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# Chilkat Lake Sockeye Salmon Escapement Goal Review

**by**

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**and**

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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, $\chi^2$, 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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# CHILKAT LAKE SOCKEYE SALMON ESCAPEMENT GOAL REVIEW


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# ABSTRACT

We reviewed the escapement goal for the Chilkat Lake sockeye salmon (*Oncorhynchus nerka*) run, which is intensely harvested in the District 15 commercial drift gillnet fishery in Lynn Canal, Southeast Alaska. The current biological escapement goal of 70,000 to 150,000 sockeye salmon was established in 2009, based on a spawner-recruit analysis with weir counts converted to mark–recapture units. We fit age-structured state-space spawner-recruit models to updated 1976–2016 data on abundance, harvest, age composition, and coefficients of variation to examine the effect of autocorrelation and fry plants on recruits and to recommend a new biological escapement goal in Dual-frequency Identification Sonar (DIDSON) units. Historical mark–recapture and weir counts were considered indices of escapement, while the DIDSON counts (2008–2016) were considered 'true' counts of escapement. Fishery management reference points as well as optimal yield, optimal recruitment, and overfishing profiles were estimated from the final state-space Ricker model. Estimates derived from the state-space Ricker model suggest that the probability of achieving yields greater than 90% of maximum sustained yield from escapements at the current upper and lower bounds is 62% and 34%, respectively, and an average 65% over the entire escapement goal range. Therefore, we recommend maintaining the current biological escapement goal of 70,000 to 150,000 sockeye salmon counted at the Chilkat Lake weir site with the DIDSON sonar.

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, DIDSON

# INTRODUCTION

The Chilkoot and Chilkat sockeye salmon (*Oncorhynchus nerka*) runs in northern Southeast Alaska, near the town of Haines, are two of the largest 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 be Chilkat and Chilkoot sockeye salmon (Rich and Ball 1933). Historically, Chilkat 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 after Alaska statehood in 1959 and Lynn Canal was developed into a designated drift gillnet fishing area (District 15), where most of the commercial harvest of Chilkat sockeye salmon takes place (Figure 1). The annual harvest of sockeye salmon in the District 15 commercial drift gillnet fishery averaged 191,500 fish from 1984 to 2015, of which an average 78,000 fish originated from Chilkat Lake, 92,000 fish originated from Chilkoot Lake, and the remainder were of mixed stock origin (Bednarski et al. 2016). A smaller portion of the Chilkat 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 sockeye salmon are also harvested annually in subsistence fisheries in Chilkat Inlet and the Chilkat River, and reported harvest for the period 1985–2015 averaged approximately 4,300 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 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). The term “mainstem” includes all sockeye salmon populations spawning in the Chilkat River and its tributaries; i.e., all non-Chilkat Lake fish. 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 Dual-frequency Identification Sonar (DIDSON) counts with mark–recapture estimates (2008–2016) (Eggers et al. 2010; Sogge and Bachman 2014; Bednarski et al. 2017). 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 (Kelley and Bachman 2000; Eggers et al. 2010). 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 and tributary spawning locations; drainagewide mark–recapture estimates were then generated and divided into Chilkat Lake and Chilkat River 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 Chilkat River mainstem spawning populations (Sogge and Bachman 2014). Biological data have been collected annually at Chilkat Lake and at Chilkat River 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 spawner-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. (2005) 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, and then fit a hierarchal set of spawner-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% of maximum sustained yield as determined by an autoregressive Ricker (density dependence with first order autoregressive term) model with fry plants. That model was selected over others 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 and update the current escapement goal for Chilkat Lake sockeye salmon. Eggers et al. (2010) recommended escapements be assessed with the DIDSON in lieu of mark–recapture starting in 2008. Most of the problems associated with visual weir counts were thought to have been overcome after the DIDSON project was established, yet mark–recapture estimates of Chilkat Lake sockeye salmon still averaged 1.6 times greater than the DIDSON counts in the same year (range: 0.7–3.0), and the mark–recapture program was discontinued following the 2016 season because of the uncertainty regarding accuracy of estimates (Bednarski et al. 2017). Bednarski et al. (2017) recommended the escapement goal be reviewed to ensure that the goal, which was developed using mark–recapture estimates (Eggers et al. 2010), is in the same units as escapement counts, which will continue to be measured with the DIDSON. In addition to the accumulation of more brood year returns since the escapement goal was last reviewed, all historical 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). We fit age-structured state-space spawner-recruit models to 1976–2016 data on abundance, harvest, age composition, and coefficients of variation to examine the effect of autocorrelation and fry plants on recruits and to recommend 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 44 river km upstream from the city of Haines, Alaska (Figures 1 and 2). It is a relatively large clear lake with a surface area of $9.8 \times 10^6$ $m^2$ (2,432 acres), a mean depth of 33 m, a maximum depth of 57 m, and a volume of $319 \times 10^6$ $m^3$. 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). Very small numbers of adult pink and chum (*O. keta*) salmon have been observed moving through the Chilkat Lake weir, but the spawning location of these fish is not known. Moderate to heavy boat traffic occurs on Clear Creek due primarily to people accessing the numerous (50–100) private cabins on Chilkat Lake, which can only be reached by jet boat and floatplane.

The Chilkat River (ADF&G Anadromous Waters Catalogue No. 115-32-10250) 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, and braided rivers that flow through glaciated valleys. The watershed encompasses approximately 1,600 $km^2$, and the main river and tributaries account for approximately 350 km of river channels. Principle tributaries include the Tahkin, Tsirku, Klehini, Kelsall, and Tahini rivers. The Chilkat River discharge rates range from 2.3 to 578 $m^3/s$ (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.

# METHODS

We analyzed Chilkat Lake sockeye salmon spawner-recruit data using a Bayesian age-structured state-space model. State-space models (Harvey 1989) are time series models that feature both observed variables and unobserved states. Use of a Bayesian age-structured state-space model allowed for consideration of 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. By correctly specifying annual age-structure in the Bayesian state-space model, missing data, common to salmon stock assessment data sets, can be represented as unknown quantities for which posterior samples are generated. Additional uncertainty then flows through to the remaining model parameters as appropriate (Fleischman et al. 2013). This provides a powerful advantage over traditional spawner-recruit analysis, in which independence of individual quantities of spawners (*S*) and recruits (*R*) is assumed and missing data must be imputed before the model is run. Compared to traditional spawner-recruit methods, another advantage of the Bayesian age-structured state space model is that they enable high quality estimates of spawning abundance at maximum sustained yield in the presence of observation error in *S*, and point estimates obtained from posterior medians are less biased (Su and Peterman 2012). As a result, Bayesian age-structured state-space models have been used with increasing frequency in place of traditional methods in spawner-recruit analysis of Pacific salmon in Alaska (Bernard and Jones 2010; Schmidt and Evans 2010; Eggers and Bernard 2011; Fleischman et al. 2011; Hamazaki et al. 2012; Fleischman and McKinley 2013; Heinl et al. 2014; Moffitt et al. 2014; Hamazaki and Conitz 2015; Fleischman and Reimer 2017).

## DATA

Data for the state-space model included: 1) harvest estimates and associated coefficients of variation (CVs) of harvest; 2) escapement counts and escapement indices with associated CVs; 3) weighted age composition of the total run (harvest and escapement data combined), and 4) fry plants. Sources of these data components are described in the following sections.

### Harvest Estimates

Information regarding harvest is limited to estimates from the District 15 (Lynn Canal) commercial drift gillnet fishery (Figure 1), which accounts for the majority of the harvest of Chilkat Lake sockeye salmon. Stock composition was estimated through a visual scale pattern analysis program that began in the early 1980s. McPherson and Olson (1992) described the methods used, which remained basically the same after the mid-1980s: escapement scale samples from three sockeye salmon stocks of known origin, Chilkoot Lake, Chilkat Lake, and “other” (which encompasses many stocks including Chilkat River mainstem and Berners Bay stocks), were aged and processed inseason on a weekly basis, after which scale samples from the commercial fishery were analyzed and assigned to one of the three stocks based on scale characteristics. The weekly proportions of classified scale samples were then 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 and age, weighted by week.

Stock composition estimates by age were available in the ADF&G Southeast Alaska Integrated Fisheries Database for the years 1984–2016 (Bednarski et al. 2017), but not for the years 1976–1983. To determine harvest age compositions for years 1976 through 1983, the age composition of sockeye salmon in the Chilkat Lake total run, harvest rates by age class, and percent of total harvest of Chilkat Lake fish in the District 15 commercial drift gillnet fishery were obtained from Tables 1.3 and 1.4 in McPherson (1990, pages 14–15) and then extrapolated to harvest age composition by year (Appendix A1 through A5; Bednarski et al. 2017). First, harvest numbers by age class were calculated as Chilkat Lake total run numbers by age class and year, multiplied by harvest rates by age class and year. Then, age composition proportions for harvest by year and age class were simply the harvest numbers by age class and year divided by the total harvest for each year. The proportions for each year across all age classes summed to one. Finally, the annual percent of total harvest of Chilkat Lake fish in the District 15 commercial drift gillnet fishery was multiplied by the age composition proportions for harvest by year and age class to calculate the reproportioned harvest by age class (Appendix A1 through A5; Table 1).

Unknown numbers of Chilkat Lake sockeye salmon are also harvested annually in the terminal subsistence fishery in Chilkat Inlet and the Chilkat River and in the non-terminal commercial purse seine fisheries in Icy and northern Chatham straits (Districts 14 and 12; Appendix A6). However, stock composition estimates of those harvests by age were not available (subsistence) or were limited to only a few years (purse seine) and, therefore, were not included in the state-space model (see *Discussion*).

## 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) (Table 2; Eggers et al. 2010; Sogge and Bachman 2014; Bednarski et al. 2017). Detailed age, sex, and length data were available in the ADF&G Southeast Alaska Integrated Fisheries Database for 1982–2016 escapements. Age composition of escapements during years of weir and DIDSON operations (1982–1995, 1999–2016) was determined from the seasonal age distribution, weighted by weekly escapement counts, which were then applied to expanded total escapement counts (see *Weir and DIDSON Counts* below) (Table 2; Bednarski et al. 2017). To estimate age compositions for years 1976 through 1981, the age composition of sockeye salmon in the Chilkat Lake total run and harvest rates by age class were obtained from Table 1.4 in McPherson (1990, page 15) and then extrapolated to escapement age composition by year. First, harvest numbers by age class were calculated as total run numbers by age class and year multiplied by harvest rate by age class and year. Then, escapement numbers by age class and year were calculated as total run numbers by age class and year minus the harvest numbers by age class and year. Finally, age composition proportions for escapement by year and age class were simply the escapement numbers by age class and year divided by the total escapement for each year (Appendix A7; Table 3).

The weir was not operated in years 1996 through 1998, and scale samples for age composition in those years were collected using beach seines at holding and spawning areas in the lake. These samples could not be weighted by weekly escapement counts at the weir and were likely biased towards early run fish as recovery crews had to cease sampling in early November due to icing on the lake that restricted access to spawning areas (Kelley and Bachman 2000). The Chilkat Lake sockeye salmon run exhibits differential migration timing by freshwater age (McPherson 1990). Freshwater-age-1 fish run earlier and represent a smaller component of the overall escapement (average = 33%) compared to freshwater-age-2 fish, which run later and account for the majority of the escapement (average = 66%) (Bednarski et al. 2017). Therefore, escapement age composition in years 1996–1998 were considered unknown.

### *Weir and DIDSON Counts*

Chilkat Lake sockeye salmon were counted through a weir (1976–1995, 1999–2007) installed on the outlet stream, Clear Creek, approximately 0.4 km downstream of Chilkat Lake as described by Bednarski et al. (2017). Weir counts provided minimum estimates of escapement due to several factors unique to the Chilkat Lake weir. A 3.6 m wide boat gate in the center of the weir was lowered and raised an average 15 times per day and more than 2,000 times per season to allow boat traffic in and out of the lake. It was assumed that fish did not move through the weir in the short time the gate was down; however, water depth at the boat gate made it difficult or impossible to determine with certainty that fish did not pass uncounted. Periodic flow reversals caused by flooding of the silty Tsirku River upstream into Chilkat Lake required opening the boat gate to prevent damage to the weir, sometimes for extended periods. It was assumed that fish did not enter the lake during flow reversals (Bergander et al. 1988); however, radio-telemetry studies (2003–2004) and operation of the DIDSON system (beginning in 2008) showed that fish movement did not always cease completely during flow reversals (Bednarski et al. 2017). Fish movement slowed, and occasionally fish were recorded backing out of the lake, but fish often continued to enter the lake at a reduced rate during flow reversals. Finally, weir operations were also interrupted when the water was too murky to see fish due to windy conditions on the lake. As a result, fish were sometimes held behind the weir for long periods, which increased the chance that fish could exploit weaknesses in the weir.

Starting in 2008, a DIDSON system was used to enumerate fish as they passed through the boat gate opening in the weir as described by Bednarski et al. (2017). Fish could be counted during flow reversals and other adverse conditions that otherwise prevented visual counts. DIDSON counts should still be considered minimum estimates of escapement due to some operational considerations. For example, from 2008 to 2015, the DIDSON was not operated at night when the boat gate was open during flow reversals, which would potentially have allowed small numbers of fish to enter the lake uncounted. (Methods were changed in 2016 to ensure the DIDSON was operated 24 hours per day during flow reversals.) Undercounting occurred to a far lesser degree after the DIDSON system was installed, however, and confidence in the DIDSON counts is much greater than in the visual weir counts (Bednarski et al. 2017).

In some years, weir and DIDSON operations did not encompass the entire sockeye salmon run, because the project was started later and/or ended earlier than average due to budget constraints, flooding, or other problems. Linear regression methods were used to expand counts in years with shortened seasons to standardize counts and make them as comparable as possible across all years (Bednarski et al. 2017; Table 2). Based on choosing the standardized range of weir operations as 16 June–15 October, the weir was installed late (between 18 June and 13 July) in years 1982, 1983, 1985, 1987, 1988, 1999, and 2001–2007, and the weir was removed early (between 28 September and 14 October) in years 1972, 1974, 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 1972, 1974, 1977, 1980, 1982–1985, 1987, 1988, 1994, 1995, 1999, and 2001–2007. DIDSON counts were also expanded to account for late installation or early removal. Based on choosing the standardized range of DIDSON operations as 20 June–10 October, the DIDSON was installed late in years 2008, 2015, and 2016 (27 June in 2008, 26 June in 2015, 24 June in 2016) and removed early (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.

### *Mark–Recapture Estimates*

Sockeye salmon mark–recapture studies were conducted annually from 1994 to 2016. Fish were marked at the Chilkat River fish wheels with a primary mark (adipose clip) to identify it as a marked fish, and marking was 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 multiplying the drainagewide estimate by the annual ratio of the two stocks at the fish wheels (weighted by fish wheel catch by week), 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 and 2010).

As part of their review of historical Chilkat sockeye salmon project data, Bednarski et al. (2017) edited and reanalyzed all available mark–recapture data from 1999 to 2016. Mark–recapture estimates from 1994 to 1998 were provided by Bachman (2010). Mark–recapture estimates averaged 2.2 times expanded weir counts and 1.6 times the expanded DIDSON counts. Although the assumptions particular to the Chilkat mark–recapture studies have been thoroughly discussed in previous reports and were assumed to have been met (Kelly and Bachman 2000; Bachman and McGregor 2001; Bachman 2005 and 2010), the degree to which they were met is uncertain (Bednarski et al. 2017). Serious, hard-to-detect bias may result when conditions of mark–recapture studies are violated (Arnason et al. 1996); the loss of marked fish due to mortality, change in behavior, or non-recognition of marks, and variation in capture and recapture probabilities could result in bias, which tends to produce inflated estimates (Simpson 1984).

## Fry Plants

Limnology work conducted at Chilkat Lake in the 1980s suggested sockeye salmon production was spawning-area limited and that Chilkat Lake had the capacity to rear 10–12 million sockeye salmon fry beyond what was produced naturally (Barto 1996; Eggers et al. 2010). An enhancement program was initiated, which included harvesting eggs and milt from sockeye salmon spawning at the lake, thermal marking and rearing the eggs in a hatchery, then stocking fry in the lake in the summer after hatching. In addition, incubation boxes located along Chilkat Lake were seeded with sockeye salmon eggs that would emerge the following spring. On average, 3.0 million fry were released annually into the lake from 1994 to 1997 and in 2001; and an average of 0.3 million fry were produced annually from incubation boxes from 1989 to 1998 and in 2003 (Table 4). Smolt and limnology sampling programs were also conducted to document the effects and success of the enhancement project.

Following initiation of the fry stocking program, smolt abundance declined, the mean length and weight freshwater-age-1 and freshwater-age-2 smolts decreased, and the age composition of smolt increased, possibly due to zooplankton food limitation that resulted from the stocking project (Eggers et al. 2010). The density of the cladoceran *Daphnia* sp. declined after 1995 and again in 2001, corresponding to lake stocking events. The copepod population (*Cyclops* sp.) declined by 98% following the initiation of lake stocking and remained depressed over the next decade (Bednarski et al. 2017). Eggers et al. (2010) examined the effect of spawner density, auto-correlation, and fry plants on recruits and smolts. Their analysis demonstrated that fry plants depressed wild smolt production, and further, the fry plants generally occurred in the face of relatively high wild stock escapements, all of which suggested to them that sockeye salmon production at Chilkat Lake may be rearing limited rather than spawning-area limited (Eggers et al. 2008 and 2010).

## 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 multiple, overlapping methods of escapement enumeration and missing age composition. Weir counts (1976–1995, 1999–2007) are reliable, but provide minimum estimates of escapement due to flow reversals, turbid water, and frequent lowering of the boat gate in the middle of the weir, all of which had the potential to allow undetected passage of fish. Therefore, weir counts were treated as an index of minimum escapement. The DIDSON counts were also considered minimum estimates due to undetected fish passage at night when the weir was open during flow reversals. However, compared to visual weir counts, the DIDSON (2008–2016) has the potential to provide highly accurate counts of fish. Mark–recapture estimates (1994–2016) may be greatly inflated but may provide an index of escapement. Since the mark–recapture estimates are potentially highly inflated and the weir counts are potentially highly underestimated, the DIDSON escapement counts were treated as the ‘true’ counts and not as an index of escapement.

The weir was not operated in years 1996 through 1998. Scale samples for age composition in those years were collected instead on the spawning grounds and holding areas of Chilkat Lake over multiple weeks. These samples could not be weighted by weir counts and were likely biased towards the early run fish; proportions of ages 2–8 were only available for the commercial harvest. Therefore, weighted annual proportions by age (escapement and harvest combined) were considered unknown in the model for years 1996 through 1998 (see *Escapement Estimates* above; Table 2; Appendix B2).

### Process Model

A hierarchical set of two spawner-recruit models were fit to the Chilkat Lake spawner-recruit data for calendar years 1976–2016. The spawner-recruit models were Ricker-type and hierarchical terms included density-dependent fry plants (to account for stocking of sockeye salmon fry) and a first order autoregressive (AR(1)) term. Returns *R* of Chilkat Lake sockeye salmon were modeled as a function of spawning escapements *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):

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

Returns for Model 2 were modeled using a linearized AR(1) Ricker (Equation 1), but an additional density-dependent fry term, $\gamma$, was included (Quinn and Deriso 1999: Equation 3.10):

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y - \gamma F_{y+1} + \phi\omega_{y-1} + \varepsilon_y \, . \tag{2}$$

Fry plants were from brood year $y$ in year $y$+1 ($F_{y+1}$). In Equations 1 and 2, $\alpha$ is the productivity parameter, $\beta$ is the inverse capacity parameter, $\phi$ is the lag-1 AR coefficient, and $\{\omega_y\}$ are the model residuals:

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

In Equations 1 and 2, $\{\varepsilon_y\}$ are independently and normally distributed process errors with standard deviation $\sigma_R$.

Age-at-maturity proportions $(p_{y,a} : a = 4:6)$ 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 $(g_{y,a} : a = 4:6)$ from the gamma distribution,

$$g_{y,a} \sim \text{gamma}\,(\text{shape} = \gamma_{\text{a,}}\ \text{inverse scale} = 0.1), \tag{4}$$

and dividing each by their sum (Evans et al. 1993):

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

The expected proportions returning at age, $\pi_a$, (Gelman et al. 2004) were calculated as

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

and implemented as a series of nested beta distributions, reflecting age-at-maturity central tendencies that sum to one. The sum of the $\{\gamma_a\}$ can be interpreted as the inverse dispersion (*D*) of the Dirichlet distribution. although a low value of *D* is reflective of a large amount of variability of age-at-maturity proportions *p* among brood years, a high value of *D* is indicative of 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*:

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

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

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

The spawning escapement count each calendar year, $S_y$, is the difference between total run abundance and the total commercial harvest of Chilkat Lake sockeye salmon in the District 15 drift gillnet fishery, $Hbelow_y$:

$$S_y = N_y - Hbelow_y. \tag{9}$$

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

$$Hbelow_y = N_y U_{Hy}, \tag{10}$$

drawn from a beta distribution (Appendix B1).

**Observation Model**

Observed data (Appendix B2) included spawning escapement counts (DIDSON), indices of escapement (weir, mark–recapture), annual commercial harvest, coefficients of variation (CV; harvest, DIDSON, weir, mark–recapture), and age compositions. Chilkat Lake sockeye salmon subsistence harvest, test fishery harvest, and commercial purse seine harvest were not included in the total harvest estimate in this analysis since stock composition estimates by age were unavailable for those fisheries (see *Discussion*). We also assumed there was no other unreported harvest of Chilkat Lake sockeye salmon.

Observed escapement counts from the DIDSON (*DS*) were modeled to be log-normally distributed (LN) with mean $\ln(DS_y)$ and variance $\sigma^2_{DS_y}$,

$$DS_{(ob)y} \sim LN(\ln(DS_y), \sigma^2_{DS_y}), \tag{11}$$

where $\sigma^2_{DS_y}$ was derived from the observed CV as

$$\sigma^2_{DS_y} = \ln(CV^2_{DS_y} + 1). \tag{12}$$

In a similar manner, observed annual commercial harvest was modeled to be log-normally distributed with mean ln(*Hbelow*) and variance derived from the observed CV,

$$Hbelow_{(ob)y} \sim LN(\ln(Hbelow_y), \sigma^2_{Hbelow_y}), \quad \sigma^2_{Hbelow_y} = \ln(CV^2_{Hbelow_y} + 1). \tag{13}$$

Instead of scaling weir counts and mark–recapture estimates to DIDSON counts by ratios or regression techniques, multiple, overlapping methods of escapement enumeration were incorporated within the Bayesian state-space framework 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, whereas the DIDSON counts were treated as ‘true’ counts. Each index (weir, mark–recapture) comprised an independent measure of relative escapement,

$$I_{iy} = q_i S_y \varepsilon_{iy}, \tag{14}$$

where subscript *i* indicates 1 of the 2 indices of escapement (weir or mark–recapture), $q_i$ is a survey coefficient relating true escapement to index $I_i$, and $\{\varepsilon_{iy}\}$ are independently and normally distributed process errors with variance $\sigma^2_{Ii}$. Parameters $q_i$ and $\sigma^2_{Ii}$ were estimated from the data.

Harvest coefficients of variation were unavailable for all years. The coefficient of variation for the estimated annual harvest of Chilkoot and Chilkat Lake fish averaged 3% to 6% in the three years 1987–1989 (McPherson 1990). Therefore, the CVs of harvest were uniformly set to 10% so as not to overstate confidence in the harvest estimates (Appendix B2; Hbelow.cv). 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 5%. Fleischman et al. (2013) found that results from a similar analysis were not sensitive to arbitrary choices of CVs for weir counts. For years when DIDSON or weir escapement counts were expanded for either late installation *or* early removal, the CVs were set at 10%. For years when DIDSON or weir escapement counts were expanded for both late installation *and* early removal, the CVs were set at 20% (see *Weir and DIDSON Counts*) (Appendix B2; DS.cv, weir.cv). The CVs for mark–recapture escapement counts were estimated as the standard error of the drainagewide point estimate divided by the drainagewide point estimate (Appendix B2; mr.cv). These are standard output from the software program Stratified Population Analysis System (SPAS; Arnason et al. 1996) that was used to analyze the mark–recapture data (Bednarski et al. 2017). The CVs for 1994–1997 mark–recapture estimates were unavailable and were uniformly set at 10% (Appendix B2; mr.cv).

Because effective sample size could not be accurately calculated for escapement or harvest due to unknown variances, and key model results from state-space analyses of Pacific salmon are typically not sensitive to the choice of $n_{Ey}$ (Fleischman and McKinley 2013), an arbitrary annual effective sample size of $n_{Ey}$ =100 was used and surrogate total run age counts, $x_{y,a}$, were obtained that summed to $n_{Ey}$ (Appendix B2). For both annual commercial harvest and escapement samples separately, proportions of ages 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, $\psi_{(\mathrm{ob})y,a}$. This method 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). After combining proportions of ages 2 through 4 and also combining ages 6 through 8, the weighted annual proportions by age were multiplied by 100,

$$x_{y,a} = \psi_{(\mathrm{ob})y,a} n_{Ey} \text{ where } \sum x_{y,a} = n_{Ey} = 100 \text{ across all ages for each year,} \tag{15}$$

to calculate the surrogate total run age counts, $x_{y,a}$ (Appendix B3 to Appendix B8). The age counts ($x_{y,a}$) were modeled as a multinomial distribution with order parameter $n_{Ey}$ and proportion parameters,

$$\psi_{y,a} = \frac{N_{y,a}}{N_y}, \tag{16}$$

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

Total run age compositions from 2008–2016 were based on weighted proportions of observed DIDSON counts and observed harvest numbers. Total run age compositions from 1976–2007 were based on weighted proportions of the observed index of escapement from the weir counts and observed harvest numbers. Therefore, the observed harvest age composition may have been arbitrarily weighted higher in the total run age composition. However, a comparison of total run age compositions from 1976–2007 based on 1) the observed index of escapement from the weir counts and 2) the observed index of escapement from the weir counts scaled to DIDSON counts (weir counts multiplied by 1.37; the average posterior median of escapement divided by weir counts) revealed little difference. The minimum and maximum difference in total run age counts, $x_{y,a}$, between the two methods was -1.88 and 1.54, respectively. Therefore, the bias introduced by the skewed total run age composition from 1976–2007 is likely minimal.

The weir was not operated from 1996 to 1998 and proportions of ages 2–8 were only available for the commercial harvest (see *Escapement Estimates* above). Therefore, the observed weighted annual proportions by age for the combined escapement and harvest data in years 1996–1998 were considered unknown in the model (Appendix B2).

## 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 spawner-recruit methods.

### Prior Distributions

For all unknowns in the model, Bayesian analysis requires that prior probabilities be specified. Most prior distributions in this model were non-informative with a few exceptions (Table 5). Normal priors with mean 0, extremely large variances, and constrained to be positive were used for $\beta$ (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 $\tau_{R0} = 1/\sigma^2_{R0}$. A flat prior on the standard deviation of log initial brood year returns, $\sigma_{R0}$, caused computational disruptions during MCMC sampling so it was changed to a slightly informative inverse gamma prior. Fleischman et al. (2013) found that an informative prior on $\sigma^2_{R0}$ may have a large effect on the posterior distribution of $\sigma_{R0}$ and the initial values of $R_y$, but negligible effects on key model quantities.

### 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 (R Core Team 2016). 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) 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, and 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 calculated based on the Lambert W function (Scheuerell 2016),

$$S_{MSY} = \frac{1 - W(e^{1-\ln(\alpha')})}{\beta}, \tag{17}$$

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 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:

$$Y_S = R - S = Se^{(\ln(\alpha') - \beta S)} - S. \tag{18}$$

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

$$S_{EQ} = \frac{\ln(\alpha')}{\beta}. \tag{19}$$

Harvest rate leading to *MSY*, $U_{MSY}$, was approximated by Scheuerell (2016) as

$$U_{MSY} = \beta S_{MSY}. \tag{20}$$

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

$$P(Y_s > X\%MSY) = \frac{\text{number of } \mathrm{Y_s} > X\%MSY}{\text{number of MCMC samples}}. \tag{21}$$

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 < $S_{MSY}$, and 0 at S > $S_{MSY}$. 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).

Optimal recruitment probability is calculated as

$$P(Y_s > X\%MSR) = \frac{\text{number of } Y_s > X\%MSR}{\text{number of MCMC samples}}. \tag{22}$$

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

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 $S_{MSY.}$

# RESULTS

Empirical (data-based) estimates of harvest, age composition, escapement, escapement indices, and coefficients of variation for Chilkat Lake sockeye salmon are summarized in Appendix B2.

## MODEL COMPARISON

A hierarchical set of two spawner-recruit models were fit to the Chilkat Lake spawner-recruit data for calendar years 1976–2016. The spawner-recruit models were Ricker-type and the hierarchical terms included density-dependent fry plants and a first order autoregressive term. The effect of the fry plant term ($\gamma$ = -5.69e-08; Table 6) 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 95% credibility intervals on the density-dependent fry term, $\gamma$, included zero (-2.66e-07, 1.47e-07), and thus the term was non-significant. Most of the parameter estimates were similar between the two competing models, although the precision of the estimates of $S_{MSY}$ were better for the autoregressive Ricker model without fry plants (Table 6), and, as a result, the estimated probability of achieving 90% of *MSY* at $S_{MSY}$ was slightly higher for the model without fry plants (~84%) compared to the model with fry plants (~80%). Therefore, the autoregressive Ricker model without fry plants was considered the most statistically sound model; thus, subsequent results and discussion pertain to the autoregressive model without fry plants.

## ABUNDANCE, TIME-VARYING PRODUCTIVITY, HARVEST RATES, AGE COMPOSITIONS, AND AGE-AT-MATURITY

Weir counts and mark–recapture estimates comprised independent measures of relative escapement that were related to the 'true' escapement (i.e., DIDSON counts) by $q_i$, a survey index in the state-space model (see Equation 14). The two indices of escapement were reconstructed in years 1976–2016 in the state-space model (Figure 3). The median survey index relating the mark–recapture estimates to the DIDSON counts was 1.58 and the median survey index relating the weir counts to the DIDSON counts was 0.73 (Table 7; Figure 3).

Reconstructed total run abundance (*N*) estimates for the autoregressive Ricker model had CVs that ranged from 4% to 10% (Figure 4C; Table 8). The years with higher uncertainty corresponded to years with missing escapement data (DIDSON; 1976–2007), missing escapement indices (weir or mark–recapture), and/or missing age composition data (1996–1998) (Table 8; Appendix B2). Excluding the first initial returns, reconstructed brood year recruitments had CVs that ranged from 6% to 58%. Across years, the Ricker recruitment model residuals (productivity residuals; Equation 3) were spread around 0, indicating a good model fit.

Stock productivity was high in the 1980s to early 1990s, as reflected in the productivity residuals, then declined from brood years 1995 through 2002 (Figure 4D). As a result, total run abundance decreased starting in 2000 and remained relatively low (average about 55% of the 1980s–1990s average) except for small spikes in years 2009 and 2013 (Figure 4C). Chilkat Lake sockeye salmon matured primarily at age 5 (mean range: 35–73%; age classes 1.3 and 2.2) and age 6–8 (mean range: 22–64%; principally age 2.3), followed by much smaller proportions at age 2–4 (mean range: 1–8%; principally age 1.2) (Figure 5). Overall mean age at maturity was more variable and exhibited an increasing trend across brood years from the early 1970s to the late 1980s, when it peaked (Figure 5A). Mean age at maturity then declined into the early 2000s (Figure 5A). From 2001 to 2016, annual run abundance of age 5 averaged 60% of the

1980s–1990s average, and annual run abundance of age 6–8 (principally age 2.3) averaged 48% of the 1980s–1990s average (Figure 5; Table 9). Median harvest rates (Figure 4E) peaked in the 1980s (mean 49%; maximum 83%) then trended downward through the 1990s (mean 45%) and the 2000s (mean 35%; minimum 19%).

## STOCK PRODUCTIVITY, CAPACITY, AND YIELD

Results of the Ricker spawner recruit relationships take into account measurement error in both *S* and *R* when derived from the age-structured state-space model fitted to escapement, harvest, and age composition data; these are depicted by the error bars (dotted lines) in Figure 6, which weight the individual data pairs based on how precisely they were estimated. Some of the plausible relationships varied greatly from the posterior medians of ln($\alpha'$) and $\beta$ (Figure 6; dark dashed line), but most were not substantially different from the median estimates. The median estimate of ln($\alpha'$) was 1.30, corresponding to $\alpha$ = 3.00 and the median estimate of the density dependent parameter $\beta$ was 5.38e-06. Uncertainty about $\beta$ is reflected in variability in the values of *S* leading to maximum recruitment $S_{MSR} = 1/\beta$, and uncertainty about equilibrium abundance, $S_{EQ}$, is reflected by variability in the values of *S* where the curves intersect the replacement line. The estimated AR(1) parameter $\phi$ was 0.42, suggesting serial correlation in residuals.

Historical estimates of escapement obtained by fitting a state-space model to Chilkat Lake sockeye salmon data ranged from 32,774 fish in 1986 to 282,636 fish in 1993 (Figure 7). To address the uncertainty about the plausible spawner-recruit relationships (Figure 6), the success or failure of a given number of spawners to achieve biological reference points across plausible spawner-recruit relationships were tallied to create optimal recruitment profiles (Figure 8; top panel), optimal yield profiles (Figure 8, middle panel), and overfishing profiles (Figure 8; 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 optimal recruitment profiles, which are highest near $S_{MSR}$ = 185,726 (Table 7), display the probability of achieving 80% and 90% of *MSR* for 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 8, shaded areas; Figure 9), 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 *MSY* by fishing too hard and supplying too few spawners.

# DISCUSSION

The current Chilkat Lake sockeye salmon BEG of 70,000−150,000 spawners is based on an autoregressive Ricker model with fry plants that incorporated data from the 1979–2002 brood years (Eggers et al. 2010). Our study was similar in methodology to Eggers et al. (2010) in that a set of hierarchical spawner-recruit models that incorporated a first order autoregressive term and fry plant term were constructed. However, Eggers et al. (2010) incorporated a slightly different Ricker model form, (Ricker 1975; Hilborn and Walters 1992, Equation 7.5.5; Table 6),

$$R = Se^{\alpha(1-\frac{S}{\beta})}, \tag{23}$$

and concluded that the model with increased recruits, independent of wild stock production, provided a correction for the effect of fry plants, whereas we determined the fry plant term was non-significant and we did not include it in our favored model. Despite the additional years of data (brood years 1976−2012), a more sophisticated age-structured model framework, a slightly different Ricker model form (Equation 23), and the exclusion of the fry plant term, our parameter estimates of $S_{MSY}$ were similar to those produced by Eggers et al. (2010). The $S_{MSY}$ reference point from Eggers et al. (2010) was 105,000, spawners while the posterior median of $S_{MSY}$ from the state space model was 98,370 spawners (Table 6). The posterior median of $S_{MSY}$ from the state space model with fry plants was slightly higher (~102,000 spawners; Table 6) and closer to the estimate obtained by Eggers et al. (2010). The slope at the origin ($e^{\alpha}$ in Equation 23 and $\alpha$ in Equation 1 and Equation 2 was very similar between the Eggers et al. (2010) autoregressive Ricker model with fry plants and the autoregressive Ricker model fit in a Bayesian state space framework (Table 6). The parameter $\beta$ used in Eggers et al. (2010) model, as shown in Equation 23, is interpreted as the value of $S$ at which $R = S$. The parameter $\beta$ applied in our models, as shown in Equation 1 and Equation 2, describes how quickly the recruits per spawner drop as $S$ increases. Therefore, they are not directly comparable.

Eggers et al. (2010) used traditional spawner-recruit analysis on the Chilkat Lake sockeye salmon data. Within the traditional framework, escapement goal analyses are forced to rely on one escapement enumeration method per year, although overlapping escapement enumeration methods may be available. Eggers et al. (2010) regressed mark–recapture estimates against weir counts for years with paired estimates, to expand weir counts to total escapement during years when mark–recapture experiments were not conducted to produce the complete time series of escapements required for analysis. Based on Tables 2 and 3 in Eggers et al. (2010; pages 16–17), the ratio of expanded weir counts divided by weir counts (years 1976–1993) was 1.44. In the state space model output, the ratio of the total median escapement (based on the DIDSON counts) divided by the median weir counts was 1.37. The similar ratios may explain the similar model estimates of $S_{MSY}$ between Eggers et al. (2010) and the current state space model output. While the fry plant term was significant in the prior analysis by Eggers et al. (2010), the fry plant term was non-significant and very small in our analysis. It is possible that the addition of more brood years in our analysis muted the effect of the fry plants compared to the analysis of Eggers et al. (2010).

## UNKNOWN HARVEST

As with previous Chilkat Lake sockeye salmon escapement goal analyses (McPherson 1990; Eggers et al. 2010), we could not include subsistence and commercial purse seine harvest because stock composition estimates by age were unavailable for those fisheries. Not including subsistence and commercial purse seine harvest in the state-space model would potentially make the Chilkat Lake sockeye salmon stock appear less productive than our results indicated; e.g., our estimates of $S_{MSY}$ may be slightly smaller than they would have been if we had included that harvest. Reported subsistence harvest, which is a mixture of Chilkat Lake and Chilkat River mainstem stocks, averaged approximately 4,300 sockeye salmon from 1985 to 2016 (Appendix A6). A portion of all sockeye salmon stocks returning to natal streams in the inside waters of northern Southeast Alaska, including Chilkat Lake fish, migrate east through Icy Strait (District 14) and into northern Chatham Strait (District 12) (Rich 1926; Rich and Suomela 1927; Rich and Morton 1929), where they are harvested incidentally in commercial mixed stock purse seine fisheries that are managed to harvest pink salmon (Ingledue 1989). The timing, location, and intensity of fishing are determined by pink salmon abundance, which varies considerably from year to year (e.g., 1985–2016 harvests ranged from 53,000 to 15,600,000 pink salmon). The purse seine fishery along the Hawk Inlet shoreline (Subdistrict 112-16) is also constrained by regulation to a cumulative harvest of 15,000 wild sockeye salmon in the month of July to conserve northbound stocks[1]. As a result, the number of sockeye salmon harvested in Icy and northern Chatham straits is highly variable (1985–2016 average harvest = 41,000 fish; range: 1,600–174,000 fish; Appendix A6), as is the stock composition (Gilk-Baumer et al. 2015), due to variation in fishing effort and differences in the run timing and relative abundance of individual sockeye salmon stocks that migrate through that corridor.

Estimates of the harvest of Chilkat Lake sockeye salmon in commercial purse seine fisheries in Icy and northern Chatham straits are limited to a qualified scale pattern analysis of 1989 harvests (Ingledue 1989) and three years of genetic mixed stock analysis, 2012–2014 (Gilk-Baumer et al. 2015). Chilkat Lake sockeye salmon contributed an estimated 17% (7,302 fish) of the harvest in 1989, 7% in 2012 (522 fish), 25% in 2013 (10,517 fish), and 11% in 2014 (655 fish; Appendix A6). Estimated proportions of Chilkat Lake fish in the sockeye salmon harvests indicated the run timing peaked later in the season; e.g., the proportion of Chilkat Lake fish in the District 12 harvest in 1989 increased from 6.8% in statistical week 27 (early July) to 68.6% in statistical week 34 (mid-August; Ingledue 1989), and in 2013 the proportion of Chilkat Lake fish in the Subdistrict 112-16 harvest increased steadily from 15.0% (90% CI: 11.3–19.1%) in statistical weeks 27–28 (early July) to 68.4% (90% CI: 64.5–72.2%) in statistical weeks 34–35 (mid-August; Gilk-Baumer et al. 2015). Estimated harvests of Chilkat Lake sockeye salmon in 2012 and 2014 were far lower, because pink salmon abundance was poor and purse seine harvests were limited to weekly openings in a very small section of District 112-14 and to the District 112-16 Hawk Inlet test fishery, which is conducted weekly only through statistical week 29 (mid-July). The highly variable sockeye salmon harvest in the commercial mixed stock purse seine fisheries, along with highly variable Chilkat Lake contribution estimates limited to only a few years, precluded making estimates of Chilkat Lake harvest. Future genetic stock analysis of Chilkat Lake sockeye salmon in commercial purse seine fisheries in Icy and northern Chatham straits would allow the inclusion of this harvest in future spawner-recruit analyses.

# ESCAPEMENT GOAL RECOMMENDATION

The Chilkat Lake sockeye salmon run is one of the largest in Southeast Alaska, and it contributes a considerable portion of the commercial sockeye salmon harvest in Lynn Canal. Achieving the spawning escapement goal while maximizing long-term sustainable yields are among the primary objectives for management of the District 15 Lynn Canal commercial drift gillnet fishery (Gray et al. 2016). In this situation, the ADF&G standard would be to establish an escapement goal that provides for greater than 90% of *MSY* (Bernard and Jones 2010). There is a fair degree of uncertainty regarding the true spawner-recruit relationship (Figure 6) and estimated production parameters (Table 7) for Chilkat Lake sockeye salmon, which is reflected in the probabilities of achieving greater than 90% of *MSY* (Figure 8).

The current Chilkat Lake sockeye salmon BEG is a range of 70,000 to 150,000 fish. We estimate the probability of achieving yields greater than 90% of *MSY* at the current upper and lower bounds is 62% and 34%, respectively (Figure 8, middle panel), and an average 65% over the entire escapement goal range. Yield would be maximized at escapements near $S_{MSY}$ (near 84% probability of achieving greater than 90% of *MSY*). These probabilities improve substantially

[1] *Northern Southeast Seine Fishery Management Plan* (5 AAC 33.366).

with respect to achieving greater than 80% of *MSY*. In addition, the estimated probability that a given spawning escapement will produce average recruitments exceeding 90% of *MSR* averages 76% across the entire escapement goal range of 70,000–150,000 fish (Figure 8, top panel). The lower bound of the escapement goal should be high enough to minimize the risk of overfishing relative to *MSY*, yet low enough to not exclude the best opportunities for high yield (Fleischman et al. 2011). Outputs from the Chilkat Lake sockeye salmon state-space model suggest the probability of overfishing relative to *MSY* increases steeply at escapements below 70,000 fish (Figure 8, bottom panel). If, for example, the lower bound of the escapement goal was reduced from 70,000 fish to 65,000 fish, the estimated probability of reducing sustained yield to less than 90% of *MSY* increases from 38% to 48% (Figure 8, bottom panel) and the probability of achieving greater than 90% of *MSY* decreases from 62% to 52%. Conversely, increasing the lower bound from 70,000 to 75,000 fish would reduce the estimated probability of overfishing to 30% and increase the probability of achieving greater than 90% of *MSY* to 70%.

For comparative purposes, we examined other options for choosing ranges around estimates of $S_{MSY}$. The current lower and upper bounds of the Chilkat Lake sockeye salmon BEG range are 0.71 and 1.52 times the estimated $S_{MSY}$ from the state-space model without fry plants. Eggers (1993) suggested that an escapement goal range from 0.8 to 1.6 times $S_{MSY}$ would enable managers more flexibility to protect weak stocks and maintain sustainable harvest levels of dominant stocks to within 90% of *MSY*. Applying Eggers's (1993) approach to our estimate of $S_{MSY}$ for Chilkat Lake sockeye salmon would result in a range of approximately 79,000 to 157,000 fish, similar to, but slightly higher than the current BEG range. We also compared the current Chilkat Lake sockeye salmon escapement goal to the BEG and SEG ranges of 22 other sockeye salmon stocks in Alaska that were based on spawner-recruit analyses (compiled from Munro and Volk 2016) and expressed those goals in terms of multiples of $S_{MSY}$ (Appendix C1). The lower bound escapement goal ranges for these 22 stocks averaged 0.68 (range: 0.57–0.86) times $S_{MSY}$ and the upper bound escapement goal ranges averaged 1.42 (range: 1.10–1.83) times $S_{MSY}$ (Appendix C1, Appendix C2). Thus, the current Chilkat Lake BEG range compares favorably with respect to sockeye salmon escapement goal ranges that have been established throughout Alaska.

Uncertainty regarding the effects that unknown subsistence and commercial purse seine harvests might have on the spawner-recruit analysis, uncertainty regarding the true spawner-recruit relationship and estimated production parameters, and higher estimated probabilities of reducing yield to less than 90% of *MSY* at escapements below 70,000 fish suggests that a precautionary approach to the lower bound of the escapement goal is warranted. Therefore, we recommend maintaining the current biological escapement goal range of 70,000–150,000 fish counted with the DIDSON at the Chilkat Lake weir site.

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# TABLES AND FIGURES

Table 1.–Estimated harvest of Chilkat Lake sockeye salmon and harvest proportions by age in the District 15 commercial drift gillnet fishery, 1976–2016.

| Year | Harvest | Harvest Proportion by Age | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Age 2 | Age 3 | Age 4 | Age 5 | Age 6 | Age 7 | Age 8 |
| 1976[a] | 58,765 | 0.00 | 0.00 | 0.05 | 0.70 | 0.25 | 0.00 | 0.00 |
| 1977[a] | 41,477 | 0.00 | 0.00 | 0.03 | 0.71 | 0.26 | 0.00 | 0.00 |
| 1978[a] | 89,558 | 0.00 | 0.00 | 0.04 | 0.63 | 0.33 | 0.00 | 0.00 |
| 1979[a] | 115,995 | 0.00 | 0.00 | 0.03 | 0.84 | 0.13 | 0.01 | 0.00 |
| 1980[a] | 31,267 | 0.00 | 0.00 | 0.02 | 0.53 | 0.44 | 0.00 | 0.00 |
| 1981[a] | 48,420 | 0.00 | 0.00 | 0.03 | 0.47 | 0.50 | 0.01 | 0.00 |
| 1982[a] | 127,174 | 0.00 | 0.00 | 0.01 | 0.44 | 0.54 | 0.00 | 0.00 |
| 1983[a] | 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.] 1976–1983 harvest estimates are based on stock compositions from McPherson (1990) applied to updated harvest data (see Appendix A).

Table 2.–Expanded Chilkat Lake sockeye salmon weir and DIDSON counts, and mark–recapture escapement estimates, 1976–2016. (Mark–recapture = MR.)

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

a. Weir and DIDSON counts were expanded to account for late installation and early removal.

b. Age composition of 1976–1981 escapements based on McPherson (1990).

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

Table 3.–Annual age composition proportions of age-class 1.2 for Chilkat Lake sockeye salmon escapement, 1976–1981, based on data from McPherson (1990). Other age-classes were calculated by the same method. Total escapement does not match the weir escapement in Table 2, but total escapement is only used to calculate the age composition proportion based on data from McPherson (1990).

| Year | Total Run (Age 1.2) | Harvest Rates (Age 1.2) | Harvest (Age 1.2) | Escapement (Age 1.2) | Total Escapement (All Age Classes) | Age Composition (Age 1.2) |
|---|---|---|---|---|---|---|
| 1976 | 5,743 | 0.47 | 2,699 | 3,044 | 69,872 | 4.36% |
| 1977 | 2,793 | 0.47 | 1,313 | 1,480 | 40,774 | 3.63% |
| 1978 | 9,715 | 0.33 | 3,206 | 6,509 | 67,781 | 9.60% |
| 1979 | 3,975 | 0.89 | 3,538 | 437 | 81,092 | 0.54% |
| 1980 | 3,053 | 0.23 | 702 | 2,351 | 95,372 | 2.46% |
| 1981 | 1,717 | 0.82 | 1,408 | 309 | 83,956 | 0.37% |

Table 4.–Number of enhanced sockeye salmon fry released in Chilkat Lake, 1989 to 2003 (updated from Eggers et al. 2010). 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 number of dead eggs counted in the spring. Total enhanced fry was entered as fry data in the autoregressive Ricker model with fry plants.

| Brood Year | Release Year | Stocked Fry (Thermal Marked)[a] | Stocked Fry (Unmarked) | Incubation Fry Box[b] | 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 |

[a] Number of stocked fry updated from ADF&G Mark, Tag, and Age Laboratory website 24 July 2017.

[b] Number of unmarked fry from incubation boxes from Table 1 in Eggers et al. (2010).

Table 5.–Prior distributions for model parameters. 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.

| Parameter | RJAGS Coding | Prior |
|---|---|---|
| $\ln(\alpha)$ | lnalpha | $\ln(\alpha)$ ~ "Uniform" (0,3) |
| $\beta$ | beta | $\beta$ ~ "Uniform" (0,∞) |
| $\sigma_R$ | sigma.R | $\tau_R = 1/\sigma_R^2$ ~gamma(0.001,0.001) |
| $\phi$ | phi | $\phi$ ~ "Uniform" (-0.98,0.98) |
| $\omega_0$ | log.resid.0 | $\omega_o \sim \text{Normal}(0, \sigma_R^2/(1-\phi^2))$ |
| $D$ | D | $1/\sqrt{D} \sim \text{Uniform}(0, 1)$ |
| $\ln(R_0)$ | mean.log.R0 | $\ln(R_0)$ ~ "Uniform" (∞,∞) |
| $\sigma_{R0}$ | sigma.R0 | $\tau_{R0} = 1/\sigma_{R0}^2$ ~gamma(0.001,0.001) |
| $\gamma$ | gam | $\gamma$ ~ "Uniform" (-0.98,0.98) |
| $\ln(R_1)$:$\ln(R_6)$ | log.R[1:6] | lognormal($\ln(R_0)$, $\tau_{R0}$) |

Table 6.– Results of model fits to the escapement-recruit data for calendar years 1976–2016 (brood years 1970–2012) compared to Eggers et al. (2010) results from brood years 1979–2002. In the Ricker form, *α, β, γ,* and $\phi$ are model parameters and the data are total recruits from brood year *i* escapement $(R_i)$, escapement in brood year *i* $(S_i)$, fry plants from brood year *i* in year *i*+1 $(F_{i+1})$, and $\varepsilon_i$ is the process error. Estimated parameters and reference points are shown. The lower and upper bound on the $S_{MSY}$ reference points for the Bayesian state-space models define the 2.5th and 97.5th percentiles, which represent the 95% credibility intervals for the parameters. The coefficients of variation of the posterior median are the number in parenthesis after the $S_{MSY}$ estimate. *Note*: The upper and lower bound on the $S_{MSY}$ from Eggers et al. (2010) is the 90% MSY escapement goal range, rather than upper and lower bounds on the $S_{MSY}$ reference point. The parameter *β* used in Eggers et al. (2010) model is interpreted as the value of *S* at which *R* = *S*. The parameter *β* applied in the Bayesian state-space models describes how quickly the recruits per spawner drop as *S* increases. Therefore, they are not directly comparable. The parameter $e^{\alpha}$ used in Eggers et al. (2010) model is interpreted as the initial slope of the curve. The parameter *α* applied in the Bayesian state-space models is the recruits-per-spawner at low stock sizes.

| Parameter or Model | Autoregressive Ricker (brood years 1976–2012) | Autoregressive Ricker-Fry Plants (brood years 1976–2012) | Autoregressive Ricker-Fry Plants (brood years 1979–2002); Eggers et al. 2010) |
|---|---|---|---|
| Ricker form | $R_i = \alpha S_i e^{-\beta S_i} e^{\phi \varepsilon_{i-1}}$ | $R_i = \alpha S_i e^{-\beta S_i - \gamma F_{i+1}} e^{\phi \varepsilon_{i-1}}$ | $R_i = S_i e^{\alpha(1-\frac{S_i}{\beta}-\gamma F_{i+1})} e^{\phi \varepsilon_{i-1}}$ |
| Model framework | Bayesian state-space | Bayesian state-space | Traditional |
| $\alpha$ | 3.00 | 2.86 | 0.87 |
| slope at origin | 3.00 | 2.86 | 2.39 |
| $\beta$ | 5.38e-06 | 5.02e-06 | 253 |
| $\varphi$ | 0.42 | 0.48 | 0.48 |
| $\gamma$ | --- | -5.69e-08 | -0.069 |
| $S_{MSY}$[a] | 98,370 (0.41) | 101,895 (0.63) | 105,000 |
| Lower | 66,765 | 64,834 | 69,000 |
| Upper | 223,966 | 315,196 | 147,000 |
| $U_{MSY}$ | 0.54 | 0.53 | 0.39 |

[a] The coefficient of variation for the reference point $S_{MSY}$ was 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 × standard errors from the median point estimate.

Table 7.–State-space model parameter estimates from the autoregressive Ricker model without fry plants for Chilkat Lake in calendar years 1976–2016. Posterior medians are point estimates; the 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 coefficients of variation (CVs) are the posterior standard deviations divided by the posterior means.

| Parameter | $2.5^{th}$ percentile | Median | $97.5^{th}$ percentile | CV |
|---|---|---|---|---|
| $\alpha$ | 1.76 | 3.00 | 5.08 | 0.28 |
| $\ln(\alpha)$ | 0.57 | 1.10 | 1.62 | 0.25 |
| $\ln(\alpha)'$ | 0.80 | 1.30 | 1.92 | 0.22 |
| $\beta$ | 1.75e-06 | 5.38e-06 | 9.18e-06 | 0.36 |
| $\phi$ | 0.07 | 0.42 | 0.76 | 0.42 |
| $\sigma_{\mathrm{R}}$ | 0.44 | 0.56 | 0.74 | 0.13 |
| $S_{EQ}$ | 164,728 | 240,618 | 637,834 | 0.50[a] |
| $S_{MSR}$ | 108,895 | 185,726 | 570,525 | 0.63[a] |
| $S_{MSY}$ | 66,765 | 98,370 | 223,966 | 0.41[a] |
| $U_{MSY}$ | 0.36 | 0.54 | 0.71 | 0.17 |
| $D$ | 19.57 | 29.87 | 46.03 | 0.22 |
| $\pi_4$ | 0.03 | 0.04 | 0.06 | 0.15 |
| $\pi_5$ | 0.51 | 0.54 | 0.57 | 0.03 |
| $\pi_6$ | 0.38 | 0.41 | 0.45 | 0.04 |
| $q_{\mathrm{m\text{-}r}}$ | 1.46 | 1.58 | 1.72 | 0.04 |
| $q_{\mathrm{weir}}$ | 0.65 | 0.73 | 0.83 | 0.06 |

[a] The coefficients of variation for the reference points $S_{EQ}$, $S_{MSR}$, and $S_{MSY}$ 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 are both ~1.96 × standard errors from the median point estimate.

Table 8.–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 coefficients of variation are the posterior standard deviations divided by the posterior means. Recruitment values are listed by brood year.

| | | | | Coefficients of Variation | | |
|---|---|---|---|---|---|---|
| Year | Total Run *N* | Escapement *S* | Recruitment *R* | Total Run *N* | Escapement *S* | Recruitment *R* |
| 1970 | --- | --- | 135,417 | --- | --- | 0.23 |
| 1971 | --- | --- | 137,247 | --- | --- | 0.09 |
| 1972 | --- | --- | 147,153 | --- | --- | 0.09 |
| 1973 | --- | --- | 169,098 | --- | --- | 0.09 |
| 1974 | --- | --- | 237,823 | --- | --- | 0.08 |
| 1975 | --- | --- | 176,965 | --- | --- | 0.09 |
| 1976 | 154,301 | 95,137 | 203,223 | 0.06 | 0.08 | 0.10 |
| 1977 | 115,914 | 73,024 | 246,450 | 0.08 | 0.12 | 0.11 |
| 1978 | 180,618 | 91,988 | 246,149 | 0.06 | 0.08 | 0.10 |
| 1979 | 221,781 | 109,326 | 329,704 | 0.06 | 0.08 | 0.08 |
| 1980 | 170,852 | 139,153 | 209,896 | 0.09 | 0.11 | 0.09 |
| 1981 | 164,822 | 115,519 | 130,119 | 0.06 | 0.08 | 0.11 |
| 1982 | 238,348 | 112,650 | 147,453 | 0.10 | 0.19 | 0.08 |
| 1983 | 296,858 | 175,781 | 154,769 | 0.08 | 0.12 | 0.11 |
| 1984 | 271,880 | 170,688 | 374,450 | 0.08 | 0.11 | 0.07 |
| 1985 | 216,201 | 80,825 | 172,343 | 0.07 | 0.12 | 0.09 |
| 1986 | 194,803 | 32,774 | 184,795 | 0.08 | 0.08 | 0.09 |
| 1987 | 138,478 | 67,763 | 347,518 | 0.07 | 0.12 | 0.08 |
| 1988 | 119,949 | 39,620 | 251,234 | 0.07 | 0.12 | 0.10 |
| 1989 | 341,732 | 191,128 | 228,960 | 0.06 | 0.08 | 0.08 |
| 1990 | 233,066 | 82,418 | 163,926 | 0.07 | 0.08 | 0.21 |
| 1991 | 134,297 | 70,786 | 272,665 | 0.06 | 0.08 | 0.22 |
| 1992 | 243,693 | 130,625 | 209,853 | 0.06 | 0.08 | 0.28 |
| 1993 | 384,909 | 282,636 | 333,953 | 0.06 | 0.08 | 0.12 |
| 1994 | 234,449 | 107,609 | 263,581 | 0.07 | 0.09 | 0.08 |
| 1995 | 169,826 | 99,143 | 53,707 | 0.06 | 0.08 | 0.15 |
| 1996 | 258,662 | 159,968 | 170,274 | 0.08 | 0.11 | 0.07 |
| 1997 | 226,155 | 151,585 | 149,541 | 0.08 | 0.11 | 0.08 |
| 1998 | 248,990 | 133,791 | 82,146 | 0.07 | 0.10 | 0.11 |
| 1999 | 304,257 | 156,663 | 134,715 | 0.06 | 0.06 | 0.07 |
| 2000 | 146,668 | 66,876 | 59,413 | 0.06 | 0.07 | 0.11 |
| 2001 | 127,086 | 66,826 | 64,457 | 0.06 | 0.08 | 0.10 |
| 2002 | 138,506 | 90,280 | 47,463 | 0.07 | 0.10 | 0.11 |
| 2003 | 124,141 | 74,175 | 161,713 | 0.06 | 0.08 | 0.08 |
| 2004 | 127,720 | 77,287 | 227,543 | 0.06 | 0.07 | 0.06 |
| 2005 | 77,048 | 53,821 | 63,492 | 0.07 | 0.10 | 0.11 |
| 2006 | 68,478 | 52,501 | 86,555 | 0.10 | 0.13 | 0.09 |
| 2007 | 53,378 | 39,011 | 220,818 | 0.07 | 0.09 | 0.07 |
| 2008 | 99,240 | 76,512 | 160,687 | 0.06 | 0.07 | 0.09 |
| 2009 | 237,633 | 154,403 | 198,585 | 0.05 | 0.05 | 0.07 |
| 2010 | 106,813 | 57,747 | 85,595 | 0.05 | 0.04 | 0.10 |
| 2011 | 80,973 | 65,179 | 115,370 | 0.04 | 0.04 | 0.18 |

-continued-

Table 8.–Page 2 of 2.

| Year | Total Run *N* | Escapement *S* | Recruitment *R* | Coefficients of Variation | | |
|---|---|---|---|---|---|---|
| | | | | Total Run *N* | Escapement *S* | Recruitment *R* |
| 2012 | 168,987 | 113,856 | 154,351 | 0.06 | 0.07 | 0.58 |
| 2013 | 201,779 | 126,769 | --- | 0.06 | 0.07 | --- |
| 2014 | 161,013 | 77,838 | --- | 0.06 | 0.05 | --- |
| 2015 | 127,419 | 93,584 | --- | 0.07 | 0.09 | --- |
| 2016 | 107,869 | 71,665 | --- | 0.06 | 0.07 | --- |

Table 9.–Total run abundance by age 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 coefficients of variation are the posterior standard deviations divided by the posterior means.

| | | | | Coefficients of Variation | | |
|---|---|---|---|---|---|---|
| Year | Ages 2–4 | Age 5 | Ages 6–8 | Ages 2–4 | Age 5 | Ages 6–8 |
| 1976 | 7,260 | 99,925 | 46,532 | 0.39 | 0.09 | 0.15 |
| 1977 | 3,662 | 81,578 | 30,488 | 0.47 | 0.10 | 0.17 |
| 1978 | 10,113 | 111,727 | 58,016 | 0.36 | 0.10 | 0.14 |
| 1979 | 4,980 | 162,720 | 53,268 | 0.55 | 0.09 | 0.17 |
| 1980 | 4,117 | 101,602 | 64,206 | 0.55 | 0.12 | 0.15 |
| 1981 | 2,592 | 91,887 | 69,683 | 0.66 | 0.10 | 0.13 |
| 1982 | 7,466 | 123,960 | 106,747 | 0.50 | 0.14 | 0.15 |
| 1983 | 14,713 | 162,313 | 118,498 | 0.40 | 0.12 | 0.14 |
| 1984 | 5,957 | 189,350 | 74,954 | 0.55 | 0.10 | 0.17 |
| 1985 | 4,292 | 86,152 | 124,512 | 0.56 | 0.13 | 0.11 |
| 1986 | 4,256 | 72,828 | 116,692 | 0.55 | 0.14 | 0.11 |
| 1987 | 4,447 | 81,788 | 51,755 | 0.49 | 0.11 | 0.14 |
| 1988 | 3,115 | 55,787 | 60,586 | 0.54 | 0.13 | 0.11 |
| 1989 | 4,664 | 241,793 | 93,771 | 0.67 | 0.09 | 0.16 |
| 1990 | 3,345 | 100,332 | 128,816 | 0.67 | 0.13 | 0.11 |
| 1991 | 3,454 | 63,597 | 66,566 | 0.54 | 0.11 | 0.11 |
| 1992 | 3,868 | 122,178 | 117,256 | 0.64 | 0.11 | 0.12 |
| 1993 | 11,290 | 150,213 | 221,290 | 0.47 | 0.14 | 0.11 |
| 1994 | 4,994 | 132,807 | 96,104 | 0.54 | 0.10 | 0.13 |
| 1995 | 6,714 | 78,433 | 83,880 | 0.43 | 0.12 | 0.11 |
| 1996 | 8,775 | 165,938 | 79,647 | 1.02 | 0.23 | 0.38 |
| 1997 | 10,440 | 113,089 | 98,816 | 0.87 | 0.29 | 0.31 |
| 1998 | 7,722 | 155,798 | 81,801 | 0.92 | 0.20 | 0.35 |
| 1999 | 2,523 | 136,239 | 164,578 | 0.69 | 0.12 | 0.11 |
| 2000 | 3,406 | 24,918 | 117,888 | 0.54 | 0.20 | 0.08 |
| 2001 | 4,070 | 96,999 | 25,630 | 0.46 | 0.08 | 0.19 |
| 2002 | 3,742 | 64,964 | 69,261 | 0.48 | 0.12 | 0.11 |
| 2003 | 4,019 | 39,675 | 80,086 | 0.47 | 0.15 | 0.09 |
| 2004 | 4,865 | 84,510 | 38,094 | 0.40 | 0.09 | 0.15 |
| 2005 | 2,219 | 29,159 | 45,415 | 0.49 | 0.14 | 0.11 |
| 2006 | 3,587 | 39,687 | 25,096 | 0.38 | 0.13 | 0.16 |
| 2007 | 2,875 | 27,991 | 22,360 | 0.40 | 0.11 | 0.13 |
| 2008 | 4,986 | 78,281 | 15,538 | 0.39 | 0.08 | 0.20 |
| 2009 | 3,629 | 152,543 | 80,313 | 0.57 | 0.08 | 0.14 |
| 2010 | 2,947 | 33,853 | 69,611 | 0.49 | 0.14 | 0.08 |
| 2011 | 6,471 | 48,841 | 25,329 | 0.32 | 0.09 | 0.14 |
| 2012 | 9,319 | 124,449 | 34,295 | 0.37 | 0.08 | 0.18 |
| 2013 | 11,236 | 100,558 | 89,264 | 0.36 | 0.11 | 0.12 |
| 2014 | 5,120 | 105,141 | 50,394 | 0.44 | 0.09 | 0.15 |
| 2015 | 4,673 | 40,404 | 81,858 | 0.43 | 0.15 | 0.10 |
| 2016 | 4,522 | 63,316 | 39,480 | 0.44 | 0.10 | 0.13 |

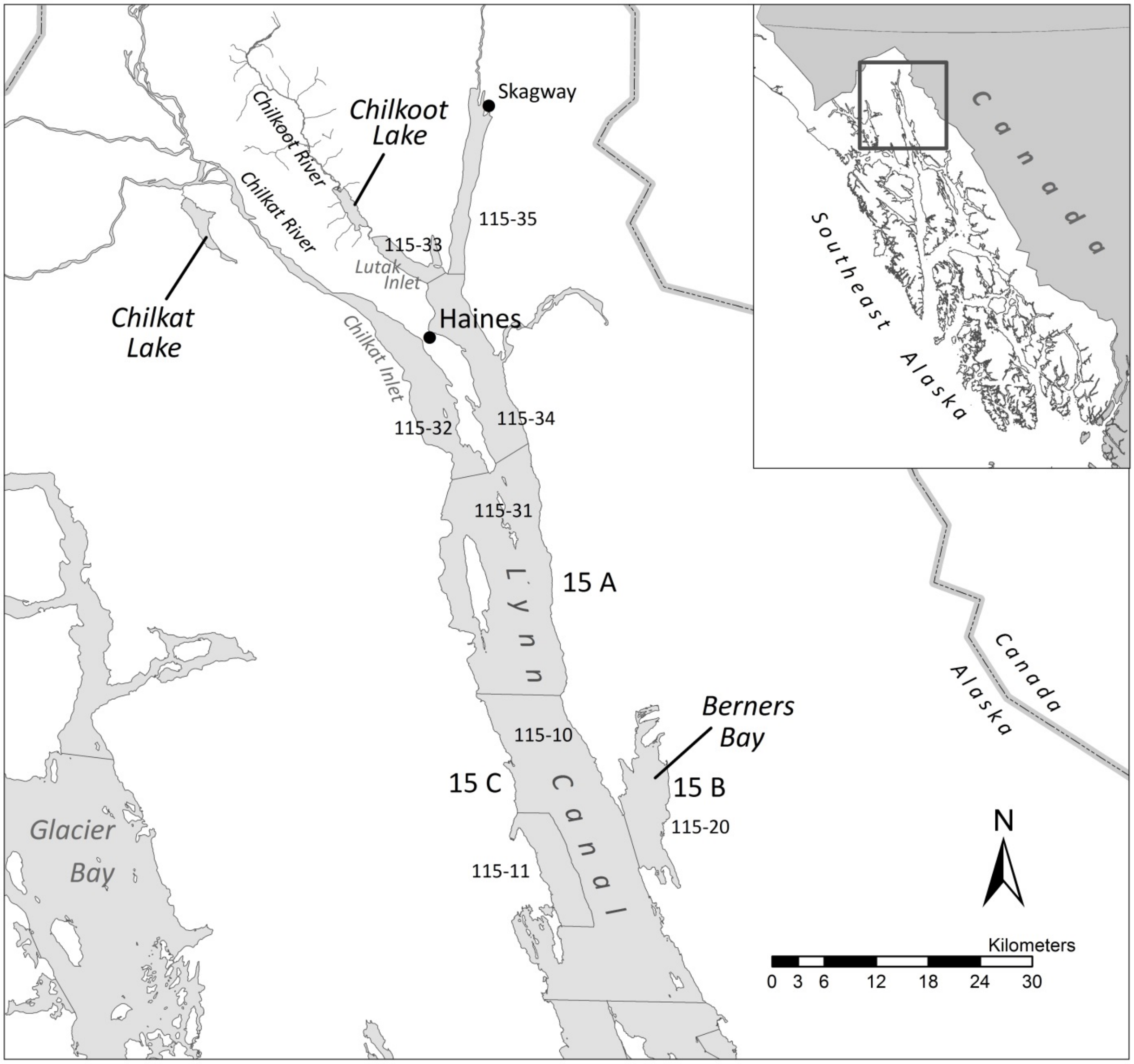


Figure 1.–Commercial fishing subdistricts and management boundary lines within District 15 in the Haines area, Southeast Alaska.

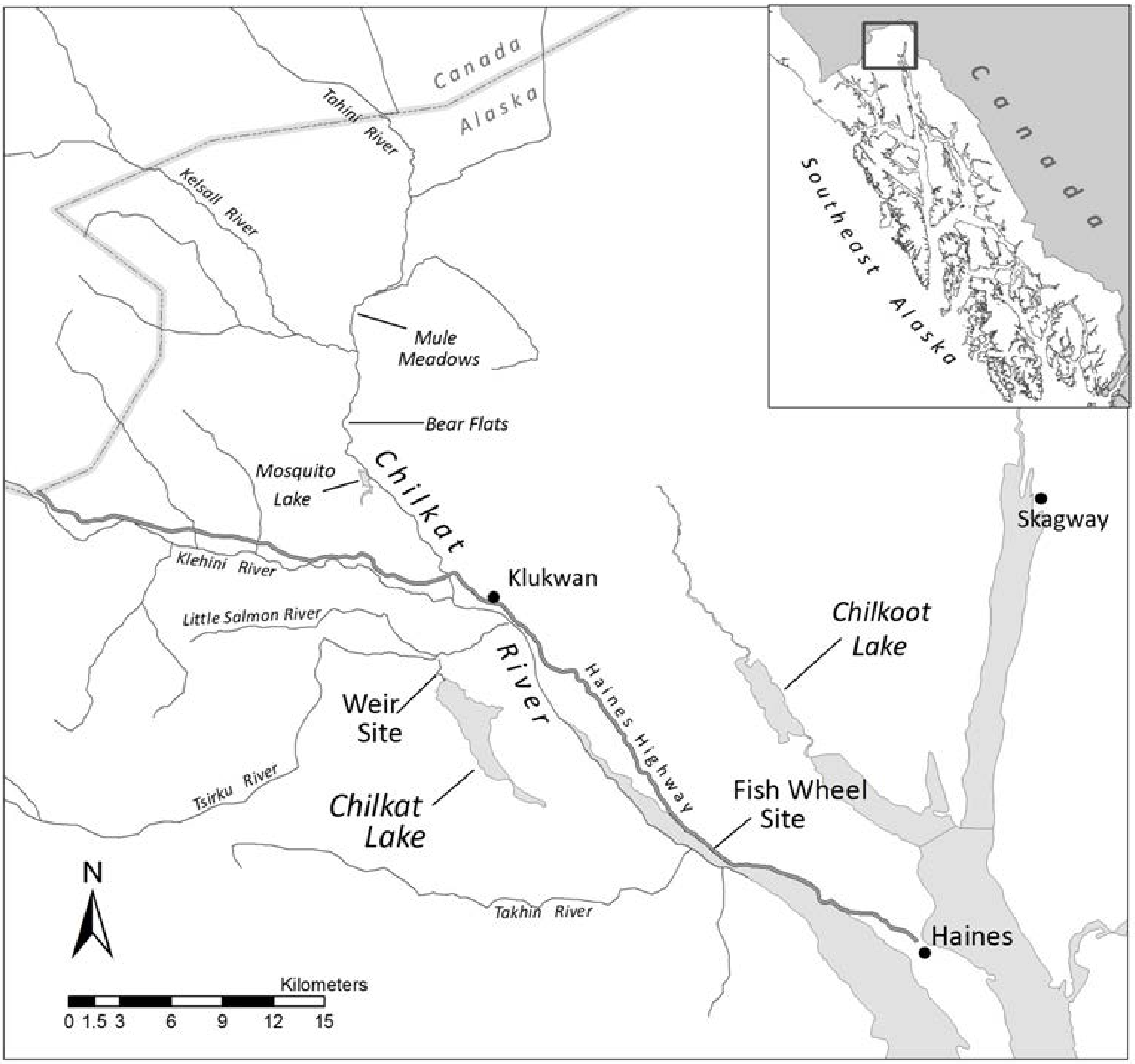


Figure 2.–Chilkat River drainage, with fish wheel locations and the Chilkat Lake weir location.

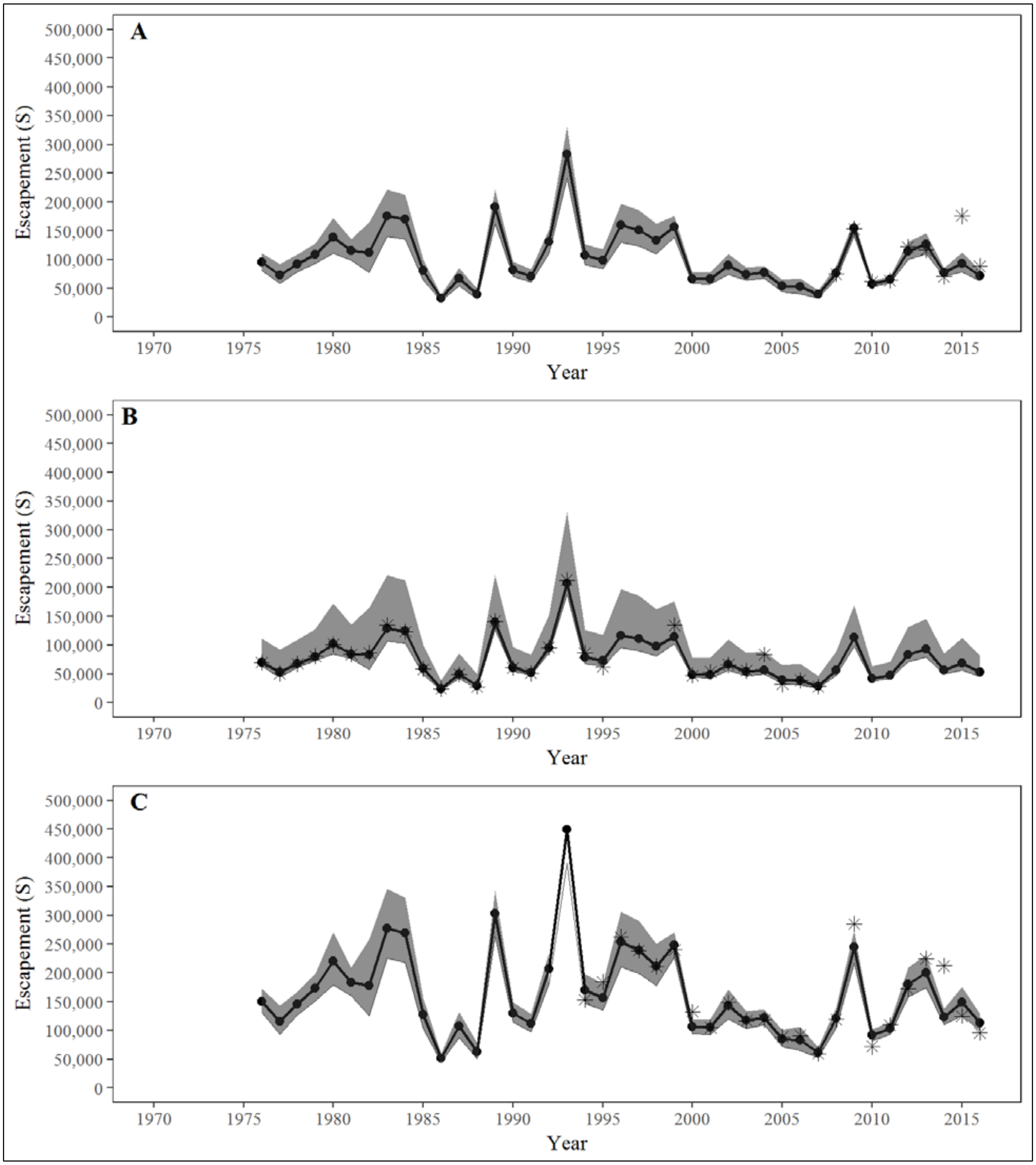


Figure 3.–Point estimates (posterior median; solid line) and 95% credibility intervals (shaded areas) of escapement (Figure A) and indices of escapement (Figure B and Figure C) from a state-space model of Chilkat Lake sockeye salmon, 1976–2016. Figure A is the observed (stars) and modeled (circles) DIDSON counts, Figure B is the observed (stars) and modeled (circles) weir counts, and Figure C is the observed (stars) and modeled (circles) mark–recapture estimates.

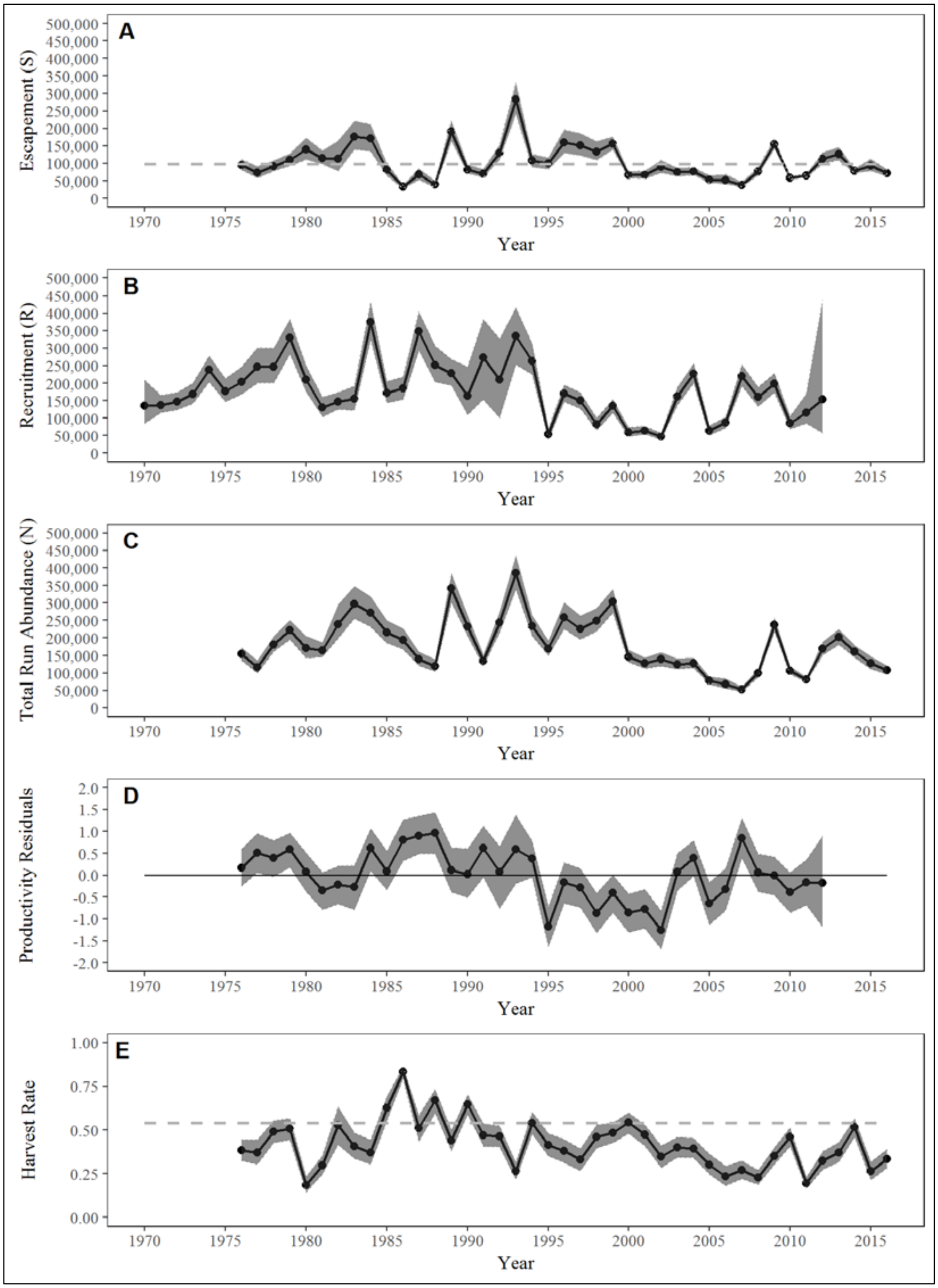


Figure 4.–Point estimates (posterior medians; solid lines) and 95% credibility intervals (shaded areas) of escapement, recruitment by brood year, total run abundance, Ricker productivity residuals by brood year, and harvest rates from a state-space model of Chilkat Lake sockeye salmon, 1976–2016. Posterior medians of $S_{MSY}$ and $U_{MSY}$ are plotted as dashed horizontal reference lines in Figures A and E, respectively.

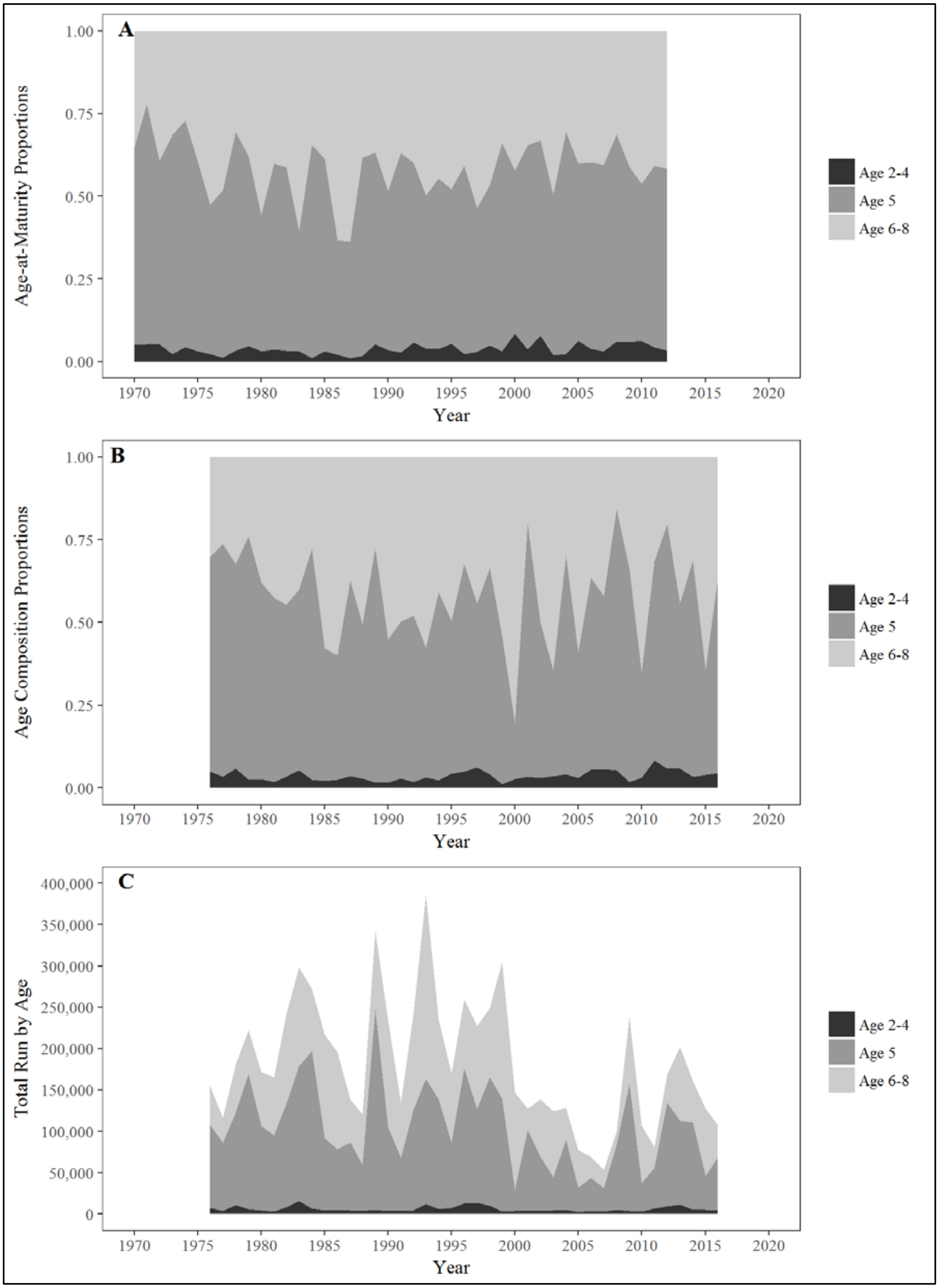


Figure 5.–Estimated mean age-at-maturity proportions by brood year (1970–2012; top), mean age composition proportions of annual run (1976–2016; middle), and mean total run by age (bottom), from a state-space model fitted to data from Chilkat Lake sockeye salmon. Top and middle figures are area graphs in which the distance between lines represents the age proportions.

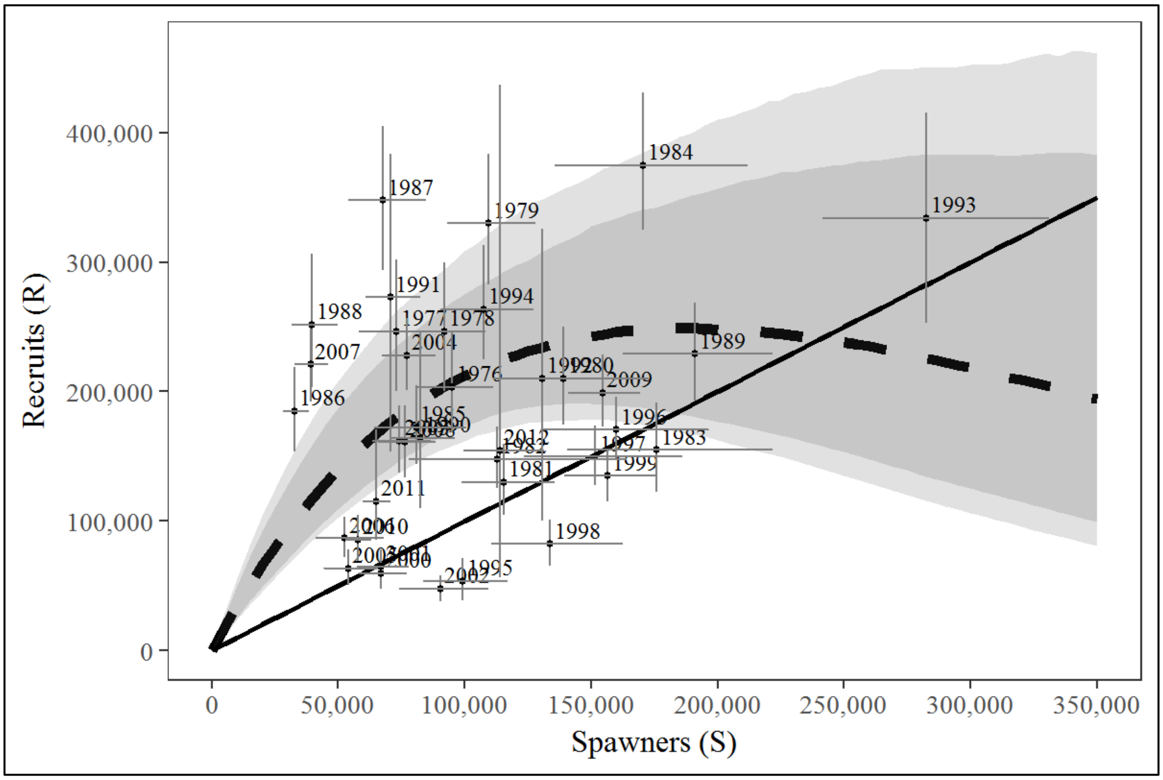


Figure 6.–Plausible spawner-recruit relationships for Chilkat Lake sockeye salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for calendar years 1976–2016. Posterior medians of recruits and spawners are plotted as brood year labels with 95% credibility intervals (grey lines). The heavy dashed line is the Ricker relationship constructed from ln($\alpha$') and $\beta$ posterior medians with 90% and 95% credibility intervals (shaded areas). Recruits replace spawners on the solid diagonal line.

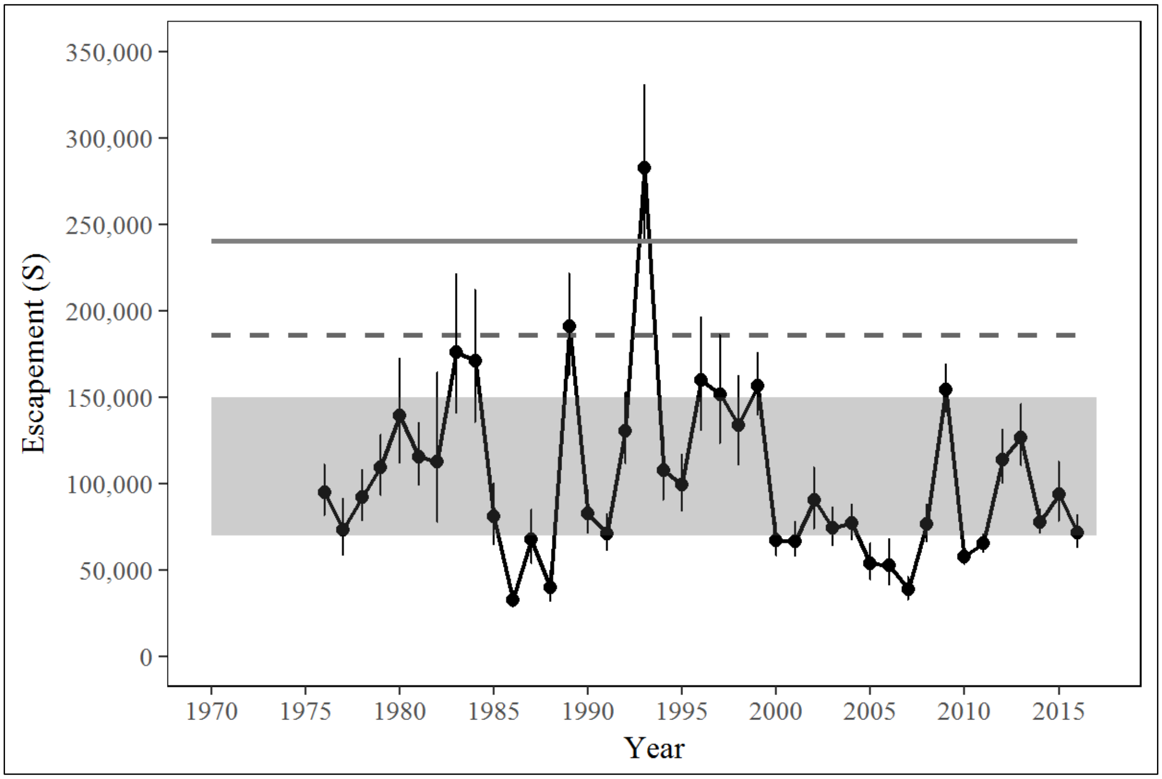


Figure 7.–Posterior medians of historical estimates of escapement and 95% credibility intervals (vertical lines) for sockeye salmon obtained by fitting a state-space model to Chilkat Lake sockeye salmon data, 1976–2016. The shaded area brackets the recommended goal range of 70,000 to 150,000 spawners. Posterior medians of $S_{MSR}$ (dotted line) and $S_{EQ}$ (solid line) are plotted as horizontal reference lines.

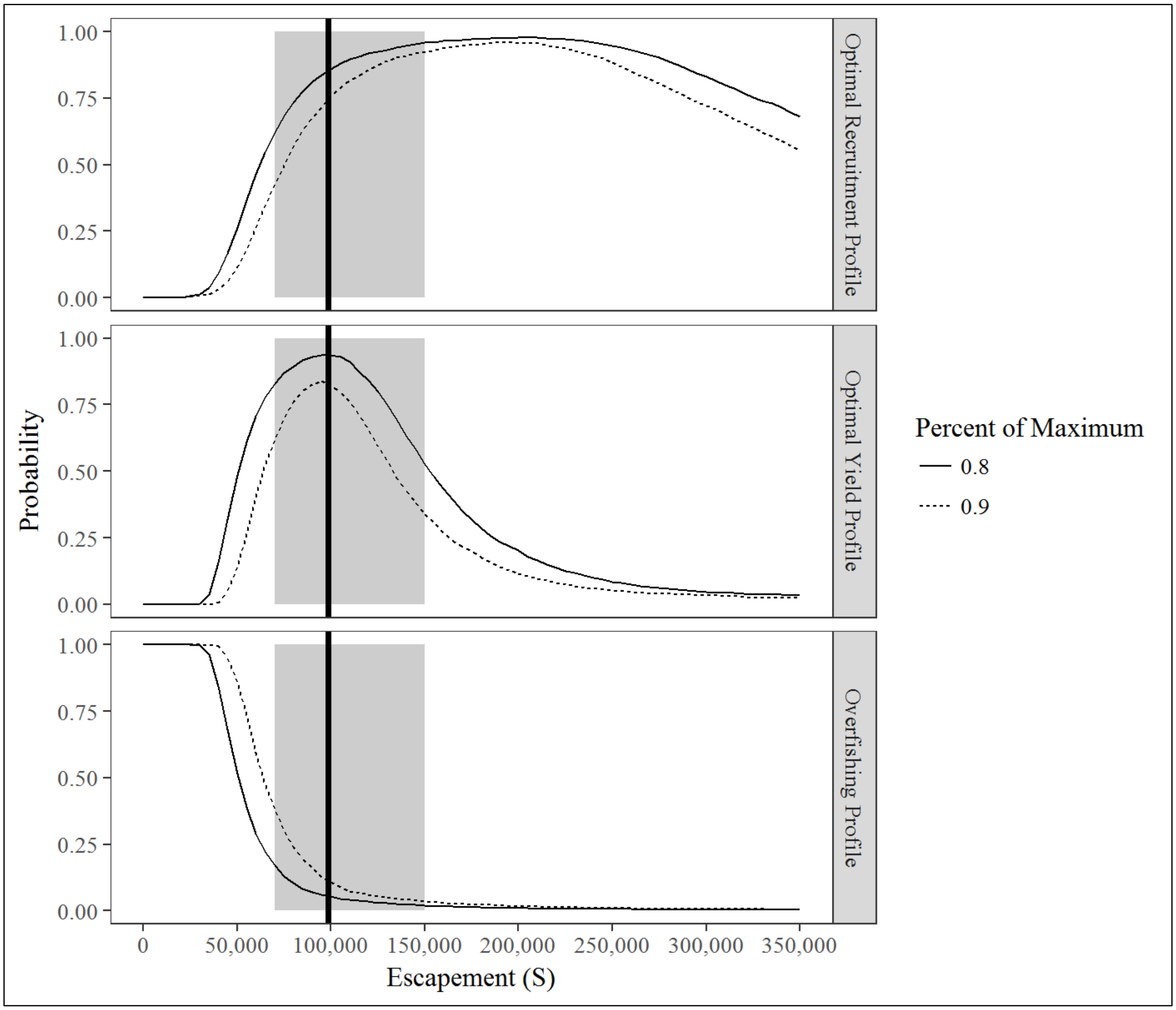


Figure 8.–Optimal recruitment profiles (ORPs), optimal yield profiles (OYPs), and overfishing profiles (OFPs) for Chilkat Lake sockeye salmon. OYPs and ORPs show probability that a specified spawning abundance will result in specified fractions (80% and 90% line) of maximum sustained yield or maximum 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 biological escapement goal range of 70,000 to 150,000 spawners and the solid vertical line is the posterior median of spawning abundance at maximum sustained yield obtained from the state-space model.

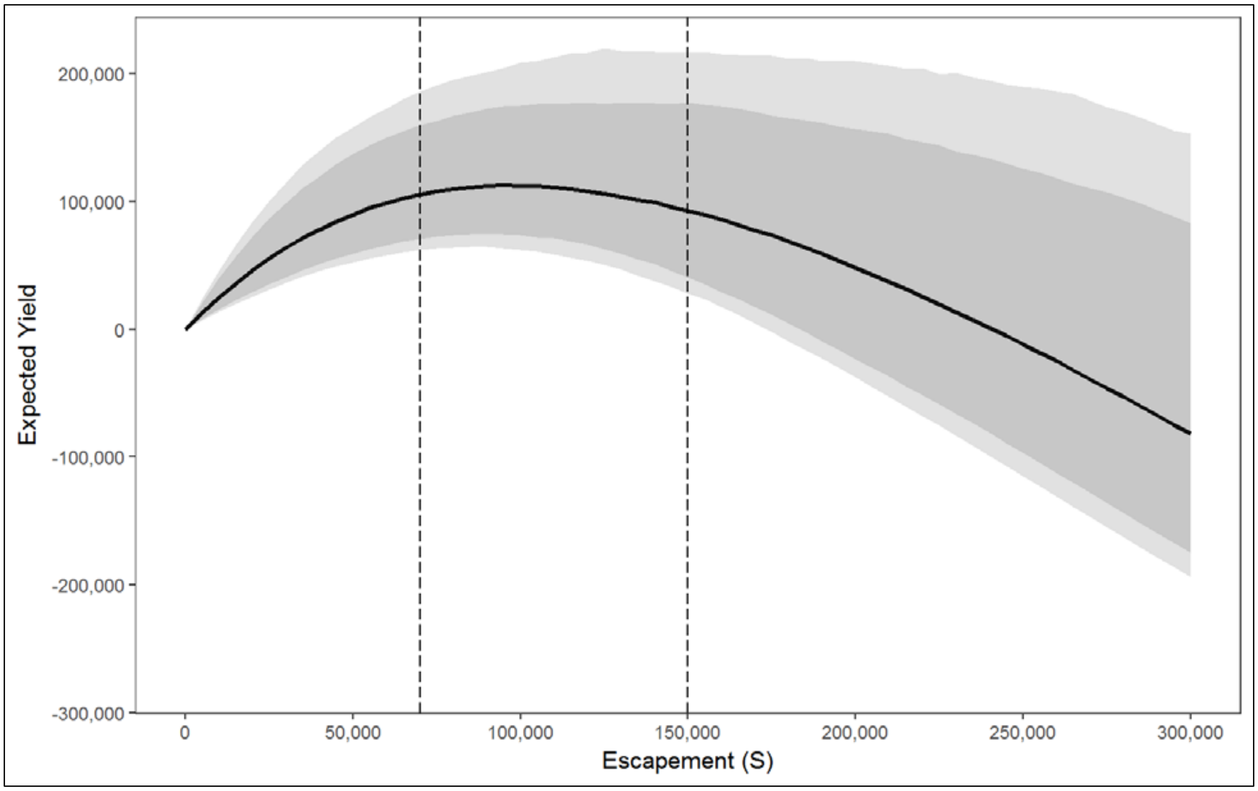


Figure 9.–Expected sustained yield (solid black line) and 90% and 95% credibility intervals (shaded areas) versus spawning escapement for Chilkat Lake sockeye salmon. Dotted vertical lines bracket the recommended escapement goal range of 70,000 to 150,000 spawners.

# APPENDIX A:
# ESTIMATES OF HARVEST BY AGE 1976–1983 AND EXCLUDED HARVESTS 1976–2016

Appendix A1.–Age composition of sockeye salmon in the Chilkat Lake total run, 1976–1983 (from Table 1.4 in McPherson 1990).

| Year | Age Class | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Age 1.1 | Age 0.3 | Age 1.2 | Age 2.1 | Age 0.4 | Age 1.3 | Age 2.2 | Age 3.1 | Age 1.4 | Age 2.3 | Age 3.2 | Age 1.5 | Age 2.4 | Age 3.3 | |
| 1976 | 175 | 0 | 5,743 | 1,050 | 0 | 21,178 | 65,584 | 0 | 0 | 34,535 | 656 | 0.00 | 0 | 136 | 129,057 |
| 1977 | 0 | 0 | 2,793 | 0 | 0 | 19,708 | 41,592 | 0 | 0 | 18,340 | 0 | 0.00 | 0 | 0 | 82,433 |
| 1978 | 0 | 0 | 9,715 | 0 | 0 | 16,232 | 84,795 | 0 | 0 | 45,651 | 693 | 0.00 | 0 | 0 | 157,086 |
| 1979 | 0 | 0 | 3,975 | 0 | 0 | 55,523 | 98,469 | 0 | 0 | 37,782 | 165 | 0.00 | 0 | 669 | 196,583 |
| 1980 | 0 | 0 | 3,053 | 0 | 0 | 9,184 | 68,309 | 0 | 0 | 35,322 | 10,160 | 0.00 | 0 | 0 | 126,028 |
| 1981 | 0 | 0 | 1,717 | 83 | 0 | 21,729 | 50,546 | 0 | 56 | 57,075 | 933 | 0.00 | 20 | 390 | 132,549 |
| 1982 | 220 | 0 | 3,503 | 1,550 | 0 | 32,174 | 69,986 | 0 | 0 | 97,129 | 1,799 | 0.00 | 0 | 896 | 207,257 |
| 1983 | 967 | 0 | 6,720 | 4,478 | 0 | 73,011 | 69,181 | 0 | 95 | 103,005 | 435 | 0.00 | 23 | 180 | 258,095 |

Appendix A2.–Harvest rates by age class for Chilkat Lake sockeye salmon, 1976–1983 (from Table 1.4 in McPherson 1990).

| Year | Age Class | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Age 1.1 | Age 0.3 | Age 1.2 | Age 2.1 | Age 0.4 | Age 1.3 | Age 2.2 | Age 3.1 | Age 1.4 | Age 2.3 | Age 3.2 | Age 1.5 | Age 2.4 | Age 3.3 | |
| 1976 | 0% | 0% | 47% | 0% | 0% | 32% | 53% | 0% | 0% | 42% | 47% | 0% | 0% | 100% | 46% |
| 1977 | 0% | 0% | 47% | 0% | 0% | 60% | 43% | 0% | 0% | 58% | 0% | 0% | 0% | 0% | 50% |
| 1978 | 0% | 0% | 33% | 0% | 0% | 29% | 61% | 0% | 0% | 64% | 65% | 0% | 0% | 0% | 57% |
| 1979 | 0% | 0% | 89% | 0% | 0% | 46% | 72% | 0% | 0% | 39% | 100% | 0% | 0% | 92% | 59% |
| 1980 | 0% | 0% | 23% | 0% | 0% | 14% | 22% | 0% | 0% | 32% | 23% | 0% | 0% | 0% | 24% |
| 1981 | 0% | 0% | 82% | 100% | 0% | 53% | 22% | 0% | 0% | 42% | 9% | 0% | 100% | 100% | 37% |
| 1982 | 0% | 0% | 54% | 0% | 0% | 76% | 45% | 0% | 0% | 71% | 20% | 0% | 0% | 29% | 61% |
| 1983 | 10% | 0% | 44% | 0% | 0% | 41% | 37% | 0% | 76% | 63% | 45% | 0% | 0% | 68% | 48% |

Appendix A3.–Estimated harvest by age class of Chilkat Lake sockeye salmon in the District 15 commercial drift gillnet fishery, 1976–1983 (age composition multiplied by harvest rates).

| | Age Class | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Age 1.1 | Age 0.3 | Age 1.2 | Age 2.1 | Age 0.4 | Age 1.3 | Age 2.2 | Age 3.1 | Age 1.4 | Age 2.3 | Age 3.2 | Age 1.5 | Age 2.4 | Age 3.3 | Total |
| 1976 | 0 | 0 | 2,699 | 0 | 0 | 6,777 | 34,760 | 0 | 0 | 14,505 | 308 | 0 | 0 | 136 | 59,185 |
| 1977 | 0 | 0 | 1,313 | 0 | 0 | 11,825 | 17,885 | 0 | 0 | 10,637 | 0 | 0 | 0 | 0 | 41,659 |
| 1978 | 0 | 0 | 3,206 | 0 | 0 | 4,707 | 51,725 | 0 | 0 | 29,217 | 450 | 0 | 0 | 0 | 89,305 |
| 1979 | 0 | 0 | 3,538 | 0 | 0 | 25,541 | 70,898 | 0 | 0 | 14,735 | 165 | 0 | 0 | 615 | 115,491 |
| 1980 | 0 | 0 | 702 | 0 | 0 | 1,286 | 15,028 | 0 | 0 | 11,303 | 2,337 | 0 | 0 | 0 | 30,656 |
| 1981 | 0 | 0 | 1,408 | 83 | 0 | 11,516 | 11,120 | 0 | 0 | 23,972 | 84 | 0 | 20 | 390 | 48,593 |
| 1982 | 0 | 0 | 1,892 | 0 | 0 | 24,452 | 31,494 | 0 | 0 | 68,962 | 360 | 0 | 0 | 260 | 127,419 |
| 1983 | 97 | 0 | 2,957 | 0 | 0 | 29,935 | 25,597 | 0 | 72 | 64,893 | 196 | 0 | 0 | 122 | 123,868 |

Appendix A4.–Estimated harvest proportions by age class of Chilkat Lake sockeye salmon in the District 15 commercial drift gillnet fishery, 1976–1983.

| | Age Class | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Age 1.1 | Age 0.3 | Age 1.2 | Age 2.1 | Age 0.4 | Age 1.3 | Age 2.2 | Age 3.1 | Age 1.4 | Age 2.3 | Age 3.2 | Age 1.5 | Age 2.4 | Age 3.3 | Total |
| 1976 | 0.000 | 0.000 | 0.046 | 0.000 | 0.000 | 0.115 | 0.587 | 0.000 | 0.000 | 0.245 | 0.005 | 0.000 | 0.000 | 0.002 | 1.000 |
| 1977 | 0.000 | 0.000 | 0.032 | 0.000 | 0.000 | 0.284 | 0.429 | 0.000 | 0.000 | 0.255 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 |
| 1978 | 0.000 | 0.000 | 0.036 | 0.000 | 0.000 | 0.053 | 0.579 | 0.000 | 0.000 | 0.327 | 0.005 | 0.000 | 0.000 | 0.000 | 1.000 |
| 1979 | 0.000 | 0.000 | 0.031 | 0.000 | 0.000 | 0.221 | 0.614 | 0.000 | 0.000 | 0.128 | 0.001 | 0.000 | 0.000 | 0.005 | 1.000 |
| 1980 | 0.000 | 0.000 | 0.023 | 0.000 | 0.000 | 0.042 | 0.490 | 0.000 | 0.000 | 0.369 | 0.076 | 0.000 | 0.000 | 0.000 | 1.000 |
| 1981 | 0.000 | 0.000 | 0.029 | 0.002 | 0.000 | 0.237 | 0.229 | 0.000 | 0.000 | 0.493 | 0.002 | 0.000 | 0.000 | 0.008 | 1.000 |
| 1982 | 0.000 | 0.000 | 0.015 | 0.000 | 0.000 | 0.192 | 0.247 | 0.000 | 0.000 | 0.541 | 0.003 | 0.000 | 0.000 | 0.002 | 1.000 |
| 1983 | 0.001 | 0.000 | 0.024 | 0.000 | 0.000 | 0.242 | 0.207 | 0.000 | 0.001 | 0.524 | 0.002 | 0.000 | 0.000 | 0.001 | 1.000 |

Appendix A5.–Reproportioned harvest by age class of Chilkat Lake sockeye salmon in the District 15 commercial drift gillnet fishery, 1976–1983, based on Table 1.3 in McPherson (1990).

| | Age Class | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Age 1.1 | Age 0.3 | Age 1.2 | Age 2.1 | Age 0.4 | Age 1.3 | Age 2.2 | Age 3.1 | Age 1.4 | Age 2.3 | Age 3.2 | Age 1.5 | Age 2.4 | Age 3.3 | Total |
| 1976 | 0.000 | 0.000 | 0.021 | 0.000 | 0.000 | 0.054 | 0.275 | 0.000 | 0.000 | 0.115 | 0.002 | 0.000 | 0.000 | 0.001 | 0.469 |
| 1977 | 0.000 | 0.000 | 0.008 | 0.000 | 0.000 | 0.073 | 0.111 | 0.000 | 0.000 | 0.066 | 0.000 | 0.000 | 0.000 | 0.000 | 0.259 |
| 1978 | 0.000 | 0.000 | 0.030 | 0.000 | 0.000 | 0.044 | 0.478 | 0.000 | 0.000 | 0.270 | 0.004 | 0.000 | 0.000 | 0.000 | 0.826 |
| 1979 | 0.000 | 0.000 | 0.018 | 0.000 | 0.000 | 0.133 | 0.369 | 0.000 | 0.000 | 0.077 | 0.001 | 0.000 | 0.000 | 0.003 | 0.601 |
| 1980 | 0.000 | 0.000 | 0.013 | 0.000 | 0.000 | 0.024 | 0.283 | 0.000 | 0.000 | 0.213 | 0.044 | 0.000 | 0.000 | 0.000 | 0.578 |
| 1981 | 0.000 | 0.000 | 0.015 | 0.001 | 0.000 | 0.123 | 0.119 | 0.000 | 0.000 | 0.256 | 0.001 | 0.000 | 0.000 | 0.004 | 0.519 |
| 1982 | 0.000 | 0.000 | 0.007 | 0.000 | 0.000 | 0.089 | 0.115 | 0.000 | 0.000 | 0.251 | 0.001 | 0.000 | 0.000 | 0.001 | 0.464 |
| 1983 | 0.000 | 0.000 | 0.008 | 0.000 | 0.000 | 0.081 | 0.069 | 0.000 | 0.000 | 0.176 | 0.001 | 0.000 | 0.000 | 0.000 | 0.335 |

Appendix A6.–Total sockeye salmon harvest and estimated Chilkat Lake contribution in the commercial purse-seine fisheries in District 12 (Subdistricts 112-14, 112-16, and Hawk Inlet test fishery) and District 14, and reported sockeye salmon subsistence harvest in Chilkat Inlet and the Chilkat River.

| | Commercial Harvest | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Total Sockeye Salmon Harvest: | | | | | | | |
| Year | Subdistrict 112-14 | Subdistrict 112-16 | Hawk Inlet Test Fishery | District 14 | Total | Estimated Percent Chilkat Lake[a] | Estimated Harvest Chilkat Lake[a] | Reported Subsistence Harvest |
| 1985 | 162 | 30,128 | 0 | 3,638 | 33,928 | | | 1,708 |
| 1986 | 0 | 4,716 | 14 | 1,479 | 6,209 | | | 1,695 |
| 1987 | 0 | 39,900 | 0 | 3,793 | 43,693 | | | 2,181 |
| 1988 | 34 | 303 | 17 | 1,244 | 1,598 | | | 2,647 |
| 1989 | 0 | 35,550 | 406 | 6,111 | 42,067 | 17% | 7,302 | 3,165 |
| 1990 | 0 | 11,397 | 29 | 4,161 | 15,587 | | | 4,001 |
| 1991 | 0 | 23,095 | 565 | 4,307 | 27,967 | | | 4,032 |
| 1992 | 1,067 | 31,104 | 188 | 6,454 | 38,813 | | | 3,932 |
| 1993 | 616 | 43,243 | 743 | 9,806 | 54,408 | | | 3,902 |
| 1994 | 2,543 | 45,797 | 668 | 10,536 | 59,544 | | | 4,029 |
| 1995 | 2,436 | 2,943 | 896 | 264 | 6,539 | | | 5,137 |
| 1996 | 5,159 | 15,100 | 1412 | 0 | 21,671 | | | 5,352 |
| 1997 | 2,066 | 10,876 | 496 | 5,123 | 18,561 | | | 4,113 |
| 1998 | 1,616 | 15,492 | 703 | 0 | 17,811 | | | 5,094 |
| 1999 | 6,067 | 26,382 | 908 | 17,301 | 50,658 | | | 5,271 |
| 2000 | 4,895 | 8,763 | 796 | 1,111 | 15,565 | | | 4,626 |
| 2001 | 13,483 | 36,006 | 1110 | 43,739 | 94,338 | | | 4,432 |
| 2002 | 3,517 | 14,155 | 884 | 4,592 | 23,148 | | | 4,481 |
| 2003 | 7,432 | 44,795 | 590 | 11,973 | 64,790 | | | 4,579 |
| 2004 | 4,461 | 132,061 | 2407 | 35,254 | 174,183 | | | 4,566 |
| 2005 | 5,481 | 74,111 | 574 | 13,354 | 93,520 | | | 3,383 |
| 2006 | 3,112 | 17,074 | 441 | 8,657 | 29,284 | | | 3,527 |
| 2007 | 7,737 | 31,925 | 1383 | 16,948 | 57,993 | | | 2,353 |
| 2008 | 2,594 | 0 | 658 | 0 | 3,252 | | | 5,670 |
| 2009 | 2,212 | 31,836 | 856 | 5,877 | 40,781 | | | 6,649 |
| 2010 | 2,640 | 0 | 649 | 0 | 3,289 | | | 6,030 |
| 2011 | 6,526 | 60,946 | 484 | 38,908 | 106,864 | | | 5,192 |
| 2012 | 5,977 | 0 | 1826 | 0 | 7,803 | 7% | 522 | 5,136 |
| 2013 | 5,083 | 23,480 | 1905 | 11,426 | 41,894 | 25% | 10,517 | 6,328 |
| 2014 | 3,604 | 0 | 2051 | 284 | 5,939 | 11% | 655 | 6,553 |
| 2015 | 6,575 | 72,641 | 734 | 22,887 | 102,837 | | | 3,431 |
| 2016 | 6,126 | 0 | 1379 | 0 | 7,505 | | | 5,348 |
| Average | 3,538 | 27,619 | 805 | 9,038 | 41,001 | 15% | 4,749 | 4,329 |

[a] Estimated Chilkat Lake sockeye salmon contribution in 1989 from Appendix B in Ingledue (1989), and in 2012–2014 from Table 4, Appendix C1, and Appendix C2 in Gilk-Baumer et al. (2015). Estimated percent contributions of Chilkat Lake fish were based only on sampled harvests so total sockeye salmon harvest × percent Chilkat Lake fish does not exactly equal the estimated Chilkat Lake harvest shown here.

Appendix A7.–Escapement proportions by age class for Chilkat Lake sockeye salmon, 1976–1981.

| | Age Class | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Age 1.1 | Age 0.3 | Age 1.2 | Age 2.1 | Age 0.4 | Age 1.3 | Age 2.2 | Age 3.1 | Age 1.4 | Age 2.3 | Age 3.2 | Age 1.5 | Age 2.4 | Age 3.3 | Total |
| 1976 | 0.003 | 0.000 | 0.044 | 0.015 | 0.000 | 0.206 | 0.441 | 0.000 | 0.000 | 0.287 | 0.005 | 0.000 | 0.000 | 0.000 | 1.000 |
| 1977 | 0.000 | 0.000 | 0.036 | 0.000 | 0.000 | 0.193 | 0.581 | 0.000 | 0.000 | 0.189 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 |
| 1978 | 0.000 | 0.000 | 0.096 | 0.000 | 0.000 | 0.170 | 0.488 | 0.000 | 0.000 | 0.242 | 0.004 | 0.000 | 0.000 | 0.000 | 1.000 |
| 1979 | 0.000 | 0.000 | 0.005 | 0.000 | 0.000 | 0.370 | 0.340 | 0.000 | 0.000 | 0.284 | 0.000 | 0.000 | 0.000 | 0.001 | 1.000 |
| 1980 | 0.000 | 0.000 | 0.025 | 0.000 | 0.000 | 0.083 | 0.559 | 0.000 | 0.000 | 0.252 | 0.082 | 0.000 | 0.000 | 0.000 | 1.000 |
| 1981 | 0.000 | 0.000 | 0.004 | 0.000 | 0.000 | 0.122 | 0.470 | 0.000 | 0.001 | 0.394 | 0.010 | 0.000 | 0.000 | 0.000 | 1.000 |

# APPENDIX B:
# RJAGS MODEL CODE, DATA OBJECTS, AND MULTINOMIAL AGE COUNTS

Appendix B1.–RJAGS model code for the Bayesian MCMC statistical analysis of the Chilkat Lake sockeye salmon data run reconstruction model, 1976–2016. This code can be found at the GitHub site, located here: https://github.com/fssem1/Chilkat-Lake-Sockeye-State-Space-Model. Please contact the authors of this report if you have problems opening this link or have questions or comments regarding the analysis.

**--LIBRARIES--**

```
Install.packages ("coda","emdbook","MASS","gtools","Hmisc","rbugs","R2OpenBUGS", "rjags","lattice",
"rmarkdown","boot", "ggplot2", "dplyr","tidyr","shinystan","reshape2","grid","runjags","matrixStats", "gdata",
"gsl")
```

**--CREATE DATA FILE--**

```
rawdat<-as.data.frame(read.csv("data/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"])#age comp count data matrix
colnames(x)<-NULL
n.a<-rowSums(x)
```

**--STATE SPACE MODEL--**

```
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,)
  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)
```

-continued-

```
  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
```

**--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)
 pi.1 ~ dbeta(1,1)
 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)—**

```
 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]
   }
 }
```

-continued-

**--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)
  log.S[y] <- log(S[y])
}
```

**--ESCAPEMENT INDICES --**

```
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])
  qS.mr[y]<-exp(log.qS.mr[y])
  qS.weir[y]<-exp(log.qS.weir[y])
}
q.mr<-exp(log.q.mr)
q.weir<-exp(log.q.weir)
}
```

-continued-

**--WRITE MODEL TO TEXT FILE TO BE CALLED BY OPENBUGS--**

```
model_file_loc=paste("code/Chilkat_Sockeye.txt", sep="")
write.model(mod, paste("code/Chilkat_Sockeye.txt", sep=""))
```

**--MODEL DATA--**

```
dat=list(Y = nyrs, A=nages, a.min=a.min, a.max=a.max,
        x=x, DS=DS, DS.cv=DS.cv, mr=mr, mr.cv=mr.cv, weir=weir,
        weir.cv=weir.cv, Hbelow=Hbelow,Hbelow.cv=Hbelow.cv, n.a=n.a)
```

**--RUN JAGS--**

```
ptm = proc.time()
jmod <- jags.model(file='code/Chilkat_Sockeye.txt', data=dat, n.chains=3, inits=inits, n.adapt=10000)
x<-update(jmod, n.iter=1000000, by=1000, progress.bar='text', DIC=T, n.burnin=10000)
post <- coda.samples(jmod, parameters, n.iter=1000000, thin=1000, n.burnin=10000)
post.samp <- post
```

**--CREATE CODA SAMPLES FOR LAMBERT W REFERENCE POINTS --**

```
post2 <- coda.samples(jmod, c("lnalpha", "beta", "lnalpha.c"), n.iter=1000000, thin=1000, n.burnin=10000)
x <- as.array(post2)
x <- data.frame(x)
coda1 <- x[,1:3]
coda2 <- x[,4:6]
coda3 <- x[,7:9]
coda1<- rename.vars(coda1, from=c("beta.1","lnalpha.1","lnalpha.c.1"), to=c("beta","lnalpha", "lnalpha.c"))
coda2<- rename.vars(coda2, from=c("beta.2","lnalpha.2","lnalpha.c.2"), to=c("beta","lnalpha", "lnalpha.c"))
coda3<- rename.vars(coda3, from=c("beta.3","lnalpha.3","lnalpha.c.3"), to=c("beta","lnalpha", "lnalpha.c"))
coda<-rbind(coda1,coda2,coda3)
coda$S.max <- 1 / coda$beta
coda$S.eq.c <- coda$lnalpha.c * coda$S.max
coda$Smsy_lambert <- (1-lambert_W0(exp(1-coda$lnalpha.c)))/coda$beta
coda$Umsy_lambert <- (1-lambert_W0(exp(1-coda$lnalpha.c)))
coda<-as.data.frame(coda)
summary<-summary(coda)
q1<-apply(coda,2,quantile,probs=c(0,0.025,0.5,0.975,1))
write.csv(q1, file= paste("results/quantiles_lambert.csv") )
write.csv(summary, file= paste("results/lambert.csv") )
write.csv(coda, file= paste("results/coda_lambert.csv") )
```

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

Appendix B2.–RJAGS data objects for the Bayesian MCMC statistical analysis of the Chilkat Lake sockeye salmon data run reconstruction model, 1976–2016. The multinomial total run age counts (*x*) may not sum exactly to the effective sample size of 100 due to rounding. The total run age count *x*4 represents ages 2–4, the total run age count *x*5 represents age 5, and the total run age count *x*6 represents ages 6–8. *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 coefficients of variation (DS.cv), 'weir' are the weir escapement counts with associated coefficients of variation (weir.cv), 'mr' are the mark–recapture escapement estimates with the associated coefficients of variation (mr.cv), and 'Hbelow' is the total harvest with associated coefficients of variation (Hbelow.cv).

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

Appendix B3.–Total observed escapement by return year (2010–2016) weighted by statistical week. Total observed escapement may not exactly equal reported DIDSON counts due to rounding.

| | Age | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Age 2 | Age 3 | Age 4 | Age 5 | Age 6 | Age 7 | Age 8 | Total |
| 2010 | 0 | 438 | 1,998 | 22,988 | 36,431 | 53 | 0 | 61,907 |
| 2011 | 0 | 138 | 5,874 | 39,039 | 18,429 | 149 | 0 | 63,628 |
| 2012 | 0 | 611 | 5,820 | 93,889 | 21,312 | 179 | 0 | 121,811 |
| 2013 | 0 | 231 | 9,312 | 56,579 | 50,002 | 176 | 0 | 116,300 |
| 2014 | 0 | 378 | 1,393 | 50,472 | 17,626 | 601 | 0 | 70,470 |
| 2015 | 0 | 208 | 7,883 | 51,505 | 116,228 | 49 | 0 | 175,872 |
| 2016 | 0 | 139 | 3,553 | 52,745 | 32,075 | 0 | 0 | 88,512 |

Appendix B4.–Total observed District 15 commercial drift gillnet fishery harvest by return year (2010–2016) and age weighted by statistical week.

| | Age | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Age 2 | Age 3 | Age 4 | Age 5 | Age 6 | Age 7 | Age 8 | Total |
| 2010 | 0 | 0 | 593 | 11,665 | 35,640 | 181 | 0 | 48,079 |
| 2011 | 0 | 0 | 397 | 9,660 | 5,520 | 22 | 0 | 15,599 |
| 2012 | 0 | 0 | 4,365 | 38,072 | 12,224 | 223 | 0 | 54,884 |
| 2013 | 0 | 0 | 2,074 | 39,767 | 33,448 | 299 | 0 | 75,588 |
| 2014 | 0 | 0 | 3,611 | 51,920 | 25,510 | 461 | 0 | 81,502 |
| 2015 | 0 | 0 | 683 | 10,463 | 21,932 | 7 | 0 | 33,085 |
| 2016 | 0 | 0 | 1,774 | 19,624 | 14,221 | 372 | 0 | 35,991 |

Appendix B5.–Total run by return year (2010–2016) and age. Observed escapement and observed harvest are combined.

| | Age | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Age 2 | Age 3 | Age 4 | Age 5 | Age 6 | Age 7 | Age 8 | Total |
| 2010 | 0 | 438 | 2,591 | 34,653 | 72,071 | 233 | 0 | 109,985 |
| 2011 | 0 | 138 | 6,271 | 48,699 | 23,949 | 171 | 0 | 79,227 |
| 2012 | 0 | 611 | 10,185 | 131,960 | 33,536 | 403 | 0 | 176,695 |
| 2013 | 0 | 231 | 11,386 | 96,345 | 83,450 | 475 | 0 | 191,888 |
| 2014 | 0 | 378 | 5,004 | 102,392 | 43,136 | 1,062 | 0 | 151,972 |
| 2015 | 0 | 208 | 8,566 | 61,967 | 138,160 | 57 | 0 | 208,957 |
| 2016 | 0 | 139 | 5,327 | 72,369 | 46,297 | 372 | 0 | 124,503 |

Appendix B6.–Total run (proportion) by return year (2010–2016) and age. Observed escapement and observed harvest are combined.

| | Age | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Age 2 | Age 3 | Age 4 | Age 5 | Age 6 | Age 7 | Age 8 | Total |
| 2010 | 0.00 | 0.00 | 0.02 | 0.32 | 0.66 | 0.00 | 0.00 | 1.00 |
| 2011 | 0.00 | 0.00 | 0.08 | 0.61 | 0.30 | 0.00 | 0.00 | 1.00 |
| 2012 | 0.00 | 0.00 | 0.06 | 0.75 | 0.19 | 0.00 | 0.00 | 1.00 |
| 2013 | 0.00 | 0.00 | 0.06 | 0.50 | 0.43 | 0.00 | 0.00 | 1.00 |
| 2014 | 0.00 | 0.00 | 0.03 | 0.67 | 0.28 | 0.01 | 0.00 | 1.00 |
| 2015 | 0.00 | 0.00 | 0.04 | 0.30 | 0.66 | 0.00 | 0.00 | 1.00 |
| 2016 | 0.00 | 0.00 | 0.04 | 0.58 | 0.37 | 0.00 | 0.00 | 1.00 |

Appendix B7.–Total run by return year and age based on an effective sample size of 100. Ages 2–4 and ages 6–8 are combined.

| | Age | | | Total |
|---|---|---|---|---|
| Year | Ages 2–4 | Age 5 | Ages 6–8 | (Effective Sample Size) |
| 2010 | 2.75 | 31.51 | 65.74 | 100 |
| 2011 | 8.09 | 61.47 | 30.44 | 100 |
| 2012 | 6.11 | 74.68 | 19.21 | 100 |
| 2013 | 6.05 | 50.21 | 43.74 | 100 |
| 2014 | 3.54 | 67.38 | 29.08 | 100 |
| 2015 | 4.20 | 29.66 | 66.15 | 100 |
| 2016 | 4.39 | 58.13 | 37.48 | 100 |

Appendix B8.–Total run multinomial age counts (rounded). The total run age counts (*x*) may not sum exactly to the effective sample size of 100 due to rounding. The total run age count *x*4 represents ages 2–4, the total run age count *x*5 represents age 5, and the total run age count *x*6 represents ages 6–8 in the state space model.

| | Age Counts | | |
|---|---|---|---|
| Year | *x*4 | *x*5 | *x*6 |
| 2010 | 3 | 32 | 66 |
| 2011 | 8 | 61 | 30 |
| 2012 | 6 | 75 | 19 |
| 2013 | 6 | 50 | 44 |
| 2014 | 4 | 67 | 29 |
| 2015 | 4 | 30 | 66 |
| 2016 | 4 | 58 | 37 |

# APPENDIX C:
# ESCAPEMENT GOALS RELATIVE TO ESTIMATES OF SPAWNING ABUNDANCE PROVIDING MAXIMUM SUSTAINED YIELD FOR 22 ALASKA SOCKEYE SALMON STOCKS

Appendix C1.–Escapement goal ranges for 22 Alaska sockeye salmon stocks that are based on estimates of escapements that provide maximum sustained yield ($S_{MSY}$). The lower bound (LB) and upper bound (UB) percentages show the change from the LB and UB value relative to the $S_{MSY}$ value. *Note*: Information was gleaned from Munro and Volk (2016); ‘Type’ describes whether the established goal is a sustainable escapement goal (SEG) or biological escapement goal (BEG); SRA = spawner-recruit analysis; PWS = Prince William Sound.

| System | Area | Type | $S_{MSY}$ | LB | UB | LB% | UB% | Basis of Escapement Goal | Source |
|---|---|---|---|---|---|---|---|---|---|
| Middle Fork Goodnews River | Kuskokwim | BEG | 21,890 | 18,000 | 40,000 | 82% | 183% | SRA | Molyneaux and Brannian 2006 |
| Eshamy Lake | PWS | BEG | 19,622 | 13,000 | 28,000 | 66% | 143% | SRA | Fair et al. 2008 |
| Kasilof River | Upper Cook Inlet | BEG | 240,000 | 160,000 | 340,000 | 67% | 142% | SRA | Fair et al. 2010 |
| Russian River (Early Run) | Upper Cook Inlet | BEG | 36,255 | 22,000 | 42,000 | 61% | 116% | SRA | Fair et al. 2010 |
| Chilkat Lake | Southeast | BEG | 105,000 | 70,000 | 150,000 | 67% | 143% | SRA | Eggers et al. 2010 |
| Chilkoot Lake | Southeast | SEG | 58,000 | 38,000 | 86,000 | 66% | 148% | SRA | Eggers et al. 2009b |
| East Alsek-Doame River | Southeast | BEG | 16,000 | 13,000 | 26,000 | 81% | 163% | SRA | Clark et al. 2003 |
| Klukshu River | Southeast | BEG | 9,102 | 7,500 | 11,000 | 82% | 121% | SRA | Eggers and Bernard 2011 |
| McDonald Lake | Southeast | SEG | 82,000 | 55,000 | 120,000 | 67% | 146% | SRA | Eggers et al. 2009a |
| Redoubt Lake | Southeast | BEG | 17,400 | 10,000 | 25,000 | 57% | 144% | SRA | Geiger 2003 |
| Situk River | Southeast | BEG | 50,000 | 30,000 | 70,000 | 60% | 140% | SRA | Clark et al. 2002 |
| Speel Lake | Southeast | SEG | 6200 | 4,000 | 9,000 | 65% | 145% | SRA | Heinl et al. 2014 |
| Nelson River | AK Peninsula | BEG | 153,000 | 97,000 | 219,000 | 63% | 143% | SRA | Nelson et al. 2006 |
| Chignik River (Early Run) | Chignik | BEG | 408,721 | 350,000 | 450,000 | 86% | 110% | SRA, Yield Analysis | Sagalkin et al. 2013 |
| Afognak (Litnik) River | Kodiak | BEG | 34000 | 20,000 | 50,000 | 59% | 147% | SRA | Nelson et al. 2005 |
| Buskin Lake | Kodiak | BEG | 6,650 | 5,000 | 8,000 | 75% | 120% | SRA | Nemeth et al. 2010 |
| Frazer Lake | Kodiak | BEG | 118,000 | 75,000 | 170,000 | 64% | 144% | SRA | Honnold et al. 2007 |
| Karluk River Early Run | Kodiak | BEG | 175,000 | 110,000 | 250,000 | 63% | 143% | SRA | Honnold et al. 2007 |
| Karluk River Late Run | Kodiak | BEG | 270,000 | 170,000 | 380,000 | 63% | 141% | SRA | Nelson et al. 2005 |
| Saltery Lake | Kodiak | BEG | 23,600 | 15,000 | 35,000 | 64% | 148% | SRA; Zooplankton Model | Nemeth et al. 2010 |
| Upper Station (Early Run) | Kodiak | BEG | 66,000 | 43,000 | 93,000 | 65% | 141% | SRA | Nemeth et al. 2010 |
| Upper Station (Late Run) | Kodiak | BEG | 186,000 | 120,000 | 265,000 | 65% | 142% | SRA | Nelson et al. 2005 |
| Average | | | | | | 68% | 142% | | |

Appendix C2.–Upper and lower escapement goal bounds for 22 Alaska sockeye salmon stocks that are based on estimates of escapements that provide maximum sustained yield ($S_{MSY}$) compared to the current Chilkat Lake escapement goal range. The current lower and upper bounds of the Chilkat Lake sockeye salmon range (70,000–150,000) are 0.67 and 1.43 times the estimated $S_{MSY}$ (105,000) from the autoregressive Ricker model with fry plants from Eggers et al. (2010) (brood years 1979–2002). The current lower and upper bounds of the Chilkat Lake sockeye salmon range (70,000–150,000) are 0.71 and 1.52 times the estimated $S_{MSY}$ (98,370) from the state-space model without fry plants (brood years 1976–2012). For reference, there is a vertical line at 1.