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Optimum Escapement Goals for Chinook Salmon in the Transboundary Alsek River

by

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and

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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 Department of Fish and Game	ADF&G
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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ABSTRACT

Escapement goal analyses for stocks of Chinook salmon in the transboundary Alsek River and in one of its tributaries, the Klukshu River, are described. Data and estimates for harvest, inriver run size, harvest rates, relative age composition, and escapements for calendar years 1976 through 2007 are provided. Bayesian statistical analysis was used to address measurement error in estimated escapements, missing information on stock-specific harvests, missing data on relative age composition of some harvests, measurement error in estimates of relative age composition, process error, the possibility of autocorrelation in that process error, and the lack of small escapements in the data. Optimum yield profiles and overfishing profiles showed that escapements to the Alsek River distributed evenly across the range of 3,500 to 5,300 adults (age 1.2-1.4) have an 89% to 97% chance of attaining optimum yield (a sustained yield ≥90% of maximum). A modified analysis showed that escapements to the Klukshu River spread evenly across the range 800 to 1,200 have a 90% to 98% chance of attaining optimum yield. The analysis also showed the current goal for the Klukshu stock (1,100 to 2,300) to be too high to regularly attain optimum yield; the chance is 95% at an escapement of 1,100, but drops to virtually 0% at 2,300.

Key words: escapement goal, Chinook salmon, Alsek River, Klukshu River, harvest rates, optimum yield profiles, overfishing profiles, SEG.

INTRODUCTION

This Fisheries Manuscript is a report on an analysis to determine escapement goals to be used to manage and possibly expand U.S. and Canadian fisheries for Chinook salmon (*Oncorhynchus tshawytscha*) of the Alsek River in Alaska and Canada. Objectives of this analysis are to 1) develop estimates (and variances) of annual runs, annual spawning abundance, and brood-year production for the aggregate stock of Chinook salmon in the Alsek River (hereafter referred to as the Alsek stock), and 2) use these statistics to determine a suite of escapement goals that are likely to produce optimum yield (maximum or nearly maximum sustained yield) from the Alsek stock. This work is an update of an earlier analysis (McPherson et al. 1998) to determine escapement goals for Chinook salmon spawning in the Klukshu River, a tributary of the Alsek River. Escapement goals from the analysis in McPherson et al. (1998) have been expanded to cover the aggregate stock for the entire drainage of the Alsek River and to include 11 years of additional data.

The Methods Section of this report is divided into 2 parts, one on statistics and one on determining goals. The first part covers annual estimates of relative age composition (of harvests and of inriver runs[1]) and of inriver run size (for years of direct estimates and for years with expansions), estimates of escapement and of brood-year production, and estimates of harvest rates. Methods for calculating statistics are described with results of these calculations displayed in tables and figures referenced in the Methods Section. Preliminary statistics and raw data have been placed in appendix tables. Collectively statistics cover years 1976 through 2007.

The second part of the Methods Section concerns the determination of escapement goals based on statistics reported in the first part. A Bayesian statistical model is described along with the particulars of simulations using this model. The use of optimum yield (OY) and overfishing (OF) profiles to convey uncertainty in escapement goals is also explained.

The Results Section of this manuscript contains only the outcomes from simulations with the Bayesian model that pertain to optimum escapement goals. Probabilities that a potential range of escapements will produce optimum yield are graphed as OY profiles. Overfishing profiles are presented to determine probabilities that a specific escapement (a threshold escapement) results in recruitment overfishing (escapements below the point that produces optimum yield). Both types of profiles are presented for the Alsek stock and for the tributary stock of Chinook salmon spawning in the Klukshu River (hereafter referred to as the Klukshu stock).

[1] All terms, abbreviations, and notation not defined in the frontispiece of this report are defined in Appendix Table C.1.

BACKGROUND

The Alsek River drains approximately 19,000 km^2 of Alaska and Canada (Figure 1) into the Gulf of Alaska at 59° 11′ N 138° 29′ W. The river is home to all 5 species of Pacific salmon; fisheries and runs of Chinook and sockeye (*O. nerka*) salmon overlap with the former species entering the river earlier in May and June. Commercial and subsistence fisheries occur in the intertidal area of the Alsek River, in the marine waters of Dry Bay adjacent to the river, and catch both Chinook and sockeye salmon in set gillnets with 127 to 152 mm (5 to 6-in) mesh. Hook-and-line sport and aboriginal fisheries occur in Canada in the Klukshu River, at and upstream of Dalton Post. Chinook salmon spawn almost exclusively in the Tatshenshini River and its tributaries (7,655 km^2 of watershed). Chinook salmon smolt exclusively at age 1.0 (2-year olds) and return predominantly at ages 1.2 (4-year olds), 1.3 (5-year olds), and 1.4 (6-year olds). On average 1% of the annual run is comprised of fish age 1.1 and 1.5 combined (3 and 7-year olds). Timing of nearby fisheries and recovery of coded wire tags implanted in smolts from the Alsek River indicate that significant harvest has been limited to terminal fisheries on the Alsek stock (McPherson et al. 1998).

Stock assessment has been focused on the Klukshu River. A weir (fence) with a trap was installed in 1976, and all migrants were counted through that year and every year thereafter. In most years catches in all fisheries, fish passing through the weir, and dead and moribund fish on spawning grounds were sampled to obtain information on

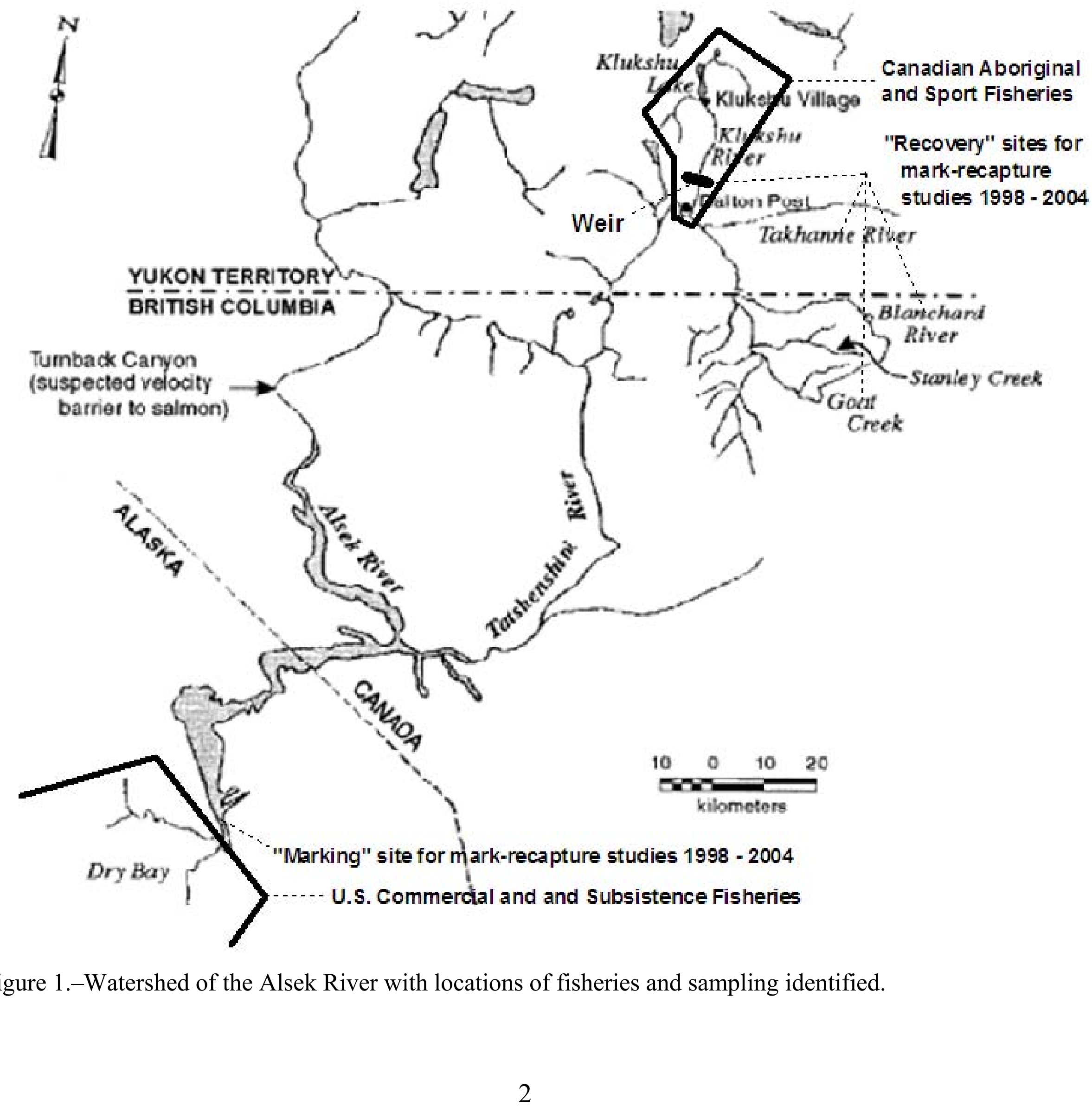

Figure 1.–Watershed of the Alsek River with locations of fisheries and sampling identified.

relative size, sex, and age composition of the annual run. In 1998 test fishing using drift gillnets with 184 mm (7¼-in) stretch mesh began in the river upstream of commercial and subsistence fisheries in Dry Bay. In that year a subset of fish captured in this test fishery was fitted with radio transmitters. Starting in 1998 and running through 2004, a 2-event mark–recapture study was used to estimate the annual inriver run past the test fishery. An escapement goal range of 1,100 to 2,300 Chinook salmon spawning in the Klukshu River was recommended in 1998 using a method of minimizing expected loss in yield (see Geiger and Koenings 1991 as cited in McPherson et al. 1998) and was accepted as the current goal for the Klukshu stock.

METHODS

STATISTICS

Relative Age Composition

Relative age composition was estimated annually for the following 5 groups of Chinook salmon: commercial harvest from U. S. waters, live salmon through the weir on the Klukshu River, spawned-out carcasses at or near that weir, spawned-out carcasses from other tributaries to the Alsek River, and harvest in Canadian sport fisheries. Scales were collected from each sampled fish, and age was determined later from those scales by respective agencies. Tallies of samples by age of salmon can be found in McPherson et al. (1998) for calendar years 1976 through 1996 and/or by querying the Integrated Fishery Data Base (IFDB) sponsored by the Alaska Department of Fish and Game for data collected after 1996. These tallies are also given in Appendix Tables A1-A5 in this report. Average age over years for each of these groups is plotted in Figure 2. Note that average ages in samples from the Canadian sport fishery and from live fish sampled at the Klukshu weir were similar in years of overlap (1986 to 1996). Also note that average ages in samples from the commercial fishery were consistently younger, most likely due to the size of mesh used in that fishery. As expected, average ages determined from spawned-out carcasses are older, most likely due to a tendency to sample larger carcasses on spawning grounds (Zhou 2002).

Relative age composition in a calendar year (*cy*) was treated as a vector of proportions that sum to 1 with each proportion representing age *a*. The proportion for each age was estimated for harvest in U. S. fisheries and for the inriver run as follows:

$$\hat{p}_{cy,a} = \frac{h_{cy,a}}{h_{cy}} \tag{1a}$$

$$\hat{q}_{cy,a} = \frac{w_{cy,a}}{w_{cy}} \tag{1b}$$

where h and w are annual sample sizes pertaining to U. S. fisheries and to the inriver run, respectively. Estimated sampling variances for each proportion above were calculated as:

$$\hat{\text{var}}(\hat{p}_{cy,a}) = \left[\frac{H_{cy} - h_{cy}}{H_{cy}}\right]\frac{\hat{p}_{cy,a}(1-\hat{p}_{cy,a})}{h_{cy}-1} \tag{2a}$$

$$\hat{\text{var}}(\hat{q}_{cy,a}) = \frac{\hat{q}_{cy,a}(1-\hat{q}_{cy,a})}{w_{cy}-1} \tag{2b}$$

Because annual sample size often represented a large fraction of the U. S. harvest in a calendar year (on average 45% since 1982), $\hat{\text{var}}(\hat{p}_{cy,a})$ includes a correction for sampling from a finite population. Because annual sample size rarely represented a large fraction of the inriver run (on average 4% since 1976), no correction for sampling from a finite population was included in $\hat{\text{var}}(\hat{q}_{cy,a})$, thereby tending to make these estimates negligibly conservative.

Inriver Run Size

Years 1998–2004

Mark–recapture studies from 1998 through 2004 (Pahlke et al. 1999; Pahlke and Etherton 2001a-b, 2002; Pahlke and Waugh 2003; 2004; 2006) were used to estimate the sizes N_{cy} of inriver runs (Table 1, Figure 3). Salmon were caught in the test fishery just above Dry Bay, marked, and released. Harvests in Canadian fisheries, live fish, and spawned-out carcasses were inspected upstream to estimate marked fractions of the run. For our

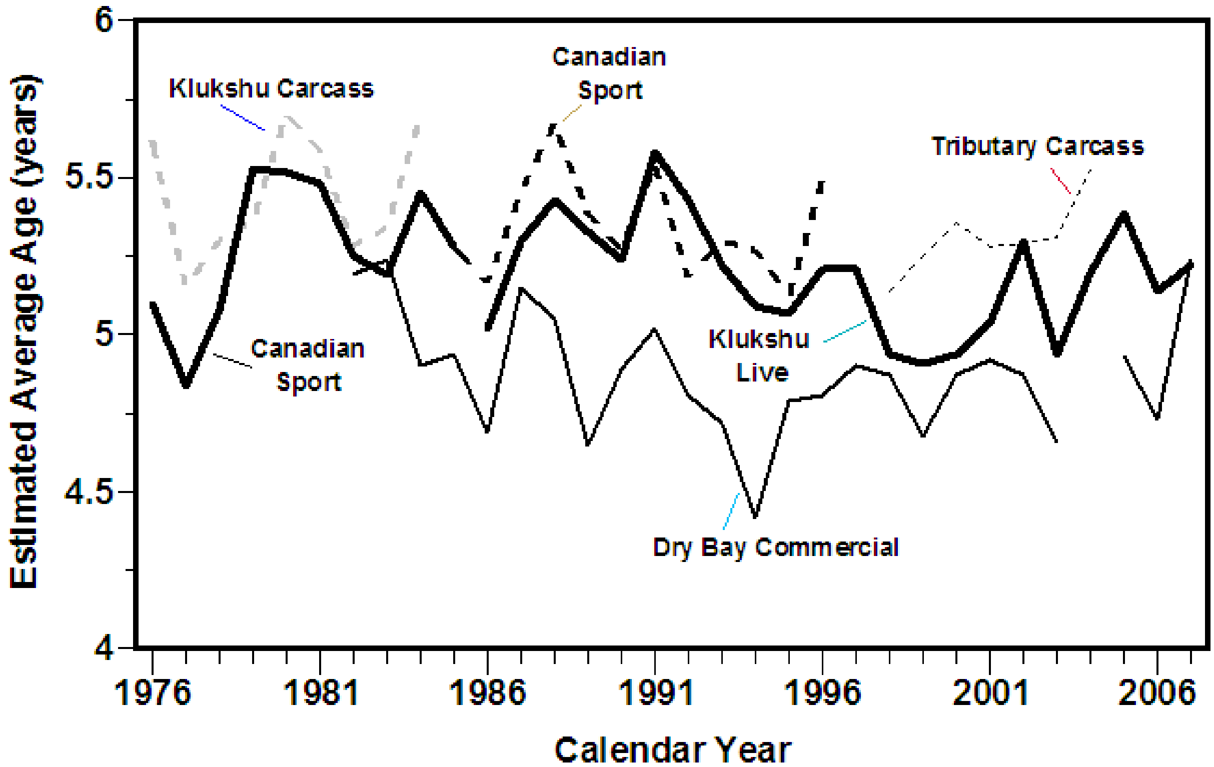

Figure 2.–Average age of Chinook salmon from different samples taken by year from the different segments of the annual run to the Alsek River. Solid lines represent samples used in the subsequent Bayesian analysis to determine escapement goals.

analysis only those live fish physically handled at the weir across the Klukshu River were used to estimate abundance $N_{cy,1.3+}$ of large salmon. A 2-event, closed population estimator was used in the calculations (Seber 1982, p. 59-61). Subsequent estimates can be found in Appendix Table A6.

Length distributions of marked and recaptured salmon during these studies indicated that live fish sampled at the weir generally represented the relative size composition, and by implication, the relative age composition of the inriver run. Length distributions of live fish recaptured upstream at the weir were similar to distributions of fish caught downstream and marked in 4 of 7 years (2000–2003) and slightly smaller in the other 3 years. Concurrently, length distributions of fish caught in the test fishery were similar to length distributions of live fish sampled at the weir in 6 of 7 years (1999 was the exception).

An overall expansion factor $\overline{\pi}$ (= 4.00) was developed from the mark–recapture studies to link counts of fish migrating into the Klukshu River (a base population of size W) to the size of the inriver run N. Each mark–recapture study produced 1 expansion factor

$$\hat{\pi}_{cy} = \frac{\hat{N}_{cy,1.3+}}{\hat{q}_{cy,1.3+} W_{cy}} = \frac{\hat{N}_{cy}}{W_{cy}} \quad (3)$$

Size W of the base population is the count of all Chinook salmon through the weir plus all the catch in the sport fishery downstream of the weir in the Klukshu River. The overall expansion factor $\overline{\pi}$ is the average of $\hat{\pi}_{cy}$ from 1998 through 2004. Measurement error in each annual expansion factor [var ($\hat{\pi}_{cy}$)] was estimated with 7 sets of 2 parametric (binomial) bootstrap simulations, one of individual mark–recapture studies ($\hat{N}_{cy,1.3+}$), and the other of annual sampling of live fish at the weir to estimate the proportion of large salmon ($\hat{q}_{cy,1.3+}$) passing through the weir (see Appendix Table A6 for

Table 1.–Sizes of the base population (*W*), U. S. harvest (*H*), and Canadian harvest (*C)*; and estimated sizes of the inriver run ($\hat{N}$) and spawning escapement ($\hat{S}$); and estimated harvest rate ($\hat{U}$) of Chinook salmon of all ages (1.1-1.5) in the Alsek River, 1976–2007.

cy	W_{cy}	H_{cy}	$\hat{N}_{cy}$	C_{cy}	$\hat{S}_{cy}$	SE($\hat{S}_{cy}$ or $\hat{N}_{cy}$)	$\hat{U}_{cy}$	SE($\hat{U}_{cy}$)
1976	1,408	512	5,632	350	5,282	1,981	0.14	0.025
1977	3,339	1,402	13,356	650	12,706	4,698	0.14	0.025
1978	3,171	2,441	12,684	650	12,034	4,462	0.20	0.035
1979	4,826	2,525	19,304	1,950	17,354	6,791	0.20	0.035
1980	2,803	1,382	11,212	350	10,862	3,944	0.14	0.025
1981	2,263	779	9,052	550	8,502	3,184	0.13	0.023
1982	2,552	532	10,208	733	9,475	3,591	0.12	0.021
1983	2,739	93	10,956	612	10,344	3,854	0.06	0.011
1984	1,947	46	7,788	550	7,238	2,740	0.08	0.014
1985	1,628	213	6,512	385	6,127	2,291	0.09	0.016
1986	2,834	503	11,336	267	11,069	3,988	0.06	0.011
1987	2,942	374	11,768	627	11,141	4,140	0.08	0.014
1988	2,286	236	9,144	427	8,717	3,217	0.07	0.012
1989	2,671	248	10,684	565	10,119	3,758	0.07	0.012
1990	2,383	163	9,532	923	8,609	3,353	0.11	0.019
1991	3,141	141	12,564	939	11,625	4,420	0.08	0.014
1992	1,506	316	6,024	251	5,773	2,119	0.09	0.016
1993	3,561	338	14,244	389	13,855	5,011	0.05	0.009
1994	4,114	865	16,456	593	15,863	5,789	0.08	0.014
1995	6,599	721	26,396	1,624	24,772	9,286	0.09	0.016
1996	4,255	831	17,020	1,098	15,922	5,987	0.11	0.019
1997	3,256	606	13,024	530	12,494	4,582	0.08	0.014
1998[a]	1,630	613	7,179	346	6,833	2,294	0.12	0.019
1999[a]	2,530	526	15,027	430	14,597	3,560	0.06	0.007
2000[a]	1,418	650	8,047	142	7,905	1,995	0.09	0.011
2001[a]	1,977	560	6,982	277	6,705	2,782	0.11	0.022
2002[a]	2,426	760	5,886	317	5,569	3,414	0.16	0.046
2003[a]	1,873	961	6,132	228	5,904	2,636	0.17	0.037
2004[a]	2,636	694	7,268	185	7,083	3,709	0.11	0.028
2005	1,148	693	4,592	114	4,478	1,615	0.15	0.026
2006	585	712	2,340	17	2,323	823	0.24	0.042
2007	717	826	2,868	41	2,827	1,009	0.23	0.040
				Average →	9,816	Average →	0.12	

[a] Years with mark–recapture studies.

statistics and for more detailed descriptions of the parametric bootstraps). Estimates of variances for $\hat{N}_{cy}$ (size of inriver run regardless of age) were obtained as part of these bootstrap simulations.

Years 1976–1997 and 2005–2007

For years without mark–recapture studies, the size of each inriver run (Table 1, Figure 3) was estimated as the product of the size *W* of the base population and the estimated overall expansion factor developed from information obtained with mark–recapture studies (see Pahlke 2008, Appendix B1, B10[2]; Appendix Table A6):

$$\hat{N}_{cy} = W_{cy}\overline{\pi} \quad (4)$$

$$\hat{\text{var}}(\hat{N}_{cy}) = W_{cy}^2 \ \hat{\text{var}}(\pi) \quad (5)$$

[2] During this analysis a transcription error was discovered in Appendix B.10 of Pahlke (2008) in the estimated size of the inriver run of large (age 1.3+) salmon for 1999. The correct estimate (11,620) was used to recalculate the expansion factor, its estimated variance, and expanded estimates of inriver run size for other years.

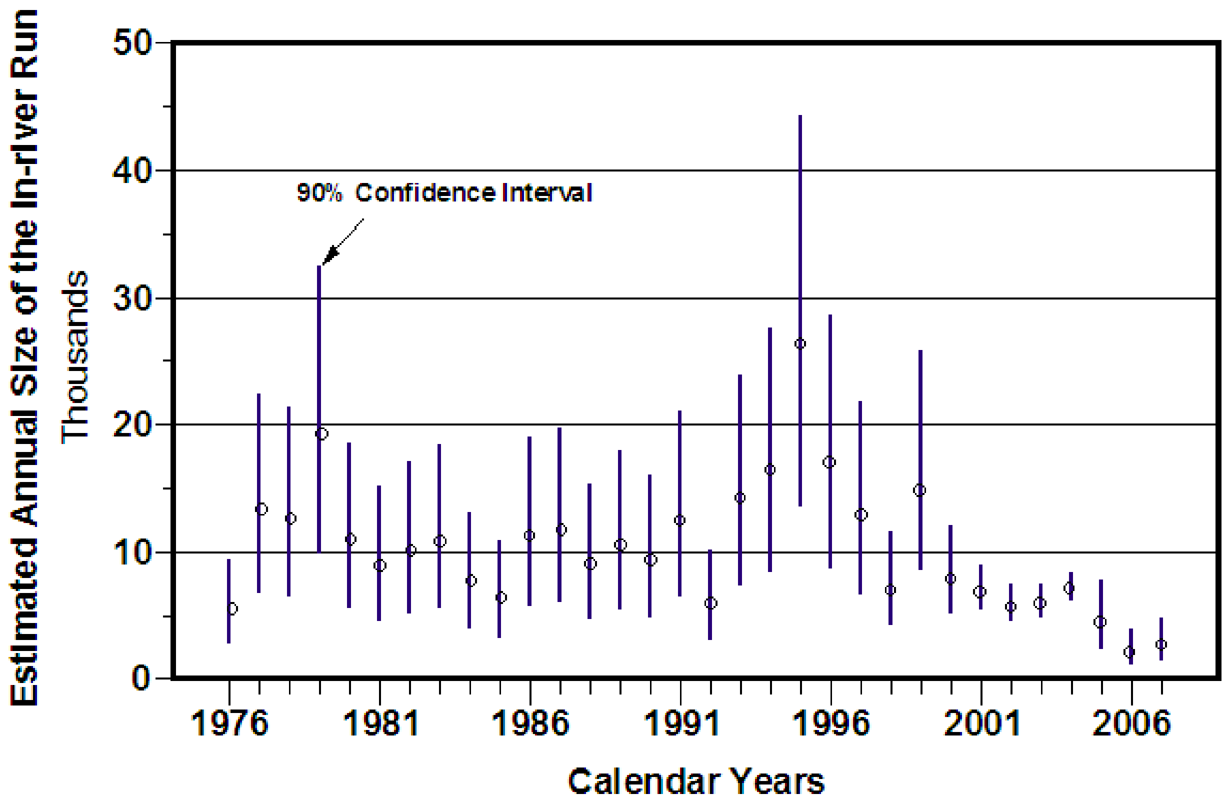

Figure 3.–Estimated sizes of the annual inriver run $\hat{N}_{cy}$ of Chinook salmon of all ages (1.1-1.5) into the Alsek River, 1976–2007. Confidence intervals were calculated using parametric bootstrap simulations based directly on mark–recapture studies (1998–2004) or on expansions of the base population W_{cy} (1976–1997 and 2005–2007).

Although the overall expansion factor is a mean, the variance of the expansion is relevant to variation across annual factors, not the overall mean of those factors. From a derivation described in Appendix B1 of Pahlke (2008):

$$\hat{\text{var}}(\pi) = \hat{\text{var}}(\hat{\pi}) + \hat{\text{var}}(\bar{\pi}) - \frac{\sum_{cy=1998}^{2004} \hat{\text{var}}(\hat{\pi}_{cy})}{7} = 1.98 \quad (6)$$

The third term (= 1.48) in Equation 6 represents measurement error due to mark–recapture studies and due to sampling to determine age (see Appendix Table A6). These 2 sources of uncertainty are not germane to expansions of base populations in years without mark–recapture studies, so their estimated variance is subtracted from overall variation. The remaining error in an expansion arises from annual variation across the π [$\text{var}(\hat{\pi})$] and variation from estimating the mean [$\text{var}(\bar{\pi})$]. From methods described in Appendix B1 of Pahlke (2008), values for $\hat{\text{var}}(\hat{\pi})$ and $\hat{\text{var}}(\bar{\pi})$ are respectively 2.90 and 0.56.

Escapement

Escapement S in this analysis is the number of salmon that survive annually to spawn (Tables 1 and 2, Figure 4). The estimate of escapement is the difference between the estimated inriver run size and harvests from inriver fishing:

$$\hat{S}_{cy} = \hat{N}_{cy} - C_{cy} \quad (7)$$

$$\hat{\text{var}}(\hat{S}_{cy}) = \hat{\text{var}}(\hat{N}_{cy}) \quad (8)$$

Over the years programs to estimate inriver harvest from Canadian sport and aboriginal fisheries have ranged from being a census to an opportunistic tally. Regardless, no estimates of measurement error are available for these harvests. For this analysis inriver harvests C_{cy} were considered to be known without error for the sake of convenience.

Production

Production by brood year (*by*) was estimated as the sum of estimated harvest by age in U.S. commercial and subsistence fisheries and of the estimated inriver run size by age (Table 2, Figure 4):

$$\hat{P}_{by} = \sum_{a=3}^{7}\left[\hat{H}_{by+a,a} + \hat{N}_{by+a,a}\right] \qquad (9)$$

$$\hat{\text{var}}\left(\hat{P}_{by}\right) = \sum_{a=3}^{7}\left[\hat{\text{var}}\left(\hat{H}_{by+a,a}\right) + \hat{\text{var}}\left(\hat{N}_{by+a,a}\right)\right] \qquad (10)$$

Commercial harvest was tallied from fish tickets for each sale while the much smaller harvests in subsistence fisheries were estimated through interviews. While estimates of variance for these subsistence harvests are not available, the measurement error they represent would be small given the relative size of the commercial and subsistence fisheries (the latter on average 10% of the former). For this reason harvests in U.S. fisheries were considered to be known without measurement error. Annual harvest by age $H_{cy,a}$ in the U.S. fisheries was estimated as the product of annual harvest and estimated relative age composition obtained from sampling catches:

$$\hat{H}_{cy,a} = H_{cy}\hat{p}_{cy,a} \qquad (11)$$

$$\hat{\text{var}}(\hat{H}_{cy,a}) = H_{cy}^2\ \hat{\text{var}}(\hat{p}_{cy,a}) \qquad (12)$$

Annual inriver run size by age $N_{cy,a}$ was estimated as the product of estimated inriver run size in a calendar year and estimated relative age composition obtained from sampling that run:

$$\hat{N}_{cy,a} = \hat{N}_{cy}\hat{q}_{cy,a} \qquad (13)$$

$$\hat{\text{var}}(\hat{N}_{cy,a}) = \hat{N}_{cy,a}^2\begin{bmatrix}\text{CV}^2(\hat{N}_{cy}) + \text{CV}^2(\hat{q}_{cy,a}) - \\ \text{CV}^2(\hat{N}_{cy})\text{CV}^2(\hat{q}_{cy,a})\end{bmatrix} \qquad (14)$$

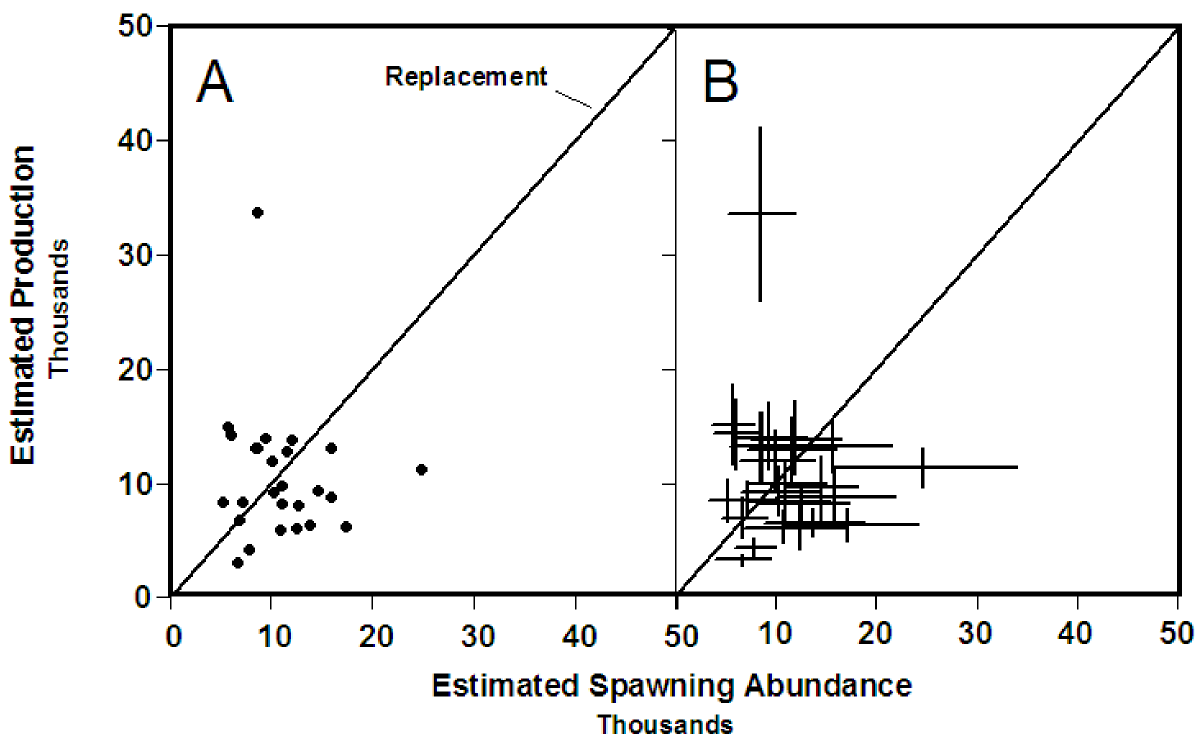

Figure 4.–Estimated production $\hat{P}_{by}$ against estimated spawning abundance $\hat{S}_{by}$ of Chinook salmon of all ages (1.1-1.5) in the Alsek River for brood years 1976–2001. Panel A is a point plot; Panel B is a bivariate plot where intervals correspond to ± 1.0 SE of points.

Table 2.–Estimated production $\hat{P}_{by}$ of adult Chinook salmon (age 1.1-1.5) by brood year and estimated spawning abundance $\hat{S}_{by}$ of their parents for the Alsek stock, 1976–2001.

by	$\hat{P}_{by}$	SE($\hat{P}_{by}$)	$\hat{S}_{by}$	SE($\hat{S}_{by}$)
1976	8,331	1,904	5,282	1,981
1977	8,042	1,839	12,706	4,698
1978	13,837	3,291	12,034	4,462
1979	6,180	1,437	17,354	6,791
1980	6,017	1,400	10,862	3,944
1981	13,084	3,060	8,502	3,184
1982	14,012	3,005	9,475	3,591
1983	9,205	2,171	10,344	3,854
1984	8,390	1,697	7,238	2,740
1985	14,212	3,093	6,127	2,291
1986	9,756	2,157	11,069	3,988
1987	8,199	2,114	11,141	4,140
1988	13,080	3,032	8,717	3,217
1989	11,938	2,560	10,119	3,758
1990	33,682	7,695	8,609	3,353
1991	12,848	2,782	11,625	4,420
1992	15,018	3,471	5,773	2,119
1993	6,368	1,146	13,855	5,011
1994	13,155	2,350	15,863	5,789
1995	11,189	1,712	24,772	9,286
1996	8,751	2,352	15,922	5,987
1997	6,028	1,924	12,494	4,582
1998	6,804	1,850	6,833	2,294
1999	9,409	2,832	14,597	3,560
2000	4,206	832	7,905	1,995
2001	3,047	533	6,705	2,782

Harvest Rates

Harvest rate by calendar year (Table 1, Figure 5) was estimated as the ratio of harvest to run size:

$$\hat{U}_{cy} = \frac{H_{cy} + C_{cy}}{\hat{N}_{cy} + H_{cy}} \qquad (15)$$

The numerator in Equation 15 is the tallied harvest of salmon of all sizes in U.S. and Canadian waters combined, and the denominator is the estimated run size. Average of these estimated rates since 1976 is 12%. Variances for estimated annual harvest rates were approximated with the delta method (see Seber 1982, p. 8):

$$\hat{\text{var}}(\hat{U}_{cy}) \cong \hat{\text{var}}(\hat{N}_{cy}) \frac{\hat{U}_{cy}^2}{(\hat{N}_{cy} + H_{cy})^2} \qquad (16)$$

ESCAPEMENT GOALS

The Model for the Alsek Stock

Bayesian statistical analysis of the information described above was used to determine optimum escapement goals for the Alsek Chinook stock because 1) information on relative age composition is missing for some years, 2) estimates of spawning abundance contain considerable measurement error, and 3) such an analysis provides an expression of the uncertainty associated with the chosen escapement goal. This expression of uncertainty is in the form of posterior probability distributions for parameters and variables given the observations of the Alsek stock made since 1976. Observations (estimates and data) are considered known without error in a Bayesian analysis while rates and variables defining states are considered to be unknown, but with an uncertainty expressible through probability distributions. The program WinBUGS[3] version 1.4.2 was used to determine these posterior probability distributions (see Appendix B1 for a listing of the code).

Bayesian analysis also allowed for the incorporation of knowledge on the productivity of Chinook salmon stocks in general to determine escapement goals for the Alsek stock. A Bayesian analysis begins with prior probability distributions for parameters and variables, distributions that are multiplied by likelihoods based on data to obtain posterior probability distributions. The usual approach is to use non-informative (sometimes called flat) prior distributions to let information in the data shape the form of the posterior distributions. However, low harvest rates since 1976 have produced no information in the data on production from small escapements to the Alsek River. As a consequence an informative prior distribution on $\ln\alpha$ based on the work of Parken et al. (2006) was used to fill the gap. The parameter $\ln\alpha$ represents intrinsic productivity of the stock. The average of this parameter across the 13 stocks described in Parken et al. (2006) as being similar to the Alsek stock (stream-type life history) is 1.58 with an approximated variance of 0.083 (as

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

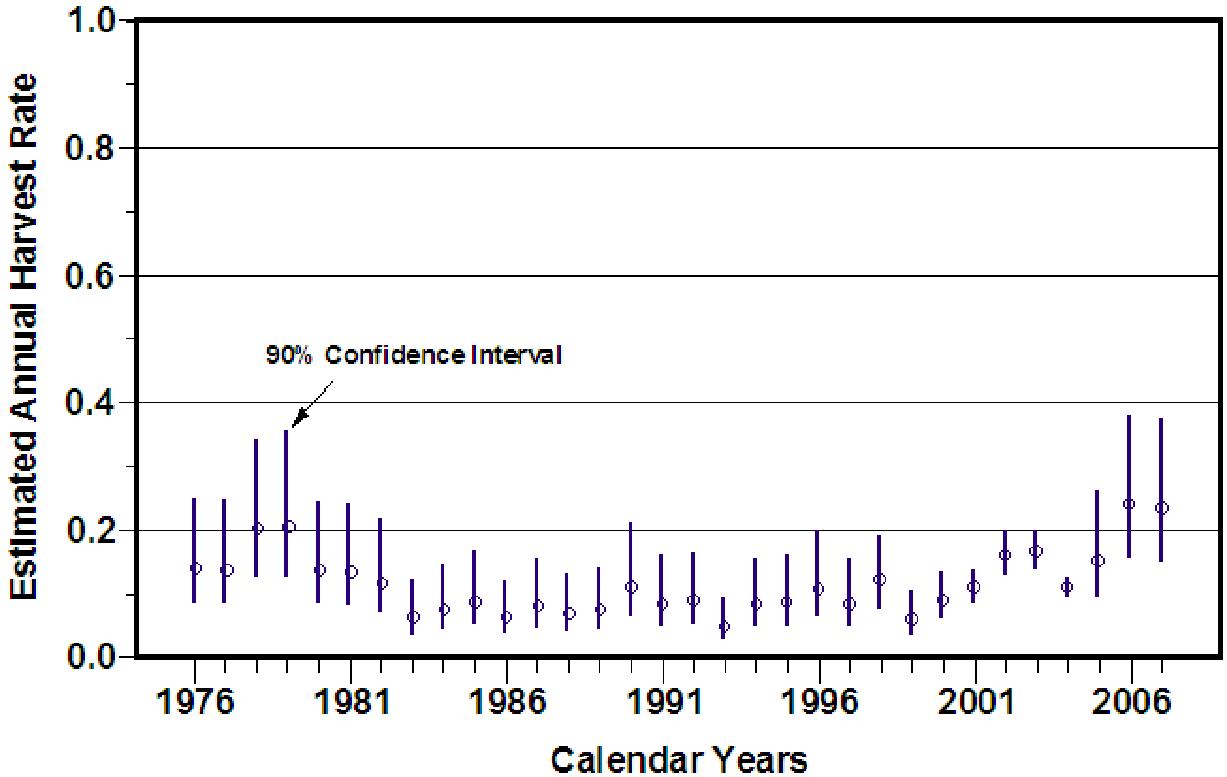

Figure 5.–Estimated annual harvest rate $\hat{U}_{cy}$ on the annual run of adult Chinook salmon of all ages (1.1-1.5) in the Alsek River, 1976–2007. Confidence intervals were calculated using parametric bootstrap simulations based directly on mark–recapture studies (1998–2004) or of expansions of the base population W_{cy} (1976–1997 and 2005–2007).

calculated from Parken et al. 2006). These statistics were used to create an informative prior distribution for ln α.

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

$$\ln(\tilde{P}_{by}) = \ln(S_{by}) + (1-\phi)\ln(\alpha) + \phi\ln(P_{by-1}/S_{by-1}) - \beta(S_{by} - \phi S_{by-1}) \quad (17)$$

$$\ln(P_{by}) = \ln(\tilde{P}_{by}) + \varepsilon_{by} \quad (18)$$

where lnα represents intrinsic productivity of the stock, β scales for density-dependant survival, ϕ discounts random process error in the production of brood year *by* for the process error in brood year *by* – 1, and ε_{by} represents independent and identically distributed ("white" noise) process error ~ *norm*(0, σ^2). Production for brood years 1970 through 1975 which contributed to harvests and escapements from 1976–1981 was modeled as following a common lognormal distribution (Table 3). Production from those early brood years was modeled differently because no estimates of escapement were available to seed Equation 17. Escapement in 1975 was also modeled as following a lognormal distribution (Table 3) to provide information required to begin the autoregressive model (Equation 17) at 1976. Production P_{by} for all brood years was allocated in the model to annual runs R_{cy} by age in the next generation as:

$$R_{cy,a} = P_{by}\theta_{by,a}\,|_{cy=by+a} \quad (19)$$

Table 3.–Prior probability distributions used in simulations involving the Bayesian model of the population dynamics of the Alsek River Chinook salmon stock from 1976 through 2007. Note that when expressing that a variable follows the normal probability distribution, the convention is to write $X \sim norm\ (mean, variance)$. However, in the program used in the analysis (WinBUGS ver. 1.4.2), the rule is to code $X \sim norm\ (mean, precision)$ where precision is the reciprocal of variance. Entries in the table below for normal distributions take this latter form. Notation is defined in the text and in Appendix C1.

Prior probability distributions	Constraints	Comments
$\ln\alpha \sim norm(1.58,12)$	$0 \rightarrow 4$	Informative prior for Ricker productivity parameter
$\ln\alpha \sim norm(1.58,0.01)$	$0 \rightarrow 4$	Non-informative prior for Ricker productivity parameter
$\beta \sim norm(0,0.001)$	$0 \rightarrow$	Non-informative prior for Ricker density dependence parameter
$\phi \sim norm(0,0.00001)$	$-0.99 \rightarrow 0.99$	Non-informative prior for autoregressive lag-1 coefficient
$\tau = 1/\sigma^2 \sim gamma(0.001,0.001)$	none	Non-informative prior for inverse variance of "white noise" process error in Ricker production
$p \sim$ Dirichlet(1,1,1)	none	Non-informative hyper-prior for Dirichlet location hyper-parameters
$\omega \sim uniform(0,1)$	$0 \rightarrow 1$	Non-informative hyper-prior Dirichlet dispersion hyper-parameter
$\overline{lnP} \sim \mathrm{norm}(0,0.0001)$	$0 \rightarrow$	Non-informative hyper-prior for mean of hierarchical lognormal production (*by* 1970–1975)
$\tau_{lnP} = 1/Var(lnP) \sim gamma(0.001,0.001)$	none	Non-informative hyper-prior for inverse variance of hierarchical lognormal production (*by* 1970–1975)
$\ln S_o \sim \mathrm{norm}(0,0.0001)$	$5 \rightarrow 13$	Non-informative prior for lognormal escapement in 1975

where $\theta_{by,a}$ is the fraction of brood year *by* that survive and mature to become members of the run in calendar year $cy = by + a$. The vectors were drawn from a common Dirichlet distribution (Table 3) re-parameterized such that the usual parameters (labeled as D) were written in terms of location (overall age proportions $\{p\}$) and scale ($\omega = \sqrt{D_{1.2} + D_{1.3} + D_{1.4}}$)[4].

Commercial/subsistence (U. S.) harvest by age in calendar year cy was the product of H_{cy} and the ratio of run sizes by age discounted for selectivity in the fishery:

$$H_{cy,a} = H_{cy} \frac{R_{cy,a}\gamma_{cy,a}}{\sum_{a'} R_{cy,a'}\gamma_{cy,a'}} \tag{20}$$

where $\gamma_{cy,a}$ is the relative selectivity rate. In turn the inriver run size by age was the age-specific harvest subtracted from the age-specific run size:

$$N_{cy,a} = R_{cy,a} - H_{cy,a} \tag{21}$$

For each calendar year discount rates $\gamma_{cy,a}$ for selectivity were scaled to the youngest age (1.2) with the other ages having non-informative prior distributions [~ *beta*(1,1)]. Values of $\theta_{by,a}$ and $\gamma_{cy,a}$ were conditioned on observations of harvest (H_{cy}), on observed numbers of sampled fish by age ($h_{cy,a}$, h_{cy}, $w_{cy,a}$, and w_{cy}), and on observed estimates of inriver run size ($\hat{N}_{cy}$) in the following manner:

[4] Initial runs with WinBUGS failed because salmon of ages 1.1 (3-year olds) and 1.5 (7-year olds) were often missing in samples, and when present were considerably less than the other 3 age groups. Over the years sampled, 3- and 7-year olds combined annually to represent no more that 6% of the inriver run or 5% of the marine harvest (median 1% representation for both). Salmon ages 1.1 and 1.5 were therefore ignored in the analysis making $h_{cy,4} + h_{cy,5} + h_{cy,6} \equiv h_{cy}$; $w_{cy,4} + w_{cy,5} + w_{cy,6} \equiv w_{cy}$; $p_{cy,4} + p_{cy,5} + p_{cy,6} = 1$; $q_{cy,4} + q_{cy,5} + q_{cy,6} = 1$; and the stock appear about 1% less productive than it really is.

$$H_{cy} \equiv \sum_{a=4}^{6} H_{cy,a} \tag{22}$$

$$(h_{cy,4}, h_{cy,5}, h_{cy,6}) \sim multinomial\,(p_{cy,4}, p_{cy,5}, p_{cy,6}, h_{cy}) \quad \text{where} \quad p_{cy,a} = H_{cy,a} / H_{cy} \tag{23}$$

$$(w_{y,4}, w_{cy,5}, w_{cy,6}) \sim multinomial\,(q_{cy,4}, q_{cy,5}, q_{cy,6}, w_{cy}) \quad \text{where} \quad q_{cy,a} = N_{cy,a} / N_{cy} \tag{24}$$

$$\hat{N}_{cy} \sim lognormal(\mu_{cy}, \lambda_{cy}^2) \tag{25}$$

where $\mu_{cy} = \ln(N_{cy}) - \lambda_{cy}^2 / 2$ and $\lambda_{cy}^2 \leftarrow \ln[cv^2(\hat{N}_{cy}) + 1]$ (relationships from Evans et al. 1993). Equation 25 represents measurement error in estimated size of the inriver run. Equation 24 represents measurement error from sampling to estimate relative age composition of the inriver run. Data used in Equation 24 came from sampling the harvest by the Canadian sport fishery from 1976 through 1985[5] and from sampling live fish at the Klukshu weir from 1986 through 2007. Equation 23 represents measurement error from sampling to estimate relative age compositions of the harvest in U.S. fisheries. Data used in this equation after 1981 came from sampling the commercial harvest in all later years except 2004; data for years 1976 through 1981 and 2004 were represented as missing. Equation 22 is a constraint. Size of the inriver run in a calendar year in the model was a matter of summing over age:

$$N_{cy} = \sum_{a=4}^{6} N_{cy,a} \tag{26}$$

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

$$S_{cy} = N_{cy} - C_{cy} \tag{27}$$

where C_{cy} is considered known. Overall annual harvest rates U_{cy} were calculated as

$$U_{cy} = \frac{H_{cy} + C_{cy}}{H_{cy} + N_{cy}} \tag{28}$$

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

$$S_{EQ} = \frac{\ln(\alpha')}{\beta} \tag{29}$$

$$S_{MSY} = S_{EQ}[0.5 - 0.07\ln(\alpha')] \tag{30}$$

with

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma^2}{2(1-\phi^2)} \tag{31}$$

Equation 31 is the correction in the expectation when there is an autoregressive process error with lag 1 brood year. All data (observations) input to the analysis are listed in lines 111–140 in Appendix B1.

MCMC Simulations

Samples from posterior probability distributions were generated with Markov Chain Monte Carlo (MCMC) methods (see Gilks et al. 1996) with the program WinBUGS. Samples consisted of 3 chains each containing 34,334 updates (samples). Each chain was initialized with a different set of starting values. The first 1,000 simulations in each chain (representing a "burn-in" period) were omitted before calculating posterior percentiles. See Appendix B1 for a listing of initializing values (Lines 142–209).

Optimum Yield and Overfishing Profiles

Results from simulations were displayed as posterior probability distributions and as OY profiles as developed by S. J. Fleischman (see Ericksen and Fleischman 2006; Szarzi et al. 2007) where OY is a sustained yield that is at or near MSY, say OY ≥ 90% of MSY. For each MCMC sample, there is a range of escapements that meet the criterion above for OY as determined from the Ricker parameters. For each sample, an array of binary numbers was maintained with each element

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

in the array corresponding to a level of escapement; one if the escapement corresponding to that element was within the optimum range for that sample, and zero otherwise. The mean of binary numbers across all MCMC samples at the same escapement represented the probability that OY would be realized at that escapement. A plot of these probabilities across elements (escapements) produced an OY profile (Figure 6, top panel) with which to determine an escapement goal range expected to produce OY. Each OY profile incorporates uncertainty due to measurement error in observations, from process error, and from missing data.

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

Goals for the Klukshu Stock

Optimum yield and overfishing profiles were also derived for just the Chinook salmon spawned in the Klukshu River. Instead of using π_{cy} in the relationship between the base population in the Klukshu River and the inriver run size N_{cy} to the Alsek River, π_{cy} was used to isolate harvests from the Klukshu stock in U.S. fisheries. In this analysis:

$$S_{cy} = W_{cy} - C_{cy} \tag{32}$$

where S_{cy} is now the spawning abundance in the Klukshu River and is known with certainty (an observation). The commercial/subsistence harvest $H'_{cy,a}$ by age and year from the Klukshu stock is still a variable and was calculated as:

$$H'_{cy,a} = H'_{cy} \frac{R_{cy,a}\gamma_{cy,a}}{\sum_{a'} R_{cy,a'}\gamma_{cy,a'}} \tag{33}$$

Note that $R_{cy,a}$ is now the age- and year-specific run size for the Klukshu stock. The harvest from this stock was calculated as:

$$H'_{cy} = R_{cy} - W_{cy} \tag{34}$$

The fraction of the entire harvest H_{cy} in U.S. fisheries composed of fish bound for the Klukshu River was $1/\pi_{cy}$, making:

$$\pi_{cy} = \frac{H_{cy}}{H'_{cy}} \tag{35}$$

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

$$p_{cy,a} = \frac{H'_{cy,a}}{\sum_{a=4}^{6} H'_{cy,a}} \tag{36}$$

The number of Chinook salmon in the inriver run belonging to the Klukshu stock by brood year and age group was calculated as:

$$W_{cy,a} = R_{cy,a} - p_{cy,a} H'_{cy} \tag{37}$$

Relative age composition for the Klukshu stock was calculated as:

$$q_{cy,a} = \frac{W_{cy,a}}{\sum_{a=4}^{6} W_{cy,a}} \tag{38}$$

The final change in equations was in regards to calculating the annual overall harvest rate:

$$U_{cy} = \frac{H'_{cy} + C_{cy}}{H'_{cy} + W_{cy}} \tag{39}$$

Changes in equations to shift emphasis of the analysis from the Alsek stock to the Klusksha stock generated corresponding changes in the statements of the WinBUGS program listed in Appendix B1. Appendix B2 contains alternative statements and the locations for their substitution in Appendix B1.

RESULTS

ALSEK STOCK

Informative Prior for lnα

Simulations resulted in a posterior distribution for the variable S_{MSY} with a mean of 4,677 and a median of 4,433 adults for the Alsek stock. Table

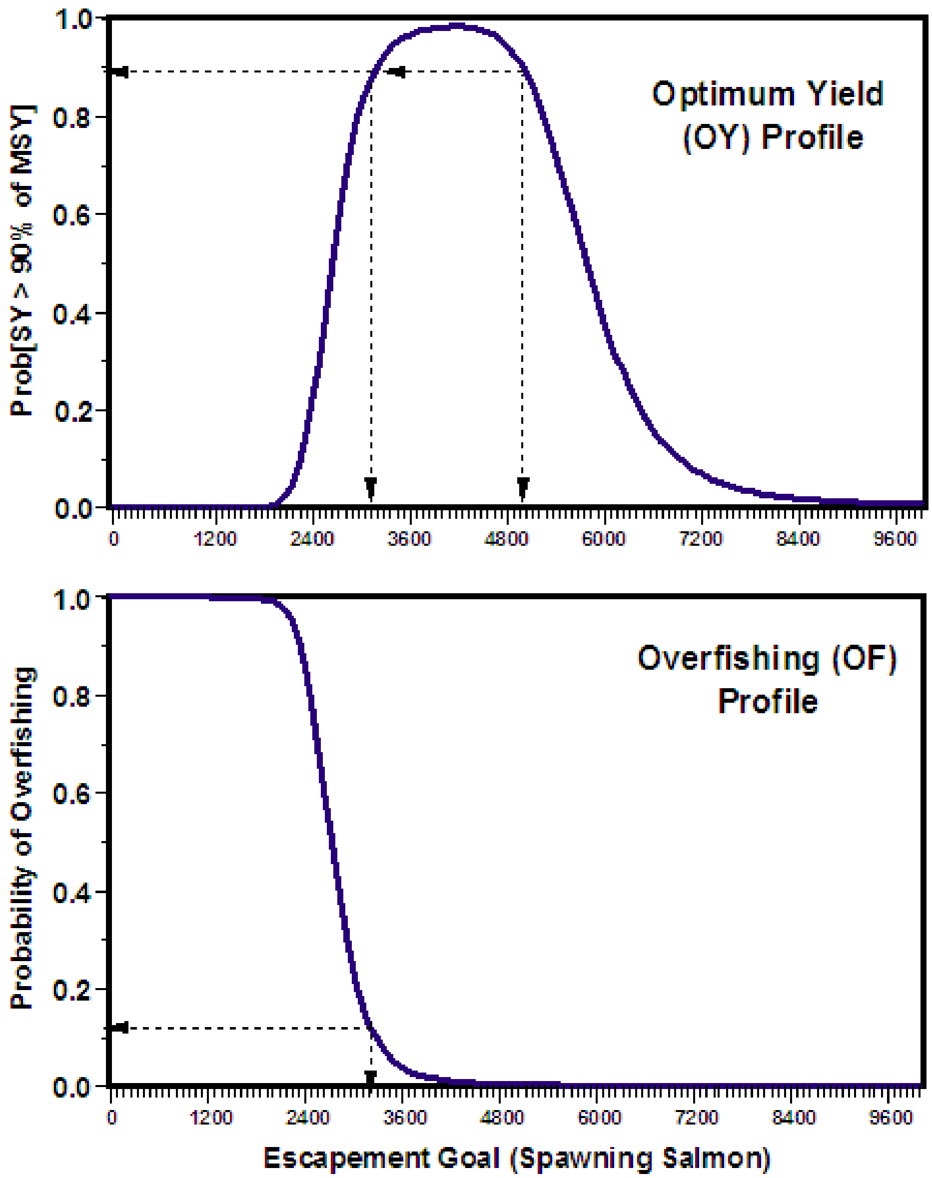

Figure 6.–Examples of optimum yield (OY) and overfishing (OF) profiles. Optimum yield for both types of profiles is a sustained yield ≥90% of MSY. Dashed lines on the OY profile connect the chance of attaining OY with a specific escapement as a goal; or on the OF profile, connect the probability of having less than optimum yield through recruitment overfishing at that escapement.

4 and Figure 7 represent these and other descriptive statistics for variables and parameters given that an informative prior was used for lnα. The median value of MSY from its posterior distribution is 5,917 adults. The expected value for the average of spawning escapements (a variable) over years 1976–2007 (9,804) compares favorably with the average (9,816) of estimated escapements (an observation). These values also compare favorably to the expected value of 11,920 for carrying capacity (the variable S_{EQ}) given that estimated annual harvest rates on this stock have an average of 12% across the years). The posterior distribution for the parameter ϕ indicates some probability of negligibly positive autocorrelation in process error. A plot of the expected P vs. S from posterior distributions embedded within possible plots from MCMC samples (Figure 8) graphically confirm a moderate amount of uncertainty in parameter

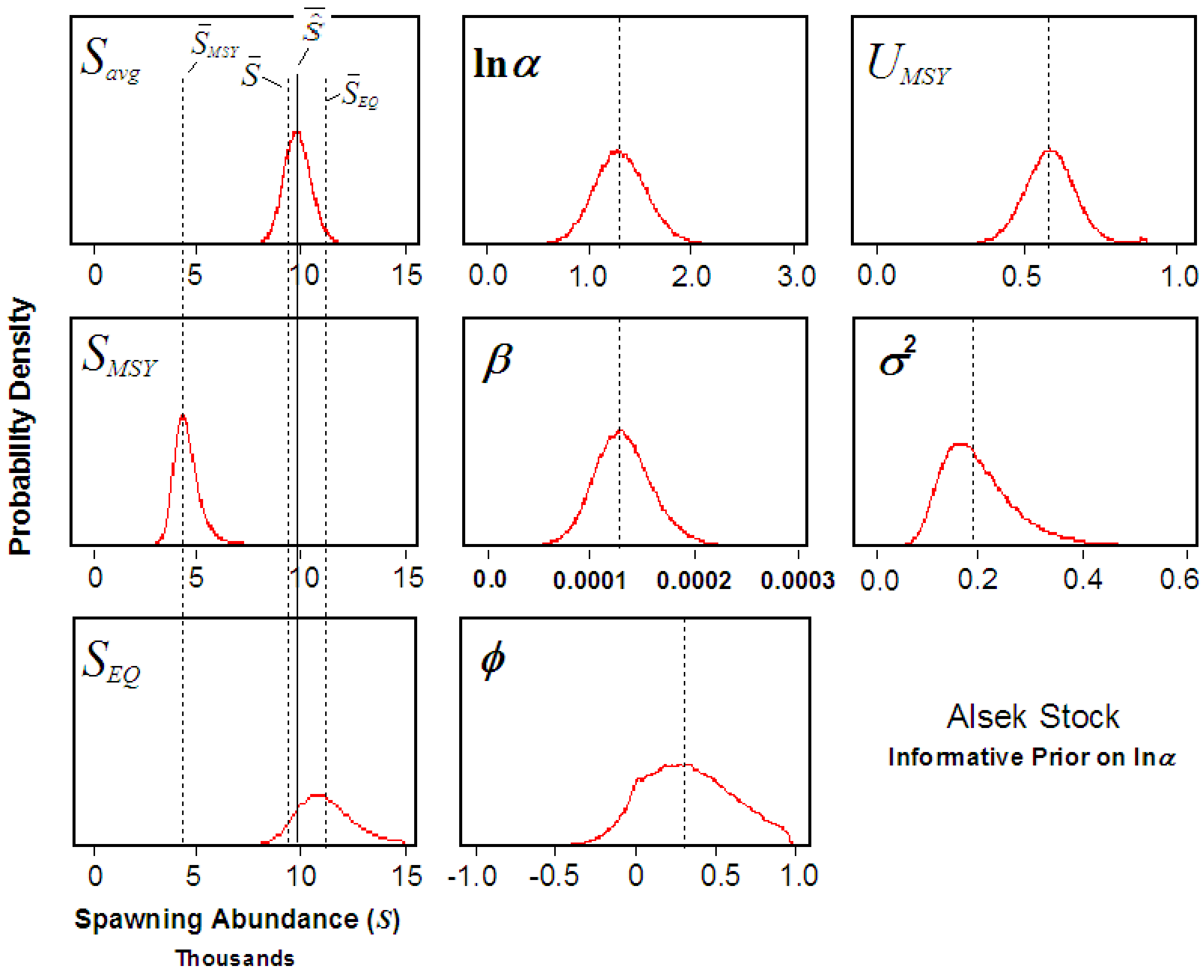

Figure 7.–Posterior probability distributions for parameters and some variables in the stock-recruitment relationship for the Alsek stock given an informative prior distribution for lnα. Dashed vertical lines correspond to expected (mean) values in each probability distribution as specified. The solid vertical line represents the average of the estimated spawning abundance $\hat{S}_{cy}$ over the data. Notation is defined in the text and in Appendix C1.

values as expressed in Table 4. The relatively large SDs for S_{MSY} and S_{EQ} reported in Table 4 indicate a few of the MCMC samples probably had unrealistically high values for these parameters; the apparent symmetry in the kernel densities for S_{MSY} and S_{EQ} in Figure 7 indicate that these outliers are relatively few.

Means from posterior distributions (variables) and estimates for annual inriver runs (observations) tracked well except for calendar years 1993–1996 and 1999 (Figure 9). During these years the CVs for estimates ranged from 35%–38% and for means from posterior distributions from 21%–27%. Descriptive statistics from posterior distributions for inriver run size N_{cy} and for spawning abundance S_{cy} can be found in Appendix Table A10.

Optimum yield profiles for the Alsek stock under an informative prior for lnα are given in Figure 10. For convenience OY was defined as a sustained yield that was at least 60%, 70%, 80%, or 90% of MSY. A range of 3,520 to 5,280 spawners was used to demonstrate how to establish a specific goal. The probability of achieving OY if escapements are kept within this range is 89% to 97%, given that OY is defined as at least 90% of MSY. The probability of achieving OY was capped at 97% because there was no escapement that was bracketed by optimum ranges in all MCMC samples. The

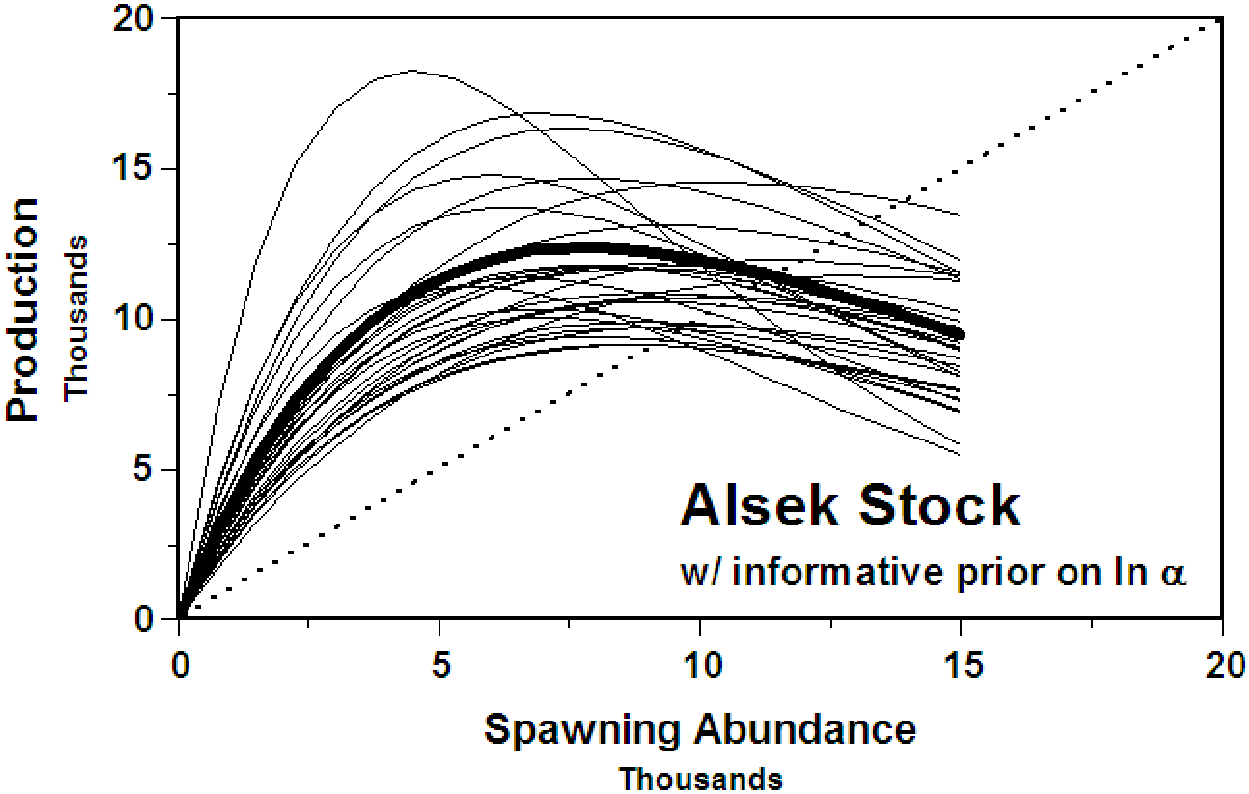

Figure 8.–Expected production *P* from posterior distributions versus escapement *S* (thick line) and *P* vs. *S* for 30 individual MCMC samples (thin lines) taken at intervals of 500 simulations with WinBUGs for the Alsek stock of Chinook salmon modeled with an informative prior for ln α. Dashed diagonal line is the replacement line.

probability of achieving a less stringent standard for OY at this range reaches near certainty at 97% to 100% (the range of 3,500–5,300 spawners was within the optimum ranges in virtually all simulations). Overfishing profiles for the Alsek stock show that an escapement of 3,520 adults runs an 11% risk of recruitment overfishing if OY is based on ≥90% of MSY (Figure 11). As expected that risk is less (2%) when OY is at least 80% of MSY and virtually nil under less stringent standards for OY.

Non-informative Prior Distribution for lnα

Use of a non-informative prior distribution for lnα (second entry in Table 3) gave substantively the same results relative to escapement goals as did use of the informative prior distribution (Table 4). Optimum yield profiles corresponding to both types of prior distribution were similar (Figure 12), which is not surprising considering that the means from the posterior distributions for S_{MSY} are also similar at 4,677 and 4,854 adults (Table 4). The medians are closer still (4,433 and 4,593). The kernel density for S_{MSY} without considering information from Parken et al. (2006) is negligibly broader than that obtained with that information (Figure 13).

The substantive difference between using or not using information from Parken et al. (2006) in the analysis can be seen in posterior values for lnα and subsequently in U_{MSY}. The mean for lnα is 1.309 when using information from Parken, and is 0.746 when not (Table 4). Means from posterior distributions of U_{MSY} follow suite (Figure 13) because U_{MSY} is a sole function of lnα (Hilborn and Walters 1992). While using or not using informative priors for lnα results in practically the same optimum escapement goal, expectations for average annual yield differ greatly. The median MSY with the informative prior is 5,917 adults and without it 2,778.

Table 4.–Means, SDs, medians, and percentiles of posterior probability distributions for parameters and variables in Bayesian analysis for the Alsek and Klukshu stocks of Chinook salmon. Notation is defined in text.

				Percentiles	
Parameter	Mean	SD	Median	2.5%	97.5%
Alsek stock with an informative prior distribution on lnα:					
$\bar{S}$	9,804	675	9,781	8,541	11,200
S_{EQ}	11,920	9,484	11,060	8,754	19,110
S_{MSY}	4,677	2,922	4,433	3,470	6,986
U_{MSY}	0.573	0.090	0.571	0.403	0.759
β	0.0001279	0.0000287	0.0001265	0.0000751	0.0001881
lnα	1.309	0.255	1.302	0.826	1.823
lnα'	1.462	0.348	1.428	0.925	2.186
ϕ	0.335	0.283	0.320	-0.167	0.896
σ^2	0.193	0.077	0.179	0.088	0.380
Alsek stock with an non-informative prior distribution on lnα:					
$\bar{S}$	9,895	678	9,873	8,631	11,280
S_{EQ}	11,150	12,360	10,580	6,311	17,900
S_{MSY}	4,854	3,733	4,593	2,978	7,734
U_{MSY}	0.367	0.149	0.366	0.090	0.669
β	0.0000799	0.0000354	0.0000772	0.0000198	0.000158
lnα	0.746	0.397	0.718	0.088	1.593
lnα'	0.866	0.436	0.828	0.186	1.783
ϕ	0.242	0.255	0.222	-0.224	0.799
σ^2	0.184	0.073	0.171	0.082	0.362
Klukshu stock with an informative prior distribution on lnα:					
S_{EQ}	2,660	514	2,574	2,022	3,872
S_{MSY}	999	142	979	786	1,336
U_{MSY}	0.649	0.073	0.647	0.511	0.808
β	0.0006598	0.0001053	0.0006580	0.0004567	0.0008716
lnα	1.507	0.229	1.504	1.064	1.965
lnα'	1.736	0.342	1.696	1.236	2.470
ϕ	0.521	0.209	0.529	0.089	0.902
σ^2	0.247	0.078	0.233	0.137	0.438
$\bar{\pi}$	4.224	0.279	4.210	3.718	4.812

KLUKSHU STOCK

Simulations resulted in a posterior distribution for the variable S_{MSY} with a mean of 999 and a median of 979 adults for the Klukshu stock (see Table 4 for these and other descriptive statistics). The median value of MSY is 1,814. The other posterior values for parameters describing this stock are similar or scaled as expected to values for the Alsek stock with one exception. Values for ϕ (median = 0.529) indicate significant autocorrelation within the process error for the Klukshu stock.

Optimum yield profiles for the Klukshu stock are given in Figure 14 and the OF profiles in Figure 15. At an escapement of 800 adults, the probability of achieving OY from the Klukshu stock is about 95% if OY is defined as at least 90% of MSY. At an escapement of 1,300 adults, the probability of achieving OY is 73%. Thus a range of 800 to 1,300 spawners provides at least a 73% to 98% chance of achieving OY if management spreads escapements evenly across the range. Note that the OY profile for the Klukshu stock has a 98% cap. If the range is 800 to 1,200 spawners, chance of attaining OY becomes 91% to 98% if OY is at least 90% of MSY. The corresponding OF profile at 800 adults in the escapement runs an 8% risk of recruitment overfishing if OY is 90% of MSY, and the risk is virtually nil if a less stringent standard for OY is used.

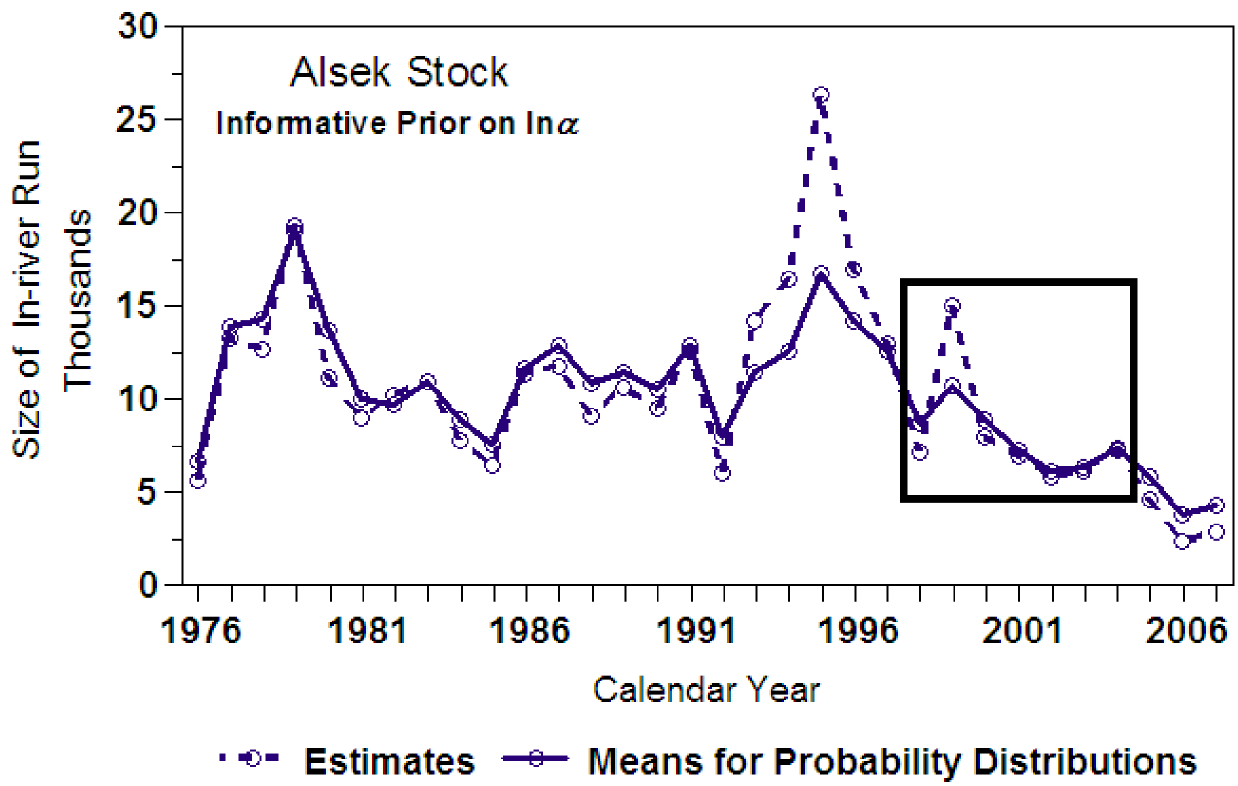

Figure 9.–Estimated size of the inriver run $\hat{N}_{cy}$ to the Alsek stock of Chinook salmon against the mean (expected value) from the posterior probability distributions for N_{cy}. The boxed comparisons represent years with mark–recapture studies.

DISCUSSION

The range of 3,500 to 5,300 adults spawning annually in the Alsek River meets the requirements for a Biological Escapement Goal (BEG) under the Sustainable Salmon Fishery Policy (5 AAC 39.222) of the State of Alaska. This range carries with it a reasonable expectation of MSY and reflects uncertainties in the data (measurement error) and in the productivity of the resource (process error). This range meets the common standard of OY used by the Alaska Department of Fish and Game (≥90% of MSY). Other possible ranges are also consistent with this standard, and some of those ranges have a higher certainty of making OY (higher than the 89% chance from the 3,500–5,300 range but still less than 97%). Those ranges with higher certainty at the boundaries are of course, narrower.

The advantage of using OY profiles to determine goals is that those goals can be tailored somewhat to fit the circumstances of management. As an example, a narrow range, say 4,000 to 4,500 for the Alsek stock represents a 95–97% chance of obtaining OY and may be a better BEG for a fishery on a single stock with inseason management based on rapid turnaround of information (that is with higher precision in management). In contrast, an asymmetrical range such as 800 to 1,300 adults for the Klukshu stock (also a BEG) may be more realistic target when there is little or no inseason management of fisheries. If fishing power is weak, a range might not be relevant at all. If harvest rates cannot be raised high enough in years with large runs to push escapements down into the BEG, an OF profile can be used to establish a lower bound (goal) that arguably would avoid recruitment overfishing during years with small runs. This kind of goal would be a Sustainable Escapement Goal (SEG) under Alaska's policy.

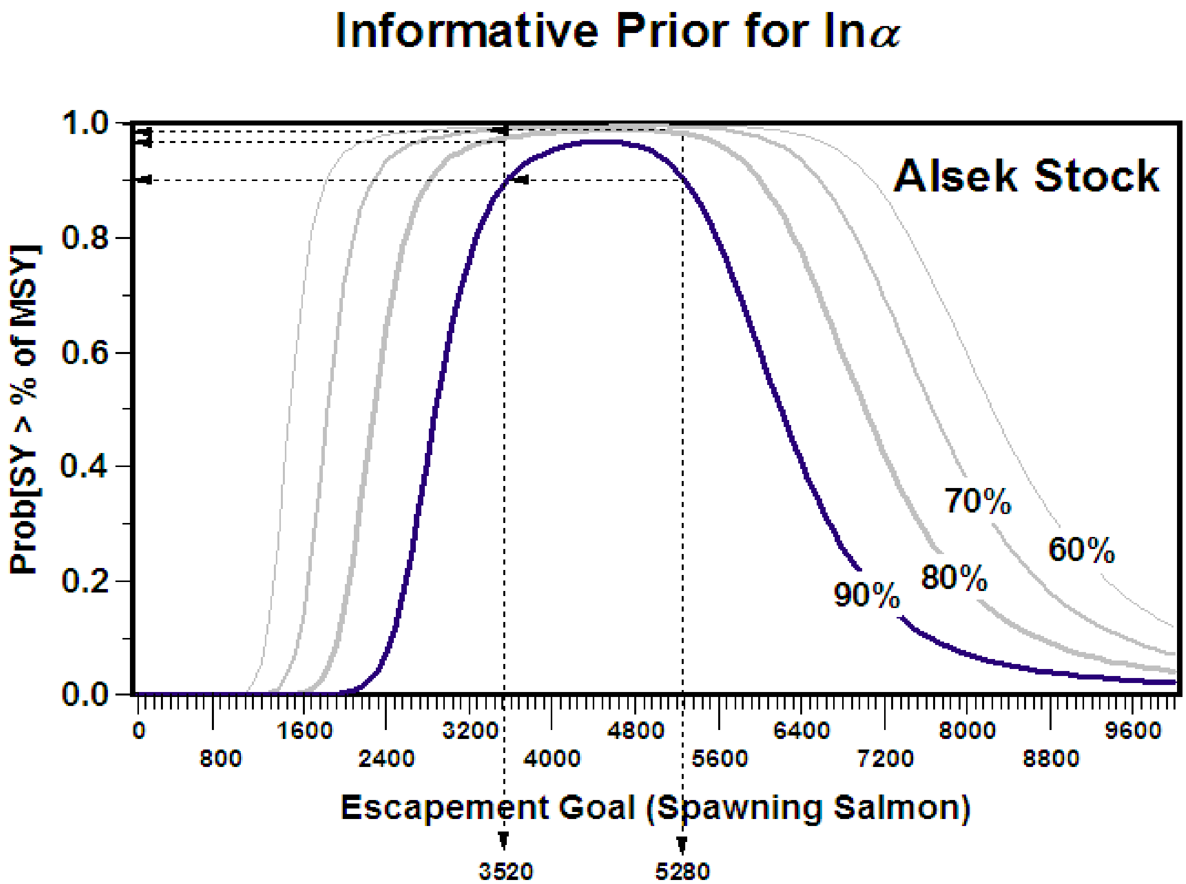

Figure 10.–Optimum yield (OY) profiles for the Alsek stock of Chinook salmon based on a Bayesian analysis given an informative prior distribution for lnα. Each dashed line connects the chance of attaining OY with a specific escapement as a goal. Profiles are provided for optimum yields that are at least 60%, 70%, 80%, or 90% of MSY.

The slightly asymmetrical range of 800 to 1,300 adults demonstrated above as a BEG for the Klukshu stock is not the only possible BEG. Symmetrical in this context is relative to the mean (999) of the posterior distribution for S_{MSY}. A symmetrical range of 800 to 1,200 adults has a higher degree of certainty (90% to 98% chance of attaining OY across the range), but does represent a slightly smaller target for management. Escapements spread evenly across the asymmetrical range of 800 to 1,300 (as required of BEG management) have less of a chance of attaining OY, but do so with a slightly higher risk of underfishing. Application of the standard rule developed by Eggers (1993) of a BEG being 80% to 160% of S_{MSY} to the Klukshu stock is even more conservative. Escapements of 800 fish carries a 95% chance of producing OY, but escapements at 1,600 correspond to only a 15% chance (derived from Figure 14). The current escapement goal range of 1,100 to 2,300 is extremely conservative with 1,100 representing a 95% chance of attaining OY, but 2,300 representing essentially no chance at all (fractionally above 0%). The current goal was not based on stock-recruit analysis per se, but on the avoidance of an estimated, substantial loss in yield from overfishing (McPherson et al. 1998).

Although the same observations were used to develop escapement goals for the Alsek and for the Klukshu stocks, circumstances differed in some fundamental ways between the 2 analyses. Annual escapement to the Alsek River was known with considerable measurement error, while escapement to the Klukshu River was known with (near) certainty. In contrast harvest of the Alsek stock in U. S. waters was known with (near) certainty, while harvest of the Klukshu stock was

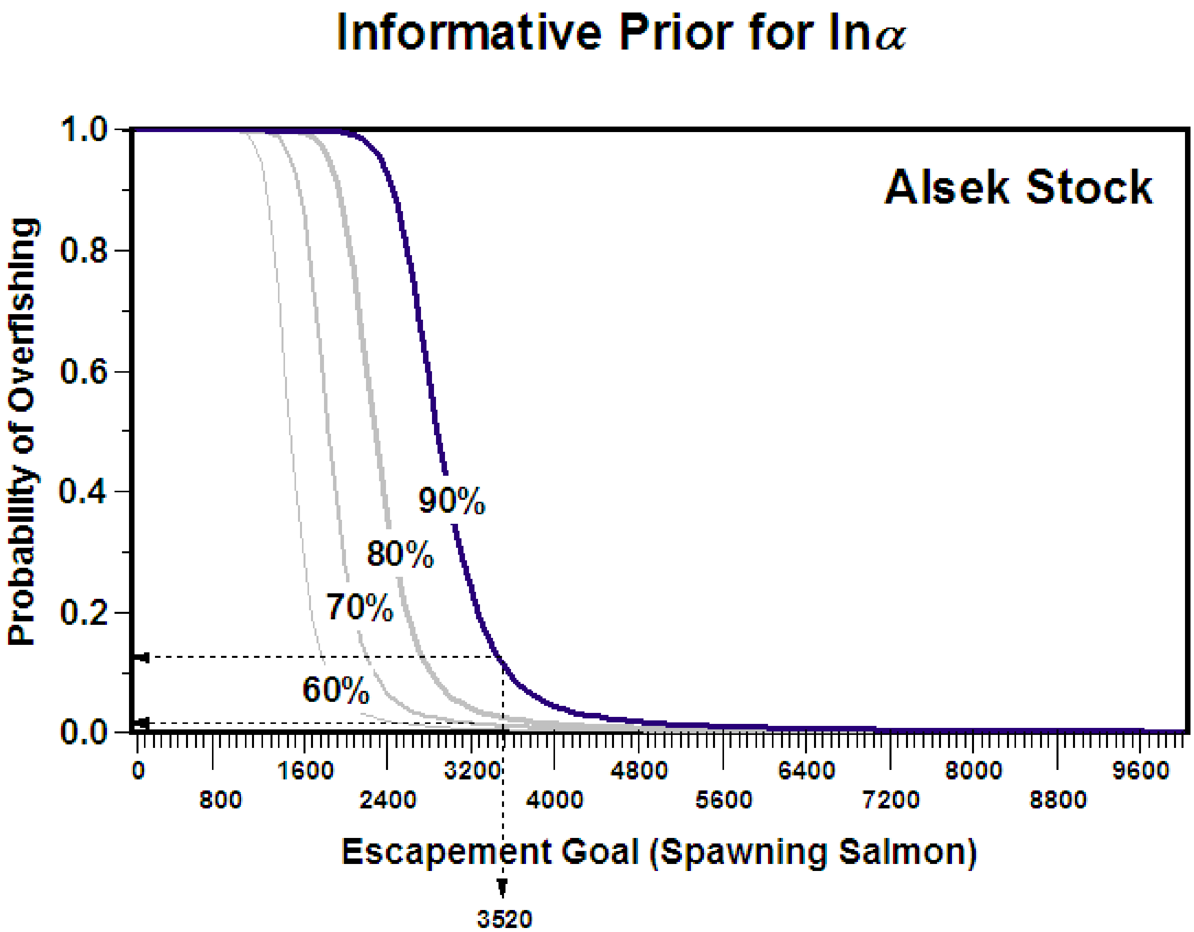

Figure 11.–Overfishing (OF) profiles for the Alsek stock of Chinook salmon based on a Bayesian analysis given an informative prior distribution for lnα. Each dashed line connects the risk of recruitment overfishing with a specific escapement used as a goal. Recruitment overfishing is defined as having escapement lower than those that produce optimum yield (OY). Profiles are provided when OY is considered to be at least 60%, 70%, 80%, or 90% of MSY.

not. McPherson et al. (1998) addressed this problem of catch allocation to the Klukshu stock by assuming this stock represented a constant 100%, 55%, or 30% of the U. S. harvest, resulting in estimates for S_{MSY} of 893, 890, and 887, respectively. The mean of the posterior distribution for S_{MSY} in our analysis is 999.

Essentially we adopted the same approach as did McPherson et al. by using $1/\hat{\pi}_{cy}$ as an observational constraint to allocation in calendar years with mark–recapture studies (1998–2004) and $1/\bar{\pi}$ (= 25%) as an observational constraint in years without such studies (1976–1997, 2005–2007). As a result of this adoption, our analysis for the Klukshu stock showed strong evidence for autocorrelation ($\phi > 0$) in process error while the analysis for the Alsek stock based on the same data did not. This divergence in result arose because the autocorrelation in the analysis for the Klukshu stock is not environmentally driven, but is an artifact of not having year-specific information on stock-specific harvests. Our remedy to this missing information, as the remedy taken by McPherson et al. (1998), tends to artificially smooth out variation in harvest allocation across calendar years and subsequently in estimated production by brood year. The main difference between the earlier analysis and ours is that we modeled possible autocorrelation and McPherson et al. did not. Not addressing autocorrelation within process error, even

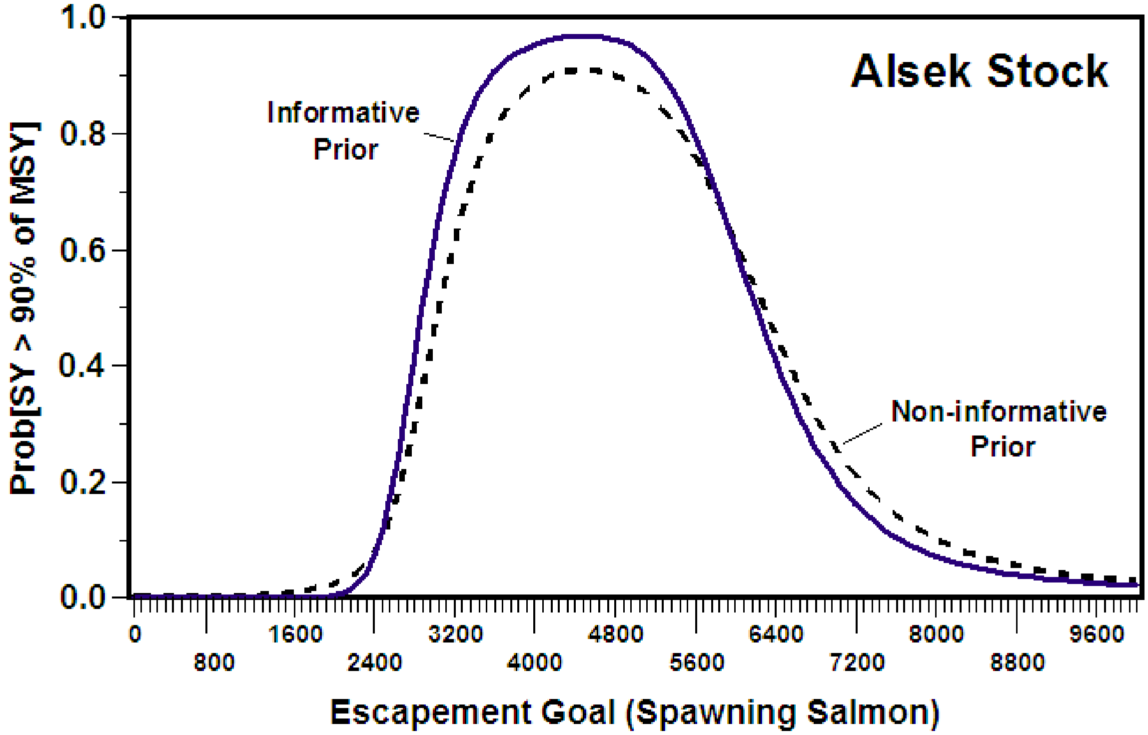

Figure 12.–Ninety percent optimum yield (OY) profiles for the Alsek stock of Chinook salmon from Bayesian analyses when the prior probability distributions for lnα were informative and non-informative.

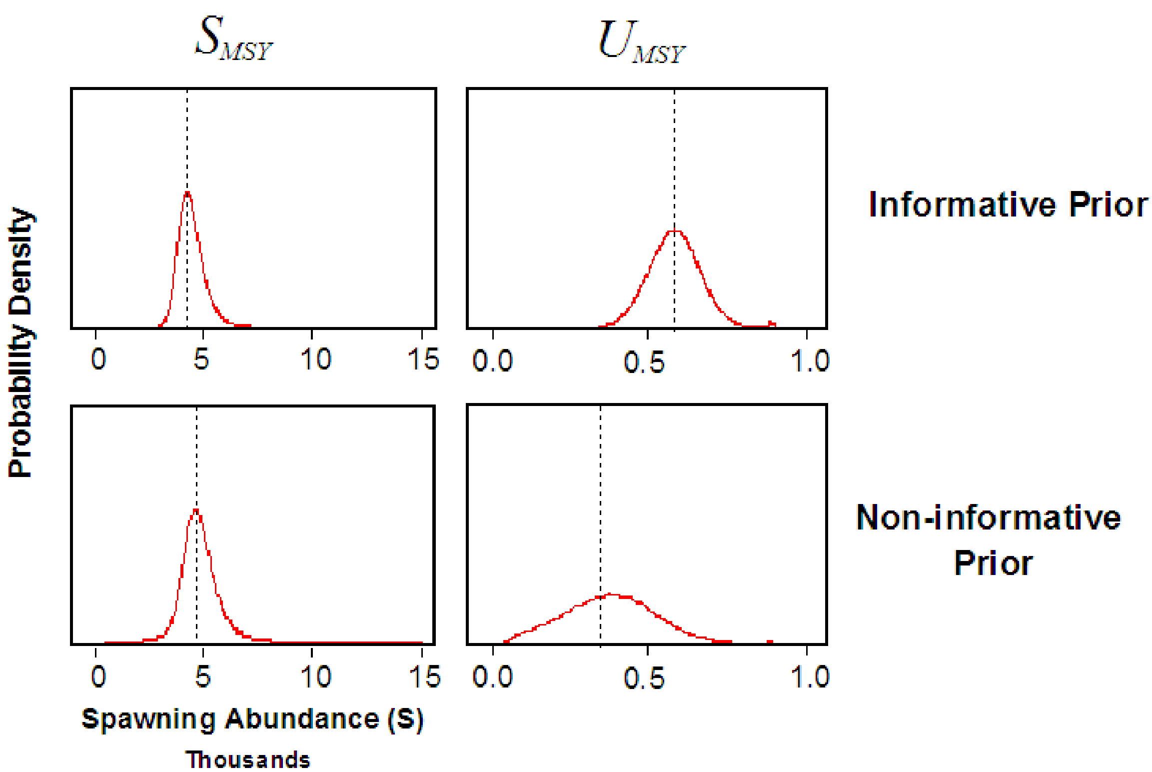

Figure 13.–Posterior probability distributions for S_{MSY} and U_{MSY} for the Alsek stock of Chinook salmon from Bayesian analyses when prior probability distributions for lnα were informative and non-informative.

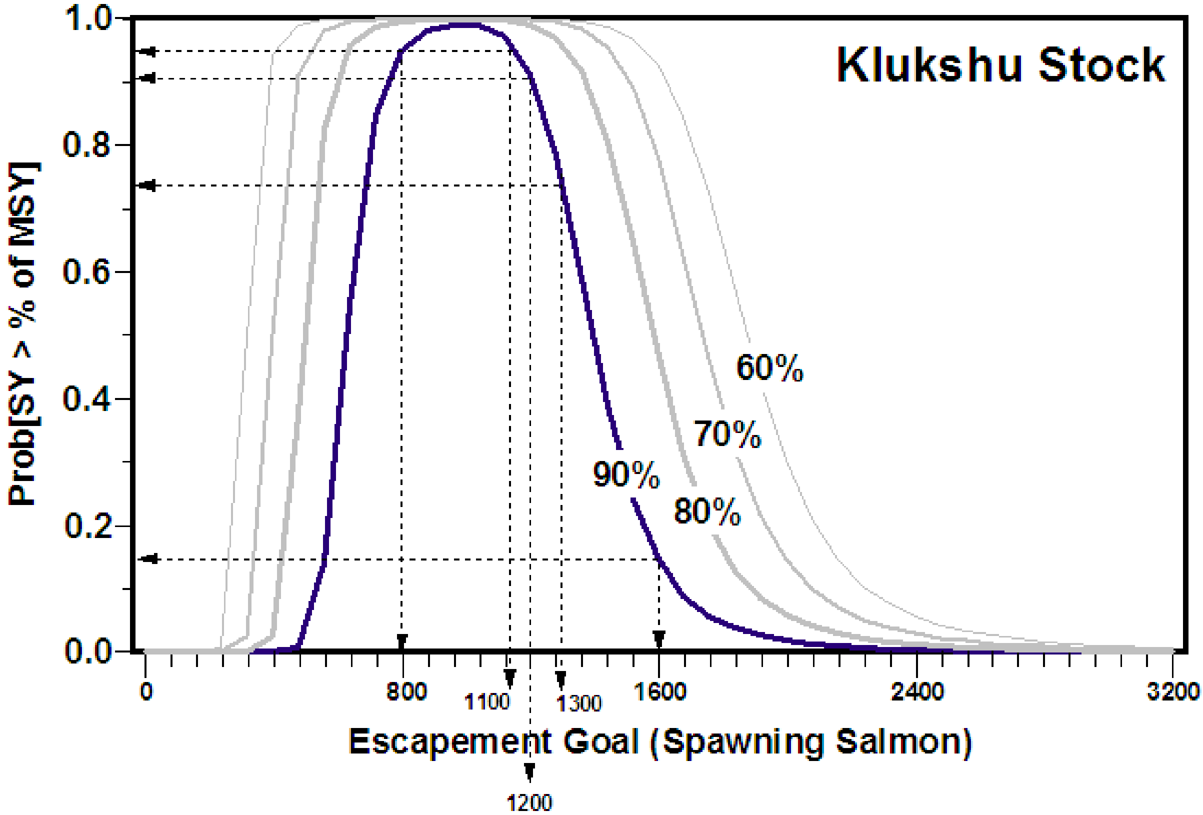

Figure 14.–Optimum yield (OY) profiles for the Klukshu stock of Chinook salmon based on a Bayesian analysis given an informative prior distribution for ln*α*. Each dashed line connects the chance of attaining OY with a specific escapement as a goal. Profiles are provided for optimum yields that are at least 60%, 70%, 80%, or 90% of MSY.

autocorrelation as artifact, will make a stock look more productive than it really is ($\ln\hat{\alpha} > \ln\alpha$ from Kope 2006). From McPherson et al. (1998) $\ln\hat{\alpha}$ = 2.00 for a 30% allocation; the mean of the posterior distribution for $\ln\alpha$ = 1.51 in our analysis. This difference in apparent productivity must also be judged against 11 years of additional data available to us, but not to McPherson et al.

Our analysis may be subject to model error, but if it is, only in a specific, conservative way. Francis and Shotten (1997) defines model uncertainty as arising from a lack of information on the population dynamics of the natural system being modeled. Considering the narrow range of escapements observed since 1976 for the Alsek stock, there is considerable uncertainty as to the appropriate stock-recruit relationship for modeling production. Model uncertainty implies the possibility of model error, that is, we may have chosen the wrong production model. We used a form of Ricker's exponential equation to model the stock-recruit relationship under the presumption that competition of adults on the spawning grounds is the cause of density dependence (Quinn and Deriso 1999). The alternative choice would be an asymptotic equation such as that of Beverton and Holt in which competition among juveniles is the mechanism limiting production. We have no evidence as to which is the correct circumstance for Chinook salmon in the Alsek River. However, if competition among juveniles limits production of the Alsek stock, model error from incorrectly using Ricker's equation will tend to produce conservative (biased high) escapement goals. The ratio of S_{MSY}/S_{EQ} in Ricker's equation is [0.5–0.07 $\ln\alpha$, from Hilborn (1985)], and in Beverton and Holt's equation [$(\sqrt{\alpha}-1)/(\alpha-1)$]. For all realistic values of α (α represents intrinsic productivity in both

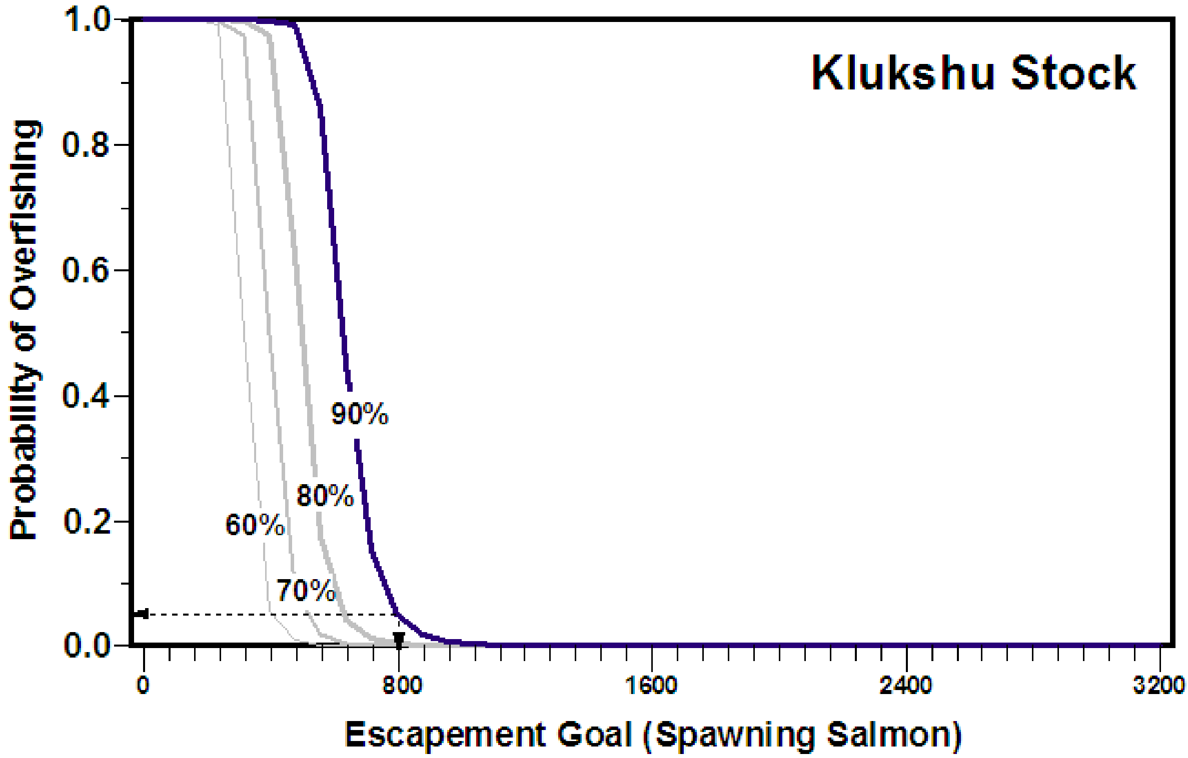

Figure 15.–Overfishing (OF) profiles for the Klukshu stock of Chinook salmon based on a Bayesian analysis given an informative prior distribution for lnα. Each dashed line connects the risk of recruitment overfishing with a specific escapement used as a goal. Recruitment overfishing is defined as having escapement lower than those that produce optimum yield (OY). Profiles are provided when OY is considered to be at least 60%, 70%, 80%, or 90% of MSY.

models), [0.5 – 0.07 lnα] > $[(\sqrt{\alpha}-1)/(\alpha-1)]$ meaning that erroneously using Ricker's equation would result in a precautionary (conservative) escapement goal relative to S_{MSY}.

Notwithstanding the possibility of model error, reference points from our analyses compared very favorably with those derived from the habitat model in Parken et al. (2006) for the Klukshu stock (Table 5). While our final analysis included an informative prior for lnα based on information in Parken et al. (2006), substitution of a non-informative prior had no real effect on the comparisons (just a few fish difference). Because Parken et al. based their meta-analysis on 13 sets of reference points estimated with Ricker's equation, estimates of $\hat{S}_{MSY}$ from their habitat model are subject to the same possibility of model error as is our analysis. However, their estimates of carrying capacity would not be subject to model error. The difference between $\hat{S}_{EQ}$ and the median or mean of the posterior distribution of S_{EQ} with the non-informative prior is -0.2% to 4.5%, respectively.

In our opinion the use of an informative prior distribution for the productivity parameter lnα was warranted for the Alsek and Klukshu stocks. Without the information gained from some history of small escapements, use of non-informative priors produced broad posterior distributions for lnα that had central tendencies well below the norm for Chinook salmon in general. Of the 13 stocks in Parken et al. (2006), the lowest estimate of lnα is 0.97; the comparable statistic (mean of the posterior) for the Alsek stock with a non-informative prior is 0.74. That value translates to 2 recruits per single spawner when per-capita production is at its highest. Although some stock somewhere must have the lowest productivity, we are skeptical that the Alsek and Klukshu stocks

Table 5.–Comparison of reference points for the Klukshu stock of Chinook salmon determined through analysis of data collected during assessment of the stock 1976–2007 and from the habitat model of Parken et al. (2006). Watershed area of the Klukshu River is 260 km^2 without any blockages to migration (McPherson et al. 1998).

Parken et al. 2006[a]	$\hat{S}_{MSY}$	994		$\hat{S}_{EQ}$	2,558	
		Mean	Median		Mean	Median
Informative prior for lnα	S_{MSY}	999	979	S_{EQ}	2,660	2,574
Non-informative prior for lnα	S_{MSY}	1,001	979	S_{EQ}	2,675	2,554

[a] From Table 4 in Parken et al. 2006: $\hat{S}_{MSY} = \exp(2.92 + 0.29/2)(260)^{0.69}$ and $\hat{S}_{EQ} = \exp(3.89 + 0.24/2)(260)^{0.69}$.

are the ones. Interestingly, small escapements in the last few years may provide the missing information on productivity for the next escapement goal analysis.

ACKNOWLEDGMENTS

We wish to acknowledge the international efforts of those many persons responsible for stock assessment on Chinook salmon of the Alsek River since 1976. We are especially grateful to Pete Etherton, Bill Waugh, Dan Reed, and Keith Pahlke. Keith's detailed knowledge on the Alsek stock and his past leadership of stock assessment projects has been especially helpful. We also wish to thank Steve Fleischman for his novel approach to expressing uncertainty in stock-recruit analysis and for his advice on our analysis. This analysis was funded by monies appropriated by the U.S. Congress through the Letter of Agreement (FY 2009) to the U.S. Chinook Technical Committee of the Pacific Salmon Commission.

REFERENCES CITED

Efron, B., and R. J. Tibshirani. 1993. 1st edition. An introduction to the bootstrap. Chapman and Hall, New York, NY

Eggers, D. M. 1993. Robust harvest policies for Pacific salmon fisheries. Pages 85-106 *in* Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Alaska Sea Grant Report No. 93-02, University of Alaska, Fairbanks, Alaska

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. http://www.sf.adfg.state.ak.us/FedAidPDFs/fms06-06.pdf

Evans, M., N. Hastings, and B. Peacock. 1993. Statistical distributions, 2nd edition. Wiley-Interscience, New York.

Francis, R. I. C. C., and R. Shotton. 1997. "Risk" in fisheries management: a review. Canadian Journal of Fisheries and Aquatic Sciences 54:1699-1715.

Geiger, H. J., and J. P. Koenings. 1991. Escapement goals for sockeye salmon with informative prior probabilities based on habitat considerations. Fisheries Research 11:239-256.

Gilks, W. R., S. Richardson, and D. J. Spiegelhalter, *editors*. 1996. Markov chain Monte Carlo in practice. Chapman and Hall, London.

Hilborn, R. 1985. Simplified calculation of optimum spawning stock size from Ricker's stock-recruitment curve. Canadian Journal of Fisheries and Aquatic Sciences 42:1833-4.

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

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.

McPherson, S. A., P. Etherton, and J. H. Clark. 1998. Biological escapement goal for Klukshu River Chinook salmon. Alaska Department of Fish and Game, Fishery Manuscript No. 98-2, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fms98-02.pdf

Noakes, D., D. W. Welch, and M. Stocker. 1987. A time series approach to stock-recruitment analysis: transfer function noise modeling. Natural Resource Modeling 2: 213-233.

REFERENCES CITED (Continued)

Pahlke, K. A. 2008. Escapements of Chinook salmon in Southeast Alaska and transboundary rivers in 2006. Alaska Department of Fish and Game, Fishery Data Series No. 08-20, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds08-20.pdf

Pahlke, K. A., and P. Etherton. 2001a. Abundance of the Chinook salmon escapement on the Alsek River, 1999. Alaska Department of Fish and Game, Fishery Data Series No. 01-11, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds01-11.pdf

Pahlke, K. A., and P. Etherton. 2001b. Abundance of the Chinook salmon escapement on the Alsek River, 2000. Alaska Department of Fish and Game, Fishery Data Series No. 01-30, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds01-30.pdf

Pahlke, K. A., and P. Etherton. 2002. Abundance of the Chinook salmon escapement on the Alsek River, 2001. Alaska Department of Fish and Game, Fishery Data Series 02-20, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds02-20.pdf

Pahlke, K. A., P. Etherton, R. E. Johnson, and J. E. Andel. 1999. Abundance and distribution of the Chinook salmon escapement on the Alsek River, 1998. Alaska Department of Fish and Game, Fishery Data Series No. 99-44, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds99-44.pdf

Pahlke, K. A., and B. Waugh. 2003. Abundance and distribution of the Chinook salmon escapement on the Alsek River, 2002. Alaska Department of Fish and Game, Fishery Data Series No. 03-20, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds03-20.pdf

Pahlke, K. A., and B. Waugh. 2004. Abundance of the Chinook salmon escapement on the Alsek River, 2003. Alaska Department of Fish and Game, Fishery Data Series No. 04-27, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds04-27.pdf

Pahlke, K. A., and B. Waugh. 2006. Abundance of the Chinook salmon escapement on the Alsek River in 2004. Alaska Department of Fish and Game, Fishery Data Series No. 06-12, Anchorage. http://www.sf.adfg.state.ak.us/FedAidpdfs/fds06-12.pdf

Parken, C. K., R. E. McNicol, and J. R. Irvine. 2006. Habitat-based methods to estimate escapement goals for data limited Chinook salmon stocks in British Columbia, 2004. Department of Fisheries and Oceans, Canadian Scientific Advisory Secretariat Research Document 2006/083.

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

Seber, G. A. F. 1982. On the estimation of animal abundance and related parameters, 2nd edition. Griffin and Company, Ltd. London.

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. http://www.sf.adfg.state.ak.us/FedAidpdfs/fms07-05

Zhou, S. 2002. Size-dependent recovery of Chinook salmon in carcass surveys. Transactions of the American Fisheries Society 131:1194-1202.

APPENDIX A: STATISTICS

Appendix Table A1.–Numbers of Chinook salmon by age in samples of live fish taken at the weir in the Klukshu River, a tributary to the Alsek River, 1986–2007. Numbers are the $w_{cy,a}$.

cy	1.1	1.2	1.3	1.4	1.5	Total	Source
1986	0	53	227	61	0	341	McPherson et al. (1998)
1987	0	23	181	117	2	323	"
1988	1	29	65	123	1	219	"
1989	0	132	220	371	1	724	"
1990	0	29	134	88	1	252	"
1991	1	11	163	230	13	418	"
1992	11	29	97	192	0	329	"
1993	15	31	142	127	1	316	"
1994	2	201	256	251	9	719	"
1995	2	60	595	120	0	777	"
1996	4	89	203	204	0	500	"
1997	0	13	227	80	0	320	Pahlke and Etherton (2002)
1998	2	51	75	44	0	172	Pahlke et al. (1999)
1999	1	38	108	25	0	172	Pahlke and Etherton (2001a)
2000	5	22	130	22	0	179	Pahlke and Etherton (2001b)
2001	1	54	313	71	1	440	Pahlke and Etherton (2002)
2002	3	30	208	141	5	387	Pahlke and Waugh (2003)
2003	7	144	415	119	0	685	Pahlke and Waugh (2004)
2004	0	40	762	254	0	1,056	Pahlke and Waugh (2006)
2005	0	25	181	172	1	379	IFDB[a]
2006	0	38	111	67	1	217	IFDB
2007	1	22	184	88	1	296	IFDB

[a] Integrated Fishery Data Base, Division of Commercial Fisheries, Alaska Department of Fish and Game, Douglas, Alaska.

Appendix Table A2.–Numbers of Chinook salmon by age in samples from the Canadian sport fishery on the Alsek stock, 1976–1996.

cy	1.1	1.2	1.3	1.4	1.5	Total	Source
1976	0	3	3	4	0	10	McPherson et al. (1998)
1977	1	16	24	10	0	51	"
1978	0	1	10	2	0	13	"
1979	0	0	7	8	0	15	"
1980	0	1	10	14	0	25	"
1981	0	4	16	26	0	46	"
1982	2	17	60	55	0	134	"
1983	0	2	61	17	0	80	"
1984	2	5	44	55	1	107	"
1985	0	7	37	27	0	71	"
1986	0	3	41	12	0	56	"
1987	0	2	74	66	0	142	"
1988	0	2	24	58	0	84	"
1989	0	7	55	43	3	108	"
1990	1	5	145	57	3	211	"
1991	0	0	52	54	2	108	"
1992	0	6	6	10	0	22	"
1993	0	10	45	30	3	88	"
1994	0	24	54	61	0	139	"
1995	0	2	84	14	0	100	"
1996	1	6	92	103	2	204	"

Appendix Table A3.–Numbers of Chinook salmon by age in samples from the U. S. commercial fishery on the Alsek stock, 1982–2007. Numbers are the $h_{cy,a}$.

cy	1.1	1.2	1.3	1.4	1.5	Total	Source
1982	0	20	28	34	1	83	McPherson et al. (1998)
1983	1	4	20	16	0	41	"
1984	1	5	10	5	0	21	"
1985	0	14	29	11	0	54	"
1986	1	59	93	10	0	163	"
1987	2	10	71	31	0	114	"
1988	1	34	33	42	0	110	"
1989	0	92	73	26	0	191	"
1990	0	6	8	4	0	18	"
1991	3	12	30	17	1	63	"
1992	2	92	48	48	5	195	"
1993	0	62	70	20	0	152	"
1994	0	142	50	14	3	209	"
1995	5	100	228	28	2	363	"
1996	4	200	151	118	0	473	"
1997	21	244	463	196	0	924	IFDB[a]
1998	5	99	69	73	2	248	IFDB
1999	1	94	112	22	0	229	IFDB
2000	1	80	224	37	0	342	Pahlke and Etherton (2001b)
2001	0	31	82	20	0	133	Pahlke and Etherton (2002)
2002	0	20	67	8	0	95	Pahlke and Waugh (2003)
2003	0	24	34	3	0	61	Pahlke and Waugh (2004)
2004							No samples taken this year
2005	0	43	505	3	0	551	IFDB
2006	0	82	112	24	0	218	IFDB
2007	5	56	327	176	14	578	IFDB

[a] Integrated Fishery Data Base, Division of Commercial Fisheries, Alaska Department of Fish and Game, Douglas, Alaska.

Appendix Table A4.–Numbers of Chinook salmon by age in samples from spawned-out carcasses collected near the weir in the Klukshu River, a tributary to the Alsek River, 1976–1984.

cy	1.1	1.2	1.3	1.4	1.5	Total	Source
1976	0	1	19	35	0	55	McPherson et al. (1998)
1977	1	31	46	51	1	130	"
1978	0	9	39	33	0	81	"
1979	0	6	41	36	0	83	"
1980	0	0	12	28	0	40	"
1981	0	2	5	8	2	17	"
1982	0	4	13	12	0	29	"
1983	0	1	17	11	0	29	"
1984	0	1	3	8	1	13	"

Appendix Table A5.–Numbers of Chinook salmon by age in samples from spawned-out carcasses collected in Goat Creek and in the Blanchard and Takhanne rivers (tributaries to the Alsek River), 1998–2004.

cy	1.1	1.2	1.3	1.4	1.5	Total	Source
1998	0	2	21	6	0	29	Pahlke et al. (1999)
1999	0	1	25	10	0	36	Pahlke and Etherton (2001a)
2000	0	2	52	34	0	88	Pahlke and Etherton (2001b)
2001	0	6	131	60	1	198	Pahlke and Etherton (2002)
2002	0	10	116	63	1	190	Pahlke and Waugh (2003)
2003	0	3	41	24	0	68	Pahlke and Waugh (2004)
2004	0	2	42	53	0	97	Pahlke and Waugh (2006)

Appendix Table A6.–Statistics from mark–recapture studies to estimate inriver run size of large (age 1.3+) Chinook salmon to the Alsek River, 1998–2004. Notation is defined in Appendix Table C1. Explanation of parametric procedures is given below.

cy	m_{cy}	c_{cy}	r_{cy}	$\hat{N}_{cy,1.3+}$	$\hat{q}_{cy,1.3+}$	w_{cy}	W_{cy}	$\hat{\pi}_{cy}$	$\hat{\text{var}}(\hat{\pi}_{cy})$	Source[a]
1998	239	206	9	4,967	0.692	172	1,630	4.404	2.293	Pahlke et al. (1999)
1999	398	232	7	11,620	0.773	172	2,530	5.940	5.134	Pahlke and Etherton (2001a)
2000	459	207	13	6,833	0.849	179	1,418	5.675	2.316	Pahlke and Etherton (2001b)
2001	524	546	46	6,109	0.875	440	1,977	3.532	0.258	Pahlke and Etherton (2002)
2002	534	462	45	5,384	0.915	387	2,426	2.426	0.125	Pahlke and Waugh (2003)
2003	504	586	61	4,780	0.780	685	1,873	3.274	0.156	Pahlke and Waugh (2004)
2004	730	1,128	117	6,993	0.962	1,056	2,636	2.757	0.060	Pahlke and Waugh (2006)
							$\bar{\pi}$ =	4.00	1.478	← average

[a] Statistics in this table are comparable to statistics reported in Appendix Table B10 in Pahlke (2008) except for calendar year 1999. Both sets of statistics are based only on capture of live fish at the Klukshu weir, however, a transcription error in Pahlke (2008) for data collected in 1999 was discovered during the present analysis. That error was corrected in the table above. Statistics here and in Pahlke (2008) are not comparable to Appendix Table C1 in Pahlke and Waugh (2006) because statistics in the latter report are based on capturing a varying mixture of live and dead fish across different tributaries in different years.

Parametric bootstrap simulations (see Efron and Tibshirani 1993) followed procedures described in Appendix B1 of Pahlke (2008). Bootstrap statistics $w'_{cy,1.3+(b)}$ and $r'_{cy(b)}$ were randomly drawn from binomial$(w_{cy}, \hat{q}_{cy,1.3+})$ and from binomial$(c_{cy}, r_{cy}/c_{cy})$, respectively for each bootstrap replication (b) [c is the number of large salmon age 1.3+ inspected during the upstream sampling event in the mark–recapture studies, and r is the number of recaptured fish within c]. Subsequent calculations for each bootstrap replication were $q'_{cy,1.3+(b)} = w'_{cy,1.3+(b)}/w_{cy}$, $N'_{cy,1.3+(b)} = (m_{cy}+1)(c_{cy}+1)/(r'_{cy(b)}+1)-1$ [where m is the number of large salmon with marks proceeding upstream], $N'_{cy(b)} = N'_{cy,1.3+(b)}/q'_{cy,1.3+(b)}$, and $\pi'_{cy(b)} = N'_{cy(b)}/W_{cy}$. Each simulation consisted of 1000 draws from each binomial distribution.

Appendix Table A7.–Counts and catch statistics of Chinook salmon of all ages at the weir on the Klukshu River and for U.S. and Canadian fisheries on the Alsek stock, 1976–2007.

			Canadian fisheries		U. S. fisheries		
cy	Counts thru weir	Catch below weir	Sport	Aboriginal	Commercial	Subsistence	Source
1976	1,278	130	200	150	512		Pahlke and Waugh (2006)
1977	3,144	195	300	350	1,402		"
1978	2,976	195	300	350	2,441		"
1979	4,404	422	650	1,300	2,525		"
1980	2,673	130	200	150	1,382		"
1981	2,113	150	400	150	779		"
1982	2,369	183	333	400	532		"
1983	2,537	202	312	300	93		"
1984	1,672	275	450	100	46		"
1985	1,458	170	210	175	213		"
1986	2,709	125	165	102	481	22	"
1987	2,616	326	502	125	347	27	"
1988	2,037	249	384	43	223	13	"
1989	2,456	215	331	234	228	20	"
1990	1,915	468	721	202	78	85	"
1991	2,489	652	430	509	103	38	"
1992	1,367	139	103	148	301	15	"
1993	3,303	258	237	152	300	38	"
1994	3,727	387	304	289	805	60	"
1995	5,678	921	1,044	580	670	51	"
1996	3,599	656	650	448	771	60	"
1997	2,989	267	298	232	568	38	"
1998	1,364	266	175	171	550	63	"
1999	2,193	337	192	238	482	44	"
2000	1,365	53	77	65	577	73	"
2001	1,825	152	157	120	541	19	"
2002	2,241	185	197	120	700	60	"
2003	1,737	136	138	90	937	24	"
2004	2,523	113	46	139	656	38	"
2005	1,070	78	56	58	662	31	IFDB[a]
2006	568	17	17	0	665	47	IFDB
2007	676	41	40	1	747	79	IFDB

[a] Integrated Fishery Data Base, Division of Commercial Fisheries, Alaska Department of Fish and Game, Douglas, Alaska.

Appendix Table A8.–Estimated sizes of inriver runs of Chinook salmon to the Alsek River by age and estimated errors, 1976–2007.

cy	$\hat{N}_{cy}$	$\hat{N}_{cy,a}$					SE($\hat{N}_{cy,a}$)				
		1.1	1.2	1.3	1.4	1.5	1.1	1.2	1.3	1.4	1.5
1976	5,632	0	1,690	1,690	2,253	0	0	751	751	911	0
1977	13,356	262	4,190	6,285	2,619	0	262	1,576	2,354	999	0
1978	12,684	0	976	9,757	1,951	0	0	976	3,655	1,105	0
1979	19,304	0	0	9,009	10,295	0	0	0	3,437	3,896	0
1980	11,212	0	448	4,485	6,279	0	0	448	1,697	2,355	0
1981	9,052	0	787	3,149	5,116	0	0	340	1,184	1,915	0
1982	10,208	152	1,295	4,571	4,190	0	90	488	1,710	1,567	0
1983	10,956	0	274	8,354	2,328	0	0	162	3,124	876	0
1984	7,788	146	364	3,203	4,003	73	86	151	1,198	1,497	73
1985	6,512	0	642	3,394	2,476	0	0	252	1,270	928	0
1986	11,336	0	1,762	7,546	2,028	0	0	659	2,822	759	0
1987	11,768	0	838	6,594	4,263	73	0	315	2,466	1,594	43
1988	9,144	42	1,211	2,714	5,136	42	42	454	1,015	1,920	42
1989	10,684	0	1,948	3,247	5,475	15	0	728	1,214	2,047	15
1990	9,532	0	1,097	5,069	3,329	38	0	411	1,895	1,245	38
1991	12,564	30	331	4,899	6,913	391	30	127	1,832	2,585	149
1992	6,024	201	531	1,776	3,516	0	77	199	664	1,315	0
1993	14,244	676	1,397	6,401	5,725	45	256	524	2,393	2,141	45
1994	16,456	46	4,600	5,859	5,745	206	27	1,720	2,191	2,148	80
1995	26,396	68	2,038	20,213	4,077	0	40	763	7,558	1,525	0
1996	17,020	136	3,030	6,910	6,944	0	60	1,133	2,584	2,597	0
1997	13,024	0	529	9,239	3,256	0	0	201	3,455	1,218	0
1998	7,179	83	2,129	3,130	1,837	0	48	732	1,076	632	0
1999	15,027	87	3,320	9,436	2,184	0	87	1,268	3,600	836	0
2000	8,047	225	989	5,844	989	0	74	268	1,565	268	0
2001	6,982	16	857	4,967	1,127	16	16	124	715	163	16
2002	5,886	46	456	3,163	2,144	76	16	68	460	312	19
2003	6,132	63	1,289	3,715	1,065	0	12	156	449	129	0
2004[a]	7,268	0	275	5,245	1,748	0	0	25	466	155	0
2005	4,626	0	305	2,209	2,100	12	0	115	826	785	12
2006	2,358	0	413	1,206	728	11	0	155	451	272	11
2007	2,890	10	215	1,796	859	10	10	81	672	321	10

[a] No sampling program occurred in 2004. Imputed statistics for that year are average proportions over years 1976–2003 and 2005–2007.

Appendix Table A9.–Estimated harvests of Chinook salmon by age and estimated standard errors for annual harvests in U.S. fisheries on the Alsek stock, 1976–2007.

		$\hat{H}_{cy,a}$					SE($\hat{H}_{cy,a}$)				
cy	H_{cy}	1.1	1.2	1.3	1.4	1.5	1.1	1.2	1.3	1.4	1.5
1976	512	0	154	154	205	0	0	78	78	84	0
1977	1,402	27	440	660	275	0	27	92	99	79	0
1978	2,441	0	188	1,878	376	0	0	188	297	254	0
1979	2,525	0	0	1,178	1,347	0	0	0	337	337	0
1980	1,382	0	55	553	774	0	0	55	138	140	0
1981	779	0	68	271	440	0	0	33	55	58	0
1982	532	0	128	179	218	6	0	25	28	29	6
1983	93	2	9	45	36	0	2	4	7	7	0
1984	46	2	11	22	11	0	2	4	5	4	0
1985	213	0	55	114	43	0	0	13	15	12	0
1986	503	3	182	287	31	0	3	19	20	9	0
1987	374	7	33	233	102	0	5	10	17	16	0
1988	236	2	73	71	90	0	2	10	10	11	0
1989	248	0	119	95	34	0	0	9	9	6	0
1990	163	0	54	72	36	0	0	19	20	16	0
1991	141	7	27	67	38	2	4	7	9	8	2
1992	316	3	149	78	78	8	2	11	10	10	4
1993	338	0	138	156	44	0	0	14	14	9	0
1994	865	0	588	207	58	12	0	28	26	15	7
1995	721	10	199	453	56	4	4	17	18	10	3
1996	831	7	351	265	207	0	4	19	18	17	0
1997	606	14	160	304	129	0	3	9	10	8	0
1998	613	12	245	171	180	5	5	19	17	18	3
1999	526	2	216	257	51	0	2	17	17	10	0
2000	650	2	152	426	70	0	2	15	17	11	0
2001	560	0	131	345	84	0	0	21	24	17	0
2002	760	0	160	536	64	0	0	32	36	22	0
2003	961	0	378	536	47	0	0	61	62	27	0
2004[a]	694	6	187	338	161	2	4	31	40	34	1
2005	693	0	54	635	4	0	0	8	8	2	0
2006	712	0	268	366	78	0	0	23	24	15	0
2007	826	7	80	467	252	20	3	10	17	16	5

[a] No sampling program occurred in 2004. Imputed statistics for that year are average proportions over years 1976–2003 and 2005–2007.

Appendix Table A10.–Descriptive statistics for posterior probability distributions N_{cy} and S_{cy} for Chinook salmon to the Alsek River based on an informative prior for ln α.

	Inriver run size (N_{cy})					Spawning escapement (S_{cy})				
				Percentiles					Percentiles	
cy	Mean	SD	Median	2.5%	97.5%	Mean	SD	Median	2.5%	97.5%
1976	6,702	2,385	6,288	3,269	12,540	6,329	2,343	5,926	2,936	12,030
1977	13,930	3,577	13,620	7,877	21,750	13,240	3,566	12,940	7,173	21,080
1978	14,310	3,487	13,950	8,534	22,110	13,690	3,483	13,330	7,913	21,480
1979	19,080	4,446	18,760	11,280	28,710	17,110	4,482	16,790	9,270	26,820
1980	13,770	3,693	13,460	7,470	21,750	13,370	3,662	13,070	7,151	21,360
1981	10,020	2,422	9,772	6,006	15,440	9,451	2,425	9,196	5,437	14,920
1982	9,757	2,287	9,507	6,003	14,890	8,971	2,269	8,741	5,205	14,060
1983	11,020	2,693	10,750	6,534	17,090	10,350	2,685	10,070	5,914	16,390
1984	8,926	2,362	8,646	5,118	14,310	8,355	2,364	8,069	4,560	13,720
1985	7,636	1,816	7,444	4,672	11,770	7,284	1,823	7,087	4,306	11,380
1986	11,650	2,866	11,370	6,879	18,020	11,320	2,862	11,040	6,573	17,690
1987	12,920	3,142	12,650	7,623	19,860	12,200	3,140	11,920	6,899	19,150
1988	10,880	2,521	10,650	6,653	16,480	10,400	2,544	10,140	6,156	16,040
1989	11,450	3,012	11,100	6,610	18,290	10,770	2,985	10,380	6,004	17,550
1990	10,610	2,262	10,400	6,825	15,630	9,690	2,249	9,467	5,917	14,680
1991	12,880	3,132	12,600	7,658	19,740	11,920	3,040	11,640	6,818	18,600
1992	7,974	1,908	7,776	4,807	12,200	7,757	1,916	7,556	4,610	12,070
1993	11,450	3,233	11,020	6,363	18,850	11,110	3,152	10,690	6,095	18,280
1994	12,600	2,894	12,290	7,800	19,080	11,930	2,830	11,650	7,221	18,250
1995	16,770	3,749	16,380	10,570	25,120	15,080	3,728	14,730	8,894	23,350
1996	14,280	3,272	13,960	8,790	21,540	13,140	3,277	12,820	7,645	20,340
1997	12,620	3,139	12,380	7,275	19,390	12,080	3,181	11,770	6,733	19,170
1998	8,689	2,248	8,405	5,094	13,860	8,386	2,251	8,146	4,688	13,450
1999	10,730	2,520	10,470	6,567	16,410	10,320	2,523	10,040	6,180	15,990
2000	8,970	2,039	8,766	5,601	13,560	8,848	2,045	8,649	5,459	13,410
2001	7,324	1,017	7,258	5,526	9,496	7,059	1,014	6,989	5,281	9,241
2002	6,171	840	6,115	4,688	7,973	5,862	840	5,808	4,371	7,660
2003	6,334	734	6,292	5,012	7,879	6,105	734	6,065	4,790	7,651
2004	7,357	636	7,330	6,181	8,676	7,180	641	7,151	6,003	8,516
2005	5,861	1,582	5,665	3,307	9,468	5,829	1,591	5,643	3,273	9,459
2006	3,856	1,132	3,709	2,070	6,449	3,924	1,184	3,768	2,081	6,674
2007	4,333	1,318	4,163	2,255	7,376	4,334	1,352	4,158	2,217	7,489

APPENDIX B: MODEL STATEMENTS

Appendix B1.–Program written in WinBUGS vers. 1.4.2 describing the life history of the Alsek stock of Chinook salmon across brood years 1976–2001. Variables, parameters, and observations (nodes) follow the nomenclature in the text. Italicized lines involve stochastic elements to represent either prior probability distributions or probability distributions involved with sampling error in estimates. Text on a line after '#' is a comment. Lines are numbered for convenience. Null lines 179–184 and 207 represent missing data.

```
1   model {
2   lnalpha ~ dnorm(1.58,12)I(0,4.0)                # ----- Informative Prior
3   beta~ dnorm(0, 0.001)I(0,)                      # ----- Non-informative Prior
4   phi ~ dnorm(0,0.000001)I(-0.99,0.99)            # ----- Non-informative Prior
5   tau ~ dgamma(0.001, 0.001)                      # ----- Non-informative Prior
6   lnPr.mean ~ dnorm(0,0.0001)I(0,)                # ----- Non-informative hyper-Prior
7   tau.Pr ~ dgamma(0.001,0.001)                    # ----- Non-informative hyper-Prior
8   lnS.0 ~ dnorm(0,0.0001)I(5,13)                  # ----- Non-informative Prior
9   for(y in 1:6) {
10  d.lnPr[y] ~ dnorm(lnPr.mean,tau.Pr)I(1,)        # ----- Non-informative Prior
11              d.Pr[y] <- exp(d.lnPr[y])
12              }
13  sigma.sq <- 1/tau
14  S.0 <- exp(lnS.0)
15  # ---------------------------------------------------- Estimate return
16  lnPr.pred[1] <- log(S[1])+(1-phi)*lnalpha+phi*(d.lnPr[6]-lnS.0)-beta*S[1]+phi*beta*S.0
17  lnPr[1] ~ dnorm(lnPr.pred[1],tau)I(0,)          # ----- Non-informative Prior
18  Pr[1] <- exp(lnPr[1])
19  for(y in 2:32) {
20              lnPr.pred[y]      <-      log(S[y])+(1-phi)*lnalpha+phi*log(Pr[y-1]/S[y-1])-
21              beta*S[y]+phi*beta*S[y-1]
22              lnPr[y] ~ dnorm(lnPr.pred[y],tau)I(0,)      # ----- Non-informative Prior
23              Pr[y] <- exp(lnPr[y])
24              }
25  # ------------------------- Generate mat/sur rates BYs 70-01
26  d.t1 ~ dbeta(1,1)                               # ----- Non-informative Prior
27  d.t2 ~ dbeta(1,1)                               # ----- Non-informative Prior
28  d.t[1] <- d.t1
29  d.t[2] <- d.t2 * (1 - d.t[1])
```

-continued-

```
    d.t[3] <- 1 - d.t[1] - d.t[2]
    d.scale ~ dunif(0,1)                          # ----- Non-informative Prior
    d.sum <- 1/d.scale/d.scale
    for(a in 1:3) {matsur[a] <- d.sum * d.t[a]}
    for(y in 1:35)  {
       for(a in 1:3) {d.theta[y,a] ~ dgamma(matsur[a],1)}  # ----- Non-informative Prior
       sum.d.theta[y] <- sum(d.theta[y,])
       for(a in 1:3) {theta[y,a] <- d.theta[y,a]/sum.d.theta[y]}
       }
 # -------------------------- Apportion return to runs CYs 76-07
  for(y in 1:4) {
    for(a in 1:3)  {Run.a[y,a] <- d.Pr[y+3-a]* theta[y+3-a,a]}
    }
  Run.a[5,1] <- Pr[1] * theta[7,1]
  Run.a[5,2] <- d.Pr[6] * theta[6,2]
  Run.a[5,3] <- d.Pr[5] * theta[5,3]
  Run.a[6,1] <- Pr[2] * theta[8,1]
  Run.a[6,2] <- Pr[1] * theta[7,2]
  Run.a[6,3] <- d.Pr[6] * theta[6,3]
  for(y in 7:32) {
    for(a in 1:3) {Run.a[y,a] <- Pr[y-3-a] * theta[y+3-a,a]}
    }
  # -------------------------------------------------- Apply rel. age comp.
  for(y in 1:32) {
    d.gam[y,1] <- 1
    for(a in 2:3) {d.gam[y,a] ~ dbeta(1,1)}           # ----- Non-informative Prior
    for(a in 1:3) {d.H.a[y,a] <- Run.a[y,a] * d.gam[y,a]}
    d.H[y] <- sum(d.H.a[y,1:3])
    for(a in 1:3) {
       H.a[y,a] <- d.H.a[y,a]/d.H[y] * H[y]
       p[y,a] <- H.a[y,a]/H[y]
```

-continued-

```
       N.a[y,a] <- max(Run.a[y,a] - H.a[y,a],1)
       }
     d.N[y] <- sum(N.a[y,1:3])
     N[y] <- max(d.N[y],W[y])
     for(a in 1:3) {q[y,a] <- N.a[y,a]/N[y]}
   # ---------------------------------------------------- ME for rel. age comp.
     n.h[y] <- sum(x.h[y,1:3])
     n.irr[y] <- sum(x.irr[y,1:3])
     x.h[y,1:3] ~ dmulti(p[y,],n.h[y])                    # ----- Stochastic Errors
     x.irr[y,1:3] ~ dmulti(q[y,],n.irr[y])                # ----- Stochastic Errors
   # ---------------------------------------------------- ME for inriver run
     var.N[y] <- log(cv.N.hat[y] * cv.N.hat[y] + 1)
     mu.N[y] <- max(log(N[y]) - var.N[y]/2,1)
     tau.irr[y] <- 1/cv.N.hat[y]/cv.N.hat[y]
     N.hat[y] ~ dlnorm(mu.N[y],tau.irr[y])                # ----- Stochastic Errors
     S[y] <- max(N[y] - C[y],W[y] - C[y])
     U[y] <- (C[y] + H[y])/(N[y] + H[y])
     }
   S.avg <- sum(S[1:32])/32
   lnalpha.c <- min(lnalpha + sigma.sq /2/(1-phi*phi),4)
   S.eq <- lnalpha.c/beta
   S.msy <- S.eq * (0.5 - 0.07 * lnalpha.c)
   U.msy <- lnalpha.c * (0.5 - 0.07 * lnalpha.c)
   Pr.msy <- S.msy * exp(lnalpha.c - beta * S.msy)
   MSY <- Pr.msy - S.msy
   # ---------------------------------------------------- OY profile
   for (i in 1:125) {
     S.star[i] <- 80 * i
     Pr.star[i] <- S.star[i] * exp(lnalpha.c - beta * S.star[i])
     SY[i] <- Pr.star[i] - S.star[i]
     OY90[i] <- step(SY[i] - .9 *MSY)
```

-continued-

```
    OY80[i] <- step(SY[i] - .8 *MSY)
    OY70[i] <- step(SY[i] - .7 *MSY)
    OY60[i] <- step(SY[i] - .6 *MSY)
    }
  # ---------------------------------------------------- OF profile
   OF90[1] <- 0
   OF80[1] <- 0
   OF70[1] <- 0
   OF60[1] <- 0
   for (i in 2:125) {
    OF90[i] <- max(OY90[i],OF90[i-1])
    OF80[i] <- max(OY80[i],OF80[i-1])
    OF70[i] <- max(OY70[i],OF70[i-1])
    OF60[i] <- max(OY60[i],OF60[i-1])
    }
}

data:
list(
C = c(
350, 650, 650, 1950, 350, 550, 733, 612, 550, 385, 267, 627, 427, 565, 923, 939, 251, 389, 593, 1624,
1098, 530, 346, 430, 142, 277, 317, 228, 185, 114, 17, 41),
H = c(
512, 1402, 2441, 2525, 1382, 779, 532, 93, 46, 213, 503, 374, 236, 248, 163, 141, 316, 338, 865, 721,
831, 606, 613, 526, 650, 560, 760, 961, 694, 693, 712, 826),
N.hat = c(
5632, 13356, 12684, 19304, 11212, 9052, 10208, 10956, 7788, 6512, 11336, 11768, 9144, 10684, 9532,
12564, 6024, 14244, 16456, 26396, 17020, 13024, 7179, 15027, 8047, 6982, 5886, 6132, 7268, 4592,
2340, 2868),
cv.N.hat = c(
0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812,
0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812, 0.3517812,
0.3517812, 0.3517812, 0.3517812, 0.3517812 ,0.3437990, 0.3814950, 0.2677850, 0.143968, 0.1455010,
0.1207350, 0.0887770, 0.3517812, 0.3517812, 0.3517812),
```

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```
x.irr = structure(.Data=c(
3, 3, 4, 16, 24, 0, 1, 10, 2, 0, 7, 8, 1, 10, 14, 4, 16, 26, 17, 60, 55, 2, 61, 17, 5, 44, 55, 7, 37, 27, 53, 227,
61, 23, 181, 117, 29, 65, 123, 132, 220, 371, 29, 134, 88, 11, 63, 230, 29, 97, 192, 31, 142, 127, 201, 256,
251, 60, 595, 120, 89, 203, 204, 13, 227, 80, 51, 75, 44, 38, 108, 25, 22, 130, 22, 54, 313, 71,   30,    208,
141, 144, 415, 119, 40, 762, 254, 25, 181, 172, 38,    111, 67, 22, 184, 88),
Dim=c(32,3)),
x.h = structure(.Data=c(
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 20, 28, 34, 4, 20, 16, 5, 10, 5, 14, 29, 11, 59, 93, 10, 10, 71,
31, 34, 33, 42, 92, 73, 26, 6, 8, 4, 12, 30, 17, 92, 48, 48, 62, 70, 20, 142, 50, 14, 100, 228, 28, 200, 151,
118, 244, 463, 196, 99, 69, 73, 94, 112, 22, 80, 224, 37, 31, 82, 20, 20, 67, 8, 24, 34, 3, 0, 0, 0, 43, 505, 3,
82, 112, 24, 56, 327, 176),
Dim = c(32,3)),
W = c(
1408, 3339, 3171, 4826, 2803, 2263, 2552, 2739, 1947, 1628, 2834, 2942, 2286, 2671, 2383, 3141, 1506,
3561, 4114, 6599, 4255, 3256, 1630, 2530, 1418, 1977, 2426, 1873, 2636, 1148, 585, 717))

initial values:
inits:
list(lnalpha=2.0, beta= 0.0001, tau=2.5, lnPr.mean = 9.3,
lnS.0 = 9.0, phi = 0,
tau.Pr = 5, d.scale = 0.1, d.t1 = 0.40, d.t2 = 0.6,
lnPr = c(
9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3,
9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3, 9.3),
d.lnPr = c(
9.3, 9.3, 9.3, 9.3, 9.3, 9.3),
d.theta = structure(.Data=c(
2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3,
2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3,
2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3, 2.0, 7.7, 3.3,
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0.1, NA, 0.1, 0.1, NA, 0.1, 0.1, NA, 0.1, 0.1, NA, 0.1, 0.1, NA, 0.1, 0.1, NA, 0.1, 0.1, NA, 0.1, 0.1, NA,
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0.1, NA, 0.1, 0.1),
Dim=c(32,3)))
list(lnalpha=1.0, beta= 0.0001, tau=0.1, lnPr.mean = 9.3,
lnS.0 = 9.0, phi = 0,
tau.Pr = 5, d.scale = 0.1, d.t1 = 0.40, d.t2 = 0.6,
lnPr = c(
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d.lnPr = c(
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d.theta = structure(.Data=c(
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0.1, NA, 0.1, 0.1),
Dim=c(32,3)))
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lnS.0 = 9.0, phi = 0.5,
tau.Pr = 5.0, d.scale = 0.1, d.t1 = 0.40, d.t2 = 0.60,
lnPr = c(
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```

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d.lnPr = c(
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d.theta = structure(.Data=c(
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d.gam = structure(.Data=c(
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0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2,
NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2, 0.2, NA, 0.2,
0.2, NA, 0.2, 0.2),
Dim=c(32,3)))
```

Appendix B2.–Alternative statements to the program described in Appendix B1, changes that create optimum yield and overfishing profiles for the Klukshu stock of Chinook salmon.

Alternative statements	Location for substitutions within program listed in Appendix B1.
for(a in 1:3){k.H.a[y,a] <- Run.a[y,a]*d.gam[y,a]}	Substitution for lines 56–68
Run[y] <- sum(Run.a[y,1:3])	
d.H[y] <- max(Run[y]-W[y],10)	
k.H[y] <- sum(k.H.a[y,1:3])	
for(a in 1:3) {	
p[y,a] <- k.H.a[y,a]/k.H[y]	
d.H.a[y,a] <- p[y,a]*d.H[y]	
k.W.a[y,a] <- max(Run.a[y,a]-d.H.a[y,a],1)	
}	
pi[y] <- H[y]/d.H[y]	
N[y] <- W[y]*pi[y]	
k.W[y] <- sum(k.W.a[y,1:3])	
for(a in 1:3) {q[y,a] <- k.W.a[y,a]/k.W[y]}	
S[y] <- W[y] - C[y]	Substitution for lines 76–79
U[y] <- (C[y] + d.H[y])/(W[y] + d.H[y])	
pi.avg <- sum(pi[1:32])/32	

APPENDIX C: DEFINITIONS

Appendix Table C1.–Definitions for notation and terms.

a	age of adult salmon in years
ln(α)	production parameter representing intrinsic productivity of the stock
ln(α')	production parameter representing intrinsic productivity of the stock adjusted for process error and for autocorrelation
β	parameter that discounts production for density-dependence
by	brood year
c	number of large (age 1.3+) salmon inspected for marks at the weir on the Klukshu River during mark-recapture studies
cy	calendar year
C	annual harvest in Canadian sport/aboriginal fisheries
^	caret symbolizing variable is a statistic estimated through sampling
ε	deviation from expected production by a brood year (process error)
γ	discount of harvest rates for selectivity in U. S. fisheries for a particular age and calendar year
H	harvest in U.S. commercial/subsistence fisheries of the Alsek stock (or the Klukshu stock if H')
h	size of sample taken from the annual harvest *H* of the Alsek stock in U.S. fisheries used to estimate relative age composition
m	number of large (age 1.3+) salmon captured, marked and released into the Alsek River during capture-recapture studies
N	number of adults in the inriver run
OF	stands for 'overfishing' which is meant recruitment overfishing where spawning abundance is lowered such that the expected sustained yield is less than optimal yield
OY	stands for 'optimal yield' which is a range of sustained yields that encompass maximum sustained yield, the extent of which is subjectively determined as per the needs of fisheries management
p	fraction of an annual harvest *H* in U.S. fisheries comprised of adults of a particular age
P	production in adults by a brood year of the Alsek (or Klukshu) stock
$\hat{\pi}$	estimated expansion factor (multiplier) used to expand the base population *W* to estimate the abundance of the inriver run *N* ($\bar{\pi} = 4.17, SE = 1.71$ from Pahlke 2008, Appendix B1 and B10).
ϕ	fraction of the deviation from expected production (ε) by a brood year that is carried forward to become part of the deviation from production for the next brood year (the autoregressive parameter)
q	fraction of the inriver run *N* (or at the weir on the Klukshu River) comprised of adults of a particular age
R	number of adults in the annual run of adults
r	number of large (age 1.3+) salmon recaptured among the fish inspected at the weir on the Klukshu River during mark-recapture studies
return	number of adults produced in a brood year

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Appendix Table C1.–Page 2 of 2.

run	adult salmon in a year that are subject to fishing (sometimes implies number of adults); or as an inriver run, adult salmon in a year that have escaped fishing in U.S. waters (sometimes implies numbers)
S	number of salmon in a year's spawning escapement for the Alsek stock (or for the Klukshu stock)
S_{avg}	average number of salmon in a year's spawning escapement for the Alsek stock
$\overline{S}$	estimated average number of salmon in a year's spawning escapement for the Alsek stock
S_{EQ}	expected number of salmon spawning in the Alsek stock (or in the Klukshu stock) in the absence of fishing (the carrying capacity)
σ^2	variance around expected production from the Alsek (or the Klukshu stock) caused by log-normal density-independent processes (process error)
θ	fraction of the production from a specific brood year that survive and mature to become members of the run in a specific calendar year
S_{MSY}	number of salmon spawning in a year that is expected to produce maximum sustained yield from the Alsek stock (or from the Klukshu stock)
U	annual harvest rate
W	annual base population (sum of salmon counted through the weir on the Klukshu River and of salmon caught in fisheries just downstream of that weir).
w	size of sample taken from the annual passage through the weir on the Klukshu River used to estimate relative age composition of the inriver run to the Alsek River (and to the Klukshu River)