

Fishery Manuscript No. 11-05

Escapement Goals for Chinook Salmon in the Blossom and Keta Rivers

by

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September 2011

Alaska Department of Fish and Game

Divisions of Sport Fish and Commercial Fisheries



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Weights and measures (metric)		General		Mathematics, statistics	
centimeter	cm	Alaska Administrative Code	AAC	<i>all standard mathematical signs, symbols and abbreviations</i>	
deciliter	dL	all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.	alternate hypothesis	H_A
gram	g	all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.	base of natural logarithm	e
hectare	ha	at	@	catch per unit effort	CPUE
kilogram	kg	compass directions:		coefficient of variation	CV
kilometer	km	east	E	common test statistics	(F, t, χ^2 , etc.)
liter	L	north	N	confidence interval	CI
meter	m	south	S	correlation coefficient	
milliliter	mL	west	W	(multiple)	R
millimeter	mm	copyright	©	correlation coefficient	
		corporate suffixes:		(simple)	r
Weights and measures (English)		Company	Co.	covariance	cov
cubic feet per second	ft ³ /s	Corporation	Corp.	degree (angular)	°
foot	ft	Incorporated	Inc.	degrees of freedom	df
gallon	gal	Limited	Ltd.	expected value	E
inch	in	District of Columbia	D.C.	greater than	>
mile	mi	et alii (and others)	et al.	greater than or equal to	≥
nautical mile	nmi	et cetera (and so forth)	etc.	harvest per unit effort	HPUE
ounce	oz	exempli gratia		less than	<
pound	lb	(for example)	e.g.	less than or equal to	≤
quart	qt	Federal Information Code	FIC	logarithm (natural)	ln
yard	yd	id est (that is)	i.e.	logarithm (base 10)	log
		latitude or longitude	lat. or long.	logarithm (specify base)	log ₂ , etc.
Time and temperature		monetary symbols		minute (angular)	'
day	d	(U.S.)	\$, ¢	not significant	NS
degrees Celsius	°C	months (tables and figures): first three letters	Jan,...,Dec	null hypothesis	H_0
degrees Fahrenheit	°F	registered trademark	®	percent	%
degrees kelvin	K	trademark	™	probability	P
hour	h	United States (adjective)	U.S.	probability of a type I error	
minute	min	United States of America (noun)	USA	(rejection of the null hypothesis when true)	α
second	s	U.S.C.	United States Code	probability of a type II error	
		U.S. state	use two-letter abbreviations (e.g., AK, WA)	(acceptance of the null hypothesis when false)	β
Physics and chemistry				second (angular)	"
all atomic symbols				standard deviation	SD
alternating current	AC			standard error	SE
ampere	A			variance	
calorie	cal			population	Var
direct current	DC			sample	var
hertz	Hz				
horsepower	hp				
hydrogen ion activity	pH				
(negative log of)					
parts per million	ppm				
parts per thousand	ppt, ‰				
volts	V				
watts	W				

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IN THE BLOSSOM AND KETA RIVERS**

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September 2011

Development and publication of this manuscript were partially financed by the Federal Aid in Sport Fish Restoration Act (16 U.S.C.777-777K), Pacific Coast Salmon Recovery Fund, and congressional funding under the U.S. Chinook Letter of Agreement.

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This document should be cited as:

Fleischman, S. J., J. A. Der Hovanisian, and S. A. McPherson. 2011. Escapement goals for Chinook salmon in the Blossom and Keta rivers. Alaska Department of Fish and Game, Fishery Manuscript No. 11-05, Anchorage.

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ABSTRACT

Production of adult Chinook salmon from the Blossom and Keta rivers was investigated using stock assessment information collected in 1975–2007. Estimates of inriver returns, relative age composition, and escapements are presented. Exploitation rates from the nearby Unuk River Chinook salmon stock were fit to a hierarchical model and used as proxies to estimate total returns. An age-structured Ricker spawner-recruit model was fitted to the data from both stocks, which allowed estimation of key population reference points and an informed choice of escapement goals. Bayesian statistical methods were employed to provide realistic assessment of uncertainty in the presence of measurement error, serial correlation, and missing data.

Biological escapement goals of 150–300 and 175–400 large (≥ 660 mm mideye to fork of tail) fish, as counted in helicopter surveys, are recommended for Chinook salmon spawning in the Blossom and Keta rivers, respectively. These goals minimize the danger of recruitment overfishing. Continuation of the annual escapement sampling and standardized peak survey count programs are recommended for both rivers.

Key words: Chinook salmon, *Oncorhynchus tshawytscha*, Keta River, Blossom River, spawning abundance, helicopter survey, expansion factor, age composition, spawner-recruit analysis, sustained yield, escapement goal, measurement error, serial correlation, missing data, Bayesian statistics, age-structured model, hierarchical model, WinBUGS.

INTRODUCTION

The Blossom and Keta rivers (Figure 1) are clearwater streams in the Misty Fjords National Monument approximately 60 km east of Ketchikan. Chinook salmon from the Blossom and Keta rivers, along with fish from the Unuk and Chickamin rivers and some other unmonitored populations, are collectively known as the Behm Canal stocks, named for the long narrow body of water that they flow into. Behm Canal and other Southeast Alaska Chinook salmon stocks, 34 in all, are harvested primarily by the commercial troll fleet and recreational anglers. An annual all-gear harvest target is set by the Pacific Salmon Commission (PSC) prior to each fishing season, harvests that include stocks in Southeast Alaska and those that originate in British Columbia and the Pacific Northwest. The annual target is based on a preseason forecast of the relative aggregate abundance of the majority of Chinook salmon stocks that are present and of legal size in Southeast Alaska for the coming year (USCTC 2005).

The status of Southeast Alaska Chinook salmon stocks is judged primarily by performance in meeting escapement requirements. For the Blossom and Keta rivers, these requirements presently consist of biological escapement goal (BEG) ranges based on helicopter surveys conducted on the spawning grounds. The current BEG for both rivers is a survey count of 250 to 500 large (≥ 660 mm mid eye to fork of tail [MEF]) Chinook salmon. These goals were developed by McPherson and Carlile (1997), based on data collected through calendar year 1995.

Beginning in 1998, several mark–recapture experiments were conducted to estimate total Chinook salmon spawning abundance in the Blossom and Keta rivers and to develop expansion factors to estimate total spawning abundance from survey counts. Age composition sampling was initiated in the same year. In this report, all stock assessment data are compiled through calendar year 2007, and results from comprehensive age-structured spawner-recruit analyses of these data are presented and discussed.

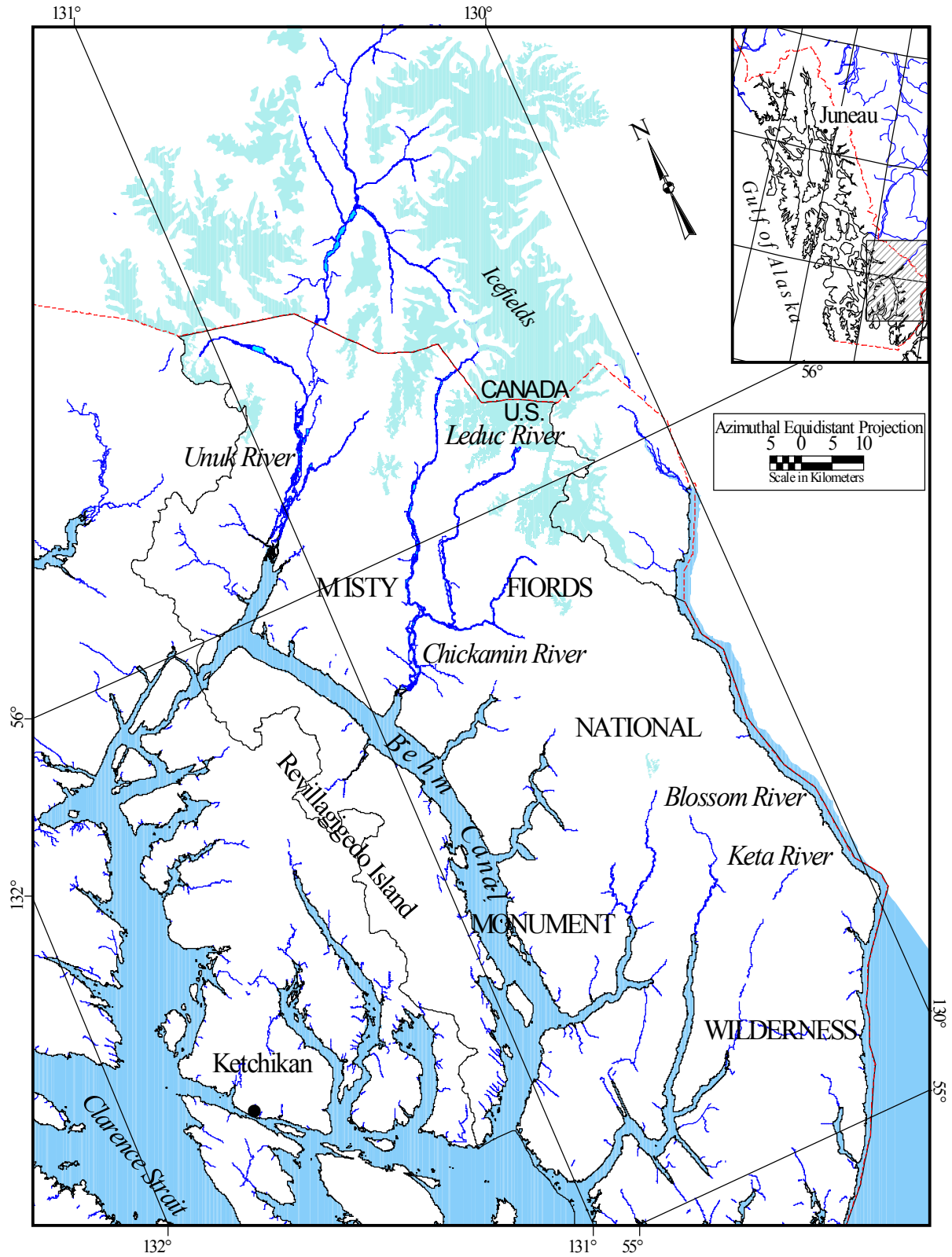


Figure 1.—Behm Canal and Misty Fjords National Monument in Southeast Alaska and location of major Chinook salmon-producing river systems.

For both analyses Markov Chain Monte Carlo (MCMC) methods, which are especially well-suited for modeling complex population and sampling processes, were employed. MCMC algorithms were implemented in WinBUGS (Lunn et al. 2000), which is a Bayesian software program. This methodology allows for inclusion of the effects of measurement error, serially correlated process errors, and missing data in the analysis; it also provides a more realistic assessment of uncertainty than is possible with classical statistical methods. For similar analyses see Ericksen and Fleischman (2006), Szarzi et al. (2007), McKinley and Fleischman (2010), Fleischman and Borba (2009), and McPherson et al. (2010).

Direct estimates of stock-specific harvest are not available for Blossom and Keta Rivers Chinook salmon. However, coded wire tag (CWT) studies have been conducted to derive estimates of Chinook salmon exploitation rates for the nearby wild stocks in the Unuk River, and also in the Chickamin River. This information is leveraged in the current analysis by modeling Blossom and Keta rivers exploitation rate as a multiple of the Unuk River rate for the corresponding brood year, thereby providing indirect proxy estimates of stock-specific harvest. The factor of multiplication was assigned a prior distribution and the results were tested for sensitivity to choice of the prior. This configuration allowed for indirect quantification of Blossom and Keta rivers Chinook salmon harvests, with appropriate assessment of the uncertainty involved.

Revised BEGs, based on these analyses, are proposed for Blossom and Keta rivers Chinook salmon stocks.

BLOSSOM RIVER

Chinook salmon spawn in the main channel of the Blossom River. Mature adults enter the river in late June to early August and complete spawning by early September, making this among the latest spawning stocks in Southeast Alaska. The drainage encompasses 176 km², but a velocity block leaves an estimated 101 km² draining the lower river accessible to anadromous species. The stock produces primarily yearling smolt (age-1.), but sub-yearling (age-0.) progeny comprised up to 15% of adult returns, which is unusual in Southeast Alaska (Pahlke 2001). The only other stocks that produce sub-yearling smolt to any degree are the Keta River and those in the Yakutat Forelands area, such as the Situk River (McPherson et al. 2003). Based on coded-wire-tagging of wild and hatchery stocks of Unuk and Chickamin Chinook salmon and its relative proximity, this stock is believed to be inside rearing, spending most of its marine residency in Southeast Alaska waters and, to a lesser extent, northern British Columbia.

The stock assessment program for Blossom River Chinook salmon consisted solely of standardized helicopter surveys from 1975 to 1998 (Pahlke 2001). In 1998, the Alaska Department of Fish and Game (ADF&G) received special funding from the U.S. Congress to improve abundance-based management for Chinook salmon in the Pacific Salmon Treaty area. ADF&G directed a portion of the money received to improve stock assessment by addressing the lack of information for Southeast Alaska Chinook stocks. Those funds, along with monies secured through the Pacific Coastal Salmon Recovery Fund program and base agency funding, were used to collect annual age, sex, and size information, and estimate total spawning abundance with mark-recapture techniques annually for 4 years.

The age data indicate that returns of large Chinook salmon in this stock are mostly comprised of 2-, 3- and 4-saltwater-age fish (Pahlke 2001). The 2-saltwater fish (primarily 4-year old, age-1.2 fish) are larger than Chinook salmon in most other systems (but similar to the Chickamin and

Keta rivers), and most (approximately 80%) 2-saltwater-age spawners in the Blossom River tend to be large fish.

Mark-recapture experiments were conducted in 1998 (Brownlee et al. 1999) and 2004–2006 (Pahlke and Magnus 2005; 2006; Weller et al. 2007), which provided the first estimates of total escapement of large fish and the relationship between Blossom River Chinook salmon abundance and helicopter survey counts.

Helicopter survey counts were the lowest in the period from 1975 to 1980, rose for 3 years to unprecedented levels, and have been relatively stable since 1989. The high counts from 1985 to 1987 are likely the result of an exceptionally high survival from one particular brood, a phenomenon that has occurred at least once in the last 30 years for most Southeast Alaska Chinook salmon stocks. The 2003 to 2007 average survey count was 291 large Chinook salmon, which is about 3 times the average escapement count from 1975 to 1980 (102 large Chinook salmon).

In 1997 a BEG range was established for the Blossom River stock based on limited data through the 1989 brood year (calendar year data through 1995). That escapement goal range was a survey count of 250 to 500 large spawners (McPherson and Carlile 1997).

KETA RIVER

The Keta River produces a small run of Chinook salmon representing about 1% of the wild stock production in Southeast Alaska. The Keta River watershed drains an area of 193 km², all of which is considered accessible to anadromous species. Like Chinook salmon found in the Blossom River and other systems in the region, they are spring-run fish. This stock primarily produces age-1. smolt, but about 10% are age-0. fish. Information inferred from coded wire tagging studies in the nearby Chickamin and Unuk rivers suggests that Keta River Chinook salmon are inside rearing in behavior, spending most of their marine residency in Southeast Alaska and perhaps northern British Columbia.

The stock assessment program for Keta River Chinook salmon mirrors the Blossom River program: standardized helicopter surveys have been conducted since 1975, mark-recapture experiments were conducted in 1998–2000 (Brownlee et al. 1999; Freeman et al. 2000, 2001), and annual age, sex, and size information has been collected since 1998.

The age data indicate that returns of large Chinook salmon in this stock are mostly comprised of 2-, 3- and 4-saltwater-age fish (Pahlke 2001). Keta River Chinook salmon are very large, attaining lengths and weights rarely seen elsewhere in the region (except nearby stocks like Blossom and Chickamin), and like Blossom River Chinook salmon, most 2-saltwater-age spawners are large fish.

Peak helicopter survey counts of Chinook salmon in the Keta River have increased from the average seen during 1975–1980, and in recent years have been within or exceeded the current BEG range (survey count of 250 to 500 large spawners; McPherson and Carlile 1997). Temporal trends in Chinook salmon abundance are reasonably consistent among the Behm Canal index systems. In general, counts were at or above escapement goal ranges for most of the 1980s, but a significant downward trend began near the end of the decade. Although this decline is apparent for the Keta River, counts have been near or above the lower end of the range since 1990. In recent years, escapements have been about double the values seen during the 1970s.

METHODS

SPAWNING ABUNDANCE

Aerial Surveys

Helicopter surveys have been flown for both stocks since 1975. Aerial surveys are conducted from a Bell 206 or Hughes 500D helicopter. Pilots are directed to fly the helicopter from 6 to 15 m above the river bed at a speed of 6–16 km/h. The helicopter door on the side of the observer is removed, and the helicopter is flown sideways while observations of spawning Chinook salmon are made.

Aerial counts are made during peak spawning times, defined as the period when the largest number of adult Chinook salmon actively spawn, which are well documented (Kissner 1982; Pahlke 1997). The proportions of fish in prespawning, spawning, and postspawning condition are used to judge whether the survey timing is correct to encompass peak spawning. Index areas are surveyed at least twice unless turbid water or unsafe conditions preclude the second survey. Only large Chinook salmon are counted during aerial surveys. No attempt is made to accurately count Chinook salmon <660 mm MEF (typically age-.1 and -.2; Mecum 1990). These Chinook salmon, also called jacks, are early maturing, precocious males considered to be surplus to spawning escapement needs. They are distinct from their older age counterparts under most conditions because of their short, compact bodies and lighter color. They are, however, difficult to distinguish from other smaller species such as pink *O. gorbuscha* and sockeye *O. nerka* salmon. Survey conditions during each index survey are rated as poor, normal, or excellent for a particular index area, and coded as to whether that survey is potentially useful for indexing or estimating escapement. Factors that affect the rating include water level, water clarity, light conditions, and weather.

Weather, distances involved, run timing, etc., can make it difficult for a single surveyor to complete all the index surveys annually under normal or excellent conditions. Thus, alternate surveyors were designated to conduct the counts when the primary surveyor was unavailable. Because between-observer variability and bias can be significant (Jones III et al. 1998), alternate surveyors were trained and calibrated against the primary surveyor to provide consistency and continuity in the data. Additional information regarding aerial surveys can be found in Appendix A.

Mark–recapture Estimates

Abundance of large spawners in the Blossom River was estimated with mark–recapture experiments in 1998 (Brownlee et al. 1999) and 2004–2006 (Pahlke and Magnus 2005, 2006; Weller et al. 2007). Adults were captured by angling on or below the spawning grounds, marked (the first event) and later recaptured (the second event). Marked Chinook salmon subsequently captured in commercial or recreational fisheries (almost none) were censored from the marked population, making the estimate germane to all Chinook salmon spawning in the Blossom River. Estimated abundance of large fish ranged from 364 (SE = 77) in 1998 to 1,270 (SE = 172) in 2006 (Table 1).

Table 1.–Peak survey counts, direct estimates from mark–recapture studies, and Bayesian posterior percentiles for large (≥ 660 mm MEF) Chinook salmon spawning in the Blossom River from 1975 through 2007.

Year	Survey counts	Direct estimate	Bayesian posterior distribution			CV
			Posterior median	0.025 percentile	0.975 percentile	
1975	146		315	153	635	38%
1976	68		247	123	474	35%
1977	112		324	171	601	33%
1978	143		346	183	646	33%
1979	54		255	131	484	34%
1980	89		356	194	686	34%
1981	159		570	324	1,020	30%
1982	345		955	535	1,635	29%
1983	589		1,369	725	2,420	31%
1984	508		1,530	824	2,663	30%
1985	709		1,973	1,078	3,397	29%
1986	1,278		2,589	1,349	4,505	30%
1987	1,349		2,470	1,283	4,317	31%
1988	384		1,504	819	2,649	30%
1989	344		1,098	594	1,962	31%
1990	257		807	432	1,434	31%
1991	239		603	322	1,100	32%
1992	150		537	294	975	32%
1993	303		669	364	1,213	31%
1994	161		628	359	1,121	30%
1995	217		642	375	1,105	28%
1996	220		590	352	999	27%
1997	132		476	297	759	24%
1998	91	364	380	271	534	18%
1999	212		479	302	781	25%
2000	231		626	388	1,012	25%
2001	204		694	428	1,132	25%
2002	224		695	435	1,105	24%
2003	203		656	433	971	21%
2004	333	734	744	625	887	9%
2005	445	926	951	792	1,138	9%
2006	339	1,270	1,119	891	1,411	12%
2007	135		826	444	1,402	29%

Abundance of large spawners in the Keta River was estimated with mark–recapture experiments conducted in 1998–2000 (Weller and Evans 2009). Adults were captured by angling on or below the spawning grounds, marked (the first event), and later recaptured (the second event). Marked Chinook salmon subsequently captured in commercial or recreational fisheries (almost none) were censored from the marked population, making the estimate germane to all Chinook salmon spawning in the Keta River. Estimated abundance of large fish ranged from 446 (SE = 50) in 1998 to 968 (SE = 116) in 1999 (Table 2).

Table 2.—Peak survey counts, direct estimates, and Bayesian posterior percentiles for large (≥ 660 mm MEF) Chinook salmon spawning in the Keta River from 1975 through 2007.

Year	Survey counts	Direct estimate	Bayesian posterior distribution			CV
			Posterior median	0.025 percentile	0.975 percentile	
1975	203		521	282	865	28%
1976	84		271	156	488	30%
1977	230		655	374	1,056	26%
1978	392		1,091	568	1,764	27%
1979	426		1,049	586	1,650	26%
1980	192		620	375	1,042	26%
1981	329		977	586	1,568	25%
1982	754		1,794	922	2,846	27%
1983	822		2,034	988	3,203	27%
1984	610		1,644	862	2,575	26%
1985	624		1,629	890	2,523	25%
1986	690		1,888	989	2,968	26%
1987	768		2,020	1,055	3,176	26%
1988	575		1,739	927	2,794	26%
1989	1,155		2,476	1,208	3,908	27%
1990	606		1,628	869	2,552	26%
1991	272		841	499	1,374	26%
1992	217		704	429	1,142	25%
1993	362		902	521	1,440	26%
1994	306		799	480	1,240	24%
1995	175		587	365	960	25%
1996	297		799	499	1,217	22%
1997	246		700	447	1,062	22%
1998	180	446	493	403	598	10%
1999	276	968	848	689	1,054	11%
2000	300	914	898	725	1,112	11%
2001	343		1,050	653	1,576	22%
2002	411		1,092	678	1,643	22%
2003	322		940	585	1,435	23%
2004	376		1,011	615	1,515	23%
2005	497		1,350	765	2,082	24%
2006	747		1,780	956	2,770	25%
2007	311		1,055	618	1,762	27%

AGE COMPOSITION

Chinook salmon spawners in the Blossom and Keta rivers have been sampled annually for age, length and sex composition since 1998; see Weller and Evans (2009) for a general description of sampling protocol. In addition, limited sampling was conducted on the Keta River in 1982 and 1984. Age composition results from these sampling programs can be found in Appendices B and C.

EXPLOITATION RATE

Direct estimates of exploitation rates were not available for Blossom and Keta river Chinook salmon, but direct estimates from the wild stock spawning in the nearby Unuk River existed for brood years 1982–1986 and 1993–2001 (Table 3; Ricker 1975; Jan Weller and Christie Hendrich, ADF&G, personal communication). To obtain inference about the magnitude of

fishery exploitation for all brood years (1975–2003)¹, a hierarchical model was fit to the Unuk estimates, i.e., the exploitation rate for individual brood years were drawn from a common beta distribution (this was a component of the spawner-recruit analysis, or SRA, model; see below for details). Exploitation rates for Blossom and Keta rivers fish from a given brood year were modeled as multiples of the corresponding rates for Unuk River fish, where the unknown factor of multiplication was given a prior probability distribution to capture the associated uncertainty.

Table 3.—Direct coded wire tag (CWT) estimates of exploitation rates for Unuk River Chinook salmon, 1982–1986 and 1992–2001, and assumed exploitation rates for Blossom and Keta Chinook salmon 1975–2003, from a hierarchical analysis and subsequent expansion of the Unuk River rates. The rates for the Unuk River are adult equivalent (AEQ) rates by brood year, include estimates of incidental mortality, and match algorithms for estimating exploitation rates used for Pacific Salmon Commission area Chinook stocks.

Brood year	Unuk River exploitation rate		Blossom and Keta exploitation rates		
	CWT estimate	SE (CV)	Posterior median	0.025 percentile	0.975 percentile
1975			0.29	0.18	0.47
1976			0.29	0.18	0.45
1977			0.29	0.17	0.44
1978			0.28	0.17	0.44
1979			0.28	0.17	0.45
1980			0.29	0.17	0.44
1981			0.28	0.17	0.44
1982	0.21	0.03 (14%)	0.26	0.17	0.39
1983	0.26	0.05 (19%)	0.29	0.20	0.44
1984	0.22	0.07 (32%)	0.28	0.18	0.43
1985	0.37	0.12 (32%)	0.30	0.20	0.47
1986	0.32	0.04 (13%)	0.32	0.22	0.47
1987			0.29	0.17	0.45
1988			0.29	0.18	0.45
1989			0.29	0.18	0.45
1990			0.29	0.18	0.45
1991			0.29	0.17	0.45
1992	0.17	0.06 (35%)	0.27	0.16	0.41
1993	0.24	0.04 (17%)	0.29	0.19	0.43
1994	0.22	0.04 (18%)	0.28	0.18	0.41
1995	0.24	0.03 (13%)	0.28	0.19	0.41
1996	0.19	0.02 (11%)	0.25	0.17	0.37
1997	0.22	0.04 (18%)	0.28	0.18	0.41
1998	0.19	0.03 (16%)	0.26	0.17	0.38
1999	0.37	0.08 (22%)	0.32	0.21	0.49
2000	0.28	0.03 (11%)	0.31	0.21	0.44
2001	0.26	0.04 (15%)	0.29	0.20	0.43
2002			0.29	0.18	0.45
2003			0.29	0.17	0.45

¹ One of the advantages of fitting an age-structured model is that estimates are still produced for 2 incomplete brood years at the end of the time series).

The exploitation rates from the Unuk River were used as a basis for the Blossom and Keta river spawner-recruit analyses because it is a nearby wild stock with a relatively long time series of precise estimates. The rates for the Unuk River were not consistent with exploitation rates estimated for hatchery fish in the region. Trends in adult escapement and production for the Unuk, Blossom and Keta river stocks did not match well with the abundance indices from the PSC Chinook Model for the Southeast Alaska (Figure 2) and northern British Columbia aggregate abundance based management (AABM) fisheries. This is not surprising given that Behm Canal stocks make up about 3% of these indices, which are dominated by stocks from British Columbia, the Columbia River, and the Oregon coast that undergo different survival and production regimes in many years. They are also based on statistics for the troll fishery on the outer coast. On average, over 50% of the estimated harvest of Unuk River fish occurs in southern inside waters of Southeast Alaska, from troll, sport and net fisheries. A covariate (effort in troll and sport sectors, abundance indices, etc.) could not be found to vary exploitation rates beyond the average used in years without exploitation rates for the Unuk River.

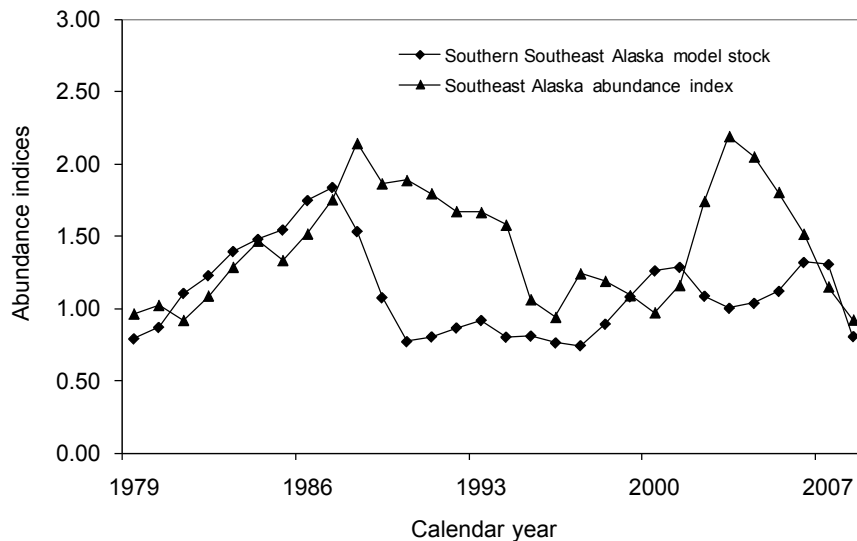


Figure 2.—Estimated abundance indices for the Southeast Alaska aggregate abundance based management fishery versus the southern Southeast Alaska aggregate abundance based management model stock for calendar years 1979–2008, from the Pacific Salmon Commission Chinook Model calibration 1107. The southern Southeast Alaska model stock consists of age-.2 to age-.5 escapement data from the Unuk, Chickamin, Blossom, Keta and King Salmon rivers and Andrew Creek, and exploitation data from selected Southeast Alaska hatcheries in southern and central Southeast Alaska.

The prior distribution for the factor of multiplication for Unuk River exploitation rates was assigned a median value of 1.2, i.e., it was assumed that Blossom and Keta river fish experienced exploitation rates approximately 20% higher than the Unuk rates. This assumption was made because Chinook salmon from the Blossom and Keta rivers are larger at age than Unuk River fish. For example, 75% of the age-1.2 fish from the Blossom and Keta rivers are of legal size (≥ 28 inches) compared to $<10\%$ of age-1.2 fish from the Unuk River. This exposes 15–20% more of these two stocks to landed-catch exploitation.

Several versions of the prior distribution for this factor were explored to test for sensitivity to this subjective choice. See equations 12–14 below for details.

SPAWNER-RECRUIT ANALYSIS

A Ricker spawner-recruit function (Hilborn and Walters 1992) was chosen to model the relationship between escapement and recruitment. Under the Ricker model, the total return R_y from brood year y is:

$$R_y = S_y \alpha e^{-\beta S_y} e^{\varepsilon_y} \quad (1)$$

where S_y is the number of spawners, α and β are parameters, and the $\{\varepsilon_y\}$ are normally distributed process errors with variance σ_{SR}^2 . 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:

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

where $\ln(\alpha)$ is corrected for asymmetric lognormal process error (Hilborn 1985) as follows:

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_{SR}^2}{2} \quad (3)$$

Number of spawners leading to maximum sustained yield S_{MSY} is approximately (Lunn et al. 2000):

$$S_{MSY} \approx S_{EQ} (0.5 - 0.07 \ln(\alpha')) \quad (4)$$

Finally, the exploitation rate U_{MSY} at S_{MSY} is approximated by:

$$\hat{U}_{MSY} \cong \ln \alpha' (0.5 - 0.07 \ln \alpha') \quad (5)$$

The classical way to estimate the Ricker parameters is to linearize the relationship by dividing both sides of equation 1 by S_y and taking the natural logarithm, yielding:

$$\ln \frac{R_y}{S_y} = \ln(\alpha) - \beta S_y + \varepsilon_y \quad (6)$$

This streamlines parameter estimation because the relationship can now be viewed as a simple linear regression (SLR) of $\ln(R_y/S_y)$ on S_y , in which the intercept is an estimate of $\ln(\alpha)$, the negative slope an estimate of β , and the mean squared error an estimate of the process error variance σ_{SR}^2 .

The SLR approach requires reasonably precise estimates of S and R , especially the independent variable (S). This was not the case for either stock because S and R pairs reconstructed from expanded aerial surveys, surrogate exploitation rate estimates, and averaged age composition estimates prior to 1998 were probably affected by substantial measurement error. Other shortcomings of the SLR approach are that it cannot account for serially correlated process error

or incomplete data. Preliminary analyses using the SLR approach showed that the ε_y (equation 6) were not independent, but were serially correlated for both stocks per an autoregressive process of lag-1 brood year (AR(1); Figure 3).

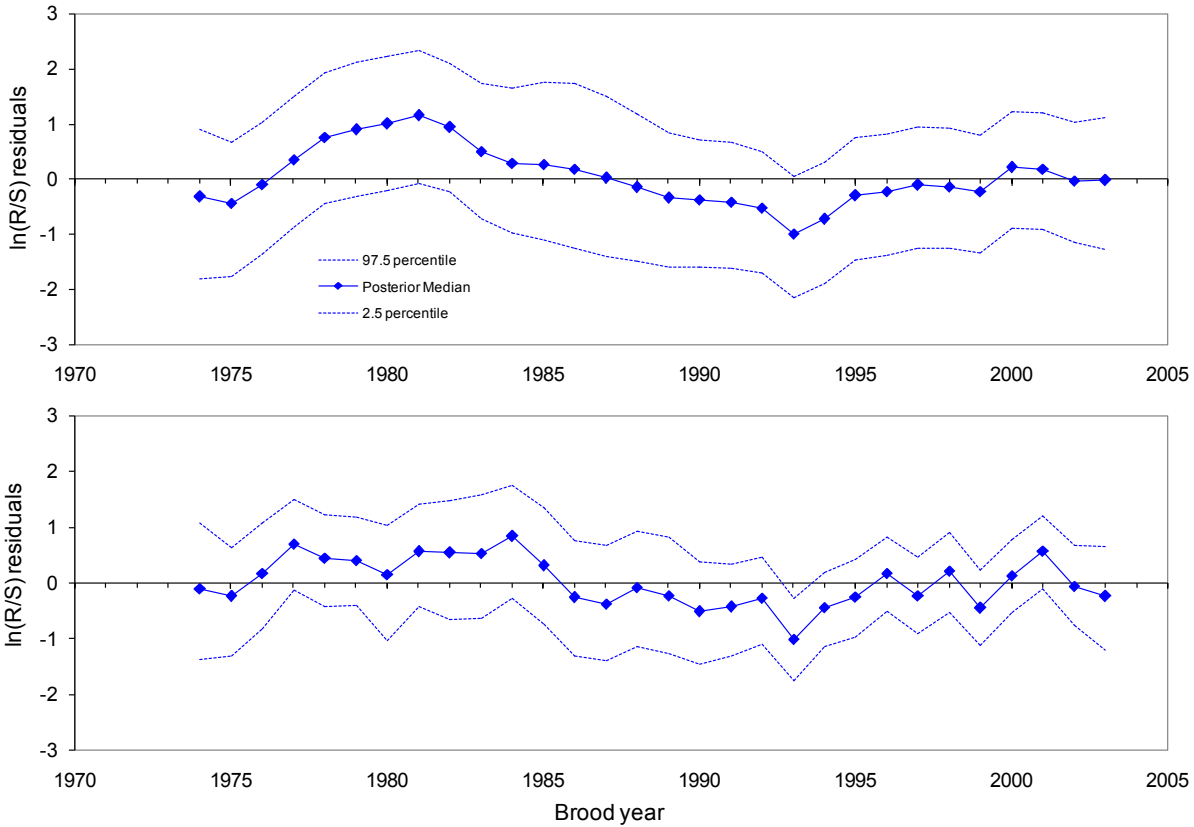


Figure 3.—Log residuals (departures of observed return per spawner from Ricker relationship), large (≥ 660 mm MEF) Blossom (top) and Keta (bottom) river Chinook salmon, brood years 1975–2003. These departures were modeled as an autoregressive process of lag-1 brood year (AR(1)) in the spawner-recruit analysis presented in this report.

For these reasons, MCMC methods were employed, which are especially well suited for modeling complex population and sampling processes. The MCMC algorithms in WinBUGS (Bernard and Jones III 2010), a Bayesian software program, were implemented. 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 statistical model.

Returns of salmon originating from spawners in brood years $y = 1975\text{--}2003$ are modeled with a Ricker stock-recruit function with autoregressive lognormal errors with a lag of 1 year (i.e., model residuals are subject to AR(1) serial correlation):

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi v_{y-1} + \varepsilon_{W_y} \quad (7)$$

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

$$v_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y, \quad (8)$$

and the $\{\varepsilon_y\}$ are independently and normally distributed process errors with “white noise” variance σ_w^2 .

Age proportion vectors² $\mathbf{p} = (p_4, p_5, p_6)$ from brood year y returning at ages 4–6 are drawn from a *Dirichlet*($\gamma_4, \gamma_5, \gamma_6$) distribution. The Dirichlet parameters are also expressed in an alternative location/scale form, where:

$$D = \sum_a \gamma_a \quad (9)$$

is the (inverse) scale of the \mathbf{p} age proportion vectors, reflecting dispersion of the age proportion vectors among brood years, and (location parameters):

$$\pi_a = \frac{\gamma_a}{D} \quad (10)$$

reflect the overall age proportions. The abundance (run size) N of age- a salmon in calendar year t is the product of the total return R from brood year $y = t-a$ and the age proportion p from brood year $t-a$ and age a :

$$N_{ta} = R_{t-a} p_{t-a,a} \quad (11)$$

Spawning abundance S of age- a salmon in calendar year t is the product of run size and the survival of fish from brood year $t-a$:

$$S_{ta} = N_{ta} (1 - \mu_{t-a}) \quad (12)$$

where μ_{t-a} is the exploitation rate of Blossom and Keta Chinook salmon for brood year $t-a$, modeled as a function of the fishing mortality for Unuk River Chinook salmon:

$$\mu_y = (1 - \exp(-F_{Unuk,y} \lambda)), \quad (13)$$

where:

$$F_{Unuk,y} = -\ln(1 - \mu_{Unuk,y}), \quad (14)$$

and λ is a multiplicative factor controlling the degree to which the actual fishing mortality for Blossom and Keta rivers salmon differs from that of Unuk River salmon.

Unuk River Chinook salmon exploitation rates $\mu_{Unuk,y}$ are modeled hierarchically, drawn from a common beta distribution with mean μ_{Unuk} and parameters $B_1 = \mu_{Unuk} B$, and $B_2 = (1 - \mu_{Unuk}) B$, where B is an inverse dispersion parameter similar to D above.

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

$$S_t = \sum_a S_{ta} \quad (15)$$

² These age proportions are maturity/survival schedules in a given brood year, across calendar years. In contrast, equation 21 describes age proportions in a given calendar year.

Spawning abundance yielding maximum return S_{MAX} is the inverse of the Ricker β parameter. Equilibrium spawning abundance S_{EQ} and spawning abundance leading to maximum sustained yield S_{MSY} are obtained using equations 2–4, except that $\ln(\alpha)$ is corrected for lognormal process error with AR(1) serial correlation³:

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_w^2}{2(1-\phi^2)}. \quad (16)$$

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

$$SY = E[R] - S = S e^{\ln(\alpha') - \beta S} - S. \quad (17)$$

The probability that a given level of spawning abundance would produce average yields exceeding $x\%$ of MSY was obtained by calculating the expected sustained yield (Equation 17) at multiple incremental values of S (0 to 2,000 by 20) for each Monte Carlo sample, then comparing SY with $x\%$ of the value of MSY for that sample. The proportion of samples in which SY exceeded $x\%$ of MSY is the desired probability. The probability P_{SY} that a given average helicopter survey count \bar{C} would produce average yields exceeding $x\%$ of MSY was obtained by then multiplying S by θ , the survey detectability factor (equation 19). The resulting plot of P_{SY} versus \bar{C} is termed a sustained yield probability profile.

The probability of overfishing (Bernard and Jones 2010), i.e., the probability that fishing down to a given level of spawning abundance would reduce average yields $x\%$ below MSY , was obtained by calculating the expected sustained yield (Equation 17) at multiple incremental values of S (0 to 2,000 by 20) for each Monte Carlo sample, then comparing SY with $x\%$ of the value of MSY , and S with S_{MSY} for that sample. The proportion of samples in which SY exceeded $x\%$ of MSY or S exceeded S_{MSY} is the desired probability. The probability of overfishing P_{OF} associated with fishing down to a given average survey count \bar{C} was obtained by then multiplying S by the survey detectability factor θ (equation 19). The resulting plot of P_{OF} versus \bar{C} has been termed an overfishing probability profile (Millar 2002).

Observed data included mark–recapture estimates of spawning abundance, helicopter survey counts, CWT estimates of Unuk Chinook salmon exploitation rates, and age counts determined from scale samples. Sampling distributions for the data are as follows.

Mark–recapture estimates of spawning abundance are modeled as:

$$\hat{S}_t = S_t e^{\varepsilon_{St}} \quad (18)$$

where the $\{\varepsilon_{St}\}$ are normal $(0, \sigma_{St}^2)$. Point estimates and CVs are in Tables 1 and 2.

Helicopter survey counts (1975–2007, Tables 1 and 2) are modeled as linearly related to true spawning abundance:

$$C_t = \theta_t S_t e^{\varepsilon_{tH}} \quad (19)$$

³ In this case the correction is based on the total “red noise” variance of the AR(1) process. For instance, see Chatfield (1989: page 36).

where θ is the fraction of spawning Chinook salmon observed in the aerial surveys, the $\{\varepsilon_{Hi}\}$ are normal $(0, \sigma_H^2)$, and the common error variance σ_H^2 is informed by the relationship between \hat{S} and C for years 1998 and 2004–2006 for the Blossom River, and 1998–2000 for the Keta River.

Estimates of Unuk Chinook salmon exploitation rates are modeled as:

$$\hat{\mu}_{Unuk,y} = \hat{\mu}_{Unuk,y} e^{\varepsilon_{Ut}} \quad (20)$$

where the $\{\varepsilon_{Ut}\}$ are normal $(0, \sigma_{Ut}^2)$. Point estimates and standard errors are in Table 3.

Numbers of fish sampled for scales (n) that were classified as age- a in calendar year t (x_{ta}) are modeled as having a multinomial(q_{ta}, n) distribution, with proportion parameters as follows⁴:

$$q_{ta} = \frac{N_{ta}}{N_t} \quad (21)$$

Bayesian analyses require that prior probability distributions be specified for all unknowns in the model. With one exception described below, non-informative priors (chosen to have a minimal effect on the posterior) were used. Initial returns $R_{1969}-R_{1974}$ (those with no linked spawner abundance) were modeled as drawn from a common lognormal distribution with median μ_{logR} and variance σ_{logR}^2 . Normal priors with mean zero, very large variances, and constrained to be positive, were used for $\ln(\alpha)$ and β (Liermann et al. 2010), as well as for μ_{logR} . The AR(1) coefficient ϕ and the helicopter survey detectability factor θ were given uniform(0,1) priors, as were the inverses of Dirichlet and beta distribution parameters D and B . The initial model residual v_0 was given a normal prior with mean zero and variance $\sigma_{SR}^2/(1-\phi^2)$.⁵ Diffuse conjugate inverse gamma priors were used for σ_W^2 , σ_H^2 , and σ_{logR}^2 .

An informative prior distribution was constructed for λ , the factor relating Blossom and Keta fishing mortality to Unuk fishing mortality. The factor was assigned a log-normal prior distribution with median 1.2 and CV = 20%. This prior was designed to include 95% of the probability mass for λ between 0.8 and 1.7, which is a reasonable range of plausible values for this parameter.⁶ The analysis was repeated for the following additional prior distributions to test for sensitivity: log-normal distribution with medians of 0.8 and 1.7, both with CV = 5%.

MCMC samples were drawn from the joint posterior probability distribution of all unknowns in the model. For each of 2 Markov chains initialized, a 4,000-sample burn-in period was discarded, and >10,000 additional updates were generated. The resulting samples were used to estimate the marginal posterior means, standard deviations, and percentiles. The diagnostic tools of WinBUGS were used to assess mixing and convergence, and no major problems were encountered. Interval estimates were obtained from the percentiles of the posterior distribution. WinBUGS code and data are provided in Appendix D.

⁴ Simulation experiments have shown that spawner-recruit analysis results are not very sensitive to typical variations in the precision of age composition estimates. Nevertheless, sample sizes for scale ages were artificially lowered to 50% of the actual number of scales sampled per year to reflect possible biases in age composition estimates and the fact that individual scale ages were not obtained strictly independently, as is assumed for a multinomial distribution.

⁵ This prior reflects the uncertainty surrounding a single unknown residual, given the presence of AR(1) serial correlation.

⁶ That is, exploitation rates for the Blossom and Keta stocks are not likely to be less than 80% or more than 170% of the Unuk River Chinook salmon exploitation rates.

WATERSHED SIZE HABITAT MODEL

For comparison with the SRA results, a watershed-size habitat model was fit based on a hierarchical analysis of Chinook salmon carrying capacity as a function of watershed size (Liermann et al. 2010). The following relationship, for stream-type Chinook salmon, was used to predict carrying capacity from watershed area alone:

$$\tilde{S}_{EQ} = \exp(a + b \ln(W / 1,503) + \varepsilon_{WS}) \quad (22)$$

where a and b are habitat model parameters, the $\{\varepsilon_{St}\}$ are normal $(0, \sigma_{WS}^2)$, and the watershed area W available to Chinook salmon was 101 km^2 in the Blossom River drainage (of 176 km^2 total area), and 193 km^2 in the Keta River drainage. Uncertainty in the estimates was assessed by assigning Student- t prior distributions to the parameters a , b , and σ_{WS} and generating MCMC samples from the emergent distribution of \tilde{S}_{EQ} (Liermann et al. 2010). The watershed model assumes a fixed productivity parameter equivalent to $\ln(\alpha)$, which has uncertainty described by a Student- t (mean = 1.45, sigma = 0.2, df = 5.6) distribution. A prediction \tilde{S}_{MSY} of optimal escapement, based on watershed area, can therefore also be generated using equation 4. See Appendix E for WinBUGS code used to generate the MCMC samples. Percentiles of the resulting distributions were used to obtain interval estimates of \tilde{S}_{EQ} and \tilde{S}_{MSY} .

Because SRA results are based on fish $\geq 660 \text{ mm}$ MEF and the watershed model is based on 2-saltwater-age (4-year old total age) and older fish, some of which are $< 660 \text{ mm}$ MEF, estimates of \tilde{S}_{EQ} and \tilde{S}_{MSY} from the watershed model were discounted by the average proportion of 4-year old and older fish $< 660 \text{ mm}$ MEF sampled in the Blossom (20%) and Keta (16%) rivers.

RESULTS

There is a moderately good relationship between Blossom River aerial survey counts and abundance as estimated by mark-recapture experiments (Figure 4). Helicopter surveys detected, on average, 26-44% (90% credibility interval, posterior median = 34%; Table 4) of large Chinook salmon spawning in the Blossom River. The inverse of θ (expansion factor for aerial survey counts) was estimated to be between 2.27 and 3.87 (90% interval, posterior median 2.98). The estimated standard deviation σ_{AS} of the lognormal process error associated with this relationship was 0.36 (posterior median, Table 4); this is the approximate CV of the prediction error associated with expanding survey counts to estimate actual spawning abundance. There are reasons to believe that, for the Blossom River, the estimate of θ is too high and the expansion factor too low. Fortunately, however, this has very little bearing on the escapement goal recommendations (see Appendix A).

The relationship between Keta River aerial survey counts and abundance as estimated by mark-recapture experiments is shown in Figure 4. Helicopter surveys detected, on average, 29-48% (90% credibility interval, posterior median = 36%; Table 4) of large Chinook salmon spawning in the Keta River. The inverse of θ (expansion factor for aerial survey counts) was estimated to be between 2.08 and 3.49 (90% interval, posterior median 2.78). The estimated standard deviation σ_{AS} of the lognormal process error associated with this relationship was 0.23 (posterior median, Table 4).

Table 4.–Parameter estimates for Bayesian age-structured Ricker spawner-recruit model, for large (≥ 660 mm MEF) Chinook salmon in the Blossom and Keta Rivers, calendar years 1975–2007. Posterior medians are point estimates, 5th and 95th percentiles define 90% credibility intervals for the parameters.

Parameter	Posterior median	0.05 percentile	0.95 percentile	Posterior mean	Posterior SD	Posterior CV
<i>Blossom River Chinook salmon</i>						
$\ln(\alpha)$	1.40	0.54	2.30	1.41	0.54	38%
α	4.05	1.71	9.98	4.13	2.22	54%
β	0.0011	0.0005	0.0019	0.0011	0.0004	38%
ϕ	0.81	0.52	0.96	0.79	0.14	18%
σ_W	0.40	0.26	0.62	0.42	0.11	26%
S_{EQ}	1,528	867	3,559	1,757	754	43%
S_{MSY}	571	333	1,133	614	229	37%
S_{MSY} in survey						
counts	191	122	358	209	68	33%
U_{MSY}	0.64	0.40	0.86	0.59	0.14	23%
D	55	20	210	76	60	79%
π_1	0.23	0.19	0.29	0.23	0.03	13%
π_2	0.52	0.46	0.58	0.52	0.04	8%
π_3	0.24	0.19	0.30	0.24	0.03	12%
θ	0.34	0.26	0.44	0.34	0.06	18%
θ^{-1}	2.98	2.27	3.87	3.02	0.54	16%
σ_{AS}	0.36	0.25	0.51	0.37	0.08	22%
<i>Keta River Chinook salmon</i>						
$\ln(\alpha)$	1.40	0.70	2.15	1.41	0.45	31%
α	4.05	2.01	8.58	4.15	1.83	44%
β	0.0009	0.0004	0.0016	0.0009	0.0004	41%
ϕ	0.49	-0.11	0.86	0.45	0.30	67%
σ_W	0.51	0.33	0.74	0.52	0.13	25%
S_{EQ}	1,812	1,161	3,344	1,970	634	32%
S_{MSY}	694	435	1,288	749	247	33%
S_{MSY} in survey						
counts	249	179	436	279	76	27%
U_{MSY}	0.62	0.40	0.80	0.60	0.12	20%
D	28	14	74	33	20	61%
π_1	0.23	0.18	0.28	0.23	0.03	13%
π_2	0.53	0.47	0.59	0.53	0.03	6%
π_3	0.24	0.19	0.29	0.24	0.03	13%
θ	0.36	0.29	0.48	0.37	0.06	16%
θ^{-1}	2.78	2.08	3.49	2.79	0.43	15%
σ_{AS}	0.23	0.15	0.36	0.24	0.07	29%

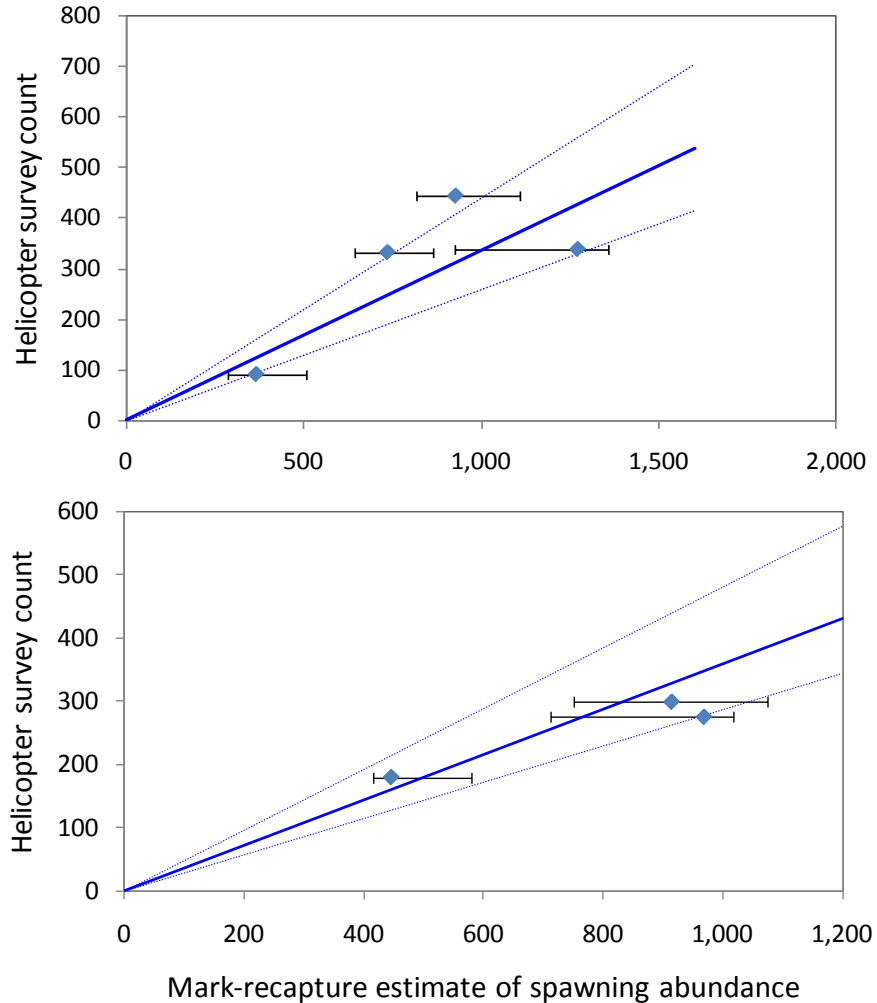


Figure 4.—Helicopter aerial survey counts versus mark–recapture estimates of spawning abundance (symbols), large (≥ 660 mm MEF) Blossom (top) and Keta (bottom) river Chinook salmon. Slope of solid line represents the posterior median (point estimate) of θ , the proportion of spawning Chinook salmon detected by aerial survey counts. Slope of dashed lines represent lower and upper 90% credibility intervals for θ . Error bars show 90% credibility intervals for annual spawning abundances, from the Bayesian age-structured spawner-recruit model.

Estimates of annual Blossom and Keta rivers spawning abundance are summarized in Tables 1 and 2, and Figure 5. Bayesian posterior percentiles summarize knowledge of spawning abundance in the context of the full age-structured spawner-recruit model. Except for years when mark–recapture experiments were conducted, knowledge of spawning abundance is uncertain, especially for the Blossom River stock. The CV for years without direct estimates ranged from 21% to 38% (median = 30%) for Blossom River Chinook salmon (Table 1) and from 22% to 30% (median = 26%) for Keta River Chinook salmon (Table 2). Exploitation rate μ was modeled as an uncertain function of fishing mortality experienced by nearby Unuk River Chinook salmon (Figure 6). A hierarchical model was first fit to the estimated Unuk River rates, which had the effect of reducing the interannual variability displayed by the raw estimates.⁷ Blossom and Keta

⁷ Some of the interannual variability was due to sampling error associated with individual estimates.

rivers Chinook salmon were assumed to experience exploitation rates 20% higher (median $\lambda = 1.2$) than Unuk River Chinook salmon (Table 3, Figure 6).⁸ Considerable uncertainty was allowed in this multiplier (95% prior probability $0.8 < \lambda < 1.7$), which contributed to the wide intervals for Blossom and Keta exploitation rate by brood year (Figure 6).

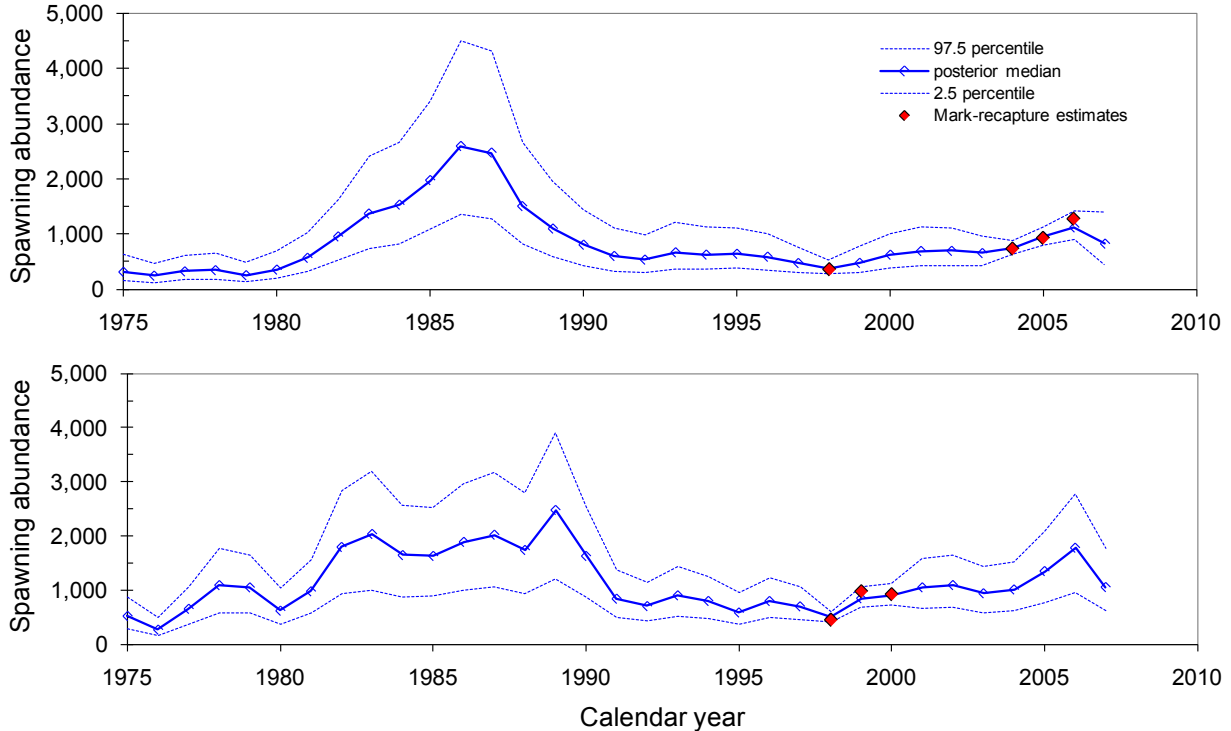


Figure 5.—Estimates, including Bayesian posterior medians, 95% credibility intervals, and direct mark-recapture estimates of the number of large (≥ 660 mm MEF) Chinook salmon spawning in the Blossom (top) and Keta (bottom) rivers, 1975–2007. Plotted values are from Tables 1 and 2.

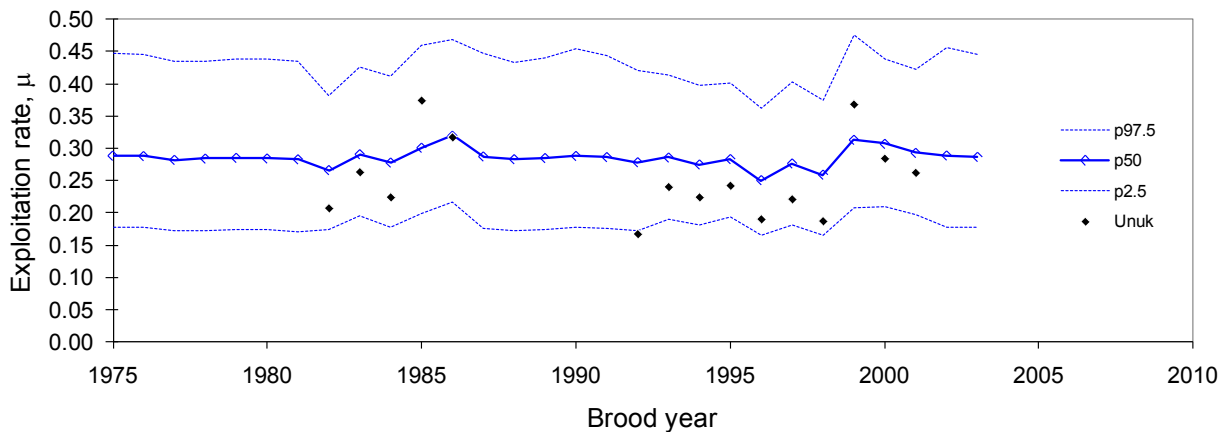


Figure 6.—Bayesian posterior percentiles of exploitation rates on large (≥ 660 mm MEF) Blossom and Keta rivers Chinook salmon, brood years 1975–2003, based on Unuk River Chinook salmon exploitation rate estimates (solid symbols). Blossom and Keta rates are an uncertain multiple (mean = 1.2, SD = 0.26) of Unuk River rates. Plotted values are from Table 3.

⁸ Chickamin Chinook salmon experienced slightly higher exploitation rates than the Unuk River.

Estimates of production by brood year (recruitment or return R), are summarized in Tables 5 and 6, and Figure 7. Not surprisingly, knowledge of production is very uncertain, given imperfect knowledge of both escapement and harvest components. Measurement error in age composition also contributed to uncertainty in R . Coefficients of variation ranged from 13% to 47% for Blossom River Chinook salmon, and from 14% to 47% for Keta River Chinook salmon (Tables 5 and 6). One of the advantages of fitting an age-structured model is that estimates are still produced for incomplete brood years at the end of the R time series (2002 and 2003), and the additional uncertainty is reflected in wider intervals (Figure 7).

Table 5.—Bayesian posterior medians, and 95% credibility intervals, for the number of large (≥ 660 mm MEF) Chinook salmon returning to the Blossom River from brood years 1975 through 2003, in adult equivalents.

Year	Bayesian posterior distribution			CV
	Posterior median	0.025 percentile	0.975 percentile	
1975	568	232	1,249	43%
1976	674	296	1,468	42%
1977	1,294	609	2,645	38%
1978	2,035	898	4,227	39%
1979	1,950	811	4,090	41%
1980	2,707	1,228	5,434	38%
1981	3,888	1,760	8,037	39%
1982	3,431	1,563	6,952	39%
1983	1,981	847	4,021	39%
1984	1,498	656	3,060	39%
1985	1,175	488	2,475	41%
1986	753	231	1,736	47%
1987	689	221	1,563	47%
1988	984	452	2,051	40%
1989	908	429	1,835	38%
1990	897	442	1,762	36%
1991	819	408	1,619	36%
1992	698	409	1,177	28%
1993	461	273	775	27%
1994	589	346	1,011	28%
1995	926	517	1,633	30%
1996	968	571	1,675	28%
1997	1,007	607	1,726	27%
1998	876	591	1,315	21%
1999	894	667	1,277	17%
2000	1,548	1,231	2,036	13%
2001	1,542	1,147	2,120	16%
2002	1,251	723	2,161	28%
2003	1,239	530	2,750	43%

Table 6.–Bayesian posterior medians, and 95% credibility intervals, for the number of large (≥ 660 mm MEF) Chinook salmon returning to the Keta River from brood years 1975 through 2003, in adult equivalents.

Year	Bayesian posterior distribution			CV
	Posterior median	0.025 percentile	0.975 percentile	
1975	1,039	389	2,121	41%
1976	1,034	430	2,119	39%
1977	3,001	1,420	5,458	33%
1978	2,645	1,029	4,932	37%
1979	2,530	1,154	4,587	34%
1980	1,704	525	3,462	42%
1981	2,942	1,064	5,829	39%
1982	2,624	805	4,960	40%
1983	2,455	680	5,154	45%
1984	3,688	1,224	7,212	39%
1985	2,117	748	4,351	41%
1986	1,088	394	2,204	41%
1987	950	369	1,877	39%
1988	1,392	593	2,761	38%
1989	920	287	1,913	43%
1990	918	383	1,771	37%
1991	1,049	479	1,952	35%
1992	1,154	702	1,924	26%
1993	576	383	897	22%
1994	1,018	776	1,331	14%
1995	1,084	808	1,450	15%
1996	1,874	1,282	2,693	19%
1997	1,204	759	1,811	22%
1998	1,593	1,028	2,414	22%
1999	1,029	599	1,657	26%
2000	1,863	1,061	2,986	25%
2001	2,973	1,623	4,700	26%
2002	1,563	825	2,846	32%
2003	1,265	513	3,040	47%

Measurement error in S and R differs by brood year (Figure 8). Furthermore, the errors are correlated with one another. For instance, a single error in the 1997 survey count expansion contributes not only to measurement error in S for that year, but also to error in R for brood years 1991–1993.

Results of the spawner-recruit analyses were moderately sensitive to the choice of prior for the exploitation rate multiplier λ (Table 7). For example, for the Keta River stock, if the prior median of λ was set to 0.8, a point estimate (posterior median) of S_{MSY} in survey count units was 233, whereas if the median of λ was 1.7, the estimate of S_{MSY} was 263.⁹ Blossom results displayed similar sensitivity (Table 7). All other analyses in this report utilize a prior (lognormal with median 1.2 and CV = 0.2) designed to integrate over a range of values of λ from 0.8 to 1.7.

“Point estimates” of the Ricker relationships for the Blossom and Keta rivers stocks, constructed from the posterior medians of $\ln(\alpha)$ and β , are plotted in Figure 8, and parameter estimates are

⁹ Higher exploitation rates mean greater total returns R relative to the same escapement S , thus implying greater productivity $\ln(\alpha)$, larger carrying capacity S_{EQ} , and a higher value for optimal spawning abundance S_{MSY} .

detailed in Table 4. The point estimates of productivity are somewhat low: $\ln(\alpha) = 1.40$ for both stocks. Serial correlation in productivity was moderately high (Keta River, $\phi = 0.49$) to very high (Blossom River, $\phi = 0.81$). For both stocks, productivity was highest in the late 1970s and early 1980s (brood years), declining to a low in the 1993 brood year (Figure 7).

Table 7.—Sensitivity of results to choice of prior distribution for exploitation rate factor λ (see text for explanation). Values of 0.8 and 1.7 represent the extremes of a plausible range for λ .

	Prior ^a for λ		S_{MSY} posterior percentiles			Overfishing probability ^b		
	Median	CV	5 th	50 th	95 th	70%	80%	90%
Blossom	0.8	0.05	118	182	360	0.05	0.10	0.23
	1.7	0.05	133	206	380	0.06	0.14	0.33
	1.2 ^c	0.20	122	191	358	0.05	0.11	0.26
Keta	0.8	0.05	170	233	390	0.04	0.09	0.26
	1.7	0.05	185	263	481	0.08	0.18	0.45
	1.2 ^c	0.20	177	247	428	0.05	0.13	0.36

^a Lognormal prior distribution.

^b Probability of reducing yield to 70, 80, or 90% of *MSY* if escapement is held constant at the lower bound of the proposed BEG range (see Figure 10).

^c A lognormal distribution with median 1.2 and $CV = 0.20$ has 90% probability of $0.8 < \lambda < 1.7$. This is the prior that was chosen for all results in this report.

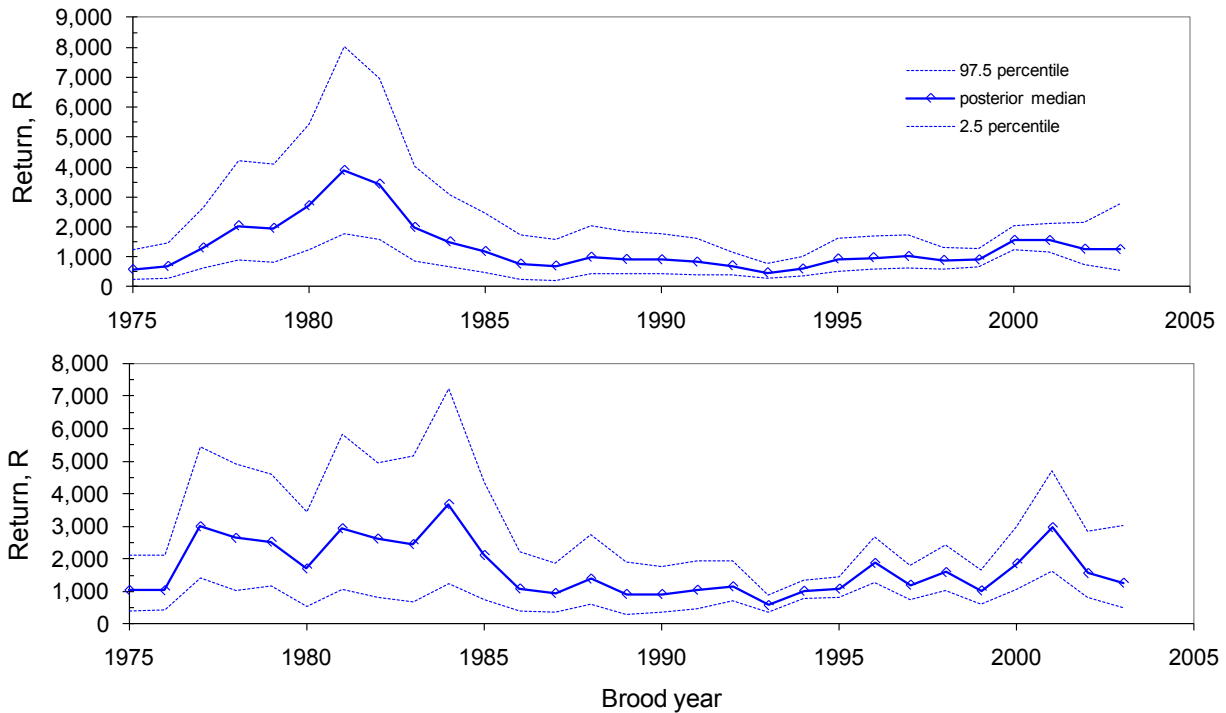


Figure 7.—Bayesian posterior medians, and 95% credibility intervals, for the number of large (≥ 660 mm MEF) Chinook salmon returning to the Blossom (top) and Keta (bottom) rivers, brood years 1975–2003.

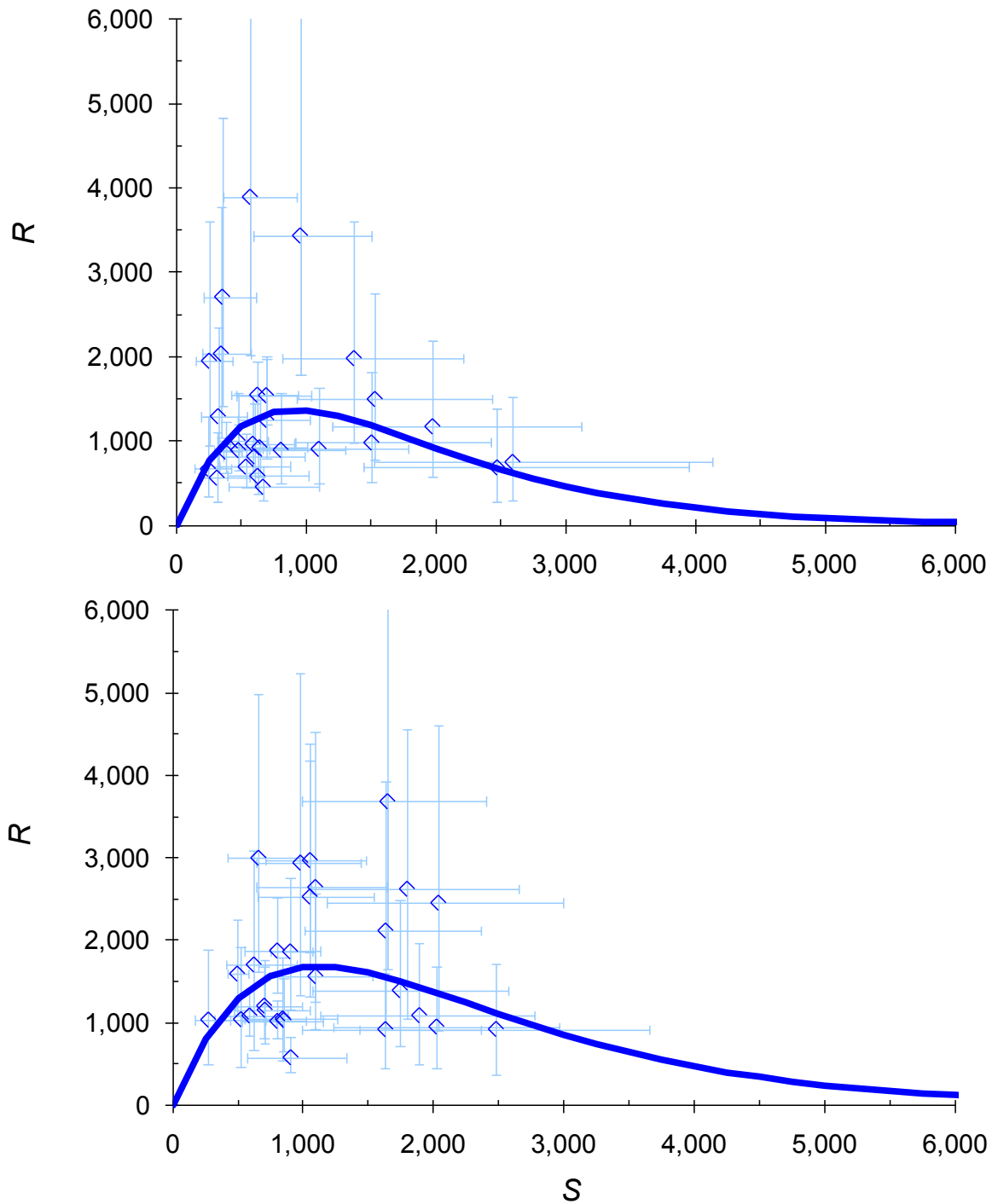


Figure 8.—Scatter plots of return (R) versus spawning abundance (S) estimates, Blossom (top) and Keta (bottom) river Chinook salmon, brood years 1975–2003. Posterior medians are plotted as open symbols, 10th and 90th posterior percentiles are bracketed by error bars. Point estimates of Ricker relationships (solid lines) are constructed from Bayesian posterior medians of α and β .

Average age-at-maturity was almost identical between the stocks (π parameters, Table 4). Age-at-maturity was more variable across brood years for the Keta stock (smaller inverse dispersion parameter D , Table 4).

The posterior median of S_{MSY} is 571 large Chinook salmon for the Blossom River, and for the Keta River it is 694 (Table 4). For management purposes, estimates of S_{MSY} expressed in terms of survey counts are required. For the Blossom River, the posterior median of survey detectability θ is 0.34¹⁰, and the posterior median of S_{MSY} in survey count currency is 191. For the Keta River, the posterior median of survey detectability θ is 0.36, and the posterior median of S_{MSY} in survey count currency is 249.

The point estimates described above must be considered in the context of a great deal of uncertainty about the Ricker relationship. Figure 9 graphically displays the degree of uncertainty about the true Ricker relationships for Blossom and Keta rivers Chinook salmon; each curve was generated from a separate MCMC sample of α and β . These represent a random collection of plausible Ricker relationships that *could have* generated the observed $\{S, R\}$ data, and for both stocks they are very diverse.

The “horsetail” plots in Figure 9 graphically illustrate the sources of uncertainty. Among the individual plausible Ricker curves for Blossom Chinook salmon in Figure 9, the slope at the origin is extremely variable among the individual curves, indicating great uncertainty about the parameter α . This is typical for stocks with very high serial correlation. Carrying capacity S_{EQ} , represented by where the curves intersect the replacement line, is also highly variable. The graphical evidence is confirmed by very wide 90% interval estimates for $\ln(\alpha)$ (0.54–2.30) and S_{EQ} (867–3,559; Table 4). Intervals for β ($5-19 \times 10^{-4}$) and S_{MSY} (333–1,133) were also wide. With 90% probability, the number of large fish counted in surveys that would produce MSY is between 122 and 358, and is equally likely to be above or below 191.

For Keta Chinook salmon, there is less uncertainty about α than for Blossom Chinook (Figure 9), probably because of reduced serial correlation. In general, most parameters and reference points for Keta River Chinook salmon were estimated with slightly less uncertainty than the Blossom stock (Table 4). With 90% probability, the number of large fish counted in surveys that would produce MSY is between 179 and 436, and is equally likely to be above or below 249.

Sustained yield probability profiles (hump-shaped curves in Figure 10) display the probability of achieving near optimal sustained yield (>70%, 80%, and 90% of MSY) for specified levels of spawning abundance (in survey count currency). Overfishing probability profiles (S-shaped curves in Figure 10) display the probability of overfishing the stock such that sustained yield is reduced to less than a specified fraction (70%, 80%, and 90%) of MSY . Expected sustained yield is a relatively flat function of aerial survey counts near the optimum of approximately 200 (Figure 11). These graphics provide useful tools to assess the performance of proposed escapement goals, with full consideration of the uncertainty about Ricker and other parameter values. See below for escapement goal recommendations.

¹⁰ There are reasons to believe that this estimate of θ may be too high. See Appendix A for details.

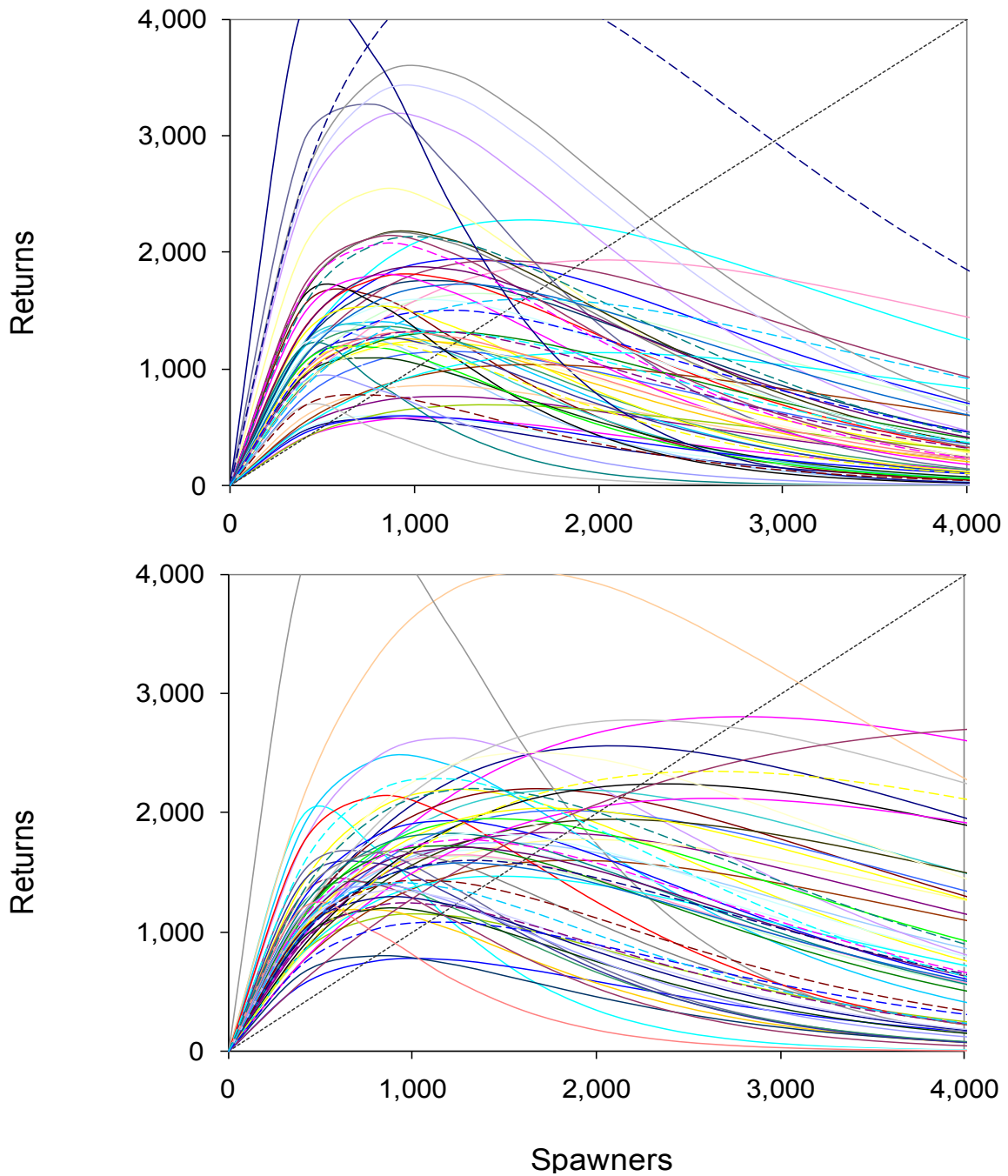
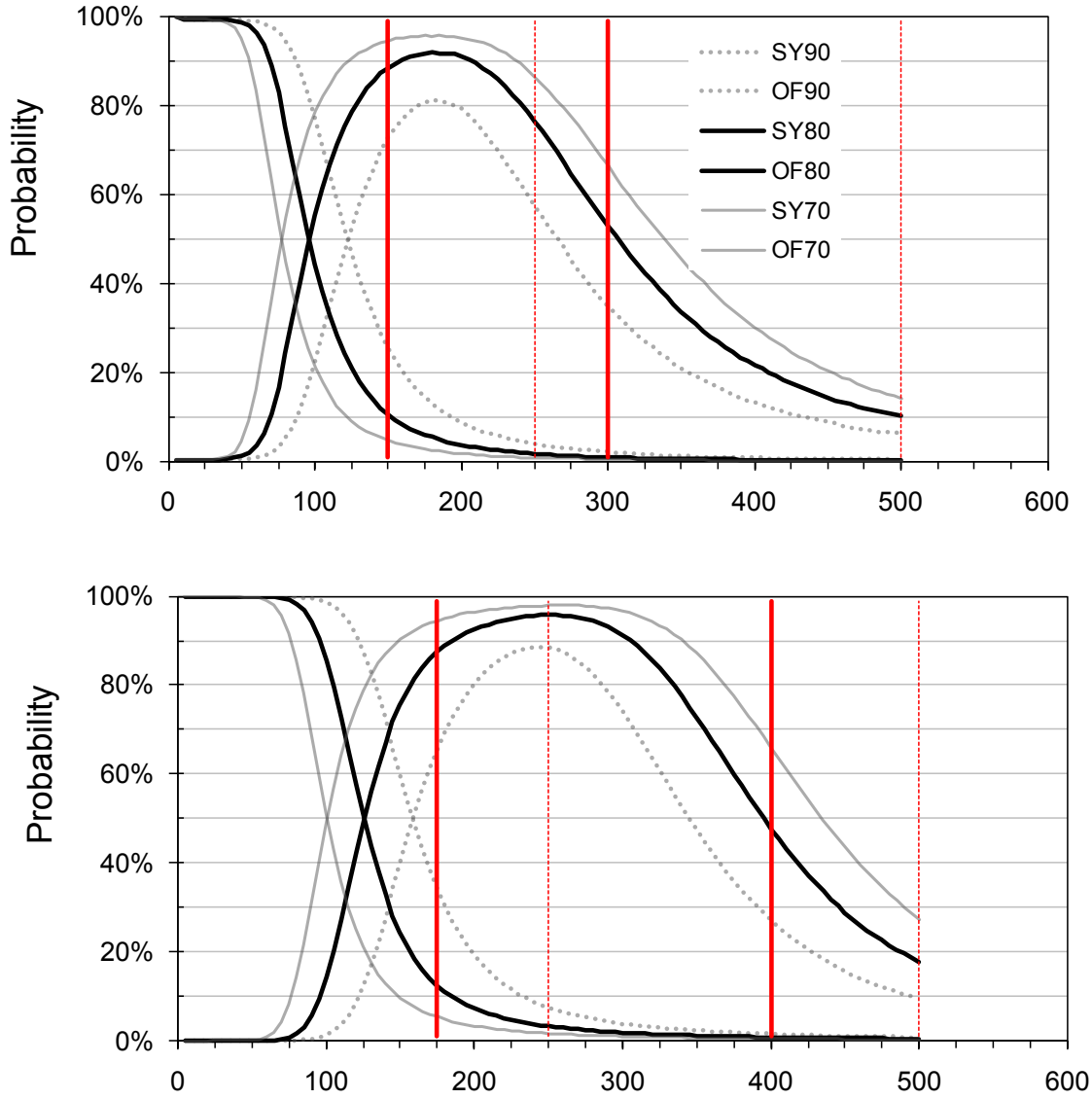


Figure 9.—Ricker relationships represented by approximately 50 paired values of α and β sampled from the posterior probability distribution of spawner-recruitment statistics for Blossom River (top) and Keta River (bottom) Chinook salmon. Curves are a random sample of plausible Ricker relationships that could have generated the observed data.



Spawners counted in aerial survey

Figure 10.—Probability that a specified average survey count of Blossom (top) and Keta (bottom) river Chinook salmon will result in sustained yield exceeding 70%, 80%, and 90% of maximum sustained yield (*MSY*) (hump-shaped functions), and probability of overfishing such that sustained yield is reduced to less than 70%, 80%, and 90% of *MSY* (monotonically decreasing functions). From Bayesian age-structured spawner-recruit analysis of Blossom and Keta rivers Chinook salmon, 1975–2007. Vertical lines are current (dashed) and proposed (solid) escapement goals. SY = sustained yield, OF = overfishing.

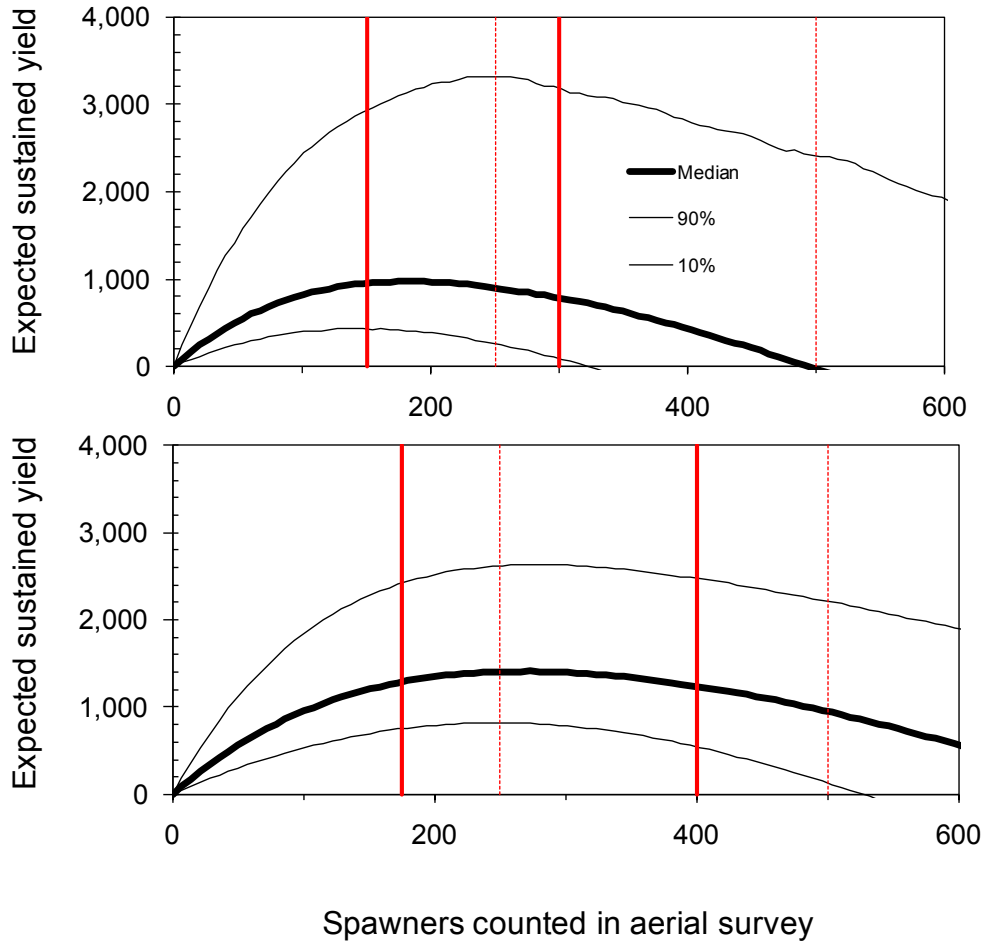


Figure 11.—Bayesian posterior percentiles of expected sustained yield from specified average counts of Chinook salmon in aerial surveys of the Blossom (top) and Keta (bottom) rivers from Bayesian age-structured spawner-recruit analysis of Blossom and Keta rivers Chinook salmon, 1975–2007. Vertical lines are current (dashed) and proposed (solid) escapement goals.

The watershed area model (Liermann et al. 2010) yielded estimates of S_{MSY} very similar¹¹ to those from the age-structured SRA. For the Blossom River watershed, with 101 km² available to Chinook salmon, the model predicted with 90% probability that S_{MSY} for total spawning abundance should be between 228 and 803 large stream-type Chinook salmon, and S_{MSY} is equally likely to be above or below 428. This compares to a 90% interval of 333 to 1,133 with a posterior median of 571 large fish from the age-structured SRA (Table 4). For the Keta River watershed, with 193 km² available to Chinook salmon, the model predicted with 90% probability that S_{MSY} for total spawning abundance should be between 382 and 1,295 large stream-type Chinook salmon, and S_{MSY} is equally likely to be above or below 702. This compares to a 90% interval of 435 to 1,288 and a posterior median of 694 large fish from the age-structured SRA (Table 4).

¹¹ These comparisons are subject to 2 caveats. First, estimates of S_{MSY} for Blossom or Keta Chinook salmon from the watershed model are problematic because information from the Blossom and Keta stocks was used in the original meta-analysis (Parken et al. 2006) conducted to estimate the watershed model parameters (see Discussion). Second, the considerations spelled out in Appendix A about the Blossom River expansion factor are relevant here, because the comparisons are expressed in terms of numbers of fish, rather than survey counts.

DISCUSSION

The classical method of fitting a Ricker spawner-recruit model, which relies on transforming the model into SLR format, requires that the usual assumptions of SLR analysis be met, including that the independent variable (S) be measured without error. Small amounts of measurement error in S have little effect; however measurement error with CVs exceeding 20%¹² can cause substantial bias in SLR estimates (Kope 2006; Pankratz 1991), as well as increased uncertainty that is not reflected in the classical estimates. The measurement error CV of the Blossom and Keta spawning abundance estimates exceeds 20% in most years (Tables 1 and 2). Another shortcoming of the SLR approach is that it cannot accommodate serially correlated process errors. Time series models (e.g., Johnson et al. 2009) are required when the residuals of a regression analysis exhibit serial correlation.^{13, 14} MCMC methods, implemented in Bayesian statistical software, were used because they are flexible enough to model serial correlation in productivity, measurement error in S and R , and missing age data. These phenomena are explicitly included in the age-structured spawner-recruit model, and thus the results automatically take such effects into account when estimating the Ricker parameters and reference points. From this standpoint, the current analysis is similar to recent spawner-recruit analyses on other Alaska salmon stocks (Ericksen and Fleischman 2006; Szarzi et al. 2007; McKinley and Fleischman 2010; Fleischman and Borba 2010; McPherson et al. 2010).

The Blossom and Keta analyses differed from previous ones in that direct estimates of stock-specific harvest were not available. However, extensive CWT studies had been conducted on the nearby Unuk River (Hendrich et al. 2008 for the 1981–1998 brood years; Jan Weller and Christie Hendrich, ADF&G, personal communication for the 1999–2001 brood years). Thus, estimates of exploitation rates for Unuk River Chinook salmon were available, in adult equivalents, as obtained by cohort analysis (USCTC 2005). Estimates included direct mortality, as well as incidental mortality of fish encountered and released. Incidental mortality accounted for about 25%, on average, of the Unuk fishing-induced total mortality. Overall exploitation rate averaged 24% in the Unuk study for brood years 1982–1986 and 1993–2001 (Table 3).

Additional CWT studies have been conducted on the nearby Chickamin River. Nominal Chickamin exploitation rates averaged 26% (4-year old total age and older fish, 2000–2002 brood years; Pahlke 2008), not including incidental mortality. If exploitation rates for the Chickamin River are adjusted for incidental mortality (i.e., increase the harvest such that incidental mortality composes 25% of the total harvest), the average rate increases to 32%. If the adjusted rates are converted to adult equivalents by reducing them by 3 percentage points (Unuk River adult equivalents were about 3 percentage points lower, on average, than nominal rates), the average exploitation rate for Chickamin River fish is 29% for brood years 2000–2002. The corresponding estimates for Unuk River Chinook salmon in 2000 and 2001 were 28% and 26%, respectively.

¹² Low, moderate, or mixed harvest rates generally result in positive bias in S_{MSY} estimates.

¹³ When productivity is serially correlated, SLR can give widely different estimates of S_{MSY} than does the appropriate time series regression analysis. The SLR estimates can be higher or lower than the preferred estimates.

¹⁴ For the Blossom and Keta datasets, a alternative to the Bayesian MCMC analysis would be to expand all survey counts by a factor of 3.0, use the Unuk River exploitation rates to obtain R , estimate α and β by SLR, and bootstrap the residuals to obtain interval estimates. For the Blossom River stock, the analysis yielded a point estimate of 262 fish observed in aerial surveys to achieve MSY , approximately 37% higher than the Bayesian posterior median. The SLR bootstrap intervals were only 40% as wide as the Bayesian credibility intervals. The SLR analysis ignores measurement error and serial correlation.

Given that Unuk and Chickamin Chinook salmon are geographically close to one another, have similar run timing (e.g., see Pahlke 2004), and travel the same migration corridors (based on CWT returns), it is not surprising that they experience similar exploitation rates. The current analyses are based on the assumption that this also holds true for Blossom and Keta rivers Chinook salmon, which are geographically close to the Unuk and Chickamin rivers (Figure 1), yet the true exploitation rates for these stocks remain unknown. Additionally, the trends in escapements for the Unuk, Blossom and Keta stocks are similar (Figure 12).

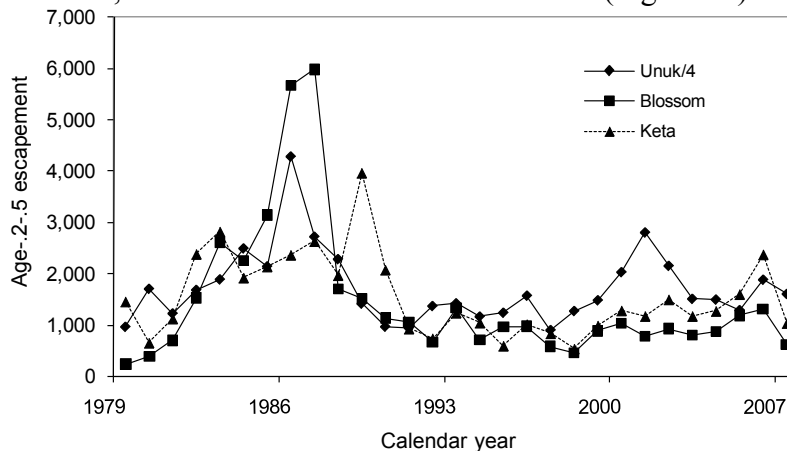


Figure 12.—Estimated age-2-5 escapements of Chinook salmon in the Unuk, Blossom and Keta rivers from 1979 through 2007. The correlation statistics were 0.75 between Unuk and Blossom, 0.60 between Blossom and Keta and 0.37 between Unuk and Keta.

A covariate to estimate exploitation rates for missing broods in the Unuk River time series was not found during analysis for this report. Comparisons where no correlation was found included: 1) Unuk River escapements versus Southeast Alaska and northern British Columbia annual abundance indices; 2) annual Unuk River total production versus Southeast Alaska abundance indices; and 3) annual Unuk River total fishing mortality versus Southeast Alaska abundance indices, and versus annual troll effort in 3 areas – the northern outside, southern inside and southern outside quadrants of Southeast Alaska. After the analysis in this report was finished, a significant relationship (correlation coefficient = 0.77) was found between the southern Southeast Alaska abundance indices and the estimated annual total fishing mortality for the Unuk River stock (Figure 13). The utility of this relationship is twofold: 1) the missing exploitation data from the 1987–1992 broods appears to be flat; and 2) this relationship could be expanded and used in future stock-recruit analysis for Behm Canal stocks.

Choice of the exploitation rate multiplier λ is a key uncertainty in the current analysis. Given moderate sensitivity of the SRA results to choice of a prior for λ (Table 7), the final analysis used a prior distribution (lognormal with median 1.2 and sigma 0.2) that was constructed so as to encompass the entire range of plausible values $0.8 < \lambda < 1.7$ with 95% probability. The resulting posterior distribution for S_{MSY} and other population quantities integrates over this range of values for λ , thereby incorporating the associated uncertainty. The choice of $\lambda = 1.2$ was based in part on the observation that age-1.2 fish from the Blossom and Keta rivers tend to be larger at age than fish from the Unuk River (see, for example, Parken et al. 2006). This could make them more vulnerable to harvest at a younger age, leading to relatively higher exploitation rates. Also, choice of a higher median exploitation rate is a conservative strategy in that it means greater total returns R relative to the same escapement S , which ultimately translates into larger values for optimal spawning abundance S_{MSY} .

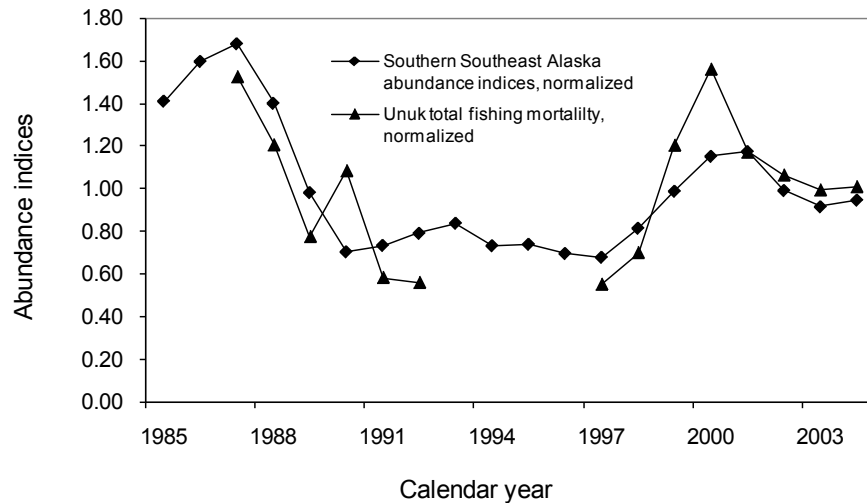


Figure 13.—Estimated abundance indices for the southern Southeast Alaska model stock for calendar years 1985–2004 versus estimated annual Unuk River total fishing mortality, both normalized to an average of 1.0 (correlation = 0.77). Unuk River total fishing mortality is the adult equivalent fishing mortality (landed catch and incidental mortality) summed across ages in a calendar year.

Although the watershed area model (Liermann et al. 2010) yielded imprecise results and technically cannot be applied to Blossom or Keta Chinook salmon because these stocks were used in the original meta-analysis (Parken et al. 2006), it yielded estimates of S_{MSY} that were very similar to those from the age-structured SRA (median = 428 from the watershed model versus 571 from the SRA for the Blossom River, and 702 versus 694 for the Keta River). There were 13 stocks used in the original meta-analysis for stream-type Chinook salmon (see Table 1 in Parken et al. 2006). In terms of watershed size, α , and S_{MSY} , the Blossom and Keta values were in the lower end of the range but did not represent extreme values with excessive leverage in the model.

The results of the SRA can be used to select escapement goals appropriate from a sustained yield perspective. For non-targeted stocks like Blossom and Keta Chinook salmon, the lower bound of the escapement goal is most critical. The lower bound should be high enough to minimize the possibility of recruitment overfishing, yet low enough to not exclude the best opportunities for high yield. Specifically, fishing down to the lower bound should pose a small risk of reducing yields below some high percentage of maximum yield (overfishing profiles in Figure 10). Also, escapements above the lower bound should have greater sustained yield potential than escapements below the lower bound, i.e., the lower bound should be to the left of the SY probability maxima in Figure 10. Blossom and Keta Chinook salmon are passively managed stocks and the 80% sustained yield and overfishing probability profiles are consistent with that management objective.

For Blossom River Chinook salmon, a lower bound of 150 large fish observed in aerial surveys is recommended. At this level of average spawning abundance, there is an 88% chance of achieving optimum yield (i.e., a sustained yield of $\geq 80\%$ of MSY ; Figure 10). Using a criterion of $\leq 10\%$ risk, this lower bound corresponds to an 11% risk that the yield will be reduced to 80% of MSY (Figure 10); the difference lies in rounding the lower bound to the nearest 25 large fish in survey counts. Average aerial survey counts above 150 fish (up to about 225 fish) would also produce greater potential for maximum yield than spawning abundances below that level

(Figures 10 and 11).¹⁵ At average survey counts less than 150 fish, the risk of overfishing sharply increases and the potential for optimal yield sharply decreases (Figure 10). An upper bound was set at the approximated inflection point of the descending arm of the 80% sustained yield probability profile. The corresponding number of large spawners is 300, and at this level of spawning abundance, there is a 53% chance of achieving 80% of *MSY* (Figure 10). Blossom River survey counts have met or exceeded the proposed goal in 24 of 33 years during 1975–2007 (Figure 14).

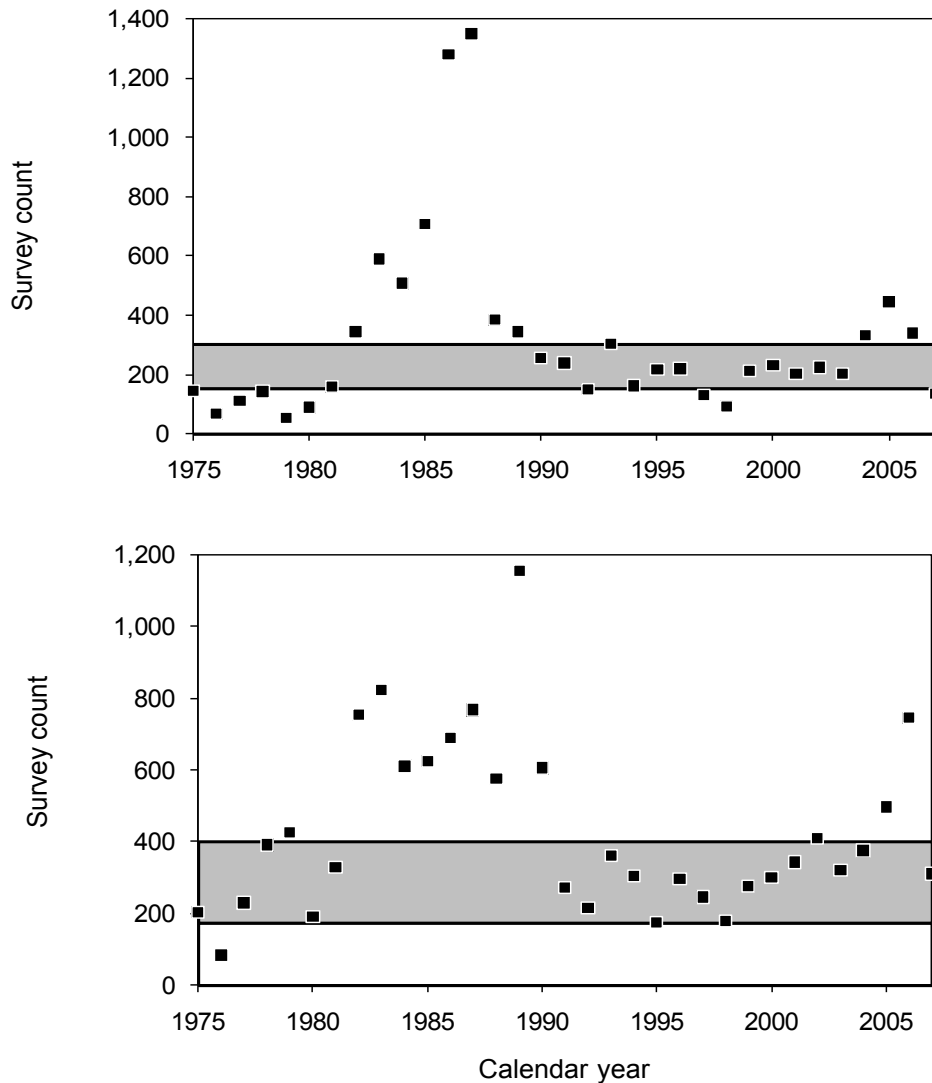


Figure 14.—Survey counts of large (≥ 660 mm MEF) Chinook salmon in the Blossom (top) and Keta (bottom) rivers, 1975–2007. Horizontal lines represent the proposed biological escapement goals in survey count currency.

¹⁵ The current Blossom River aerial survey lower bound of 250 is clearly too large from this standpoint—it excludes escapements with the greatest probability of optimal yield.

For Keta River Chinook salmon, a lower bound of 175 large fish observed in aerial surveys is recommended. At this level of average spawning abundance, there is an 87% chance of achieving optimum yield (i.e., a sustained yield of $\geq 80\%$ of *MSY*; Figure 10). Again using a criterion of $\leq 10\%$ risk, this lower bound corresponds to an 13% risk that the yield will be reduced to 80% of *MSY* (Figure 10); the difference lies in rounding the lower bound to the nearest 25 large fish in survey counts. Average aerial survey counts above 175 fish (up to about 275 fish) would also produce greater potential for maximum yield than spawning abundances below that level (Figures 10 and 11).¹⁶ At average survey counts less than 175 fish, the risk of overfishing sharply increases and the potential for optimal yield sharply decreases (Figure 10). An upper bound was set at the approximate inflection point of the descending arm of the 80% sustained yield probability profile. The corresponding number of large spawners is 400, and at this level of spawning abundance, there is a 48% chance of achieving 80% of *MSY* (Figure 10). Keta River survey counts have met or exceeded the proposed goal in 31 of 33 years during 1975–2007 (Figure 14).

Additional mark–recapture studies are not needed for escapement goal analysis on these systems, because choice of an escapement goal in the currency of aerial survey counts is not sensitive to the estimate of the aerial survey detectability factor θ . However, it is important to note that escapement estimates based on aerial survey counts are generated for other purposes¹⁷, and only limited information can be gleaned about θ from the existing small numbers of mark–recapture estimates (note wide intervals for θ in Table 4), See Appendix A for further discussion of aerial survey detectability.

RECOMMENDATIONS

1. An BEG range of 150 to 300 large fish, as counted in helicopter surveys, is recommended for Chinook salmon spawning in the Blossom River.
2. An BEG range of 175 to 400 large fish, as counted in helicopter surveys, is recommended for Chinook salmon spawning in the Keta River.
3. Aerial surveys must continue. The escapement goals are based on the helicopter survey counts. Survey counts should be expanded by 3.87 for the Blossom River and 3.01 for the Keta River to provide estimates of escapement to the Alaska Board of Fisheries and Pacific Salmon Commission.
4. Sampling to estimate age composition of annual escapements should continue. Knowledge of return by age is an important component of the information required to estimate production by year class. Emphasis should continue to be placed on quality (obtaining a representative sample) rather than quantity, of samples.

¹⁶ The current Keta River aerial survey lower bound of 250 is clearly too large from this standpoint—it excludes escapements with the greatest probability of optimal yield.

¹⁷ For example, estimates of escapement are provided to the Pacific Salmon Commission annually. See Appendix A.

ACKNOWLEDGMENTS

The authors thank Paul Kissner, formerly of ADF&G, for implementing the stock assessment program for Chinook salmon in Southeast Alaska in the early 1970s and standardizing the helicopter surveys. We thank Keith Pahlke for conducting helicopter surveys, assistance in field sampling and project design. We also thank Kevin Brownlee, Glenn Freeman, Red Weller, and Dave Magnus for planning, conducting and reporting the results of the Blossom and Keta rivers mark-recapture studies. The authors thank Bob Marshall for his assistance in planning, analysis and reporting of the helicopter survey studies from 1992–2000, the 1999–2000 Keta River mark-recapture studies, and the 2004 Blossom River mark-recapture study. We also thank Dan Reed for his help on the 2004 Blossom River mark-recapture analysis, assistance with the planning, analysis and reporting of the 2005–2006 Blossom River mark-recapture studies, and for calculating SEs for expansion factors. We thank the following personnel for their efforts conducting field work and collecting the essential base data: Dave Magnus, Dale Brandenburger, Mike Wood, Tom Cappiello, Matt LaPlante, Jason Levitt, Steve McCurdy, Paul Overturf, Phil Richards, Tim Sands, Chris Stack, Troy Tydingco, Jeff Williams, and Nicole Zeiser. Amy Holm in Ketchikan coordinated field logistics from 1998–2007. Sue Millard aged most of the scales collected over the years. Joanne McClellan prepared the final layout of this manuscript. This work was partially funded by aid authorized under the U.S. Federal Sport Fish Restoration Act, the Pacific Coast Salmon Recovery Fund, U.S. Chinook Letter of Agreement, and by recreational anglers fishing in Alaska.

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APPENDIX A

Appendix A1.—Additional considerations regarding the expansion factor for Blossom and Keta rivers aerial surveys.

The Blossom and Keta rivers spawner-recruit analyses rely on a small number of mark-recapture experiments to learn about the proportion of fish detected in aerial surveys. The detectability of fish during aerial surveys is heavily dependent upon conditions that affect visibility, especially water depth and clarity. Thus the accuracy with which the proportion θ and its inverse, the expansion factor θ^{-1} , was estimated depended largely on the degree to which a representative range of counting conditions was encountered during mark-recapture years.

Mark-recapture experiments were conducted on the Blossom River in 1998 and in 2004–2006. In 2004 and 2005, water levels were extremely low (Keith Pahlke, ADF&G, Division of Sport Fish, Douglas, personal communication), leading to very high visibility and “excellent” survey conditions (Weller et al. 2007). The estimated expansion factors were 2.20 in 2004 and 2.08 in 2005, compared to 4.0 in 1998 and 3.75 in 2006, when survey conditions were considered to be “normal” (Appendix Table A1). The mean expansion factor for all 4 years is 3.01 (SE = 1.03, CV = 34.3%). The spawner-recruit analysis presented in the main body of this report uses all 4 years of mark-recapture data, hence the posterior median for θ^{-1} reported in Table 4 is very close to 3.01 (2.98).

Given that “normal” conditions prevailed during 12 of the last 17 years (1991–2007), the 4-year average expansion factor of 3.01 may be unduly influenced by the 2 highly unusual years of excellent conditions. Additionally, it is generally agreed¹⁸ that, under similar survey conditions, it is more difficult to count Chinook salmon in the Blossom River than in the Keta River; therefore the expansion factor for the Blossom River should be greater than that for the Keta River. The mean expansion factor for the Keta is 3.01, from mark-recapture experiments conducted in 1998–2000 (Appendix Table A2), during which time there were no concerns about unrepresentative conditions.

The point is that multiple biologists with considerable experience generally agree that the 4-year mean expansion factor of 3.01 is too low for the Blossom River. Therefore an alternative analysis was conducted that omitted the two years (2004, 2005) of mark-recapture data with anomalously good conditions, retaining only the years (1998, 2006) with “normal” conditions (average expansion factor $\theta^{-1} = 3.87$). Point estimates (posterior medians) from analysis of the abridged dataset are presented in Appendix Table A3, along with those from Table 4 repeated for comparison.

Estimates from the abridged data were very similar to those from the original analysis. The Ricker β parameter was estimated to be approximately 10% smaller, whereas carrying capacity S_{EQ} and optimal escapement S_{MSY} were 10% higher. Other parameters were virtually unchanged, including the most critical parameter from the perspective of escapement goal analysis: S_{MSY} in survey count currency. The point estimate of this quantity from analysis of the abridged data (192 fish) was almost identical to the original analysis value (191). Fortunately, for this analysis, moderate bias in the estimate of aerial survey detectability has negligible consequences with respect to establishment of an escapement goal.

Annual estimates of Blossom and Keta rivers Chinook salmon spawning abundance are supplied to the PSC for input into a coastwide Chinook salmon model. Estimates of spawning abundance *are* sensitive to choice of expansion factor. Historically, for the reasons discussed above, expansion factors of 3.87 for the Blossom River and 3.01 for the Keta River have been used to generate escapement estimates for the PSC model (Appendix Tables A1 and A2, Appendix F). At this time, there is no plan to change this convention, in order to preserve historical comparability.

¹⁸ Personal communications from Keith Pahlke (ADF&G, Division of Sport Fish, retired), who conducted the surveys; David Magnus (ADF&G, Division of Sport Fish, retired), who was project leader on the Keta and Blossom mark-recapture and many other projects over the past 30 years; and Edgar Jones (ADF&G, Division of Sport Fish, Douglas), who has sampled Chinook salmon throughout the region.

Appendix Table A1.—Peak survey counts, direct estimates, and expanded counts provided to the Pacific Salmon Commission, of large (≥ 660 mm MEF) Chinook salmon spawning in the Blossom River 1975–2007. Expansion factor (3.87) is the mean of the ratio of direct estimates to survey counts for 1998 and 2006. See text of Appendix A.

Year	Survey counts	Direct estimates	Estimate/count	Counts x 3.87
1975	146			565
1976	68			263
1977	112			434
1978	143			554
1979	54			209
1980	89			345
1981	159			616
1982	345			1,336
1983	589			2,281
1984	508			1,968
1985	709			2,746
1986	1,278			4,950
1987	1,349			5,225
1988	384			1,487
1989	344			1,332
1990	257			995
1991	239			926
1992	150			581
1993	303			1,174
1994	161			624
1995	217			840
1996	220			852
1997	132			511
1998	91	364	4.00	
1999	212			821
2000	231			895
2001	204			790
2002	224			868
2003	203			786
2004	333	734	2.20	
2005	445	926	2.08	
2006	339	1,270	3.75	
2007	135			523
Mean of 1998 and 2004–2006			3.01	
Mean of 1998 and 2006			3.87	

Appendix Table A2.–Peak survey counts, direct estimates, and expanded counts provided to the Pacific Salmon Commission, of large (≥ 660 mm MEF) Chinook salmon spawning in the Keta River 1975–2007. Expansion factor (3.01) is the mean of the ratio of direct estimates to survey counts for 1998–2000.

Year	Survey counts	Direct estimates	Estimate/count	Counts x 3.01
1975	203			611
1976	84			253
1977	230			692
1978	392			1,180
1979	426			1,283
1980	192			578
1981	329			990
1982	754			2,270
1983	822			2,475
1984	610			1,836
1985	624			1,879
1986	690			2,077
1987	768			2,312
1988	575			1,731
1989	1,155			3,477
1990	606			1,824
1991	272			819
1992	217			653
1993	362			1,090
1994	306			921
1995	175			527
1996	297			894
1997	246			741
1998	180	446	2.48	
1999	276	968	3.51	
2000	300	914	3.05	
2001	343			1,033
2002	411			1,237
2003	322			969
2004	376			1,132
2005	497			1,496
2006	747			2,249
2007	311			936
Mean			3.01	

Appendix Table A3.–Selected parameter estimates (posterior medians) from Bayesian age-structured Ricker spawner-recruit model for Blossom River Chinook salmon fitted to abridged data set, in which mark–recapture estimates of spawning abundance were omitted for 2004 and 2005, due to anomalously high visibility. Corresponding values from the same analysis on the full data set, from Table 1, are repeated for comparison.

Parameter	Posterior median abridged data	Posterior median full data, from Table 4
$\ln(\alpha)$	1.40	1.40
α	4.06	4.05
β	0.0010	0.0011
ϕ	0.81	0.81
σ_w	0.41	0.40
S_{EQ}	1,682	1,528
S_{MSY}	626	571
S_{MSY} in survey counts	192	191
U_{MSY}	0.64	0.64

APPENDIX B

Appendix B1.—Numbers of large (≥ 660 mm MEF) Chinook salmon sampled from the Blossom River, by age class, 1998–2007.

	Age class								<i>n</i>
	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5	
1998	0	16	5	36	7	43	0	2	109
1999	1	5	0	4	1	1	0	0	12
2000	0	8	2	16	2	9	0	0	37
2001	0	0	6	7	0	5	0	0	18
2002	0	10	3	31	10	23	0	0	77
2003	0	3	0	14	2	9	1	0	29
2004	8	107	14	130	8	77	0	0	345
2005	2	50	8	163	1	40	1	2	266
2006	0	24	9	101	1	29	0	2	166
2007	1	13	1	22	4	6	0	0	47

APPENDIX C

Appendix C1.—Numbers of large (≥ 660 mm MEF) Chinook salmon sampled from the Keta River, by age class, 1982, 1984, and 1998–2007.

	Age class								<i>n</i>
	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5	
1982	0	1	0	14	0	4	0	0	19
1984	0	0	0	9	3	8	0	0	20
1998	0	17	3	44	11	85	0	2	162
1999	2	47	4	75	6	18	2	0	154
2000	2	48	6	60	4	35	0	0	155
2001	4	12	16	88	3	9	1	0	133
2002	0	43	11	78	11	67	0	0	210
2003	0	17	5	67	5	20	0	0	114
2004	2	25	4	24	3	26	1	0	85
2005	4	27	3	44	0	7	0	2	87
2006	1	11	5	67	3	10	0	0	97
2007	1	6	3	30	2	20	0	0	62

APPENDIX D

Appendix D1.–WinBUGS code for Bayesian age-structured spawner-recruit model. Prior distributions are in *italics* and likelihoods (sampling distributions of the data) are underlined.

```

model {
# RICKER STOCK-RECRUIT RELATIONSHIP WITH AR1 ERRORS;
# R[y] IS THE TOTAL RETURN FROM BROOD YEAR y
# THERE ARE A TOTAL OF Y+A-1 = 33 + 3 - 1 = 35 BROOD YRS REPRESENTED IN DATA
# THE FIRST a.max = 6 DO NOT HAVE CORRESPONDING SPAWNING ABUNDANCES
# THE REMAINING Y-a.min = 29 DO (BROOD YEARS A+a.min=7 - 35)

for (y in A+a.min:Y+A-1) {
  log.R[y] ~ dt(log.R.mean2[y],tau.white,500)
  R[y] <- exp(log.R[y])
  log.R.mean1[y] <- log(S[y-a.max]) + lnalpha - beta * S[y-a.max]
  log.resid[y] <- log(R[y]) - log.R.mean1[y]
}
log.R.mean2[A+a.min] <- log.R.mean1[A+a.min] + phi * log.resid.0
for (y in A+a.min+1:Y+A-1) {
  log.R.mean2[y] <- log.R.mean1[y] + phi * log.resid[y-1]
}
lnalpha ~ dnorm(0,1.0E-6)l(0,)
beta ~ dnorm(0,1.0E-1)l(0,)
phi ~ dnorm(0,1.0E-4)l(-1,1)
tau.white ~ dgamma(0.01,0.01)
log.resid.0 ~ dnorm(0,tau.red)l(-3,3)
alpha <- exp(lnalpha)
tau.red <- tau.white * (1-phi*phi)
sigma.white <- 1 / sqrt(tau.white)
sigma.red <- 1 / sqrt(tau.red)
lnalpha.c <- lnalpha + (sigma.white * sigma.white / 2 / (1-phi*phi) )
S.max <- 1 / beta
S.eq <- lnalpha.c * S.max
S.msy <- S.eq * (0.5 - 0.07*lnalpha.c)
U.msy <- lnalpha.c * (0.5 - 0.07*lnalpha.c)
Pct.Harv.Incr <- 100* U.msy / mu
step.HI <- step(U.msy - mu)

# BROOD YEAR RETURNS W/O SR LINK DRAWN FROM COMMON LOGNORMAL DISTN
mean.log.R ~ dnorm(0,1.0E-4)l(0,)
tau.R ~ dgamma(0.1,0.1)
for (y in 1:a.max) {
  log.R.lag[y] ~ dt(mean.log.R,tau.R,500)
  R.lag[y] <- exp(log.R.lag[y])
}

# GENERATE Y+A-1 = 35 MATURITY SCHEDULES, ONE PER BROOD YEAR
D.scale ~ dunif(0,1)
D.sum <- 1 / (D.scale * D.scale)
pi[1] ~ dbeta(1,1)
pi2p ~ dbeta(1,1)
pi[2] <- pi2p * (1 - pi[1])
pi[3] <- 1 - pi[1] - pi[2]
for (a in 1:A) {
  gamma[a] <- D.sum * pi[a]
}

```

```

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

# ASSIGN PRODUCT OF P AND R TO ALL CELLS IN N MATRIX
# y SUBSCRIPT INDEXES BROOD YEAR
# y=1 IS THE BROOD YEAR OF THE OLDEST FISH IN YEAR 1 (upper right cell, BY=1975-6=1969)
# y=35 IS THE BROOD YEAR OF THE YOUNGEST FISH IN YEAR Y (lower left cell, BY=2007-4=2003)
# N.ta decremented by brood-year exploitation rates

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

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

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

# ESCAPEMENT AND EXPLOITATION RATE ESTIMATED
# MU^ AND S^ ARE DATA
#log.lambd ~ dnorm(0.18,25) # median factor = 1.2, CV=20%
#log.lambd ~ dnorm(-0.223,100) # median factor = 0.8, CV=10%
log.lambd ~ dnorm(0.531,100) # median factor = 1.7, CV=10%
mu.Unuk ~ dbeta(1,1)
B.scale ~ dunif(0,1)
mu <- mean(mu.y[])
lambda <- exp(log.lambd)
B.sum <- 1 / (B.scale * B.scale)
B1 <- B.sum * mu.Unuk
B2 <- B.sum - B1
for (y in 1:Y+A-1) {
  mu.Unuk.y[y] ~ dbeta(B1,B2)
  mu.Unuk.hat[y] ~ dlnorm(log.mu.Unuk[y],tau.log.mu[y])
  log.mu.Unuk[y] <- log(mu.Unuk.y[y])
}

```

```

tau.log.mu[y] <- 1 / mu.cv[y] / mu.cv[y]
F.Unuk.y[y] <- -log(1-mu.Unuk.y[y])
F.y[y] <- F.Unuk.y[y] * lambda
mu.y[y] <- 1 - exp(-F.y[y])
}
theta.AS ~ dunif(0,1)
tau.AS ~ dgamma(0.1,0.1)
theta.inv <- 1 / theta.AS
sigma.AS <- 1 / sqrt(tau.AS)
AS.msy <- S.msy * theta.AS
for (y in 1:Y) {
log.S[y] <- log(S[y])
tau.log.S[y] <- 1 / S.cv[y] / S.cv[y]
S.hat[y] ~ dlnorm(log.S[y],tau.log.S[y])
log.qS[y] <- log(theta.AS * S[y])
Air[y] ~ dlnorm(log.qS[y],tau.AS)
}

# GENERATE FITTED VALUES OF R EVERY 1000 SPAWNING FISH FOR GRAPHICS;
for (i in 1:25) {
S.star.1[i] <- 100*i
R.fit[i] <- S.star.1[i] * exp(lnalpha - beta * S.star.1[i])
}
# CALCULATE SUSTAINED YIELD AT REGULAR INTERVALS OF S;
# FIND THE PROBABILITY THAT EACH VALUE OF S WILL RESULT IN YIELDS WITHIN 10% OF
MSC;
# GENERATE DUMMY AIR SURVEY DATA FOR EACH STATE OF NATURE AT EACH PROPOSED S;
# FIND THE PROBABILITY OF NOT CONDUCTING RECRUITMENT OVERFISHING AT EACH S;
R.msy <- S.msy * exp(lnalpha - beta * S.msy)*exp(sigma.red*sigma.red/2)
MSY <- R.msy - S.msy
for (i in 1:100) {
S.star.2[i] <- 20*i
R.fit2[i] <- S.star.2[i] * exp(lnalpha - beta * S.star.2[i])*exp(sigma.red*sigma.red/2)
SY[i] <- R.fit2[i] - S.star.2[i]
I90[i] <- step(SY[i] - 0.9 * MSY)
I80[i] <- step(SY[i] - 0.8 * MSY)
I70[i] <- step(SY[i] - 0.7 * MSY)
lqS[i] <- log(theta.AS * S.star.2[i])
Air2[i] ~ dlnorm(lqS[i],tau.AS)
OF90[i] <- 1 - nOF90[i]
OF80[i] <- 1 - nOF80[i]
OF70[i] <- 1 - nOF70[i]
}
nOF90[1] <- 0
nOF80[1] <- 0
nOF70[1] <- 0
for (i in 2:100) {
nOF90[i] <- max(I90[i],nOF90[i-1])
nOF80[i] <- max(I80[i],nOF80[i-1])
nOF70[i] <- max(I70[i],nOF70[i-1])
}

```

APPENDIX E

Appendix E1.–WinBUGS code for watershed area habitat model (Liermann et al. 2010), as applied to Blossom River Chinook salmon.

```
model {
  W <- 101 # Blossom River drainage area below barrier
  sigma.red <- 0.694 # posterior median from Blossom BASSR version 3e
  prop.small <- 0.20 # 4-year-old less than 660 mm MEF, from John D report draft
  a.tau <- 1 / 0.11478 / 0.11478
  b.tau <- 1 / 0.04819 / 0.04819
  k.new.tau <- 1 / 0.29662 / 0.29662
  r.new.tau <- 1 / 0.19769 / 0.19769

  a ~ dt(9.06814, a.tau, 19.6)
  b ~ dt(0.67462, b.tau, 15.3)
  r.new ~ dt(1.45468, r.new.tau, 5.6)

  log.Enew ~ dt(mean.log.Enew, k.new.tau, 8.8)
  mean.log.Enew <- a + b * log(W / 1502.6)
  E.new <- exp(log.Enew)
  S.eq <- E.new
  S.large.eq <- (1-prop.small) * S.eq
  lnalpha <- r.new

  alpha <- exp(lnalpha)
  lnalpha.c <- lnalpha + (sigma.red * sigma.red / 2)
  S.large.msy <- S.large.eq * (0.5 - 0.07*lnalpha.c)
  beta <- lnalpha / S.large.eq
  S.large.max <- 1 / beta
}
```

APPENDIX F

Appendix F1.–Empirical spawner-recruit data for Blossom and Keta river Chinook, salmon.

The following section provides empirical estimates of the spawner-recruit data for large Chinook salmon for both stocks, in Tables F1–F8. Estimates are also presented for all ages of Chinook by adding in estimates of younger-age Chinook (<660 mm MEF) in Appendix Tables F9–F12. Note that point estimates here will differ from MCMC estimates based on medians and percentiles from simulation for both stocks, but will also differ for the Blossom stock because the expansion factor of 3.87 (see Appendix Table A1) is used in this section instead of the factor of about 3.0 used in the main body. Standard errors (SEs) and CVs where presented in this section are based on closed-form statistics rather than the Bayesian approach in the main body.

Appendix Table F1.—Estimated numbers \hat{N}_i of large (≥ 660 mm MEF) Chinook salmon by age class and large females and males spawning in the Blossom River from 1975 through 2007. Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples. Age composition of all others are based on average mark–recapture and spawning ground samples collected from 1998–2007. Escapements in years that mark–recapture experiments were not conducted are based on expanded survey counts using a factor of 3.87. Estimated SEs for these statistics are in Table F2.

Calendar year	Age class								Age-2 to age-.5 total	Large females	Large males	<i>n</i>
	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5				
1975	8	109	35	250	29	129	2	2	565	250	315	
1976	4	51	16	117	14	60	1	1	263	116	147	
1977	6	84	27	192	23	99	2	2	433	192	389	
1978	8	107	35	245	29	126	2	2	553	245	309	
1979	3	40	13	93	11	48	1	1	209	92	117	
1980	5	66	22	153	18	78	1	1	344	152	192	
1981	9	119	39	273	32	140	2	2	615	272	343	
1982	19	258	84	591	69	304	5	5	1,335	591	745	
1983	32	440	143	1,010	119	519	9	8	2,279	1,008	1,271	
1984	28	379	123	871	102	447	8	7	1,966	870	1,096	
1985	39	530	172	1,215	143	624	11	10	2,744	1,214	1,530	
1986	70	954	310	2,191	257	1,126	20	18	4,946	2,188	2,758	
1987	73	1,008	327	2,313	271	1,188	21	19	5,221	2,309	2,912	
1988	21	287	93	658	77	338	6	5	1,486	657	829	
1989	19	257	83	590	69	303	5	5	1,331	589	742	
1990	14	192	62	441	52	226	4	4	995	440	555	
1991	13	178	58	410	48	211	4	3	925	409	516	
1992	8	112	36	257	30	132	2	2	581	257	324	
1993	16	226	74	519	61	267	5	4	1,173	519	654	
1994	9	120	39	276	32	142	2	2	623	276	347	
1995	12	162	53	372	44	191	3	3	840	371	468	
1996	12	164	53	377	44	194	3	3	851	377	475	
1997	7	99	32	226	27	116	2	2	511	226	285	
1998	0	53	17	120	23	144	0	7	364	180	184	109
<i>1999</i>	<i>68</i>	<i>342</i>	<i>0</i>	<i>273</i>	<i>68</i>	<i>68</i>	<i>0</i>	<i>0</i>	<i>820</i>	<i>273</i>	<i>547</i>	<i>154</i>
<i>2000</i>	<i>0</i>	<i>193</i>	<i>48</i>	<i>387</i>	<i>48</i>	<i>217</i>	<i>0</i>	<i>0</i>	<i>894</i>	<i>377</i>	<i>537</i>	<i>12</i>
<i>2001</i>	<i>0</i>	<i>0</i>	<i>263</i>	<i>307</i>	<i>0</i>	<i>219</i>	<i>0</i>	<i>0</i>	<i>789</i>	<i>526</i>	<i>263</i>	<i>18</i>
<i>2002</i>	<i>0</i>	<i>113</i>	<i>34</i>	<i>349</i>	<i>113</i>	<i>259</i>	<i>0</i>	<i>0</i>	<i>867</i>	<i>484</i>	<i>383</i>	<i>77</i>
<i>2003</i>	<i>0</i>	<i>87</i>	<i>0</i>	<i>378</i>	<i>58</i>	<i>233</i>	<i>29</i>	<i>0</i>	<i>786</i>	<i>495</i>	<i>291</i>	<i>27</i>
2004	18	227	30	277	18	164	0	0	734	247	487	291
2005	6	174	28	567	3	140	3	6	926	376	193	325
2006	0	180	71	776	8	220	0	16	1,270	604	666	162
<i>2007</i>	<i>14</i>	<i>141</i>	<i>14</i>	<i>240</i>	<i>42</i>	<i>71</i>	<i>0</i>	<i>0</i>	<i>522</i>	<i>240</i>	<i>282</i>	<i>37</i>

Appendix Table F2.—Estimated SEs for numbers \hat{N}_i of large (≥ 660 mm MEF) Chinook salmon by age class and large females and males spawning in the Blossom River from 1975 through 2007. Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples. All others are based on average mark–recapture and spawning ground samples collected from 1998–2007. Escapements in years that mark–recapture experiments were not conducted are based on expanded survey counts using a factor of 3.87.

Calendar year	Age class								Age-.2 to age-.5 total	Large females	Large males
	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5			
1975	15	67	54	69	24	56	7	4	91	63	71
1976	7	31	25	32	11	26	3	2	42	29	33
1977	11	52	42	53	19	43	5	3	69	48	88
1978	15	66	53	68	24	55	6	4	89	62	69
1979	5	25	20	26	9	21	2	1	33	23	26
1980	9	41	33	42	15	34	4	2	55	38	43
1981	16	73	59	75	27	61	7	4	99	69	77
1982	35	159	129	164	58	132	15	9	214	149	168
1983	60	272	220	279	98	226	26	15	365	254	286
1984	52	235	189	241	85	195	23	13	315	219	247
1985	72	327	264	336	118	272	32	18	440	306	344
1986	130	590	477	606	213	491	57	32	792	552	620
1987	137	623	503	640	225	518	60	34	836	583	655
1988	39	177	143	182	64	147	17	10	238	166	186
1989	35	159	128	163	57	132	15	9	213	149	167
1990	26	119	96	122	43	99	11	6	159	111	125
1991	24	110	89	113	40	92	11	6	148	103	116
1992	15	69	56	71	25	58	7	4	93	65	73
1993	31	140	113	144	51	116	13	8	188	131	147
1994	16	74	60	76	27	62	7	4	100	70	78
1995	22	100	81	103	36	83	10	5	135	94	105
1996	22	102	82	104	37	84	10	6	136	95	107
1997	13	61	49	63	22	51	6	3	82	57	64
1998	0	17	8	30	10	35	0	5	77	42	42
<i>1999</i>	<i>68</i>	<i>132</i>	<i>0</i>	<i>123</i>	<i>68</i>	<i>68</i>	<i>0</i>	<i>0</i>	<i>131</i>	<i>123</i>	<i>145</i>
<i>2000</i>	<i>0</i>	<i>68</i>	<i>34</i>	<i>96</i>	<i>34</i>	<i>72</i>	<i>0</i>	<i>0</i>	<i>143</i>	<i>86</i>	<i>116</i>
<i>2001</i>	<i>0</i>	<i>0</i>	<i>99</i>	<i>104</i>	<i>0</i>	<i>92</i>	<i>0</i>	<i>0</i>	<i>126</i>	<i>123</i>	<i>99</i>
<i>2002</i>	<i>0</i>	<i>38</i>	<i>20</i>	<i>74</i>	<i>38</i>	<i>61</i>	<i>0</i>	<i>0</i>	<i>139</i>	<i>92</i>	<i>78</i>
<i>2003</i>	<i>0</i>	<i>50</i>	<i>0</i>	<i>97</i>	<i>41</i>	<i>79</i>	<i>29</i>	<i>0</i>	<i>126</i>	<i>108</i>	<i>87</i>
2004	15	31	9	35	7	25	0	0	76	33	54
2005	9	27	9	66	3	24	3	4	99	47	64
2006	0	42	25	116	8	48	0	11	172	96	103
<i>2007</i>	<i>28</i>	<i>44</i>	<i>14</i>	<i>58</i>	<i>24</i>	<i>31</i>	<i>0</i>	<i>0</i>	<i>84</i>	<i>58</i>	<i>62</i>

Appendix Table F3.—Estimated numbers \hat{N}_i of large (≥ 660 mm MEF) Chinook salmon by age class and large females and males spawning in the Keta River from 1975 through 2007. Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples. Age composition of all others are based on average mark–recapture and spawning ground samples collected from 1998–2007. Escapements in years that mark–recapture experiments were not conducted are based on expanded survey counts using a factor of 3.01. Estimated SEs for these statistics are in Table F4.

Calendar year	Age class								Age-.2 to age-.5 total	Large females	Large males	<i>n</i>
	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5				
1975	9	121	29	289	21	137	2	2	611	265	346	
1976	4	50	12	120	9	57	1	1	253	110	143	
1977	11	137	33	327	24	155	2	2	692	300	392	
1978	18	233	57	558	41	264	4	4	1,180	512	668	
1979	19	254	62	606	45	287	4	5	1,282	556	726	
1980	9	114	28	273	20	130	2	2	578	251	327	
1981	15	196	48	468	35	222	3	3	990	429	561	
1982	0	119	0	1,672	0	478	0	0	2,270	1,672	597	19
1983	38	490	119	1,170	87	555	8	9	2,474	1,073	1,401	
1984	0	0	0	826	275	734	0	0	1,836	1,193	643	20
1985	29	372	90	888	66	421	6	7	1,878	814	1,064	
1986	32	411	100	982	73	466	7	7	2,077	901	1,176	
1987	35	457	111	1,093	81	518	7	8	2,312	1,002	1,309	
1988	26	342	83	819	61	388	6	6	1,731	751	980	
1989	53	688	167	1,644	122	779	11	12	3,477	1,508	1,969	
1990	28	361	88	863	64	409	6	6	1,824	791	1,033	
1991	12	162	39	387	29	184	3	3	819	355	464	
1992	10	129	31	309	23	146	2	2	653	283	370	
1993	17	216	52	515	38	244	4	4	1,090	472	617	
1994	14	182	44	436	32	206	3	3	921	399	522	
1995	8	104	25	249	18	118	2	2	527	228	298	
1996	14	177	43	423	31	200	3	3	894	388	506	
1997	11	147	36	350	26	166	2	3	740	321	419	
1998	0	47	8	121	30	234	0	6	446	240	206	162
1999	13	295	25	471	38	113	13	0	968	390	578	154
2000	12	283	35	354	24	206	0	0	914	377	537	155
2001	31	93	124	683	23	70	8	0	1,032	466	567	133
2002	0	253	65	459	65	395	0	0	1,237	465	772	210
2003	0	145	43	570	43	170	0	0	969	391	578	114
2004	27	333	53	320	40	346	13	0	1,132	466	666	85
2005	69	464	52	757	0	120	0	34	1,496	602	894	87
2006	23	255	116	1,553	70	232	0	0	2,248	1,089	1,159	97
2007	15	91	45	453	30	302	0	0	936	453	483	62

Appendix Table F4.—Estimated SEs of numbers \hat{N}_i of large (≥ 660 mm MEF) Chinook salmon by age class and large females and males spawning in the Keta River from 1975 through 2007. Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples. All others are based on average mark–recapture and spawning ground samples collected from 1998–2007. Escapements in years that mark–recapture experiments were not conducted are based on expanded survey counts using a factor of 3.01.

Calendar year	Age class								Age-.2 to age-.5 total	Large females	Large males
	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5			
1975	9	63	18	103	12	91	3	5	114		
1976	4	26	7	43	5	38	1	2	47		
1977	10	71	20	117	13	103	4	5	129		
1978	17	121	34	199	22	175	6	9	220		
1979	19	132	37	216	24	190	7	10	239		
1980	9	59	17	97	11	86	3	4	108		
1981	15	102	28	167	19	147	5	8	184		
1982	0	119	0	388	0	232	0	0	422	388	257
1983	37	254	71	417	47	367	13	19	460		
1984	0	0	0	257	156	244	0	0	342	297	231
1985	28	193	54	316	36	279	10	15	349		
1986	31	214	59	350	39	308	11	16	386		
1987	34	238	66	389	44	343	12	18	430		
1988	26	178	50	291	33	257	9	13	322		
1989	51	357	100	585	66	516	18	27	647		
1990	27	188	52	307	35	271	10	14	339		
1991	12	84	23	138	16	122	4	6	152		
1992	10	67	19	110	12	97	3	5	122		
1993	16	112	31	183	21	162	6	8	203		
1994	14	95	26	155	17	137	5	7	171		
1995	8	54	15	89	10	78	3	4	98		
1996	13	92	26	151	17	133	5	7	166		
1997	11	76	21	125	14	110	4	6	138		
1998	0	12	5	21	9	32	0	4	50	32	29
<i>1999</i>	9	50	13	69	16	28	9	0	116	60	79
<i>2000</i>	8	51	15	59	12	41	0	0	122	62	80
<i>2001</i>	16	31	37	134	14	26	8	0	192	97	114
<i>2002</i>	0	58	22	95	22	83	0	0	230	96	149
<i>2003</i>	0	42	20	115	20	46	0	0	180	85	116
2004	19	83	28	81	24	85	13	0	211	105	137
2005	36	113	30	162	0	49	0	25	278	136	184
2006	23	86	54	307	41	81	0	0	418	232	243
<i>2007</i>	15	39	27	103	22	79	0	0	174	103	107

Appendix Table F5.—Estimated inriver returns \hat{E}_i of large (≥ 660 mm MEF) Chinook salmon by total age in the Blossom River for the 1975–2001 brood years. SEs are shown in (). Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples. All others are based on average mark–recapture and spawning ground samples collected from 1998–2007. Escapements in years that mark–recapture experiments were not conducted are based on expanded survey counts using a factor of 3.87.

Brood year	Age 3	(SE)	Age 4	(SE)	Age 5	(SE)	Age 6	(SE)	Age 7	(SE)	Total	(SE)
1975	8	(15)	53	(32)	170	(45)	143	(61)	5	(9)	379	(84)
1976	3	(5)	88	(53)	88	(80)	309	(133)	8	(15)	497	(165)
1977	5	(9)	157	(94)	661	(174)	528	(228)	7	(13)	1,358	(302)
1978	9	(16)	341	(205)	1,128	(296)	455	(196)	10	(18)	1,944	(411)
1979	19	(35)	583	(350)	973	(255)	635	(274)	18	(32)	2,228	(515)
1980	32	(60)	503	(302)	1,358	(357)	1,145	(494)	19	(34)	3,058	(683)
1981	28	(52)	702	(421)	2,448	(643)	1,209	(522)	5	(10)	4,392	(930)
1982	39	(72)	1,264	(759)	2,584	(678)	344	(148)	5	(9)	4,236	(1031)
1983	70	(130)	1,335	(801)	736	(193)	308	(133)	4	(6)	2,452	(845)
1984	73	(137)	380	(228)	659	(173)	230	(99)	3	(6)	1,346	(333)
1985	21	(39)	340	(204)	492	(129)	214	(92)	2	(4)	1,070	(262)
1986	19	(35)	254	(153)	458	(120)	134	(58)	4	(8)	870	(206)
1987	14	(26)	236	(142)	287	(75)	272	(117)	2	(4)	812	(201)
1988	13	(24)	148	(89)	580	(152)	144	(62)	3	(5)	889	(189)
1989	8	(15)	300	(180)	308	(81)	195	(84)	3	(6)	814	(215)
1990	16	(31)	159	(96)	416	(109)	197	(85)	2	(3)	791	(171)
1991	9	(16)	215	(129)	421	(111)	118	(51)	7	(5)	770	(178)
1992	12	(22)	218	(131)	253	(66)	144	(35)	0	0	626	(152)
1993	12	(22)	131	(78)	144	(32)	68	(68)	0	0	355	(111)
1994	7	(13)	70	(18)	<i>342</i>	(141)	<i>217</i>	(72)	0	0	637	(160)
1995	0	0	<i>342</i>	(132)	<i>435</i>	(102)	<i>219</i>	(92)	0	0	996	(190)
1996	68	(68)	242	(76)	307	(104)	259	(61)	0	0	876	(158)
1997	0	0	263	(99)	462	(83)	262	(84)	0	0	987	(154)
1998	0	0	<i>146</i>	(42)	<i>436</i>	(105)	164	(25)	6	(4)	752	(116)
1999	0	0	87	(50)	295	(36)	142	(24)	16	(11)	541	(67)
2000	0	0	257	(32)	570	(66)	220	(48)	0	0	1,047	(87)
2001 ^a	18	(15)	202	(29)	784	(116)	<i>71</i>	(31)	<i>15</i>	(15)	1,089	(125)

^a The 2001 brood year was deemed complete because age-7 fish generally compose a minor portion of inriver returns.

Appendix Table F6.—Estimated inriver returns \hat{E}_i of large (≥ 660 mm MEF) Chinook salmon by total age in the Keta River for the 1975–2001 brood years. SEs are shown in (). Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples collected from 1998–2007. Escapements in years that mark–recapture experiments were not conducted are based on expanded survey counts using a factor of 3.01.

Brood year	Age 3	(SE)	Age 4	(SE)	Age 5	(SE)	Age 6	(SE)	Age 7	(SE)	Total	(SE)
1975	18	(17)	315	(137)	294	(98)	225	(147)	0	(0)	852	(224)
1976	19	(19)	142	(62)	503	(168)	478	(232)	9	(19)	1,151	(294)
1977	9	(9)	244	(106)	<i>1,672</i>	<i>(388)</i>	563	(368)	0	(0)	2,487	(545)
1978	15	(15)	<i>119</i>	<i>(119)</i>	<i>1,257</i>	(419)	<i>734</i>	<i>(244)</i>	7	(15)	2,132	(500)
1979	0	(0)	609	(264)	<i>1,102</i>	<i>(301)</i>	427	(279)	7	(16)	2,145	(488)
1980	38	(37)	0	(0)	954	(318)	472	(309)	8	(18)	1,472	(445)
1981	0	(0)	462	(200)	1,055	(352)	526	(343)	6	(13)	2,049	(531)
1982	29	(28)	511	(222)	1,174	(392)	394	(257)	12	(27)	2,119	(520)
1983	32	(31)	569	(247)	879	(293)	791	(517)	6	(14)	2,276	(644)
1984	35	(34)	426	(185)	1,766	(589)	415	(271)	3	(6)	2,644	(675)
1985	26	(26)	855	(371)	926	(309)	186	(122)	2	(5)	1,996	(499)
1986	53	(51)	449	(195)	416	(139)	149	(97)	4	(8)	1,070	(263)
1987	28	(27)	201	(87)	332	(111)	248	(162)	3	(7)	812	(217)
1988	12	(12)	161	(70)	553	(185)	209	(137)	2	(4)	938	(241)
1989	10	(10)	268	(116)	468	(156)	120	(78)	3	(7)	869	(210)
1990	17	(16)	227	(98)	268	(89)	203	(133)	3	(6)	717	(189)
1991	14	(14)	130	(56)	454	(151)	168	(110)	6	(4)	771	(196)
1992	8	(8)	220	(95)	376	(125)	234	(32)	0	(0)	838	(161)
1993	14	(13)	182	(79)	151	(23)	126	(30)	0	(0)	473	(88)
1994	11	(11)	55	(13)	509	(70)	206	(41)	0	(0)	782	(83)
1995	0	(0)	321	(52)	377	(60)	78	(27)	0	(0)	776	(84)
1996	13	(9)	318	(53)	<i>706</i>	<i>(134)</i>	395	(83)	0	(0)	1,432	(167)
1997	12	(8)	<i>217</i>	<i>(48)</i>	<i>524</i>	<i>(97)</i>	<i>170</i>	<i>(46)</i>	0	(0)	923	(118)
1998	<i>31</i>	<i>(16)</i>	<i>318</i>	<i>(62)</i>	<i>612</i>	<i>(117)</i>	<i>360</i>	<i>(86)</i>	<i>34</i>	<i>(25)</i>	1,355	(160)
1999	0	(0)	<i>187</i>	<i>(46)</i>	<i>360</i>	<i>(84)</i>	<i>120</i>	<i>(49)</i>	0	(0)	667	(108)
2000	0	(0)	<i>386</i>	<i>(87)</i>	<i>757</i>	<i>(162)</i>	<i>232</i>	<i>(81)</i>	0	(0)	1,375	(201)
2001	27	(19)	<i>516</i>	<i>(117)</i>	<i>1,623</i>	<i>(310)</i>	<i>302</i>	<i>(0)</i>			2,467	(332)

^a The 2001 brood year was deemed complete because age-7 fish generally compose a minor portion of inriver returns.

Appendix Table F7.—Estimated inriver returns \hat{E}_y , production \hat{R}_y by brood year based on Unuk River exploitation rates \hat{U}_y , the estimated abundance of their parents \hat{S}_y based on an expansion factor of 3.87, and the return per spawner (\hat{R}_y/\hat{S}_y) for the population of large (≥ 660 mm MEF) Chinook salmon spawning in the Blossom River. SEs are in parentheses where available.

Brood year	\hat{S}_y (SE)	\hat{E}_y (SE)	\hat{U}_y^a	\hat{R}_y	\hat{R}_y/\hat{S}_y
1975	565 (91)	379 (84)	<i>0.239</i>	498	0.9
1976	263 (42)	497 (165)	<i>0.239</i>	937	3.6
1977	433 (69)	1,358 (302)	<i>0.239</i>	1,785	4.1
1978	553 (89)	1,944 (411)	<i>0.239</i>	2,554	4.6
1979	209 (33)	2,228 (515)	<i>0.239</i>	2,928	14.0
1980	344 (55)	3,058 (683)	<i>0.239</i>	4,018	11.7
1981	615 (99)	4,392 (930)	<i>0.239</i>	5,771	9.4
1982	1,335 (214)	4,236 (1031)	0.207	5,339	4.0
1983	2,279 (365)	2,452 (845)	0.263	3,325	1.5
1984	1,966 (315)	1,346 (333)	0.224	1,734	0.9
1985	2,744 (440)	1,070 (262)	0.374	1,710	0.6
1986	4,946 (792)	870 (206)	0.317	1,273	0.3
1987	5,221 (836)	812 (201)	<i>0.239</i>	1,067	0.2
1988	1,486 (238)	889 (189)	<i>0.239</i>	1,168	0.8
1989	1,331 (213)	814 (215)	<i>0.239</i>	1,070	0.8
1990	995 (159)	791 (171)	<i>0.239</i>	1,039	1.0
1991	925 (148)	770 (178)	<i>0.239</i>	1,012	1.1
1992	581 (93)	626 (152)	0.167	752	1.3
1993	1,173 (188)	355 (111)	0.240	467	0.4
1994	623 (100)	637 (160)	0.224	821	1.3
1995	840 (135)	996 (190)	0.242	1,314	1.6
1996	851 (136)	876 (158)	0.190	1,082	1.3
1997	511 (82)	987 (154)	0.221	1,267	2.5
1998	364 (77)	752 (116)	0.187	926	2.5
1999	820 (131)	541 (67)	0.368	855	1.0
2000	894 (143)	1,047 (87)	0.284	1,462	1.6
2001	789 (126)	1,089 (125)	0.262	1,476	1.9

^a Rate in italics is the average of the 1982–1986 and 1992–1998 brood year estimates (from Hendrich et al. 2008) in adult equivalents.

Appendix Table F8.—Estimated inriver returns \hat{E}_y , production \hat{R}_y by brood year based on Unuk River exploitation rates, the estimated abundance of their parents \hat{S}_y based on an expansion factor of 3.01, and the return per spawner (\hat{R}_y / \hat{S}_y) for the population of large (≥ 660 mm MEF) Chinook salmon spawning in the Keta River. SEs are in parentheses where available.

Brood year	\hat{S}_y (SE)	\hat{E}_y (SE)	\hat{U}_y^a	\hat{R}_y	\hat{R}_y / \hat{S}_y
1975	611 (114)	852 (224)	<i>0.239</i>	1,120	1.8
1976	253 (47)	1,151 (294)	<i>0.239</i>	1,513	6.0
1977	692 (129)	2,487 (545)	<i>0.239</i>	3,268	4.7
1978	1,180 (220)	2,132 (500)	<i>0.239</i>	2,802	2.4
1979	1,282 (239)	2,145 (488)	<i>0.239</i>	2,818	2.2
1980	578 (108)	1,472 (445)	<i>0.239</i>	1,934	3.3
1981	990 (184)	2,049 (531)	<i>0.239</i>	2,692	2.7
1982	2,270 (422)	2,119 (520)	0.207	2,671	1.2
1983	2,474 (460)	2,276 (644)	0.263	3,087	1.2
1984	1,836 (342)	2,644 (675)	0.224	3,407	1.9
1985	1,878 (349)	1,996 (499)	0.374	3,191	1.7
1986	2,077 (386)	1,070 (263)	0.317	1,566	0.8
1987	2,312 (430)	812 (217)	<i>0.239</i>	1,067	0.5
1988	1,731 (322)	938 (241)	<i>0.239</i>	1,232	0.7
1989	3,477 (647)	869 (210)	<i>0.239</i>	1,141	0.3
1990	1,824 (339)	717 (189)	<i>0.239</i>	942	0.5
1991	819 (152)	771 (196)	<i>0.239</i>	1,014	1.2
1992	653 (122)	838 (161)	0.167	1,007	1.5
1993	1,090 (203)	473 (88)	0.240	622	0.6
1994	921 (171)	782 (83)	0.224	1,008	1.1
1995	527 (98)	776 (84)	0.242	1,023	1.9
1996	894 (166)	1,432 (167)	0.190	1,769	2.0
1997	740 (138)	923 (118)	0.221	1,186	1.6
1998	446 (50)	1,355 (160)	0.187	1,667	3.7
1999	968 (116)	667 (108)	0.368	1,055	1.1
2000	914 (122)	1,375 (201)	0.284	1,920	2.1
2001	1,032 (192)	2,467 (341)	0.262	3,343	3.2

^a Rate in italics is the average of the 1982–1986 and 1992–1998 brood year estimates (from Hendrich et al. 2008) in adult equivalents.

Appendix Table F9.—Estimated numbers \hat{N}_i of age-.2-.5 Chinook salmon by age class spawning in the Blossom River from 1975 through 2007. Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples. Age composition of all others are based on average mark–recapture and spawning ground samples collected from 1998–2007. The expansion factor for large fish included is 3.87.

Calendar year	Age class								Age-.2 to age-.5 total	<i>n</i>
	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5		
1975	12	175	38	256	30	131	2	2	647	
1976	6	81	18	119	14	61	1	1	302	
1977	9	134	29	197	23	101	2	2	497	
1978	12	171	37	251	29	129	2	2	634	
1979	5	65	14	95	11	49	1	1	239	
1980	7	107	23	156	18	80	2	1	395	
1981	13	190	41	279	33	143	3	2	705	
1982	29	413	90	606	71	311	6	5	1,530	
1983	49	705	154	1,034	121	530	10	8	2,612	
1984	43	608	132	892	105	457	9	7	2,253	
1985	60	849	185	1,245	146	638	12	10	3,144	
1986	107	1,530	333	2,245	263	1,151	22	18	5,668	
1987	113	1,615	352	2,369	278	1,215	23	19	5,983	
1988	32	460	100	674	79	346	7	5	1,703	
1989	29	412	90	604	71	310	6	5	1,526	
1990	22	308	67	451	53	231	4	4	1,140	
1991	20	286	62	420	49	215	4	3	1,060	
1992	13	180	39	263	31	135	3	2	665	
1993	25	363	79	532	62	273	5	4	1,344	
1994	14	193	42	283	33	145	3	2	714	
1995	18	260	57	381	45	195	4	3	962	
1996	18	263	57	386	45	198	4	3	976	
1997	11	158	34	232	27	119	2	2	585	
1998	0	148	17	120	23	144	0	7	458	140
<i>1999</i>	<i>68</i>	<i>410</i>	<i>0</i>	<i>273</i>	<i>68</i>	<i>68</i>	<i>0</i>	<i>0</i>	<i>889</i>	<i>14</i>
<i>2000</i>	<i>0</i>	<i>335</i>	<i>48</i>	<i>387</i>	<i>48</i>	<i>217</i>	<i>0</i>	<i>0</i>	<i>1,036</i>	<i>44</i>
<i>2001</i>	<i>0</i>	<i>0</i>	<i>263</i>	<i>307</i>	<i>0</i>	<i>219</i>	<i>0</i>	<i>0</i>	<i>789</i>	<i>18</i>
<i>2002</i>	<i>19</i>	<i>160</i>	<i>34</i>	<i>349</i>	<i>113</i>	<i>259</i>	<i>0</i>	<i>0</i>	<i>933</i>	<i>85</i>
<i>2003</i>	<i>0</i>	<i>110</i>	<i>0</i>	<i>378</i>	<i>58</i>	<i>233</i>	<i>29</i>	<i>0</i>	<i>808</i>	<i>29</i>
2004	18	357	30	282	18	164	0	0	869	345
2005	10	433	28	567	3	140	3	6	1,190	398
2006	11	202	71	787	8	220	0	16	1,314	166
<i>2007</i>	<i>34</i>	<i>222</i>	<i>14</i>	<i>240</i>	<i>42</i>	<i>71</i>	<i>0</i>	<i>0</i>	<i>623</i>	<i>47</i>

^a The age-.2-.5 total does not include age-1.1 fish.

Appendix Table F10.—Estimated numbers \hat{N}_i of age-2-.5 Chinook salmon by age class spawning in the Keta River from 1975 through 2007. Bold numbers came directly from mark–recapture experiments, numbers in italics are from spawning ground samples. Age composition of all others are based on average mark–recapture and spawning ground samples collected from 1998–2007. The expansion factor for large fish included is 3.01.

Calendar year	Age class									Age-.2 to age-.5 total	<i>n</i>
	1.1	0.2	1.2	0.3	1.3	0.4	1.4	0.5	1.5		
1975	39	10	207	32	275	22	151	0	0	698	
1976	16	4	86	13	114	9	63	0	0	289	
1977	44	12	234	37	312	25	172	0	0	791	
1978	74	20	400	63	531	42	292	0	0	1,347	
1979	81	21	434	68	577	45	318	0	0	1,464	
1980	36	10	196	31	260	20	143	0	0	660	
1981	62	17	335	53	446	35	245	0	0	1,131	
1982	0	0	239	0	1,672	0	478	0	0	2,389	20
1983	156	41	838	131	1,114	88	613	0	0	2,826	
1984	0	0	92	0	826	275	734	0	0	1,928	21
1985	119	31	636	100	846	66	465	0	0	2,145	
1986	131	35	703	110	935	74	515	0	0	2,372	
1987	146	39	783	123	1,041	82	573	0	0	2,640	
1988	109	29	586	92	779	61	429	0	0	1,976	
1989	219	58	1,177	185	1,566	123	861	0	0	3,970	
1990	115	31	618	97	821	65	452	0	0	2,083	
1991	52	14	277	43	369	29	203	0	0	935	
1992	41	11	221	35	294	23	162	0	0	746	
1993	69	18	369	58	491	39	270	0	0	1,244	
1994	58	15	312	49	415	33	228	0	0	1,052	
1995	33	9	178	28	237	19	131	0	0	602	
1996	56	15	303	47	403	32	222	0	0	1,021	
1997	47	12	251	39	333	26	183	0	0	846	
1998	9	5	131	13	126	30	234	0	6	545	185
1999	21	13	323	25	471	38	113	13	0	995	170
2000	0	62	608	35	354	24	206	0	0	1,289	200
2001	175	40	216	124	701	23	70	8	0	1,181	171
2002	23	17	498	65	465	65	395	0	0	1,505	261
2003	300	11	333	43	581	43	170	0	0	1,180	162
2004	177	36	471	53	320	40	346	13	0	1,279	119
2005	44	91	553	52	757	0	120	0	34	1,607	94
2006	44	23	387	116	1,553	70	232	0	0	2,381	105
2007	36	15	199	45	453	30	302	0	0	1,045	70

^a The age-.2-.5 total does not include age-1.1 fish, which are likely underestimated.

Appendix Table F11.—Estimated inriver returns \hat{E}_y , production \hat{R}_y by brood year based on Unuk River exploitation rates \hat{U}_y , the estimated abundance of their parents \hat{S}_y , and the return per spawner (\hat{R}_y / \hat{S}_y) for the population of age-2-.5 Chinook salmon spawning in the Blossom River.

Brood year	\hat{S}_y (SE)	\hat{E}_y (SE)	\hat{U}_y ^a	\hat{R}_y	\hat{R}_y / \hat{S}_y
1975	647 (118)	416 (86)	<i>0.239</i>	547	0.8
1976	302 (55)	589 (165)	<i>0.239</i>	1,013	3.4
1977	497 (90)	1,464 (301)	<i>0.239</i>	1,923	3.9
1978	634 (115)	2,148 (430)	<i>0.239</i>	2,822	4.4
1979	239 (43)	2,552 (584)	<i>0.239</i>	3,354	14.0
1980	395 (72)	3,372 (709)	<i>0.239</i>	4,431	11.2
1981	705 (128)	4,826 (959)	<i>0.239</i>	6,342	9.0
1982	1,530 (278)	4,926 (1190)	<i>0.207</i>	6,209	4.1
1983	2,612 (474)	3,146 (1087)	<i>0.263</i>	4,266	1.6
1984	2,253 (409)	1,587 (387)	<i>0.224</i>	2,045	0.9
1985	3,144 (571)	1,259 (311)	<i>0.374</i>	2,013	0.6
1986	5,668 (1,029)	1,014 (240)	<i>0.317</i>	1,485	0.3
1987	5,983 (1,086)	944 (231)	<i>0.239</i>	1,241	0.2
1988	1,703 (309)	984 (195)	<i>0.239</i>	1,293	0.8
1989	1,526 (277)	972 (262)	<i>0.239</i>	1,278	0.8
1990	1,140 (207)	890 (185)	<i>0.239</i>	1,169	1.0
1991	1,060 (192)	889 (205)	<i>0.239</i>	1,168	1.1
1992	665 (121)	741 (187)	<i>0.167</i>	891	1.3
1993	1,344 (244)	423 (130)	<i>0.240</i>	557	0.4
1994	714 (130)	735 (163)	<i>0.224</i>	947	1.3
1995	962 (175)	1,064 (203)	<i>0.242</i>	1,404	1.5
1996	976 (177)	1,018 (170)	<i>0.190</i>	1,258	1.3
1997	585 (106)	987 (154)	<i>0.221</i>	1,267	2.2
1998	536 (92)	800 (119)	<i>0.187</i>	983	1.8
1999	889 (149)	587 (72)	<i>0.368</i>	928	1.0
2000	1,056 (156)	1,177 (98)	<i>0.284</i>	1,643	1.6
2001	789 (126)	1,360 (152)	<i>0.262</i>	1,842	2.3

^a Rate in italics is the average of the 1982–1986 and 1992–1998 brood year estimates (from Hendrich et al. 2008) in adult equivalents.

Appendix Table F12.—Estimated inriver returns \hat{E}_y , production \hat{R}_y by brood year based on Unuk River exploitation rates \hat{U}_y , the estimated abundance of their parents \hat{S}_y based on an expansion factor of 3.01, and the return per spawner (\hat{R}_y / \hat{S}_y) for the population of age-2-5 Chinook salmon spawning in the Keta River.

Brood year	\hat{S}_y (SE)	\hat{E}_y (SE)	\hat{U}_y^a	\hat{R}_y	\hat{R}_y / \hat{S}_y
1975	698 (121)	1,048 (236)	<i>0.239</i>	1,377	2.0
1976	289 (50)	1,207 (300)	<i>0.239</i>	1,586	5.5
1977	791 (137)	2,683 (554)	<i>0.239</i>	3,525	4.5
1978	1,347 (234)	2,192 (516)	<i>0.239</i>	2,880	2.1
1979	1,464 (254)	2,536 (505)	<i>0.239</i>	3,332	2.3
1980	660 (115)	1,560 (462)	<i>0.239</i>	2,050	3.1
1981	1,131 (196)	2,317 (554)	<i>0.239</i>	3,045	2.7
1982	2,389 (440)	2,397 (545)	<i>0.207</i>	3,021	1.3
1983	2,826 (491)	2,642 (670)	<i>0.263</i>	3,583	1.3
1984	1,928 (354)	2,857 (706)	<i>0.224</i>	3,682	1.9
1985	2,145 (372)	2,480 (532)	<i>0.374</i>	3,963	1.8
1986	2,372 (412)	1,332 (282)	<i>0.317</i>	1,951	0.8
1987	2,640 (458)	938 (226)	<i>0.239</i>	1,233	0.5
1988	1,976 (343)	1,027 (251)	<i>0.239</i>	1,350	0.7
1989	3,970 (689)	1,016 (222)	<i>0.239</i>	1,335	0.3
1990	2,083 (362)	856 (198)	<i>0.239</i>	1,125	0.5
1991	935 (162)	845 (205)	<i>0.239</i>	1,110	1.2
1992	746 (130)	953 (170)	<i>0.167</i>	1,144	1.5
1993	1,244 (216)	587 (95)	<i>0.240</i>	772	0.6
1994	1,052 (183)	872 (88)	<i>0.224</i>	1,125	1.1
1995	602 (104)	807 (85)	<i>0.242</i>	1,065	1.8
1996	1,021 (177)	1,775 (196)	<i>0.190</i>	2,192	2.1
1997	846 (147)	1,102 (127)	<i>0.221</i>	1,414	1.7
1998	545 (60)	1,620 (172)	<i>0.187</i>	1,993	3.7
1999	995 (117)	873 (122)	<i>0.368</i>	1,381	1.4
2000	1,289 (168)	1,523 (206)	<i>0.284</i>	2,128	1.7
2001	1,181 (209)	2,566 (335)	<i>0.262</i>	3,477	2.9

^a Rate in italics is the average of the 1982–1986 and 1992–1998 brood year estimates (from Hendrich et al. 2008) in adult equivalents.