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Chilkoot Lake Sockeye Salmon Stock Status and Escapement Goal Review

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

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Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

Alaska 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

Chilkoot Lake, located in upper Lynn Canal near the city of Haines, supports one of the largest runs of sockeye salmon (*Oncorhynchus nerka*) in southeast Alaska. This stock is currently managed as a sustainable escapement goal range with a lower bound of 38,000 and an upper bound of 86,000 spawners. Escapement is monitored by the Alaska Department of Fish and Game with a weir on the Chilkoot River, and stock of origin from the District 15 commercial drift gillnet fishery harvest is determined using scale pattern analysis. We used Ricker spawner–recuit models in a Bayesian framework to fit data from brood years 1976–2010. Given significant autocorrelation at lag-1, we chose an autoregressive Ricker model for this assessment. Based on model results, maximum sustainable yield would be achieved with an escapement of approximately 52,900 sockeye salmon (median of spawning abundance at maximum sustained yield), and a range of 45,000–60,000 spawners would result in a greater than 80% probability of achieving at least 90% of maximum sustainable yield. This range of escapements fits within the current escapement goal range and, given considerable uncertainty in parameter estimates, we do not recommend changes to the goal at this time. However, some large escapements since 2012 will provide contrast to the existing data once the resulting recruits can be enumerated; thus, we recommend reassessing this escapement goal prior to the Alaska Board of Fisheries meeting in 2021.

Key words: Bayesian statistics, escapement goal, maximum sustained yield, missing data, sockeye salmon, *Oncorhynchus nerka*, Chilkoot Lake, spawner–recruit analysis

INTRODUCTION

The Chilkoot and Chilkat river watersheds, located in northern Southeast Alaska near the town of Haines, support 2 of the largest sockeye salmon (*Oncorhynchus nerka*) runs in Southeast Alaska (Figure 1). Between 1900 and 1920, the annual commercial harvest of sockeye salmon in northern Southeast Alaska averaged 1.5 million fish, the majority of which were believed to originate from Chilkat and Chilkoot river watersheds (Rich and Ball 1933). Since the mid-1980s, the average annual sockeye salmon harvest in northern Southeast Alaska was 500,000 fish, of which an estimated 78,000 originated from Chilkat Lake and 91,500 originated from Chilkoot Lake (Bednarski et al. 2016; Eggers et al. 2010). Historically, Chilkoot Lake sockeye salmon were harvested in the large fish trap and purse seine fisheries in Icy and northern Chatham straits as well as in terminal drift gillnet areas of Lynn Canal. Fish traps were eliminated with Alaska statehood in 1959 and Lynn Canal developed into a designated drift gillnet fishing area (District 15) where most of the commercial harvest of Chilkoot Lake sockeye salmon takes place (Figure 1). A smaller portion of the Chilkoot Lake run is harvested in the commercial purse seine fisheries that target pink salmon (*O. gorbuscha*) in Icy and northern Chatham straits. Annual contributions to those fisheries are not known and likely vary annually depending on fishing effort and the strength of pink salmon runs. Chilkoot Lake sockeye salmon are also harvested annually in subsistence fisheries in Chilkoot Inlet and Lutak Inlet, with reported harvests for the period 1985–2016 averaging approximately 2,000 fish per year.

The Alaska Department of Fish and Game (ADF&G) initiated a scale pattern analysis program in 1980 to estimate contributions of sockeye salmon stocks to the District 15 commercial drift gillnet fishery. Bergander (1974) first developed a dichotomous key to classify sockeye salmon scale samples from the fishery as Chilkoot Lake or Chilkat Lake fish, based on distinct differences in their freshwater scale patterns (Stockley 1950). Marshall et al. (1982) improved the sample design and estimated stock contributions using linear discriminant function analysis. McPherson and Marshall (1986) showed that all age classes of the 2 stocks could be identified accurately using a visual classification technique and blind testing procedure. That technique was expanded to include a group of "other" stocks—a combination of Chilkat River mainstem and Berners Bay stocks that contribute to early-season harvests in Lynn Canal (McPherson 1987a).

Blind tests to verify accuracy and correct for misclassification have not been conducted since the early 1990s; however, historical stock-specific harvest estimates based solely on visual classification were highly accurate and the difference between initial and corrected estimates varied by only 2% or less (McPherson and Marshall 1986; McPherson 1987a, 1987b; McPherson and Jones 1987; McPherson 1989; McPherson et al. 1992; McPherson and Olsen 1992). The consistent differences in freshwater scale patterns makes visual scale pattern analysis highly accurate, and it was more cost effective and required less time than other stock identification methods (McPherson 1990; McPherson and Olsen 1992). Starting in 2017 genetic stock identification will be used as the sole method to attribute stock of origin in District 15 sockeye salmon harvests.

Chilkoot Lake sockeye salmon escapements have been counted annually through an adult counting weir on the Chilkoot River since 1976 (Bachman and Sogge 2006; Bachman et al. 2013, 2014). The run has 2 components, an early and a late run, which were managed as separate units through 2005 (Geiger et al. 2005). Total annual weir counts averaged 80,000 sockeye salmon through 1993, but declined to an average of only 30,000 fish from 1994 to 2000. Weir counts have averaged 68,000 fish since 2000. In addition to salmon counts, biological data have been collected annually at the weir to estimate age, size, and sex composition of the escapement and for use in scale pattern analysis. Basic information about lake productivity and rearing sockeye salmon fry populations has also been collected through limnological and hydroacoustic sampling conducted most years since 1987 (Barto 1996; Riffe 2006; Bachman et al. 2014). Those studies have been used to assess potential sockeye salmon production from the lake (Barto 1996).

The Chilkoot Lake run has been managed for at least 5 different escapement goals since 1976. Informal goals of 80,000–100,000 fish (1976–1980) and 60,000–80,000 fish (1981–1989; Bergander et al. 1988) were replaced in 1990 by a biological escapement goal (BEG) of 50,500–91,500 sockeye salmon (McPherson 1990). The goal was divided into separate goals for early (16,500– 31,500 fish) and late runs (34,000–60,000 fish). In 2006, the escapement goal was rounded to 50,000–90,000 sockeye salmon and classified as a sustainable escapement goal due to uncertainty in escapement levels based on weir counts (Geiger et al. 2005). Early- and late-run goals were eliminated and replaced with weekly cumulative escapement targets based on historical run timing. The existing sustainable escapement goal of 38,000–86,000 sockeye salmon was established in 2009 based on an autoregressive Ricker spawner–recruit model by Eggers et al. (2009) that relied on brood year escapement and returns data from 1976 to 2003. Specifically, the recommended escapement goal by Eggers et al. (2009) was the range of spawners expected to produce at least 90% of MSY, with a recommendation for escapements distributed according to the historical average run timing since 1976.

The objectives of this study of Chilkoot Lake sockeye salmon are as follows.

1) Update escapement and return data from all available brood years (1976–2010).
2) Conduct a spawner–recruit analysis using Bayesian methods.
3) Provide a recommendation for an escapement goal.

STUDY SITE

Chilkoot Lake (ADF&G Anadromous Waters Catalogue No. 115-33-10200-0010; 59°21′16″ N, 135°35′42″ W) is located at the head of Lutak Inlet, approximately 16 km northeast of the city of Haines, Alaska (Figures 1–2). It is glacially turbid and has a surface area of 7.2 km^2 (1,734 acres), a mean depth of 55 m, a maximum depth of 89 m, and a total volume of 382.4 × 106 m^3. The Chilkoot River begins at glacier terminuses east of the Takshunak Mountains and west of the Ferebee Glacier. The glacial river flows approximately 26 km southeast into Chilkoot Lake, then flows approximately 2 km into Lutak Inlet. Early-run sockeye salmon spawn in small lake and river tributaries and late-run fish spawn in the main channel of the Chilkoot River and along lake beaches where upwelling water occurs (McPherson 1990). Chilkoot Lake is located within the northern temperate rainforest that dominates the Pacific Northwest coast of North America. Although the climate is characterized by cold winters and cool, wet summers, the lake is set in a transitional zone, with warmer and drier summers and cooler winters than the rest of Southeast Alaska (Bieniek et al. 2012). Average precipitation in the study area is approximately 165 cm/year (Bugliosi 1988). Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and Sitka alder (*Alnus viridis*) dominate the forested watershed.

METHODS

DATA

Harvest Estimates

Annual commercial harvests of sockeye salmon caught in the District 15 commercial drift gillnet fishery in northern Lynn Canal were obtained from the ADF&G Southeast Alaska Integrated Fisheries Database. However, harvest from District 15 contains sockeye salmon from multiple stocks. Thus, visual scale pattern analysis was used to determine stock composition of sockeye salmon harvested in the District 15 commercial drift gillnet fishery and estimate harvest of fish bound for Chilkoot Lake (Bachman et al. 2014). The general methods of stock apportionment using visual scale pattern analysis have remained unchanged since the mid-1980s: escapement scale samples from 3 stocks of known origin, Chilkoot Lake, Chilkat Lake, and “other” (includes Chilkat River mainstem and Berners Bay stocks), were aged and compared to scale samples from the commercial fisheries, which were apportioned to these 3 stocks for each statistical week. Since total District 15 commercial drift gillnet fishery harvest was not apportioned to a particular stock in years 1976 through 1983, the apportionment percentages from McPherson (1990) were reapplied to updated harvest from those years (Bednarski et al. 2016).

Escapement Estimates

Sockeye salmon entering into Chilkoot Lake have been counted through a weir on the Chilkoot River, located downstream of the lake outlet, from 1976 through 2017 (Bergander 1989; Kelley and Bachman 1999; Bachman 2003; Bachman and Sogge 2006; Bednarski et al. 2016). The early and late components of the run are currently managed as a single unit. The sockeye salmon weir counts have varied dramatically during these years, from 7,177 (1995) to 118,166 (2012) fish (Table 1). Weir counts have averaged 68,462 sockeye salmon between 1976 and 2016, but were generally quite low from 1994 to 2000, when they averaged approximately 30,600.

The extremely low weir count in 1995 prompted ADF&G to verify the weir counts by conducting a mark–recapture project on Chilkoot Lake sockeye salmon. The mark–recapture project was conducted annually from 1996 to 2004 and again in 2007, 2010, and 2011 (Kelley and Bachman 1999, Bachman and Sogge 2006, Bachman et al. 2014). The mark–recapture estimates were consistently higher than the weir counts—averaging 1.73 times the weir count (Bachman et al. 2014). Because spawning in Chilkoot Lake occurs primarily in beach spawning areas and in the remote upper reaches of the Chilkoot watershed, the second-event recovery is difficult and low tag recoveries have likely contributed to imprecise mark–recapture estimates. Differences between mark–recapture and weir counts were not consistent enough for a calibration of the weir counts. Thus, assessments of Chilkoot Lake sockeye salmon escapements in this report are based solely on weir counts, with the recognition that these estimates are likely conservative.

Recruits from Parent Escapement by Age

Scale samples from commercial harvests and escapement were analyzed at the ADF&G salmon-aging laboratory in Douglas, Alaska. Age classes were designated by the European aging system where freshwater and saltwater years were separated by a period (e.g., 1.3 denoted a fish with 1 freshwater and 3 ocean years; Koo 1962). Sockeye salmon harvested in sport and personal use fisheries were assigned ages based on proportions of age classes from the District 15 commercial drift gillnet fishery. Weekly age distributions (the seasonal age distribution weighted by week) were calculated using equations from Cochran (1977). Table 2 shows annual estimates of sockeye salmon apportioned by age class from the Chilkoot Lake weir; Table 3 shows annual estimates of Chilkoot Lake sockeye salmon apportioned by age class that were harvested in the District 15 commercial drift gillnet fishery.

Escapement and harvest data (Tables 2–3) were used to estimate total recruits, by age, for the 1976 to 2010 brood years (Table 4). The recruits from brood year *y* and age *a* is the escapement and harvest for age *a* in calendar year *y* + *a*.

$$\hat{R}_{a,y} = \hat{E}_{a,y+a} + \hat{C}_{a,y+a} \tag{1}$$

$R_{a,y}$ is the recruits for age *a* and brood year *y*, $E_{a,y+a}$ is the escapement by age *a* and calendar year *y*+*a*, and $C_{a,y+a}$ is harvest by age *a* and calendar year *y*+*a*.

Production for year classes 1976 through 2010 was estimated as the sum of recruits originating from each brood year:

$$\hat{R}_y = \sum_{a=3}^{7} \hat{R}_{a,y} \tag{2}$$

As of this writing, some of the older and rarer age class from the 2010 brood year had not yet returned and been enumerated. However, based on previous years, the incomplete age classes were estimated to represent less than 1% of the total brood year recruits; therefore, we consider it unlikely that these will have a substantial influence on the results of our analysis.

SPAWNER–RECRUIT ANALYSIS

Spawner–recruit models were fit to the Chilkoot Lake data for the 1976 to 2010 brood years. The spawner–recruit models were Ricker type (Ricker 1975) in which returns *R* of Chilkoot Lake sockeye salmon were modeled as a function of spawning escapement *S* in year *y*,

$$R_y = \alpha S_y \exp\left(-\beta S_y + \varepsilon_i\right) \tag{3}$$

where parameter α (number of recruits per spawner in the absence of density dependence) is a measure of productivity, and parameter β is a measure of density dependence. In the model, productivity is allowed to vary among brood years, fluctuating around a central tendency. Time-varying productivity often manifests as serially correlated model residuals, so an autoregressive lognormal error term with a lag of 1 year (AR[1]) was included in an autoregressive Ricker model. The autoregressive Ricker model is the result of a first order autoregressive process where observations are linearly related to the prior year observation (c.f. Noakes et al. 1987),

$$R_y = \alpha S_y e^{-\beta S_y + \phi \varepsilon_{i-1}} \qquad (4)$$

In this model ϕ is the lag-1 autoregressive coefficient. Given significant autocorrelation at a lag of 1 year (Figure 3), we used the autoregressive form (equation 4) exclusively for this analysis, with a linearized form of the AR1 model

$$\ln(R_y / S_y) = \ln(\alpha) - \beta S_y + \phi \nu_{y-1} + \varepsilon_y , \qquad (5)$$

where $\{\nu_y\}$ are model residuals

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

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

MODEL FITTING

Model fitting involves finding the values of population parameters that can plausibly result in the observed data. Using the package RJAGS[1] within R,[2] Markov Chain Monte Carlo (MCMC) methods were employed to provide a more realistic assessment of uncertainty than is possible with traditional spawner–recruit model fitting methods.

Bayesian statistical methods employ the language of probability to quantify uncertainty about model parameters. Knowledge existing about the parameters outside the framework of this analysis 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 contained in the data. See Fleischman et al. (2013), Staton et al. (2016), and Fair et al. 2012 for similar applications of the methods used in this report.

Prior Distributions

For all unknown parameters in the model, Bayesian analysis requires that prior probabilities be specified. Most prior distributions in this model were noninformative and chosen to have minimal effect on the posterior (Table 5). Normal priors with mean 0, large variances, and constrained to be positive were used for α, β, and σ_w^2 (Millar 2002). The initial model residual ν_0 was given a normal prior with mean zero and variance $\sigma_W^2(1-\phi^2)$.

Sampling from the Posterior Distribution

MCMC methods were used to generate the joint posterior probabilities of the unknown quantities using the package RJAGS[3] with R.[4] Three Markov chains were initiated. After a 10,000 sample burn-in period was discarded, 3,000 samples (1,000,000 iterations, thinned by 1000; 1000

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1 Plummer, M., A. Stukalov, and M. Denwood. 2016. rjags: Bayesian Graphical Models using MCMC. R package version 4-6. https://CRAN.R-project.org/package=rjags

2 The R project for statistical computing. R Foundation, Vienna, Austria. URL https://www.R-project.org/

3 See note 1.

4 See note 2.

samples per chain) MCMC updates were retained for analysis to estimate posterior medians, standard deviations, and percentiles. The diagnostic tools of the package RJAGS[5] such as time series and density plots, the Gelman Rubin convergence diagnostics (Brooks and Gelman 1998), autocorrelation plots, and Monte Carlo standard errors (e.g., MC error should be less than 5% of the sample standard; Toft et al. 2007) were used to assess mixing and convergence. No major problems were encountered. Interval estimates (credible intervals) were constructed from the percentiles of the posterior distribution.

Reference Points, Optimal Yield Profiles, Overfishing Profiles, Optimal Recruitment Profiles, and Sustained Yield

Reference points were calculated for each individual MCMC sample. Spawning abundance at maximum sustained yield (MSY), S_{MSY}, was approximated by (Hilborn 1985),

$$S_{\text{MSY}} \cong \frac{\ln(\alpha')}{\beta}[0.5 - 0.07\ln(\alpha')], \qquad (7)$$

where $\ln(\alpha') = \ln(\alpha) + \frac{\sigma_R^2}{2(1-\phi^2)}$, to correct for the difference between the median and the mean of a lognormal error distribution and AR(1) process (Parken et al. 2006). Sustained yield at a specified level of S was obtained by subtracting spawning escapement from recruitment,

$$Y_S = R - S = Se^{(\ln(\alpha') - \beta S_{\text{MSY}})} - S. \qquad (8)$$

Spawning escapement at peak return, S_{Max}, was calculated as $1/\beta$ and equilibrium spawning abundance (recruitment exactly replaces spawners) as

$$S_{\text{EQ}} = \frac{\ln(\alpha')}{\beta}. \qquad (9)$$

Harvest rate leading to MSY, U_{MSY}, was approximated by (Hilborn 1985),

$$U_{\text{MSY}} \cong \ln(\alpha')[0.5 - 0.07\ln(\alpha')], \qquad (10)$$

Optimal yield probabilities are the probabilities that a given level of spawning escapement (S) will produce average yields exceeding X% of *MSY*: P(Y_S > X% of *MSY*). These probabilities were calculated as

$$P(Y_s > X\%MSY) = \frac{\text{number of } \mathrm{Y_s} > X\%MSY}{\text{number of MCMC samples}}. \qquad (11)$$

Optimal yield profiles are plots of P versus S (Fleischman et al. 2013).

Overfishing probability was calculated as 1 – P(Y_S > X% of *MSY*) at $S < S_{\text{MSY}}$, and 0 at $S > S_{\text{MSY}}$. These profiles show the probability of overfishing the stock such that sustained yield is reduced to less than a fraction (80%, 90%) of *MSY* (Bernard and Jones 2010).

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[5] See note 1.

Optimal recruitment probability is calculated as

$$P(Y_s > X\%MAX) = \frac{\text{number of } Y_s > X\%MAX}{\text{number of MCMC samples}}. \quad (12)$$

Optimal recruitment profiles are then a plot of *P* versus *S* (Fleischman et al. 2013).

Expected sustained yield is the number of fish in the expected recruitment over and above that needed to replace the spawners (Fleischman et al. 2011).

RESULTS

ESCAPEMENT, HARVEST RATE, AND ANNUAL PRODUCTIVITY

Tables 1–3 summarize historical escapement goals, weir-based escapement estimates, harvests, and the harvest rate for Chilkoot Lake sockeye salmon. We do not present (or use) mark–recapture-based estimates of escapement for this report, but these data can be found within Bachman et al. (2013). With the exception of 2009 (escapement of 33,705 fish), the lower bound of the current escapement goal (38,000–86,000 spawners) has been achieved in all other years since this goal was implemented (Eggers et al. 2009). Annual escapement has been below the lower bound of the current goal 7 times across available years (1976–present), during which escapement has averaged 68,462 fish, with a low of 7,177 fish (1995) and a high of 118,116 fish (2014). The vast majority of the estimated harvest has occurred in the D15 commercial drift gillnet fishery, with substantially smaller portions from sport and subsistence fisheries. The historical average harvest rate is 48%, with a range of 18% (1980) to 84% (1989).

The number and ages of Chilkoot Lake sockeye salmon in spawning escapements (Table 2) and the commercial harvests (Table 3) were used to estimate total brood year returns (Table 4). Total returns of sockeye salmon that originated from a given brood year, divided by the number of parental spawners during that brood year, provide an estimate of brood year productivity (returns per spawner or R/S). Since 1976, brood year productivity has ranged from an R/S of 0.2 (1990) to an R/S of 9.2 (1999). Over time, historical productivity has fluctuated dramatically, with discrete periods of high and low productivity (Figure 4). Of particular note is the period of continuously low productivity from 1988 to 1994 and a 3-year period of low productivity during the mid-2000s. While escapements below about 30,000 fish have resulted in high productivity, productivity has been highly variable for escapements greater than 30,000 fish (Figure 5).

RESULTS OF SPAWNER–RECRUIT ANALYSIS

For the results presented herein, we chose the autoregressive Ricker model because of significant autocorrelation of productivity at a lag of 1 year (Figure 3). We note that Eggers et al. (2009) also chose the autoregressive Ricker to inform their escapement goal bounds based on significant autocorrelation and a lower information criterion score for the autoregressive Ricker model compared to the Ricker model without an autoregressive term and a linear model that did not include density dependence.

Table 6 provides a summary of parameter estimates and management reference points as estimated from the autoregressive Ricker model. Because our model was run in a Bayesian framework using iterative MCMC sampling techniques, estimates are provided for 95% credibility intervals. In the Ricker model the parameter α reflects the potential productivity of the stock and is considered constant over time. In the autoregressive Ricker, the time series factor

$\exp(\phi)(R_{i-1}/\hat{R}_{i-1})$ corrects for the serial correlation in the Ricker model residuals fit to the data. The potential productivity reflected in the autoregressive Ricker model is the product of the base Ricker potential productivity and the autocorrelation correction (i.e., $\exp(\alpha\phi)(R_{i-1}/\hat{R}_{i-1})$) and varies over time. The parameter $\ln(\alpha')$ in Table 6 is the logarithm of the productivity parameter from the autoregressive model. From this table we can see that the median value of the AR(1) parameter ϕ is 0.59 (95% credibility interval, range of 0.27–0.88), which strongly suggests autocorrelation of the model residuals and provides additional justification for using the AR(1) model.

In general, 95% credibility intervals and CV for parameter estimates and management reference points were often quite large (Table 6); this was the direct result of the large variation in productivity over time (Figure 4), no clear trend in productivity across a range of spawning escapements (Figure 5), and thus a large range in values for α. In addition, the 95% credibility interval for S_{MSY}, the escapement that would result in MSY, ranged from 32,718 to 161,690 spawners, which extends beyond any previously observed escapement for this stock. The 95% credibility interval for U_{MSY}, the harvest rate that would result in MSY, ranged from 0.49 to 0.89.

Probability profiles for overfishing, optimum recruitment, and optimum yield are shown in Figure 6, along with the current escapement goal range (shaded area). The optimal yield and optimal recruitment profiles show the probability that a given spawning abundance will result in specified fractions (80% and 90% lines) of MSY or maximum recruitment. The profile lines represent the 80% and 90% probabilities of achieving MSY or maximum recruitment. The profile for overfishing shows the probability that reducing escapement to a specified spawning abundance would result in less than the specified fractions (80% or 90%) of MSY. At the low end of the current escapement goal range, 38,000 spawners would result in as much as an approximate 30% probability of overfishing, if overfishing is defined as failure to achieve 90% of maximum yield; or, an approximate 15% probability of overfishing if defined as a failure to achieve 80% of MSY. At the high end of the current goal range there is less than 5% probability of not achieving 80% or 90% of MSY.

The current escapement goal range would result in a greater than 80% probability of achieving 80% and 90% levels of maximum recruitment. However, throughout the current escapement goal range there are a wide array of probabilities of achieving 80% and 90% of MSY. If we focus solely on achieving 90% of MSY, there is only a 70% probability of achieving 90% of MSY at 38,000 spawners. This probability increases to approximately 85% at about 53,000 spawners and then declines to an approximate 40% probability of achieving 90% of MSY at 86,000 spawners. Narrowing escapements to a range of 45,000–61,000 spawners would ensure a greater than 80% probability of achieving at least 90% of MSY.

Expected sustained yield, or the numbers of fish over and above those necessary to replace spawners, averaged over the brood years 1976–2010 is maximized near approximately 53,000 spawners, the median estimate of S_{MSY} (Figure 7, Table 6). However, there is considerable uncertainty about expected yield, as well as S_{MSY} (Figure 8, Table 6).

DISCUSSION

In our view, pertinent management reference point estimates from our revised analysis do not provide appreciably different results to the most recent assessment of this escapement goal

(Eggers et al. 2009). Based on an autoregressive Ricker model, Eggers et al. (2009) recommended a sustainable escapement goal (SEG) for Chilkoot Lake sockeye salmon of 38,000 to 86,000 spawners per year to be assessed with a weir at the Chilkoot River weir site. This goal range was the escapement range that produced 90% MSY as determined by the autoregressive Ricker model for the brood years 1976 to 2003 spawner–recruit data. In the present analysis, we used methods similar to those of Eggers et al. (2009), in that a set of hierarchical stock-recruitment models, including a first order autoregressive term, were constructed and model comparisons were made through a fit criteria. However, whereas Eggers et al. (2009) utilized more traditional model fitting methods, our study employed a Bayesian modeling approach. Bayesian models are becoming increasing common for the analysis of escapement goal ranges for Pacific salmon in Alaska (Fleischman and Reimer 2017; Hamazaki et al. 2012; Fleischman and McKinley 2013) and provide a variety of benefits, which we mention in the *Methods* section. Our results provide a point estimate for S_{MSY} of 53,000 spawners that is relatively similar to the 58,000 spawners from Eggers et al. (2009), albeit with a narrower range of escapements expected to result in achieving more than 90% of MSY (45,000–61,000 fish) compared to the range from Eggers et al. (2009).

Escapements for the Chilkoot Lake sockeye salmon have been generally within or above the recommended BEG (Table 1–2), except for 3 years during the mid- to late 1990s when runs were reduced due to the extended period of low production.

Management of sockeye salmon runs to Chilkoot Lake has presented a major challenge following the collapse of sockeye recruitment to this system in the mid-1990s. The very low recruitment in 1995 appeared after a slow erosion of the stock's productivity, and after at least a decade of very large returns and large escapements. The decline was concurrent with a severe crash in zooplankton populations in the lake (Bachman 2003). Currently, Chilkoot Lake appears to be recovering from this downturn in productivity (Figure 4).

Our operating hypothesis is that the amount of glacial silt in the lake periodically increases due to glacial melt during periods of very warm summertime conditions. During times of increased silt in the lake, the euphotic volume the lake is reduced. The euphotic volume determines the level of primary and secondary production, as well as the amount of the sockeye food base (Koenings and Burkett 1987). The environmental conditions that drive these variations in lake conditions are typically highly autocorrelated and can be modeled as a first order autoregressive process. This explains the high serial correlation observed in the time series of recruits per spawner for Chilkoot Lake sockeye salmon. It is likely that several large escapements of sockeye salmon into the system, which occurred during the period of reduced zooplankton abundance, further reduced the production of sockeye salmon.

Note that the management reference points estimated for Chilkoot Lake sockeye salmon and the current sustainable escapement goal for the stocks are not specific to any individual time period or production regime. These are integrated over the variation in productivity observed for the stock and are reflective of the stock over the long term. It is not possible to condition escapement goals and associated management decisions to achieve MSY (which varies in concert with the varying lake productivity) because of the inability to forecast rearing conditions that affect the productivity expected for the escapement. In other words, knowledge about mechanisms responsible for freshwater density dependence does not necessarily translate into being able to more readily manage for maximum yield.

Management actions designed to reduce the harvest rate of Chilkoot Lake sockeye salmon when harvesting other salmon stocks and species have been successful during years of low abundance. In recent years, management has directed harvests on Chilkoot Lake sockeye salmon to reduce the potential of exceeding the carrying capacity of Chilkoot Lake during years of low zooplankton abundance. Summer conditions have often been cooler since 1999, and Chilkoot Lake sockeye salmons runs have increased. During 2001–2016, the total weir count has generally been within or above the current escapement goals for this system. Note that 2008–2009 escapements were slightly below the goal, due to extremely weak return from the 2003–2004 brood years that reared in Chilkoot Lake during the very warm summers of 2004–2005 (Bachman et al. 2013, Eggers et al. 2009).

ESCAPEMENT GOAL RECOMMENDATION

In Alaska, most salmon BEGs are developed using Ricker spawner–recruit models (Ricker 1954), and by definition in the *Policy for the Management of Sustainable Salmon Fisheries* (5AAC 39.222), BEG ranges are estimates of the number of spawners that provide the greatest potential for MSY (S_{MSY}). However, although utilizing a spawner–recruitment analysis, Eggers et al. (2009) recommended an SEG instead of a BEG for Chilkoot Lake sockeye salmon due to a relatively high level of uncertainty of the weir counts. Our study reaffirms that even without including uncertainty in escapement into our analysis, there is also a large amount of uncertainty surrounding parameter estimates and management reference points for this stock.

Given the high uncertainty in estimates of management reference points and fact that our point estimate of S_{MSY} is very similar to that from Eggers et al. (2009), <u>we recommend that the existing SEG of 38,000–86,000 spawners for Chilkoot Lake sockeye salmon remain unchanged for the time being</u>. Results from our revised analysis suggest that the existing goal brackets the range of escapements (45,000–61,000 fish) likely to result in achieving 90% or more of MSY. That the lower bound of the current escapement goal (38,000 spawners) has been achieved in the vast majority of years since 1976 (Table 1; Figure 9) lends support to this goal being achievable within the context of fisheries management, including the mixed stock fisheries of upper Lynn Canal.

Since 2012 there have been large escapements into Chilkoot Lake and the resulting recruits from these brood years could help to better define the current state of productivity and density dependence for this stock. Thus, we suggest keeping the current escapement goal unchanged until at least the time these recruits can be enumerated and included in a revised spawner–recruitment model. As such, we also suggest keeping the existing weekly schedule of recommended escapements past the Chilkoot Lake weir (Table 7). In this regard, although we do see a biological reason for maintaining a diversity of spawn timing and entry into Chilkoot Lake, we reiterate the conclusions of Eggers et al. (2009) that there is no clear evidence of discrete early and late components that would warrant separate escapement goals.

Finally, as has been done for other stocks in recent years, we recommend using an age-structured hierarchical Bayesian modeling approach in future analyses, possibly also one that incorporates multiple estimates of escapement (Fleischman et al. 2013; Miller and Heinl *In prep*) and density dependence in Chilkoot Lake. Although more complicated, such approaches can facilitate the inclusion of multiple sources of data (i.e., mark–recapture estimates and weir counts) into escapement, harvest, and age composition, thereby enabling the quantification of uncertainty for key model inputs and providing a more realistic assessment of the relationship between spawners and resulting recruits.

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TABLES AND FIGURES

Table 1.–Annual Chilkoot Lake sockeye salmon escapements based on weir counts, and estimated harvests (commercial, sport, and subsistence), total run size, and harvest rates for return years 1976–2016.

Return Year	Escapement goal range (1000s) Lower	Upper	Escapement Estimate	Harvest Commercial	Sport	Subsistence	Total	Total run	Harvest Rate (%)
1976	80.0	100.0	71,291	61,833	ND	ND	62,452	133,743	47%
1977	80.0	100.0	97,368	113,577	400	ND	113,713	211,081	54%
1978	80.0	100.0	35,454	14,211	500	ND	14,764	50,218	29%
1979	80.0	100.0	96,122	69,857	300	ND	70,164	166,286	42%
1980	80.0	100.0	98,673	21,261	700	ND	21,546	120,219	18%
1981	60.0	80.0	84,047	43,792	1,200	ND	44,992	129,039	35%
1982	60.0	80.0	103,038	144,592	800	ND	145,392	248,430	59%
1983	60.0	80.0	80,141	241,469	600	ND	242,069	322,210	75%
1984	60.0	80.0	100,781	225,634	1,000	ND	232,792	333,573	70%
1985	60.0	80.0	69,141	153,533	1,100	1,055	155,688	224,829	69%
1986	60.0	80.0	88,024	110,114	3,000	1,640	114,754	202,778	57%
1987	60.0	80.0	94,208	327,323	1,700	1,237	330,260	424,468	78%
1988	60.0	80.0	81,274	248,640	300	1013	249,953	331,227	75%
1989	60.0	80.0	54,900	292,830	900	2,055	295,785	350,685	84%
1990	50.5	91.5	76,119	181,260	2,600	2,391	186,251	262,370	71%
1991	50.5	91.5	92,375	228,607	600	4,399	233,606	325,981	72%
1992	50.5	91.5	77,601	142,471	500	4,104	147,075	224,676	65%
1993	50.5	91.5	52,080	52,080	100	2,896	55,076	107,156	51%
1994	50.5	91.5	37,007	30,717	400	1,592	32,709	69,716	47%
1995	50.5	91.5	7,177	9,637	200	384	10,221	17,398	59%
1996	50.5	91.5	50,741	19,882	400	2,311	22,593	73,334	31%
1997	50.5	91.5	44,254	31,822	500	1,784	34,106	78,360	44%
1998	50.5	91.5	12,335	2,838	closed	160	2,998	15,333	20%
1999	50.5	91.5	19,284	4,604	closed	115	4,719	24,003	20%
2000	50.5	91.5	43,555	14,622	400	252	15,274	58,829	26%
2001	50.5	91.5	76,283	66,355	2,300	1,499	70,154	146,437	48%
2002	50.5	91.5	58,361	24,200	1,500	1,258	26,958	85,319	32%
2003	50.5	91.5	75,065	32,446	1,500	2,091	36,037	111,102	32%
2004	50.5	91.5	77,660	66,498	889	1,766	69,153	146,813	47%
2005	50.5	91.5	51,178	29,276	566	1,427	31,269	82,447	38%
2006	50.0	90.0	96,203	119,201	520	2,279	122,000	218,203	56%
2007	50.0	90.0	72,678	125,199	303	3,290	128,792	201,470	64%
2008	50.0	90.0	33,117	7,491	298	1,894	9,683	42,800	23%
2009	38.0	86.0	33,705	17,038	165	892	18,095	51,800	35%
2010	38.0	86.0	71,657	32,064	567	2,251	34,882	106,539	33%
2011	38.0	86.0	65,915	26,766	973	1,977	29,716	95,631	31%
2012	38.0	86.0	118,166	115,509	1,025	3,080	119,614	237,780	50%
2013	38.0	86.0	46,329	23,111	204	2,439	25,754	72,083	36%
2014	38.0	86.0	105,467	110,487	318	3,231	114,036	219,749	52%
2015	38.0	86.0	71,122	58,568	912	2,222	61,072	132,587	46%
2016	38.0	86.0	86,700	119,843	215	4,982	125,040	211,740	59%
		Average	68,462	91,834	764	2,003	94,143	162,605	48%
		Median	72,678	61,833	543	1,936	61,833	133,124	47%

Note: Bold type indicates preliminary estimates. ND = Not determined.

Table 2.–Escapement of Chilkoot Lake sockeye salmon by age class, for return years 1976 to 2016.

Return	Age in Years											Total
	3		4		5		6			7		
Year	1.1	0.2	0.3	1.2	1.3	2.2	2.3	1.4	3.2	3.3	2.4	Escapement
1976[a]	761	0	0	22,183	26,951	6,577	14,818	0	0	0	0	71,291
1977[a]	0	0	0	5,529	66,392	4,358	20,934	155	0	0	0	97,368
1978[a]	0	0	0	3,959	21,852	1,957	7,686	0	0	0	0	35,454
1979[a]	0	0	0	29,191	45,452	6,018	15,392	0	69	0	0	96,122
1980	0	0	0	8,418	55,770	9,266	24,895	23	301	0	0	98,673
1981	24	0	0	8,681	58,744	2,723	14,035	199	0	0	0	84,407
1982	0	0	139	19,342	80,980	560	914	972	0	0	0	103,038
1983	84	0	95	9,852	48,435	1,352	20,043	238	0	0	0	80,141
1984	0	0	0	4,712	86,112	345	8,635	977	0	0	0	100,781
1985	46	0	0	8,132	45,675	1,661	11,517	1,857	45	0	208	69,141
1986	43	0	0	11,398	59,561	1,934	14,425	493	0	67	102	88,024
1987	0	0	0	7,706	62,153	2,074	21,773	283	0	79	139	94,208
1988	0	0	0	3,265	63,381	2,103	11,060	1,115	0	52	299	81,274
1989	0	0	0	1,743	30,584	2,169	19,213	649	0	304	238	54,900
1990	0	0	0	1,227	35,537	1,006	36,830	736	11	64	708	76,119
1991	0	0	0	12,537	50,513	4,648	24,249	158	0	100	169	92,375
1992	0	0	17	1,824	52,400	4,028	18,410	419	56	105	342	77,601
1993	0	0	0	1,560	18,693	901	30,396	180	0	91	239	52,080
1994	0	0	48	671	24,876	549	10,573	194	23	22	50	37,007
1995	0	0	0	3,360	2,176	298	1,219	78	0	0	46	7,177
1996	0	0	11	3,364	43,230	517	3,559	35	23	0	0	50,739
1997	0	0	23	1,022	39,858	183	3,114	45	0	8	0	44,254
1998	0	0	0	631	7,478	268	3,753	165	0	13	13	12,335
1999	0	0	0	5,934	8,550	1,597	3,136	34	0	0	34	19,284
2000	0	24	0	6,678	25,864	1,041	9,903	29	0	0	15	43,555
2001	0	0	157	3,565	68,859	50	3,600	53	0	0	0	76,283
2002	0	0	0	4,989	50,880	800	1,400	292	0	0	0	58,361
2003	0	0	0	42,648	24,883	2,594	4,776	132	0	0	33	75,065

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Table 2.–Page 2 of 2.

Return	Age in Years											Total
	3		4		5		6			7		
Year	1.1	0.2	0.3	1.2	1.3	2.2	2.3	1.4	3.2	3.3	2.4	Escapement
2004	0	0	0	11,846	54,309	5,738	5,732	36	0	0	0	77,660
2005	0	0	0	11,048	32,908	2,242	4,909	71	0	0	0	51,178
2006	0	0	22	8,492	76,211	817	10,578	48	0	0	34	96,203
2007	0	0	0	7,128	55,604	618	8,908	421	0	0	0	72,678
2008	0	0	55	3,405	26,672	330	1,403	1,213	0	0	39	33,117
2009	0	0	0	9,539	22,801	647	615	103	0	0	0	33,705
2010	0	0	0	4,269	58,284	2,922	6,099	48	34	0	0	71,657
2011	0	0	4	20,450	32,475	1,421	11,301	120	0	136	8	65,915
2012	0	0	0	2,730	102,954	449	11,803	230	0	0	0	118,166
2013	0	0	0	13,563	22,493	2,821	5,908	1,383	0	102	59	46,329
2014	0	0	0	28,533	64,114	5,901	6,769	116	0	0	0	105,467
2015	0	0	9	11,065	53,959	1,496	4,405	180	0	0	7	71,122
2016	5	0	0	2,186	73,042	362	11,022	73	0	9	0	86,700

Note: The exclusion of minor age classes may result in the sum of individual ages not equaling total escapement for a given year.

[a] Data from McPherson (1990).

Table 3.–Commercial harvest of Chilkoot Lake sockeye salmon by age class, for return years 1976 to 2016.

Return Year	Age in Years: 3		4		5		6			7		Commercial Harvest
	1.1	0.2	0.3	1.2	1.3	2.2	2.3	1.4	3.2	3.3	2.4	
1976[a]	0	0	0	8,091	20,881	3,195	29,666	0	0	0	0	61,833
1977[a]	0	0	0	2,635	89,140	1,717	20,372	113	0	0	0	113,977
1978[a]	0	0	0	2,272	8,672	325	3,361	80	0	0	0	14,711
1979[a]	0	0	0	8,732	47,378	1,414	12,613	0	19	0	0	69,857
1980	0	0	0	747	15,120	497	5,574	3	20	0	0	21,261
1981	0	0	0	986	40,033	178	3,587	75	0	52	23	43,733
1982	0	0	0	10,544	120,826	1,522	12,211	441	4	108	0	144,858
1983	0	0	0	7,138	175,332	719	58,721	741	0	0	46	242,097
1984	0	0	0	5,197	206,252	270	13,335	419	0	0	161	225,634
1985	72	0	0	7,994	121,399	1,312	19,894	2,652	10	53	140	153,533
1986	0	0	0	7,074	85,760	1,287	15,117	529	0	141	207	110,114
1987	27	0	0	19,356	220,580	2,490	84,079	411	0	220	160	327,323
1988	0	0	0	18,607	195,645	8,277	24,743	955	0	0	378	248,640
1989	62	0	0	10,816	165,699	12,665	100,825	599	0	1,961	203	292,830
1990	76	0	0	8,361	90,538	3,512	77,274	566	0	125	808	181,260
1991	19	0	0	12,224	156,030	3,376	56,210	405	76	141	126	228,607
1992	0	0	0	2,632	87,805	3,981	46,492	1,125	39	219	178	142,471
1993	0	0	0	1,089	24,702	550	25,438	144	0	50	107	52,080
1994	23	0	0	318	18,638	175	6,033	157	0	0	23	25,367
1995	0	0	0	3,022	4,150	228	2,105	114	0	9	9	9,637
1996	0	0	0	1,608	16,482	306	1,478	8	0	0	0	19,882
1997	0	0	0	968	28,061	133	2,593	67	0	0	0	31,822
1998	0	0	0	144	2,161	173	350	10	0	0	0	2,838
1999	0	0	0	829	2,433	321	1,013	8	0	0	0	4,604
2000	0	0	0	2,393	9,788	412	2,003	26	0	0	0	14,622
2001	0	0	0	1,452	61,761	0	3,115	27	0	0	0	66,355
2002	0	0	0	878	22,544	40	668	69	0	0	0	24,200
2003	0	0	0	9,493	19,025	552	3,300	77	0	0	0	32,446

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Return Year	3: 1.1	3: 0.2	4: 0.3	4: 1.2	5: 1.3	5: 2.2	6: 2.3	6: 1.4	6: 3.2	7: 3.3	7: 2.4	Commercial Harvest
	Age in Years											
2004	0	0	0	8,776	50,188	3,039	4,422	73	0	0	0	66,498
2005	0	0	0	3,307	20,885	678	4,320	87	0	0	0	29,276
2006	0	0	0	6,090	100,174	757	12,074	107	0	0	0	119,201
2007	0	0	0	6,471	102,515	410	15,403	366	0	0	34	125,199
2008	0	0	0	528	6,285	37	387	247	0	0	8	7,491
2009	0	0	0	1,409	14,016	205	892	100	0	0	0	16,622
2010	0	0	0	1,047	26,995	488	3,465	70	0	0	0	32,064
2011	0	0	0	5,765	15,219	421	5,330	0	0	31	0	26,766
2012	0	0	0	1,680	108,677	580	13,283	135	0	0	11	124,366
2013	0	0	0	2,862	14,631	726	4,229	567	0	0	96	23,111
2014	0	0	0	21,510	74,722	4,445	9,760	43	0	0	7	110,487
2015	0	0	0	1,670	52,183	491	4,097	127	0	0	0	58,568
2016	0	0	0	1,575	102,966	314	14,828	106	0	0	0	119,843

Note: The exclusion of minor age classes may result in the sum of individual ages not equaling total escapement for a given year.

[a] Data from McPherson (1990).

Table 4.–Total recruits of Chilkoot Lake sockeye salmon by age class that originated from brood years 1976 to 2010. Recruits include fish from commercial, personal use, and sport harvests, and escapements.

	Age at return in Years												
Brood	3		4		5		6			7		Total	
Year	1.1	0.2	0.3	1.2	1.3	2.2	2.3	1.4	3.2	3.3	2.4	Recruits	R/S
1976[a]	0	0	0	9,188	99,846	2,906	13,193	1,416	4	0	46	123,362	1.7
1977[a]	0	0	0	9,694	202,469	2,090	78,909	981	0	0	162	292,305	3.0
1978[a]	24	0	139	29,944	224,200	2,072	22,029	1,398	0	53	350	279,209	7.9
1979[a]	0	0	95	17,008	293,278	616	31,690	4,547	56	215	318	350,528	3.6
1980	84	0	0	9,932	168,778	2,991	30,179	1,044	0	301	301	213,676	2.2
1981	0	0	0	16,238	148,935	3,275	106,606	698	0	52	679	276,488	3.3
1982	120	0	0	18,770	284,712	4,587	35,934	2,075	0	2,284	443	348,926	3.4
1983	43	0	0	27,235	260,059	10,424	121,056	1,254	0	193	1,538	421,800	5.3
1984	27	0	0	21,971	197,955	14,962	116,231	1,318	11	244	298	353,052	3.5
1985	0	0	0	12,669	128,568	4,615	81,725	572	78	331	525	229,083	3.3
1986	63	0	0	9,818	210,056	8,100	66,405	1,581	96	144	353	296,617	3.4
1987	78	0	0	25,036	143,043	8,137	57,298	332	0	22	75	234,019	2.5
1988	19	0	17	4,540	44,816	1,483	17,079	363	23	10	55	68,424	0.8
1989	0	0	0	2,712	44,976	738	3,452	199	0	0	0	52,076	0.9
1990	0	0	48	1,014	6,577	540	5,245	44	23	8	0	13,499	0.2
1991	25	0	0	6,565	62,022	866	5,891	116	0	13	13	75,512	0.8
1992	0	0	11	5,198	69,911	326	4,123	175	0	0	34	79,777	1.0
1993	0	0	23	2,058	9,761	450	4,180	42	0	0	15	16,529	0.3
1994	0	0	0	783	11,058	1,928	11,993	57	0	0	0	25,819	0.7
1995	0	0	0	6,789	36,078	1,471	6,895	81	0	0	0	51,314	7.1
1996	0	0	0	9,175	134,197	50	2,145	369	0	0	33	145,983	2.9
1997	0	24	157	5,101	75,996	845	8,441	218	0	0	0	90,782	2.1
1998	0	0	0	5,968	46,019	3,207	10,330	111	0	0	0	65,635	5.3
1999	0	0	0	53,194	106,500	8,899	9,522	164	0	0	34	178,314	9.2
2000	0	0	0	20,972	55,214	2,966	22,936	157	0	0	35	102,280	2.3
2001	0	0	0	14,580	178,737	1,592	24,752	797	0	0	49	220,508	2.9
2002	0	0	22	14,725	161,061	1,040	1,904	1,533	0	0	0	180,285	3.1
2003	0	0	0	13,785	34,795	377	1,564	210	0	0	0	50,731	0.7

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Brood Year	Age in Years 3		4		5		6			7		Total Recruits	R/S
	1.1	0.2	0.3	1.2	1.3	2.2	2.3	1.4	3.2	3.3	2.4		
2004	0	0	55	4,087	37,708	866	9,868	124	34	170	8	52,919	0.7
2005	0	0	0	11,037	87,652	3,453	17,218	120	0	0	11	119,490	2.3
2006	0	0	0	5,408	49,371	1,889	25,524	369	0	102	166	82,830	0.9
2007	0	0	4	26,851	215,218	1,049	10,621	2,014	0	0	8	255,800	3.5
2008	0	0	0	4,465	38,797	3,630	16,842	161	0	0	7	63,902	1.9
2009	0	0	0	16,752	141,236	10,489	8,657	312	0	9	0	177,455	5.3
2010	0	0	0	50,733	108,122	2,006	26,466	184	0	[b]	[b]	187,511	2.6

[a] Data from McPherson (1990; Table 2.1, p. 32)

[b] Age 7 returns from 2010 brood year not available. These typically amount to <1% of brood year recruits.

Table 5.–Prior distributions for model parameters.

Parameter [a]	RJAGS coding	Prior [b]
$\ln(\alpha)$	lnalpha	$\ln(\alpha)$ ~ "Uniform" (0,10)
β	beta	β ~ "Uniform" (0,10)
ϕ	phi	ϕ ~ "Uniform" (-0.98,0.98)
v_0	resid.red.0	v_{0}~"Normal" (0, $\sigma_W^2(1-\phi^2)$)
σ_w	sigma.white	Uniform(0, 10)

[a] Parameter definitions are in the *Methods* section.

[b] Where "Uniform" is in quotes, a normal distribution with mean 0 and a large variance was used in the actual RJAGS code to prevent computational disruptions during MCMC sampling.

Table 6.–Spawner–recruit model estimates for Chilkoot Lake sockeye salmon for calendar years 1976–2016. Posterior medians are point estimates. 2.5th and 97.5th percentiles define 95% credibility intervals for the parameters. Point estimates are posterior medians and CVs are posterior standard deviations divided by posterior means.

Parameter [a]	2.5^{th} percentile	Median	97.5^{th} percentile	CV
α	2.02	5.28	16.71	0.84
$\ln(\alpha)$	0.70	1.66	2.82	0.32
$\ln(\alpha')$	1.25	2.16	4.05	0.34
β	3.81e-06	1.38e-05	2.46e-05	0.39
ϕ	0.27	0.59	0.88	0.26
σ_R	0.71	0.96	1.82	0.30
S_{EQ}	102,035	158,167	464,948	0.59 [b]
S_{MSY}	32,718	53,257	161,690	0.62 [b]
S_{Max}	40,609	72,415	262,573	0.78 [b]
MSY	65,722	175,675	1,195,772	1.64 [b]
R_{MSY}	111,994	235,263	1,354,493	1.35 [b]
U_{MSY}	0.49	0.75	0.89	0.14 [b]

[a] Parameter definitions are in the *Methods* section.

[b] The CVs for the reference points S_{EQ}, S_{MSY}, $S_{Max,}$ *MSY*, R_{MSY}, and U_{MSY} were calculated as (97.5th percentile – 2.5th percentile)/3.92/posterior median point estimate. If the posterior median is approximately normal, then the lower and upper bound of the 95% credibility interval are both ~1.96 × standard errors from the median.

Table 7.–Proposed escapement targets, by ADF&G statistical week, for Chilkoot Lake sockeye salmon, based on average historical run timing.

Statistical Week	Weekly Point Goal	Weekly Point Cum. Goal	Weekly Cum. Lower end Bound	Weekly Cum. Upper end Bound
23	577	577	378	856
24	2,359	2,936	1,924	4,354
25	4,075	7,011	4,593	10,396
26	3,448	10,459	6,852	15,508
27	2,259	12,718	8,333	18,858
28	2,701	15,420	10,102	22,863
29	4,859	20,279	13,286	30,069
30	6,720	26,998	17,689	40,032
31	8,467	35,466	23,236	52,587
32	7,679	43,145	28,267	63,973
33	5,034	48,179	31,565	71,437
34	4,282	52,461	34,371	77,787
35	2,906	55,367	36,275	82,096
36	1,906	57,274	37,524	84,923
37	726	58,000	38,000	86,000

Source: Eggers et al. (2009).

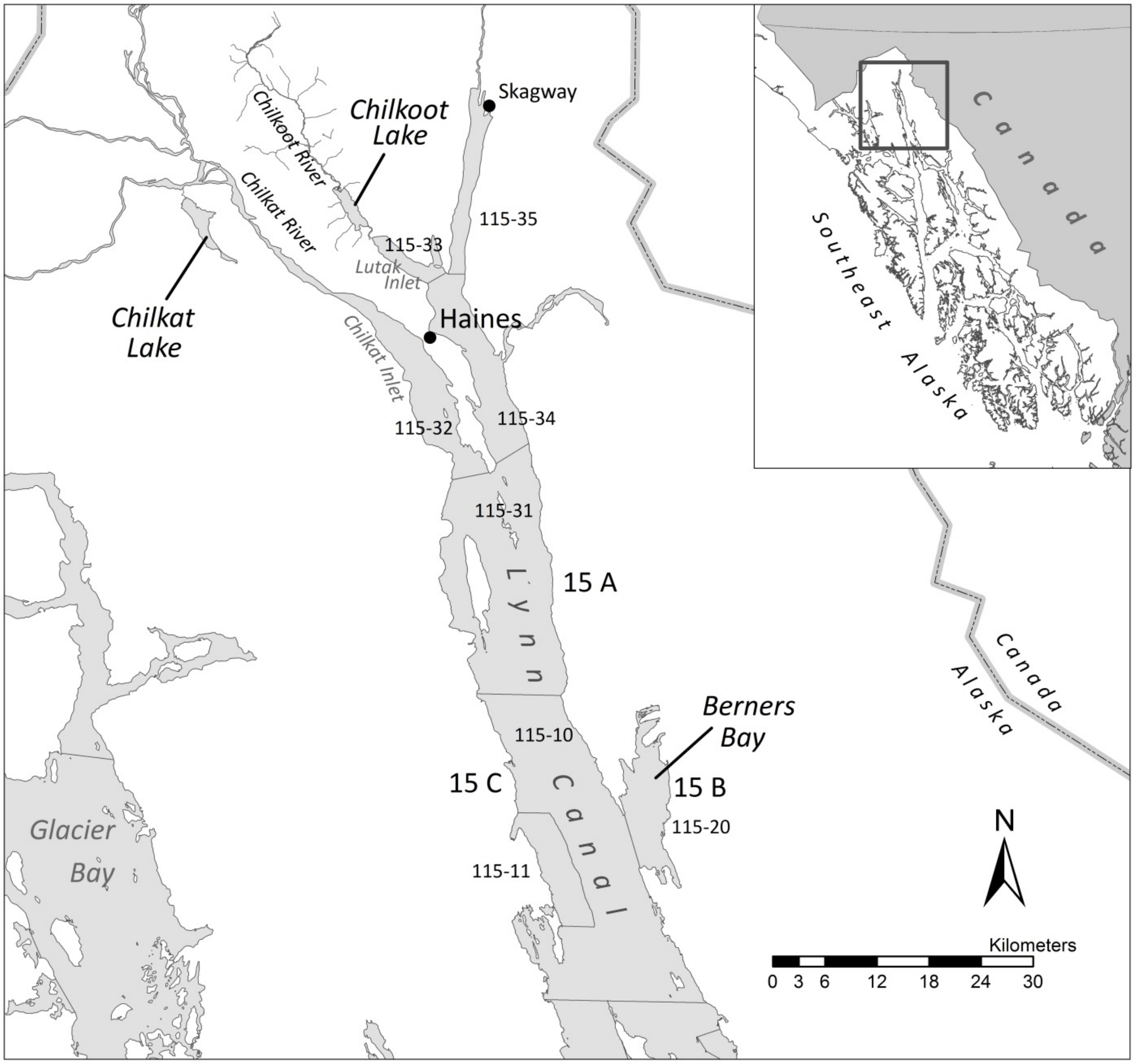

Figure 1.–Commercial fishing subdistrict and management boundary lines within District 15 in the Haines area, Southeast Alaska.

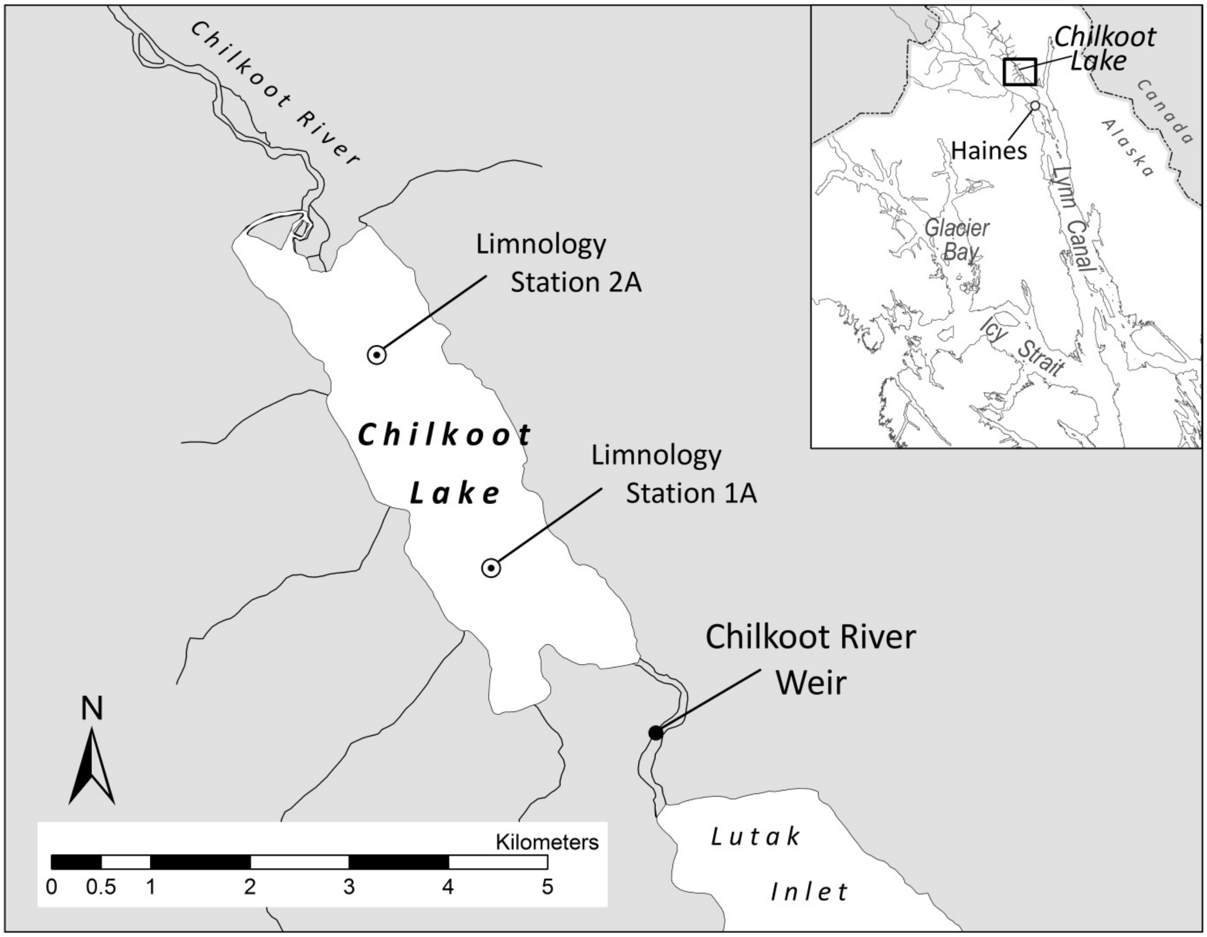

Figure 2.–Map showing Lutak Inlet, Chilkoot Lake, and the location of the limnology stations and salmon counting weir.

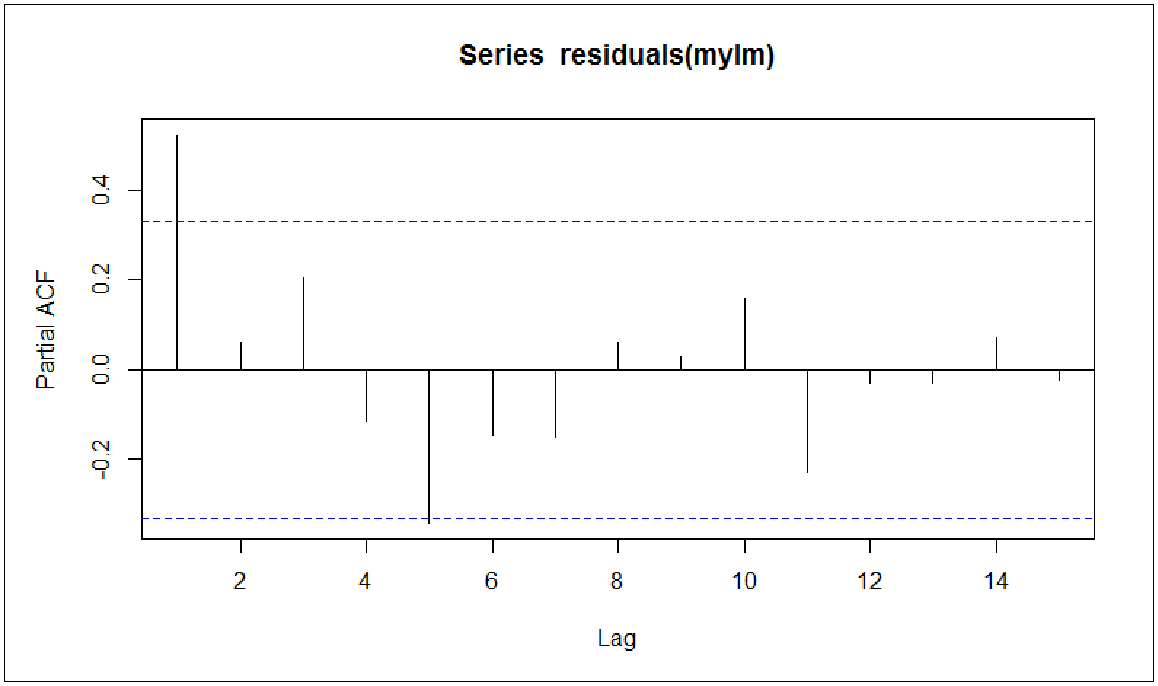

Figure 3.–Partial autocorrelation function (ACF) of Chilkoot Lake sockeye salmon productivity (*y*-axis) for successive lags of 1–15 years (*x*-axis). This figure indicates positive serial autocorrelation of productivity at a lag of 1 year and marginal negative autocorrelation at a lag of 5 years.

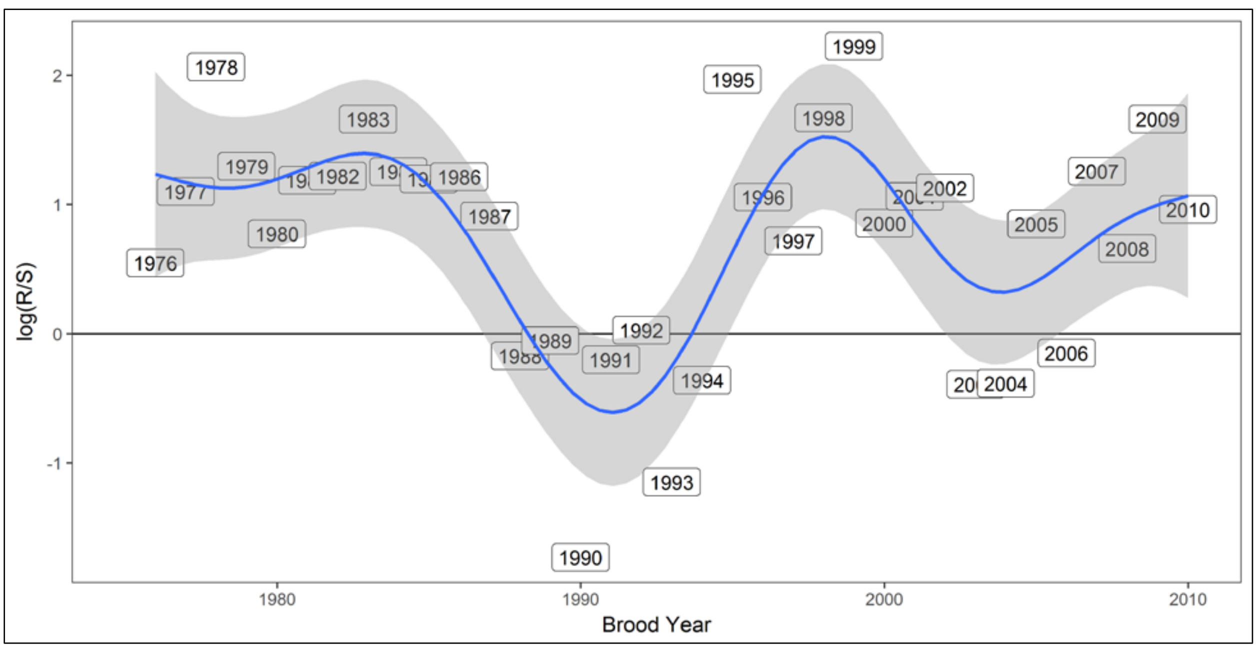

Figure 4.–Productivity of Chilkoot Lake sockeye salmon by brood year, 1976–2010. Productivity (*y*-axis) is expressed as the natural log of recruits per spawner (R/S). The blue line is the best fit line from a general additive model (GAM) and the shaded area is the 95% confidence intervals for the model fit. Productivity below 0 (e.g., 1988–1994) indicates that this stock is not replacing itself.

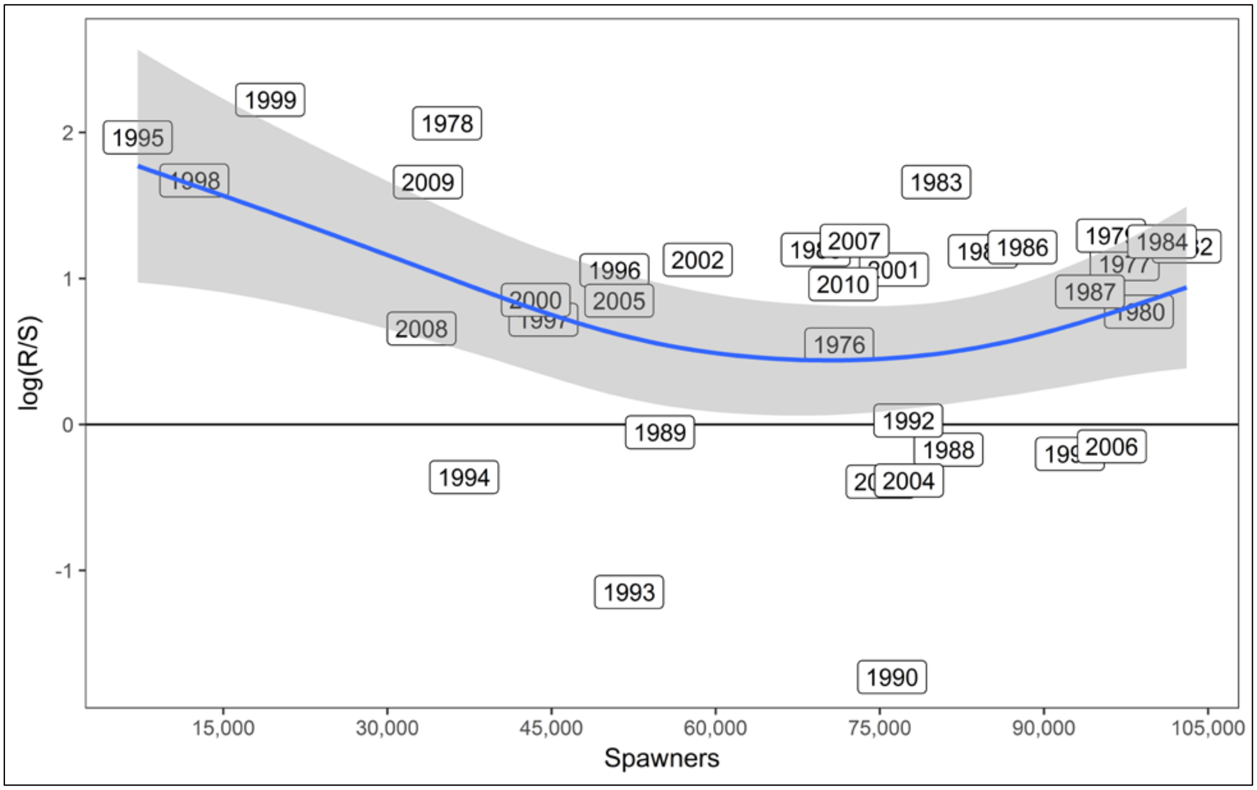

Figure 5.–Productivity of Chilkoot Lake sockeye salmon by spawning escapements (*x*-axis) for brood years 1976–2010. Productivity (*y*-axis) is expressed as the natural log of recruits per spawner. The blue line is the best fit line from a general additive model (GAM) and the shaded area is the 95% confidence intervals for the model fit. Productivity below 0 indicates that this stock is not replacing itself.

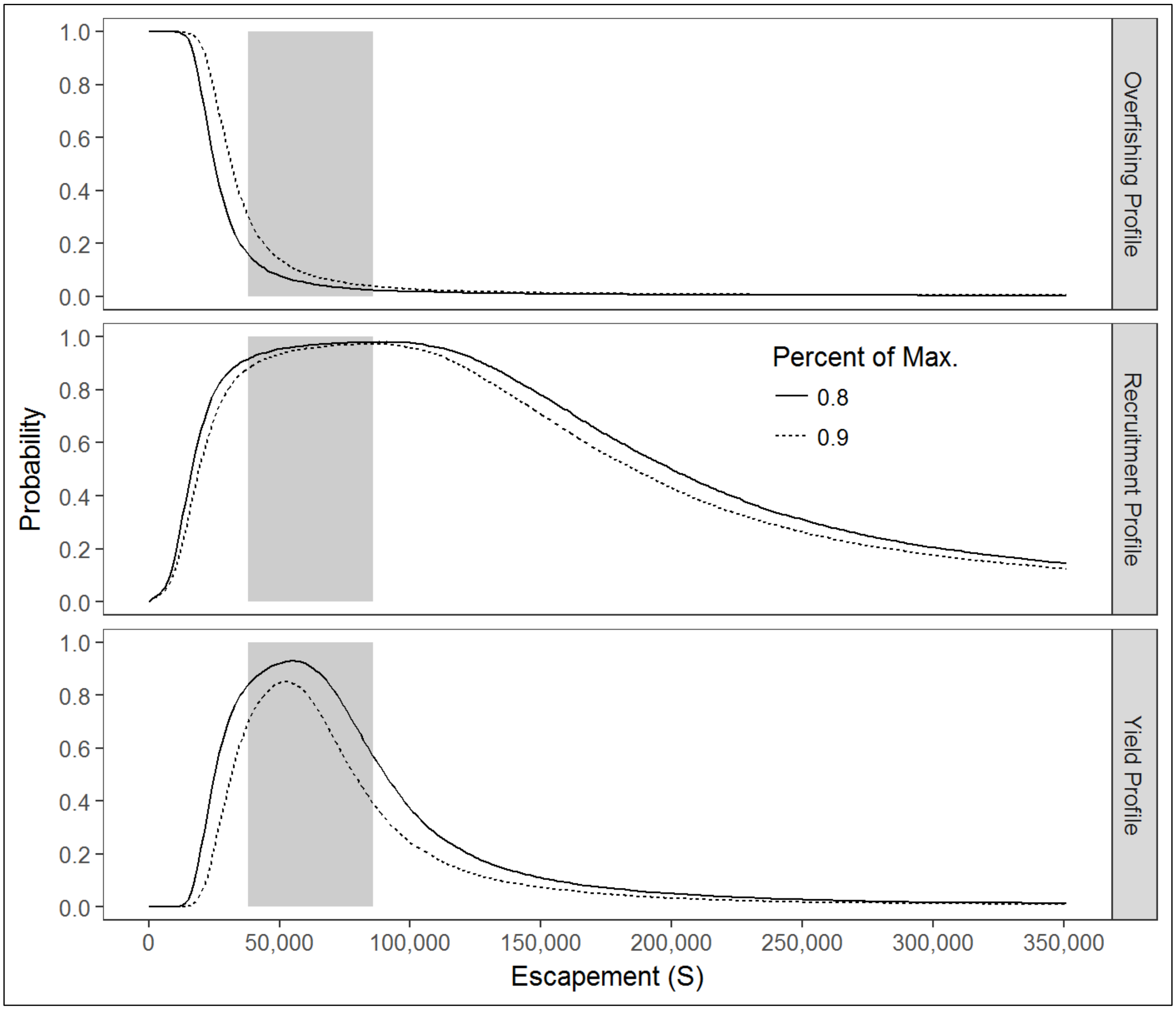

Figure 6.–Overfishing profiles, optimal recruitment profiles, and optimal yield profiles for Chilkoot Lake sockeye salmon. Optimal yield profiles and optimal recruitment profiles show probability that a specified spawning abundance will result in specified fractions (80% and 90% line) of maximum sustained yield or maximum recruitment. Overfishing profiles show the probability that reducing escapement to a specified spawning abundance will result in less than specified fractions of maximum sustained yield. The shaded region shows the existing escapement goal range of 38,000–86,000 spawners.

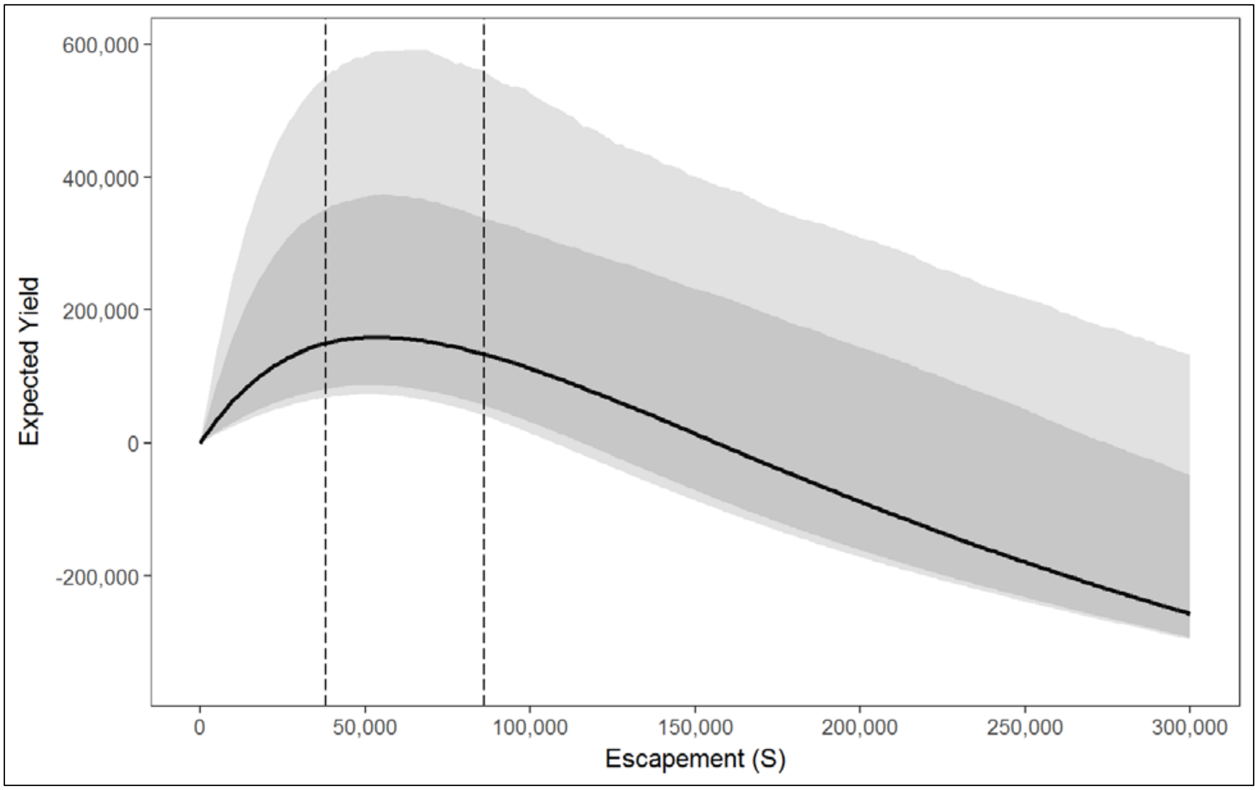

Figure 7.–Expected sustained yield (solid black line) and 90% and 95% credibility intervals (shaded areas) versus spawning escapement for Chilkoot Lake sockeye salmon. Dotted vertical lines bracket the current escapement goal range of 38,000–86,000 spawners.

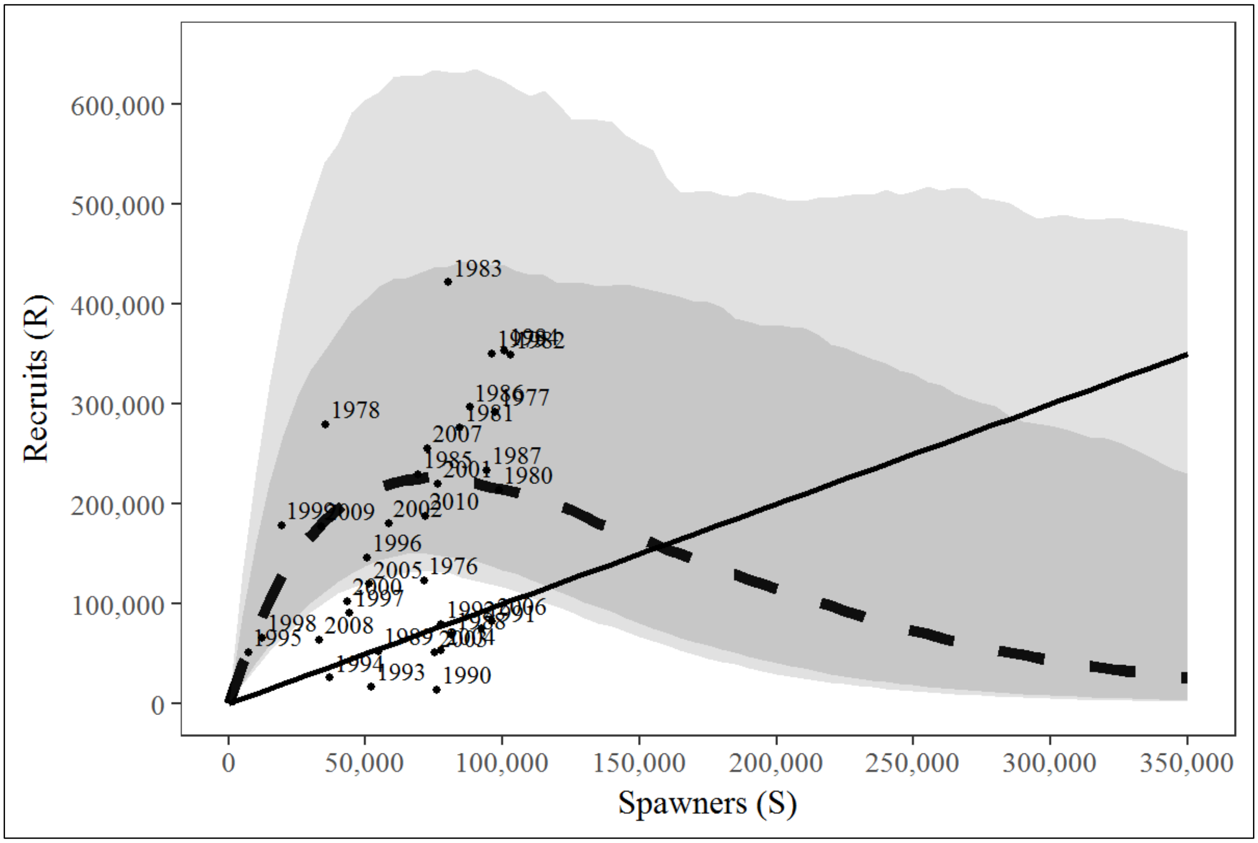

Figure 8.–Plausible spawner–recruit relationships for Chilkoot Lake sockeye salmon as derived from a Bayesian spawner–recruit analysis for brood years 1976–2010. Posterior medians of *R* and *S* are plotted as brood year labels. The heavy dashed line is the Ricker relationship constructed from ln(α') and β posterior medians with 90% and 95% credibility intervals (shaded areas). Recruits equal spawners on the solid diagonal "replacement" line.

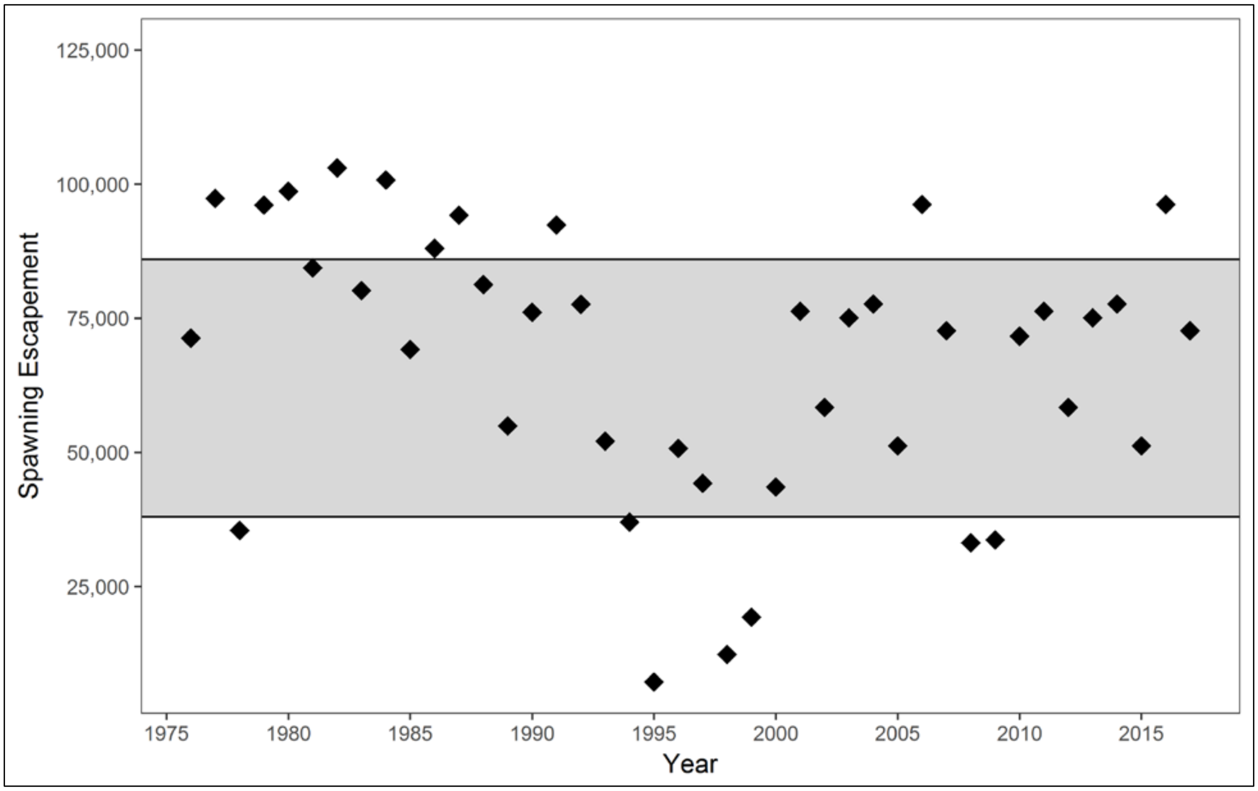

Figure 9.–Chilkoot Lake sockeye salmon spawning escapements by year. The shaded area represents the current escapement goal range of 38,000–86,000 spawners.

APPENDIX

Appendix A.–RJAGS model code for the Bayesian MCMC analysis of the Chilkoot Lake sockeye salmon model, 1976–2016, can be found at the ADF&G GitHub site, located here: https://github.com/commfish/AlaskaSalmon. Please contact the authors of this report if you have problems opening this link or have questions or comments regarding the analysis.