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Speel Lake Sockeye Salmon Stock Status and Escapement Goal Review

by

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Weights and measures (metric)	
centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm
Weights and measures (English)	
cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd
Time and temperature	
day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s
Physics and chemistry	
all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

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

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

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ABSTRACT

We reviewed the sockeye salmon (*Oncorhynchus nerka*) escapement goal for Speel Lake, a small system located approximately 50 km southeast of Juneau, Alaska, that contributes to commercial drift gillnet fisheries in Southeast Alaska District 11. The current biological escapement goal of 4,000–13,000 fish was established in 2003, based on stock-recruit analysis of the 1983–1996 brood years, which required expansion of incomplete weir counts in nearly all years in the time series. In order to address shortcomings of the dataset and problematic assumptions of the simple linear regression method, we used Bayesian statistical methods to assess uncertainty in the presence of measurement error in escapement counts, serial correlation, and missing data (two missing years of escapement data and four years of missing harvest data). We fit an age-structured state-space spawner–recruit model to harvest data and age composition of the total run from 1983 to 2011, along with estimates of expanded escapement counts (based on a longer time series of complete weir counts). A sustainable escapement goal of 4,000–9,000 fish is recommended for Speel Lake sockeye salmon based on the range of escapements estimated to provide greater than 70–80% of maximum sustained yield.

Key words: age composition, age-structured model, Bayesian statistics, state space, escapement goal, maximum sustained yield, measurement error, missing data, OpenBugs, Snettisham Hatchery, sockeye salmon, *Oncorhynchus nerka*, Speel Lake, spawner-recruit analysis, spawning abundance.

INTRODUCTION

Speel Lake, located on mainland Alaska about 50 km southeast of Juneau, supports a small run of sockeye salmon (*Oncorhynchus nerka*), which are harvested primarily in the Southeast Alaska District 11 commercial drift gillnet fisheries in Taku Inlet, Stephens Passage, and Port Snettisham (Figure 1; Appendix C). Wild Speel Lake sockeye salmon have also been harvested in hatchery common property and cost recovery fisheries conducted in Speel Arm, Port Snettisham, since the late 1990s. Peak migration timing for wild Snettisham sockeye salmon (Crescent and Speel lakes) through Stephens Passage is normally from mid-July through the first week in August (Alaska Department of Fish and Game [ADF&G], 2004).

On average, Speel Lake sockeye salmon represent a small portion of the harvest in the traditional mixed stock District 11 fishery (Riffe and Clark 2003). From 1983 to 1998, sockeye salmon harvests in the traditional District 11 fishery were dominated by wild stocks from the Taku River drainage (82%) and Speel and Crescent lakes in Port Snettisham (15%) (TTC 2012b). Those proportions changed in the late 1990s as a result of increased production from mostly domestic sockeye salmon enhancement projects. From 1999 to 2008, District 11 harvests were composed of wild stocks from the Taku River drainage (64%), hatchery fish from Snettisham Hatchery (26%), wild fish from Speel and Crescent lakes in Port Snettisham (7%), and sockeye salmon produced from U.S./Canada enhancement projects in the Taku River drainage (2%) (Transboundary Technical Committee [TTC] unpublished data).

The Snettisham Hatchery was established by the State of Alaska in 1976 at the Snettisham hydropower facility, adjacent to the mouth of the Speel River, six miles down-river from Speel Lake. The hatchery was converted into a sockeye salmon central incubation facility in the 1990s and dedicated exclusively to sockeye salmon production by 1995 (Riffe and Clark 2003). Speel Lake sockeye salmon were used as the brood source to develop a self-sustaining run to the facility. In 1996, the state transferred operation of Snettisham Hatchery to Douglas Island Pink and Chum, Inc. (DIPAC). The annual Snettisham Hatchery management plan[1] includes stipulations for DIPAC to operate an adult counting weir at Speel Lake and, if the escapement goal is not met for two consecutive years, to develop a recovery plan and conduct egg takes and back-plants at Speel Lake in consultation with ADF&G. In addition, the Alaska Board of Fisheries adopted the *District 11: Snettisham Hatchery Salmon Management Plan* (5 AAC 33.378) into regulation in 2000. The plan requires the department to manage Snettisham hatchery production and returns to sustain production of wild sockeye salmon from Crescent and Speel lakes, and to conduct common property harvests in the special harvest area (in Speel Arm) by limiting time and area of harvest through emergency order authority. Thus, the Speel Lake sockeye salmon escapement goal is an integral part of managing Snettisham hatchery production and terminal harvests, while sustaining production of nearby wild stocks.

The department managed the Speel Lake sockeye salmon run to achieve informal escapement goals of 10,000 sockeye salmon during the 1980s and 5,000 sockeye salmon from 1992 to 2002 (Riffe and Clark 2003). In 2003, a biological escapement goal of 4,000–13,000 sockeye salmon was established based on run-reconstruction for the years 1983–2002 and stock-recruit analysis of the 1983–1996 brood years (Riffe and Clark 2003). Riffe and Clark (2003) outlined the challenges these data presented and the resulting uncertainty in their analysis. The primary concern was that escapement estimates in all but three years were incomplete—the Speel Lake weir was removed in late August, missing a large portion of the escapement that passed in September, and available information was insufficient to properly reconstruct weir counts. Riffe and Clark (2003) recommended the Speel Lake weir continue to be operated through late September to ensure complete enumeration of the escapement, and recommended the escapement goal be reviewed once sufficient new information had been collected.

The Speel Lake weir has been operated annually into late September since 2002, providing a much better base to recalibrate historical weir counts. In our analysis, historical weir counts were expanded by regressing cumulative escapement by date on cumulative total weir counts. This expansion has the potential for large measurement error in the spawning escapement counts. To calculate reference points and to provide an escapement goal range, Riffe and Clark (2003) used the traditional Ricker stock-recruit analysis (SRA) with simple linear regression (SLR) procedures. One assumption of SLR is that the number of spawners is measured without error. Failure to meet this assumption can cause substantial bias in estimates of management reference points (Kehler et al. 2002, Kope 2006, Su and Peterman 2012). Also, SRA based on SLR methods cannot account for serially correlated process errors or brood years that are incomplete (i.e., missing data).

In order to address the shortcomings of the dataset for Speel Lake sockeye salmon and the problematic assumptions of the SLR method, we used a Bayesian age-structured state-space model to conduct stock-recruit analysis of updated Speel Lake sockeye salmon data and provide information to update the escapement goal. The state-space model estimates all parameters simultaneously, accounts for both observation (measurement) error as well as process variation (natural fluctuations in the actual quantities), and allows for missing data. Posterior medians from the state-space model are less biased and interval estimates have better coverage of the

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[1] Snettisham Management Plan, 2013, unpublished document. http://www.adfg.alaska.gov/index.cfm?adfg=fishingHatcheriesPlanning.annual (Accessed May 7, 2014).

estimated spawning size that produces maximum sustained yield in the presence of observation error in spawning escapement (Su and Peterman 2012).

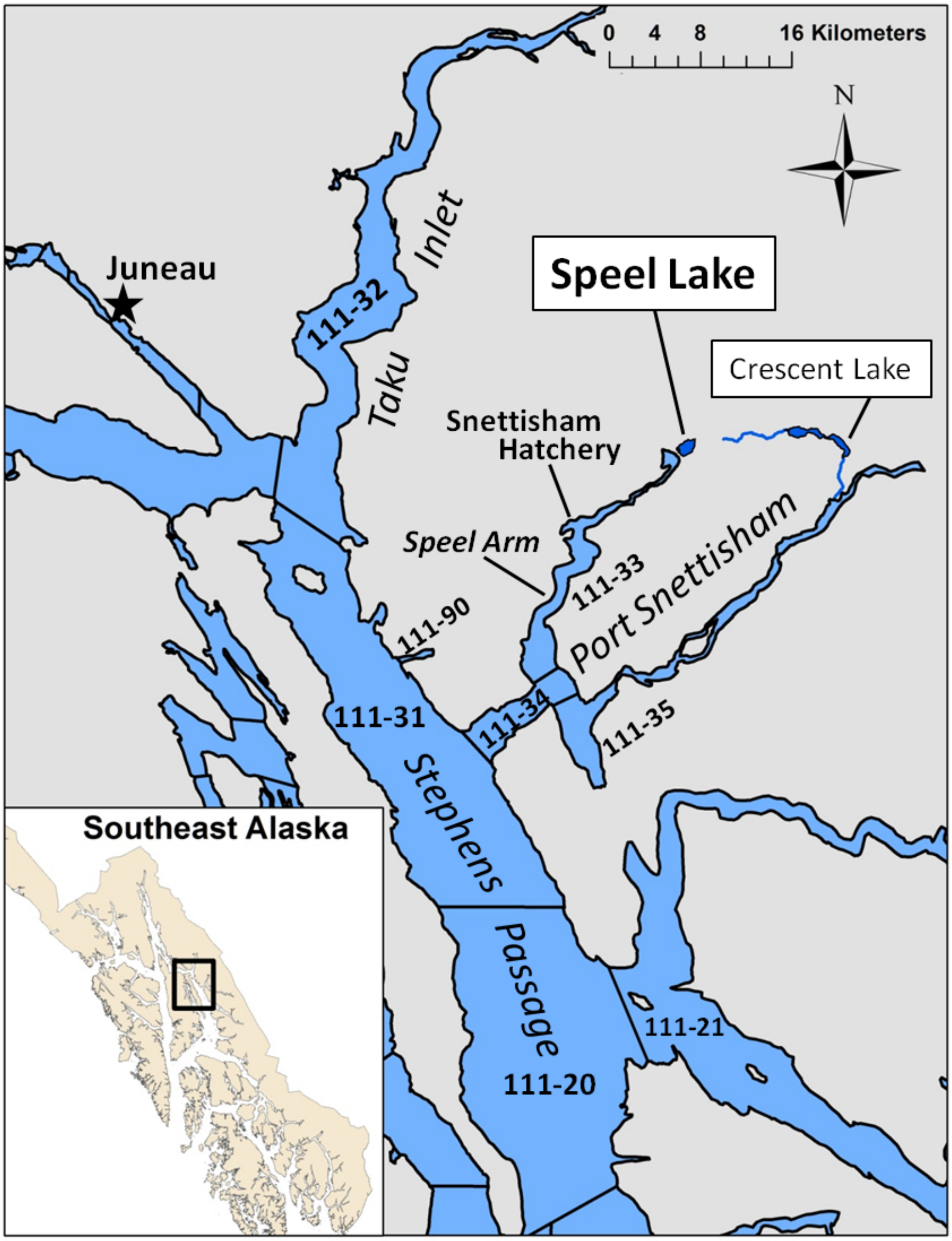

Figure 1.–Map of the District 11 Taku-Snettisham commercial drift gillnet fishing area, including numbered subdistricts and the locations of Speel Lake, Speel Arm, and Snettisham Hatchery.

METHODS

The state-space model requires the following input data: 1) estimates and associated coefficient of variations (CVs) of harvest; 2) estimates and associated CVs of escapement counts; and 3) age composition of the total run (harvest and escapement data combined). Sources of these data components are described in the following sections.

HARVEST ESTIMATES

Information regarding Speel Lake sockeye salmon harvests is limited to data from District 11 fisheries (subdistricts 20, 31, 32, 33, 34, 35, and 90). Speel Lake fish must migrate through other, more distant, mixed stock fisheries where small numbers are certainly harvested; e.g., commercial purse seine fisheries in Icy and Chatham straits that are managed to harvest pink salmon (*O. gorbuscha*). Stock composition of sockeye salmon harvests in distant mixed stock fisheries, however, are not known but are likely dominated by very large northern Southeast Alaska sockeye salmon stocks (e.g., Chilkat, Chilkoot, Taku, and Snettisham Hatchery) and include contributions from many other small sockeye salmon runs (Eggers et al. 2010). We assumed harvests of Speel Lake sockeye salmon outside of District 11 were negligible in most years compared to harvest in District 11.

Estimated total harvests of Speel Lake sockeye salmon by age, 1986–2011, are presented in Table 1. An estimate of the harvest was not available for 1991, because the Speel Lake escapement was too small (299 fish) to provide sufficient samples for scale pattern analysis (Riffe and Clark 2003). Estimates of harvest after 2011 were not available because U.S./Canada stock identification methods switched from scale pattern analysis to genetic stock identification in 2012 (TTC 2012a), and analyses are pending.

District 11 harvest—Stephens Passage and Taku Inlet

Estimates of Speel Lake sockeye salmon harvests in the traditional District 11 drift gillnet fishery in Stephens Passage and Taku Inlet (subdistricts 20, 31, 32, and 90) were available from U.S./Canada stock identification studies conducted since the mid-1980s. Scale pattern analysis was used from 1983 to 1985 to estimate annual contributions of aggregate Taku River and Port Snettisham sockeye salmon stocks (McGregor 1985), but was refined in 1986 to provide separate estimates for four Taku stocks (Kuthai, Little Trapper, Little Tatsamenie, and mainstem spawners), based on run timing from Taku River fish wheel catches, and two Port Snettisham stocks (Crescent and Speel) (McGregor and Walls 1987). Jensen and Bloomquist (1994) summarized the methods used to conduct scale pattern analysis through 1990. Further refinements included analysis of brain parasites (*Myxobolus arcticus*; Moles and Jensen 2000) beginning in 1992 (TTC 1993), thermal-mark sampling to identify hatchery-produced fish beginning in 1995 (TTC 1997), and addition of King Salmon Creek (Taku stock) in most years since 2003 (TTC 2005).

Annual harvest estimates of Speel Lake sockeye salmon have been reported in ADF&G and Pacific Salmon Commission Transboundary Technical Committee reports through 2008 (TTC 2012b). With the exception of the years 1986–1988, however, those reports lack age-specific information needed to reconstruct annual Speel Lake runs. We obtained estimated harvests by age for the years 1989–2011 directly from the original summary analyses provided by ADF&G. These analyses were contained in Excel spreadsheets that included stock composition estimates from model outputs of scale pattern and other analyses and calculations involving model outputs and catch and sampling data[2]. We reviewed spreadsheet calculations and updated data associated

[2] To assign the Speel origin fish in the District 11 mixed stock fishery, non-thermally marked escapement and harvest samples of the dominant age classes (ages 1.2 and 1.3) were digitized, grouped by the presence or absence of brain parasites and by run timing, and modeled using the linear discriminant function (Jensen and Bloomquist 1994). For the minor age classes (2.2, 2.3, .0 and other), estimates were based on their proportion in the escapement data; all .0 aged fish were considered mainstem Taku River spawners. Estimates were then proportionally applied to the weekly wild harvest; determined by the proportion of hatchery harvest processed through age, sex, and length (ASL) samples matched to otolith samples. Proportions of thermally marked fish in the ASL samples were applied to the total harvest weighted by statistical

with the calculations, including catch data, and age composition of catch and escapements from scale sampling data. As a result, our annual estimates of the Speel Lake sockeye salmon harvest are slightly different from reported values, but are within 3% on average.

District 11 harvest—Port Snettisham

Speel Lake sockeye salmon are harvested in traditional drift gillnet fisheries and hatchery common property and cost recovery fisheries conducted inside Port Snettisham; in the entrance to Port Snettisham (subdistrict 34); in Gilbert Bay, on the south side of Port Snettisham (subdistrict 35); and in Speel Arm, on the north side of Port Snettisham (subdistrict 33) (Figure 1). Sockeye salmon harvests in these fisheries were not included in US/Canada stock separation studies because harvests were assumed to comprise 100% domestic stocks (Speel, Crescent, and hatchery fish). Otolith sampling provided estimates of the contribution of hatchery and wild fish in these fisheries. Age composition was assumed to be the same as the age composition in the Stephens Passage–Taku Inlet fisheries.

Traditional common property drift gillnet fisheries

Otolith sampling of traditional common property fisheries inside Port Snettisham provided estimates of the contributions of wild and hatchery fish. To estimate the contribution of Speel Lake fish we made the following assumptions:

Speel Arm (subdistrict 33): Traditional common property fisheries were conducted in several years in the early 1990s, prior to returns of hatchery fish; the largest total harvest of sockeye salmon was 2,742 in 1992, and smaller harvests (<100 fish) were made in 1987, 1993, and 1994. We assumed these harvests were 90% wild Speel Lake and 10% wild Crescent Lake fish.

Entrance to Port Snettisham (subdistrict 34): Traditional common property fisheries were conducted nearly annually. Small harvests of sockeye salmon (<700 fish) were made in most years prior to 2000, followed by much larger harvests from 2000 to 2007 (range: 2,024–63,514). We assumed that annual proportions of wild Speel Lake and Crescent Lake sockeye salmon in this subdistrict were the same as the annual proportions of the two stocks in Stephens Passage–Taku Inlet as estimated from U.S./Canada stock identification analyses.

Gilbert Bay (subdistrict 35): A traditional common property fishery was conducted in only one year, 1996 (harvest 820 sockeye salmon). We assumed the wild sockeye salmon harvest was 90% wild Crescent Lake and 10% wild Speel Lake fish.

Hatchery cost recovery fisheries

Hatchery cost recovery fisheries were conducted annually in the Speel Arm Special Harvest Area (subdistrict 33) beginning in 1996. Harvests averaged 73,000 sockeye salmon and ranged from 5,273 (1996) to 209,585 (2004) fish. Otolith sampling was conducted by DIPAC during most weeks in most years. The DIPAC otolith data were used to apportion the wild versus hatchery percentage in the catch. If there was harvest during a statistical week when DIPAC did not collect samples, the percentage from a close week within the same year, was used as the percentage of hatchery versus wild in the harvest. The boundaries of the cost recovery area changed in 2002. Prior to 2002, cost recovery was conducted in a broad region of the Speel Arm

week and subdistrict by age class. To obtain the wild harvest, the total enhanced harvest was subtracted from the total harvest. To calculate the final weekly stock specific contributions, the weekly wild harvest was multiplied by the weekly stock proportions.

Special Harvest Area. In 2002, the cost recovery area was restricted to the west side of Speel Arm north of Bride Point. As a result, the percentage of wild fish in the cost recovery harvest declined from an average of about 4% during 1996–2001 to an average of less than 1% since 2002. Hatchery cost recovery fisheries were also conducted in Gilbert Bay (subdistrict 35) from 1994–1999. We assumed those harvests were entirely (100%) hatchery fish (i.e., 0% wild Speel Lake fish).

Hatchery common property fisheries

Hatchery common property fisheries have been conducted nearly annually in the Speel Arm Special Harvest Area since 1998 (with the exception of 2007–2009). Harvests averaged 33,000 sockeye salmon and ranged from 602 (1998) to 127,746 (2006) fish. The Special Harvest Area is defined as those waters in Speel Arm north of the latitude of 58° 03.42'N (a point about 0.5 nautical miles south of Bogart Point). Otolith sampling of those harvests was conducted intermittently due to the difficulty of obtaining clean samples. Therefore, DIPAC cost recovery samples from 1998 to 2011, weighted by the total cost recovery harvest by week, were used to apportion the wild versus hatchery percentage in the catch. For statistical weeks 29–35 (approximately mid-July to late August), the percentages of wild Speel fish in the harvest were 0.1, 0.1, 1.9, 1.2, 1.2, 0.0, and 0.1.

Table 1.–Estimated total harvest of Speel Lake sockeye salmon and harvest proportions by age, 1983–2011. Harvest estimates were not available for 1983–1985, and 1991.

	Traditional fishery harvest		Hatchery fishery harvest			Harvest proportion by age		
Year	Stephens Passage –Taku Inlet	Port Snettisham	Common property Speel Arm	Cost recovery Speel Arm	Total harvest	Age 4	Age 5	Age 6
1983	ND	ND	0	0	ND	ND	ND	ND
1984	ND	ND	0	0	ND	ND	ND	ND
1985	ND	ND	0	0	ND	ND	ND	ND
1986	5,346	0	0	0	5,346	0.42	0.53	0.06
1987	9,284	0	0	0	9,284	0.01	0.96	0.03
1988	2,637	0	0	0	2,637	0.41	0.57	0.02
1989	7,425	0	0	0	7,425	0.14	0.78	0.08
1990	4,065	0	0	0	4,065	0.29	0.64	0.07
1991	ND	ND	0	0	ND	ND	ND	ND
1992	7,562	2,464	0	0	10,026	0.22	0.73	0.05
1993	18,399	2	0	0	18,401	0.13	0.82	0.05
1994	1,414	101	0	0	1,515	0.05	0.94	0.01
1995	8,116	1	0	0	8,117	0.31	0.57	0.11
1996	6,239	37	0	665	6,941	0.05	0.95	0.00
1997	2,515	34	0	585	3,134	0.11	0.88	0.01
1998	513	36	0	847	1,396	0.56	0.43	0.01
1999	1,492	0	2	53	1,547	0.35	0.63	0.01
2000	9,085	63	130	563	9,841	0.32	0.68	0.00
2001	9,501	407	26	3,380	13,314	0.26	0.74	<0.01
2002	6,070	408	265	98	6,841	0.45	0.55	<0.01
2003	6,043	6,753	298	1,485	14,579	0.05	0.95	0.00
2004	7,256	3,332	277	1,117	11,982	0.09	0.91	<0.01
2005	6,809	822	65	1,015	8,711	0.07	0.91	0.03
2006	4,550	2,192	1,037	406	8,185	0.29	0.70	0.02
2007	2,512	197	0	562	3,271	0.27	0.68	0.06
2008	5,732	0	0	0	5,732	0.17	0.83	0.00
2009	5,492	0	0	0	5,492	0.06	0.94	0.00
2010	7,422	0	15	257	7,694	0.08	0.91	0.01
2011	2,600	13	2	69	2,684	0.07	0.88	0.05

ESCAPEMENT ESTIMATES

Sockeye salmon escapements at Speel Lake have been measured with a salmon counting weir in all years since 1983, except 1993 and 1994 (Appendix B.1). The weir, located in the outlet stream a short distance below the lake, was operated by ADF&G through 1995 and by DIPAC since 1996. The weir is relatively small, about 70 feet long, with six wooden tripods in the center that support aluminum channel and pickets across the face and a trap on the upstream side for sampling fish. The 8-foot long aluminum channel stringers are drilled to accommodate 43, ¾-inch EMT electrical conduit pickets at 2-1/8-inch center-to-center spacing. This spacing prevents adult sockeye salmon (age 2- and 3-ocean fish) from swimming through the weir uncounted, but allows jack sockeye salmon (age 1-ocean males <400 mm mideye to fork length) to swim through weirs with this picket spacing (Riffe 2005, Brunette and Piston 2013). A mark-recapture study conducted at Speel Lake in 2004 corroborated the weir count of large fish, but it was estimated that 7% of the population, primarily jacks, was not counted at the weir (Riffe 2005). Very few jacks have been observed or sampled at the weir (Eric Prestegard, DIPAC, personal communication) and most probably swim through the pickets undetected (Riffe and Clark 2003).

We assume accurate counts of adult sockeye salmon were obtained when the weir was operated. Weir operations in many years, however, did not encompass the entire run, which extends from mid-July to late September. The weir was not installed until 1 August in 1995, and it was removed between 26 August and 8 September in 1984–1992 and 1996–2001. Weir counts in those years had to be expanded in order to estimate total escapement. Weir counts in 1988 (969) and 1991 (299) were also unusually small, which may indicate problems with weir operations in those years. Finally, the weir was not operated in 1993 and 1994.

Thirteen years of complete weir data (1983 and 2002–2013) were used as base years with which to expand truncated weir counts using simple linear regression. We expanded the 1995 weir count first, which was missing escapement data prior to 1 August, by regressing cumulative escapement between 1 August and late September in the base years against total escapement in the base years. The expanded 1995 escapement was then added to the base years. Weir counts in all other years were then expanded by regressing cumulative escapement by date (26 August–8 September) in the base years (including 1995) against total escapement in the base years (Table 2). For example, in 2001 the weir was terminated on 1 September and the total weir count up to that date was 8,060 (X) sockeye salmon. To determine the expansion, cumulative escapement to 1 September (X) in the base years was regressed against total escapement in the base years (Y). Using the results of this regression,

$$\hat{Y}_i = a + bX_i, \tag{1}$$

the expanded weir count in 2001 ($\hat{Y}$) was then calculated as 9,349, where a = 103 and b = 1.15. The standard error $(s_{\hat{Y}_y})_1$ of the weir expansions were then calculated as,

$$(s_{\hat{Y}_y})_1 = \sqrt{s^2_{Y \bullet X}[1 + \frac{1}{n} + \frac{(X_i - \overline{X})^2}{\sum x^2}]}, \text{where } \sum x^2 = \sum X_i^2 - (\sum X_i)^2 / n, \tag{2}$$

and n = 14, (the number of base years) (Zar 1999) (Table 2).

In 1995, a much larger portion of the escapement occurred after 8 September than in the other base years, which introduced more uncertainty into the expansion regressions. By 8 September, 90–100% of the run had passed the weir in the base years 1983 and 2002–2013, while in 1995 only 80% of the run had passed the weir by this date. While the regressions of cumulative escapement by date in the base years (including 1995) against total escapement in the base years had an R^2 of >90% for the cumulative escapement from 1 September on, the regressions using cumulative escapement by date prior to 1 September had R^2 values as low as 54%. Expanded weir counts based on these regressions prior to 1 September had higher CVs than those using the regression of cumulative escapement from 1 September on (Table 2).

Table 2.–Speel Lake escapement expansions for years of early weir removal (1984–1992; 1996–2001) and late weir installation (1995), compared to expanded weir counts used by Riffe and Clark (2003).

Year	Date that weir project terminated	Weir count	Slope (*b*)	Intercept (*a*)	Expanded weir count	SE	CV	Riffe and Clark (2003)
1984	8-Sep	9,764	1.11	-217	10,619	452	4%	11,424
1985	29-Aug	7,073	0.92	1643	8,157	1,684	21%	14,483
1986	29-Aug	5,857	0.92	1643	7,037	1,614	23%	11,062
1987	27-Aug	9,353	0.90	1848	10,257	1,988	19%	35,927
1988	31-Aug	969	1.07	783	1,819	1,414	78%	1,903
1989	5-Sep	12,854	1.11	-113	14,198	596	4%	15,039
1990	29-Aug	18,095	0.92	1643	18,309	3,393	19%	34,463
1991	29-Aug	299	0.92	1643	1,918	1,842	96%	359
1992	26-Aug	9,439	0.88	1959	10,299	2,063	20%	15,623
1995[a]	1-Aug	7,668	1.01	428	8,201	521	6%	7,668
1996	1-Sep	10,442	1.15	103	12,082	942	8%	16,215
1997	1-Sep	4,999	1.15	103	5,838	748	13%	6,906
1998	27-Aug	13,358	0.90	1848	13,858	2,616	19%	26,155
1999	30-Aug	10,277	0.92	1622	11,060	2,011	18%	22,115
2000	31-Aug	6,763	1.07	783	8,011	1,299	16%	9,426
2001	1-Sep	8,060	1.15	103	9,349	815	9%	12,735

[a] Weir not installed until 1 August 1995; calculation for 1995 was to estimate escapement prior to 1 August; calculations in all other years were to estimate escapement after weir removal.

Hatchery brood stock, collected at Speel Lake nearly annually from 1988 to 1996, was subtracted from estimated escapements to provide estimates of spawning escapement for stock-recruit analysis (Table 3). Age composition of the escapement was estimated from scale samples collected annually at the weir (1983–1992 and 1995–2011) and from scale samples collected on the spawning grounds (1993–1994). An average of 1,000 scale samples were collected annually, of which an average of 72% could be aged. The large sample sizes were adequate to estimate proportions of dominant age classes with high precision in most years (Appendix B.2). Escapements were dominated by 4-year-old (average 42%) and 5-year-old (average 52%) fish.

Table 3.–Estimated Speel Lake sockeye salmon escapement by age, 1983–2013. The weir was not operated 1993–1994; age composition in those years was estimated from samples obtained on the spawning grounds.

Year	Weir count	Weir end date	Estimated escapement	Brood-stock removed	Estimated spawning escapement	Escapement proportion by Age			
						Age 3	Age 4	Age 5	Age 6
1983	10,484	19-Nov	10,484	0	10,484	0.02	0.33	0.63	0.02
1984[a]	9,764	8-Sep	10,619	0	10,619	0.00	0.43	0.56	0.01
1985[a]	7,073	29-Aug	8,157	0	8,157	0.08	0.24	0.68	0.01
1986[a]	5,857	29-Aug	7,037	0	7,037	<0.01	0.53	0.43	0.03
1987[a]	9,353	27-Aug	10,257	0	10,257	0.00	0.08	0.91	0.01
1988[a]	969	31-Aug	1,819	259	1,560	<0.01	0.40	0.58	0.02
1989[a]	12,854	5-Sep	14,198	2,115	12,083	<0.01	0.29	0.65	0.06
1990[a]	18,095	29-Aug	18,309	1,197	17,112	<0.01	0.45	0.52	0.02
1991[a]	299	29-Aug	1,918	0	1,918	0.01	0.24	0.72	0.03
1992[a]	9,439	26-Aug	10,299	1,517	8,782	0.00	0.57	0.41	0.02
1993	ND	ND	ND	1,042	ND	0.00	0.35	0.62	0.03
1994	ND	ND	ND	628	ND	0.04	0.22	0.74	0.01
1995[a]	7,668	12-Sep	8,201	1,703	6,498	<0.01	0.53	0.36	0.10
1996[a]	10,442	1-Sep	12,082	1,927	10,155	0.02	0.17	0.82	<0.01
1997[a]	4,999	1-Sep	5,838	0	5,838	0.02	0.69	0.28	0.01
1998[a]	13,358	27-Aug	13,858	0	13,858	0.03	0.48	0.48	<0.01
1999[a]	10,277	30-Aug	11,060	0	11,060	0.03	0.36	0.60	0.01
2000[a]	6,763	31-Aug	8,011	0	8,011	0.05	0.60	0.34	<0.01
2001[a]	8,060	1-Sep	9,349	0	9,349	0.08	0.52	0.39	<0.01
2002	5,071	20-Sep	5,071	0	5,071	0.01	0.76	0.22	<0.01
2003	7,014	18-Sep	7,014	0	7,014	0.01	0.39	0.60	<0.01
2004	7,813	19-Sep	7,813	0	7,813	<0.01	0.56	0.44	<0.01
2005	7,549	20-Sep	7,549	0	7,549	0.16	0.39	0.44	0.01
2006	4,165	16-Sep	4,165	0	4,165	0.01	0.64	0.34	<0.01
2007	3,099	21-Sep	3,099	0	3,099	0.00	0.18	0.81	0.02
2008	1,763	20-Sep	1,763	0	1,763	0.01	0.40	0.58	<0.01
2009	3,689	20-Sep	3,689	0	3,689	0.00	0.64	0.35	0.01
2010	5,640	19-Sep	5,640	0	5,640	0.00	0.43	0.57	0.01
2011	4,777	20-Sep	4,777	0	4,777	0.00	0.51	0.48	0.01
2012	5,681	20-Sep	5,681	0	5,681	0.01	0.40	0.58	0.01
2013	6,426	1-Oct	6,426	0	6,426	<0.01	0.52	0.47	0.02

[a] Expanded weir count

SPAWNER–RECRUIT ANALYSIS

State Space Model

State-space models (Harvey 1989) are time series models that feature both observed variables and unobserved states. The Bayesian age structured state-space model considers process variation (natural fluctuations) in stock productivity, recruitment, and age-at-maturation independently from observation error (uncertainty in measurements of observed data) in run size, harvest, and age composition. Speel Lake sockeye salmon spawner-recruit data were analyzed using a Bayesian age-structured state-space model to assess the uncertainty introduced in to the estimate of spawning size that produce maximum sustained yield (MSY) due to the following factors.

(1) Late installation of the weir in 1995. The spawning escapement count in 1995 had to be back-calculated based on earlier installations of the weir during other years.
(2) The truncation of weir counts that were then expanded forwards based on regressing cumulative spawning escapement by date on cumulative total weir counts in 1983, 1995, and 2002–2013; potential for large measurement error in the spawning escapement counts.
(3) The weir was not installed in 1993 and 1994. These data were considered missing in the model.
(4) Harvest data that could not be accurately calculated in years 1983–1985, and 1991. These data were considered missing in the model.

For similar applications of the age-structured state-space stock-recruit model implemented in a Bayesian framework, see Hamazaki et al. (2012), Fleischman and McKinley (2013), and Fleischman et al. (2013).

Process Model

Returns *R* (1983–2011) of Speel lake sockeye salmon were modeled as a function of spawning escapement *S* in year *y* using a linearized Ricker (1954) spawner recruit function with autoregressive (AR) lognormal process error with a lag of 1 year (Noakes et al. 1987),

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi\omega_{y-1} + \varepsilon_y . \tag{3}$$

In Equation (3), α is the productivity parameter, β is the inverse capacity parameter, ϕ is the AR lag-1 coefficient, and ω_y are the model residuals,

$$\omega_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y = \phi\omega_{y-1} + \varepsilon_y . \tag{4}$$

In Equation (4), ε_y are independent normally distributed process errors with standard deviation σ_R. Six initial returns (1977–1982) were modeled as draws from a common log normal distribution with parameters $\ln(R_0)$ and σ_{R0}. These returns were not linked to the escapement data in the spawner recruit relationship. Age-at-maturity proportions $(p_{y,a} : a = 4:6)$ from year *y* and returning at ages 4–6 (ages 3–4 were combined) were drawn from a common Dirichlet distribution that was implemented by generating independent random variables $(g_{y,a} : a = 4:6)$ from the gamma distribution $g_{y.a} \sim \text{gamma}(\gamma_a, 0.1)$ and dividing each by their sum (Evans et al. 1993),

$$p_{y,a} = \frac{g_{y,a}}{\sum_a g_{y,a}} . \tag{5}$$

Proportions of recruits at age, π_a, (Gelman et al. 2004) were calculated as

$$\pi_a = \frac{\gamma_a}{D}, \tag{6}$$

and implemented as a series of nested beta distributions. The sum of the Dirichlet parameters, $D = \sum \gamma_a$, is the inverse dispersion (D) of the Dirichlet distribution.

The abundance of Speel Lake sockeye salmon of age a returning to spawn in calendar year y (y = 1983–2011), N_y, is the product of the proportion of age–a fish from cohort y-a and total return R from brood year y-a,

$$N_{y,a} = R_{y-a} p_{y-a,a} . \tag{7}$$

Total run abundance during calendar year y is the sum of the abundance-at-age across ages,

$$N_y = \sum_a N_{y,a} , \tag{8}$$

and the total brood year return is

$$R_y = \sum_{a=4}^{6} N_{y+a,a} . \tag{9}$$

The number of sockeye salmon that reach the Speel Lake weir each calendar year, S_y, or the spawning escapement, is the difference between total run abundance and the total District 11 commercial harvest (common property terminal harvest, cost-recovery harvest) below the weir, H_y. Hatchery brood stock, F_y , is also subtracted from spawning escapement counts,

$$S_y = N_y - H_y - F_y . \tag{10}$$

Harvest was modeled as the product of abundance and hierarchical harvest rates,

$$H_y = N_y U_{Hy} , \tag{11}$$

drawn from a common beta distribution with parameters B_1 and B_2 (Appendix A.1).

Model Data

Observed data (Appendix A.2) included spawning escapement counts, w_y, annual commercial harvest below the weir, CVs for the spawning escapement counts and harvest converted to lognormal variance parameters,

$$\sigma^2_{w_y} = \ln[\mathrm{CV}^2_{w_y} + 1] \text{, and} \tag{12}$$

$$\sigma^2_{Hy} = \ln[\mathrm{CV}^2_{H_y} + 1] , \tag{13}$$

and age composition. For this analysis, we assume no unreported harvest of Speel Lake sockeye salmon. Observed commercial harvest and observed spawning escapement counts were modeled to be log-normally distributed with mean ln(H) or mean ln(w) and variance derived from the CVs of the observed data,

$$H_{(ob)y} \sim LN(\ln(H_y), \sigma^2_{H_y}) \text{ and} \tag{14}$$

$$w_{(ob)y} \sim LN(\ln(w_y), \sigma^2_{w_y}) . \tag{15}$$

As discussed on pages 4–6, harvest estimates were subject to several assumptions, and standard errors were not available from all fisheries; therefore, harvest coefficients of variation CV_{H_y} were uniformly set to an arbitrarily high value of 0.20 so as not to overstate confidence in the harvest estimates.

For the years when no temporal expansion of weir counts was necessary (1983, 2002–2011), the CV_{w_y} of the spawning escapement was set to an arbitrarily small value of 0.05. Fleischman et al. (2013) found that results from a similar analysis were not sensitive to arbitrary choices of weir count CVs. For years when weir counts were expanded for missing time periods (1984–1992, 1995–2001), the CV was estimated as the standard error of the weir expansion (Equation (2)) divided by the expanded count.

For both harvest and escapement samples separately, proportions of age 3–6 fish by return year were first converted to numbers by age based on the annual escapement and harvest numbers. Then, the numbers by age for annual escapement and annual harvest were combined for each age group (ages 3–6). Next, these combined numbers by age were converted to annual proportions by age, $q_{(\mathrm{ob})y,a}$. This method basically weights the proportions by the escapement and harvest numbers (i.e., if harvest was higher, the proportions by age in the harvest received more weight). Since effective sample size could not be accurately calculated for escapement or harvest due to unknown variances, and key model results from state-space analyses of Pacific salmon are typically not sensitive to the choice of n_{Ey} (Fleischman and McKinley 2013), an arbitrarily small annual effective sample size of n_{Ey} =100 was used. After combining proportions of ages 3 and 4, the weighted annual proportions by age were multiplied by 100,

$$x_{y,a} = q_{(\mathrm{ob})y,a} n_{Ey} \text{ where } \sum x_{y,a} = n_{Ey} \text{ across all ages for each year,} \quad (16)$$

to calculate the age counts, $x_{y,a}$. The age counts were assumed to have a multinomial distribution with order parameter n_{Ey} and proportion parameters,

$$q_{y,a} = \frac{N_{y,a}}{\sum_a N_{y,a}}, \quad (17)$$

where $\sum q_{y,a} = 1$ across all ages for each calendar year.

Prior Distributions and Markov Chain Monte Carlo (MCMC) Simulation

For all unknowns in the model, Bayesian analysis requires that prior probabilities be specified. Most prior distributions in this model were uninformative with a few exceptions (Table 4). For some parameters (β, ln(α), ϕ), a uniform prior caused computational disruptions during MCMC sampling in OpenBUGS[3]. For these parameters, a normal distribution with mean 0 and extremely large variances was substituted. A flat prior on the standard deviation of log initial brood year returns, σ_{R0}, caused computational disruptions during MCMC sampling, so it was changed to a slightly informative inverse gamma prior. Fleischman et al. (2013) found that an

[3] Product names are used for completeness but do not constitute endorsement.

informative prior on σ_{R0}^2 may have a large effect on the posterior of σ_{R0} and the initial values of R_y, but negligible effects on key model quantities.

Table 4.–Prior distributions for model parameters. Where "Uniform" is in quotes, a normal distribution with mean 0 and large variance was used in the actual OpenBUGS code to prevent computational disruptions during MCMC sampling.

Parameter	Prior
$\ln(\alpha)$	$\ln(\alpha)$ ~ "Uniform" (0,∞)
β	β ~ "Uniform" (0,∞)
σ_R	$1/\sigma_R^2 \sim \text{gamma}(0.001, 0.001)$
ϕ	ϕ ~ "Uniform" (-1,1)
ω_0	$\omega_o \sim \text{Normal}(0, \sigma_R^2/(1-\phi^2))$
D	$1/\sqrt{D} \sim \text{Uniform}(0, 1)$
$\ln(R_0)$	$\ln(R_0)$ ~ "Uniform" (∞,∞)
σ_{R0}	$1/\sigma_{R0}^2 \sim \text{gamma}(0.1, 0.1)$

MCMC methods were used to generate the joint posterior probabilities of the unknown quantities using the program OpenBUGS (Lunn et al. 2009). Three Markov chains were initiated. After a 20,000 sample burn-in period was discarded, 140,000 (1,400,000 iterations, thinned by 10) MCMC updates per chain were retained for analysis to estimate posterior medians, standard deviations, and percentiles.

Reference Points, Optimal Yield Profiles, and Overfishing Profiles

Spawning abundance at MSY, S_{MSY}, was approximated based on Peterman et al. (2000),

$$S_{\text{MSY}} \cong \frac{\ln(\alpha')}{\beta}\left(0.5 - \frac{0.65\ln(\alpha')^{1.27}}{8.7 + \ln(\alpha')^{1.27}}\right), \tag{18}$$

where $\ln(\alpha') = \ln(\alpha) + \frac{\sigma_R^2}{2(1-\phi^2)}$, to correct for AR(1) serial correlation and lognormal process error (Parken et al. 2006). An estimate of MSY was calculated as,

$$\text{MSY} = S_{\text{MSY}} e^{(\ln(\alpha') - \beta S_{\text{MSY}})} - S_{\text{MSY}}. \tag{19}$$

Spawning abundance at peak return, S_{MAX}, was calculated as 1/β and equilibrium spawning abundance as,

$$S_{\text{EQ}} = \frac{\ln(\alpha')}{\beta}. \tag{20}$$

Harvest rate leading to MSY, U_{MSY}, was approximated by,

$$U_{\text{MSY}} \cong \ln(\alpha')\left(0.5 - \frac{0.65\ln(\alpha')^{1.27}}{8.7 + \ln(\alpha')^{1.27}}\right). \tag{21}$$

Optimal yield probabilities are the probabilities that a given level of spawning abundance will produce average yields exceeding X% (70%, 80%, 90%) MSY. These probabilities are created by calculating expected sustained yield, Y, at incremental levels of S (0 to 25,000 by 500) for each MCMC sample,

$$Y = R - S = Se^{\ln(\alpha') - \beta S} - S, \tag{22}$$

comparing Y with X% (70%, 80%, 90%) of the value of MSY for the sample, and then determining what proportion of P_{OY} samples fit the criteria: Y > X% of MSY. Optimal yield profiles are plots of P_{OY} versus S (Fleischman et al. 2013).

Overfishing probability profiles show the probability of overfishing the stock such that sustained yield is reduced to less than a fraction (70%, 80%, 90%) of MSY. To produce the overfishing probability profiles, expected sustained yield (Equation (22)) at multiple incremental levels of S (0 to 15,040 by increments of 160) are calculated for each MCMC sample. Then, the number of MCMC samples for which Y is less than X% of MSY and S is less than S_{MSY} is tabulated. Overfishing probability profiles are then a plot of the fraction of samples in which this condition occurred versus S (Bernard and Jones 2010).

RESULTS

Abundance, Time-Varying Productivity, Harvest Rates, and Age at Maturity

Reconstructed total run abundance (N) had CVs from 7% to 36% (Figure 2c). The years with higher uncertainty correspond to years with missing harvest or escapement data (Table 5). Excluding the first initial returns, reconstructed brood year recruitment had CVs from 9% to 34%. Productivity residuals were spread around 0 across years, indicating a good model fit (Figure 2d) and σ_R was 0.37 (95% CI: 0.24–0.56) (Table 6). Median harvest rates (U) ranged from 0.11 to 0.77 (Figure 2e). Median brood year recruit age proportions were 0.34 for ages 3 and 4 (π_4), 0.64 for age 5 (π_5), and 0.02 for age 6 (π_6). These proportions have fluctuated moderately from brood year to brood year (Figure 3a). Age composition has also fluctuated from year to year (Figure 3b).

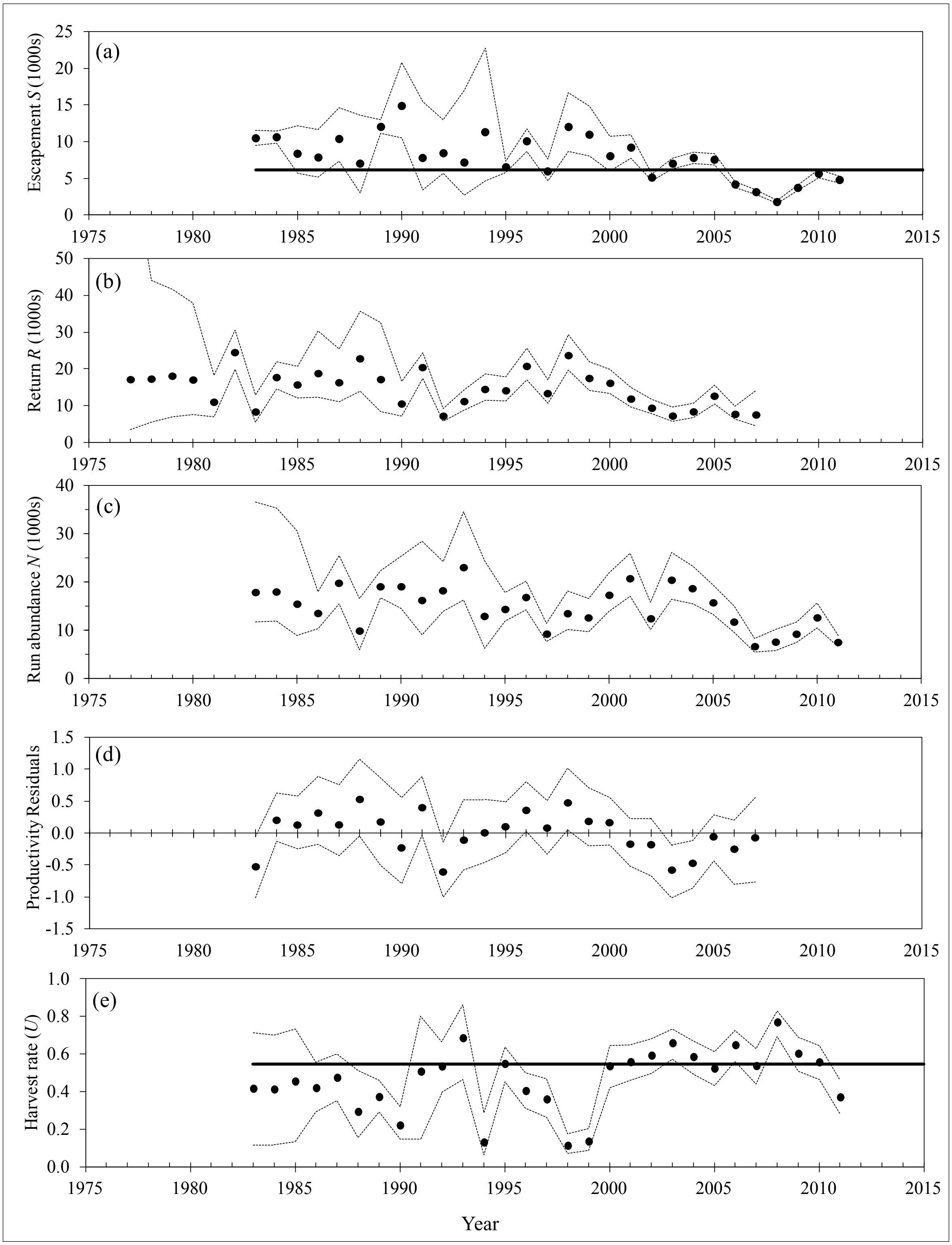

Figure 2.–Point estimates (posterior medians; black circles) and 95% credibility intervals (bracketed by dashed lines) of (a) spawning escapement, (b) return by brood year, (c) run abundance, (d) productivity residuals, and (e) harvest rate, from the state-space spawner-recruit model of Speel Lake sockeye salmon, 1983–2011. Posterior medians of optimal escapement, S_{MSY}, and harvest, U_{MSY}, are plotted as horizontal reference lines in (a) and (e), respectively.

Table 5.–Posterior medians of the parameter estimates for the state-space model fitted to the Speel Lake sockeye salmon data for calendar years 1983–2011. Six initial returns (1977–1982) were modeled as draws from a common log normal distribution and were not linked to the escapement data in the spawner recruit relationship. Total run abundance and escapement are in calendar years (1983–2011), while returns are by brood years (1983–2007).

Year	Total Run (*N*)	Total Run *N* (CV)	Escapement (*S*)	Escapement *S* (CV)	Return (*R*)	Return *R* (CV)
1977	–	–	–	–	17,270	>1.0[a]
1978	–	–	–	–	17,420	0.55
1979	–	–	–	–	18,210	0.45
1980	–	–	–	–	17,170	0.43
1981	–	–	–	–	11,140	0.25
1982	–	–	–	–	24,620	0.11
1983	17,940	0.36	10,470	0.05	8,493	0.22
1984	18,050	0.32	10,610	0.04	17,840	0.10
1985	15,530	0.35	8,358	0.19	15,830	0.14
1986	13,610	0.14	7,845	0.21	18,920	0.24
1987	19,860	0.13	10,370	0.18	16,430	0.22
1988	9,967	0.27	7,012	0.37	22,930	0.24
1989	19,130	0.07	12,020	0.04	17,290	0.34
1990	19,140	0.14	14,870	0.17	10,660	0.22
1991	16,290	0.30	7,783	0.38	20,550	0.09
1992	18,300	0.14	8,431	0.22	7,348	0.13
1993	23,100	0.20	7,159	0.48	11,320	0.12
1994	13,000	0.34	11,300	0.39	14,610	0.13
1995	14,440	0.11	6,521	0.06	14,250	0.12
1996	16,910	0.09	10,060	0.08	20,870	0.10
1997	9,334	0.10	5,952	0.13	13,480	0.12
1998	13,560	0.15	12,010	0.17	23,800	0.10
1999	12,680	0.14	10,950	0.16	17,590	0.11
2000	17,370	0.12	8,027	0.15	16,280	0.10
2001	20,800	0.11	9,193	0.09	12,000	0.11
2002	12,510	0.11	5,107	0.05	9,515	0.10
2003	20,490	0.12	7,002	0.05	7,382	0.13
2004	18,740	0.11	7,788	0.05	8,518	0.12
2005	15,810	0.10	7,543	0.05	12,780	0.10
2006	11,820	0.12	4,167	0.05	7,853	0.11
2007	6,741	0.11	3,125	0.05	7,689	0.31
2008	7,670	0.14	1,775	0.05	–	–
2009	9,312	0.11	3,707	0.05	–	–
2010	12,700	0.10	5,632	0.05	–	–
2011	7,602	0.08	4,784	0.05	–	–

[a] Computational issues prevented exact calculation of CV(*R*) for 1977.

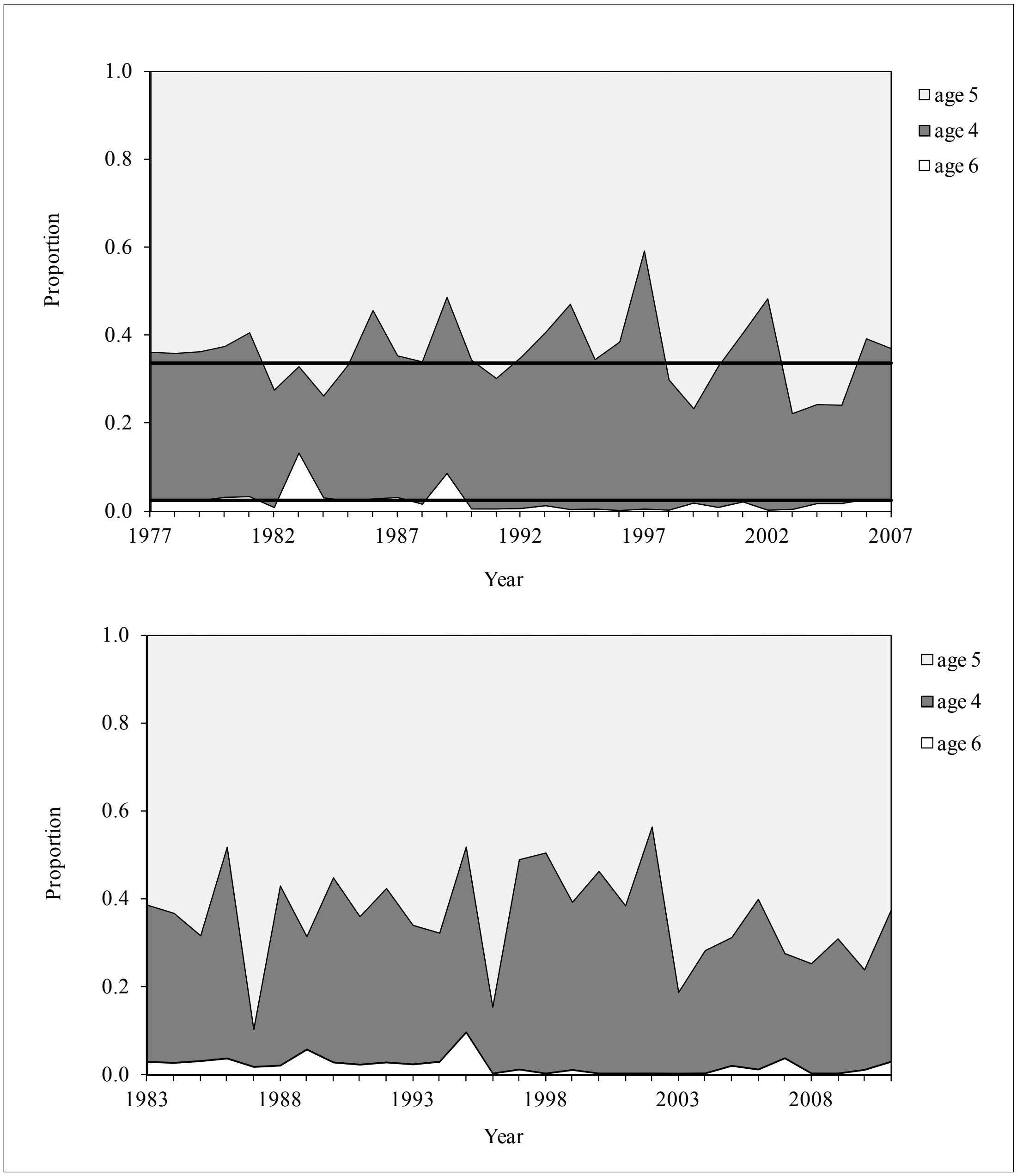

Figure 3.–Area graph of mean age-at-maturity proportions (π) by brood year (a) and age composition by calendar year (b) of Speel Lake sockeye salmon. Distances between the solid lines are posterior medians of proportions. Horizontal lines in the top figure are posterior medians of age-at-maturity central tendency proportions π_a.

Table 6.–Parameter estimates from the state-space model fitted to the Speel Lake sockeye salmon data for calendar years 1983–2011. Posterior medians are point estimates and the 2.5 and 97.5 credible percentiles define the 95% credible intervals for the parameters.

Parameter	2.5 Percentile	Median	97.5 percentile
α	1.78	3.47	8.55
$\ln(\alpha)$	0.58	1.24	2.15
β	1.53E-05	8.80E-05	1.87E-04
ϕ	-0.48	0.24	0.81
σ	0.24	0.37	0.56
S_{EQ}	10,800	15,360	46,990
S_{MAX}	5,346	11,370	65,360
S_{MSY}	3,928	6,200	20,810
U_{MSY}	0.30	0.54	0.78
D	9	18	35
π_4	0.29	0.34	0.39
π_5	0.58	0.64	0.69
π_6	0.01	0.02	0.04
B_{sum}	3.38	6.13	10.64

Stock Productivity, Capacity, and Yield

The Ricker stock recruit relationships derived from the age-structured state-space model fitted to escapement, harvest, and age composition data are variable. Results take into account measurement error in both *S* and *R* as depicted by the error bars in Figure 4, which weight the individual data pairs depending on how precisely they were estimated. Some of the plausible relationships vary greatly from the posterior medians of $\ln(\alpha)$ and β, but most are not substantially different from the median estimates. The median estimate of $\ln(\alpha)$ was 1.24 (95% CI: 0.58–2.15), corresponding to α = 3.47 (95% CI: 1.78–8.55; Table 6). The estimate of the density dependent parameter β was 8.80×10^{-5} (95% CI: 1.53×10^{-5}–1.87×10^{-4}). The estimated AR(1) parameter ϕ was 0.24 (95% CI: -0.48–0.81), suggesting weak serial correlation in residuals. Posterior medians of reference points S_{MSY}, S_{MAX}, and S_{EQ} were 6,200 (95% CI: 3,928–20,810), 11,370 (95% CI: 5,346–65,360), and 15,360 (95% CI: 10,800–46,990), respectively. Expected sustained yield or the numbers of fish over and above those necessary to replace spawners for the brood years 1977–2007 is maximized near 6,100 spawners (Figure 5) and estimated MSY is 7,917 (95% CI: 4,442–19,580).

The probability profiles in Figure 6 display the probability of achieving near optimal sustained yield (>70%, >80%, and >90% of MSY) for specified levels of spawning abundance, and the overfishing probability profiles 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. These probabilities, generated from all the plausible stock-recruit relationships, can be used to evaluate prospective escapement goals, taking into consideration the uncertainty about the true abundance, productivity, and capacity of the stock.

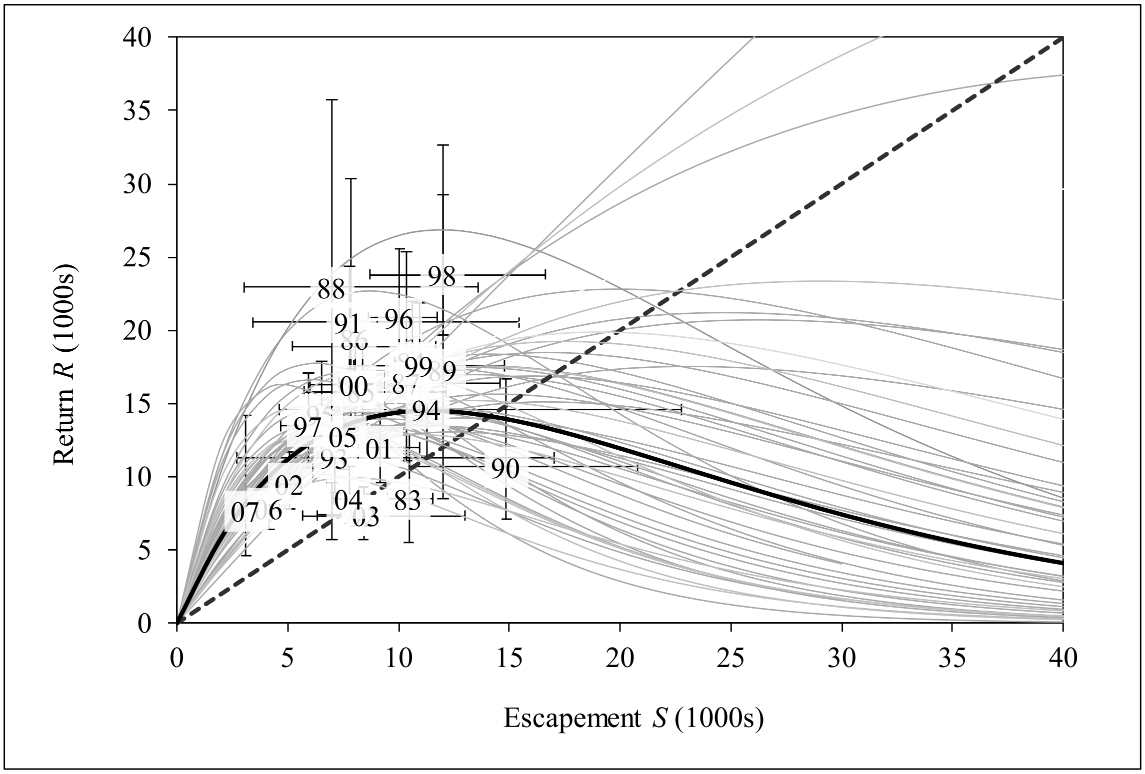

Figure 4.–Plausible Ricker relationships (gray lines) for 50 paired values of α and β sampled from the posterior probability distribution. Posterior medians of R and S are plotted as brood year labels; error bars bracket the 95% credibility intervals from the Bayesian state-space age-structured model. The heavy dark line is the Ricker relationship constructed from the α and β posterior medians. The diagonal dotted line is the replacement line (R=S).

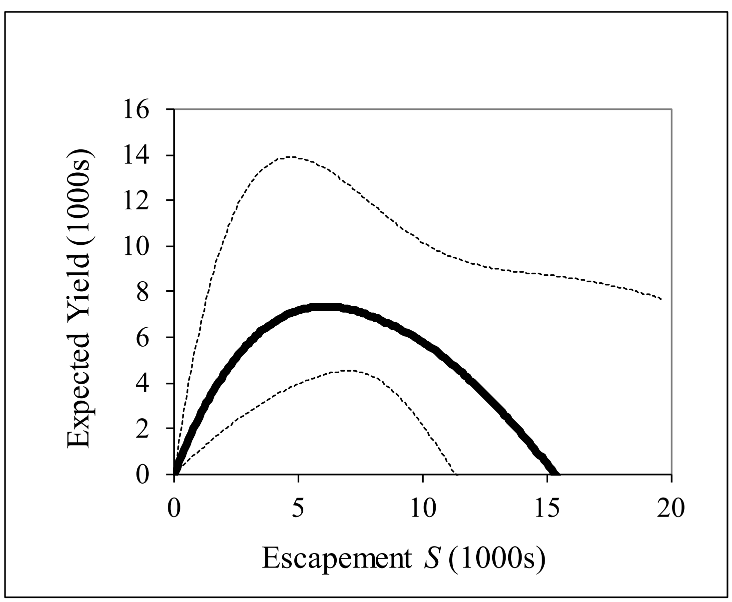

Figure 5.–Expected sustained yield (solid line) and 90% credible intervals (short dashed black lines) versus spawning escapement for Speel lake sockeye salmon for brood years 1977–2007.

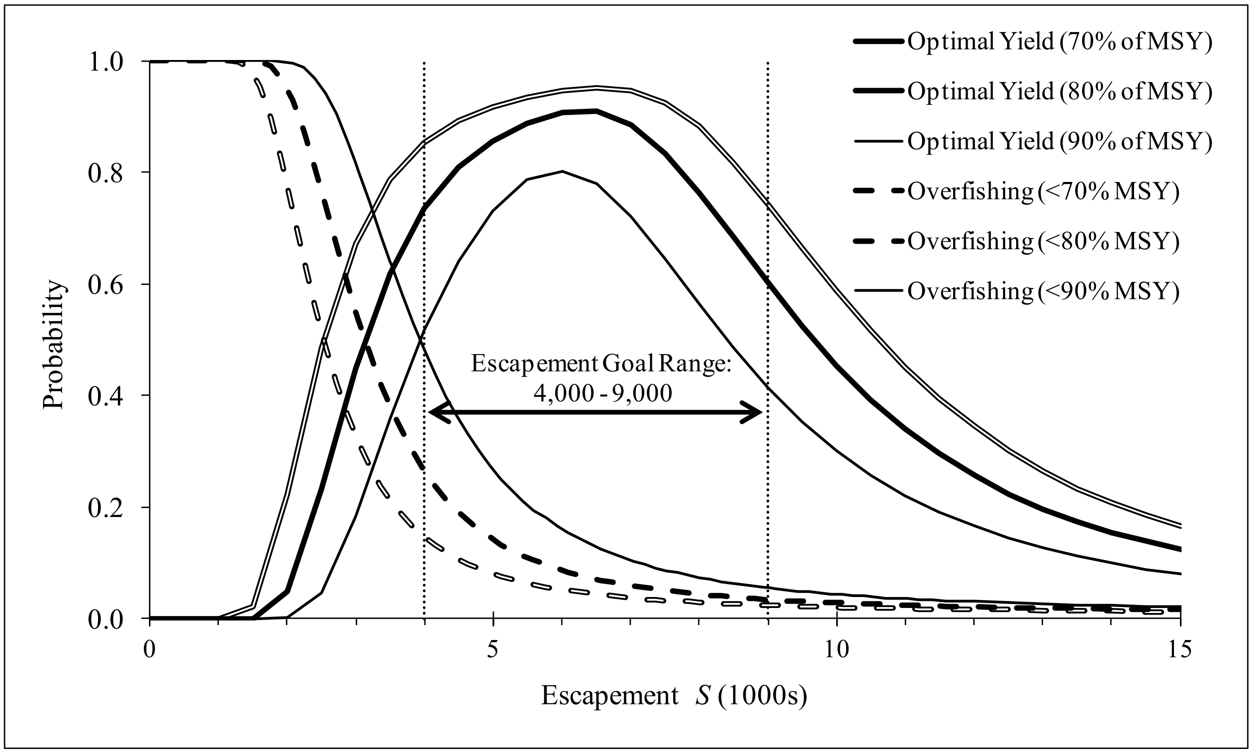

Figure 6.–Optimal yield and overfishing profiles for Speel Lake sockeye salmon. Optimal yield profiles show the probability that a specified spawning abundance will achieve 70%, 80%, or 90% of maximum sustained yield (MSY). Overfishing profiles show the probability that reducing the escapement to a specified spawning abundance will result in less than 70%, 80%, or 90% of MSY. Vertical dotted lines show the recommended escapement goal range of 4,000–9,000 fish.

DISCUSSION

Many of our stock-recruit parameter estimates (e.g., S_{MSY} = 6,200; S_{EQ} = 15,360; MSY = 7,917; U_{MSY} = 54%) are lower than those initially estimated for Speel Lake sockeye salmon by Riffe and Clark (2003) (e.g., S_{MSY} = 7,766; S_{EQ} = 25,000; MSY = 48,000; U_{MSY} = 86%). The differences are due not only to the longer time series of information available to us, but also to improved estimates of historical escapements and use of a Bayesian age-structured state space model to better account for missing data and provide a realistic assessment of the uncertainty in the stock assessment information and stock productivity.

Riffe and Clark (2003) noted "serious deficiencies" in their stock-recruit analysis, which stemmed primarily from the expansion of weir counts, because there were too few data available to properly reconstruct truncated escapements. At the time, only 3 of 18 weir counts were considered complete, and they modeled cumulative weir count and precipitation by date to estimate escapements as reasonably as possible. We used 13 complete years of weir data to expand truncated weir counts based directly on run timing. Our estimates averaged 30% smaller for 14 of 15 expanded weir counts, and our maximum expanded weir count was 18,309 fish. Four escapements estimated by Riffe and Clark (2003) were greater than 20,000 fish and two were greater than 30,000 fish (Table 2).

Missing data were also a problem because sockeye salmon return at multiple ages, and one missing estimate of escapement or harvest can influence several years of stock-recruit data. In traditional stock recruit analysis, independence of individual quantities of spawners (*S*) and recruits (*R*) is assumed, and missing data must be imputed before the model is run. Riffe and Clark (2003) had to impute three years of missing harvest (1991) and escapement (1993, 1994) data. As a result, 7 of the 14 brood years in their analysis were missing either a parent-year escapement or estimates of harvest/escapement of a major age class. One advantage of the Bayesian state-space model is that missing data are no longer an issue. To account for missing data, we were able to model harvest rates as hierarchical; information from missing escapement or catch data was derived from historical average harvest rate and its variability. By correctly specifying annual age structure in the Bayesian state space model, missing data such as parameters can be represented as unknown quantities for which posterior samples are generated. Additional uncertainty then flows through to the remaining model parameters as appropriate. For example, the missing estimate of Speel Lake sockeye salmon escapement (*S*) in 1993 leads to an increased uncertainty in the 1993 total run abundance (*N*), which in turn increases the uncertainty in the returns (*R*) from the 1987, 1988, and 1989 cohorts, contributors of 6-, 5-, and 4-year old fish, respectively, to the 1993 run (Table 5). Given that missing data is a common occurrence in Pacific salmon stock assessments, an age structured approach provides a powerful advantage over traditional stock recruit analysis that uses the assumptions and methods of simple linear regression.

Along with overcoming the issue of missing data, another advantage of the Bayesian age-structured state space model over traditional stock recruit methods is the ability to obtain good quality estimates of S_{MSY} in regards to bias reduction and interval coverage (Su and Peterman 2012). Although most of our reference points had large 95% credible intervals, this may be a true representation of the process variation and observation error in the wild Speel lake sockeye salmon run.

STOCK STATUS

Several trends are apparent from our review of available stock assessment information and in our run reconstruction analysis. Speel Lake sockeye salmon escapements have averaged lower and less variable since 2000 (Figure 2a). This downward trend is due to a decrease in production beginning in 2002 (Figure 2d), which resulted in lower returns (Table 5; Figure 2b, Figure 2c), coupled with an increase in estimated harvest rate since 2000 (Figure 2e). Escapements fell below the escapement goal for three consecutive years, 2007–2009, but have been within the escapement goal range since 2010 (Table 3).

Estimated harvest rates on Speel Lake sockeye salmon were more variable and averaged 38% prior to 2000, but have been less variable and averaged 58% since that time (Figure 2e). The increase in estimated harvest rates was due both to increased effort in Port Snettisham fisheries to target runs of Snettisham Hatchery sockeye salmon, and also to an increase in fishing effort in the traditional District 11 drift gillnet fishery in Stephens passage to target hatchery runs of chum (*O. keta*) and sockeye salmon. The increase in effort in Stephens Passage to target hatchery runs is mentioned repeatedly in management reports (TTC 2005, 2011, 2013a, 2013b; Bachman et al. 2005a, 2005b; Davidson et al. 2008a, 2008b, 2008c, 2011). Fishing effort in Stephens Passage during statistical weeks 27–32 (July–early August) increased from an average of 518 boat days from 1986 to 1999 to an average of 890 boat days from 2000 to 2013. Fishing time in the commercial drift gillnet fishery in Stephens Passage has been balanced with 6" minimum mesh size restriction in July to reduce the harvest rate on wild Port Snettisham sockeye salmon during their peak weeks of migration.

Along with the mesh restrictions in Stephens Passage, ADF&G has managed the common property hatchery fishery in Speel Arm to protect wild Speel Lake and Crescent Lake sockeye salmon runs in accordance with 5 AAC 33.378. Fisheries inside Port Snettisham were greatly curtailed or not prosecuted at all during 2007–2009, when the Speel Lake escapement goal was not met. Since 2009, the common property hatchery fishery in Speel Arm has not been opened until the lower bound of the Speel Lake escapement goal is achieved.

Finally, we note there has been remarkably little straying of Snettisham Hatchery sockeye salmon into Speel Lake, despite their close proximity and common ancestry. All sockeye salmon released from the hatchery have been thermally marked since the inception of the program. Given the much larger size of the hatchery run compared to the wild Speel population, even a very small amount of straying would be easily detected; yet only two thermal-marked Snettisham Hatchery fish have been recovered from 12 years of otolith collections at Speel Lake since 1997 (single recoveries in 2003 and 2008; Appendix B3). The water source used at the hatchery, which originates from two high-elevation lakes above Port Snettisham (Stopha 2014), is very different from the adjacent Speel River and Speel Lake water sources (Eric Prestegard, DIPAC, Juneau, personal communication). That, together with the tendency for sockeye salmon to exhibit a high degree of fidelity to natal sites (Quinn et al. 1999; Quinn 2005), likely accounts for strong homing of Snettisham fish to the hatchery site.

ESCAPEMENT GOAL RECOMMENDATION

We recommend a Speel Lake sockeye salmon *sustainable* escapement goal range of 4,000–9,000 fish. Our recommendation is based on the following considerations:

(1) The first objective of the Snettisham Hatchery Management Plan (5 AAC 33.378) is to sustain the production of wild sockeye salmon runs in Port Snettisham.
(2) The Speel Lake sockeye salmon run accounts for only a small portion of mixed stock harvests in the traditional District 11 drift gillnet fishery.
(3) The District 11 drift gillnet fishery is managed primarily to achieve escapement goals for Taku River sockeye and coho (*O. kisutch*) salmon, as specified in the Pacific Salmon Treaty.

Given these considerations, an escapement goal based on maximizing yield, as is common practice for large stocks that drive management of fisheries (e.g., Chilkat and Chilkoot sockeye salmon stocks in Lynn Canal; Eggers et al. 2009, 2010), is not required to sustain the Speel Lake run or manage the traditional mixed stock fisheries in District 11 or terminal fisheries inside Port Snettisham. An escapement goal based on achieving greater than 90% of MSY would likely require raising the lower bound of the escapement goal to 5,000 fish. At the current lower bound of 4,000 fish, we estimate there is an 85–95% probability of achieving greater than 70% of MSY, and a 73–91% probability of achieving greater than 80% of MSY (Figure 6). In addition, there is only a 15% probability that yields will be reduced to <70% of MSY, and a 27% probability that yields will be reduced to <80% of MSY. Conversely, reducing the lower bound of the goal to 3,000 fish would potentially reduce sustained yields (45% compared to 73% probability of achieving 80% of MSY) and increase the risk of overfishing relative to MSY (55% compared to 27% probability of reducing sustained yield to less than 80% MSY) (Figure 6). Additional considerations that suggest it would be prudent to maintain the lower bound of the escapement goal at 4,000 fish include a downward trend in production that resulted in recent poor escapements, and the increase in estimated harvest rates over the last decade.

The upper bound of the goal could be higher in light of uncertainty in estimated carrying capacity (S_{EQ}=15,360), but with the recommended upper bound of 9,000 fish, we estimate the probability of achieving greater than 70% or 80% of MSY is 74% and 60%, respectively (Figure 6). Therefore, escapements within the recommended range of 4,000–9,000 should sustain the run while also providing for harvests of Speel Lake sockeye salmon that occur in traditional mixed stock fisheries in District 11 as well as in terminal fisheries inside Port Snettisham. The recommended goal could be classified as a *sustainable* escapement goal, given that the range does not provide the "greatest potential" to maximize yield as specified for *biological* escapement goals in the *Policy for the Management of Sustainable Salmon Fisheries* (5 AAC 39.222).

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APPENDIX A:
OPENBUGS CODE AND DATA

Appendix A1.–OpenBUGS model code for the Bayesian MCMC statistical analysis of the Speel Lake sockeye salmon data run reconstruction model, 1983–2013. Stochastic relationships are denoted with '~' and logical or deterministic relationships are denoted with a '<-'. Prior distributions are italicized and sampling distributions of the data are in bold font.

```
model {
lnalpha ~ dnorm(0,1.0E-6)I(0,)
beta ~ dnorm(0,1.0E-6)I(0,)
phi ~ dnorm(0,1.0E-6)I(-1,1)
mean.log.R0 ~ dnorm(0,1.0E-6)
tau.R0 ~ dgamma(0.1,0.1)
log.resid.0 ~ dnorm(0,tau.red)
tau.R ~ dgamma(0.001,0.001)
sigma.R <- 1/sqrt(tau.R)
alpha <- exp(lnalpha)
sigma.R0 <- 1 / sqrt(tau.R0)
tau.red <- tau.R * (1-phi*phi)
lnalpha.c <- lnalpha + (sigma.R * sigma.R / 2 / (1-phi*phi) )

#BROOD YEAR RETURNS WITH AR(1) LOGNORMAL PROCESS ERROR
for (c in A+a.min:C) {
log.R[c] ~ dnorm(log.R.mean2[c],tau.R)
R[c] <- exp(log.R[c])
log.R.mean1[c] <- log(S[c-a.max]) + lnalpha - beta * S[c-a.max]
log.resid[c] <- log(R[c]) - log.R.mean1[c]}
log.R.mean2[A+a.min] <- log.R.mean1[A+a.min] + phi * log.resid.0
for (c in A+a.min+1:C) {
log.R.mean2[c] <- log.R.mean1[c] + phi * log.resid[c-1]}
```

-continued-

```
# THE FIRST SEVERAL COHORTS ORIGINATE FROM UNMONITORED SPAWNING EVENTS
R.0 <- exp(mean.log.R0)
for (c in 1:a.max) {
log.R[c] ~ dnorm(mean.log.R0,tau.R0)
R[c] <- exp(log.R[c])}

# CORRECTION FOR LOGNORMAL SKEWNESS
alpha.c <- min(exp(lnalpha.c),1.0E4)
positive.lna.c <- step(lnalpha.c)
lnalpha.c.nonneg <- lnalpha.c * positive.lna.c
S.eq.c <- lnalpha.c.nonneg * SMax
peterman.approx.c <- (0.5 - 0.65*pow(lnalpha.c.nonneg,1.27) / (8.7 +
pow(lnalpha.c.nonneg,1.27)))

#REFERENCE POINTS
SMax <- 1 / beta
U.msy.c <- lnalpha.c.nonneg * peterman.approx.c
S.msy.c <- U.msy.c / beta
U.max.c <- 1 - 1 / exp(lnalpha.c.nonneg)
MSY<-S.msy.c*exp(lnalpha.c-beta*S.msy.c)-S.msy.c

# MATURITY SCHEDULE BY COHORT
D.scale ~ dunif(0,1)
D <- 1 / (D.scale * D.scale)
pi[1] ~ dbeta(0.2,0.8)
pi.2p ~ dbeta(0.2,0.6)
pi[2] <- pi.2p * (1 - pi[1])
pi[3] <- (1 - pi[1] - pi[2])
for (a in 1:A) {
gamma[a] <- D * pi[a] for (c in 1:C) {
g[c,a] ~ dgamma(gamma[a],0.1)
```

-continued-

```
p[c,a] <- g[c,a]/sum(g[c,])}}

#ANNUAL ABUNDANCE (NUMBER RETURNING TO SPAWN)
for (a in 1:A) {
for (y in a:(Y + (a - 1))) {
N.ya[y - (a - 1), (A + 1 - a)] <- p[y, (A + 1 - a)] * R[y] }}

# MULTINOMIAL AGE COUNTS OBSERVED
for (y in 1:Y) {
N[y] <- sum(N.ya[y,1:A])
for (a in 1:A) {
q[y,a] <- N.ya[y,a] / N[y]}
n[y] <- sum(x[y,1:A])
x[y,1:A] ~ dmulti(q[y,],n[y])}

# HARVEST BELOW WEIR
B.scale ~ dunif(0,1)
mu_B ~ dbeta(0.1,0.1)
B.sum <- 1 / B.scale / B.scale
B[1] <- mu_B * B.sum
B[2] <- B.sum - B[1]
for (y in 1:Y) {
mu.HB[y] ~ dbeta(B[1],B[2])
H.B[y] <- mu.HB[y] * N[y]
log.HB[y] <- log(H.B[y])
tau.log.hb[y] <- 1 / log(cv.hb[y]*cv.hb[y] + 1)
h.b[y] ~ dlnorm(log.HB[y],tau.log.hb[y])
W[y] <- max(N[y] - H.B[y], 1)
log.W[y] <- log(W[y])
tau.log.w[y] <- 1 / log(cv.w[y]*cv.w[y] + 1)
w[y] ~ dlnorm(log.W[y],tau.log.w[y])
S[y] <- W[y]}}
```

Appendix A2.–OpenBUGS data objects for the Bayesian MCMC statistical analysis of the Speel Lake sockeye salmon data run reconstruction model, 1983–2011. The multinomial age counts (x) may not sum exactly to the effective sample size of 100 due to rounding. Y is the number of calendar years, A is the number of age classes, and C is the number of cohorts represented in the data (C=Y+A-1). In the table, w[] are the spawning escapement counts (weir counts minus broodstock), cv.w[] are the coefficient of variations on the spawning escapement counts, h.b[ ] are the harvest estimates below the weir, and cv.hb[] are the coefficient of variations on the harvest estimates below the weir.

list(Y=29, A=3, C=31, a.min=4, a.max=6)

w[ ]	cv.w[ ]	h.b[ ]	cv.hb[ ]	x[,1]	x[,2]	x[,3]
10484	0.05	ND	0.90	0	0	0
10619	0.04	ND	0.90	0	0	0
8157	0.21	ND	0.90	0	0	0
7037	0.23	5346	0.20	48	47	4
10257	0.19	9284	0.20	5	93	2
1560	0.78	2637	0.20	41	57	2
12083	0.04	7425	0.20	24	69	7
17112	0.19	4065	0.20	43	54	3
1918	0.96	ND	0.90	0	0	0
8782	0.20	10026	0.20	40	57	3
ND	0.90	18401	0.20	0	0	0
ND	0.90	1515	0.20	0	0	0
6498	0.06	8117	0.20	43	47	11
10155	0.08	6941	0.20	13	87	0
5838	0.13	3134	0.20	50	49	1
13858	0.19	1396	0.20	52	48	0
11060	0.18	1547	0.20	39	60	1
8011	0.16	9841	0.20	47	53	0
9349	0.09	13314	0.20	40	59	0
5071	0.05	6841	0.20	59	41	0
7014	0.05	14579	0.20	16	84	0
7813	0.05	11982	0.20	27	72	0
7549	0.05	8711	0.20	29	69	2
4165	0.05	8185	0.20	41	58	1
3099	0.05	3271	0.20	22	74	4
1763	0.05	5732	0.20	23	77	0
3689	0.05	5492	0.20	29	70	0
5640	0.05	7694	0.20	22	77	1
4777	0.05	2684	0.20	35	62	3

APPENDIX B:
BIOLOGICAL DATA

Appendix B1.–Estimated age composition of Speel Lake sockeye salmon escapement, 1983–2013.

		Age class											
		Age 2	Age 3		Age 4			Age 5		Age 6		Age 7	
Year	Statistic	0.1	0.2	1.1	0.3	1.2	2.1	1.3	2.2	1.4	2.3	3.3	Total
1983	Sample size		4	13	2	256	1	489	11	1	16		793
	% by age class		0.5%	1.6%	0.3%	32.3%	0.1%	61.7%	1.4%	0.1%	2.0%		
	SE of %		0.3%	0.5%	0.2%	1.7%	0.1%	1.7%	0.4%	0.1%	0.5%		
	Escapement by age class		53	172	26	3,384	13	6,465	145	13	212		10,484
	SE of Escapement		25	45	18	167	13	174	42	13	50		
1984	Sample size				13	316		420	8		8		765
	% by age class				1.7%	41.3%		54.9%	1.0%		1.0%		
	SE of %				0.5%	1.8%		1.8%	0.4%		0.4%		
	Escapement by age class				180	4,386		5,830	111		111		10,619
	SE of Escapement				48	182		184	38		38		
1985	Sample size			30		94		265	4	1	2		396
	% by age class			7.6%		23.7%		66.9%	1.0%	0.3%	0.5%		
	SE of %			1.3%		2.1%		2.4%	0.5%	0.3%	0.4%		
	Escapement by age class			618		1,937		5,460	82	21	41		8,158
	SE of Escapement			106		170		188	40	20	28		
1986	Sample size		3		1	462		370	9	1	26		872
	% by age class		0.3%		0.1%	53.0%		42.4%	1.0%	0.1%	3.0%		
	SE of %		0.2%		0.1%	1.7%		1.7%	0.3%	0.1%	0.6%		
	Escapement by age class		24		8	3,729		2,986	73	8	210		7,038
	SE of Escapement		13		8	111		110	23	8	38		
1987	Sample size				17	85		1220	1		18		1341
	% by age class				1.3%	6.3%		91.0%	0.1%		1.3%		
	SE of %				0.3%	0.7%		0.8%	0.1%		0.3%		
	Escapement by age class				130	650		9,332	8		138		10,258
	SE of Escapement				29	64		75	7		30		
1988	Sample size			1		266		333	47	1	11		659
	% by age class			0.2%		40.4%		50.5%	7.1%	0.2%	1.7%		
	SE of %			0.2%		1.9%		1.9%	1.0%	0.2%	0.5%		
	Escapement by age class			3		735		920	130	3	30		1,820
	SE of Escapement			2		28		28	15	2	7		

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Year	Statistic	Age class: Age 2	Age 3		Age 4			Age 5		Age 6		Age 7	Total
		0.1	0.2	1.1	0.3	1.2	2.1	1.3	2.2	1.4	2.3	3.3	
1989	Sample size		1			323		703	28	1	72		1128
	% by age class		0.1%			28.6%		62.3%	2.5%	0.1%	6.4%		
	SE of %		0.1%			1.3%		1.4%	0.5%	0.1%	0.7%		
	Escapement by age class		13			4,062		8,841	352	13	906		14,187
	SE of Escapement		12			183		196	63	12	99		
1990	Sample size		9		1	844	1	935	26	3	43		1862
	% by age class		0.5%		0.1%	45.3%	0.1%	50.2%	1.4%	0.2%	2.3%		
	SE of %		0.2%		0.1%	1.2%	0.1%	1.2%	0.3%	0.1%	0.3%		
	Escapement by age class		89		10	8,299	10	9,194	256	30	423		18,310
	SE of Escapement		28		9	200	9	201	47	16	60		
1991	Sample size		1		4	33		107	4	2	3		154
	% by age class		0.6%		2.6%	21.4%		69.5%	2.6%	1.3%	1.9%		
	SE of %		0.6%		1.3%	3.3%		3.7%	1.3%	0.9%	1.1%		
	Escapement by age class		12		50	411		1,334	50	25	37		1,919
	SE of Escapement		12		24	61		69	24	17	21		
1992	Sample size				1	453		320	11	1	12		798
	% by age class				0.1%	56.8%		40.1%	1.4%	0.1%	1.5%		
	SE of %				0.1%	1.8%		1.7%	0.4%	0.1%	0.4%		
	Escapement by age class				13	5,847		4,130	142	13	155		10,300
	SE of Escapement				12	174		172	41	12	43		
1993	Sample size				6	173	1	318	6		17		521
	% by age class				1.2%	33.2%	0.2%	61.0%	1.2%		3.3%		
	SE of %				0.5%	2.1%	0.2%	2.1%	0.5%		0.8%		
	Escapement by age class				280	8,079	47	14,851	280		794		24,331
	SE of Escapement				113	497	46	515	113		188		
1994	Sample size		2	11		76		239	14		2		344
	% by age class		0.6%	3.2%		22.1%		69.5%	4.1%		0.6%		
	SE of %		0.4%	0.9%		2.2%		2.5%	1.1%		0.4%		
	Escapement by age class		12	64		443		1,392	82		12		2,003
	SE of Escapement		7	17		41		45	19		7		

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Year	Statistic	Age class: Age 2	Age 3		Age 4			Age 5		Age 6		Age 7	Total
		0.1	0.2	1.1	0.3	1.2	2.1	1.3	2.2	1.4	2.3	3.3	
1995	Sample size		2	1	2	336	3	209	21		64	2	640
	% by age class		0.3%	0.2%	0.3%	52.5%	0.5%	32.7%	3.3%		10.0%	0.3%	
	SE of %		0.2%	0.2%	0.2%	2.0%	0.3%	1.9%	0.7%		1.2%	0.2%	
	Escapement by age class		26	13	26	4,306	38	2,678	269		820	26	8,201
	SE of Escapement		17	12	17	156	21	146	55		93	17	
1996	Sample size		2	8	12	84		473			1		580
	% by age class		0.3%	1.4%	2.1%	14.5%		81.6%			0.2%		
	SE of %		0.2%	0.5%	0.6%	1.5%		1.6%			0.2%		
	Escapement by age class		42	167	250	1,750		9,853			21		12,082
	SE of Escapement		29	57	70	172		190			20		
1997	Sample size		5	2	1	274		110		1	3		396
	% by age class		1.3%	0.5%	0.3%	69.2%		27.8%		0.3%	0.8%		
	SE of %		0.6%	0.4%	0.3%	2.3%		2.3%		0.3%	0.4%		
	Escapement by age class		74	29	15	4,039		1,622		15	44		5,838
	SE of Escapement		32	20	14	131		127		14	25		
1998	Sample size		29		20	413		431	3		4		900
	% by age class		3.2%		2.2%	45.9%		47.9%	0.3%		0.4%		
	SE of %		0.6%		0.5%	1.7%		1.7%	0.2%		0.2%		
	Escapement by age class		447		308	6,360		6,637	46		62		13,859
	SE of Escapement		79		66	223		223	26		30		
1999	Sample size	1	1	28		347		566	5	1	9		958
	% by age class	0.1%	0.1%	2.9%		36.2%		59.1%	0.5%	0.1%	0.9%		
	SE of %	0.1%	0.1%	0.5%		1.6%		1.6%	0.2%	0.1%	0.3%		
	Escapement by age class	12	12	323		4,006		6,535	58	12	104		11,060
	SE of Escapement	11	11	58		164		168	25	11	33		
2000	Sample size		14	10	2	298		170	1	1			496
	% by age class		2.8%	2.0%	0.4%	60.1%		34.3%	0.2%	0.2%			
	SE of %		0.7%	0.6%	0.3%	2.2%		2.1%	0.2%	0.2%			
	Escapement by age class		226	162	32	4,813		2,746	16	16			8,011
	SE of Escapement		58	49	22	171		166	16	16			

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Year	Statistic	Age class: Age 2	Age 3		Age 4			Age 5		Age 6		Age 7	Total
		0.1	0.2	1.1	0.3	1.2	2.1	1.3	2.2	1.4	2.3	3.3	
2001	Sample size			77	3	480		359		1	2		922
	% by age class			8.4%	0.3%	52.1%		38.9%		0.1%	0.2%		
	SE of %			0.9%	0.2%	1.6%		1.6%		0.1%	0.2%		
	Escapement by age class			781	30	4,867		3,640		10	20		9,349
	SE of Escapement			81	17	146		143		10	14		
2002	Sample size		6	1	1	394		111	3	1	1		518
	% by age class		1.2%	0.2%	0.2%	76.1%		21.4%	0.6%	0.2%	0.2%		
	SE of %		0.5%	0.2%	0.2%	1.9%		1.8%	0.3%	0.2%	0.2%		
	Escapement by age class		59	10	10	3,857		1,087	29	10	10		5,071
	SE of Escapement		23	9	9	90		87	16	9	9		
2003	Sample size		7	2	4	430		674	1	1			1119
	% by age class		0.6%	0.2%	0.4%	38.4%		60.2%	0.1%	0.1%			
	SE of %		0.2%	0.1%	0.2%	1.5%		1.5%	0.1%	0.1%			
	Escapement by age class		44	13	25	2,695		4,225	6	6			7,014
	SE of Escapement		15	8	11	94		94	6	6			
2004	Sample size		2		5	705		560	4	2	1		1279
	% by age class		0.2%		0.4%	55.1%		43.8%	0.3%	0.2%	0.1%		
	SE of %		0.1%		0.2%	1.4%		1.4%	0.2%	0.1%	0.1%		
	Escapement by age class		12		31	4,307		3,421	24	12	6		7,813
	SE of Escapement		8		12	99		99	11	8	6		
2005	Sample size		1	203	2	487	2	543	4		8		1250
	% by age class		0.1%	16.2%	0.2%	39.0%	0.2%	43.4%	0.3%		0.6%		
	SE of %		0.1%	1.0%	0.1%	1.4%	0.1%	1.4%	0.2%		0.2%		
	Escapement by age class		6	1,226	12	2,941	12	3,279	24		48		7,549
	SE of Escapement		6	72	8	95	8	97	11		16		
2006	Sample size			3		208		106	5		1		323
	% by age class			0.9%		64.4%		32.8%	1.5%		0.3%		
	SE of %			0.5%		2.7%		2.6%	0.7%		0.3%		
	Escapement by age class			39		2,682		1,367	64		13		4,165
	SE of Escapement			21		107		105	28		12		

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		Age class											
		Age 2	Age 3		Age 4			Age 5		Age 6		Age 7	
Year	Statistic	0.1	0.2	1.1	0.3	1.2	2.1	1.3	2.2	1.4	2.3	3.3	Total
2007	Sample size				2	92		426			9		529
	% by age class				0.4%	17.4%		80.5%			1.7%		
	SE of %				0.3%	1.6%		1.7%			0.6%		
	Escapement by age class				12	539		2,496			53		3,099
	SE of Escapement				8	47		49			16		
2008	Sample size		1	2	4	113		170		1			291
	% by age class		0.3%	0.7%	1.4%	38.8%		58.4%		0.3%			
	SE of %		0.3%	0.5%	0.7%	2.9%		2.9%		0.3%			
	Escapement by age class		6	12	24	685		1,030		6			1,763
	SE of Escapement		6	8	11	46		47		6			
2009	Sample size				2	234		129	2	4			371
	% by age class				0.5%	63.1%		34.8%	0.5%	1.1%			
	SE of %				0.4%	2.5%		2.5%	0.4%	0.5%			
	Escapement by age class				20	2,327		1,283	20	40			3,689
	SE of Escapement				13	88		87	13	19			
2010	Sample size					321		410	18		4		753
	% by age class					42.6%		54.4%	2.4%		0.5%		
	SE of %					1.8%		1.8%	0.6%		0.3%		
	Escapement by age class					2,404		3,071	135		30		5,640
	SE of Escapement					95		95	29		14		
2011	Sample size					212		194	4		6		416
	% by age class					51.0%		46.6%	1.0%		1.4%		
	SE of %					2.5%		2.4%	0.5%		0.6%		
	Escapement by age class					2,434		2,228	46		69		4,777
	SE of Escapement					112		112	22		27		
2012	Sample size		3	1		239		332	14		7		596
	% by age class		0.5%	0.2%		40.1%		55.7%	2.3%		1.2%		
	SE of %		0.3%	0.2%		2.0%		2.0%	0.6%		0.4%		
	Escapement by age class		29	10		2,278		3,165	133		67		5,681
	SE of Escapement		16	9		108		109	33		24		

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		Age class											
		Age 2	Age 3		Age 4			Age 5		Age 6		Age 7	
Year	Statistic	0.1	0.2	1.1	0.3	1.2	2.1	1.3	2.2	1.4	2.3	3.3	Total
2013	Sample size			1		298		259	10		9		577
	% by age class			0.2%		51.6%		44.9%	1.7%		1.6%		
	SE of %			0.2%		2.1%		2.1%	0.5%		0.5%		
	Escapement by age class			11		3,319		2,884	111		100		6,426
	SE of Escapement			11		128		127	33		32		

Appendix B2.–Daily escapement counts of sockeye salmon at Speel Lake weir, 1983–2013.

Date	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
1 Jul–11 Jul	17	–[a]	–	–	–	–	–	–	–	–
12-Jul	0	–	–	–	–	–	0	–	0	–
13-Jul	2	–	–	–	–	–	0	0	0	–
14-Jul	1	–	–	–	–	–	0	0	0	–
15-Jul	4	0	0	–	0	0	0	3	1	0
16-Jul	3	0	0	0	0	0	0	10	7	2
17-Jul	12	0	3	0	0	0	0	9	1	5
18-Jul	2	0	5	0	0	0	0	24	0	1
19-Jul	4	0	2	0	0	0	1	40	6	11
20-Jul	11	0	2	0	6	0	0	19	4	4
21-Jul	4	0	8	0	10	0	0	15	2	2
22-Jul	7	0	1	0	12	1	3	21	1	1
23-Jul	11	0	0	0	6	0	0	36	0	39
24-Jul	4	1	1	11	36	0	5	46	0	84
25-Jul	2	0	4	0	268	0	14	55	0	132
26-Jul	0	1	0	246	26	16	21	39	2	104
27-Jul	2	0	2	176	23	16	2	580	1	91
28-Jul	0	0	9	30	613	14	101	140	0	2,367
29-Jul	0	2	26	73	228	9	424	524	5	99
30-Jul	0	19	18	10	32	17	459	3,331	3	78
31-Jul	48	0	138	110	279	3	343	94	2	364
1-Aug	0	0	752	123	33	0	368	93	2	707
2-Aug	4	0	203	135	148	1	331	123	2	368
3-Aug	15	0	6	25	533	45	4,253	101	12	892
4-Aug	61	0	50	175	143	12	28	2,912	3	217
5-Aug	60	0	201	337	117	23	169	37	0	588
6-Aug	151	0	376	497	49	21	5	65	0	289
7-Aug	2,025	0	117	230	103	33	199	53	0	136
8-Aug	47	0	270	220	28	20	133	56	0	20
9-Aug	74	622	296	39	8	41	222	2,239	0	252
10-Aug	2,237	3,860	402	649	994	42	229	23	0	56
11-Aug	587	0	408	269	44	26	182	522	0	77
12-Aug	328	220	6	12	1,252	31	1,188	305	0	371
13-Aug	75	1,311	12	2,140	10	21	47	56	0	286
14-Aug	485	0	30	18	39	20	95	1,042	12	85
15-Aug	1,390	0	4	0	527	30	40	415	20	77
16-Aug	119	0	17	0	2,950	55	15	825	5	326
17-Aug	19	44	9	18	277	12	93	176	0	71
18-Aug	29	70	9	32	70	7	8	208	21	31
19-Aug	62	61	21	112	23	121	10	818	30	28
20-Aug	38	0	31	28	42	15	88	677	7	164

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Date	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
21-Aug	70	764	3,431	23	16	16	894	93	5	219
22-Aug	805	94	101	6	218	69	400	170	33	278
23-Aug	100	0	14	30	0	34	123	476	17	130
24-Aug	53	16	29	16	38	11	60	488	21	156
25-Aug	6	2,540	1	13	2	66	138	162	0	171
26-Aug	1	64	1	18	0	29	166	139	0	60
27-Aug	0	42	31	6	150	18	85	91	36	–[a]
28-Aug	1	14	1	0	–	29	38	713	8	–
29-Aug	3	2	25	30	–	34	3	31	30	–
30-Aug	16	3	–	–	–	11	0	–	–	–
31-Aug	18	6	–	–	–	0	34	–	–	–
1-Sep	13	1	–	–	–	–	0	–	–	–
2-Sep	117	3	–	–	–	–	20	–	–	–
3-Sep	67	1	–	–	–	–	1,114	–	–	–
4-Sep	270	1	–	–	–	–	18	–	–	–
5-Sep	60	2	–	–	–	–	685	–	–	–
6-Sep	18	0	–	–	–	–	–	–	–	–
7-Sep	2	0	–	–	–	–	–	–	–	–
8-Sep	13	0	–	–	–	–	–	–	–	–
9-Sep	14	–	–	–	–	–	–	–	–	–
10-Sep	6	–	–	–	–	–	–	–	–	–
11-Sep	5	–	–	–	–	–	–	–	–	–
12-Sep	22	–	–	–	–	–	–	–	–	–
13-Sep	20	–	–	–	–	–	–	–	–	–
14-Sep	70	–	–	–	–	–	–	–	–	–
15-Sep	120	–	–	–	–	–	–	–	–	–
16-Sep	27	–	–	–	–	–	–	–	–	–
17-Sep	36	–	–	–	–	–	–	–	–	–
18-Sep	6	–	–	–	–	–	–	–	–	–
19-Sep	7	–	–	–	–	–	–	–	–	–
20-Sep	161	–	–	–	–	–	–	–	–	–
21-Sep	235	–	–	–	–	–	–	–	–	–
22 Sep–19 Nov	182	–	–	–	–	–	–	–	–	–
Total	10,484	9,764	7,073	5,857	9,353	969	12,854	18,095	299	9,439
End Date	19-Nov	8-Sep	29-Aug	29-Aug	27-Aug	31-Aug	5-Sep	29-Aug	29-Aug	26-Aug

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Date	1993[a]	1994[a]	1995	1996	1997	1998	1999	2000	2001	2002
1 Jul–11 Jul	–[b]	–	–	–	–	–	–	–	–	–
12-Jul	–	–	–	–	–	–	–	–	–	–
13-Jul	–	–	–	–	–	–	–	–	–	–
14-Jul	–	–	–	–	–	–	–	0	–	–
15-Jul	–	–	–	15	–	–	–	0	–	–
16-Jul	–	–	–	0	–	–	0	0	0	0
17-Jul	–	–	–	0	–	–	0	0	0	0
18-Jul	–	–	–	0	10	–	0	0	0	0
19-Jul	–	–	–	0	30	–	0	0	0	0
20-Jul	–	–	–	0	36	–	0	0	0	3
21-Jul	–	–	–	0	70	–	35	0	0	0
22-Jul	–	–	–	0	46	7	100	0	0	19
23-Jul	–	–	–	28	77	202	0	0	0	22
24-Jul	–	–	–	62	119	87	0	0	0	17
25-Jul	–	–	–	179	120	47	0	2	22	9
26-Jul	–	–	–	116	90	33	0	6	2	10
27-Jul	–	–	–	86	66	19	0	4	1	7
28-Jul	–	–	–	66	567	405	108	16	2	14
29-Jul	–	–	–	64	130	284	8	48	5	0
30-Jul	–	–	–	156	76	127	0	40	7	0
31-Jul	–	–	–	111	27	1,151	1	89	24	7
1-Aug	–	–	24	97	15	335	30	210	188	5
2-Aug	–	–	26	162	29	643	33	188	100	110
3-Aug	–	–	66	237	7	45	43	168	229	239
4-Aug	–	–	31	270	22	36	18	412	5	190
5-Aug	–	–	1	166	14	86	74	412	161	228
6-Aug	–	–	43	3,802	33	286	104	318	821	220
7-Aug	–	–	46	215	147	6,090	21	64	36	1,671
8-Aug	–	–	43	81	42	50	103	3,432	628	499
9-Aug	–	–	1	104	96	26	311	204	626	103
10-Aug	–	–	47	78	100	234	39	27	215	127
11-Aug	–	–	169	68	124	69	30	65	677	8
12-Aug	–	–	282	112	103	105	40	6	157	54
13-Aug	–	–	285	110	1,017	44	2,732	8	58	157
14-Aug	–	–	152	86	137	195	1,572	0	139	9
15-Aug	–	–	44	167	65	435	29	813	440	0
16-Aug	–	–	32	118	72	145	91	0	607	0
17-Aug	–	–	17	76	57	196	195	31	291	0
18-Aug	–	–	11	62	92	166	594	19	75	0
19-Aug	–	–	32	64	33	40	112	3	1,383	1
20-Aug	–	–	25	83	240	152	22	49	111	3

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Date	1993[a]	1994[a]	1995	1996	1997	1998	1999	2000	2001	2002
21-Aug	–[b]	–	4	332	80	63	25	30	50	15
22-Aug	–	–	30	1,163	254	1	691	2	17	43
23-Aug	–	–	50	1,354	200	188	45	47	2	228
24-Aug	–	–	4	11	41	675	13	1	35	5
25-Aug	–	–	33	110	63	30	106	3	22	13
26-Aug	–	–	54	106	63	108	71	0	42	9
27-Aug	–	–	16	137	80	553	20	0	751	3
28-Aug	–	–	7	44	100	–	2,189	35	37	56
29-Aug	–	–	233	32	64	–	187	0	4	21
30-Aug	–	–	56	72	64	–	485	11	5	0
31-Aug	–	–	1,386	28	49	–	–	0	12	14
1-Sep	–	–	2,283	12	32	–	–	–	73	4
2-Sep	–	–	357	–	–	–	–	–	–	0
3-Sep	–	–	210	–	–	–	–	–	–	5
4-Sep	–	–	33	–	–	–	–	–	–	34
5-Sep	–	–	22	–	–	–	–	–	–	73
6-Sep	–	–	3	–	–	–	–	–	–	34
7-Sep	–	–	11	–	–	–	–	–	–	26
8-Sep	–	–	11	–	–	–	–	–	–	8
9-Sep	–	–	194	–	–	–	–	–	–	15
10-Sep	–	–	1,185	–	–	–	–	–	–	7
11-Sep	–	–	98	–	–	–	–	–	–	58
12-Sep	–	–	11	–	–	–	–	–	–	210
13-Sep	–	–	–	–	–	–	–	–	–	86
14-Sep	–	–	–	–	–	–	–	–	–	51
15-Sep	–	–	–	–	–	–	–	–	–	2
16-Sep	–	–	–	–	–	–	–	–	–	0
17-Sep	–	–	–	–	–	–	–	–	–	18
18-Sep	–	–	–	–	–	–	–	–	–	220
19-Sep	–	–	–	–	–	–	–	–	–	26
20-Sep	–	–	–	–	–	–	–	–	–	55
21-Sep	–	–	–	–	–	–	–	–	–	–
22 Sep–19 Nov	–	–	–	–	–	–	–	–	–	–
Total	–	–	8,201	10,442	4,999	13,358	10,277	6,763	8,060	5,071
End Date	–	–	12-Sep	1-Sep	1-Sep	27-Aug	30-Aug	31-Aug	1-Sep	20-Sep

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Date	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
1 Jul–11 Jul	–[a]	–	–	–	–	–	–	–	–	–	–
12-Jul	–	–	–	–	–	–	–	–	–	0	0
13-Jul	–	–	–	–	–	–	–	–	–	0	0
14-Jul	0	–	0	–	0	–	–	–	0	0	0
15-Jul	0	–	0	0	0	0	0	0	0	0	0
16-Jul	0	–	0	0	0	0	0	0	0	0	9
17-Jul	0	2	13	14	0	0	0	0	0	0	3
18-Jul	0	0	11	0	0	0	0	0	0	0	7
19-Jul	8	25	9	0	0	8	1	57	0	0	10
20-Jul	0	23	0	0	0	0	0	32	1	20	9
21-Jul	5	22	9	4	0	6	0	44	32	20	48
22-Jul	3	35	7	0	38	0	0	79	15	22	20
23-Jul	9	25	15	19	0	16	7	66	3	20	11
24-Jul	2	23	12	0	51	0	0	59	1	7	12
25-Jul	42	154	18	0	0	2	29	28	53	11	9
26-Jul	56	96	55	20	33	4	0	16	37	11	13
27-Jul	286	198	28	1	41	4	6	27	5	22	63
28-Jul	624	194	35	5	38	7	38	82	23	36	54
29-Jul	150	110	56	3	34	9	104	92	25	19	77
30-Jul	87	31	25	0	44	33	191	320	23	6	177
31-Jul	198	25	57	0	31	38	203	281	22	5	232
1-Aug	325	42	46	2	98	40	176	69	44	38	211
2-Aug	892	344	96	0	81	21	128	207	29	24	383
3-Aug	31	157	936	0	128	14	168	147	85	53	359
4-Aug	18	548	233	1	40	65	282	78	1,773	109	383
5-Aug	66	238	62	40	31	62	303	50	76	57	1,578
6-Aug	209	196	21	100	14	49	151	74	34	27	371
7-Aug	382	32	18	34	46	468	151	142	71	20	101
8-Aug	156	110	48	24	56	4	86	109	71	58	125
9-Aug	71	164	86	70	2	154	44	51	93	88	133
10-Aug	4	26	66	207	22	1	62	16	62	99	108
11-Aug	39	933	56	18	5	0	8	38	676	35	111
12-Aug	52	16	77	769	117	0	9	78	35	8	57
13-Aug	139	203	81	272	243	113	7	103	29	57	45
14-Aug	304	57	77	19	42	4	8	239	5	60	7
15-Aug	538	90	21	3	213	0	34	158	958	847	26
16-Aug	360	34	56	0	0	2	452	656	214	1,551	74
17-Aug	32	42	267	750	275	4	77	139	63	304	92
18-Aug	0	20	2,287	32	70	0	0	1,015	24	514	63
19-Aug	21	14	135	8	12	1	0	44	20	300	21
20-Aug	48	67	40	64	0	0	0	52	125	191	41

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Date	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
21-Aug	35	11	27	2	143	1	45	15	0	115	20
22-Aug	11	53	318	373	10	0	118	10	0	34	36
23-Aug	14	5	92	56	0	360	27	21	0	51	6
24-Aug	10	42	27	17	0	1	20	74	0	24	26
25-Aug	19	9	295	968	6	25	34	41	1	14	4
26-Aug	15	4	407	8	5	50	5	40	2	28	9
27-Aug	13	511	68	1	11	0	27	4	4	11	6
28-Aug	4	410	55	0	1	2	0	2	0	471	5
29-Aug	0	44	12	109	19	0	142	7	2	28	21
30-Aug	3	31	257	0	3	2	101	4	0	1	21
31-Aug	130	34	170	131	39	2	30	3	3	25	22
1-Sep	223	35	74	0	3	3	13	303	0	25	813
2-Sep	710	6	42	0	4	0	20	187	3	2	57
3-Sep	67	576	33	0	1	0	5	75	9	3	16
4-Sep	42	466	39	0	79	3	53	45	9	29	24
5-Sep	35	136	43	0	567	3	36	34	0	15	114
6-Sep	45	125	55	0	317	8	23	15	0	1	27
7-Sep	30	235	128	2	45	0	0	20	0	2	22
8-Sep	26	149	26	4	17	10	36	19	9	13	8
9-Sep	54	76	31	6	18	0	5	2	8	106	28
10-Sep	78	28	20	1	3	1	0	21	0	5	20
11-Sep	12	26	41	2	0	47	65	13	0	12	16
12-Sep	18	80	70	0	0	67	34	1	0	22	5
13-Sep	67	58	47	0	0	2	19	9	0	1	16
14-Sep	159	80	51	4	0	0	20	6	0	0	4
15-Sep	31	170	19	2	0	21	17	7	0	0	2
16-Sep	4	54	6	0	0	2	2	6	0	2	5
17-Sep	2	–[a]	9	–	0	5	4	3	0	1	0
18-Sep	0	–	10	–	3	0	3	5	0	0	8
19-Sep	–	–	7	–	0	15	28	0	0	1	7
20-Sep	–	–	11	–	0	4	32	–	0	0	15
21-Sep	–	–	–	–	0	–	–	–	–	–	0
22 Sep–19 Nov	–	–	–	–	–	–	–	–	–	–	0
Total	7,014	7,813	7,549	4,165	3,099	1,763	3,689	5,640	4,777	5,681	6,426
End Date	18-Sep	19-Sep	20-Sep	16-Sep	21-Sep	20-Sep	20-Sep	19-Sep	20-Sep	20-Sep	1-Oct

[a] An "n-dash" indicates dates the weir was not in operation.

Appendix B3.–Otolith samples and Snettisham Hatchery thermal marks recovered from the Speel Lake sockeye salmon spawning escapement, 1997–2013.

Year	Sample date	Number of otoliths sampled	Number of otoliths assayed	Snettisham Hatchery marks	Snettisham Hatchery thermal mark
1997	10/22/1997	143	142	0	
1998	10/29/1998	110	110	0	
1999	10/27/1999	93	93	0	
2000	10/10/2000	115	114	0	
2001	10/16/2001	107	107	0	
2002	Not sampled				
2003	10/3/2003	137	137	1	SPEELARM00LSM
2004	10/10/2004	97	96	0	
2005	10/9/2005	100	100	0	
2006	Not sampled				
2007	Not sampled				
2008	10/16/2008	90	90	1	SPEELARM03LLG
2009	Not sampled				
2010	10/14/2010	113	108	0	
2011	11/3/2011	10	10	0	
2012	10/4/2012	81	81	0	
2013	10/6/2013	95	94	0	

APPENDIX C:
SPEEL LAKE PHYSICAL DESCRIPTION

Appendix C1.–Description of Speel Lake.

Speel Lake (Anadromous Waters Catalogue no. 111-33-10300-0010; 58° 11.95’ N, 133° 33.72’ 43 W), is located on mainland Alaska, about 50 km southeast of Juneau. The Speel Lake watershed encompasses approximately 16.5 km^2. The lake elevation is about 14 m. It is a relatively small, shallow lake, with surface area 168 ha, average depth 3.0 m, and maximum depth 9.5 m. The total lake volume is approximately 4.4×10^6 m^3. Sockeye salmon spawn primarily along the northeast shore where steep scree slopes plunge into the lake (Riffe 2005). Shallower portions of the lake support extensive aquatic vegetation. The outlet stream flows southwest 2 km into the Speel River (Anadromous Waters Catalogue no. 111-33-10300), which continues southwest another 9.5 km to the head of Speel Arm. Glacially occluded water in the Speel River obscures visibility; thus, migrating sockeye salmon are not visible until the fish enter clear water in the outlet stream below Speel Lake.

Appendix C 2.–Bathymetric map of Speel Lake.