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.30,  0.45,  0.30,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.30,  0.40,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.30,  0.40,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.30,  0.40,  0.30,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.30,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.25,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.25,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.25,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.25,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.25,  0.40,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.20,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.20,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.20,  0.10,  0.20,  0.99,  0.99,
0.20,  0.99,  0.15,  0.99,  0.99,  0.20,  0.10,  0.20,  0.99,  0.99,
0.30,  0.99,  0.20,  0.99,  0.15,  0.20,  0.20,  0.20,  0.99,  0.19,
0.20,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.99,  0.26,
0.20,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.99,  0.29,
0.20,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.99,  0.19,
0.20,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.20,  0.33,
0.20,  0.99,  0.15,  0.99,  0.15,  0.30,  0.30,  0.20,  0.21,  0.22,
0.30,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.14,  0.33,
0.20,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.11,  0.18,
0.25,  0.99,  0.15,  0.99,  0.15,  0.25,  0.10,  0.20,  0.14,  0.08,
0.20,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.09,  0.15,
0.30,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.11,  0.12,
0.99,  0.99,  0.15,  0.99,  0.15,  0.20,  0.10,  0.20,  0.10,  0.16,
0.99,  0.99,  0.15,  0.99,  0.10,  0.20,  0.10,  0.20,  0.09,  0.12
),.Dim=c(34,10))
)
```

Appendix A4.–WinBUGS data objects for Bayesian analysis of Yukon River fall chum salmon data, age-structured spawner recruit model, 1974-2007.

Data for Age-structured Spawner Recruit Model

```
list( Y=34, A=3, a.min=3, a.max=5,
x = structure(.Data =c(
0,0,0,
0,0,0,
0,0,0,
10 ,    85 ,    5 ,
20 ,    66 ,   14 ,
  7 ,   88 ,    5 ,
14 ,    78 ,    8 ,
2 ,     87 ,    11 ,
7 ,     60 ,    33 ,
1 ,     88 ,    11 ,
7 ,     53 ,    40 ,
1 ,     81 ,    18 ,
2 ,     58 ,    41 ,
1 ,     83 ,    17 ,
7 ,     60 ,    33 ,
0 ,     83 ,    17 ,
2 ,     60 ,    39 ,
4 ,     60 ,    36 ,
1 ,     37 ,    62 ,
0 ,     64 ,    36 ,
0 ,     62 ,    38 ,
0 ,     70 ,    30 ,
1 ,     62 ,    38 ,
1 ,     68 ,    31 ,
1 ,     67 ,    32 ,
0 ,     64 ,    36 ,
1 ,     69 ,    29 ,
0 ,     64 ,    36 ,
7 ,     63 ,    30 ,
1 ,     91 ,    8 ,
22 ,    48 ,    29 ,
0 ,     94 ,    6 ,
2 ,     39 ,    59 ,
0 ,     76 ,    24
),.Dim = c(34, 3)),
Hhat.belowPilot=c(
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,131735,0,46517,6424,24662,6293,4929,2818,9821,4303,135619,128322,63468),
PS.hat=c(
NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,1053245,NA,506621,372927,379493,247935,376182,326858,889778,
594060,1813589,790563,684001),
```

-continued-

```
Hhat.above=c(
478875,473062,339043,447918,434030,615377,488373,683391,373519,525485,
412323,515481,318028,406143,353685,545166,352007,439096,148846,91015,
169225,329412,260923,123542,64396,106513,22250,40047,24593,69708,
71993,154564,142149,131318),
Ha.cv=c(
0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,
0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1),
S.hat=c(
587400,2068000,491300,663100,502000,1245000,314800,529900,229700,483400,331800,661500,
500800,675000,327500,504900,468800,556400,384600,353000,895800,1006000,813000,502400,
258600,271800,217700,320600,388200,689700,525400,1823000,834100,884400),
S.cv=c(
0.25,0.22,0.24,0.25,0.26,0.25,0.22,0.20,0.21,0.19,0.20,0.18,0.18,0.17,0.18,0.18,0.19,0.17,0.17,0.17,0.16,
0.09,0.09,0.09,0.09,0.09,0.09,0.09,0.07,0.07,0.07,0.07,0.08,0.06)
)
```