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Chilkat Lake Sockeye Salmon Stock Status and Escapement Goal Review

by

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and

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Month 2017

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 ft3/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 pH

(negative log of)

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 HA

base of natural logarithm *e*

catch per unit effort CPUE

coefficient of variation CV

common test statistics (F, t, χ2, 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) log2, etc.

minute (angular) '

not significant NS

null hypothesis HO

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

fishery manuscript series no. 17-XX

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Month 2017

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# abstract

Age-structured state-space spawner-recruit models were fit to 1976–2016 data on abundance, harvest, and age composition for Chilkat Lake sockeye salmon (*Oncorhynchus nerka*) to examine the effect of autocorrelation and fry plants on recruits. Mark–recapture and weir counts were considered indices of escapement, while the DIDSON counts were considered ‘true’ counts of escapement. Fishery management reference points and optimal yield profiles, optimal recruitment profiles, and overfishing probability profiles were estimated from these models. A biological escapement goal of xxx-xxx is recommended and the attributes and limitations discussed.

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

# 

# introduction

The Chilkoot and Chilkat river watersheds, located in northern Southeast Alaska near the town of Haines, support two 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 the Chilkat and Chilkoot river watersheds (Rich and Ball 1933). Over the past two decades, the average sockeye salmon harvest in northern Southeast Alaska was 500,000 fish, of which an average 96,000 fish originated from Chilkat Lake and 65,000 fish originated from Chilkoot Lake (Eggers et al. 2010). Historically, Chilkat 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 Chilkat Lake sockeye salmon takes place (Figure 1). A smaller portion of the Chilkat Lake run is harvested in the commercial purse seine fisheries that target pink salmon (*O. gorbuscha*) in Icy and northern Chatham straits (Ingledue 1989; Gilk-Baumer et al. 2015). Annual contributions to those fisheries are not known and likely vary annually depending on fishing effort and the strength of pink salmon runs. Chilkat Lake sockeye salmon are also harvested annually in subsistence fisheries in Chilkat Inlet and Chilkat River, and reported harvests for the 10-year period 2006–2015 averaged approximately 5,100 fish per year.

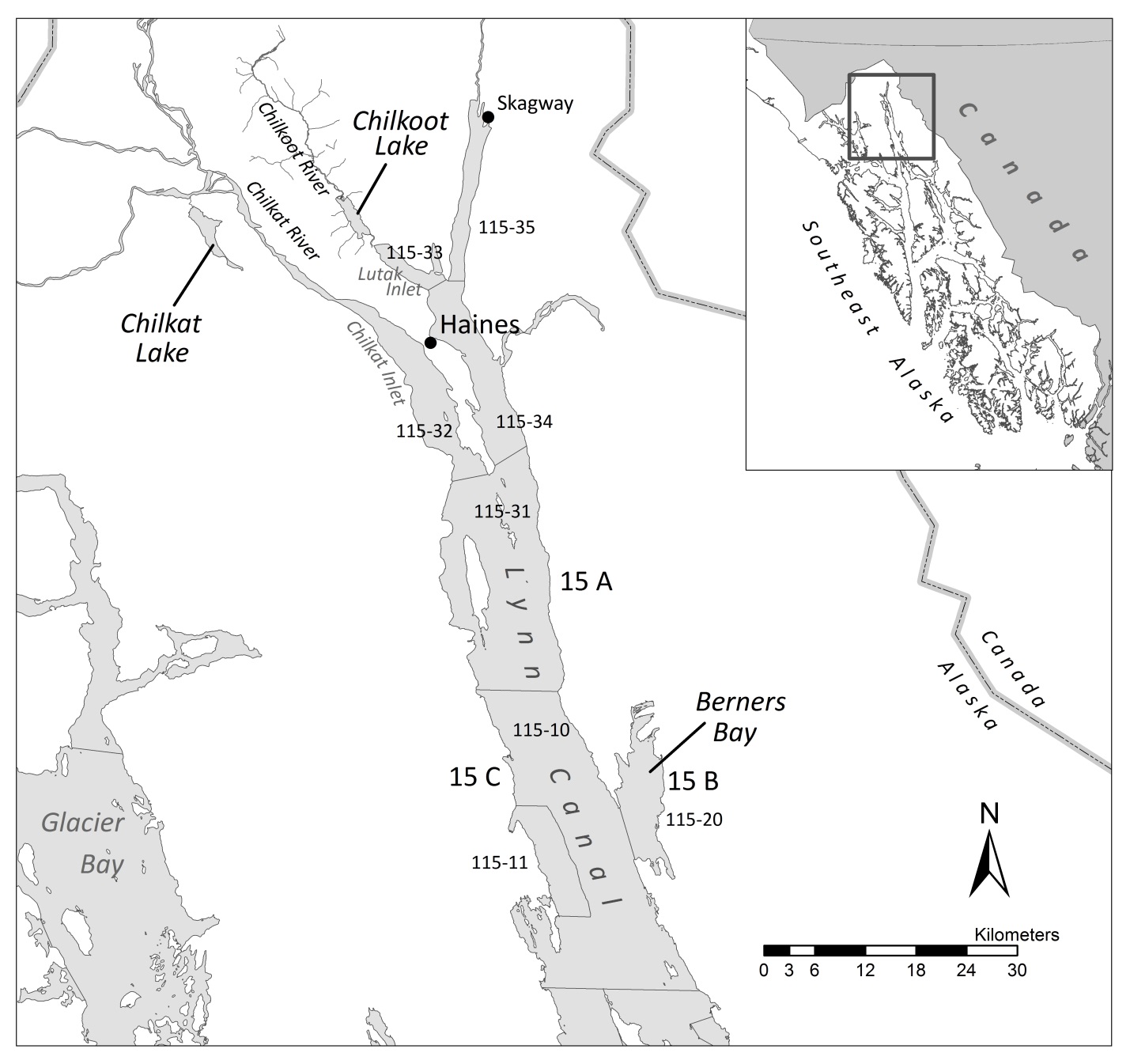


Figure 1.–Commercial fishing subdistrict and management boundary lines within District 15 in the Haines area, Southeast Alaska.

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 drainage 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 two 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 1987b). 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 made 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).

Chilkat Lake sockeye salmon escapements have been estimated through weir counts (1967–1993), weir counts with mark–recapture estimates (1994 and 1995, 1999–2007), mark–recapture estimates only (1996–1998), and **D**ual-frequency **Id**entification **Son**ar (DIDSON) counts with mark–recapture (2008–2016) (Eggers et al. 2010; Sogge and Bachman 2014). Two-event mark–recapture studies in conjunction with operation of fish wheels in the lower Chilkat River were initiated in 1994 because weir counts at Chilkat Lake were thought to underestimate escapement. Periodic flooding of the silty Tsirku River into Chilkat Lake required removing pickets from the weir, sometimes for extended periods, and increased boat traffic in and out of the lake required frequent lowering of a boat gate in the center of the weir through which fish could pass uncounted (Kelley and Bachman 2000). Sockeye salmon were marked at the fish wheels and sampled for marks at the Chilkat Lake weir and various Chilkat River mainstem spawning locations; drainagewide mark–recapture estimates were then generated and divided into Chilkat Lake and mainstem estimates (Kelley and Bachman 2000; Bachman and McGregor 2001; Bachman 2005, 2010). Mark–recapture estimates of Chilkat Lake fish in 1994 and 1995 (and most other years) were substantially larger than weir counts. As a result, the weir was not operated from 1996 to 1998; however, it was reinstated in 1999 to improve mark–recapture sampling at the lake (Kelley and Bachman 2000). In 2008, a DIDSON was installed at the Chilkat Lake weir to improve counts (Eggers et al. 2010), and the purpose of the mark–recapture studies was changed to primarily provide estimates of mainstem spawning populations (Sogge and Bachman 2014). Biological data have been collected annually at Chilkat Lake and at mainstem spawning locations to estimate age, size, and sex composition of escapements, and for use in scale pattern analysis.

The Chilkat Lake sockeye salmon run has been managed for at least five different escapement goals since 1976. Informal goals of 60,000–70,000 fish (1976–1980) and 70,000–90,000 fish (1981–1989) (Bergander et al. 1988) were replaced in 1990 with a biological escapement goal (BEG) of 52,000–106,000 sockeye salmon based on extensive stock-recruit analysis by McPherson (1990). Efforts to update the escapement goal were hindered by lake stocking in the 1990s and concerns regarding accuracy of weir counts (Geiger et al. 2005). Geiger et al. converted the weir based goal to mark–recapture units and the goal was revised to a sustainable escapement goal (SEG) of 80,000–200,000 sockeye salmon from 2006 to 2008. In 2009, the Chilkat Lake escapement goal was revised again to the present BEG of 70,000–150,000 sockeye salmon (Eggers et al. 2008, 2010). Eggers et al. (2010) scaled weir counts to mark–recapture estimates, then fit a hierarchal set of stock-recruit models to the Chilkat River recruits from parental escapements of the 1979 to 2002 brood years. The BEG is the escapement range that produces 90% MSY as determined by an autoregressive Ricker (density dependence with first order autoregressive term) model with fry plants. While this model was not the most parsimonious (i.e., minimum AIC) it was selected because it accounted for the bias in assessing wild stock production due to the added production from enhancement stocking of fry that occurred from 1989 to 2003 and was, therefore, considered the most meaningful biological model.

The purpose of our report is to review the current BEG that was established in 2009 by Eggers et al. (2010). Eggers et al. (2010) fit a hierarchal set of stock-recruitment models fit to Chilkat River stock–recruit data for the 1979 to 2003 brood years. The linear regression relationship between paired weir counts and mark–recapture estimates was used to expand the weir counts to total escapement for years when mark–recapture studies were not conducted. Prior to 1994, estimated total escapement by age was based on the age composition at the Chilkat weir applied to the scaled Chilkat weir counts, and, after 1994, to the mark–recaptures estimates. With the cessation of the mark–recapture studies in 2016, along with concerns regarding mark–recapture as a reliable index of abundance, it was determined that the DIDSON would be maintained to estimate minimum escapement into Chilkat Lake from 2017 on (Bednarksi et al. 2017). Therefore, since the BEG established by Eggers et al. (2010) is in mark–recapture units and mark–recapture estimates can be 0.7 to 3.0 greater than DIDSON counts within the same year, a new escapement goal range in DIDSON units is warranted. To update the escapement goal range, all historic information associated with Chilkat Lake sockeye salmon stock assessment was recently reviewed, edited, and updated, including weir counts, DIDSON counts, fish wheel counts, age composition data, and mark–recapture and commercial harvest estimates (Bednarski et al. 2017). Then, age-structured state-space spawner-recruit models were fit to 1976–2016 data on abundance, harvest, and age composition for Chilkat Lake sockeye salmon to examine the effect of autocorrelation and fry plants on recruits and to establish a new BEG in DIDSON units.

# STUDY SITE

Chilkat Lake (ADF&G Anadromous Waters Catalogue No. 115-32-10250-2067-3001-0010; 59.32577 N 135.89436 W) is located approximately 27 river miles upstream from the city of Haines, Alaska (Figure 1 and 2). It is a relatively large clear lake with a surface area of 9.8 × 106 m2 (2,432 acres), mean depth of 32.5 m, a maximum depth of 57 m, and a volume of 319 × 106 m3. The lake drains through Clear Creek, a 0.5 km long channel, which is also the location of the weir, and into the Chilkat River by way of the Tsirku River. Resident fish include sockeye salmon, coho salmon (*O. kisutch*), Dolly Varden (*Salvelinus malma*), cutthroat trout (*Salmo clarki*), threespine stickleback (*Gasterosteus aculeatus*), sculpin (*Cottus sp.*) and whitefish (*Prosopium cylindraceum*) (Johnson and Daigneault 2013). Small numbers of adult pink and chum salmon (*O. keta*) have been observed moving through the Chilkat Lake weir, but it is not known if these fish enter the lake. Chilkat Lake is a remote lake with moderate to heavy boat traffic. There are several private cabins on the lake (50 to 100 cabins) with access limited to jet boats and floatplanes only.

The Chilkat River drains a large watershed stretching from British Columbia, Canada to the northern end of Lynn Canal, near Haines, Alaska (Figure 2). It is characterized by rugged, highly dissected mountains with steep-gradient streams, braided rivers through glaciated valleys. The watershed encompasses approximately 1,600 km2, and the main river and tributaries comprise approximately 350 km of river channels. Principle tributaries include the Tahkin, Tsirku, Klehini, Kelsall, and Tahini rivers. The Chilkat River discharge rates range from 80 to 20,400 ft3/s (Bugliosi 1988). The river supports large runs of sockeye, coho, chum, Chinook (*O. tshawytscha*), and pink salmon. The Chilkat River receives input from several glaciers, and heavy silt loads in the main river impairs visual salmon stock assessment methods.



Figure .–Chilkat River drainage, with fish wheel locations, mainstem sockeye salmon recovery sites, and Chilkat Lake weir location.

# Methods

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. Chilkat Lake sockeye salmon spawner-recruit data were analyzed using a Bayesian age-structured state-space model. The models assumed a Ricker spawner-recruit relationship and time-varying productivity and were fit to multiple sources of information on historical abundance as well as data on age composition and harvest. This permitted simultaneous reconstruction of historical abundance and estimation of stock productivity and yield.

## Data

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 escapement indices; 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

Commercial harvest data for the District 15 commercial drift gillnet fishery were obtained from the ADF&G Southeast Alaska Integrated Fisheries Database. Known-origin scale samples were processed inseason on a weekly basis, after which commercial fishery samples were analyzed and assigned to one of three stocks, Chilkoot Lake, Chilkat Lake, and “other,” based on scale characteristics. The weekly proportions of classified scale samples were applied to the District 15 commercial drift gillnet harvest to provide weekly estimates of stock contribution for inseason management and postseason estimates of total harvest by stock, weighted by statistical week. Since total District 15 commercial drift gillnet harvest was not apportioned to Chilkoot Lake, Chilkat Lake, and “other” in the ADF&G database in years 1976 through 1983, the apportionment percentages from McPherson (1990) were reapplied to updated harvest from those years (Bednarski et al. 2017).

Table 1.–Estimated total harvest of Chilkat Lake sockeye salmon and harvest proportions by age, 1976–2016.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Harvest proportion by age** | | |  |  |  |  |
| **Year** | **Harvest** | **Age 2** | **Age 3** | **Age 4** | **Age 5** | **Age 6** | **Age 7** | **Age 8** |
| 1976a | 58,765 | 0.00 | 0.00 | 0.05 | 0.70 | 0.25 | 0.00 | 0.00 |
| 1977a | 41,477 | 0.00 | 0.00 | 0.03 | 0.71 | 0.26 | 0.00 | 0.00 |
| 1978a | 89,558 | 0.00 | 0.00 | 0.04 | 0.63 | 0.33 | 0.00 | 0.00 |
| 1979a | 115,995 | 0.00 | 0.00 | 0.03 | 0.84 | 0.13 | 0.01 | 0.00 |
| 1980a | 31,267 | 0.00 | 0.00 | 0.02 | 0.53 | 0.44 | 0.00 | 0.00 |
| 1981a | 48,420 | 0.00 | 0.00 | 0.03 | 0.47 | 0.50 | 0.01 | 0.00 |
| 1982a | 127,174 | 0.00 | 0.00 | 0.01 | 0.44 | 0.54 | 0.00 | 0.00 |
| 1983a | 124,180 | 0.00 | 0.00 | 0.02 | 0.45 | 0.53 | 0.00 | 0.00 |
| 1984 | 99,592 | 0.00 | 0.00 | 0.00 | 0.70 | 0.30 | 0.00 | 0.00 |
| 1985 | 131,091 | 0.00 | 0.00 | 0.00 | 0.33 | 0.66 | 0.00 | 0.00 |
| 1986 | 168,006 | 0.00 | 0.00 | 0.01 | 0.37 | 0.61 | 0.00 | 0.00 |
| 1987 | 69,900 | 0.00 | 0.00 | 0.01 | 0.60 | 0.39 | 0.00 | 0.00 |
| 1988 | 76,883 | 0.00 | 0.00 | 0.03 | 0.46 | 0.51 | 0.00 | 0.00 |
| 1989 | 156,160 | 0.00 | 0.00 | 0.00 | 0.68 | 0.32 | 0.00 | 0.00 |
| 1990 | 149,377 | 0.00 | 0.00 | 0.01 | 0.45 | 0.54 | 0.00 | 0.00 |
| 1991 | 60,721 | 0.00 | 0.00 | 0.01 | 0.39 | 0.60 | 0.01 | 0.00 |
| 1992 | 113,146 | 0.00 | 0.00 | 0.01 | 0.46 | 0.53 | 0.00 | 0.00 |
| 1993 | 103,531 | 0.00 | 0.00 | 0.02 | 0.32 | 0.66 | 0.00 | 0.00 |
| 1994 | 126,852 | 0.00 | 0.00 | 0.01 | 0.55 | 0.41 | 0.02 | 0.00 |
| 1995 | 68,737 | 0.00 | 0.00 | 0.04 | 0.46 | 0.50 | 0.00 | 0.00 |
| 1996 | 99,677 | 0.00 | 0.00 | 0.02 | 0.48 | 0.50 | 0.00 | 0.00 |
| 1997 | 73,761 | 0.00 | 0.00 | 0.04 | 0.39 | 0.57 | 0.00 | 0.00 |
| 1998 | 112,630 | 0.00 | 0.00 | 0.02 | 0.68 | 0.30 | 0.00 | 0.00 |
| 1999 | 149,410 | 0.00 | 0.00 | 0.01 | 0.46 | 0.52 | 0.00 | 0.00 |
| 2000 | 78,265 | 0.00 | 0.00 | 0.02 | 0.12 | 0.85 | 0.00 | 0.00 |
| 2001 | 60,183 | 0.00 | 0.00 | 0.03 | 0.76 | 0.19 | 0.02 | 0.00 |
| 2002 | 47,332 | 0.00 | 0.00 | 0.03 | 0.45 | 0.52 | 0.00 | 0.00 |
| 2003 | 49,955 | 0.00 | 0.00 | 0.02 | 0.28 | 0.70 | 0.00 | 0.00 |
| 2004 | 51,110 | 0.00 | 0.00 | 0.05 | 0.69 | 0.25 | 0.01 | 0.00 |
| 2005 | 22,852 | 0.00 | 0.00 | 0.03 | 0.36 | 0.62 | 0.00 | 0.00 |
| 2006 | 15,979 | 0.00 | 0.00 | 0.08 | 0.53 | 0.38 | 0.01 | 0.00 |
| 2007 | 14,208 | 0.00 | 0.00 | 0.02 | 0.64 | 0.33 | 0.01 | 0.00 |
| 2008 | 22,156 | 0.00 | 0.00 | 0.04 | 0.82 | 0.14 | 0.00 | 0.00 |
| 2009 | 85,551 | 0.00 | 0.00 | 0.01 | 0.51 | 0.48 | 0.00 | 0.00 |
| 2010 | 48,079 | 0.00 | 0.00 | 0.01 | 0.24 | 0.74 | 0.00 | 0.00 |
| 2011 | 15,599 | 0.00 | 0.00 | 0.03 | 0.62 | 0.35 | 0.00 | 0.00 |
| 2012 | 54,884 | 0.00 | 0.00 | 0.08 | 0.69 | 0.22 | 0.00 | 0.00 |
| 2013 | 75,588 | 0.00 | 0.00 | 0.03 | 0.53 | 0.44 | 0.00 | 0.00 |
| 2014 | 81,502 | 0.00 | 0.00 | 0.04 | 0.64 | 0.31 | 0.01 | 0.00 |
| 2015 | 33,085 | 0.00 | 0.00 | 0.02 | 0.32 | 0.66 | 0.00 | 0.00 |
| 2016 | 35,991 | 0.00 | 0.00 | 0.05 | 0.55 | 0.40 | 0.01 | 0.00 |

a. McPherson 1990.

### Escapement Estimates

Chilkat Lake sockeye salmon escapements have been estimated through weir counts (1967–1993), weir counts with mark–recapture estimates (1994, 1995, and 1999–2007), mark–recapture estimates only (1996–1998), and DIDSON counts with mark–recapture estimates (2008–2016) (Eggers et al. 2010; Sogge and Bachman 2014; Bednarski et al. 2017).

#### Mark–recapture Estimates

Sockeye salmon mark–recapture studies were conducted annually from 1994 to 2016. Fish were marked at the fish wheels with a primary mark (adipose clip) to identify it as a marked fish. Marking was then stratified through time by applying secondary fin clips in different combinations. Fish were then recovered at Chilkat Lake and Chilkat River spawning areas. This information was used to generate mark–recapture estimates of sockeye salmon abundance in the entire drainage. Chilkat Lake and Chilkat River mainstem populations were then estimated by simply multiplying the drainagewide estimate by the ratio of the two stocks at the fish wheels, which was determined from scale pattern analysis of sockeye salmon scale samples collected at the fish wheels (Kelley and Bachman 2000; Bachman and McGregor 2001; Bachman 2005; Bachman 2010; Bednarski et al. 2017).

#### Weir and DIDSON Estimates

Using linear regression methods, weir and DIDSON counts were expanded in years with shortened seasons to allow for comparison across all years, because weir and DIDSON operations did not always encompass the entire run. In some years weir and DIDSON operations were started later and/or ended earlier than average due to budget constraints, flooding, or other problems (Bednarski et al. 2017).

### Fry Plants

Based on results of Koenings’ Euphotic Volume model (Koenings and Burkett 1987), it was determined, in the 1980s, that Chilkat Lake was spawning-area limited and zooplankton biomass

Table .–Expanded Chilkat Lake sockeye salmon escapement estimates (1976-2016); mark–recapture (MR)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | **Escapement proportion by age** | | | | | | |  | |  | |  | |  | |
| **Year** | **DIDSON** | **MR** | **Weir** | **Age 2** | | **Age 3** | | **Age 4** | | **Age 5** | | | **Age 6** | | **Age 7** | | **Age 8** | |
| 1976a | NA | NA | 69,729 | 0.00 | 0.00 | | 0.06 | | 0.65 | | | 0.29 | | 0.00 | | 0.00 | |
| 1977a | NA | NA | 50,363 | 0.00 | 0.00 | | 0.04 | | 0.77 | | | 0.19 | | 0.00 | | 0.00 | |
| 1978a | NA | NA | 67,528 | 0.00 | 0.00 | | 0.10 | | 0.66 | | | 0.25 | | 0.00 | | 0.00 | |
| 1979a | NA | NA | 80,588 | 0.00 | 0.00 | | 0.01 | | 0.71 | | | 0.28 | | 0.00 | | 0.00 | |
| 1980a | NA | NA | 101,135 | 0.00 | 0.00 | | 0.02 | | 0.64 | | | 0.33 | | 0.00 | | 0.00 | |
| 1981a | NA | NA | 84,097 | 0.00 | 0.00 | | 0.00 | | 0.59 | | | 0.41 | | 0.00 | | 0.00 | |
| 1982 | NA | NA | 86,213 | 0.00 | 0.01 | | 0.04 | | 0.60 | | | 0.36 | | 0.00 | | 0.00 | |
| 1983 | NA | NA | 134,601 | 0.00 | 0.01 | | 0.06 | | 0.65 | | | 0.28 | | 0.00 | | 0.00 | |
| 1984 | NA | NA | 123,190 | 0.00 | 0.00 | | 0.03 | | 0.76 | | | 0.21 | | 0.00 | | 0.00 | |
| 1985 | NA | NA | 58,335 | 0.00 | 0.01 | | 0.04 | | 0.49 | | | 0.46 | | 0.00 | | 0.00 | |
| 1986 | NA | NA | 23,947 | 0.00 | 0.00 | | 0.05 | | 0.29 | | | 0.66 | | 0.00 | | 0.00 | |
| 1987 | NA | NA | 48,972 | 0.00 | 0.01 | | 0.05 | | 0.59 | | | 0.34 | | 0.00 | | 0.00 | |
| 1988 | NA | NA | 27,722 | 0.00 | 0.00 | | 0.01 | | 0.38 | | | 0.61 | | 0.00 | | 0.00 | |
| 1989 | NA | NA | 141,475 | 0.00 | 0.00 | | 0.01 | | 0.71 | | | 0.28 | | 0.00 | | 0.00 | |
| 1990 | NA | NA | 60,230 | 0.00 | 0.00 | | 0.02 | | 0.42 | | | 0.56 | | 0.00 | | 0.00 | |
| 1991 | NA | NA | 51,138 | 0.00 | 0.00 | | 0.02 | | 0.55 | | | 0.42 | | 0.00 | | 0.00 | |
| 1992 | NA | NA | 95,880 | 0.00 | 0.00 | | 0.01 | | 0.42 | | | 0.57 | | 0.00 | | 0.00 | |
| 1993 | NA | NA | 212,757 | 0.00 | 0.00 | | 0.04 | | 0.41 | | | 0.55 | | 0.00 | | 0.00 | |
| 1994 | NA | 153,540 | 86,385 | 0.00 | 0.00 | | 0.02 | | 0.60 | | | 0.37 | | 0.01 | | 0.00 | |
| 1995 | NA | 184,541 | 61,783 | 0.00 | 0.00 | | 0.04 | | 0.46 | | | 0.49 | | 0.00 | | 0.00 | |
| 1996b | NA | 262,852 | NA | NA | NA | | NA | | NA | | | NA | | NA | | NA | |
| 1997b | NA | 238,803 | NA | NA | NA | | NA | | NA | | | NA | | NA | | NA | |
| 1998b | NA | 211,114 | NA | NA | NA | | NA | | NA | | | NA | | NA | | NA | |
| 1999 | NA | 240,002 | 134,048 | 0.00 | 0.00 | | 0.01 | | 0.40 | | | 0.59 | | 0.00 | | 0.00 | |
| 2000 | NA | 132,687 | 47,077 | 0.00 | 0.00 | | 0.02 | | 0.14 | | | 0.84 | | 0.00 | | 0.00 | |
| 2001 | NA | 105,064 | 53,239 | 0.00 | 0.00 | | 0.03 | | 0.79 | | | 0.16 | | 0.02 | | 0.00 | |
| 2002 | NA | 148,465 | 65,611 | 0.00 | 0.00 | | 0.03 | | 0.45 | | | 0.52 | | 0.00 | | 0.00 | |
| 2003 | NA | 116,891 | 55,516 | 0.00 | 0.00 | | 0.03 | | 0.30 | | | 0.67 | | 0.00 | | 0.00 | |
| 2004 | NA | 118,795 | 83,534 | 0.00 | 0.00 | | 0.04 | | 0.65 | | | 0.30 | | 0.01 | | 0.00 | |
| 2005 | NA | 89,072 | 32,098 | 0.00 | 0.00 | | 0.04 | | 0.39 | | | 0.57 | | 0.00 | | 0.00 | |
| 2006 | NA | 91,439 | 38,850 | 0.00 | 0.00 | | 0.05 | | 0.62 | | | 0.32 | | 0.00 | | 0.00 | |
| 2007 | NA | 59,884 | 27,915 | 0.00 | 0.00 | | 0.07 | | 0.48 | | | 0.45 | | 0.00 | | 0.00 | |
| 2008 | 74,919 | 119,808 | NA | 0.00 | 0.00 | | 0.05 | | 0.82 | | | 0.12 | | 0.00 | | 0.00 | |
| 2009 | 153,033 | 285,218 | NA | 0.00 | 0.00 | | 0.03 | | 0.71 | | | 0.25 | | 0.00 | | 0.00 | |
| 2010 | 61,906 | 72,318 | NA | 0.00 | 0.01 | | 0.03 | | 0.37 | | | 0.59 | | 0.00 | | 0.00 | |
| 2011 | 63,628 | 109,335 | NA | 0.00 | 0.00 | | 0.09 | | 0.61 | | | 0.29 | | 0.00 | | 0.00 | |
| 2012 | 121,810 | 171,924 | NA | 0.00 | 0.01 | | 0.05 | | 0.77 | | | 0.17 | | 0.00 | | 0.00 | |
| 2013 | 116,300 | 224,516 | NA | 0.00 | 0.00 | | 0.08 | | 0.49 | | | 0.43 | | 0.00 | | 0.00 | |
| 2014 | 70,470 | 212,201 | NA | 0.00 | 0.01 | | 0.02 | | 0.72 | | | 0.25 | | 0.01 | | 0.00 | |
| 2015 | 175,874 | 124,892 | NA | 0.00 | 0.00 | | 0.04 | | 0.29 | | | 0.66 | | 0.00 | | 0.00 | |
| 2016 | 88,513 | 96,148 | NA | 0.00 | 0.00 | | 0.04 | | 0.60 | | | 0.36 | | 0.00 | | 0.00 | |

a.The weir was not operated in 1996, 1997, or 1998.

was sufficient to feed an additional 10 to 12 million fry. Enhancement programs included harvesting eggs and milt from sockeye salmon returning to the lake, then stocking fry in the lake in the summer after hatching (1994–1997; 2001) along with seeding incubation boxes, located along Chilkat Lake, with sockeye eggs that would emerge the following spring (1989–1998 and 2003) (Table 3).

The result of the fry stocking was a decline in smolt abundance, a decrease in mean length and weight of age-1. and age-2. smolts, and a change in the smolt age composition that was possibly linked to zooplankton food limitation. The density of the zooplankton prey *Daphnia* declined after 1995 and again in 2001, corresponding to increased lake stocking efforts. Analysis of the production of wild and enhanced smolts demonstrated that the fry plants depressed the wild smolt production, and further, the fry plants generally occurred in the face of relatively high wild stock escapements. This suggests that production is rearing-limited, and that fry plants in the face of moderate to high wild stock escapement resulted in decreased wild smolt production (Eggers et al. 2008).

Table .–Number of enhanced sockeye salmon fry in Chilkat Lake for release years 1989 to 2003 (Eggers et al. 2010). The stocked fry were incubated as eggs in the hatchery and released as fry into Chilkat Lake in the spring. The number of fry that emerged in the spring each year from incubation boxes was estimated from the number of eggs seeded in incubation boxes minus the dead eggs counted in the spring.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Brood Year** | **Release Year** | **Stocked fry (thermal marked)a** | **Stocked fry (unmarked)** | **Incubation fry boxb** | **Total enhanced fry** |
| 1988 | 1989 | 0 | 0 | 15,094 | 15,094 |
| 1989 | 1990 | 0 | 0 | 300,127 | 300,127 |
| 1990 | 1991 | 0 | 0 | 388,000 | 388,000 |
| 1991 | 1992 | 0 | 0 | 201,753 | 201,753 |
| 1992 | 1993 | 0 | 0 | 594,000 | 594,000 |
| 1993 | 1994 | 4,817,929 | 0 | 550,700 | 5,368,629 |
| 1994 | 1995 | 2,334,264 | 0 | 289,500 | 2,623,764 |
| 1995 | 1996 | 2,691,311 | 6,138 | 572,350 | 3,269,799 |
| 1996 | 1997 | 3,038,171 | 0 | 96,500 | 3,134,671 |
| 1997 | 1998 | 0 | 0 | 437,950 | 437,950 |
| 1998 | 1999 | 0 | 0 | 0 | 0 |
| 1999 | 2000 | 0 | 0 | 0 | 0 |
| 2000 | 2001 | 2,743,374 | 0 | 0 | 2,743,374 |
| 2001 | 2002 | 0 | 0 | 0 | 0 |
| 2002 | 2003 | 0 | 0 | 49,500 | 49,500 |

aNumber of stocked fry updated from ADF&G Mark, Tag, and Age Laboratory website 20 June 2012.

bNumber of unmarked fry from incubation boxes from Eggers et al. 2010 (Table 1; FMS 10-05).

## State Space Model

Chilkat Lake sockeye salmon spawner-recruit data were analyzed using a Bayesian age-structured state-space model to assess the uncertainty introduced into the estimate of spawning size that produces maximum sustained yield (MSY) due to the following factors.

1. Late installation of the weir (between 18 June and 13 July) in years 1982, 1983, 1985, 1987, 1988, 1999, and 2001–2007, and early removal of the weir (between 28 September and 14 October) in years 1977, 1980, 1982, 1984, 1994, 1995, 2001, and 2003–2006. In years 1982, 2001, and 2003–2006 the weir was installed late *and* removed early. Therefore, the spawning escapement counts had to be expanded in years 1977, 1980, 1982, 1983, 1984, 1985, 1987, 1988, 1994, 1995, 1999, and 2001–2007.
2. Late installation of the DIDSON (27 June in 2008, 26 June in 2015, 24 June 2016) in years 2008, 2015, and 2016, and early removal (between 30 September and 7 October) in years 2012, 2013, and 2015. Therefore, the spawning escapement counts had to be expanded in years 2008, 2012, 2013, 2015, and 2016.
3. Multiple, overlapping methods of escapement enumeration; Weir counts (1976–2007) are reliable, but provide minimum estimates of escapement due to flow reversals, turbid water, and increased lowering of the boat gate allowing undetected fish passage. Therefore, weir counts are an index of escapement. Compared to the weir, the DIDSON (2008–2016) has the potential to provide highly accurate counts of fish; however, the DIDSON count is also considered a minimum estimate due to undetected fish passage at night, misidentification of species, and miscounts of fish. Mark–recapture estimates (1994–2016) may be greatly inflated, but may provide an index of escapement. Since the mark–recapture estimates are highly inflated and the weir counts are highly underestimated, the DIDSON escapement counts were treated as the ‘true’ counts and not as an index of escapement.
4. The weir was not operated from 1996 to 1998. Therefore, proportions of ages 2–8 were only available for the commercial harvest and weighted annual proportions by age (escapement and harvest combined) were considered unknown.

### Process Model

A hierarchical set of two stock-recruitment models were fit to the Chilkat Lake stock-recruit data for calendar years 1976–2016. The stock-recruitment models were Ricker-type and hierarchical terms included density-dependent fry plants and a first order autoregressive (AR(1)) term. Returns *R* of Chilkat lake sockeye salmon were modeled as a function of spawning escapement *S* in year *y* using a linearized Ricker (1954) spawner-recruit function with an AR lognormal process error with a lag of 1 year (Noakes et al. 1987),

. (3)

Returns for Model 2 were modeled using a linearized AR(1) Ricker (eq. 3), but an additional density-dependent fry term, *γ*, was included,

. (4)

Fry plants were from brood year *y* in year *y*+1 (Fy+1). In eq. 3 and 4, **is the productivity parameter, ** is the inverse capacity parameter, **is the AR lag-1 coefficient, and {} are the model residuals,

 (5)

In eq. 3, {} are independently and normally distributed process errors with standard deviation  Six initial returns (1970–1975) were modeled as draws from a common log normal distribution with parameters ln(*R*0) and  These returns were not linked to the escapement data in the spawner recruit relationship.

Age-at-maturity proportions  from year *y* and returning at ages 4–6 (ages 2–4 were combined and ages 6–8 were combined) were drawn from a common Dirichlet distribution that was implemented by generating independent random variables from the gamma distribution  and dividing each by their sum (Evans et al. 1993),

. (6)

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

, (7)

and implemented as a series of nested beta distributions, reflecting age-at-maturity central tendencies. The sum of the Dirichlet parameters, , is the inverse dispersion (*D*) of the Dirichlet distribution. A low value of *D* is reflective of a large amount of variability of age-at-maturity proportions *p* among brood years, whereas a high value of *D* indicates more consistency in *p* over time.

The abundance *N* of Chilkat Lake sockeye salmon of age-*a* returning to spawn in calendar year *y* (*y* = 1976–2016) is the product of the age proportion scalar *p* and the total return (recruitment) *R* from year *y*-*a*,

. (8)

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

. (9)

The spawning escapement count each calendar year, *Sy*, is the difference between total run abundance and the total District 15 Chilkat Lake commercial harvest, *Hbelowy*,

 (10)

Annual commercial harvest was modeled as the product of the total run and annual harvest rate,

, (11)

drawn from a beta distribution (Appendix A.1).

### Observation Model

Observed data (Appendix A.2) included spawning escapement counts (DIDSON), indices of escapement (weir, mark–recapture), annual commercial harvest, and age compositions. For this analysis, we assume no unreported harvest of Chilkat Lake sockeye salmon.

Estimated escapement counts from the DIDSON were

, (12)

where the  were normal (0, ) and

 (13)

Estimated annual commercial harvest was

, (14)

where the {} were normal (0, ) and the variances followed Equation 13. Two indices of escapement were available. Each comprised an independent measure of relative escapement,

, (15)

where subscript *i* indicates 1 of the 2 indices of escapement (weir or mark–recapture), *qi* is a factor of proportionality relating true escapement to index *Ii* ,and the are independently and normally distributed process errors with variance . Parameters *qi* and  were estimated from the data.

Harvest coefficients of variation were unavailable. Therefore, they 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 DIDSON or weir counts was necessary, the CV 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 DIDSON or weir escapement counts were expanded for either late installation *or* early removal, the CVs were set at 0.10 (Bednarski et al. 2017). For years when DIDSON or weir escapement counts were expanded for both late installation *and* early removal, the CVs were set at 0.20. The CVs for mark–recapture escapement counts were estimated as the standard error of the drainagewide point estimate divided by the drainagewide point estimate. These are standard output from the software program Stratified Population Analysis System (SPAS) that was used to analyze the mark–recapture data (Arnason et al. 1996). The CVs for 1994–1997 were unavailable. Therefore, they were uniformly set at 0.10.

For both annual commercial harvest and escapement samples separately, proportions of age 2–8 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 2–8). Next, these combined numbers by age were converted to annual proportions by age, *q*(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 *nEy* (Fleischman and McKinley 2013), an arbitrarily small annual effective sample size of *nEy* =100 was used. After combining proportions of ages two through four and also combining ages six through eight, the weighted annual proportions by age were multiplied by 100,

 where  across all ages for each year, (16)

to calculate the age counts, *xy,a*. The age counts were assumed to have a multinomial distribution with order parameter *nEy*and proportion parameters,

, (17)

where  across all ages for each calendar year. The weir was not operated from 1996–1998. Therefore, proportions of ages 2–8 were only available for the commercial harvest and weighted annual proportions by age for the combined escapement and harvest data were considered unknown.

## Model Fitting

Model fitting involves finding the values of population parameters that can plausibly result in the observed data. Using the package RJAGS (Plummer 2016) within R (R Core Team 2016), Markov Chain Monte Carlo (MCMC) methods were employed to provide a more realistic assessment of uncertainty than is possible with traditional stock-recruit methods.

The significance of the fit of the alternative models (Model 1: l linearized AR(1) Ricker; Model 2: linearized AR(1) Ricker with density-dependent fry plants) were evaluated using the deviance information criterion (DIC; Spiegelhalter et al. 2002), a Bayesian version or generalization of the Akaike information criterion (AIC; Akaike 1973) and related to the Bayesian (or Schwarz) information criterion (BIC; Schwarz 1978). Similar to both the AIC and BIC, it trades off a measure of model adequacy against a measure of complexity. Models receiving a DIC within 1-2 of the ‘best’ model deserve consideration, while models within 3–7 of the ‘best’ model have considerably less support (Spiegelhalter et al. 2002).

### Prior Distributions

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). Normal priors with mean 0, extremely large variances, and constrained to be positive were used for *β* (Millar 2002). Log transformed initial recruitments *R*1970*-R*1976 (those with no linked spawner abundance) were modeled as drawn from a common normal distribution with mean ln(*R*0) and variance . A flat prior on the standard deviation of log initial brood year returns, , caused computational disruptions during MCMC sampling so it was changed to a slightly informative inverse gamma prior. Fleischman et al. (2013) found that an informative prior on  may have a large effect on the posterior of  and the initial values of *Ry*, but negligible effects on key model quantities.

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

|  |  |  |
| --- | --- | --- |
| **Parameter** | **RJAGS coding** | **Prior** |
| ln(**) | lnalpha | ln(**) ~ “Uniform” (0,3) |
| ** | beta | **~ “Uniform” (0,∞) |
| *R* | sigma.R | ~gamma(0.001,0.001) |
| ** | phi | **~ “Uniform” (-0.98,0.98); |
| ** | log.resid.0 |  |
| *D* | D |  |
| ln(*R*0) | mean.log.R0 | ln(*R*0) ~ “Uniform” (∞,∞) |
| *R0* | sigma.R0 | ~gamma(0.001,0.001) |
| *γ* | gam | *γ*~ “Uniform” (-0.98,0.98) |
| ln(*R*1):ln(*R*7) | log.R[1:7] | ~Normal(ln(*R*0), ) |

### Sampling from the Posterior Distribution

MCMC methods were used to generate the joint posterior probabilities of the unknown quantities using the package RJAGS (Plummer 2016) with R. 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 samples per chain) MCMC updates were retained for analysis to estimate posterior medians, standard deviations, and percentiles. The diagnostic tools of the package RJAGS (Plummer 2016) 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 deviation) (Toft et al. 2007) were used to assess mixing and convergence. No major problems were encountered. Interval estimates 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),

 (18a)

and approximated based on Peterman et al. (2000),

 (18b)

where to correct for the difference between the median and the mean of a lognormal error distribution from an AR(1) process (Parken et al. 2006). Sustained yield at a specified level of *S* was obtained by subtracting spawning escapement from recruitment,

 (19)

Spawning escapement at peak return, *S*MSR, was calculated as 1/ and equilibrium spawning abundance (recruitment exactly replaces spawners) as,

. (20)

Harvest rate leading to MSY, *U*MSY, was approximated by (Hilborn 1985),

, (21a)

and approximated based on Peterman et al. (2000),

 (21b)

Optimal yield probabilities are the probabilities that a given level of spawning escapement (*S*) will produce average yields exceeding X% of MSY. These probabilities are created by calculating expected sustained yield, *YS*, at incremental levels of *S* (0 to 322,460 by 4,600) for each MCMC sample using equation 19, and then comparing *YS* with X% (80%, 90%) of the value of MSY for the sample. The proportion (*P*OY) of samples that fit the criteria: *YS* > X% of MSY is an estimate of the desired probability. 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 (80%, 90%) of MSY. To produce the overfishing probability profiles, expected sustained yield (eq. 19) at multiple incremental levels of *S* (0 to 322,460 by 4,600) are calculated for each MCMC sample. Then, the number of MCMC samples for which *YS*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 III 2010).

Optimal recruitment profiles are the probabilities that a given spawning escapement (*S*) will produce average recruitments (*R*) exceeding X% (80%, 90%) of maximum sustained recruitment (MSR). These probabilities are created by calculating *R* from

 (23)

at incremental levels of *S* (0 to 322,460 by 4,600) for each MCMC sample, then comparing *R* with X% of the value of MSR for that sample. The proportion *PR* of samples in which *R* exceeded X% of MSR is an estimate of the desired probability. Optimal recruitment profiles are then a plot of *PR* 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

Appendix A2 summarizes empirical (data-based) estimates of harvest, age composition, escapement, and escapement indices for Chilkat Lake sockeye salmon.

### Model Comparison

A hierarchical set of two stock-recruitment models were fit to the Chilkat Lake stock-recruit data for calendar years 1976–2016. The stock-recruitment models were Ricker-type and hierarchical terms included density-dependent fry plants and a first order autoregressive term. The effect of the fry plant term (*γ* = -5.81E-08; Table 5) was to correct the increased production due to the fry plants and to provide an unbiased estimate of the wild stock MSY escapement goal. The best model based on the fit criteria (i.e., minimum DIC) was the autoregressive Ricker with fry plants, but the difference between the best fit model fit and the autoregressive Ricker model fit was negligible (∆0.31) and the 95% credibility intervals on the density-dependent fry term, *γ*, included zero (-2.74E-07, 1.69E-07) and thus the term was non-significant. Therefore, the autoregressive Ricker model was considered the most meaningful biological model.

Table 5.–Results of model fits to the escapement-recruit data for calendar years 1976 to 2016. Estimated parameters, reference points, and measures of fit (DIC). The lower and upper bound on the *S*MSY and *S*MSY(Peterman) reference points define the 2.5th and 97.5th percentiles which represent the 95% credibility intervals for the parameters.

|  |  |  |
| --- | --- | --- |
| Parameters | Autoregressive Ricker | Autoregressive Ricker-fry plants |
| *α* | 3.02 | 2.89 |
| *β* | 5.45E-06 | 5.11E-06 |
| ** | 0.42 | 0.49 |
| *γ* |  | -5.81E-08 |
| *S*MSY | 97,275 | 101,425 |
| Lower | 66,413 | 65,484 |
| Upper | 231,148 | 308,889 |
| *S*MSY(Peterman) | 97,497 | 101,626 |
| Lower | 66,447 | 65,520 |
| Upper | 232,408 | 311,043 |
| Harvest Rate | 0.53 | 0.73 |
| Harvest Rate Peterman | 0.54 | 0.73 |
| DIC | 3090.51 | 3090.20 |

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

Reconstructed total run abundance (*N*) for the autoregressive Ricker model had CVs from 5% to 14% (Figure 3; Table 6). The years with higher uncertainty corresponded to years with missing

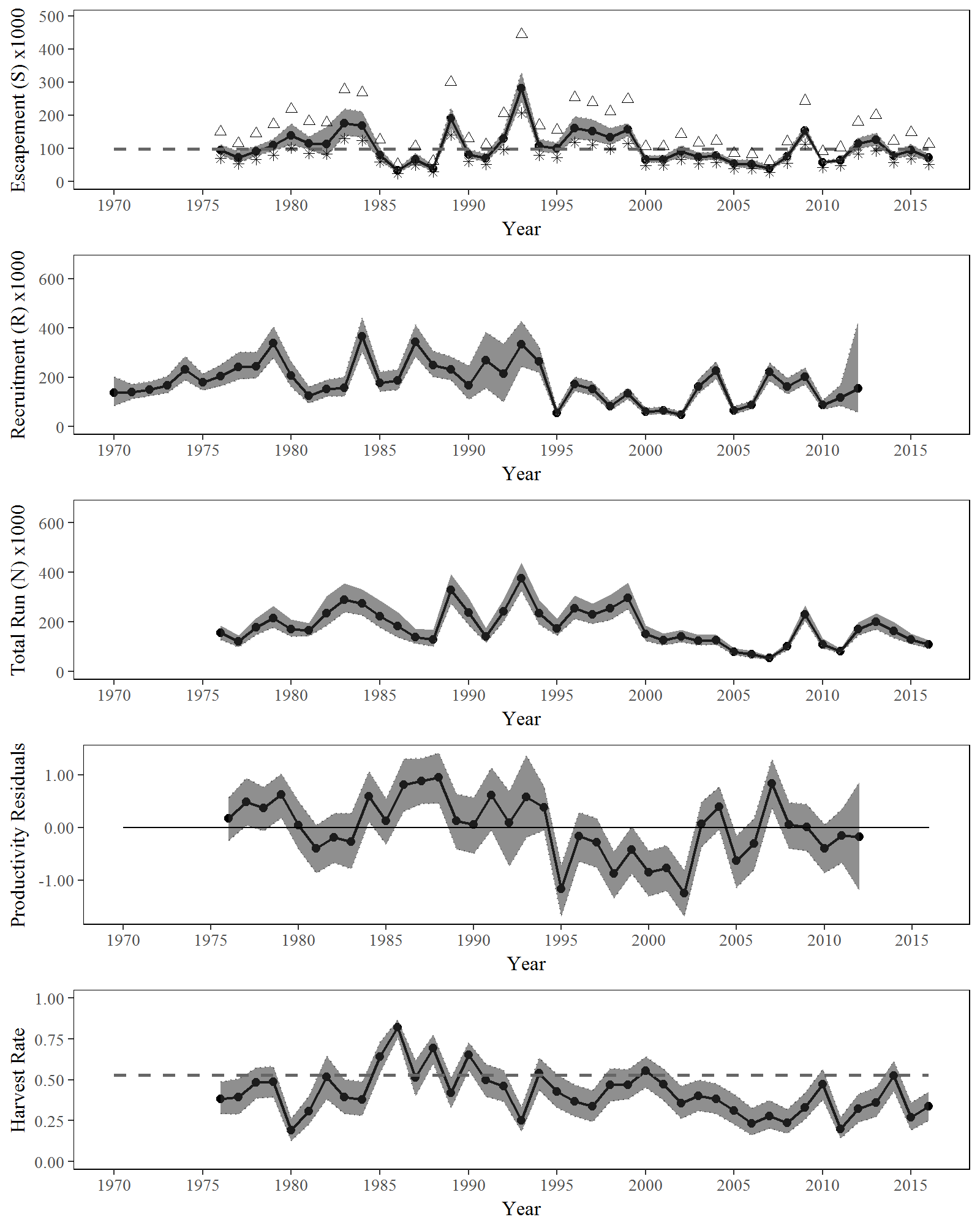


Figure .–Point estimates (posterior medians; solid lines) and 95% credibility intervals (shaded areas) of spawning escapement with the two indices of escapement (weir (stars); mark–recapture (open triangles)), recruitment by brood year, total run abundance, Ricker productivity residuals, and harvest rate from a state-space model of Chilkat Lake sockeye salmon, 1976–2016. Posterior medians of *S*MSY and *U*MSY are plotted as dashed horizontal reference lines.

Table 6.–Annual abundance estimates for Chilkat Lake sockeye salmon obtained by fitting a state-space model to data for calendar years 1976–2016. Point estimates are posterior medians and CVs are posterior standard deviations divided by posterior means. Recruitment values are listed by brood year.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | Coefficients of Variations | |  |
| Year | Total Run | Escapement | Return | Total Run | Escapement | Return |
| 1970 |  |  | 137,316 |  |  | 0.22 |
| 1971 |  |  | 138,731 |  |  | 0.11 |
| 1972 |  |  | 149,647 |  |  | 0.10 |
| 1973 |  |  | 166,317 |  |  | 0.10 |
| 1974 |  |  | 230,729 |  |  | 0.10 |
| 1975 |  |  | 178,517 |  |  | 0.10 |
| 1976 | 154,759 | 94,767 | 203,002 | 0.09 | 0.08 | 0.11 |
| 1977 | 120,150 | 72,454 | 240,751 | 0.10 | 0.12 | 0.12 |
| 1978 | 177,258 | 91,665 | 243,163 | 0.10 | 0.08 | 0.11 |
| 1979 | 213,916 | 109,033 | 337,173 | 0.10 | 0.08 | 0.10 |
| 1980 | 171,241 | 138,874 | 205,394 | 0.10 | 0.11 | 0.12 |
| 1981 | 166,555 | 114,918 | 125,111 | 0.08 | 0.08 | 0.13 |
| 1982 | 235,682 | 112,566 | 152,666 | 0.13 | 0.19 | 0.11 |
| 1983 | 289,335 | 175,171 | 155,779 | 0.10 | 0.11 | 0.13 |
| 1984 | 273,751 | 169,155 | 365,918 | 0.10 | 0.11 | 0.09 |
| 1985 | 223,643 | 80,025 | 177,253 | 0.12 | 0.12 | 0.12 |
| 1986 | 182,155 | 32,763 | 187,376 | 0.14 | 0.08 | 0.11 |
| 1987 | 138,713 | 67,242 | 343,729 | 0.11 | 0.12 | 0.09 |
| 1988 | 129,464 | 39,289 | 248,168 | 0.13 | 0.12 | 0.11 |
| 1989 | 328,466 | 190,175 | 231,251 | 0.09 | 0.08 | 0.10 |
| 1990 | 236,104 | 82,037 | 166,363 | 0.12 | 0.08 | 0.21 |
| 1991 | 141,265 | 70,541 | 268,761 | 0.11 | 0.08 | 0.22 |
| 1992 | 241,875 | 129,999 | 213,594 | 0.10 | 0.08 | 0.28 |
| 1993 | 376,584 | 281,305 | 333,692 | 0.08 | 0.08 | 0.14 |
| 1994 | 234,189 | 107,365 | 263,850 | 0.11 | 0.09 | 0.10 |
| 1995 | 174,126 | 99,241 | 54,392 | 0.10 | 0.08 | 0.16 |
| 1996 | 255,615 | 161,020 | 170,871 | 0.10 | 0.11 | 0.09 |
| 1997 | 228,785 | 151,191 | 151,164 | 0.09 | 0.11 | 0.09 |
| 1998 | 253,565 | 133,811 | 81,823 | 0.10 | 0.10 | 0.12 |
| 1999 | 296,766 | 156,537 | 133,277 | 0.09 | 0.06 | 0.08 |
| 2000 | 149,615 | 66,770 | 59,773 | 0.11 | 0.07 | 0.11 |
| 2001 | 126,445 | 66,897 | 65,214 | 0.09 | 0.08 | 0.10 |
| 2002 | 140,668 | 90,054 | 48,135 | 0.09 | 0.10 | 0.11 |
| 2003 | 124,193 | 74,104 | 160,581 | 0.09 | 0.08 | 0.09 |
| 2004 | 125,953 | 77,162 | 225,809 | 0.08 | 0.07 | 0.08 |
| 2005 | 78,435 | 53,820 | 64,638 | 0.09 | 0.10 | 0.12 |
| 2006 | 68,537 | 52,341 | 87,719 | 0.10 | 0.12 | 0.09 |
| 2007 | 54,114 | 38,855 | 220,408 | 0.08 | 0.08 | 0.08 |
| 2008 | 100,740 | 76,643 | 161,408 | 0.07 | 0.07 | 0.10 |
| 2009 | 230,761 | 154,202 | 201,367 | 0.07 | 0.05 | 0.09 |
| 2010 | 109,848 | 57,719 | 86,419 | 0.09 | 0.05 | 0.11 |
| 2011 | 81,821 | 65,333 | 117,568 | 0.05 | 0.04 | 0.18 |
| 2012 | 169,313 | 114,024 | 154,752 | 0.08 | 0.07 | 0.56 |
| 2013 | 200,024 | 126,732 |  | 0.08 | 0.07 |  |
| 2014 | 164,112 | 77,737 |  | 0.10 | 0.05 |  |
| 2015 | 129,403 | 93,986 |  | 0.08 | 0.09 |  |
| 2016 | 108,283 | 71,703 |  | 0.08 | 0.07 |  |

escapement data (DIDSON; 1976–2007), missing escapement indices (weir or mark–recapture), and/or missing age composition data (1996–1998; Table 6; Appendix A2). Excluding the first initial returns, reconstructed brood year recruitment had CVs from 8% to 56%. The Ricker recruitment residuals (productivity residuals) in Figure 3 are deviations in recruitment from that predicted by the Ricker S–R relationship, reflecting time-varying changes in productivity after controlling for density-dependent effects. Productivity residuals were spread around 0 across years, indicating a good model fit and *σ*R was 0.55 (95% CI: 0.43–0.74) (Table 7). Median harvest rates (*U*MSY) ranged from 0.37 to 0.71 (Figure 3) and ranged from 0.37 to 0.70 for *U*MSY(Peterman). Chilkat Lake sockeye salmon matured at ages 2– 4 (mean **4; 1%–8%), age-5 (mean **5; 36%–72%), and ages 6–8 (mean **6; 23% to 63%). These proportions have fluctuated moderately from brood year to brood year (Figure 4; top panel). Chilkat Lake sockeye salmon are mainly composed of age–5 (1.3, 2.2) and age–6 (2.3) fish (Table 8). Age compositions have also fluctuated from year to year (Figure 4; middle and bottom panel).

Table 7.–State-space model parameter estimates for Chilkat Lake for calendar years 1976–2016. Posterior medians are point estimates; 2.5th and 97.5th percentiles define 95% credibility intervals for the parameters. Parameter definitions are in the *Methods* section. Point estimates are posterior medians and CVs are posterior standard deviations divided by posterior means.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | 2.5th percentile | Median | 97.5th percentile | CV |
| ** | 1.81 | 3.02 | 5.21 | 0.28 |
| ln(**) | 0.59 | 1.11 | 1.65 | 0.24 |
| ** | 1.90E-06 | 5.45E-06 | 9.24E-06 | 0.35 |
| ** | 0.07 | 0.42 | 0.76 | 0.42 |
| **R | 0.43 | 0.55 | 0.74 | 0.14 |
| *S*EQ | 165,943 | 239,069 | 555,984 | 0.42 |
| *S*MSR | 108,227 | 183,490 | 527,649 | 0.58 |
| *S*MSY | 66,413 | 97,275 | 231,148 | 0.43 |
| *U*MSY | 0.37 | 0.53 | 0.71 | 0.16 |
| *S*MSY(Peterman) | 66,447 | 97,497 | 232,408 | 0.43 |
| *U*MSY(Peterman) | 0.37 | 0.54 | 0.70 | 0.16 |
| D | 20.50 | 32.45 | 51.78 | 0.24 |
| ** | 0.03 | 0.04 | 0.06 | 0.15 |
| ** | 0.51 | 0.54 | 0.57 | 0.03 |
| ** | 0.38 | 0.41 | 0.45 | 0.04 |
| *q*m-r | 1.46 | 1.58 | 1.72 | 0.04 |
| *q*weir | 0.65 | 0.74 | 0.83 | 0.06 |

Note: The CVs for the reference points *S*EQ, *S*MSR, *S*MSY, and *S*MSY(Peterman) 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 are both ~1.96 x standard errors from the median point estimate.

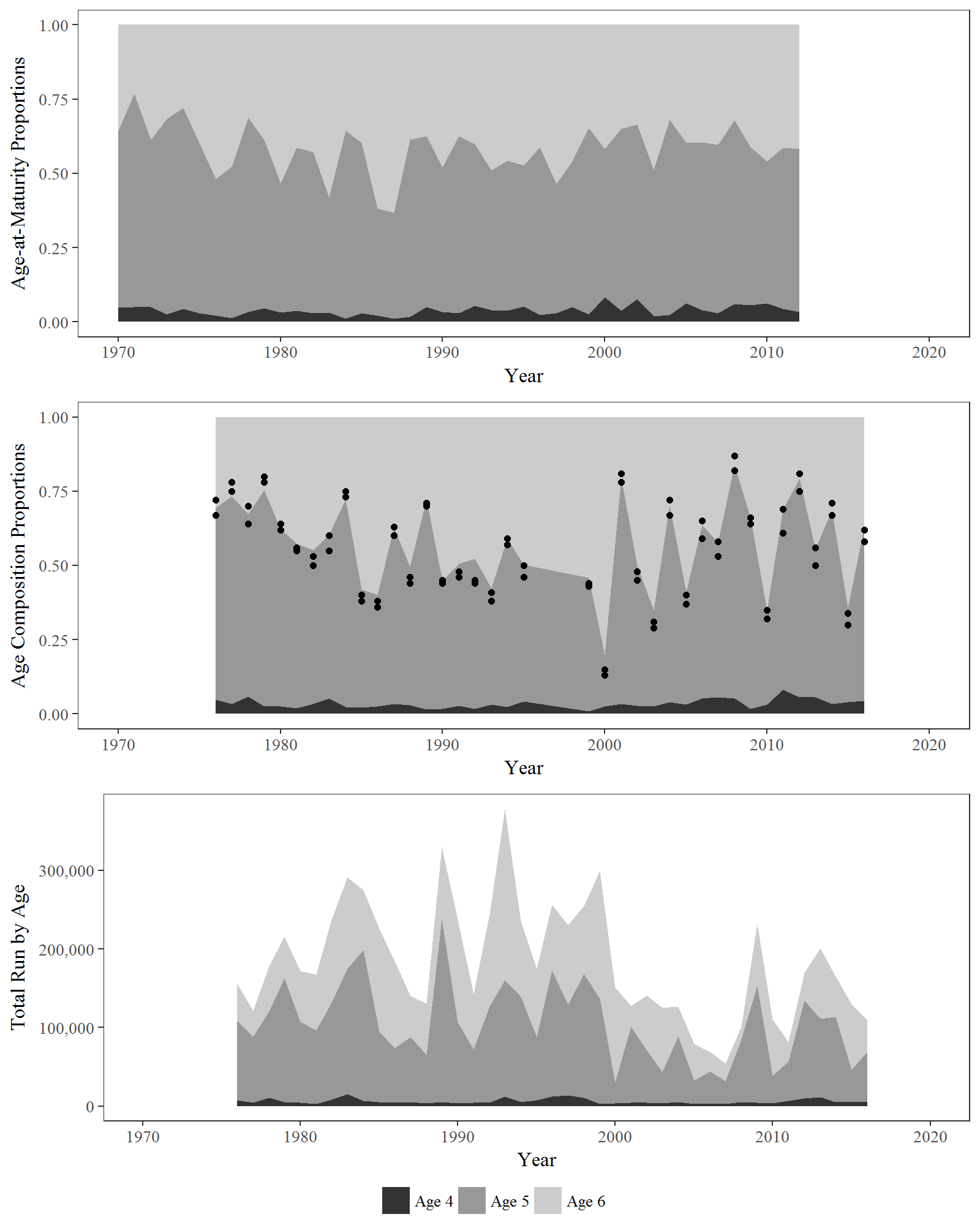


Figure .–Estimated age-at-maturity proportions by brood year (1970–2012; top), age composition proportions by calendar year (1976–2016; middle), and total run by age (bottom), from a state-space model fitted to data from Chilkat Lake sockeye salmon. Top and middle figures are area graphs in which distance between lines represent age proportions. Dots in the middle plot are data-based estimates of age composition from Appendix A2.

Table .–Total run abundance by age-class obtained by fitting a state-space model to data from Chilkat Lake sockeye salmon for calendar years 1976–2016. Point estimates are posterior medians and CVs are posterior standard deviations divided by posterior means.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | Coefficients of Variations | | |
| Year | Age-4 | Age-5 | Age-6 | Age-4 | Age-5 | Age-6 |
| 1976 | 7,220 | 99,708 | 47,244 | 0.40 | 0.11 | 0.17 |
| 1977 | 3,760 | 84,142 | 31,817 | 0.48 | 0.12 | 0.18 |
| 1978 | 9,859 | 109,095 | 57,578 | 0.38 | 0.12 | 0.16 |
| 1979 | 4,889 | 155,475 | 52,417 | 0.54 | 0.12 | 0.18 |
| 1980 | 4,068 | 101,874 | 64,302 | 0.55 | 0.12 | 0.15 |
| 1981 | 2,757 | 92,507 | 70,848 | 0.64 | 0.11 | 0.13 |
| 1982 | 7,500 | 121,748 | 104,937 | 0.50 | 0.15 | 0.17 |
| 1983 | 14,506 | 158,817 | 115,008 | 0.40 | 0.13 | 0.15 |
| 1984 | 5,745 | 191,204 | 75,516 | 0.56 | 0.12 | 0.17 |
| 1985 | 4,313 | 88,984 | 129,554 | 0.56 | 0.17 | 0.15 |
| 1986 | 4,136 | 68,373 | 109,233 | 0.56 | 0.18 | 0.16 |
| 1987 | 4,431 | 82,265 | 51,177 | 0.48 | 0.13 | 0.16 |
| 1988 | 3,377 | 60,297 | 65,140 | 0.55 | 0.16 | 0.16 |
| 1989 | 4,546 | 231,198 | 89,939 | 0.67 | 0.11 | 0.17 |
| 1990 | 3,420 | 101,139 | 129,709 | 0.66 | 0.16 | 0.14 |
| 1991 | 3,626 | 67,296 | 69,874 | 0.55 | 0.14 | 0.14 |
| 1992 | 3,800 | 121,830 | 115,242 | 0.66 | 0.14 | 0.14 |
| 1993 | 10,757 | 147,488 | 216,630 | 0.51 | 0.14 | 0.12 |
| 1994 | 4,933 | 132,262 | 95,515 | 0.55 | 0.14 | 0.15 |
| 1995 | 6,943 | 80,007 | 86,326 | 0.44 | 0.14 | 0.13 |
| 1996 | 8,689 | 161,579 | 79,936 | 0.99 | 0.24 | 0.36 |
| 1997 | 10,214 | 114,822 | 99,112 | 0.87 | 0.29 | 0.31 |
| 1998 | 7,859 | 158,142 | 83,642 | 0.89 | 0.22 | 0.35 |
| 1999 | 2,454 | 133,142 | 160,372 | 0.69 | 0.13 | 0.13 |
| 2000 | 3,516 | 25,527 | 119,870 | 0.55 | 0.21 | 0.12 |
| 2001 | 4,069 | 96,370 | 25,503 | 0.48 | 0.11 | 0.20 |
| 2002 | 3,731 | 65,867 | 70,101 | 0.48 | 0.14 | 0.13 |
| 2003 | 2,963 | 39,944 | 80,775 | 0.55 | 0.16 | 0.11 |
| 2004 | 4,714 | 83,341 | 37,350 | 0.40 | 0.11 | 0.16 |
| 2005 | 2,257 | 29,698 | 46,239 | 0.49 | 0.14 | 0.12 |
| 2006 | 3,496 | 39,898 | 24,864 | 0.37 | 0.13 | 0.16 |
| 2007 | 2,926 | 28,264 | 22,683 | 0.38 | 0.12 | 0.13 |
| 2008 | 5,128 | 79,296 | 16,056 | 0.39 | 0.09 | 0.20 |
| 2009 | 3,658 | 148,245 | 78,266 | 0.55 | 0.10 | 0.14 |
| 2010 | 3,171 | 34,826 | 71,468 | 0.48 | 0.16 | 0.12 |
| 2011 | 6,493 | 49,572 | 25,466 | 0.32 | 0.09 | 0.14 |
| 2012 | 9,301 | 124,695 | 34,538 | 0.36 | 0.10 | 0.19 |
| 2013 | 10,929 | 99,599 | 88,768 | 0.37 | 0.12 | 0.13 |
| 2014 | 5,145 | 106,674 | 51,404 | 0.44 | 0.12 | 0.17 |
| 2015 | 4,786 | 41,066 | 82,783 | 0.43 | 0.15 | 0.11 |
| 2016 | 4,546 | 63,641 | 39,569 | 0.44 | 0.11 | 0.14 |

### 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 5, which weight the individual data pairs depending on how precisely they were estimated. Some of the plausible relationships (Figure 5; light grey lines) vary greatly from the posterior medians of ln(**) and **Figure 5; dark dashed line, but most are not substantially different from the median estimates*.* The median estimate of ln(*α*) was 1.11 (95% CI: 0.59–1.65), corresponding to *α* = 3.02 (95% CI: 1.81–5.21; Table 7) and the median estimate of the density dependent parameter *β* was 5.45 × 10-6 (95% CI: 1.90× 10-6–9.24 × 10-6). Uncertainty about *α* (CV = 0.28; Table 7) is evident in the extent to which the plausible S–R relationships differ with respect to their slope at *S* = 0 (Figure 5). Similarly, uncertainty about *β* is reflected in variability in the values of *S* leading to maximum recruitment *S*MSR= 1/*β,* and uncertainty about equilibrium abundance, *SEQ,* is reflected by variability in the values of *S* where the curves intersect the replacement line. The estimated AR(1) parameter **was 0.42 (95% CI: 0.07–0.76), suggesting serial correlation in residuals.

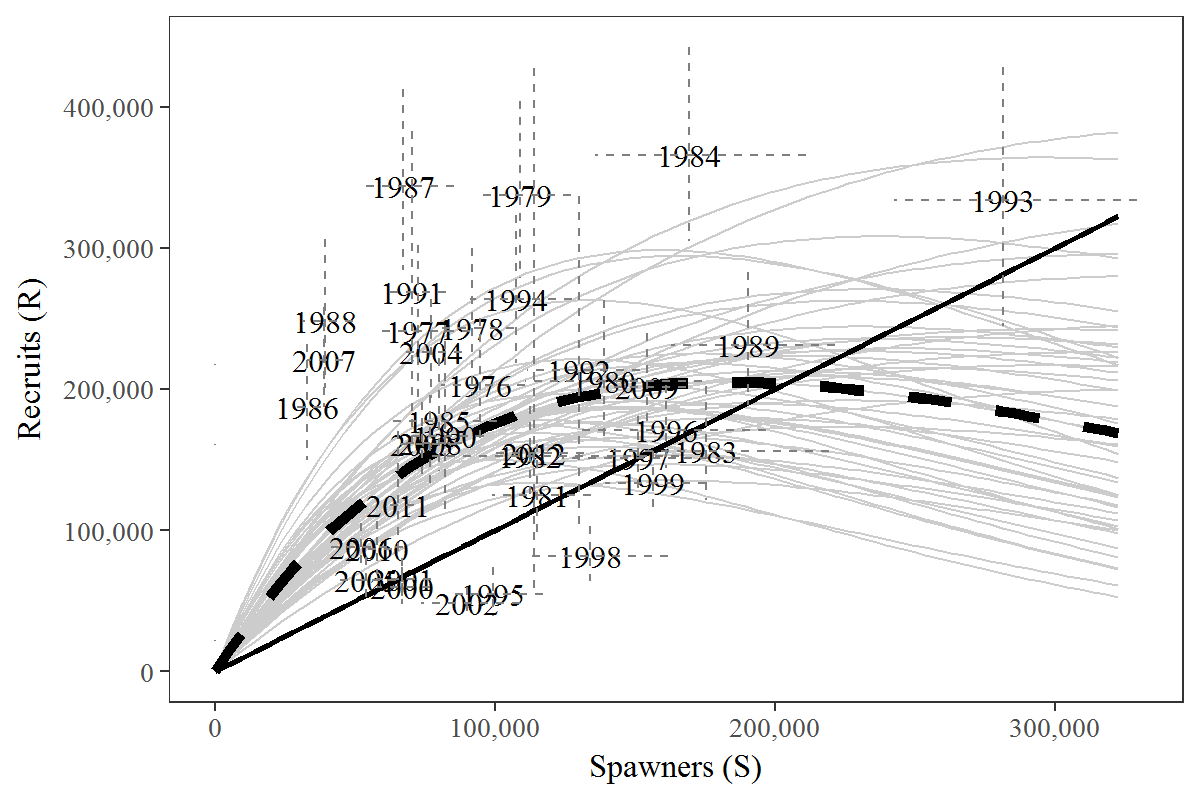


Figure .–Plausible spawner-recruit relationships for Chilkat Lake sockeye salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for calendar years 1976–2016. Posterior medians of *R* and *S* are plotted as brood year labels with 95% credibility intervals plotted as dashed lines. The heavy dashed line is the Ricker relationship constructed from ln(*α*) and *β* posterior medians. Ricker relationships are also plotted (light grey lines) for 50 paired values of ln(*α*) and *β* sampled from the posterior probability distribution, representing plausible Ricker relationships that could have generated the observed data. Recruits replace spawners on the solid diagonal line.

Posterior medians of escapement leading to maximum sustained yield, *S*MSY and *S*MSY(Peterman),were 97,275 (95% CI: 66,413–231,148) and 97,497 (95% CI: 66,447–232,408), respectively (Figure 6). Given the diversity of plausible S–R relationships (Figure 5), it is important to choose

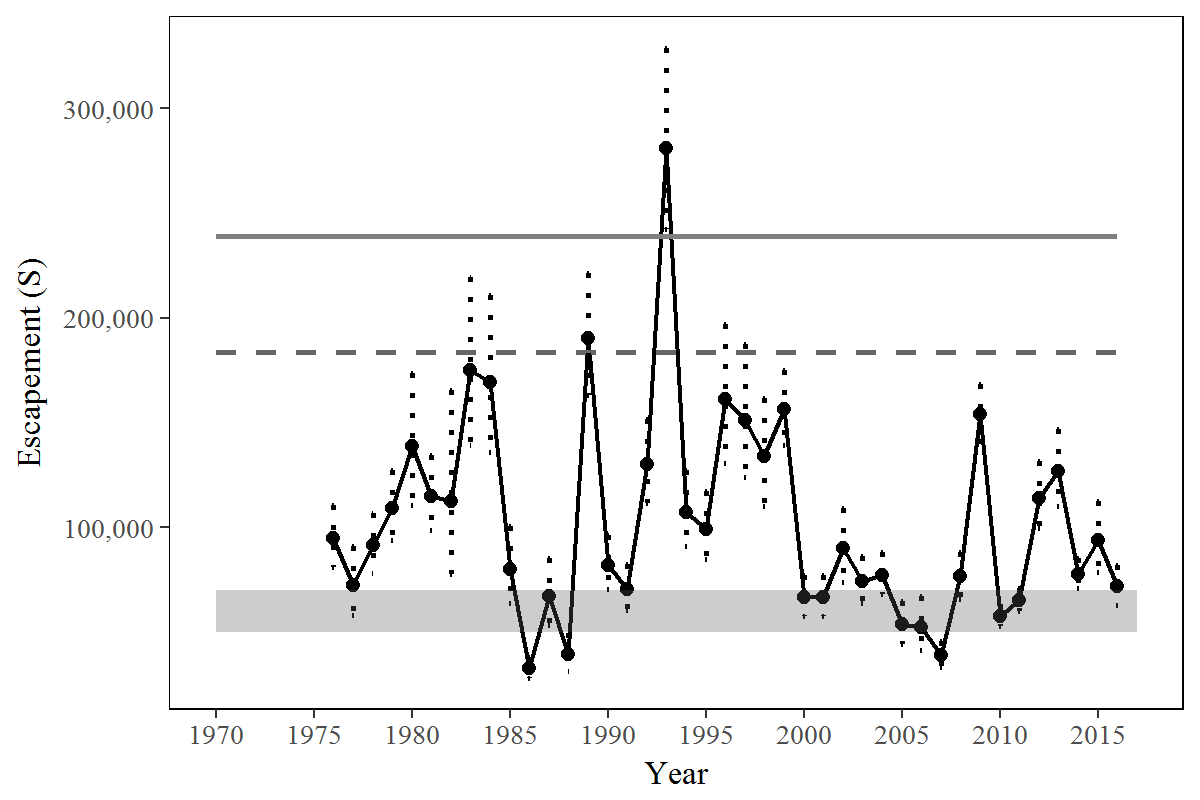


Figure 6.– Historical estimates of escapement and 95% credibility intervals (vertical dotted lines) for sockeye salmon obtained by fitting a state-space model to Chilkat Lake sockeye salmon data, 1976–2016. Shaded areas bracket the recommended goal ranges. Posterior medians of *S*MSR (dotted line), and *S*EQ (solid line) are plotted as horizontal reference lines.

an escapement goal that is robust to this uncertainty rather than one tailored solely to the median S-R relationship. To address this uncertainty, the success or failure of a given number of spawners to achieve biological reference points across plausible S-R relationships are tallied to create optimal recruitment profiles (Figure 7; top panel), optimal yield profiles (Figure 7; middle panel), and overfishing profiles (Figure 7; bottom panel). Optimal recruitment profiles are the probabilities that a given spawning escapement will produce average recruitments exceeding 80% or 90% of maximum sustained recruitment. The profiles, which are highest near *S*MSR= 183,490 (Table 7), display the probability of achieving 80% and 90% of MSRfor specified levels of escapement. Optimal yield profiles show the probability of a given number of spawners achieving 80% and 90% of MSY. These probabilities, which are highest near *S*MSY, can be used to quantify the yield performance of prospective escapement goals (Figure 7; shaded areas), taking into consideration all of the uncertainty about the true abundance and productivity of the stock. Overfishing profiles show the probability that sustained yield would be reduced to less than 80% or 90% of MSYby fishing too hard and supplying too few spawners.

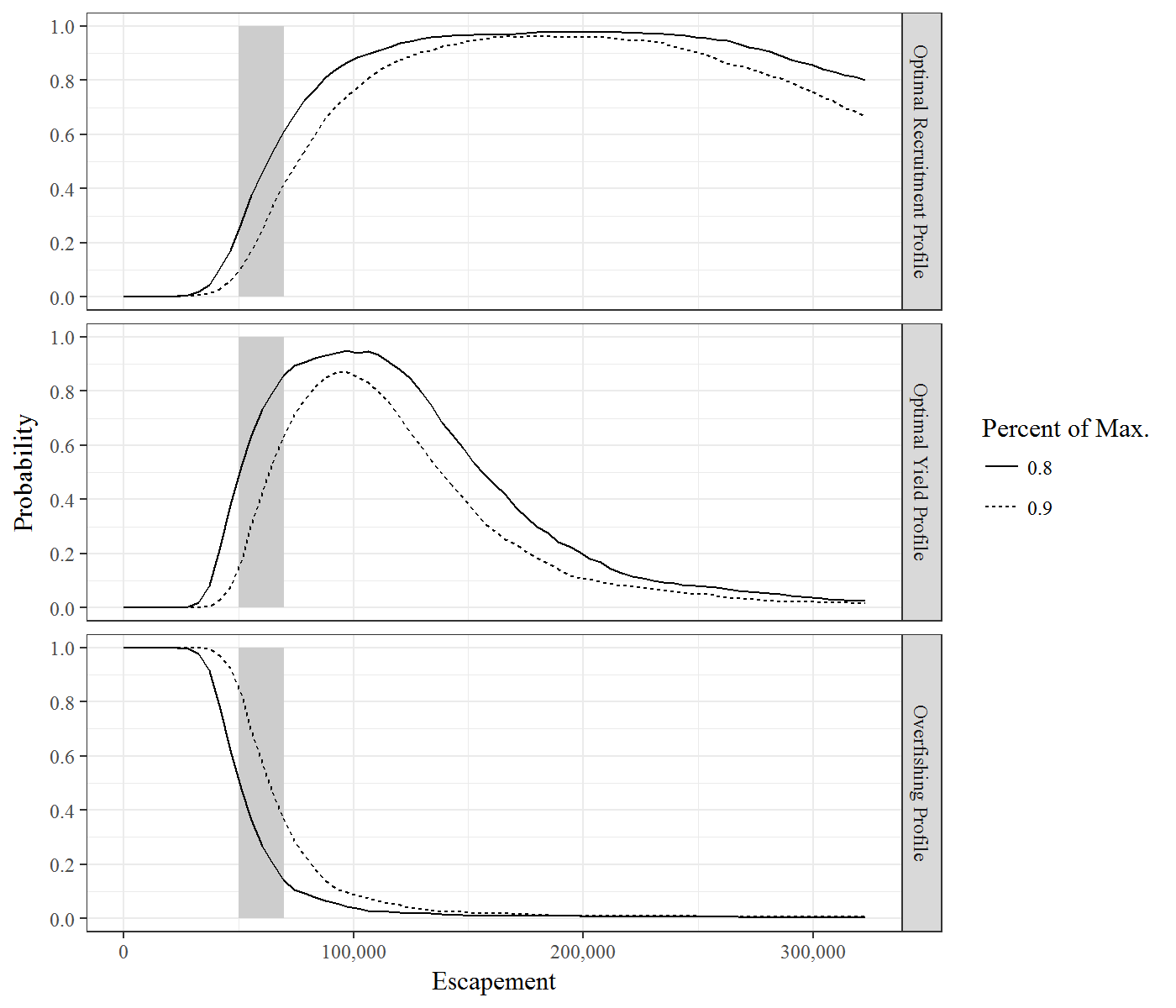


Figure .– Optimal recruitment profiles (ORPs), optimal yield profiles (OYPs), and overfishing profiles (OFPs) for Chilkat Lake sockeye salmon. OYPs and ORPs show probability that a specified spawning abundance will result in specified fractions (80% and 90% line) of maximum sustained yield or maximum recruitment. OFPs 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 recommended escapement goal range of ….

Expected sustained yield or the numbers of fish over and above those necessary to replace spawners averaged over the brood years 1970–2012 is maximized near *S*MSY (Figure 8).

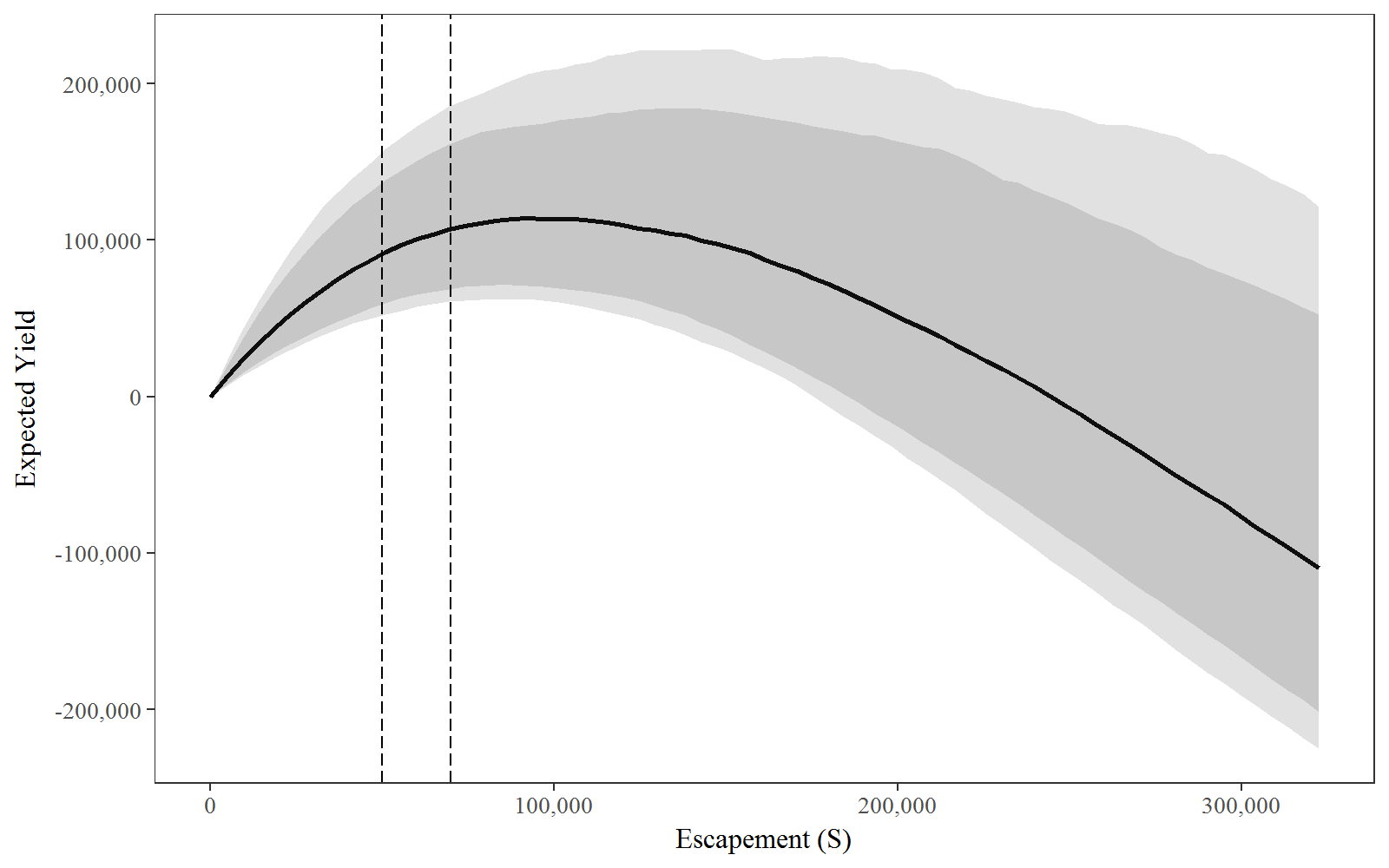


Figure .– Expected sustained yield (solid black line) and 90% and 95% credibility intervals (shaded areas) versus spawning escapement for Chilkat Lake sockeye salmon. Dotted vertical lines bracket the recommended escapement goal range of ….

# Discussion

Based on the autoregressive Ricker model with fry plants models, Eggers et al. (2010) recommended a BEG for Chilkat Lake sockeye salmon of 70,000 to 150,000 spawers per year to be assessed with the DIDSON at the Chilkat River weir site. This goal range was the escapement range that produced 90% MSY as determined by the autoregressive Ricker with fry plants model for to the 1979 to 2002 stock-recruit data with a reference point, *S*MSY of 105,000. This study was similar in methodology to Eggers et al. (2010) in that a set of hierarchical stock-recruitment models that incorporated a first order autoregressive term and fry plant term were constructed and model comparisons were accomplished through a fit criteria. While Eggers et al. (2010) utilized the traditional stock-recruit analysis, a Bayesian age-structured state-space model approach was employed in this study. 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. One advantage of the Bayesian state-space model is that missing data are no longer an issue. By correctly specifying annual age-structure in the Bayesian state-space model, missing data, like 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. Along with overcoming the issue of missing data, another advantage of the Bayesian age-structured state space model over traditional stock recruit methods is on obtaining good quality estimates of spawning abundance at maximum sustained yield(*S*MSY) in regards to bias reduction and interval coverage (Su and Peterman 2012).

Within the traditional framework, Eggers et al. (2010) was forced to rely on one escapement enumeration method per year, although overlapping escapement enumeration methods were available. Eggers et al. (2010) regressed mark-recapture estimates against weir counts for years with paired estimates, so that weir counts could be expanded to total escapement during years when mark-recapture experiments were not conducted. Thus, an uninterrupted time series of escapement was created for analysis. Within the Bayesian analysis state-space framework, we were able to incorporate multiple, overlapping methods of escapement enumeration within the models with allowances for missing data. Weir and mark-recapture data were considered independent measures of relative escapement that likely under-estimated and over-estimated escapement, respectively, while the DIDSON counts were treated as ‘true’ counts.

In addition to the limitations of missing data and multiple sources of data, traditional stock-recruit analysis does not fully consider the complexity introduced by age structure. Sockeye salmon return at multiple ages to spawn and maturity schedules can differ between cohorts. Estimates of age composition of the total run, weighted by the relative abundance of each component (harvest, escapement), are incorporated into the state-space model as data input. The model then predicts maturity-at-age and age composition of the total run.

Bayesian age-structured state-space 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)). Sockeye salmon escapement goals were assessed in a Bayesian framework for Buskin River, Kodiak Island (Schmidt and Evans 2010), Speel Lake (Heinl et al. 2014), and the transboundary Alsek River and one of its tributaries, the Klukshu River (Eggers and Bernard 2011). A sustainable escapement goal (SEG) range of 5,000-8,000 would ensure sustained yield is within 90% of *S*MSY with 90% probability for the Buskin River. Optimum yield profiles and overfishing profiles showed that a biological escapement goal (BEG) range of 24,000 to 33,500 for the Alsek River has a 90–96% chance of attaining optimum yield escapements and that a biological escapement goal range of 7,500 to 11,000 has a 79–90% chance of attaining optimum yield for the Klukshu River. An SEG of 4,000–9,000 fish for Speel Lake sockeye salmon is based on the range of escapements estimated to provide greater than 70–80% of *S*MSY.

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 maximum sustained yield (*S*MSY). Eggers (1993) suggests that an escapement goal range from 0.8 to 1.6 times the *S*MSY will enable managers more flexibility to protect weak stocks and maintain sustainable catch levels of dominant stocks to within 90% of *S*MSY. Based on Eggers (1993), the escapement goal range of Chilkat Lake sockeye salmon to the nearest 100 fish would be would be 77,800 to 155,600. Across the state, BEGs that were set based on spawner-recruit analyses had an average lower bound escapement goal range that was 0.68 times *S*MSY and an upper bound escapement foal range that was 1.40 times *S*MSY (Appendix C). Using these average ratios, the escapement goal range for Chilkat Lake sockeye salmon to the nearest 100 fish would be 66,400 to 136,600.

# Escapement Goal Recommendation

# Acknowledgments

The escapement goal review team included the authors,…. Numerous ADF&G staff collected the stock assessment data over the decades.

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# APPENDICES

Appendix .–RJAGS model code for the Bayesian MCMC statistical analysis of the Chilkat Lake sockeye salmon data run reconstruction model, 1976–2016.

library(coda)

library(emdbook)

library(MASS)

library(gtools)

library(Hmisc)

library(rbugs)

library(R2OpenBUGS)

library(rjags)

library(lattice)

library(rmarkdown)

library(boot)

library(ggplot2)

library(dplyr)

library(tidyr)

library(shinystan)

library(reshape2)

library(grid)

library(runjags)

library(matrixStats)

CREATE DATA FILE

rawdat=as.data.frame(read.csv('Chilkat\_Sockeye.csv',header=T) )

nyrs=as.numeric(length(rawdat$year))

fyr=min(rawdat$year)

lyr=max(rawdat$year)

nages=3

a.min=4

a.max=6

A=3

year=as.numeric(as.character(rawdat$year))

DS=as.numeric(as.character(rawdat$DS))

DS.cv=as.numeric(as.character(rawdat$DS.cv))

mr=as.numeric(as.character(rawdat$mr))

mr.cv=as.numeric(as.character(rawdat$mr.cv))

weir=as.numeric(as.character(rawdat$weir))

weir.cv=as.numeric(as.character(rawdat$weir.cv))

Hbelow=as.numeric(as.character(rawdat$Hbelow))

Hbelow.cv=as.numeric(as.character(rawdat$Hbelow.cv))

x=as.matrix(rawdat[,substr(colnames(rawdat), 1,1)=="x"])

colnames(x)=NULL

n.a=rowSums(x)#effective sample size

--STATE SPACE MODEL--

RICKER STOCK-RECRUIT RELATIONSHIP WITH AR1 ERRORS;

R[y] IS THE TOTAL RETURN FROM BROOD YEAR y

Y=41; A=3; a.min=4; a.max=6;

THERE ARE A TOTAL OF Y+A-1 = 41 + 3 - 1 = 43 BROOD YRS REPRESENTED IN DATA (INCL FORECAST)

mod=function(){

for (y in (A+a.min):(Y+A-1)) {

log.R[y] ~ dnorm(log.R.mean2[y],tau.R)

R[y] <- exp(log.R[y])

log.R.mean1[y] <- log(S[y-a.max]) + lnalpha - beta \* S[y-a.max]

log.resid[y] <- log(R[y])-log.R.mean1[y]

}

log.R.mean2[A+a.min] <- log.R.mean1[A+a.min] + phi \* log.resid.0

for (y in (A+a.min+1):(Y+A-1)) {

log.R.mean2[y] <- log.R.mean1[y] + phi \* log.resid[y-1]

}

PRIORS

lnalpha ~ dnorm(0,1.0E-6)%\_%T(0,3)

beta ~ dnorm(0,1.0E-6)%\_%T(0,) 0

phi ~ dnorm(0,1.0E-6)%\_%T(-0.98,0.98)

mean.log.RO ~ dnorm(0,1.0E-6)

tau.RO ~ dgamma(0.001,0.001)

log.resid.0 ~ dnorm(0,tau.red)

tau.R ~ dgamma(0.001,0.001)

sigma.R <- 1 / sqrt(tau.R)

alpha <- exp(lnalpha)

sigma.RO <- 1 / sqrt(tau.RO

tau.red <- tau.R \* (1-phi\*phi)

lnalpha.c <- lnalpha + (sigma.R \* sigma.R / 2 / (1-phi\*phi) )

THE FIRST SEVERAL COHORTS ORIGINATE FROM UNMONITORED SPAWNING EVENTS

DRAW THESE RETURNS FROM A COMMON LOGNORMAL DISTRIBUTION

R.O<-exp(mean.log.RO)

for (y in 1:a.max) {

log.R[y] ~ dnorm(mean.log.RO,tau.RO)

R[y] <- exp(log.R[y])

}

REFERENCE POINTS (WITH CORRECTION FOR LOGNORMAL SKEWNESS)

S.max <- 1 / beta

alpha.c <- min(exp(lnalpha.c),1.0E4)

S.eq.c <- lnalpha.c \* S.max

U.msy.c <- lnalpha.c \* (0.5-0.07\*lnalpha.c)

S.msy.c <- S.eq.c\*(0.5-0.07\*lnalpha.c)

positive.lna.c <- step(lnalpha.c)

lnalpha.c.nonneg <- lnalpha.c \* positive.lna.c

S.eq.c2 <- lnalpha.c.nonneg \* S.max

peterman.approx.c <- (0.5 - 0.65\*pow(lnalpha.c.nonneg,1.27) / (8.7 +pow(lnalpha.c.nonneg,1.27)))

U.msy.c2 <- lnalpha.c.nonneg \* peterman.approx.c

S.msy.c2 <- U.msy.c2 / beta

U.max.c2 <- 1 - 1 / exp(lnalpha.c.nonneg)

GENERATE Y+A-1 = 43 MATURITY SCHEDULES, ONE PER BROOD YEAR USING THE DIRICHLET DISTRIBUTION; "pi" (central tendency of "p"), and "D.scale" (dispersion of "p")

D.scale ~ dunif(0,1)#uninformative

D.sum <- 1 / (D.scale \* D.scale)

pi.2p ~ dbeta(1,1)#uninformative

pi.1 ~ dbeta(1,1)#uninformative; Eq.6

pi[1] <- pi.1

pi[2] <- pi.2p \* (1 - pi[1])

pi[3] <- 1 - pi[1] - pi[2]

for (a in 1:A) {

gamma[a] <- D.sum \* pi[a]

for (y in 1:(Y+A-1)) {

g[y,a] ~ dgamma(gamma[a],0.001)

p[y,a] <- g[y,a]/sum(g[y,])

}

}

CALCULATE THE NUMBERS AT AGE MATRIX (Number returning to spawn at age in year y);

Product of the total return from brood year y-a and the prop. mature from cohort y-a returning at age a

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 SCALE SAMPLING ON TOTAL ANNUAL RETURN N;

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]

}

}

for (t in 1:Y){

x[t,] ~ dmulti(q[t,],n.a[t])

}

HARVESTS BELOW THE WEIR (No harvest above weir);

for (y in 1:Y) {

mu.Hbelow[y] ~ dbeta(1,1)

H.below[y] <- mu.Hbelow[y] \* N[y]

log.Hb[y] <- log(H.below[y])

tau.log.Hb[y] <- 1 / log(Hbelow.cv[y]\*Hbelow.cv[y] + 1)

Hbelow[y] ~ dlnorm(log.Hb[y],tau.log.Hb[y])

S[y] <- max(N[y] - H.below[y], 1)#Eq.8;number of fish reaching weir = total run abundance minus harvest

log.S[y] <- log(S[y])

}

log.q.weir ~ dnorm(0,1.0E-4)

log.q.mr ~ dnorm(0,1.0E-4)

for (y in 1:Y) {

tau.log.weir[y] <- 1 / log(weir.cv[y]\*weir.cv[y] + 1)

tau.log.mr[y]<- 1 / log(mr.cv[y]\*mr.cv[y] + 1)

log.qS.weir[y] <- log.q.weir+log.S[y]

log.qS.mr[y] <- log.q.mr+log.S[y]

weir[y]~ dlnorm(log.qS.weir[y],tau.log.weir[y])

mr[y]~ dlnorm(log.qS.mr[y],tau.log.mr[y])

tau.log.DS[y] <- 1 / log(DS.cv[y]\*DS.cv[y] + 1)

DS[y] ~ dlnorm(log.S[y],tau.log.DS[y])

}

q.mr<-exp(log.q.mr)

q.weir<-exp(log.q.weir)

}

***Note*: Not all notations corresponds directly to text of report.**

Appendix .–RJAGS data objects for the Bayesian MCMC statistical analysis of the Chilkat Lake sockeye salmon data run reconstruction model, 1976–2016. 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, ‘DS’ are the DIDSON escapement counts with associated coefficient of variations (DS.cv), ‘weir’ are the weir escapement counts with associated coefficient of variations (weir.cv), ‘mr’ are the mark–recapture escapement counts with the associated coefficient of variations (mr.cv), and ‘Hbelow’ is the total harvest with associated coefficient of variations (Hbelow.cv).

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Year | DS | DS.cv | mr | mr.cv | weir | weir.cv | Hbelow | Hbelow.cv | x4 | x5 | x6 |
| 1976 | NA | 0.90 | NA | 0.90 | 69,729 | 0.05 | 58,765 | 0.20 | 5 | 67 | 27 |
| 1977 | NA | 0.90 | NA | 0.90 | 50,363 | 0.10 | 41,477 | 0.20 | 3 | 75 | 22 |
| 1978 | NA | 0.90 | NA | 0.90 | 67,528 | 0.05 | 89,558 | 0.20 | 6 | 64 | 30 |
| 1979 | NA | 0.90 | NA | 0.90 | 80,588 | 0.05 | 115,995 | 0.20 | 2 | 78 | 20 |
| 1980 | NA | 0.90 | NA | 0.90 | 101,135 | 0.10 | 31,267 | 0.20 | 2 | 62 | 36 |
| 1981 | NA | 0.90 | NA | 0.90 | 84,097 | 0.05 | 48,420 | 0.20 | 1 | 55 | 44 |
| 1982 | NA | 0.90 | NA | 0.90 | 86,213 | 0.20 | 127,174 | 0.20 | 3 | 50 | 47 |
| 1983 | NA | 0.90 | NA | 0.90 | 134,601 | 0.10 | 124,180 | 0.20 | 5 | 55 | 40 |
| 1984 | NA | 0.90 | NA | 0.90 | 123,190 | 0.10 | 99,592 | 0.20 | 2 | 73 | 25 |
| 1985 | NA | 0.90 | NA | 0.90 | 58,335 | 0.10 | 131,091 | 0.20 | 2 | 38 | 60 |
| 1986 | NA | 0.90 | NA | 0.90 | 23,947 | 0.05 | 168,006 | 0.20 | 2 | 36 | 62 |
| 1987 | NA | 0.90 | NA | 0.90 | 48,972 | 0.10 | 69,900 | 0.20 | 3 | 60 | 37 |
| 1988 | NA | 0.90 | NA | 0.90 | 27,722 | 0.10 | 76,883 | 0.20 | 2 | 44 | 54 |
| 1989 | NA | 0.90 | NA | 0.90 | 141,475 | 0.05 | 156,160 | 0.20 | 1 | 70 | 30 |
| 1990 | NA | 0.90 | NA | 0.90 | 60,230 | 0.05 | 149,377 | 0.20 | 1 | 44 | 55 |
| 1991 | NA | 0.90 | NA | 0.90 | 51,138 | 0.05 | 60,721 | 0.20 | 2 | 46 | 52 |
| 1992 | NA | 0.90 | NA | 0.90 | 95,880 | 0.05 | 113,146 | 0.20 | 1 | 44 | 55 |
| 1993 | NA | 0.90 | NA | 0.90 | 212,757 | 0.05 | 103,531 | 0.20 | 3 | 38 | 59 |
| 1994 | NA | 0.90 | 153,540 | 0.1 | 86,385 | 0.10 | 126,852 | 0.20 | 2 | 57 | 41 |
| 1995 | NA | 0.90 | 184,541 | 0.1 | 61,783 | 0.10 | 68,737 | 0.20 | 4 | 46 | 50 |
| 1996 | NA | 0.90 | 262,852 | 0.1 | NA | 0.05 | 99,677 | 0.20 | 0 | 0 | 0 |
| 1997 | NA | 0.90 | 238,803 | 0.1 | NA | 0.05 | 73,761 | 0.20 | 0 | 0 | 0 |
| 1998 | NA | 0.90 | 211,114 | 0.09 | NA | 0.05 | 112,630 | 0.20 | 0 | 0 | 0 |
| 1999 | NA | 0.90 | 240,002 | 0.05 | 134,048 | 0.10 | 149,410 | 0.20 | 1 | 43 | 55 |
| 2000 | NA | 0.90 | 132,687 | 0.12 | 47,077 | 0.05 | 78,265 | 0.20 | 2 | 13 | 85 |
| 2001 | NA | 0.90 | 105,064 | 0.07 | 53,239 | 0.20 | 60,183 | 0.20 | 3 | 78 | 20 |
| 2002 | NA | 0.90 | 148,465 | 0.17 | 65,611 | 0.10 | 47,332 | 0.20 | 3 | 45 | 52 |
| 2003 | NA | 0.90 | 116,891 | 0.07 | 55,516 | 0.20 | 49,955 | 0.20 | 2 | 29 | 68 |
| 2004 | NA | 0.90 | 118,795 | 0.06 | 83,534 | 0.20 | 51,110 | 0.20 | 5 | 67 | 29 |
| 2005 | NA | 0.90 | 89,072 | 0.10 | 32,098 | 0.20 | 22,852 | 0.20 | 3 | 37 | 59 |
| 2006 | NA | 0.90 | 91,439 | 0.17 | 38,850 | 0.20 | 15,979 | 0.20 | 6 | 59 | 35 |
| 2007 | NA | 0.90 | 59,884 | 0.10 | 27,915 | 0.10 | 14,208 | 0.20 | 5 | 53 | 41 |
| 2008 | 74,919 | 0.10 | 119,808 | 0.11 | NA | 0.05 | 22,156 | 0.20 | 5 | 82 | 13 |
| 2009 | 153,033 | 0.05 | 285,218 | 0.13 | NA | 0.05 | 85,551 | 0.20 | 2 | 64 | 34 |
| 2010 | 61,906 | 0.05 | 72,318 | 0.09 | NA | 0.05 | 48,079 | 0.20 | 3 | 32 | 66 |
| 2011 | 63,628 | 0.05 | 109,335 | 0.08 | NA | 0.05 | 15,599 | 0.20 | 8 | 61 | 30 |
| 2012 | 121,810 | 0.10 | 171,924 | 0.10 | NA | 0.05 | 54,884 | 0.20 | 6 | 75 | 19 |
| 2013 | 116,300 | 0.10 | 224,516 | 0.10 | NA | 0.05 | 75,588 | 0.20 | 6 | 50 | 44 |
| 2014 | 70,470 | 0.05 | 212,201 | 0.12 | NA | 0.05 | 81,502 | 0.20 | 4 | 67 | 29 |
| 2015 | 175,874 | 0.20 | 124,892 | 0.10 | NA | 0.05 | 33,085 | 0.20 | 4 | 30 | 66 |
| 2016 | 88,513 | 0.10 | 96,148 | 0.09 | NA | 0.05 | 35,991 | 0.20 | 4 | 58 | 37 |

Appendix .– Escapement goals for the Southeast Region, Central Region (Upper Cook Inlet Prince William Sound), Arctic-Yukon-Kuskokwim (AYK) Region, Westward Region (Alaska Peninsula/Aleutian Islands, Kodiak). This table is modified from Munro and Volk 2016. The lower bound (LB) and upper bound (UB) percentages show the change from the LB and UB to the *S*MSY value.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Area | System | *S*MSY | LB | UB | Type | Initial Year | LB% | UB% | Sources |
| Southeast | Tahltan Lake | 24,000 | 18,000 | 30,000 | BEG | 1993 | 75% | 125% | Humphreys et al. 1994; TTC 1993 |
| Southeast | Redoubt Lake | 17,400 | 10,000 | 25,000 | BEG | 2003 | 57% | 144% | Geiger 2003 |
| Southeast | Chilkat Lake | 105,000 | 70,000 | 150,000 | BEG | 2009 | 67% | 143% | Eggers et al. 2010 |
| Southeast | East Alsek-Doame River | 16,000 | 13,000 | 26,000 | BEG | 2003 | 81% | 163% | Clark et al. 2003 |
| Southeast | Klukshu River | 9,102 | 7,500 | 11,000 | BEG | 2013 | 82% | 121% | Eggers and Bernard 2011 |
| Southeast | Alsek River | 28,190 | 24,000 | 33,500 | BEG | 2013 | 85% | 119% | Eggers and Bernard 2011 |
| Southeast | Situk River | 50,000 | 30,000 | 70,000 | BEG | 2003 | 60% | 140% | Clark et al. 2002 |
| Upper Cook Inlet | Kasilof River | 240,000 | 160,000 | 340,000 | BEG | 2011 | 67% | 142% | Fair et al. 2010 |
| Upper Cook Inlet | Russian River - Early Run | 36,255 | 22,000 | 42,000 | BEG | 2011 | 61% | 116% | Fair et al. 2010 |
| Prince William Sound | Eshamy Lake | 19,622 | 13,000 | 28,000 | BEG | 2009 | 66% | 143% | Fair et al. 2008 |
| Kuskokwim Area | Middle Fork Goodnews River | 21,890 | 18,000 | 40,000 | BEG | 2007 | 82% | 183% | Brannian et al. 2006; Molyneaux and Brannian 2006 |
| AK Peninsula | Nelson River | 153,000 | 97,000 | 219,000 | BEG | 2004 | 63% | 143% | Nelson et al. 2006 |
| Kodiak | Afognak (Litnik) River | 34000 | 20,000 | 50,000 | BEG | 2005 | 59% | 147% | Nelson et al. 2005 |
| Kodiak | Karluk River Early Run | 175,000 | 110,000 | 250,000 | BEG | 2008 | 63% | 143% | Honnold et al. 2007a |
| Kodiak | Karluk River Late Run | 266,000 | 170,000 | 380,000 | BEG | 2005 | 64% | 143% | Nelson et al. 2005 |
| Kodiak | Upper Station River Early Run | 66,000 | 43,000 | 93,000 | BEG | 2011 | 65% | 141% | Nemeth et al. 2010 |
| Kodiak | Upper Station River Late Run | 186,000 | 120,000 | 265,000 | BEG | 2005 | 65% | 142% | Nelson et al. 2005 |
| Kodiak | Frazer Lake | 118,000 | 75,000 | 170,000 | BEG | 2008 | 64% | 144% | Honnold et al. 2007a |
| Kodiak | Saltery Lake | 23,600 | 15,000 | 35,000 | BEG | 2011 | 64% | 148% | Nemeth et al. 2010 |
| Kodiak | Buskin Lake | 6,650 | 5,000 | 8,000 | BEG | 2011 | 75% | 120% | Nemeth et al. 2010 |
| Average |  |  |  |  |  |  | 68% | 140% |  |