Fishery Manuscript No. 07-05

Stock Status and Recommended Escapement Goal for Anchor River Chinook Salmon

by

Nicole J. Szarzi,

Steve J. Fleischman,

Robert A. Clark,

and

Carol M. Kerkvliet

October 2007

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

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Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

Alaska 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)	$\text{log}_{2,}$ 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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by
Nicole J. Szarzi
Division of Sport Fish, Homer, Alaska

Steve J. Fleischman and
Robert A. Clark
Division of Sport Fish, Anchorage Alaska
and
Carol M. Kerkvliet
Division of Sport Fish, Homer, Alaska

Alaska Department of Fish and Game
Division of Sport Fish, Research and Technical Services
333 Raspberry Road, Anchorage, Alaska, 99518-1599

October 2007

This investigation was made possible, in part, by funding under the Federal Aid in Sport Fish Restoration Act (16 U.S.C. 777-777K) Projects F-10-14, 15, 16, 17, and 18, Job S-1-5, Southeast Sustainable Salmon and Fisheries Fund Projects 45315 and 45455, and NOAA-LOA Grants NA17FP1279, NA17FP2457, and NA03NMF4380248.

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Nicole J. Szarzi [a] *and Carol M. Kerkvliet*
Alaska Department of Fish and Game, Division of Sport Fish
3298 Douglas Place, Homer Alaska 99603-8027
and
Steve J. Fleischman and Robert A. Clark
Alaska Department of Fish and Game, Division of Sport Fish,
333 Raspberry Road, Anchorage Alaska 99518-1565

[a] *Author to whom all correspondence should be addressed: nicky.szarzi@alaska.gov*

This document should be cited as:
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.

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ABSTRACT

The Policy for Management of Sustainable Salmon Fisheries (5 AAC 39.222) and the Policy for Statewide Salmon Escapement Goals (5 AAC 39.223) direct the Alaska Department of Fish and Game to develop, periodically review and update salmon escapement goals to maintain escapements at a level that sustains yield into the future. The Anchor River sustainable escapement goal (SEG) for Chinook salmon, based on single aerial counts conducted annually, was rescinded in 2004 because a new sonar and weir project begun in 2003 found that many more Chinook salmon *Oncorhynchus tsawytscha* escaped into the Anchor than were indicated by aerial counts. The department recommends an SEG threshold of 5,000 adult Chinook salmon in the Anchor River based on a full probability spawner recruit model using all available data including 31 years (1977–2007) of aerial survey escapement indices and inriver recreational harvest estimates, plus 5 years (2003-2007) of weir/sonar estimates of escapement and age composition. Implementation of the stock assessment project should continue to improve estimation of population statistics and management of this stock.

Key words: Chinook salmon, *Oncorhynchus tshawytscha*, Anchor River, spawning abundance, escapement goal, stock-recruit analysis, Ricker Spawner-Recruit model, sustained yield, Bayesian statistics, Markov Chain Monte Carlo, WinBUGS

INTRODUCTION

The Anchor River, located on the southwestern portion of the Kenai Peninsula (Figure 1), supports a popular Chinook salmon fishery in the lower 2 river-miles. Chinook salmon escapement was indexed in the past to monitor stock sustainability. Full enumeration of recent escapements has allowed the development of an escapement goal threshold for the Anchor River. This report recounts the management history and historical database for Anchor River Chinook salmon, and details the statistical methods employed to develop and evaluate the recommended threshold.

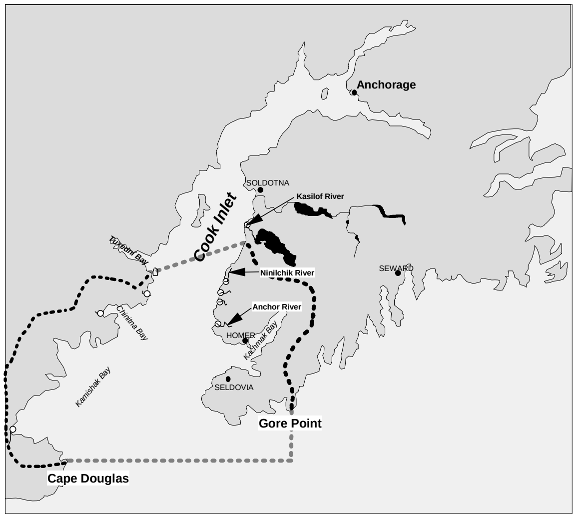

Figure 1.–The location of the Anchor River within the Lower Cook Inlet Management Area.

MANAGEMENT HISTORY

Chinook salmon escapements have been monitored in the Anchor River since 1962 with a combination of aerial and foot surveys conducted once per year. Aerial counts were expanded if foot survey counts in an index area within the aerial survey area were higher. Beginning in 1976, helicopters rather than fixed wing aircraft were used.

Escapement goals, first adopted in 1993, were the average of the expanded aerial surveys (Fried 1994). Beginning in 1996, only aerial counts were conducted to index escapement because ground counts were redundant (Szarzi and Begich 2004a). In 1998, escapement goals were changed to the 40^{th} and 80^{th} percentiles of aerial counts from 1976 to 1997 (Szarzi and Begich 2004a). After passage of the Sustainable Fisheries and Escapement Goal policies by the Board of Fisheries (BOF) in 2001, the criteria for setting escapement goals in streams such as the Anchor River, where total returns cannot be enumerated, were standardized and based upon different percentiles depending upon the contrast or range of escapement counts (Bue and Hasbrouck *Unpublished*). In 2001, Anchor River escapement goals were evaluated using these criteria.

No change was needed to the Anchor River goal in 2001 but restriction of the Anchor River fishery was indicated by the general decline in escapement index counts, with six of 12 escapement indices measured since 1989 (1989-2001) below the SEG range of 750 to 1,500 fish and by escapements in 4 of the last 6 consecutive years (1996-2001) below the SEG range (Table 1). During the BOF meeting in November 2001, in response to the guidelines established in the Sustainable Salmon Fisheries Policy, the BOF designated Anchor River Chinook salmon as a stock of "management concern" defined in the policy as "a concern arising from a chronic inability, despite use of specific management measures, to maintain escapements for a salmon stock within the bounds of the SEG, BEG, OEG, or other specified management objectives for the fishery" (5 AAC 39.222 (f) (21)). The regulatory fishery openings were reduced from five to four 3-day weekends.

The department re-evaluated the Anchor River escapement goal in 2004 incorporating the additional data collected since the last review in 2001 (Otis and Hasbrouck 2004). Staff recommended rescinding the Anchor River goal because a sonar and weir project begun in 2003 found that many more Chinook salmon returned to the river than was evident from aerial surveys.

At their meeting in 2004, the BOF approved the department's recommendation to rescind the stock of management concern designation and remove the Sustainable Escapement Goal (SEG) for Anchor River Chinook salmon because of the higher than expected escapements and low exploitation rates. The Department clarified to the Board that there were insufficient data for an escapement goal at that time, but pledged to initiate the development of a biological escapement goal (BEG) for the Anchor River using return data from the sonar and weir project and present a preliminary goal in 2007.

HISTORICAL HARVEST AND ESCAPEMENT DATA

The Anchor River supports the largest freshwater sport harvest of wild Chinook salmon within the Lower Cook Inlet Management Area (LCIMA). The annual freshwater harvest has been estimated since 1977 with a mail survey administered to the households of a random sample of Alaska sport fishing license holders (Table 2). The estimated harvest has ranged from 605 (in 1980) to 2,787 (in 1993) but is relatively stable (no trend) over the range of the data; the average annual harvest from 2001 to 2006 of 1,222 is close to the historic annual average from 1977 to 2000 of 1,323 (Mills 1979-1980, 1981a-b, 1982-1994; Howe et al. 1995, 1996, 2001 a-d; Walker et al. 2003; Jennings et al. 2007, In prep.; Jennings et al. 2004; 2006 a-b; Jennings[1]).

Chinook salmon bound for the Anchor River are harvested in the Cook Inlet marine sport fishery. The number harvested is unknown, but the exploitation rate of Anchor River Chinook salmon in the marine recreational fishery should be similar to that of Deep Creek and Ninilchik River Chinook salmon, which was estimated to be approximately 4% in the late 1990s (Begich and Evans *In prep.*, King and Breakfield 1999 and Szarzi and Begich 2004b).

Anchor River Chinook salmon are also harvested in fresh water, in a sport fishery that has been consistently and heavily restricted. Only the lower 2 river-miles of the drainage have been open and only on weekends and the following Mondays in late May and June. From 1977 to 1988 Chinook salmon fishing was open for four 3-day weekends (Table 2). To increase fishing opportunity a fifth weekend opening was added in 1989. The fishery has been open for five 3-day weekends each year since, except 2002 and 2003, when it was restricted to four 3-day weekends because aerial survey counts were below the lower bounds of the SEG range. A fifth 3-day weekend was added after the last weekend opening by Emergency Order in 2004, based upon sonar and weir counts. The fifth 3-day weekend opening was restored by regulation in 2005, when the Board approved a proposal to liberalize the sport fishery for Chinook salmon by adding a 3-day weekend fishery opening before Memorial Day weekend.

Aerial surveys may not precisely represent the yearly trends in Chinook salmon escapement to the Anchor River, however, in general[2], they have been conducted in a consistent manner throughout the history of the survey and the average counts

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[1] Preliminary data from Area P0_Detail_Harvest_06.xls, 2006 Statewide Harvest Survey, Alaska Department of Fish and Game, Division of Sport Fish, Research and Technical Services, Gretchen Jennings, Program Coordinator, ADF&G, Anchorage: personal communication.

[2] One potential exception is that the drop in survey counts from 1988 and before to 1989 and after may be due to the change in observers between the 1988 and 1989 seasons.

Table 1.–Anchor River Chinook salmon aerial index counts (South Fork only) and DIDSON/weir estimates 1976-2007.

		Sonar/weir	
Year	Aerial survey count	(number)	SE
1976	2,125		
1977	3,585		
1978	2,209		
1979	1,335		
1980	No survey		
1981	1,066		
1982	1,493		
1983	1,033		
1984	1,087		
1985	1,328		
1986	2,287		
1987	2,524		
1988	1,458		
1989	940		
1990	967		
1991	589		
1992	99		
1993	1,110		
1994	837		
1995	No survey		
1996	277		
1997	477		
1998	789		
1999	685		
2000	752		
2001	414		
2002	748		
2003	680	13,280[a]	196
2004	834	12,016	283
2005	651	11,156	299
2006	899	8,945	289
2007	678	9,622	238

[a] 2003 sonar count expanded temporally; actual count 9,238.

Table 2.–Anchor River Chinook salmon inriver sport harvest, standard error and fishery openings 1977-2006, plus estimates of inriver sport fishery exploitation rates 2002-2006.

	Harvest					Estimated	Inriver	Exploitation
Year	(number)	(SE)	Fishing days per week	Weeks	Total fishing days	Escapement[a]	Return	Rate
1977	1,077		2	4	8			
1978	2,109		3	4	12			
1979	1,913		3	4	12			
1980	605		3	4	12			
1981	1,069		3	4	12			
1982	718		3	4	12			
1983	1,269		3	4	12			
1984	998		3	4	12			
1985	672		3	4	12			
1986	1,098		3	4	12			
1987	761	163	3	4	12			
1988	976	217	3	4	12			
1989	578	115	3	5	15			
1990	1,479	201	3	5	15			
1991	1,047	142	3	5	15			
1992	1,685	245	3	5	15			
1993	2,787	339	3	5	15			
1994	2,478	351	3	5	15			
1995	1,475	190	3	5	15			
1996	1,483	201	3	5	15			
1997	1,563	186	3	5	15			
1998	783	119	3	5	15			
1999	1,409	192	3	5	15			
2000	1,730	193	3	5	15			
2001	889	162	3	5	15			
2002	1,047	192	3	4	12			
2003	1,011	157	3	4	12	13,280	14,291	0.071
2004[b]	1,561	198	3	5	15	12,016	13,577	0.115
2005	1,432	233	3	5	15	11,156	12,588	0.114
2006	1,394	197	3	5	15	8,945	10,294	0.131
2007	na	na	3	5	15			

[a] Data from Table 1, above.

[b] In 2004 opened a 5th weekend by EO.

should reflect large scale changes in escapement. Helicopter surveys of Chinook salmon escapement have been conducted on the same reach of the South Fork of the Anchor River since their inception in 1976. Three observers conducted the bulk of the surveys: one from 1976 to approximately 1989, a second from 1989 until 1995 and a third from 1997 through 2005. Counts have been made by tandem observers since 1996 to compare consistency between surveyors. The average aerial survey count for each decade declined from 2,314 in the latter 1970's to 1,468 in the 1980's and 648 in the 1990's. In the 21st century, the aerial counts average 707 (Table 1).

Dual Frequency Identification Sonar (DIDSON) and a floating weir have been used in combination to enumerate Chinook salmon escapement above the sport fishery in the Anchor River since 2003 (Kerkvliet et al. *In prep*, Kerkvliet and Burwen *In prep*). Only the sonar was operated in 2003, and it was installed on May 30, after the beginning of the Chinook salmon migration. Since 2003, the sonar has been in place at the start of migration on approximately May 15 and operated until spring high water conditions receded to a level where installation of a floating weir was possible.

Species of similar size cannot be differentiated with DIDSON so netting was conducted upstream in the North and South forks to apportion sonar counts and collect sex, length and age composition information. Netting has been prevented by high water until approximately June 1 each year since 2003.

Escapement counts ranged from 8,945 (SE 289) in 2006 to 12,016 (SE 283) in 2004 (Table 1). If the 2003 sonar count is expanded to include the period when counts were missed between approximately May 15 and May 29, using the average proportion of the run that escaped up the river in 2004 and 2005 (two years with similar water temperature and flow rate patterns) the estimated escapement in 2003 would have been 13,280 (SE 196; Table 1).

Sonar estimates of Chinook salmon escapement are biased very slightly low. To calculate net upstream passage, all downstream-traveling fish are subtracted from gross upstream passage. These downstream fish include a few outmigrating steelhead, which cannot be distinguished from Chinook salmon by the sonar. The number of fish subtracted from the count that are truly outmigrating steelhead is thought to be negligible based on the low numbers of netted steelhead, the low steelhead population size relative to the more abundant Chinook salmon, lack of discontinuity in the Chinook salmon counts at the time of transition from sonar to weir and the high correlation of downstream counts with upstream counts.

A weir was operated in the North Fork of the Anchor River in 2004. An estimated 16% (1,919/12,016) of the Chinook salmon counted in the mainstem in 2004 used the North Fork for spawning and 84% used the South Fork (Kerkvliet et al. *In prep*).

Exploitation rates of Anchor River Chinook salmon in recreational fisheries (~4% in the marine fishery, 7-13% inriver; Table 2) are low. Historic exploitation rates are probably also low, based on the stability of aerial survey counts and harvest estimates throughout the history of data collection.

Age composition of the Chinook salmon escapement was estimated from fish netted in the North and South forks during sonar operation in combination with fish subsampled at the weir after its installation. Age composition differed statistically between the North and South forks in 2003 and 2004, but the difference was not biologically meaningful (Kerkvliet et al. *In prep*). Age composition from the two forks was pooled in 2005 and 2006 because few fish were observed in 2005 in the North Fork (Kerkvliet et al. *In prep*). Overall, age 1.3 was the dominant age class each year from 2003-2006. Age 1.4 were the second most dominant in the escapement in 2004 and 2006 and age 1.2 the second most dominant in 2003 and 2005 (Table 3).

In summary, the Anchor River Chinook dataset consists of a long historical record of imprecise escapement index counts with no age data, followed by four to five years of accurate escapement and age composition estimates. Throughout the historical record, the inriver recreational harvest was estimated consistently and precisely, and the marine recreational harvest was not measured but small.

Table 3.–Estimated ocean age composition of Chinook salmon sampled from the Anchor River escapement, 2003-2006**.**

		Ocean Age			
		1	2	3	4
2003	Percent	5	23	58	14
	SE Percent	1.1	2.1	2.5	1.8
2004	Percent	8.8	20.7	48.6	21.9
	SE Percent	1.9	2.6	3.2	2.6
2005	Percent	5	23.9	52.2	18.9
	SE Percent	1.2	2.1	2.5	2
2006	Percent	6.4	16.5	52.1	25
	SE Percent	2.1	2.7	3.8	3.5

METHODS

Two separate statistical methods were used to analyze the Anchor River Chinook data. The first is termed a "full probability model" for this report, because it leverages the entire historical database, explicitly incorporating and considering the effects of measurement error and missing age data. Markov Chain Monte Carlo (MCMC) methods were employed to fit this model. This methodology reduces bias caused by the measurement error, and provides a more realistic assessment of uncertainty than is possible with other statistical methods. The second method, labeled a "theoretical model" for this report, analyzes only the most recent, high-quality data, making reasonable assumptions about productivity in order to make inference about carrying capacity and optimal escapement levels.

FULL PROBABILITY MODEL

Anchor River Chinook spawner-recruit data were analyzed in the context of the following statistical model. For a similar analysis see Ericksen and Fleischman 2006.

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

$$R_y = S_y \, \alpha \, e^{-\beta S_y} e^{\varepsilon_y} \tag{1}$$

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

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

$$S_{EQ} = \frac{\ln(\alpha')}{\beta} \tag{2}$$

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

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma^2_{SR}}{2} \tag{3}$$

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

$$S_{MSY} \approx S_{EQ}\left(0.5 - 0.07\ln(\alpha')\right). \tag{4}$$

The Ricker relationship can be linearized by dividing both sides of equation 1 by *S* and taking the natural logarithm, yielding:

$$\ln\frac{R}{S} = \ln(\alpha) - \beta S + \varepsilon \qquad (5)$$

This streamlines parameter estimation, because the relationship can now be viewed as a simple linear regression (SLR) of ln(*R*/*S*) on *S*, in which the intercept is an estimate of ln(α), the negative slope an estimate of β, and the mean squared error an estimate of the process error variance σ^2_{SR}.

The SLR approach requires reasonably precise estimates of S and R for a minimum of 8-10 complete brood years. Accurate estimates of S are especially important because moderate to high measurement error in S can cause standard estimates of S_{MSY} to be biased. Zero pairs of precise S and R estimates exist for the Anchor River, because the weir, sonar, and age sampling projects have been operating for less than one full life cycle. S and R pairs from 1977 to 2000 can be reconstructed from expanded aerial surveys and freshwater harvest estimates, with imputed age composition estimates. However such estimates are likely affected by substantial measurement error.

Ricker parameters can be estimated using imprecise estimates of S and R, however it is critical to assess how much uncertainty and bias is introduced into the parameter estimates as a result of the imprecision. This is difficult to accomplish with classical statistical methods. Therefore we employed Markov Chain Monte Carlo (MCMC) methods, which are especially well-suited for modeling complex population and sampling processes, including measurement error. We implemented the MCMC algorithms in WinBUGS, which is a Bayesian software program. Bayesian statistical methods employ probability as a language to quantify uncertainty about model parameters. Knowledge existing about the parameters outside the framework of the experimental design is the "prior" probability distribution. The output of the Bayesian analysis is called the "posterior" probability distribution, which is a synthesis of the prior information and the information in the data.

The Bayesian MCMC analysis considers all the data simultaneously in the context of the following "full-probability" statistical model. Returns of Chinook salmon originating from spawning escapement in brood years y = 1971 - 2004 are modeled as a Ricker stock-recruit function with autoregressive lognormal errors

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi\nu_{y-1} + \varepsilon_y \qquad (6)$$

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

$$\nu_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y, \qquad (7)$$

and the $\{\varepsilon_y\}$ are independently and normally distributed process errors with variance σ^2_{SR}.

Age proportion vectors $\underline{\mathbf{p}}_y = (p_{y3}, p_{y4}, p_{y5}, p_{y6})$ from brood year *y* returning at age *a* are drawn from a common Dirichlet distribution (multivariate analogue of the beta). The Dirichlet is re-parameterized such that the usual parameters:

$$D_a = \pi_a D \qquad (8)$$

are written in terms of location (overall age proportions π_a) and inverse scale (D, which governs the inverse dispersion of the $\underline{\mathbf{p}}_y$ age proportion vectors among brood years).

The abundance *N* of age-*a* Chinook salmon in calendar year *t* (*t* = 1977-2007) is the product of the age proportion scalar *p* and the total return *R* from brood year *y* = *t*-*a*:

$$N_{ta} = R_{t-a}\, p_{t-a,a} \qquad (9)$$

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

$$N_{t\cdot} = \sum_a N_{ta}\,. \qquad (10)$$

Inriver return is total abundance minus marine harvest,

$$IR_t = N_{t\cdot} - H_{Mt} \qquad (11)$$

where H_{Mt} is marine recreational harvest in Cook Inlet, with exploitation rates $\{\mu_{Mt}\}$.[3]

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[3] Marine harvests of Anchor River chinook salmon are unobserved, however both Ninilchik and Deep Creek Chinook had approximately 4% exploitation rates in the marine fishery in the late 1990s. Thus we modeled the harvest rate as beta(40,960) ≥1996 and beta(50,950) ≤1995, when fishery regulations were less restrictive and harvests averaged approximately 20% higher

$$H_{Mt} = \mu_{Mt} N_{t.} \qquad (12)$$

Spawning abundance during year *t* is:

$$S_t = IR_t - H_{Ft} \qquad (13)$$

where H_{Ft} is the freshwater sport harvest, which in turn is the product of the annual exploitation rate μ_{tFt} and inriver return IR_t:

$$H_{Ft} = \mu_{Ft} IR_t \, . \qquad (14)$$

Freshwater exploitation rate is an exponential function of annual freshwater fishing mortality F

$$\mu_{Ft} = 1 - \exp(-F_t) \, , \qquad (15)$$

which in turn is the product of an annual catchability coefficient q_t and annual fishing effort (days the fishery was open) E_t:

$$F_t = q_t E_t \, . \qquad (16)$$

Annual catchability coefficients $\{q_t\}$ (fraction of the population harvested by a single unit of effort) are drawn from a common beta distribution with parameters:

$$B_1 = Q\sigma_Q^{-2} \, . \qquad (17)$$

and $B_2 = 1 - B_1$, where the location parameter Q is the mean catchability coefficient and the scale parameter σ_Q governs the dispersion of the annual catchability coefficients $\{q_t\}$.

Spawning abundance yielding peak return S_{MAX} is calculated as the inverse of the Ricker β parameter. Equilibrium spawning abundance S_{EQ} and spawning abundance leading to maximum sustained yield S_{MSY} are obtained using equations 2-4, except that $\ln(\alpha)$ is corrected for AR1 serial correlation as well as lognormal process error:

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_{SR}^2}{2(1-\phi^2)} \, . \qquad (18)$$

Expected sustained yield at a specified escapement S is calculated by subtracting spawning escapement from the expected return, again incorporating corrections for lognormal process error and AR1 serial correlation:

$$SY = E[R] - S = Se^{\ln(\alpha') - \beta S} - S \, . \qquad (19)$$

Probability that a given level of escapement would produce yields exceeding 90% of MSY was obtained by calculating expected sustained yield SY (Equation 19) at multiple incremental values of S (0 to 10,000) for each Monte Carlo sample, then comparing SY with 90% of the value of MSY for that sample. The proportion of samples in which SY exceeded 0.9 MSY is the desired probability.

Observed data include estimates of spawning abundance, aerial survey counts, estimates of harvest, and scale age counts. Likelihood functions for the data follow.

Estimated spawning abundance is modeled as:

$$\hat{S}_t = S_t e^{\varepsilon_{WSt}} \qquad (20)$$

where the $\{\varepsilon_{WSt}\}$ are normal $(0,\sigma^2_{WSt})$ with individual variances $\{\sigma^2_{WSt}\}$ assumed known from weir / sonar coefficients of variation.

Aerial survey counts (1977-2007, except 1980 and 1995) are modeled as linearly related to true spawning abundance[4]

$$c_t = \lambda_i S_t e^{\varepsilon_{ASt}} \qquad (21)$$

where λ is the fraction of spawning salmon observed in the aerial surveys during period i = 1 (1977-1988) or i = 2 (1989-2007)[5], the $\{\varepsilon_{ASt}\}$ are normal $(0,\sigma^2_{AS})$, and the common error variance σ^2_{AS} is informed by the relationship between $\hat{S}$ and *c* for years 2003-2006.

Estimated harvest (1977–2006) is modeled as

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

where ε_{Ht} are normal $(0,\sigma^2_{Ht})$ with individual variances σ^2_{Ht} assumed known from SWHS coefficients of variation.

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[4] We cannot test the assumption of linearity at present because we lack contrast in recent escapements. An alternative model choice would be an allometric relationship between aerial counts and escapement, which would allow for the possibility that aerial survey detection could saturate, i.e., the fraction detected would decline as abundance increased. However, given the low density of Chinook salmon on the Anchor River spawning grounds, we consider saturation very unlikely.

[5] There was a change in observers between 1988 and 1989 that caused an apparent drop in the proportion of Chinook salmon detected.

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

$$r_{ta} = \frac{N_{ta}}{N_{t\cdot}} \qquad (23)$$

Bayesian analyses require that prior probability distributions be specified for all unknowns in the model. Non-informative priors (chosen to have a minimal effect on the posterior) were used throughout. Initial returns R_{1971}-R_{1976} (those with no linked spawner abundance) were modeled as drawn from a common lognormal distribution with median μ_{LOGR} and variance σ^2_{LOGR}. Normal priors with mean zero, very large variances, and constrained to be positive, were used for ln(α) and β (Millar 2002), as well as for μ_{LOGR}. The initial model residual ν_0 was given a normal prior with mean zero and variance $\sigma^2_{SR}/(1-\phi^2)$. Diffuse conjugate inverse gamma priors were used for σ^2_{SR}, σ^2_{AS}, and σ^2_{LOGR}.

A uniform prior was used for σ_Q. An informative lognormal(4,6) prior was used for the Dirichlet inverse scale parameter D, based on a meta-analysis of 7 other Pacific salmon stocks.

Markov-chain Monte Carlo samples were drawn from the joint posterior probability distribution of all unknowns in the model. For each of two Markov chains initialized, a 5,000-sample burn-in period was discarded, thinning by a factor of 10 was initiated, and 7,500 additional updates were generated. The resulting total of 15,000 samples were used to estimate the marginal posterior means, standard deviations, and percentiles. The diagnostic tools of WinBUGS (Gilks et al. 1994) assessed mixing and convergence, and no major problems were encountered. Interval estimates were obtained from the percentiles of the posterior distribution.

THEORETICAL MODEL

Theoretical spawner-recruit (S-R) relationships were investigated for Chinook salmon in the Anchor River, in a manner similar to the methods used by Clark 2005 and Clark et al. 2006 for coho salmon. The results from this analysis provide no assessment of uncertainty, but point estimates were generated for comparison with those from the full-probability model.

Long term yields and escapement in the Anchor River are likely at equilibrium because historic harvests are relatively stable and full enumeration of the spawning escapement since 2003 has revealed that the exploitation rate of Anchor River Chinook salmon stocks is low. Average escapements estimated with DIDSON/weir were assumed to represent average historical escapements and average harvests during years when escapement was fully enumerated to represent historic exploitation. The S-R relationship for Anchor River Chinook salmon was assumed to follow the form of Ricker (Ricker 1975). A range of productivity parameters for Chinook salmon stocks were used to estimate preliminary escapement goal ranges that may result in maximized yields.

Escapement counts ($\bar{s}$) were averaged (I = 2003-2006):

$$\bar{s} = \frac{1}{n}\sum_{i}^{n} s_i \qquad (24)$$

Harvest estimates (h), including marine harvests replaced escapement counts (s) in equation (24) to estimate average harvest ($\bar{h}$).

Assuming that harvest and escapements are in equilibrium, average maximum exploitation rate ($\bar{u}$) was estimated as:

$$\bar{u} = \frac{\bar{h}}{(\bar{s}+\bar{h})} \qquad (25)$$

Exploitation rate at maximum sustained yield (MSY) depends solely on the Ricker productivity parameter α. The range of the productivity chosen (2.72 to 4.85) brackets a conservative estimate of the productivity of Chinook salmon stocks where 4.85 is the average productivity parameter for stream-type Chinook salmon from Parken et al. 2004. Assuming α was known and the observed average exploitation rate from 2003-2006 and average escapement counted with DIDSON and weir from 2003-2006 represent equilibrium, estimates of escapement that will produce MSY can be calculated from Hilborn and Walters 1992) and Ricker 1975):

$$S_{MSY} = \bar{s}\,\frac{0.5\ln(\alpha) - 0.07\ln(\alpha)^2}{\ln(\alpha(1-\bar{u}))} \qquad (26)$$

To compare estimates of S_{MSY} and S-R relationships derived from the two different assumed α's, the β parameters were estimated for each S-R by first estimating the exploitation rate at MSY by solving:

$$\ln(\alpha) = \mu_{MSY} - \ln(1-\mu_{MSY}) \qquad (27)$$

for u_{MSY} (from Ricker 1975). The β parameter was then calculated from (Ricker 1975):

$$\beta = \frac{\mu_{MSY}}{s_{MSY}} \qquad (28)$$

From these S-R relationships the range around S_{MSY} that produces 90% or more of MSY was also calculated.

RESULTS

FULL PROBABILITY MODEL

The posterior distribution from an age-structured fisheries model is multivariate with many dozens of free parameters. Additionally, any quantity that can be calculated from model parameters can also be monitored by WinBUGS and its posterior density estimated. A summary of posterior percentiles from key model quantities is in Table 4.

Information from both the aerial surveys and the harvests contribute to our knowledge of individual annual escapements, as synthesized and summarized by the posterior percentiles for S (Figure 2). As expected, uncertainty in S differs dramatically before and after the weir/sonar projects were initiated in 2003.

The estimates of R show a similar pattern, except that precision changes more gradually with time because each brood year crosses four calendar years (Figure 2). Brood years at the beginning and end of the time series show additional uncertainty due to incomplete data from missing ages. The uncertainty in *R* is primarily due to measurement error in S, because escapement has comprised a large fraction of the total return. Harvest estimate sampling error, and lack of scale sampling data before 2003 also contribute to uncertainty in R.

When the 80% intervals of R vs S are plotted against each other (Figure 3), most individual {R,S} pairs are only marginally distinguishable from each other. Due to the low contrast and moderate to high measurement error, information about {R,S} is mostly limited to knowledge of their central location, rather than the individual annual values. Yet, because of the large number of years of data, our information about the central location of the cluster of points is strong. It is located near the replacement line, meaning harvest rate is very low and the stock is oscillating near carrying capacity.

A sampling of Ricker relationships that could have resulted in the observed data (Figure 4) shows that most of the possible curves pass through the replacement line within a fairly narrow window, i.e., S_{EQ} is well-defined. This is borne out in a narrow 80% interval estimate for S_{EQ} (11,080 to 14,550; Table 4) On the other hand the corresponding intervals are much wider for ln(α) (0.78–1.93) and β (6.0–16.7 x 10^{-5}). S_{MSY} is fairly well estimated (80% interval 4,155–6,248; Table 4). S_{MSY} is equally likely to be above or below 5,006.

The width of the 80% interval divided by the posterior median of S_{MSY} is an index of the relative uncertainty (RU) of our knowledge about S_{MSY}. For Anchor Chinook this ratio was RU_{80} = 0.42, which is near the lower end of the range of values from other salmon stocks analyzed in a similar manner (Table 5).

The probability that a given spawning escapement will result in *SY* exceeding 90% of maximum sustained yield is plotted in Figure 5. The probability of achieving sustained yields in excess of 90% of MSY is at least 60% between spawning abundances of 3,400 and 6,800 fish (Figure 5). That probability reaches a maximum of 97% near S_{MSY} = 5,000.

Table 4.–Posterior percentiles from a Bayesian Ricker spawner-recruit analysis of Anchor River Chinook salmon, 1977–2004 brood years. Parameters are defined in text of Methods section.

Parameter	$p_{2.5}$	p_{10}	p_{50}	p_{90}	p_{95}
$\ln(\alpha)$	0.48	0.78	1.35	1.93	2.25
α	1.62	2.19	3.85	6.90	9.47
$\beta \times 10^5$	3.31	5.95	11.04	16.71	19.77
σ_{SR}	0.08	0.10	0.17	0.29	0.38
ϕ	-0.72	-0.44	0.23	0.76	0.92
S_{MAX}	5,058	5,985	9,061	16,800	30,260
S_{EQ}	10,280	11,080	12,480	14,550	17,170
S_{MSY}^{c}	3,765	4,155	5,006	6,248	7,592
MSY	2195	3449	6499	11,400	15,390
π_1	0.046	0.0655	0.076	0.100	0.114
π_2	0.173	0.192	0.227	0.263	0.283
π_3	0.436	0.461	0.504	0.546	0.570
π_4	0.142	0.159	0.191	0.226	0.247
D	40	50	82	126	159
λ_1	0.101	0.116	0.148	0.190	0.219
λ_2	0.044	0.049	0.058	0.069	0.076
$1/\lambda_1$	4.57	5.27	6.78	8.65	9.93
$1/\lambda_2$	13.11	14.47	17.25	20.59	22.80
σ_{AS}	0.38	0.42	0.51	0.62	0.69
$Q_H \times 10^3$	6.9	7.4	8.3	9.4	10.2
σ_H	0.014	0.019	0.026	0.035	0.041

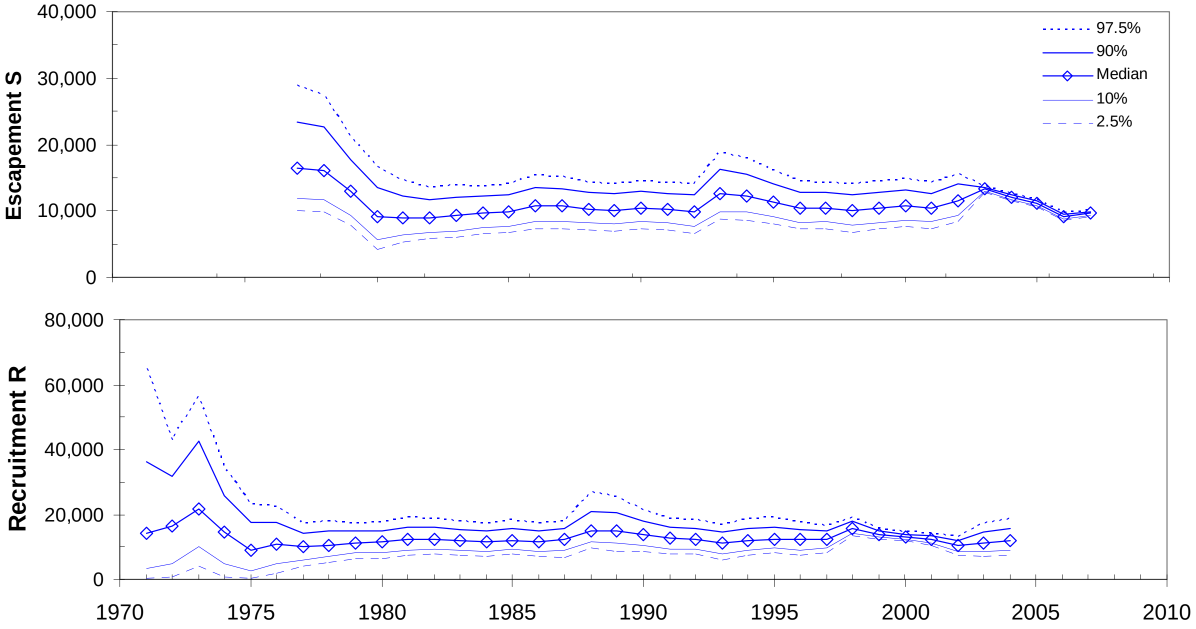

Figure 2.–Posterior percentiles of estimated escapement and recruitment, Anchor River Chinook salmon.

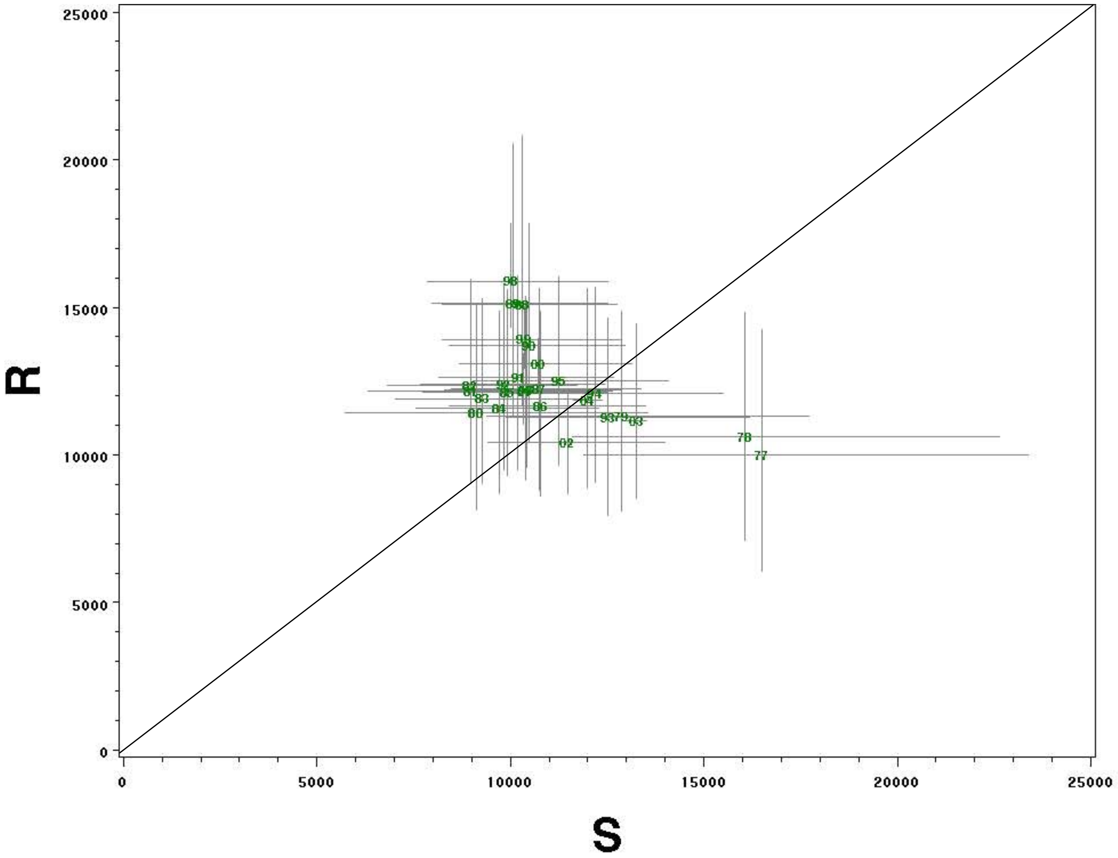

Figure 3.– Scatter plot of point/interval estimates of recruitment versus escapement, Anchor River Chinook salmon, brood years 1977-2003. Posterior medians are plotted as two-digit year labels, 10th and 90th posterior percentiles are bracketed by error bars.

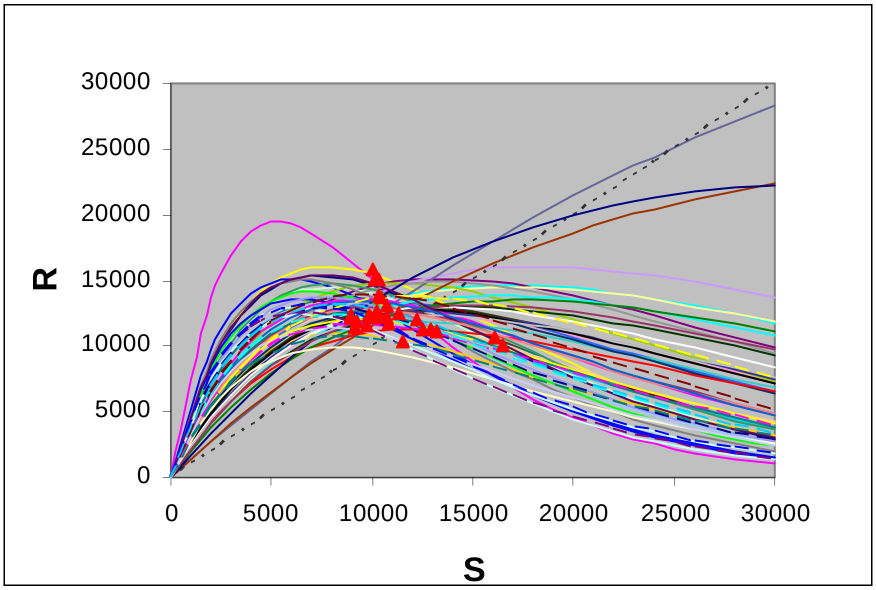

Figure 4.–Ricker curves represented by ~40 paired values of ln(α) and β sampled from the posterior probability distribution of stock-recruitment statistics, Anchor River Chinook salmon. Symbols are posterior medians of R and S. Curves can be interpreted as a sampling of Ricker relationships that could have resulted in the observed data.

Table 5.–Relative uncertainty (RU_{80}) of Ricker spawner-recruit parameter estimates for Pacific salmon populations analyzed with Bayesian age-structured spawner recruit methods. RU_{80} is defined as the width of 80% credibility intervals (90th posterior percentile – 10th posterior percentile) divided by the posterior median.

					RU_{80}				
Species	River	Years[a]	*S* contrast[b]	*S* uncertainty	$\hat{\phi}$	$\hat{\sigma}_{SR}$	$\ln(\alpha)$	β	S_{MSY}
Coho	Chilkat	7/9	5.5	high	0.69	0.31	0.67	0.60	0.51
Chinook	Anchor[c]	5/31	2.5	high	0.23	0.17	0.85	0.98	0.42
Chinook	Karluk[d]	12/29	3.2	low	0.16	0.49	1.46	1.63	1.39
Chinook	Ayakulik[d]	12/28	22.2	low	-0.17	0.51	1.44	0.59	0.38
Chinook	Kenai, early run[d]	17	2.5	mod	0.35	0.26	0.67	0.86	0.55
Chinook	Kenai, late run[d]	17	2.6	mod	0.58	0.25	0.87	1.52	1.70
Chinook	Deshka[d]	10/31	10.1	low	0.67	0.44	0.77	0.69	0.57
Sockeye	Buskin[d]	8	1.7	low	0.43	0.57	1.21	1.63	2.11

[a] Years of complete data/any data.

[b] *S* contrast = max(*S*) / min(*S*).

[c] this stock.

[d] Ericksen and Fleischman 2006.

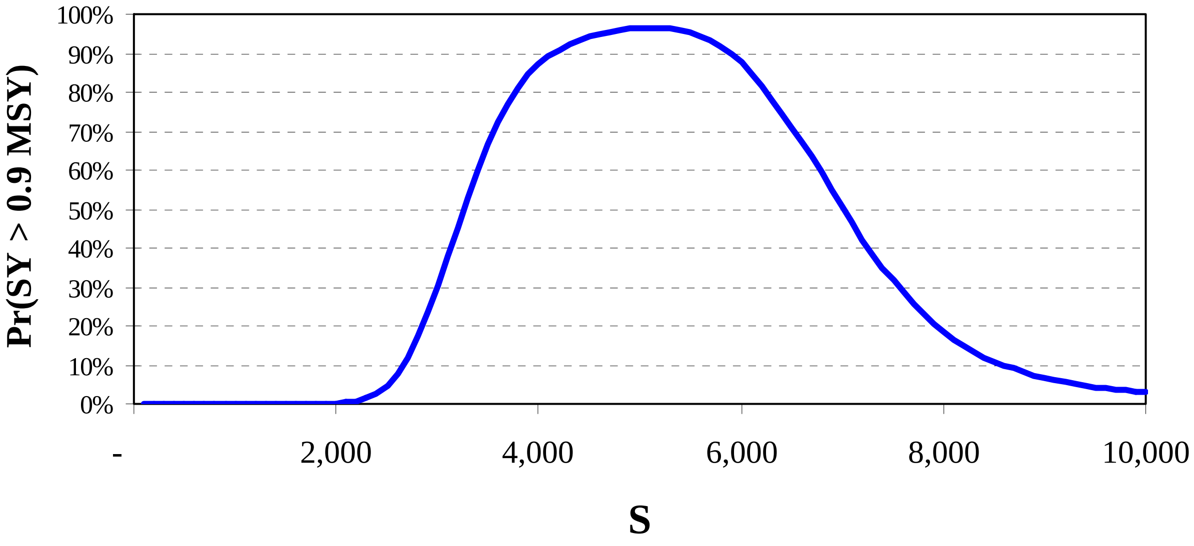

Figure 5.–Probability that a specified spawning abundance will result in sustained yield exceeding 90% of maximum sustained yield, Anchor River Chinook salmon.

THEORETICAL MODEL

The average of annual escapements counted by DIDSON and weir between 2003 and 2006 was 11,349 and average return for the same years was (average return=average escapement + average harvest; 13,228=11,349 + 1,879) (Table 1). Assuming Ricker α for Chinook salmon ranged from 2.72 to 4.85 (ln(α) ranged from 1.0 to 1.58) and that the average escapement and average harvest represented an equilibrium exploitation rate of 0.14, two theoretical S-R relationships that have the same equilibrium values were calculated (Figure 6). In addition, from the two theoretical S-R relationships, escapements that would produce MSY and a range of escapements that would produce 90% or more of MSY were also calculated. When ln(α) = 1.0, S_{MSY} = 5,801 and the range of escapements that would produce 90% or more of MSY was 3,812-7,966. For ln(α) = 1.58, S_{MSY} = 4,914 and the range of escapements that would produce 90% or more of MSY was 3,162-6,923. S_{EQ} was 13,402 for ln(α) = 1.0 and 12,568 for ln(α) = 1.58.

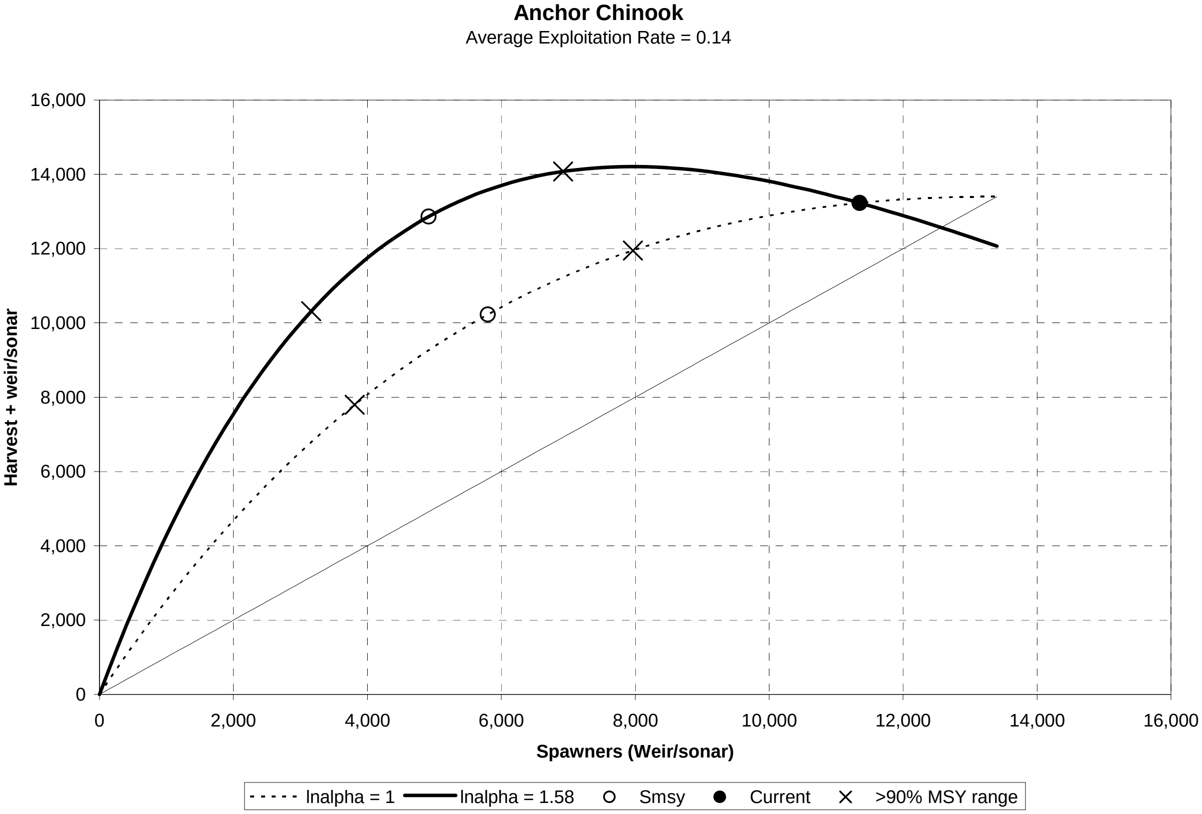

Figure 6.–Theoretical Ricker stock-recruitment relationships for Chinook salmon in the Anchor River.

Note: Relationship based on average escapement from sonar/weir of 11,349 and average freshwater and marine harvest of 1,879 (2003-2006; •·). The dotted line represents the Ricker curve with an α-parameter of 2.72; the heavy solid line represents the Ricker curve with an α-parameter of 4.85 and the straight solid line, the replacement line. S_{msy} (o) and escapements that produce 90% of MSY (x) are also shown.

DISCUSSION

The results from the full probability model, based on 31 years of data, and the theoretical model, based on 5 years of full, high-quality data and some reasonable assumptions about productivity, were in close agreement. The posterior median of S_{MSY} from the full probability model (5,006) was similar to estimates from the theoretical model of 5,801 (ln (α) = 1.0) and 4,914 (ln (α) = 1.58). From the full probability model, there is a 60–97% probability that escapements between 3,400 and 6,800 will produce sustained yields exceeding 90% of MSY. This was also consistent with the results of the theoretical model.

Clearly, by comparing these numbers with recent high-quality estimates of escapement, the stock is able to support higher exploitation rates. We recommend a sustainable escapement goal (SEG) threshold of 5,000 fish based on the point estimate (posterior median) of S_{MSY} from the full probability model (5,006). Cautious incremental increase of the harvest through liberalization of sport fishing regulations is justified, and this escapement goal will allow that. Continued collection and analysis of stock assessment data is strongly recommended.

From a statistical and theoretical perspective, we have enough information about S_{MSY} to specify a biological escapement goal (BEG). Of the stocks listed in Table 5, the Anchor River Chinook stock has the second lowest amount of uncertainty about S_{MSY}, and all except Buskin sockeye currently have BEGs.

On the other hand, our certainty about the (low) exploitation level of this stock is very recent, being based almost entirely on only five weir/sonar estimates of escapement. As recently as 2002, the stock was thought to be at risk of over-exploitation. Both of the statistical methodologies employed assume to some degree that the most recent five years are representative of previous years. We believe that this is a reasonable assumption, yet it cannot be proven. Moreover, we cannot directly evaluate the performance of our estimate of S_{MSY} because we have no actual production data from escapements at or near our estimate of S_{MSY}. Therefore we recommend that changes to the fishery be implemented gradually, allowing time for their impact to be evaluated and for more production data to be collected, especially at escapements closer to the recommended SEG threshold than previously observed.

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