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Run Reconstruction, Spawner–Recruit Analysis, and Escapement Goal Recommendation for Chinook Salmon in the Copper River

by

Philip J. Joy

James W. Savereide

Matt Tyers

and

Steven J. Fleischman

January 2021

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

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Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

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

Mathematics, statistics

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

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RUN RECONSTRUCTION, SPAWNER-RECRUIT ANALYSIS, AND ESCAPEMENT GOAL RECOMMENDATION FOR CHINOOK SALMON IN THE COPPER RIVER

by
Philip Joy
James W. Savereide
Matt Tyers
Alaska Department of Fish and Game Division of Sport Fish, Fairbanks
and
Steven J. Fleischman (retired)
Alaska Department of Fish and Game Division of Sport Fish, Anchorage

Alaska Department of Fish and Game
Division of Sport Fish, Research and Technical Services
333 Raspberry Road, Anchorage, Alaska 99518-1565

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Philip J. Joy and James W. Savereide
Alaska Department of Fish and Game, Division of Sport Fish
1300 College Road, Fairbanks, AK 99701-1599, USA
and
Steven J. Fleischman (retired) and Matt Tyers
Alaska Department of Fish and Game, Division of Sport Fish
333 Raspberry Road, Anchorage, AK 99518, USA

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ABSTRACT

An age-structured state-space spawner–recruit model was fit to estimates of relative and absolute abundance, harvest, and age composition for Copper River Chinook salmon (*Oncorhynchus tshawytscha*) from 1980 to 2018. Bayesian statistical methods were employed to assess uncertainty in the presence of measurement error, serial correlation, and missing data. Ricker spawner–recruit parameters and management reference points were estimated, including the escapement that provides for maximum sustained yield (S_{MSY}). An additional analysis was performed on a subset of data from 1999 to 2018 that used only mark–recapture estimates of escapement and excluded abundance indices used in the full data set. The full data set produced an S_{MSY} of 22,844 spawners (95% credibility interval of 12,920–84,942 spawners) and the 1999–2018 data set produced an S_{MSY} of 26,951 spawners (95% credibility interval of 15,371–98,262 spawners). Different results may be partially explained by differences in data structure and may also indicate reduced productivity in more recent years. It is important to note that many escapements observed since 1999 were greater than those observed prior to 1999 and the increased contrast in observed escapements increased information and our understanding of true underlying stock production. After examining both analyses, it is recommended that a sustainable escapement goal range of 21,000 to 31,000 fish be adopted for Copper River Chinook salmon. Escapement is evaluated by subtracting estimates of inriver harvest from estimates of inriver abundance. Escapements within this range have a high probability of producing sustainable yields.

Key words: Chinook salmon, *Oncorhynchus tshawytscha*, Copper River, escapement, age composition, escapement goal, run reconstruction, spawner–recruit analysis, maximum sustained yield, measurement error, serial correlation, missing data, Bayesian statistics, JAGS

BACKGROUND

The Copper River is a glacially dominated system located in Southcentral Alaska and is the second largest river in Alaska in terms of mean annual discharge (Brabets 1997). It flows south from the Alaska, Wrangell, and Chugach Mountain ranges and empties into the Gulf of Alaska, east of Prince William Sound (Figures 1 and 2). The Copper River drainage (61,440 km^2) supports spawning populations of Chinook salmon *Oncorhynchus tshawytscha*, sockeye salmon *O. nerka*, coho salmon *O. kisutch*, chum salmon *O. keta*, and pink salmon *O. gorbuscha* as well as several resident fish species. The Copper River Chinook salmon stock is composed of 6 genetically identifiable major spawning populations (Upper Copper, Gulkana, Tazlina, Klutina, Tonsina, and Chitina; Templin et al. 2011). Radiotelemetry studies suggest there is negligible spawning downstream of the Chitina River (Savereide 2005; Figure 2).

Copper River Chinook salmon supports commercial, subsistence, personal use, and sport fisheries. The average annual Chinook salmon harvest from 2009–2018 was ~19,000 fish from these fisheries (Somerville 2019). Since 1999, the Copper River drainage has produced an average run of ~70,800 Chinook salmon; however, the recent 10-year average (2009–2018) is ~50,000 fish (Somerville 2019). This decline in production is likely due to the downward trend in Chinook salmon age-at-maturity and a decrease in age-specific size across Alaska (Lewis et al. 2015).

FISHERIES MANAGEMENT

Harvest of Copper River Chinook salmon is managed under guidelines established in 4 fishery management plans: 1) the *Copper River District Salmon Management Plan* (5 AAC 24.360); 2) the *Copper River King Salmon Management Plan* (5 AAC 24.361); 3) the *Copper River Personal Use Dip Net Salmon Management Plan* (5 AAC 77.591); and 4) the *Copper River Subsistence Salmon Fisheries Management Plan* (5 AAC 01.647). A drainagewide sustainable escapement goal of 24,000 or more spawning Chinook salmon was established in 2003 based on the average of escapement estimates from 1980–1998 derived from a catch-age model (Bue et al. 2002, Savereide 2001). A mainstem mark–recapture project in place since 1999, along with commercial and inriver harvest estimates, are used to generate annual estimates of escapement and total run size.

Copper River Chinook Salmon Fisheries

Commercial Fishery

The Copper River District includes all waters of the Gulf of Alaska between Hook Point and Point Martin (Figure 1). There has been a directed commercial fishery on Copper River salmon stocks since the early 1900s (Appendices A1 and A2). In general, fishing time has been reduced over the years in response to increased efficiency of the commercial fleet and reallocations by the Alaska Board of Fisheries (BOF). The recent schedule has been two commercial fishing periods per week on Mondays and Thursdays with the duration of each fishing period dependent upon trends in escapement, harvest, and environmental conditions. The fishery opens in mid-May and period lengths are established in season by emergency order (EO). The fishery is a drift gillnet fishery with approximately 500 active permits fished in recent years. The average 10-year commercial harvest from the Copper River District for 2009–2018 was 13,740 Chinook salmon and the 2018 harvest was 9,099 Chinook salmon (Russell et al. *In prep*).

Sport Fishery

Sport fisheries for salmon in the Copper River primarily target Chinook and sockeye salmon. The fisheries occur in tributaries to the Copper River with the largest harvest occurring in the Gulkana and Klutina Rivers (Figure 2). The Chinook salmon fishery was historically the most important sport salmon fishery in the Copper River in terms of effort and economic value. However, Chinook salmon fisheries have been restricted in recent years while sockeye salmon runs have increased, and sockeye salmon fisheries have gained in economic importance and angling effort, particularly in the Klutina River (Somerville 2019). Sport harvest and effort has been estimated annually since 1977 by the Statewide Harvest Survey (http://www.adfg.alaska.gov/sf/sportfishingsurvey/). The survey does not estimate fishing effort by species, but most effort in the major tributaries is likely directed at salmon. Sport harvest of Chinook salmon from the Upper Copper River drainage increased through 1996 when the harvest peaked at 9,116 Chinook salmon (Somerville and Taube 2007). Since 1996, sport harvest of Chinook salmon from the Upper Copper River drainage has declined to a low of 235 fish in 2013 (Somerville 2019). Approximately 95% of the estimated sport harvest of Chinook salmon taken from the Upper Copper River drainage comes from the Gulkana and Klutina River drainages. The average 10-year sport harvest from the Copper River for 2009–2018 was 1,265 Chinook salmon and the 2018 harvest was 1,278 Chinook salmon (Somerville 2019).

Subsistence Fishery

Subsistence use of Chinook salmon from the Copper River dates back over 2,000 years (Naves et al. 2015). From statehood until 1978, the dip net and fish wheel fisheries in the Copper River were classified as subsistence. In 1980, the BOF adopted the *Copper River Subsistence Salmon Fisheries Management Plan*. The management plan established seasons, open areas, legal gears, permit requirements, and bag limits for a subsistence salmon fishery in the Copper River. The plan also directed Alaska Department of Fish and Game (ADF&G) to manage the Copper River commercial salmon fishery to assure adequate escapement past the Miles Lake sonar to provide for subsistence harvest. In 1999, federal management of the Copper River subsistence fisheries was initiated, primarily due to the state not complying with rural preference for subsistence uses as mandated by Alaska National Interest Lands Conservation Act (ANILCA). Under federal management, residents from rurally qualified communities may attain a subsistence permit for either or both the Glennallen Subdistrict and the Chitina Subdistrict; the federal subsistence harvest in the Chitina Subdistrict is reported with state personal use harvest (see personal use fishery) because the fisheries are within the same management subdistrict. Federal and state subsistence salmon fishing is restricted to 3 areas on the Copper River: 1) the Copper River District; 2) the Upper Copper River District (Glennallen and Chitina Subdistricts); and 3) the Batzulnetas area, which only harvests sockeye salmon (Figure 2).

Boundary lines for the Copper River District subsistence fishery are the same as the commercial fishery. Subsistence fishing is allowed by permit from May 15 until September 30. From May 15 until 2 days before the commercial opening of the Copper River District, subsistence fishing is allowed 7 days per week. Once the commercial season has commenced, subsistence fishing is allowed only during commercial fishing periods, on Saturday, or by EO. Drift gillnets are the only legal gear and prior to July 15 may have a maximum length of 50 fathoms with a maximum mesh size of 6 inches.

The federal fishery in the Glennallen Subdistrict opens on May 15 through September 30; the state fishery is open June 1 through September 30. Both fisheries are open for continuous subsistence salmon fishing in all waters of the mainstem Copper River upstream of the Chitina–McCarthy Bridge to the mouth of the Slana River (Figure 2). A federal or state subsistence permit is required to participate in the fishery. Under federal management, permit holders have an annual cumulative limit of 200 salmon for a household of 1 and 500 salmon for a household of 2. Federal permit holders may harvest salmon with a dip net, fish wheel, or rod and reel, or combination of these gear types through the season. Under state management, users must select only one gear type (dip net or fish wheel) when getting their permit. Permit limits are 30 salmon for a household of 1, 60 salmon for a household of 2, and 10 salmon for each additional person in a household of more than 2 people. Individuals may request additional salmon up to a maximum of 200 salmon and households may request up to 500 salmon. For participants using dip nets, only 5 of the salmon may be Chinook salmon. A subsistence fishery by permit is also allowed in a portion of Tanada Creek and in the adjacent Copper River with spears and dip nets and near the traditional Ahtna Native fishing site of Batzulnetas with a fish wheel, dip net, fyke net or rod and reel. The average 10-year subsistence harvest from all districts (state and federal) for 2009–2018 was 3,173 Chinook salmon and the 2018 harvest was 7,668 Chinook salmon (Somerville 2019).

Personal Use Fishery

In 1980, with the passage of ANILCA, the federal government mandated subsistence hunting and fishing preference for rural residents on federal public lands. To comply with this requirement and prevent federal involvement in fishery management, the joint Boards of Fish and Game adopted a regulation in 1982 stating only local residents were eligible to participate in subsistence fishing and hunting and established 8 criteria for identifying fish stocks and game populations with customary and traditional uses. The preclusion of non-Copper River basin residents from participating in the Copper River subsistence fisheries prevented many individuals from harvesting fish for their personal use. This led the BOF to create a personal use salmon fishery in 1984 in the Copper River under the *Copper River Personal Use Salmon Management Plan*.

The Chitina Subdistrict includes the mainstem Copper River between the downstream edge of the Chitina–McCarthy Bridge and a department marker located about 200 yards upstream of Haley Creek (Figure 2). The personal use dip net salmon fishery is opened each year by EO between June 7 and June 15 and the federal subsistence fishery opens May 15 through September 30. Under state management a permit is required, and the annual limit is 25 salmon for the head of a household and 10 salmon for each additional household member; only 1 Chinook salmon may be harvested per household. Under federal management a permit is required, and qualified fishers may use dip nets, fish wheels, or rod and reel, or a combination of these gear types to harvest salmon. The federal harvest limits are the same as the Glennallen Subdistrict, but are not additive and are a total limit for the Upper Copper River District. The average 10-year personal use harvest (federal and state) from the Chitina Subdistrict for 2009–2018 was 955 Chinook salmon and the 2018 harvest was 1,374 Chinook salmon (Somerville 2019).

CURRENT AND HISTORIC COPPER RIVER CHINOOK SALMON ASSESSMENT

Age-Structured Assessment Model

Prior to the adoption of state-space models as the preferred analytical method for determining escapement goals in the Copper River (Savereide et al. 2018), an age-structured assessment model was developed to estimate the abundance and escapement of Chinook salmon from 1980–1999 (Savereide 2001). Information consisted of catch-age data from all fisheries and 2 sources of auxiliary data (escapement index and spawner–recruit relationship). Results implied that an approach (time-varying) that allowed for measurement error in the pooled catch-age data from all 4 fisheries and return proportions by age to vary over time produced parameter estimates with high precision and low bias. The model integrated all available sources of data at the time, accounted for uncertainty, and provided an estimate of escapement (19,711) that was expected to produce maximum sustained yield (MSY; Savereide 2001).

Miles Lake Sonar

The Miles Lake sonar project does not directly assess Chinook salmon but it does use sonar technology to enumerate the upriver migration of all salmon into the Copper River just downstream from Miles Lake, from mid-May (dependent on river ice) until late July (Appendix B1, Table 1; Russell et al. *In prep*). Sockeye and Chinook salmon are the two species that migrate during that period, and thus the enumeration encompasses the sum of both species. Sonar has been used since 1984 to enumerate salmon passage and currently one Adaptive Resolution Imaging Sonar (ARIS) 1800 and one ARIS 1200 on each bank (north and south banks, four units total) are used to ensonify the river. Sonar images of the entire river bottom from the north to the south shore obtained by the Division of Commercial Fisheries showed that a majority of salmon migrate through the ensonified area. The sonar count is regarded as an absolute estimate of inriver abundance, rather than an index, even though the species composition of that count is uncertain.

Until recently, the sonars used at Miles Lake were unable to measure fish lengths and hence it has not been possible to apportion sonar counts by species. For species apportionment, biologists have used the relative proportions of Chinook and sockeye salmon caught in upriver dip net fisheries. The proportion of Chinook salmon harvested in the personal use fishery is relatively consistent and has ranged from <1% to 7% since 1984. Regulation changes in 2000 decreased the harvest limit and the range has been between <1% and 3% ever since (Somerville 2019). The proportion of Chinook salmon harvested in the subsistence fishery is also relatively consistent and has ranged from 2% to 9% since 1980 (Somerville 2019).

Drainagewide Escapement, Spawning Distribution, Run Timing, and Aerial Surveys

Prior to the development of more robust stock assessment tools, little was known about spawning distribution, run timing, or escapements of Chinook salmon in the Copper River. Prior to 1999 aerial surveys were conducted for Chinook salmon in the Copper River but there were no direct estimates of escapement, distribution, or run timing. Chinook salmon spawn in at least 40 tributaries of the Copper River and aerial surveys have been conducted during peak spawning in 35 of those systems (Table 1). Of those 35 systems, aerial surveys were consistently conducted in 9 streams between 1966 and 2004, including the Little Tonsina River, Greyling Creek, Mendeltna Creek, Kaina Creek, Indian River, Gulkana River, East Fork Chistochina River, Manker Creek, and St. Anne Creek.

Beginning in 1999, a series of studies were initiated to estimate spawning abundance, determine spawning distribution, and understand run-timing patterns in the sub-stocks of the Copper River. To better understand run timing patterns and spawning distribution the department conducted radiotelemetry studies on migrating Chinook salmon from 1999–2004. These studies demonstrated that the majority of Chinook salmon spawning occurs in the Upper Copper River tributaries, and the Gulkana and Chitina Rivers (Wuttig and Evenson 2001; Savereide 2005). These studies also demonstrated that, in general, upriver stocks returned earlier than downriver stocks (Wuttig and Evenson 2001; Savereide 2005).

Since 1999, an estimate of escapement has been produced by a mark–recapture project in the Copper River located below spawning tributaries and inriver subsistence and personal use fisheries. The Native Village of Eyak (NVE) conducted the mark–recapture project using fish wheels in Baird and Wood Canyon (Piche et al. 2019; Appendix A1). To obtain drainagewide estimates of escapement, the inriver harvest from all fisheries is subtracted from the estimate of inriver abundance produced by the mark–recapture project. The average 10-year escapement estimate for 2009–2018 was 31,837 Chinook salmon (Appendix A1).

The radiotelemetry data, in conjunction with the mark–recapture estimates of escapements, demonstrated that aerial counts are an unreliable index of overall escapement due to high variability in the relative proportion of the entire escapement. This is likely due to high interannual variability in the actual proportion of spawners by tributary combined with a general lack of precision in aerial survey indices relative to actual abundance. Additionally, the 9 surveyed systems disproportionally represented sub-stocks with early run timing (Somerville 2019). As such, aerial surveys were reduced to 4 index streams: the Gulkana and East Fork Chistochina Rivers, and Manker and St. Anne Creeks. Of those 4 index streams, only the Gulkana River aerial index correlates well with overall Copper River escapements (Savereide et al. 2018) and thus is the only index used in the state-space model to make inferences about escapements and abundance in years prior to 1999.

Gulkana River Counting Tower, Distribution, and Run Timing

The Gulkana River is the most important Chinook salmon sport fishery in the Copper River drainage in terms of angler-days (Somerville 2019). Spawning escapement in the Gulkana River has been indexed since 1969 using aerial survey counts (Table 1; Evenson and Savereide 1999; Taube 2006; Somerville *unpublished data*[1]), and since 2002, ADF&G and the Bureau of Land

[1] Mark Somerville, Upper Copper/Upper Susitna Sport Fish management biologist. October 2020. Copper River Chinook salmon aerial escapement data, unpublished. Glennallen, Alaska.

Management have jointly operated a counting tower to estimate the escapement of Chinook salmon on the Gulkana River above the West Fork. Counts are conducted from late May to mid-August and the average 10-year escapement estimate for 2009–2018 was 3,130 Chinook salmon.

Results from a drainagewide telemetry study in 2002–2004 showed that the Gulkana River counting tower assesses 50% to 85% of the entire Gulkana River Chinook salmon escapement. However, the distribution estimates within the river are relatively imprecise because of the low number of radiotagged fish used to derive those estimates (Savereide 2005). To obtain precise estimates of the proportion of the escapement that is enumerated by the counting tower, ADF&G conducted a 3-year telemetry study in the Gulkana River. In the 3 years of the study (2013–2015), 51%, 45%, and 54% of the radiotagged Chinook salmon spawned above the counting tower (Schwanke and Tyers 2018). In addition, the relationship between escapement above the counting tower and drainagewide Copper River escapement is relatively strong ($R^2 = 0.49$), implying the Gulkana River escapement estimate is a good indicator of run strength (Schwanke and Tyers 2019).

Genetic Stock Composition of the Commercial Harvest and Run Timing of Copper River Sub-Stocks

The Copper River commercial harvest occurs in the nearshore marine waters outside of the Copper River Delta and intercepts fish destined to spawn in the Copper River as well as fish destined to spawn in other natal rivers throughout the Gulf of Alaska (GOA), British Columbia, and the West Coast United States. Genetic studies of the commercial harvest were conducted to determine the proportion of the harvest comprised of Copper River spawners. The goals of these studies were intended to 1) determine the potential of genetic markers to distinguish among sub-stocks within the Copper River drainage, 2) determine the proportion of the commercial harvest that is comprised of Copper River Chinook salmon, 3) delineate major geographic and temporal sub-stocks of Chinook salmon harvested in the Copper River drainage fisheries, and 4) investigate run timing of these sub-stocks within the Copper River (Templin et al. 2011; Gilk-Baumer et al. 2017). The results of these studies indicated that the genetic structure was adequate to delineate between 3 reporting groups within the Copper River (Upper Copper River, Gulkana River, and Lower Copper River), and 5 large-scale groups in the rest of the Gulf of Alaska (GOA) and south (Northwest GOA, Northeast GOA, Coastal Southeast Alaska, British Columbia, and West Coast U.S.). Marine fisheries targeting Chinook salmon near the mouth of the Copper River harvested mostly Copper River Chinook salmon (Templin et al. 2011; Gilk-Baumer et al. 2017). The proportion of the harvest comprised of Copper River Chinook salmon ranged from 86% to 97% between 2005 and 2008 (Templin et al. 2011) and from 64% to 93% between 2013 and 2017 (Gilk-Baumer et al. 2017). The mixed stock analysis demonstrated that sub-stocks further up the drainage arrived earlier than downriver sub-stocks, corroborating the results of radiotelemetry studies (Wuttig and Evenson 2001; Savereide 2005). The results suggest that the historical commercial management approach has provided inriver passage for all sub-stocks of the run. Additionally, genetic data provide the only accurate method for estimating the population-specific harvests of wild stocks or of untagged stocks from areas outside of the Copper River.

COPPER RIVER CHINOOK SALMON SUSTAINABLE ESCAPEMENT GOAL

In 2001, the BOF adopted the *Policy for Statewide Salmon Escapement Goals* (5 AAC 39.223) that formalized the procedure for establishing escapement goals. Most salmon (*Oncorhynchus* spp.) fisheries in Alaska are currently managed by monitoring the number of adult spawners (escapement) and, where possible, modeling the relationship between escapements and subsequent returns (recruitment) in a density-dependent framework (Ricker 1975). Modeling salmon recruitment is often constrained by the amount and quality of data and even the best models contain high degrees of process variability in recruitment rates attributable to both freshwater and oceanic conditions (Cunningham et al. 2018; Needle 2002; Peterman et al. 1998).

The current Copper River Chinook salmon lower bound sustainable escapement goal (SEG) (5 AAC 39.222[f][36]) of 24,000 or more spawners was established in 2003 (Bue et al. 2002) to keep escapements near the historical average of 25,800 fish from 1980–2000, estimated using a catch-age model (Savereide 2001). A number of approaches to the catch-age model were used depending on the quality of data from each fishery; the approach chosen allowed the return proportions by age to vary over time and estimated that the number of spawners needed to produce MSY, denoted as S_{MSY}, was approximately 19,700 Chinook salmon (Savereide and Quinn 2004). This SEG has been reviewed every board cycle since 2002 (Evenson et al. 2008; Fair et al. 2008 and 2011; Moffitt et al. 2014; Haught et al. 2017). During these reviews, the escapement goal committee considered the percentile approach (Clark et al. 2014) and habitat-based models (Liermann et al. 2010) as methodology for setting an escapement goal, but the goal has remained unchanged.

During the last escapement goal review in 2017, a state-space model was used to estimate total return, escapement, and recruitment of Copper River Chinook salmon from 1980–2016 (Savereide et al. 2018). This model simultaneously reconstructed salmon runs while fitting spawner recruit models and incorporated uncertainty and variability in the data (Fleischman et al. 2013). The model assessed the productivity of the stock over numerous environmental regimes, management strategies, and catchability scenarios and estimated the escapement level with the highest probability of resulting in MSY. The state-space model estimated an S_{MSY} of 18,595 fish, which resulted in a recommended goal (SEG) of 18,500–33,000. The escapement goal committee believed the lower bound of the SEG much below the estimate of S_{MSY} would be untenable to stakeholders, and perhaps not sufficiently precautionary given the recent observed decline in Chinook salmon production. After all user groups expressed unease with lowering the goal, the department ultimately agreed to not implement the committee recommendation and the lower bound SEG of 24,000 was retained.

For this escapement goal review, the same state-space model (Savereide et al. 2018) was used with 2 additional years of escapement and return data (now 1980–2018) and 5 more years of genetic stock composition of commercial harvests (Gilk-Baumer et al. 2017). This analysis follows the same modelling structure described in Savereide et al. (2018) and contained all data sources, including sonar data and apportionment data from dip net fisheries, Gulkana River aerial indices and tower counts, and mark–recapture estimates of escapement. The inclusion of various indices of abundance is necessary to estimate inriver abundance and escapement prior to 1999, the year that a mark–recapture project was established to explicitly estimate abundance (Piche et al. 2019). Prior to 1999, there are no direct measures of abundance in the watershed, and there are only indirect indices of abundance such as aerial surveys, the Gulkana tower counts, and the sonar counts as apportioned by dip net catches. As the state-space model simultaneously fits the various sources of information to the spawner–recruit model, it infers inriver abundance prior to 1999 based on the relationship between the various indices and the coinciding abundance estimates between 1999 and 2018.

To assess recent productivity and take advantage of the 20 years of mark–recapture estimates of inriver abundance, a second analysis was performed on a subset of data from 1999–2018 (hereafter referred to as the '99 analysis). Year 1999 roughly coincides with an apparent drop in stock productivity (Savereide et al. 2018), and this analysis examined model parameter estimates and yield curves during the most recent 20 years. Additionally, 1999 was the first year that mark–recapture estimates of escapement became available, whereas prior to 1999, escapements were derived from an array of indices (i.e., dip net apportioned Miles Lake sonar counts and Gulkana River aerial indices). Abundance estimates with quantified error estimates are preferable to indices that lack estimates of precision and error and the mark–recapture data set is now of sufficient length to examine spawner–recruit dynamics without the use of indices. Thus, this analysis only included the higher quality data sources consisting of harvest records, genetic make-up of the harvest, and mark–recapture estimates of escapement. This analysis used the same state-space model (Savereide et al. 2018) but only included model parameters associated with the high-quality data sources and excluded those parameters associated with the various indices used to assess productivity prior to 1999. Both analyses were examined and considered in the selection of the goal.

OBJECTIVES

The objectives of this analysis were to:

1. Conduct a comprehensive analysis of all relevant stock assessment data in the context of an integrated state-space model of historical run abundance and stock dynamics;
2. Provide an updated summary of abundance, harvest, and age composition statistics for this stock for the years 1980–2018;
3. Provide an updated summary of abundance, harvest, and age composition statistics for this stock for the years 1999–2018; and
4. Recommend an escapement goal based on the state-space model estimates of S_{MSY}.

METHODS

DATA SOURCES

The state-space model incorporated the following input data (Appendices B1 and B2):

1. Estimates of total annual harvest and associated coefficients of variation (CV) from 1980–2018 below (downstream of) and above (upstream of) Miles Lake sonar;
2. Miles Lake sonar counts (1984–2018);
3. Estimates of inriver abundance and associated uncertainty (CVs) from mark–recapture (1999–2018);
4. Gulkana River aerial counts (1980–2018);
5. Gulkana River counting tower escapement estimates and associated uncertainty (CVs) (2002–2018);
6. Genetic stock identification estimates (2005–2008 and 2013–2017); and
7. Age-composition estimates from the commercial harvest (1980–2018).

Annual Harvest

Copper River District harvests (annual harvest below the sonar) include commercial harvest from fish tickets for every fishing period throughout the fishing season including home-pack and donated fish, as well as subsistence and educational permits (Appendix A1; Russell et al. *In prep*). Genetic stock identification techniques were used to estimate the harvest of Copper River Chinook salmon in the commercial fishery (Templin et al. 2011; Gilk-Baumer et al. 2017). In years when there was no genetic stock composition data (including years prior to these studies), stock composition was estimated within the state-space model using the Templin et al. (2011) and Gilk-Baumer et al. (2017) data. Inriver harvest (annual harvest above the sonar) includes personal use, subsistence, and sport harvests (Appendix A1; Somerville 2019). Personal use and subsistence harvest estimates were determined from returned harvest permits and sport harvests were estimated from the Statewide Harvest Survey.

Miles Lake Sonar

The Miles Lake sonar uses sonar technology to enumerate the upriver migration of all salmon into the Copper River just downstream from Miles Lake from mid-May (dependent on river ice) until late July (Appendix B1; Russell et al. *In prep*). Sockeye and Chinook salmon are the only two salmon species migrating during this time period and harvest data from dip net fisheries located upriver of the sonar are used to apportion sonar abundance estimates by species, and estimate Chinook salmon abundance at the sonar site. To obtain relative measures of Chinook salmon abundance for the state-space model, we assumed the species composition of the sonar count was the same as the species composition from the personal use and subsistence harvests. This methodology may not be ideal, but the model accommodates for different management regimes and reiterates why a state-space model is used because the model does not rely on only one piece of information. The proportion of Chinook salmon harvested in the personal use fishery is relatively consistent and has ranged from <1% to 7% since 1984; however, regulation changes in 2000 decreased the harvest limit and the range has been between <1% and 3% ever since (Somerville 2019). The regulation changes warranted a division of the personal use harvest data into 3 management regimes (1984–1999, 2000–2008, 2009–present) to reflect the progressive decrease from a bag limit of 5 Chinook salmon down to 1. The proportion of Chinook salmon harvested in the subsistence fishery is also relatively consistent and has ranged from 2% to 9% since 1980 (Somerville 2019). The age composition of the sonar targets is also not known but age composition estimates from the personal use and subsistence fisheries are similar to the commercial fishery, where the majority of the harvests are age-5 and age-6.

Measures of Abundance

Estimates of inriver abundance from mark–recapture studies and the Gulkana River counting tower are the measures of absolute abundance used by the model (Appendix A1; Savereide 2005; Piche et al. 2019). Relative measures of abundance include 1) the proportion of Chinook salmon harvested in the personal use fishery multiplied by the sonar count of all salmon; 2) the proportion of Chinook salmon harvested in the subsistence fishery multiplied by the sonar count of all salmon; and 3) the annual Gulkana River aerial index (Appendix B1).

Age Composition

Age composition estimates from 1980–2018 (Appendix B2) were obtained from the commercial fishery sampling program that samples a portion of Chinook salmon harvested from each fishing period throughout the season (Brenner and Moffitt 2014; Russell et al. *In prep*). The fishery uses 6-inch or smaller mesh drift gillnets that capture age-4 through age-7 Chinook salmon with relatively equal selectivity (Savereide 2001; Savereide and Quinn 2004). Age composition estimates from the personal use, subsistence, and sport fisheries are similar to the commercial fishery but they are based on relatively small samples sizes and are either sporadic (sport fishery) or only collected since 1992 (personal use and subsistence; Savereide 2001). Thus, because of the inconsistency of the upriver fisheries and the lack of size selectivity identified in the commercial fishery, the age-composition estimates from the commercial harvest were assumed to be representative of the age composition of the total run.

STATE-SPACE MODEL

The state-space model (Appendix B3) assumes a Ricker spawner–recruit relationship and time-varying productivity and maturity. It has an age-structured framework, which facilitates an accurate depiction of observation error in total and inriver abundance, age composition, and harvest. The model is fit to multiple sources of information on historical abundance, age composition, and harvest, which allows the model to simultaneously reconstruct historical abundance and obtain estimates of stock productivity. Uncertainty from the run reconstruction is passed through to the spawner–recruit analysis and subsequent reference points such as MSY and S_{MSY}. The model accommodates missing data, measurement error in the data, absolute and relative abundance indices, and changes in age at maturity. By constructing an integrated model, all relevant data are considered and weighted by their precision. Sensitivity analyses are conducted to assess robustness of the results to assumptions of the run reconstruction and spawner–recruit analyses.

MODEL DETAILS

The total recruitment (R) produced from fish spawning in year y follows a Ricker (1975) formulation:

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

where S is the number of spawners, parameter α is a measure of productivity (i.e., number of recruits per spawner in the absence of density dependence), and parameter β is a measure of density dependence. The inverse of β is the number of spawners that produce the theoretical maximum recruitment (S_{MAX}).

To account for time-varying productivity, which manifests as serially correlated model residuals, an autoregressive lognormal error term with a lag of one year (AR[1]) was included in the linearized form of the spawner–recruit relationship (Noakes et al. 1987)

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi v_{y-1} + \epsilon_{Wy} \quad (2)$$

where ϕ is the lag-1 autoregressive coefficient, the $\{v_y\}$ are model residuals by year

$$v_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y \quad (3)$$

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

Age at maturity was modeled hierarchically (i.e., it was allowed to vary among cohorts to a specified extent). Age-at-maturity vectors $\boldsymbol{p_y}$ = (p_{y3}, p_{y4}, p_{y5}, p_{y6}, p_{y7}) from year y returning at ages 3–7 were drawn from a *Dirichlet* ($\gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7$) distribution. These age proportions are maturity and survival schedules for a given brood year (cohort) across calendar years. The Dirichlet parameters can also be expressed in an alternate form where

$$D = \sum_a \gamma_a \tag{4}$$

is the (inverse) dispersion of the annual age-at-maturity vectors, reflecting consistency of age at maturity among brood years. A low value of D is reflective of a large amount of variability of age-at-maturity proportions $\boldsymbol{p}$ among brood years, whereas a high value of D indicates more consistency in $\boldsymbol{p}$ over time.

The location parameters π_a, where

$$\pi_a = \frac{\gamma_a}{D}, \tag{5}$$

are proportions that sum to one, reflecting the age-at-maturity central tendencies. To model time-varying age at maturity, the location parameters were assumed to trend according to a multivariate logistic relationship, with each $\eta 1_a$ and $\eta 2_a$ denoting logistic slope and intercept parameters associated with each age a.

$$\pi_{ya} = \frac{e^{\eta 1_a + \eta 2_a y}}{\sum_a e^{\eta 1_a + \eta 2_a y}} \tag{6}$$

The abundance (N) of age-a Chinook salmon in calendar year y is the product of the age proportion scalar p and the total return (recruitment) R from year $y-a$:

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

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

$$N_y = \sum_a N_{ya} \tag{8}$$

Annual harvest (H) of Copper-origin Chinook salmon below (downstream of) the Miles Lake sonar site was modeled as the product of the annual harvest rate below the site and total run,

$$H_{By} = \mu_{By} N_y \tag{9}$$

Inriver run IR at the sonar site was modeled as follows:

$$IR_y = N_y - H_{By} \tag{10}$$

Annual harvest above (upstream of) the sonar site was the product of the annual harvest rate above the sonar site and inriver run abundance:

$$H_{Ay} = \mu_{Ay} IR_y \tag{11}$$

Finally, spawning escapement S was inriver run abundance minus harvest above the sonar site:

$$S_y = IR_y - H_{Ay} \tag{12}$$

Sampling Distributions of Observed Data

Observed data included estimates of annual harvest below and above the Miles Lake sonar site (1980–2018), a mark–recapture estimate of inriver run (MR 1999–2018), 4 indices of inriver run relative abundance (dip net apportioned sonar or DNAS 1984–2018; subsistence apportioned sonar or SubAS 1980–2018; Gulkana aerial or GA 1980–2018; Gulkana tower or GT 2002–2018), age composition estimates from the commercial harvest, and genetic stock identification from the commercial harvest (2005–2008 and 2013–2017). Sampling distributions (likelihood functions) for the data are found below.

Estimated annual harvest ($\widehat{H}_{Ay}$) of Copper River Chinook salmon above the sonar site was modeled in the form

$$\widehat{H}_{Ay}=H_{Ay}e^{\epsilon_{HAy}}, \tag{13}$$

in which the $\{\epsilon_{HAy}\}\sim N(0,\sigma^2_{HAy})$ and

$$\sigma^2_{HAy}=\ln((CV(\widehat{H}_{Ay}))^2+1). \tag{14}$$

The CVs for the annual harvest estimates above the sonar $\{CV(\widehat{H}_{Ay})\}$ were assumed to be 0.10; available CV estimates (2001–2018 personal use and subsistence, 1996–2018 sport) from fisheries above the sonar have ranged from 0.01–0.04 for personal use and subsistence and 0.01–0.39 for sport, with an average over all years of 0.06.

Chinook salmon commercial harvest in the Copper River District below the sonar site consisted primarily of fish originating from the Copper River; however, some Chinook salmon from other stocks were also present. Estimated total annual harvest ($\widehat{H}_{By}$) of all Chinook salmon (regardless of origin) below (downstream of) the sonar site was modeled as

$$\widehat{H}_{By}=H_{By}/p_{Cy}e^{\epsilon_{HBy}}, \tag{15}$$

in which the $\{\epsilon_{HBy}\}\sim N(0,\sigma^2_{HBy})$ and

$$\sigma^2_{HBy}=\ln\left(\left(CV(\widehat{H}_{By})\right)^2+1\right). \tag{16}$$

The CVs for the annual harvest estimates $\{CV(\widehat{H}_{By})\}$ below the sonar were assumed to be 0.05. There are no CV estimates for harvests below the sonar because the harvests are all reported by fish ticket and are assumed to be a census; however, there is some error associated with this process and it was assumed to be lower than the error associated with estimates of harvest above the sonar.

The true annual proportions of Copper-origin fish p_{Cy} in the commercial harvest below the sonar H_{By} were modeled hierarchically, as beta distributed quantities

$$p_{Cy}\sim Beta(\zeta_1,\zeta_2), \tag{17}$$

with hyperparameters ζ_1 and ζ_2. Estimates of these proportions $(\hat{p}_{Cy})$ were directly observed in years 2005–2008 and 2013–2017 using genetic stock identification (GSI) methods such that $(\hat{p}_{Cy})$ was calculated as the proportion of the harvest attributed to 3 of 8 genetic groupings attributed to Copper River stocks (Upper Copper River, Gulkana River, and Lower Copper River, versus NW Gulf of Alaska, NE Gulf of Alaska, Coastal Southeast Alaska, British Columbia, and West Coast United States; Templin et al. 2011; Gilk-Baumer et al. 2017). The GSI data were recast as binomial counts with effective sample sizes (*EFS*) of 556–1,274, obtained by back-calculating from the standard errors of GSI estimates (Templin et al. 2011; Gilk-Baumer et al. 2017). Thus, for each year the *EFS* was calculated as the average *EFS* across the 8 genetic groupings, *l*, where each EFS_l was calculated as

$$EFS_l = \frac{\hat{p}_l(1-\hat{p}_l)}{\left({}^{SE\ GSI_l}/_{\sum_l GSI_l}\right)^2} \tag{18}$$

where p_l is the proportion of the harvest attributed to genetic grouping l, $SE\ GSI_l$ is the standard error of the estimated harvest from genetic grouping l and GSI_l is the estimated harvest of genetic group l as reported in Templin et al. (2011) and Gilk-Baumer et al. (2017).

Mark–recapture (MR) estimates were assumed to be unbiased estimates of inriver run at Baird Canyon (just upstream from the Miles Lake sonar site):

$$\widehat{MR}_y = IR_y e^{\epsilon_{MRy}} \tag{19}$$

in which the $\left\{\epsilon_{MR_y}\right\} \sim N(0, \sigma^2_{MRy})$ and

$$\sigma^2_{MRy} = \ln\left(\left(CV(MR_y)\right)^2 + 1\right) \tag{20}$$

where the $\{CV(MR_y)\}$ are coefficients of variation associated with the MR estimates.

Four indices of abundance were available, with dip net apportioned sonar (DNAS) and subsistence apportioned sonar (SubAS) treated as indices of inriver run, and GA and GT treated as indices of drainagewide escapement. Each comprised a measure of relative abundance:

$$I_{iy} = q_{iy} X_y \epsilon_{iy} \tag{21}$$

where q_{iy} is a factor of proportionality relating true abundance to index I_{iy}, X_y is the generic true abundance, and $\{\epsilon_{iy}\}$ are independently and normally distributed process errors with variance σ^2_{Ii}. Parameters q_i and σ^2_{Ii} were estimated from the data. Separate factors of proportionality for DNAS were modeled for years 1984–1999 ($DNAS_1$), 2000–2008 ($DNAS_2$), and 2009–2018 ($DNAS_3$) to reflect changes in harvest regulations. The DNAS management regimes were assumed to have a single common process error variance (σ^2_{Ii}).

The model requires annual data on the age composition of the total run abundance. Because the average commercial harvest rate since 1999 was 39% and the commercial fishery harvests a more representative sample of age classes, we used commercial harvest age composition as a surrogate for total run age composition. The model requires multinomial age counts and assumes that age counts come from a simple random sample of the total run. This assumption cannot be met for real-world fisheries data, so we rescaled the age data with an "effective sample size" of $n_{Ey} = 100$. Surrogate scale-age counts x_{ya} were summed to n_{Ey} rather than n_y. Scale age counts x_{ya} were modeled as multinomial distributed with order parameter n_{Ey} and proportion parameters θ_a. One study found that key results from state-space analyses of Pacific salmon data were not sensitive to choice of n_{Ey} (e.g., Fleischman and McKinley 2013). Furthermore, although this formulation likely inflates uncertainty regarding age at maturity, it does have the advantage of producing a more conservative analysis relative to uncertainty in the age data.

MODEL FITTING

Markov Chain Monte Carlo (MCMC) methods, well suited for modeling complex population and sampling processes, were employed. The MCMC algorithms were implemented in the Bayesian software program JAGS (Plummer 2003). This methodology allows for inclusion of the effects of measurement error, serially correlated process variation, and missing data in the analysis and provides a more realistic assessment of uncertainty than is possible with classical statistical methods. By properly specifying process variation, measurement error, and time-dependent linkage separately in the model, biases in the analysis can be reduced (Su and Peterman 2012).

Bayesian statistical methods employ the language of probability to quantify uncertainty about model parameters. Existing knowledge about the parameters outside the framework of the current analysis is used to specify the "prior" probability distributions for model parameters. The output of the Bayesian analysis is called the "posterior" probability distribution, which is a synthesis of the prior information and the information contained in the data, from which samples are simulated. See Fleischman et al. (2013), Staton et al. (2016), and Fleischman and Reimer (2017) for similar applications of the methods used in this report.

Prior Distributions

Non-informative priors were chosen to minimize their effect on the posterior. Initial recruitments R_{1973}–R_{1979} (those with no linked spawner abundance) were modeled as drawn from a common lognormal distribution with median μ_{logR} and variance σ^2_{logR}. This was necessary because although there were no estimates of escapement for that period, it was necessary to include those parameters in the model to account for the brood year escapements whose recruits returned in 1980–1986 and were observed. Beta hyperparameters B_1 and B_2 for Copper-origin proportions in the harvest below the sonar were given *Uniform (1,1000)* priors. Normal priors with mean zero, very large variances, and constrained to be positive, were used for $\ln(\alpha)$ and β (Millar 2002), as well as for μ_{logR}, coefficients of proportionality q_i (log transformed), and for the logistic Dirichlet hyperparameters (slope and intercept) for trending age at maturity. The initial model residual ν_0 was given a normal prior with mean zero and variance $\sigma^2_W/(1-\phi^2)$. Annual harvest rates $\{\mu_{By}\}$ and $\{\mu_{Ay}\}$ were given beta (0.1, 0.1) prior distributions. Diffuse conjugate inverse gamma priors were used for σ^2_W and σ^2_{logR}, as well as for index uncertainty parameters $\{\sigma^2_{Ii}\}$.

Sampling from the Posterior Distribution

MCMC samples were drawn from the joint posterior probability distribution of all unknowns in the model. For results presented here, 2 Markov chains were saved. Of these, the first 50,000 samples were discarded, and every 300th sample from 600,000 additional samples were used to estimate the marginal posterior medians, standard deviations, and percentiles. The diagnostic tools of RJAGS (Plummer 2013) within R (R Development Core Team 2016), including trace plots and the Gelman-Rubin statistic (Gelman and Rubin 1992), were used to assess mixing and convergence. Gelman-Rubin statistics were all determined to be less than 1.1 and effective sample sizes were 2,000 for the full analysis and 3,000 for the '99 analysis. Credibility interval estimates were constructed from the percentiles of the posterior distribution.

Reference Points, Optimal Yield Profile

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

$$S_{MSY} \approx \frac{\ln(\alpha')}{\beta}\left[0.5 - 0.07\ln(\alpha')\right]. \quad (22)$$

Yield at a specified level of S was obtained by subtracting spawning escapement from recruitment:

$$Y_S = R - S = Se^{\ln(\alpha') - \beta S} - S. \quad (23)$$

Other relevant quantities include harvest rate leading to maximum sustained yield, approximated by (Hilborn 1985):

$$U_{MSY} \approx \ln(\alpha')[0.5 - 0.07\ln(\alpha')], \tag{24}$$

escapement leading to maximum sustained recruitment

$$S_{MAX} = \frac{1}{\beta}\ , \tag{25}$$

and equilibrium spawning abundance, where recruitment exactly replaces spawners:

$$S_{EQ} = \frac{\ln(\alpha')}{\beta}\ . \tag{26}$$

To determine maximum sustained recruitment (MAX) and maximum sustained yield (MSY) one can substitute equations 21 and 24 into equation 22 such that

$$MSY = \frac{\ln(\alpha')}{\beta}[0.5 - 0.07\ln(\alpha')]e^{\ln(\alpha') - (\ln(\alpha')[0.5 - 0.07\ln(\alpha')])} - \frac{\ln(\alpha')}{\beta}[0.5 - 0.07\ln(\alpha')] \tag{27}$$

and

$$MAX = \frac{1}{\beta}e^{\ln(\alpha') - 1} - \frac{1}{\beta}. \tag{28}$$

The quantity

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_R^2}{2(1 - \phi^2)} \tag{29}$$

in equations 21, 22, 23, and 25, 26, and 27 adjusts for the difference between the median and the mean of a right-skewed lognormal error distribution and the AR(1) process.

The probability that a given spawning escapement *S* would produce average yields exceeding X% of *MSY* was obtained by calculating Y_S at incremental values of *S* for each MCMC sample, and then comparing Y_S with X% of the value of *MSY* for that sample. The proportion P_Y of samples in which Y_S exceeded X% of *MSY* is an estimate of the desired probability, and the plot of P_Y versus *S* is termed an optimal yield probability profile (Fleischman et al. 2013).

The probability that yield would be reduced to less than X% of *MSY* by supplying too few spawners *S* was obtained by calculating Y_S at incremental values of *S* and tallying the number of MCMC samples for which Y_S was less than X% of *MSY* and *S* was less than S_{MSY}. A plot of the fraction of samples in which this condition occurred versus *S* is termed an overfishing profile (Bernard and Jones III 2010).

The probability that a given *S* would produce average recruitments exceeding X% of maximum sustained recruitment (*MAX*) was obtained by calculating *R* at incremental values of *S* for each MCMC sample, then comparing *R* with X% of the value of *MAX* for that sample. The proportion P_S of samples in which *R* exceeded X% of *MAX*, plotted versus escapement, is an optimal recruitment probability profile (Fleischman and Reimer 2017).

RESULTS

The data and model in Appendices B1, B2, and B3 produced the results described below.

INRIVER ABUNDANCE, ESCAPEMENT, HARVEST RATES, AND AGE AT MATURITY

Indices of relative abundance exhibited similar trends through time (Figure 3). An increasing trend in abundance and escapement occurred during 1996–2006, with a decline in the following decade (2007–2016) and large returns in 2017 and 2018. Uncertainty surrounding estimates of escapement and inriver abundance was greatest before 2005, when few measures of abundance were available or mark–recapture estimates were imprecise (Figure 3, Appendix A1). After 2004, estimates of inriver abundance and escapement are more precise.

Estimates of total run and recruitment are less uncertain than estimates of escapement and inriver run abundance because the harvest component of the total run is large, averaging over half of the run (Figure 4) and well-estimated (Appendix A1). Productivity and harvest rate have trended downward since the mid-1990s, although harvest rate and productivity have increased somewhat since 2013 (Figure 4d and 4e, respectively). Coefficients of variation for total run, inriver run, escapement, and recruitment ranged from 4% to 57% but were relatively small (<20%) in most years (Table 2). Recruitment estimates for the latest cohorts are less precise because one or more age classes had not yet returned (Figure 4).

Chinook salmon runs were dominated by age-5 and age-6 fish in all years (Table 3, Figure 5b and 5c), although age-4 fish have increased notably in relative proportion, indicating that the stock is trending towards earlier maturation (Figure 5a). The relative abundance of age-5 versus age-6 fish varied greatly before 1995 (Figure 5b).

PRODUCTIVITY, YIELD, AND RECRUITMENT

Estimates of population parameters from the state-space model account for measurement error in escapement S and recruitment R (Figure 6). The individual paired estimates of spawners and subsequent recruitment are weighted differentially by the model based on the level of uncertainty in the data.

None of the 1980–2014 escapements have failed to replace themselves (Figure 6). Consequently, the Ricker relationships that could plausibly explain the observed data are quite varied (Figure 6: light lines), and some deviate substantially from the median Ricker relationship (Figure 6: heavy line).

Median productivity (recruits per spawner in the absence of density effects) during 1980–2018 was high ($\alpha = 5.58$; Table 4) as was the uncertainty in the parameter estimate (CV = 0.48). This is illustrated by the variation in the slopes of the left-hand side of plausible spawner–recruit relationships (Figure 6). Analysis of the '99 data series indicated a less productive population during the most recent 20 years ($\alpha = 3.44$; Table 4) with even greater uncertainty in the estimate (CV = 2.37). The uncertainty surrounding estimates of equilibrium abundance S_{EQ} is illustrated by the variation of values of S where the curves intersect the replacement line; the influence of uncertainty on β is reflected in the variability in values of S that lead to maximum recruitment $S_{MAX} = 1/\beta$ (i.e., the peaks of all plausible spawner–recruit curves; Figure 6).

Time-varying changes in productivity after controlling for density-dependent effects are reflected in the recruitment residuals, which are deviations from recruitment expected from the median spawner–recruit relationship (Figure 4d). Productivity has been below average for all cohorts since

2003, which coincides with the decline of many other Alaska Chinook salmon stocks (ADF&G Chinook Research Team 2013).

The credibility interval around escapement leading to maximum sustained yield S_{MSY} was estimated to be 12,920 to 84,942 fish (posterior median 22,844 fish, CV = 0.80; Table 4). Yield is the number of fish in the expected recruitment over and above that needed to replace the spawners. The success or failure of a given number of spawners to achieve reference points across plausible spawner–recruit relationships was tallied to address this uncertainty (see Methods). The optimal yield profiles derived from this procedure illustrate the probability that a given number of spawners would achieve 70%, 80%, and 90% of MSY (Figure 7a). These probabilities increase as they approach S_{MSY} and can be used to quantify the yield performance of potential escapement goals (Figure 7: shaded areas) that account for uncertainty in the true abundance and productivity of the stock. Overfishing profiles (Figure 7: panel 2) show the probability that sustained yield would be reduced to less than 70%, 80%, or 90% of MSY with lower escapements produced by overfishing. For this stock, these probabilities are nearly the exact complements ($1 - p$) of the probabilities (p) in the left-hand limbs of the optimal yield profiles. Expected yield for the complete brood year returns from the '99 data series (1999–2018) has decreased to approximately 60% of the 1980–2018 average (Figure 8).

Because run size is an important quantity for all fisheries and depends on recruitment, we constructed optimal recruitment profiles from the success or failure of a given number of spawners to achieve stated percentages of maximum recruitment across a number of plausible spawner-recruit (SR) relationships. The profiles are highest near S_{MAX} (34,775 fish, CV = 0.93; Table 4) and display the probability of achieving at least 70%, 80%, and 90% of *MSR* for specified levels of escapement (Figure 7: panel 3).

DISCUSSION

SPAWNER–RECRUIT ANALYSIS

Obtaining reliable estimates of escapement and subsequent recruitment is arguably the most challenging problem a salmon stock assessment biologist endures. Management of many Alaska salmon stocks is based on a fixed escapement goal that attempts to maximize sustainable yields. The reference point upon which a number of these goals are based, S_{MSY}, was commonly derived under the assumption that the SR relationship remains stationary over time. Clark et al. (2009) demonstrated the effectiveness of this approach; however, issues arising from several factors can result in biased parameter estimates that affect derived reference points. These issues include bias in time-series (Walters 1985) and errors-in-variables (Kope 2006), differing maturity schedules, lack of contrast in escapement (Hilborn and Walters 1992), and the fact that spawner abundance is not independent of recruitment (Fleischman et al. 2013). To address some of these concerns, Fleischman et al. (2013) developed a generalized age-structured state-space model that accommodates process (time-varying productivity) and observation error. The model improved the methodology for selecting an escapement goal by providing a better reflection of the biological reality and informative content of the age-structured data.

Fitting this model to estimates of relative and absolute abundance, harvest, and age composition from Copper River Chinook salmon provided relatively precise estimates of escapement, recruitment, and total run size (Tables 2 and 3). However, inferences related to the true SR relationship and subsequent reference points are uncertain given that the population has never failed to replace itself and thus there is little basis for estimating the carrying capacity of the population (i.e., the β parameter). The number of plausible curves derived from the posterior distribution of the α and β parameters illustrates the uncertainty in the relationship between recruits and spawners (Figure 6). Lack of spawner contrast can help explain the uncertainty in β because the stock has never experienced density dependence at a level where the stock fails to replace itself. Large observation error in some estimates of R (Figure 6) coupled with moderate serial correlation (ϕ) in model residuals can explain some of this uncertainty. The serial correlation suggests nonstationary productivity, which is reflected in the overall decline in productivity since the early 2000s (Figure 4d). Even though there is a lot of uncertainty about the true SR relationship and reference points, one can still evaluate what levels of S will lead to optimal yields in the long term using the optimal yield and overfishing profiles (Figure 7). These profiles illustrate the probability of achieving specified percentages of MSY while maintaining a low probability of overfishing. These optimal yield profiles provide an objective appraisal of the quality of information about optimal escapement levels contained in the data, and actual probabilities are available to help weigh risks and benefits of alternative management choices (Fleischman et al. 2013).

ESCAPEMENT GOAL RECOMMENDATION

Based on the previous information and analyses, the Alaska Department of Fish and Game recommends a sustainable escapement goal (SEG) of 21,000–31,000 Copper River Chinook salmon.

During this review, two integrated state-space models were fit to all relevant harvest, age composition, and abundance data from 1980–2018 and 1999–2018. The method simultaneously reconstructs historical abundance and fits a spawner-recruit relationship. The model accommodates missing data, measurement error, and changes in age at maturity, while accounting for the associated uncertainty. The number of spawners that provide maximum sustained yield, S_{MSY}, is the biological reference point of most interest. The state-space model using the full data set (1980–2018; S_{MSY} = 22,844), similar to the catch-age model (S_{MSY} = 19,711), estimates S_{MSY} to be lower than the current lower bound SEG of 24,000. The ’99 analysis indicated a less productive population beginning in the early 2000s and produced a higher S_{MSY} estimate of 26,951. Both models were considered in selecting an escapement goal.

Ideally, an escapement goal would contain the estimate of S_{MSY} within the goal range to encompass the range of escapements expected to produce the largest harvestable surplus. However, a decrease in the number of recruits-per-spawner and age-at-maturity in recent years, strongly suggest a drop in stock production (Figures 4 and 5). A decline in productivity is further supported by the lower α estimate and higher S_{MSY} estimated in the ’99 analysis. For these reasons, it may be beneficial to recommend a goal where the lower-bound starts near the full model’s estimate of S_{MSY} rather than bracketing in some fashion around the full model estimate of S_{MSY}. Thus, a 21,000 fish lower bound satisfies estimates of S_{MSY} produced in both analyses (Figure 7). The upper-bound should then be set at a point where the probability of achieving at least 70%, 80%, or 90% of MSY is not too low. In this case, the recommended upper goal of 31,000 has an 61% chance of producing 90% of MSY based on the ’99 analysis and a 44% chance of producing 90% of MSY based on the full analysis (1980–2018; Figure 7). The recommended goal thus contains S_{MSY} from both analyses, minimizes the chances of overfishing regardless of which analysis is considered, and allows for conservative management if the stock continues to demonstrate the low productivity seen in the last decade.

The optimum yield and recruitment profiles (Figure 7) illustrate how the recommended goal is trading yield for recruitment.

The department is recommending an SEG rather than a BEG because of the lack of certainty regarding the carrying capacity for the stock (i.e., β). Normally, a full-scale analysis that produces both an upper and lower bound would meet the criteria for a BEG. However, it is general department policy to *not* declare a BEG when the stock has produced zero escapements that failed to replace themselves and hence the data provides little, if any, indication of what the upper carrying capacity is for the stock. Due to the lack of data informing the inflection point of the Ricker curve and uncertainty regarding carrying capacity, this recommendation constitutes an SEG rather than a BEG. However, the quality of the data for this analysis continues to improve and should future escapements provide information on the upper limits of the population, the department may upgrade to a BEG in future analysis.

The circumstances surrounding each individual stock are unique, and this is reflected in their respective escapement goals. Fleischman and Reimer (2017) compiled and published escapement goal ranges for 22 Alaska Chinook salmon stocks and standardized them by dividing the upper and lower bounds by estimated values of S_{MSY} for each stock (Appendix C1). These standardized values provide a useful way to compare the attributes of escapement goals across stocks. Among Alaska Chinook salmon stocks, lower bounds ranged from 62% to 100% (mean 77%) of S_{MSY}, and upper bounds ranged from 120% to 192% (mean 155%) of S_{MSY}. For Copper River Chinook salmon, the proposed lower bound of the SEG is 92% and 78% of S_{MSY} from the full and ’99 analysis, respectively. The upper bound is 136% and 115% of S_{MSY} for the full and ’99 analysis, respectively (Appendix C1).

SUMMARY AND CONCLUSIONS

The state-space model has been recognized as a scientifically sound method to use when selecting an escapement goal. Escapement goals based on estimation of S_{MSY} and robust evaluation of the uncertainty surrounding plausible SR relationships (Figure 7) are more credible than goals based solely on the record of historic returns. The state-space model used for this analysis has been effectively applied to Chinook salmon stocks throughout the state (Fleischman and Reimer 2017; Fleischman and McKinley 2013; Hamazaki et al. 2012).

The recommended goal preserves the original intent of the current SEG with respect to providing sustained yield. The recommended goal attempts to accomplish this by encompassing the estimate of S_{MSY} (22,844) but also accounts for having a low probability of overfishing and high probability of maximizing recruitment (S_{MSR}). Based on the analysis of the full data series escapements near the lower bound have a high probability (92%, 85%, and 62%) of achieving yields that are at least 70%, 80%, and 90% of MSY, respectively. The probability of maximum yield decreases as the SEG range approaches the upper bound (75%, 62%, and 44%). This decrease in the probability of achieving MSY as we approach the upper bound illustrates the utility of liberalizing fishing when returns are large enough to maintain escapements that maximize the probability of achieving MSY. This decrease is also offset by maintaining a high probability of achieving at least 70% of maximum recruitment within the proposed escapement goal range. The lower bound of this recommendation is well above observed past escapements (Table 2) and the range of the goal encompasses S_{MSY} from both sets of analyses.

The effect of the recommended goal on fishery management will depend upon total run abundance. Run-timing patterns of Copper River Chinook salmon sub-stocks is varied but, in most years, a larger proportion of upriver sub-stocks (i.e., Gulkana and East Fork Chistochina) migrate through the various fisheries earlier than downriver sub-stocks (i.e., Klutina, Tonsina, and Chitina; Savereide et al. 2005; Templin et al. 2011; Gilk-Baumer et al. 2017). The first commercial openers occur during this time period when prices for sockeye and Chinook salmon are at their highest. Furthermore, personal use and subsistence users also value "first run" salmon and effort may be skewed accordingly. Typically, large recruitments for this stock have resulted in larger runs and constructing optimum recruitment profiles illustrates this point (Figure 7).

Our knowledge of Copper River Chinook salmon stock dynamics will improve over time. The full analysis (1980–2018) relied partially upon run reconstructions in early years (pre-1999) that used indices of abundance that were informed by later years where indices overlap with actual abundance estimates. These early years have higher variance in parameter estimates due to uncertainty in the relationship between indices of abundance and actual abundance. However, the full data series provides both a long-term data series and greater contrast in escapements and recruitments for estimating productivity parameters of the population. Stock assessment capabilities have improved greatly since 1998 and there are currently 20 estimates of escapement (1999–2018) derived from mark–recapture experiments. The state-space model that only used information from 1999–2018 estimated S_{MSY} to be 26,951, but the precision of this estimate was less than the model that used all available relevant data (1980–2018; Table 4). The shorter time series has less contrast in escapements, which likely caused a decrease in precision. However, the difference is also likely from the decrease in production of this stock over time (Figure 4d). While pre-1999 data relies on indices and a range of associated assumptions, the '99 analysis used only high-quality data that did not necessitate these assumptions. Considering both analyses simultaneously allowed us to examine how those indices may affect parameter estimation when selecting a goal. Statistical methods that accommodate varying levels of measurement error and give greater weight to more precise estimates were used during this analysis, and acquiring more estimates of inriver abundance will contribute further to state-space model estimates in the future.

In an effort to improve inseason monitoring of the Chinook salmon runs and produce more precise escapement estimates, the department began measuring insonified fish at the Miles Lake sonars in 2018 and instituted a length threshold of 772 mm to differentiate sockeye and small Chinook salmon (below 772 mm) from known Chinook salmon (greater than 772 mm). The exact cutoff length is an evolving target as of this writing and is intended to exclude 4-year-old males and sockeye salmon and include only known 5-, 6-, and 7-year-old Chinook salmon. Escapements are currently monitored by the mark–recapture experiment run by the Native Village of Eyak (NVE) (Piche et al. 2019, Appendix A1), which, by its nature, produces run estimates that lag substantially behind actual run timing (one to two weeks). The department's long-term goal of managing the fishery based on Miles Lake sonar counts of measured salmon is still under development and will likely take one or more board cycles before the department has the ability to incorporate those methods. Multiple years of paired estimates with the NVE mark–recapture estimates, as well as other indices, will ultimately produce a stronger data set with improved precision of escapement estimates and more accurate estimates of in-season escapement. The goal of switching to sonar-based escapement goals will take time but promises further improvements in our understanding of stock dynamics and subsequent improved management.

Beginning in 2014, the department also began a study of juvenile Chinook salmon as part of the Chinook Salmon Research Initiative (CSRI) that holds promise to improve model precision and further inform our understanding of Chinook salmon productivity in the system (Joy and

Huang 2017). To better understand these processes, ADF&G began a coded wire tag (CWT) study to estimate the annual abundance of Chinook salmon smolt emigrating from the Copper River and their subsequent marine survival. CWT studies are large mark–recapture experiments whereby fish are marked as juveniles and then examined for marks when they return as adults to spawn. The number of fish marked and the proportion of sampled adults possessing marks provides the data for estimating smolt abundance, and hence, marine survival when combined with estimates of adult abundance. Recoveries of coded-wire tagged fish in the mixed-stock commercial fishery will also provide more accurate estimates of stock-specific harvest and understanding of Copper River Chinook production. Since 2015, Chinook salmon smolt (age-1) and parr (fall pre-smolt, age-0) have been tagged in multiple spawning tributaries and in the Copper River Delta. Fall parr catches have ranged from 35,000 to over 40,000 while spring smolt catches have ranged from 10,400 to 33,500. Since 2017, returning adults have been examined for clipped adipose fins and CWTs in the commercial harvests in Cordova, as well as in the NVE fish wheels used to estimate escapements (Piche et al. 2019). Estimates of smolt abundance and survival will increase our understanding of the freshwater capacity for Chinook salmon in the Copper River, provide insight into marine factors that affect smolt survival, and will eventually be incorporated into the state-space model used to determine escapement goals.

The escapement goals for Copper River Chinook salmon will be periodically reviewed. All Pacific salmon escapement goals in the State of Alaska are subject to triennial review to allow for consideration of recent data, improvements in escapement assessment, and changes in stock productivity. During the next review, prior to the next Prince William Sound board meeting, there will be 3 more years of direct assessment data, and it will be possible to quantify the recruitment from escapements in 2013–2016. Furthermore, the state-space model may accommodate further modifications that test its robustness to various assumptions as well as incorporate new data. For example, future constructions of the model may test assumptions of harvest selectivity in the various fisheries and its subsequent effect on assumed age-structure. We may also allow the model to estimate effective sample sizes for age data as a pathway towards more robust model-based data weighting.

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TABLES AND FIGURES

Table 1.–Summary table of Copper River Chinook salmon research projects.

Category	Years	Description	Citations
Aerial indices	1966–2004	Aerial surveys of spawning abundance in 35 sections of Copper River tributaries.	Somerville 2019
	2005–present	Aerial surveys in 4 index streams of Copper River; only Gulkana River used in escapement goal analysis.	
Miles Lake sonar	1984–present	Combined count of all salmon migrating up the Copper River.	Russell et al. *In prep*
Mark–recapture abundance estimation	1999–present	Estimates Chinook salmon abundance above Baird Canyon and below personal use and subsistence fisheries using fish wheels to conduct a mark–recapture estimate.	Piche et al. 2019
Gulkana River counting tower	2002–present	Count of Chinook salmon passage to the mainstem Gulkana river above its confluence with the West Fork Gulkana River.	Schwanke and Tyers 2019
Copper River radio-telemetry studies	1999–2004	Determined the spawning distribution and run timing of Chinook salmon sub-stocks in the Copper River watershed.	Wuttig and Evenson 2001; Savereide 2005
Mixed-stock analysis of Cordova commercial catch	2005–2008; 2013–2017	Determine the proportion of the commercial harvest comprised of Copper River spawners, delineated major sub-stocks in the Copper River and documented run timing of those sub-stocks.	Templin et al. 2011; Gilk-Baumer et al. 2017
Gulkana River radio-telemetry studies	2013–2015	Determine the proportion of Chinook salmon spawning above and below the counting tower on the Gulkana River.	Schwanke and Tyers 2018
Smolt abundance and marine survival	2014–present	Determine the abundance and marine survival of Chinook salmon smolt emigrating from the Copper River.	Joy and Huang 2017

Table 2.–Annual median abundance estimates and CV for Copper River Chinook salmon obtained by fitting a state-space model to data from 1980 through 2018.

Year	Total Run (CV)	Inriver Run (CV)	Escapement (CV)	Recruitment (CV)
1973	–	–	–	46,441 (0.55)
1974	–	–	–	32,534 (0.38)
1975	–	–	–	28,099 (0.29)
1976	–	–	–	50,820 (0.23)
1977	–	–	–	42,777 (0.19)
1978	–	–	–	80,573 (0.10)
1979	–	–	–	56,263 (0.09)
1980	30,696 (0.33)	23,356 (0.42)	16,319 (0.58)	44,331 (0.09)
1981	34,862 (0.19)	17,222 (0.37)	11,655 (0.53)	76,137 (0.09)
1982	56,874 (0.14)	18,379 (0.29)	11,896 (0.43)	55,929 (0.10)
1983	68,431 (0.12)	25,421 (0.21)	12,639 (0.39)	52,012 (0.10)
1984	55,065 (0.10)	19,660 (0.22)	14,585 (0.29)	40,162 (0.11)
1985	55,117 (0.10)	18,563 (0.21)	13,218 (0.29)	36,650 (0.11)
1986	60,328 (0.10)	25,438 (0.19)	18,808 (0.26)	78,441 (0.08)
1987	55,996 (0.12)	19,149 (0.32)	12,941 (0.46)	27,795 (0.11)
1988	54,730 (0.11)	28,089 (0.19)	22,552 (0.23)	73,441 (0.08)
1989	50,469 (0.11)	24,144 (0.20)	18,639 (0.25)	64,329 (0.09)
1990	42,127 (0.11)	23,224 (0.19)	17,602 (0.25)	85,624 (0.09)
1991	55,834 (0.10)	26,247 (0.17)	15,940 (0.28)	74,648 (0.10)
1992	57,957 (0.09)	23,293 (0.16)	13,987 (0.27)	85,681 (0.10)
1993	54,299 (0.10)	28,556 (0.16)	16,070 (0.28)	103,487 (0.09)
1994	67,811 (0.09)	26,222 (0.17)	13,868 (0.31)	69,123 (0.09)
1995	83,212 (0.10)	26,817 (0.16)	13,290 (0.32)	73,894 (0.09)
1996	82,669 (0.09)	32,950 (0.17)	18,688 (0.30)	75,036 (0.09)
1997	87,582 (0.10)	43,075 (0.17)	26,644 (0.27)	89,958 (0.08)
1998	98,059 (0.10)	38,536 (0.16)	21,863 (0.28)	98,031 (0.07)
1999	87,231 (0.09)	33,326 (0.09)	17,426 (0.19)	67,595 (0.07)
2000	70,067 (0.09)	41,855 (0.14)	27,967 (0.21)	63,572 (0.07)
2001	76,324 (0.09)	40,791 (0.14)	29,186 (0.20)	82,738 (0.06)
2002	86,978 (0.09)	52,502 (0.12)	41,201 (0.16)	85,628 (0.06)
2003	88,831 (0.08)	45,931 (0.12)	35,270 (0.15)	49,893 (0.06)
2004	76,825 (0.07)	42,414 (0.09)	32,583 (0.12)	32,781 (0.08)
2005	65,312 (0.03)	30,507 (0.05)	21,659 (0.07)	29,806 (0.09)
2006	88,392 (0.05)	61,185 (0.06)	51,668 (0.08)	53,260 (0.07)
2007	84,848 (0.04)	46,088 (0.06)	34,255 (0.09)	42,066 (0.09)
2008	53,005 (0.04)	41,426 (0.05)	32,478 (0.06)	39,840 (0.08)
2009	39,219 (0.05)	30,140 (0.06)	25,465 (0.08)	34,827 (0.08)
2010	33,652 (0.07)	24,258 (0.08)	18,684 (0.11)	43,062 (0.07)
2011	50,879 (0.07)	34,076 (0.08)	28,092 (0.10)	46,060 (0.06)
2012	38,293 (0.09)	27,114 (0.12)	23,429 (0.14)	37,513 (0.10)
2013	42,266 (0.08)	34,007 (0.10)	30,364 (0.11)	60,133 (0.12)
2014	34,176 (0.06)	26,268 (0.08)	22,844 (0.09)	54,417 (0.31)
2015	48,820 (0.06)	33,641 (0.09)	28,092 (0.11)	58,805 (0.45)
2016	28,262 (0.04)	16,596 (0.07)	12,982 (0.09)	–
2017	53,227 (0.06)	39,052 (0.08)	31,058 (0.10)	–
2018	61,378 (0.06)	53,666 (0.07)	43,249 (0.09)	–

Note: En dashes mean values were not estimated using the model.

Table 3.–Total run abundance estimates and CV by age class obtained by fitting a state-space model to data from Copper River Chinook salmon, 1980–2018. Note that the sums of all ages may not match Table 2 due to uncertainty in estimates (note CVs).

Year	Age-4	Age-5	Age-6	Age-7
1980	786 (0.96)	9,053 (0.39)	21,174 (0.38)	2,651 (0.63)
1981	1,688 (0.69)	14,810 (0.28)	17,580 (0.29)	1,999 (0.65)
1982	3,414 (0.88)	16,979 (0.37)	34,664 (0.27)	1,887 (0.86)
1983	2,551 (0.29)	42,373 (0.13)	22,992 (0.14)	566 (0.61)
1984	1,242 (0.41)	18,514 (0.13)	33,771 (0.11)	1,834 (0.34)
1985	3,784 (0.23)	16,238 (0.13)	33,751 (0.11)	1,397 (0.37)
1986	3,365 (0.25)	31,807 (0.12)	23,826 (0.12)	1,472 (0.37)
1987	1,484 (0.38)	14,870 (0.16)	37,461 (0.13)	3,212 (0.26)
1988	1,967 (0.36)	15,423 (0.15)	34,030 (0.12)	3,566 (0.28)
1989	1,563 (0.41)	13,881 (0.16)	31,472 (0.13)	3,882 (0.28)
1990	3,045 (0.29)	12,349 (0.16)	23,097 (0.13)	3,986 (0.25)
1991	2,356 (0.34)	32,156 (0.12)	19,995 (0.14)	1,415 (0.45)
1992	2,904 (0.30)	10,036 (0.16)	41,939 (0.10)	2,946 (0.28)
1993	4,081 (0.24)	34,094 (0.11)	14,839 (0.14)	1,433 (0.41)
1994	4,069 (0.27)	27,501 (0.12)	35,638 (0.11)	760 (0.58)
1995	5,343 (0.26)	44,370 (0.12)	32,079 (0.13)	1,016 (0.57)
1996	6,381 (0.25)	39,036 (0.12)	36,537 (0.12)	780 (0.70)
1997	8,420 (0.23)	49,551 (0.12)	29,153 (0.14)	796 (0.72)
1998	6,631 (0.26)	61,110 (0.11)	28,841 (0.14)	1,205 (0.57)
1999	7,995 (0.23)	44,144 (0.11)	33,218 (0.12)	1,185 (0.61)
2000	4,861 (0.26)	46,707 (0.11)	18,102 (0.15)	610 (0.74)
2001	9,588 (0.20)	47,806 (0.10)	18,867 (0.14)	261 (1.15)
2002	11,253 (0.18)	52,970 (0.10)	22,277 (0.14)	580 (0.76)
2003	6,445 (0.24)	55,085 (0.10)	26,948 (0.13)	261 (1.21)
2004	6,050 (0.23)	38,724 (0.10)	31,426 (0.11)	558 (0.76)
2005	5,686 (0.21)	37,361 (0.06)	21,891 (0.10)	436 (0.78)
2006	13,775 (0.17)	54,372 (0.07)	19,740 (0.14)	666 (0.82)
2007	8,165 (0.19)	54,198 (0.06)	22,150 (0.11)	464 (0.79)
2008	5,659 (0.22)	30,217 (0.08)	16,687 (0.12)	478 (0.83)
2009	7,286 (0.16)	19,818 (0.09)	11,091 (0.13)	1,040 (0.48)
2010	8,661 (0.18)	17,329 (0.12)	7,257 (0.20)	470 (0.85)
2011	8,165 (0.17)	37,373 (0.08)	5,214 (0.21)	91 (1.59)
2012	4,699 (0.22)	26,725 (0.10)	7,081 (0.18)	70 (1.61)
2013	8,279 (0.20)	26,702 (0.11)	7,303 (0.21)	126 (1.73)
2014	9,915 (0.12)	16,472 (0.09)	7,801 (0.14)	53 (1.73)
2015	11,100 (0.13)	27,254 (0.08)	9,883 (0.13)	718 (0.48)
2016	5,833 (0.14)	16,695 (0.07)	5,470 (0.15)	286 (0.65)
2017	9,866 (0.16)	24,900 (0.1)	18,094 (0.11)	499 (0.66)
2018	12,501 (0.32)	42,025 (0.12)	6,731 (0.37)	218 (2.07)

Table 4.–State-space model parameter estimates for Copper River Chinook salmon for calendar years 1980–2018.

Parameter Name	Description	1980–2018 Data Median	1980–2018 Data 2.5th Percentile	1980–2018 Data 97.5th Percentile	1980–2018 Data CV	1999–2018 Data Median	1999–2018 Data 2.5th Percentile	1999–2018 Data 97.5th Percentile	1999–2018 Data CV
α (alpha)	Measure of productivity	5.58	2.23	12.69	0.48	3.44	1.65	10.27	2.37
β (beta)	Measure of density-dependence	2.88×10^{-5}	6.99×10^{-6}	6.20×10^{-5}	0.49	1.95×10^{-5}	4.51×10^{-6}	4.06×10^{-5}	0.46
ϕ (phi)	Autocorrelation between recruitment residuals	0.64	0	0.97	0.39	0.69	0.09	0.98	0.38
S_{MAX}[a]	Number of spawners providing MSR	34,775	16,141	143,150	0.93	51,224	24,635	221,620	0.98
S_{EQ}[a]	Equilibrium spawning abundance	61,075	39,700	275,432	0.98	66,808	40,636	338,711	1.14
S_{MSY}[a]	Number of spawners providing MSY	22,844	12,920	84,942	0.8	26,951	15,371	98,262	0.78
U_{MSY}[a]	Harvest rate at MSY	0.69	0.44	0.84	0.15	0.54	0.28	0.84	0.26
q.GA	Index scale factor for Gulkana aerial counts	0.04	0.03	0.06	0.14				
$q.DNAS_1$	Index scale factor for 1st dip net regime	0.97	0.86	1	0.04				
$q.DNAS_2$	Index scale factor for 2nd dip net regime	0.41	0.32	0.51	0.12				
$q.DNAS_3$	Index scale factor for 3rd dip net regime	0.19	0.15	0.24	0.11				
q.SubAS	Index scale factor for subsistence fishery	0.87	0.75	0.97	0.06				
q.GT	Index scale factor for Gulkana tower counts	0.12	0.11	0.14	0.07				
σ^2.GA	Standard deviation of scaled relationship with Gulkana aerial counts	0.64	0.47	0.88	0.16	Parameters not part of model in '99 analysis			
σ^2.DNAS	Standard deviation of scaled relationship with dip net fishery	0.32	0.24	0.43	0.15				
σ^2.SubAS	Standard deviation of scaled relationship with subsistence fishery	0.32	0.23	0.44	0.17				
σ^2.GT	Standard deviation of scaled relationship with Gulkana tower counts	0.23	0.15	0.38	0.26				

Note: Prior distributions of all free parameters were specified as flat and non-informative and truncated as necessary to censor impossible values. Vague conjugate inverse-gamma priors were used on all variance parameters. Details are described in the text.

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

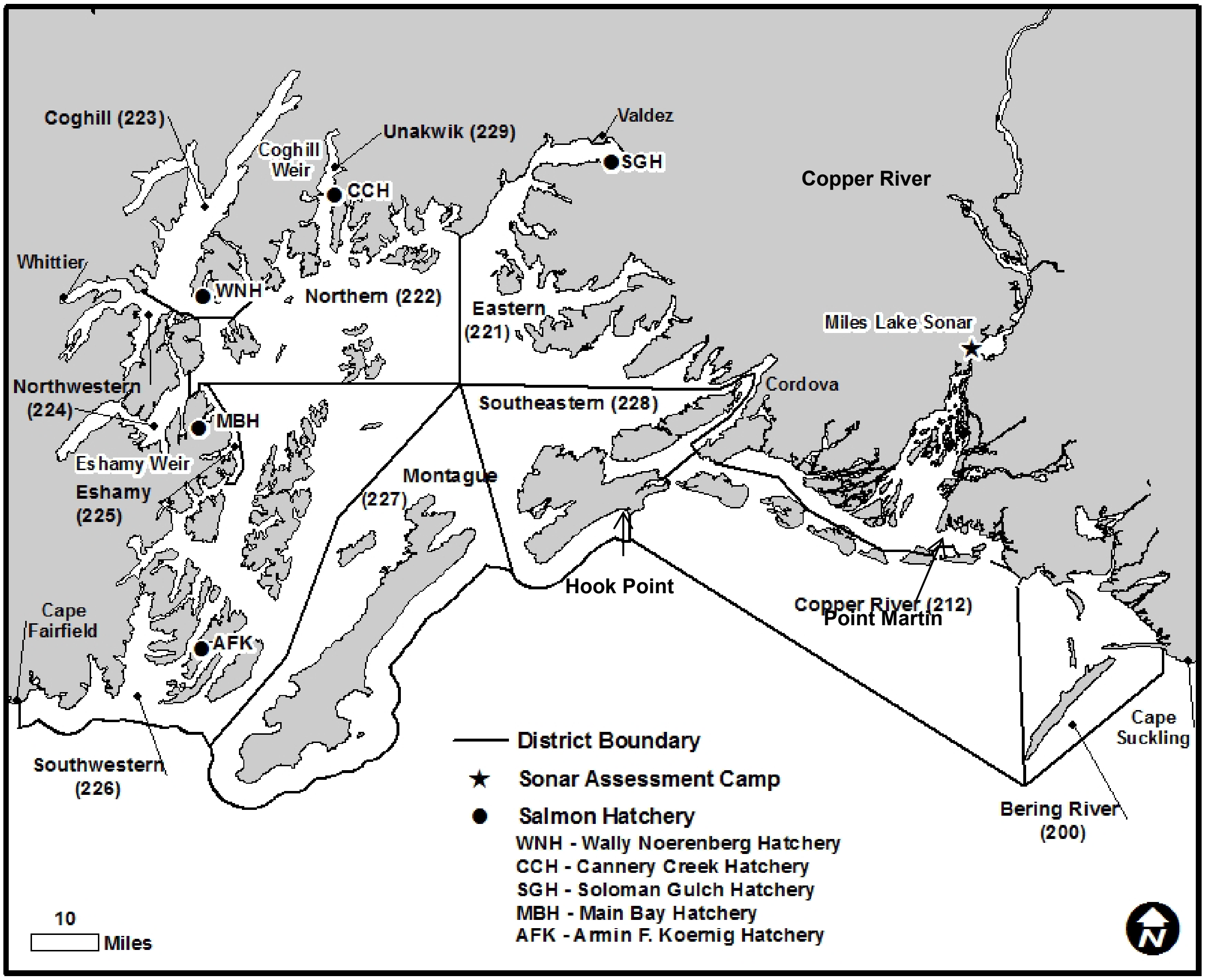

Figure 1.–Prince William Sound Management Area showing commercial fishing districts, salmon hatcheries, and Miles Lake sonar.

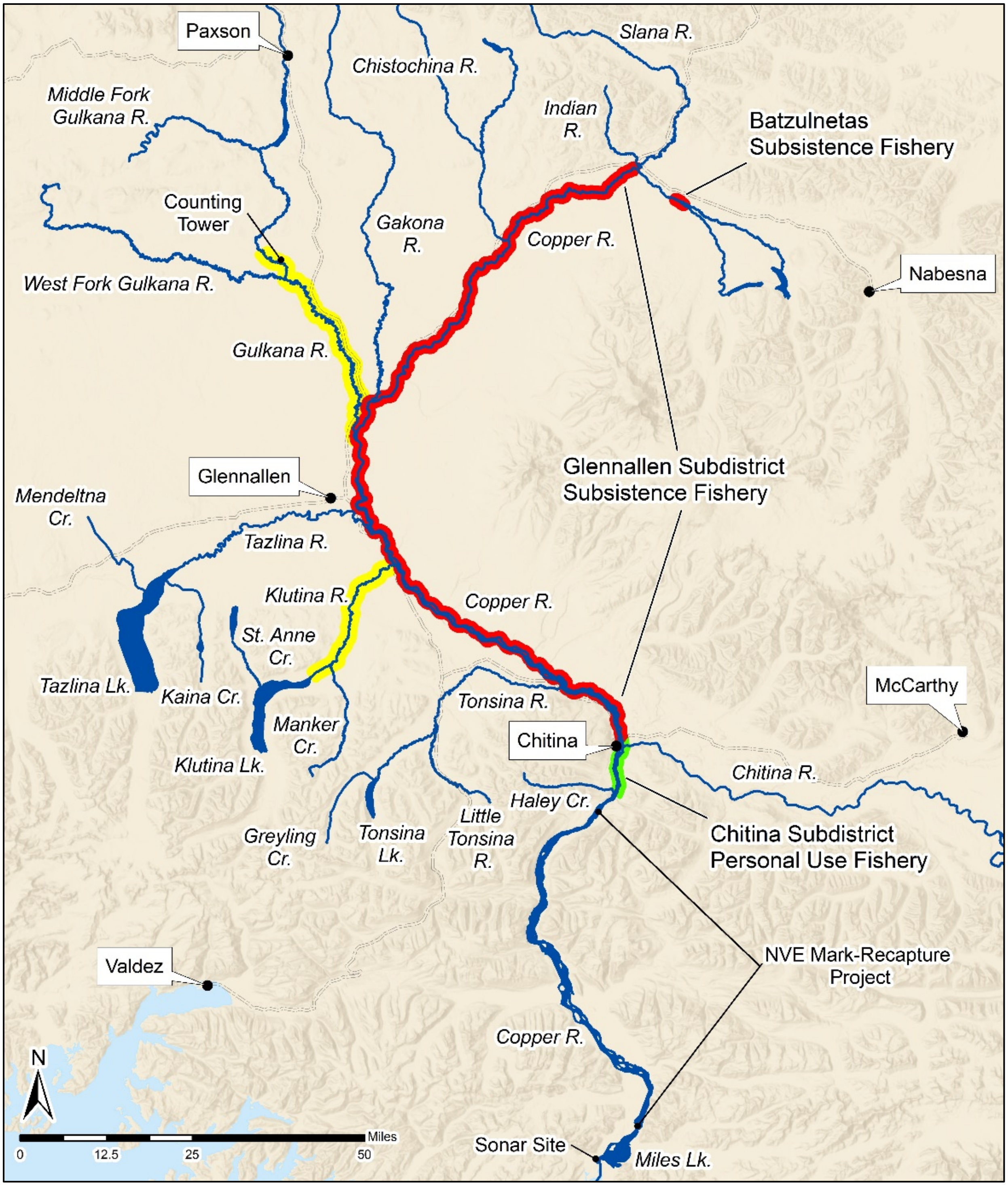

Figure 2.–A map of the Upper Copper River drainage and major tributaries demarcating the personal use (green), subsistence (red), and major sport fisheries (yellow), and the locations of the Miles Lake sonar, the Native Village of Eyak (NVE) mark–recapture project, and the Gulkana River counting tower.

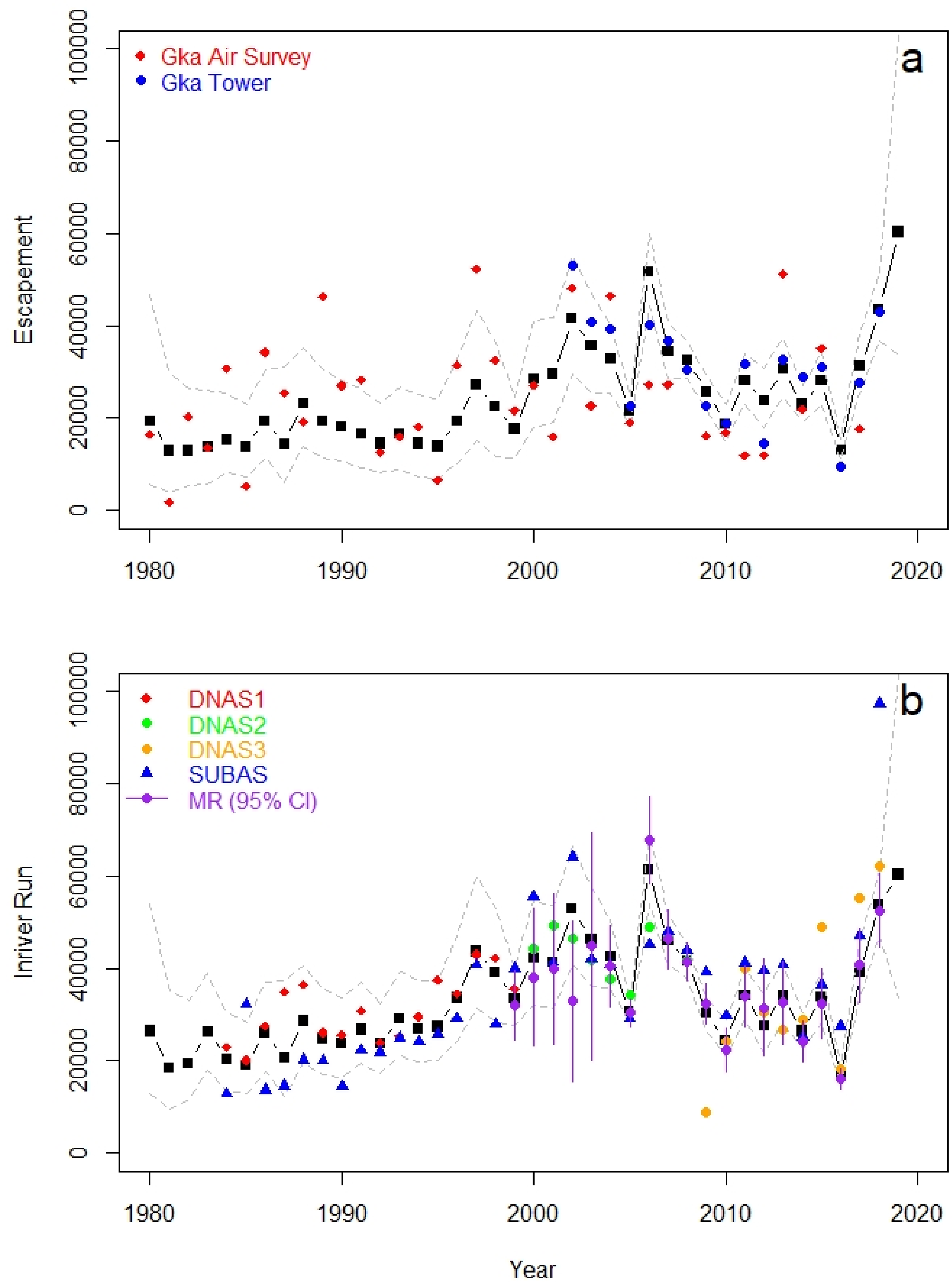

Figure 3.–Escapement (a) and inriver run abundance (b) of Copper River Chinook salmon as reconstructed from indices of relative abundance (black squares): Gulkana aerial index (Gka Air), escapement estimates past the Gulkana River counting tower (Gka Twr), dip net apportioned sonar (DNAS1:1984–1999, DNAS2: 2000–2008, and DNAS3: 2009–2018), subsistence apportioned sonar (SubAS), plus a measure of absolute abundance: mark–recapture estimates of inriver abundance (MR, 95% credibility interval bounds plotted). Dark black dashed lines show the median and dotted lines the 95% credibility intervals of modeled Escapement and Inriver Run.

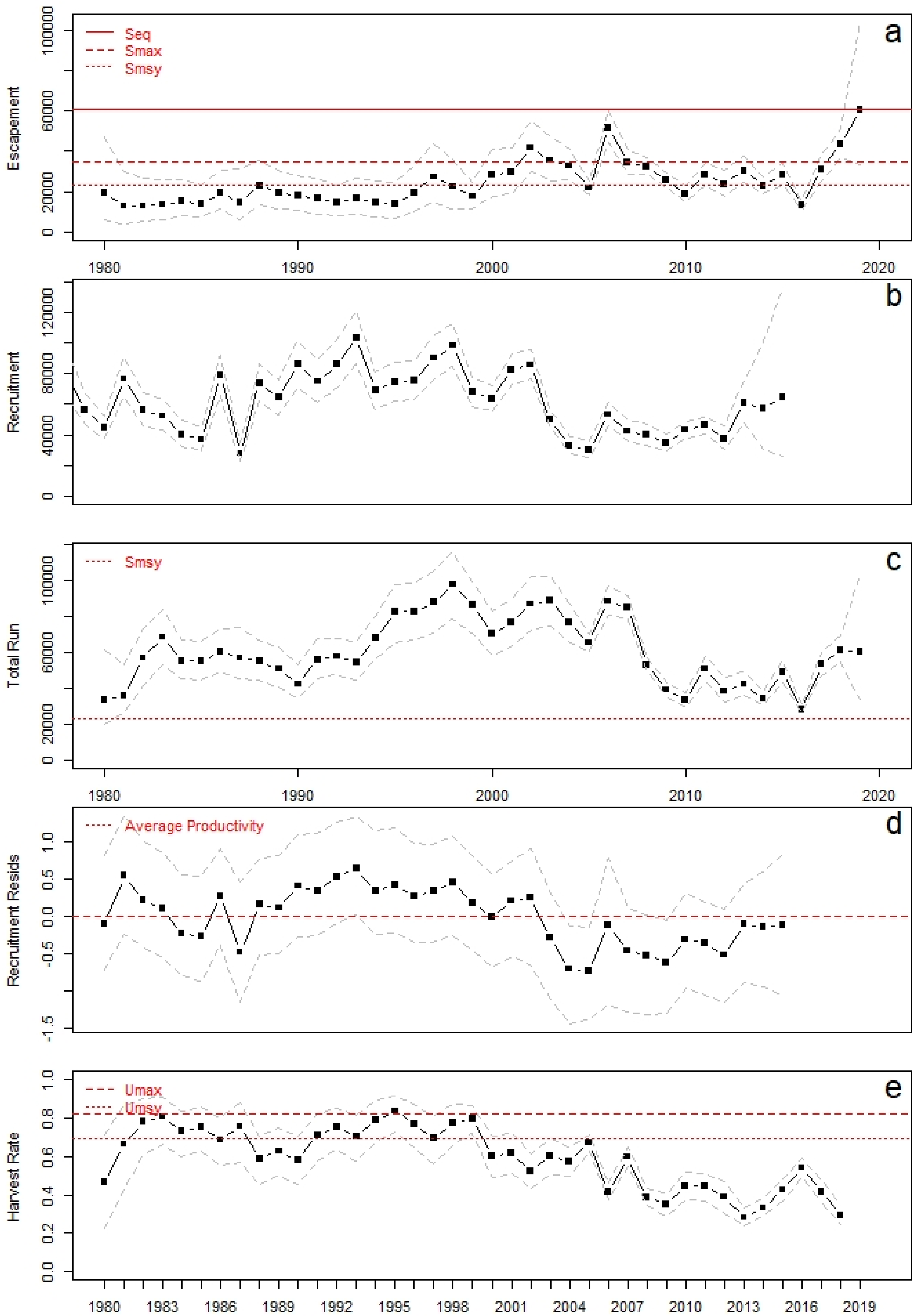

Figure 4.–Point estimates (posterior medians; solid lines) and 95% credibility intervals (dotted lines) of spawning escapement (a), recruitment by brood year (b), total run size (c), Ricker productivity residuals (d), and harvest rate, *U*, (e) from a state-space model of Copper River Chinook salmon, 1980–2018. The 2019 values are projections from the model and do not reflect actual returns in 2019. Posterior medians of S_{MSY} and U_{MSY} are plotted as short dash horizontal reference lines; the posterior median of S_{MAX} is plotted as a long dash horizontal reference line.

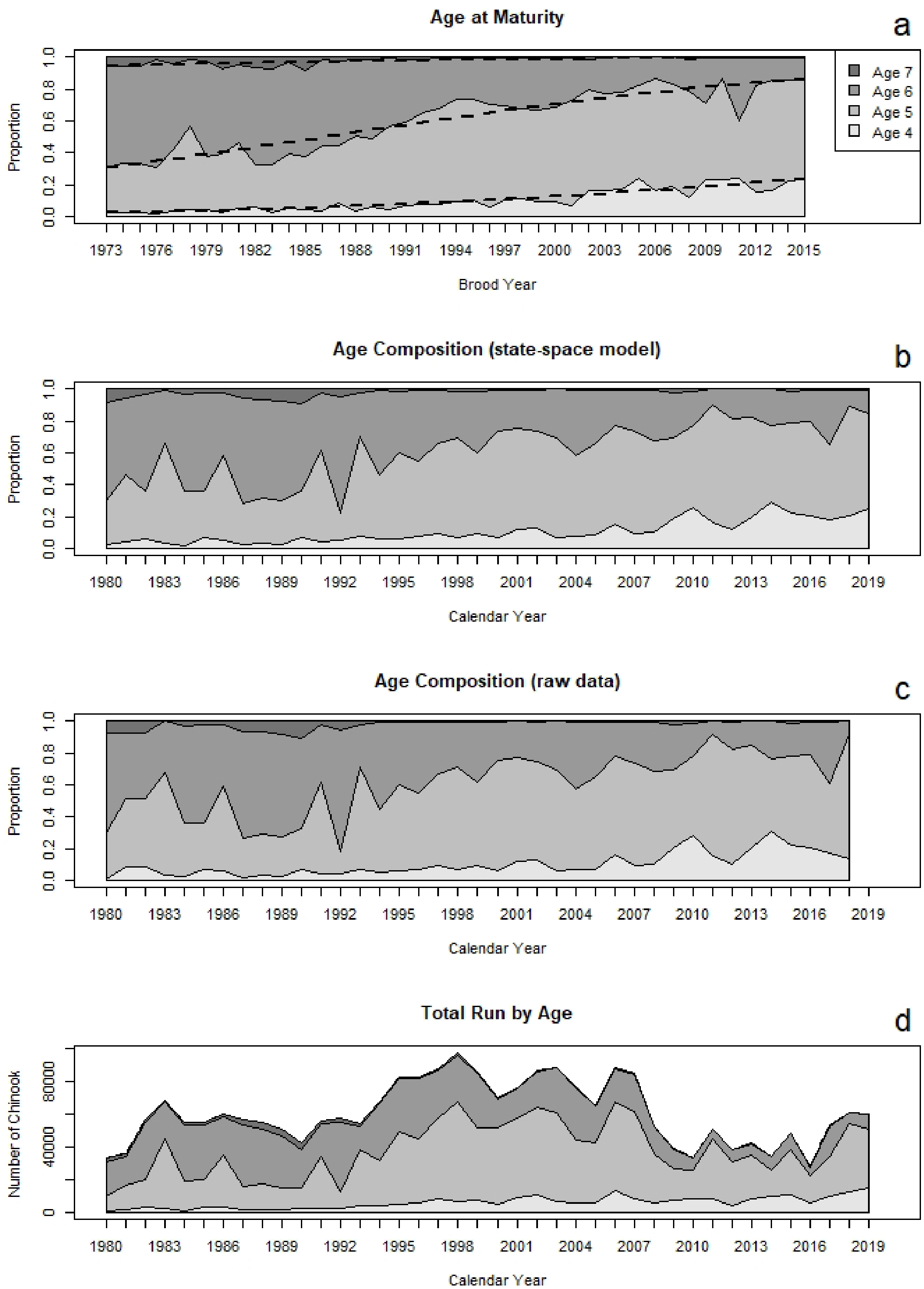

Figure 5.–Estimated age-at-maturity proportions by brood year (a), age composition proportions by calendar year derived in the model (b), the age composition in the raw data (c), and total run by age (d) from state-space model fitted to data from Copper River Chinook salmon harvest and escapement monitoring projects. Graphs *a*, *b*, and *c* are area graphs in which distance between lines represent age proportions.

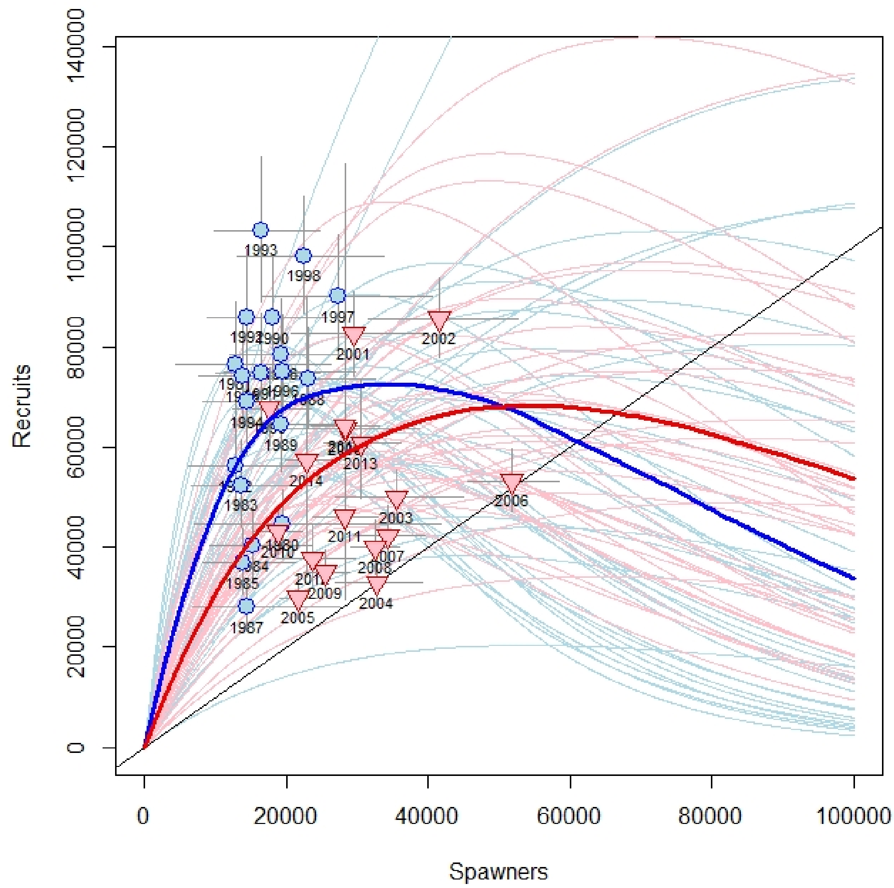

Figure 6.–Plausible spawner–recruit relationships for Copper River Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1980–2018 (blue) and 1999–2018 (red). Blue circles indicate pre-1999 modeled data while red triangles indicate data from 1999–2018. Posterior medians of R and S are plotted as brood year labels with 95% credibility intervals plotted as light lines. The heavy red and blue lines are the Ricker relationship constructed from ln(α) and β posterior medians. Ricker relationships are also plotted (light red and blue lines) for paired values of ln(α) and β sampled from the posterior probability distribution, representing plausible Ricker relationships that could have generated the observed data. Recruits replace spawners (R = S) on the diagonal line.

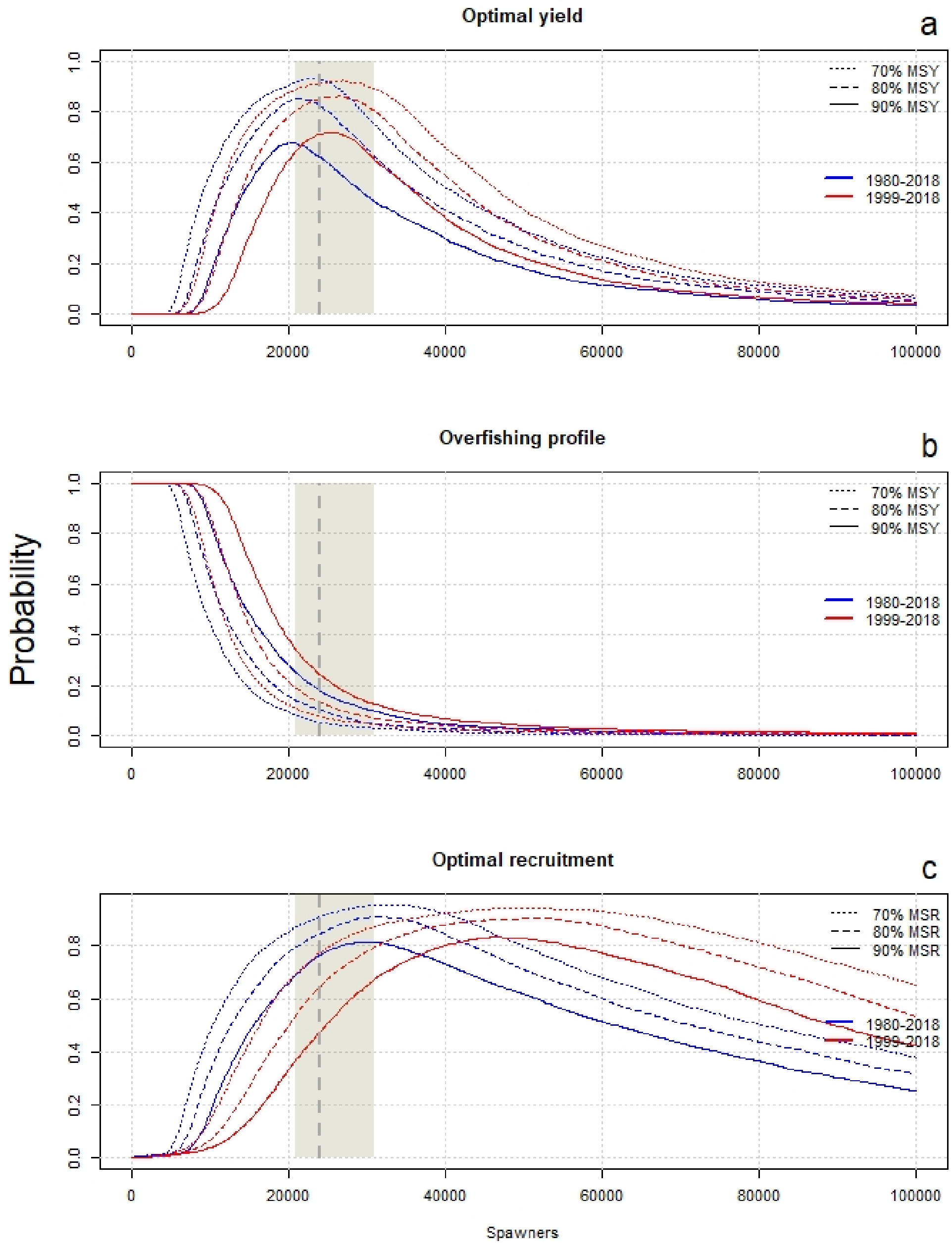

Figure 7.–Optimal yield profiles (OYPs, a), overfishing profiles (OFPs, b), and optimal recruitment profiles (ORPs, c) for Copper River Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1980–2018 (blue) and 1999–2018 (red). Shaded areas bracket the recommended goal range and the vertical, dashed grey lines represent the current escapement goal.

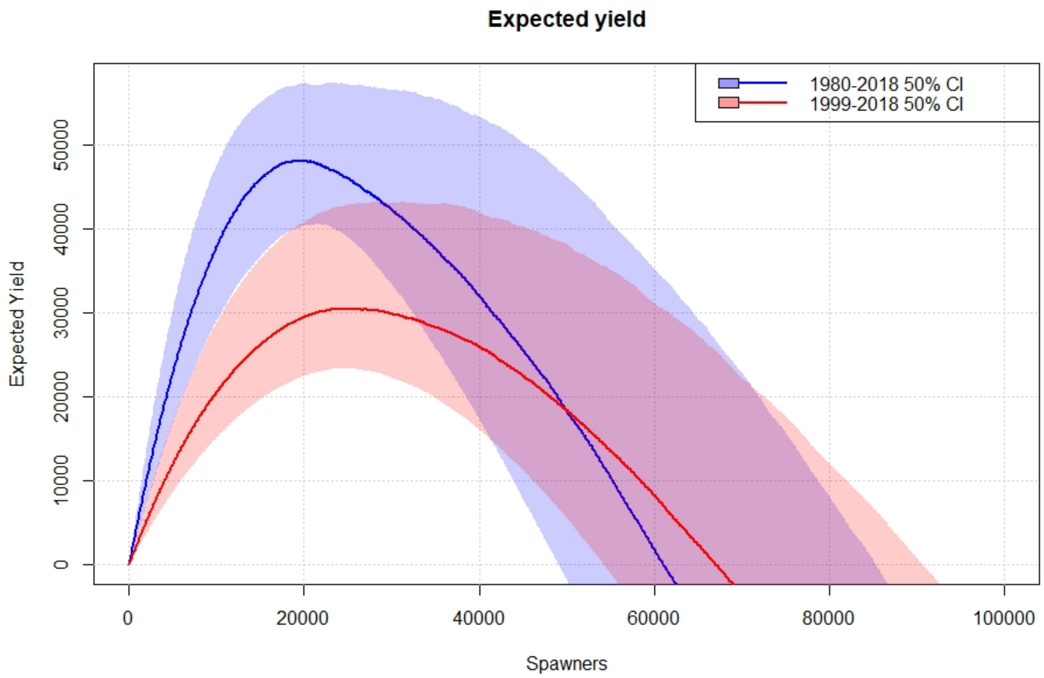

Figure 8.–Expected median yield (solid line) and 50% credibility interval (shaded area) for Copper River Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1980–2018 (blue) and 1999–2018 (red).

APPENDIX A: SUPPORTING INFORMATION FOR ESCAPEMENT GOAL RECOMMENDATION FOR COPPER RIVER CHINOOK SALMON

Appendix A1.–Estimates of Chinook salmon harvest from the Copper River District, Chitina Subdistrict, and Glennallen Subdistricts (1980–2018).

	Copper District						Chitina Subdistrict			Glennallen Subdistrict		
							Harvest			Harvest		
Year	Commercial Harvest	Subsistence Harvest	Homepack Harvest	Donated Harvest	Educational Harvest	District Total Harvest	State	Federal	Total	State	Federal	Total
1980	8,454	19				8,473	1,767		1,767	3,035		3,035
1981	20,178	48				20,226	1,410		1,410	2,410		2,410
1982	47,362	60				47,422	1,900		1,900	2,764		2,764
1983	52,500	79				52,579	4,255		4,255	5,950		5,950
1984	38,957	68				39,025	1,760		1,760	509		509
1985	42,214	88				42,302	1,329		1,329	1,958		1,958
1986	40,670	86				40,756	2,367		2,367	686		686
1987	41,001	49				41,050	2,968		2,968	813		813
1988	30,741	59				30,800	2,994		2,994	992		992
1989	30,863	56				30,919	2,251		2,251	787		787
1990	21,702	60				21,762	2,708		2,708	647		647
1991	34,787	136				34,923	4,056		4,056	1,328		1,328
1992	39,810	142				39,952	3,405		3,405	1,449		1,449
1993	29,727	120				29,847	2,846		2,846	1,434		1,434
1994	47,061	164	751			47,976	3,743		3,743	1,989		1,989
1995	65,675	154	1,688			67,517	4,707		4,707	1,892		1,892
1996	55,646	276	2,169	0	0	58,091	3,584		3,584	1,482		1,482
1997	51,273	200	1,243	0	0	52,716	5,447		5,447	2,583		2,583
1998	68,827	295	1,411	0	0	70,533	6,723	0	6,723	1,842	0	1,842
1999	62,337	353	1,115	0	14	63,819	5,913	0	5,913	3,278	0	3,278
2000	31,259	689	740	6	8	32,702	3,168	0	3,168	4,856	0	4,856
2001	39,524	826	935	0	16	41,301	3,113	0	3,113	3,553	0	3,553
2002	38,734	549	773	4	27	40,087	2,023	33	2,056	3,653	564	4,217
2003	47,721	710	1,073	3	0	49,507	1,903	18	1,921	2,538	554	3,092
2004	38,191	1,106	539	5	0	39,841	2,495	7	2,502	3,346	636	3,982
2005	34,624	260	760	11	92	35,747	2,043	51	2,094	2,229	389	2,618
2006	30,278	779	779	3	11	31,850	2,663	18	2,681	2,769	460	3,229
2007	39,095	1,145	1,019	0	70	41,329	2,694	28	2,722	3,276	663	3,939

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Year	Copper District						Chitina Subdistrict Harvest			Glennallen Subdistrict Harvest		
	Commercial Harvest	Subsistence Harvest	Homepack Harvest	Donated Harvest	Educational Harvest	District Total Harvest	State	Federal	Total	State	Federal	Total
2008	11,437	470	537	4	47	12,495	1,999	23	2,022	2,381	837	3,218
2009	9,457	212	876	0	50	10,595	214	9	223	2,493	543	3,036
2010	9,645	276	906	0	31	10,858	700	18	718	2,099	326	2,425
2011	18,500	212	1,282	0	6	20,000	1,067	13	1,080	2,319	743	3,062
2012	11,764	237	853	0	6	12,860	567	5	572	2,095	415	2,510
2013	8,826	854	564	0	55	10,299	744	18	762	2,148	374	2,522
2014	10,207	153	768	0	36	11,164	719	14	733	1,365	420	1,785
2015	22,506	167	1,145	0	50	23,868	1,570	15	1,585	2,212	402	2,614
2016	12,348	73	727	0	86	13,234	711	15	726	2,075	396	2,471
2017	13,834	778	744	0	50	15,406	1,961	12	1,973	2,935	431	3,366
2018	7,618	1,356	85	0	40	9,099	1,273	101	1,374	4,351	2,429	6,960

Appendix A2.–Estimates of Chinook salmon harvest from the sport fishery (1980–2018), total harvest (including commercial and subsistence harvests presented in Appendix A1) and, when available, estimates of inriver abundance, total run, harvest rate, and escapement (1999–2018).

Year	Sport Harvest	Total Harvest[a]	Inriver Abundance	Total Run Size	Harvest Rate	Total Escapement
1980	2,101	15,376				
1981	1,717	25,763				
1982	1,802	53,888				
1983	2,579	65,363				
1984	2,787	44,081				
1985	1,939	47,528				
1986	3,663	47,472				
1987	2,301	47,132				
1988	1,562	36,348				
1989	2,356	36,313				
1990	2,302	27,419				
1991	4,884	45,191				
1992	4,412	49,218				
1993	8,217	42,344				
1994	6,431	60,139				
1995	6,709	80,825				
1996	9,116	72,273				
1997	8,346	69,092				
1998	8,245	87,343				
1999	6,742	79,752	32,090	95,909	83%	16,157
2000	5,531	46,257	38,047	70,749	65%	24,492
2001	4,904	52,871	39,778	81,079	65%	28,208
2002	5,098	51,458	32,873	72,960	71%	21,502
2003	5,717	60,237	44,764	94,271	64%	34,034
2004	3,435	49,760	40,564	80,405	62%	30,645
2005	4,093	44,552	30,333	66,080	67%	21,528
2006	3,425	41,185	67,789	99,639	41%	58,454
2007	5,123	53,113	46,349	87,678	61%	34,565
2008	3,618	21,353	41,343	53,838	40%	32,485
2009	1,355	15,209	32,401	42,996	35%	27,787
2010	2,409	16,410	22,323	33,181	50%	16,771
2011	1,753	25,895	33,889	53,889	48%	27,994
2012	459	16,401	31,452	44,312	37%	27,911
2013	285	13,868	32,581	42,880	32%	29,012
2014	931	14,613	24,158	35,322	41%	20,709
2015	1,343	29,410	32,306	56,174	52%	26,764
2016	327	16,758	16,009	29,243	57%	12,485
2017	1,731	22,476	40,725	56,131	40%	33,655
2018	1,278	18,711	52,524	61,623	30%	42,912

Note: Blank cells mean there is no data for that year and estimate.

[a] Total Harvest calculated from sport harvest added to commercial and subsistence harvests presented in Appendix A1.

APPENDIX B:
DATA OBJECTS AND RJAGS CODE

Appendix B1.–State-space model input: Estimates of harvest below and above Miles Lake sonar, Miles Lake sonar abundance of all salmon, inriver abundance of Chinook salmon, Gulkana River counting tower escapement of Chinook salmon, harvest of Chinook and sockeye salmon in the personal use and subsistence fisheries, and the Gulkana River aerial index, 1980–2018.

Year	Harvest Below Sonar[a]	Proportion of Copper Stocks in Harvest below sonar	Miles Lake Sonar Count	Harvest above sonar[b]	Inriver abundance (CV)	Gulkana Counting Tower Escapement (CV)	Proportion in Personal Use Harvest	Proportion in Subsistence Harvest	Gulkana Aerial Index (Quality Score[c])
1980	8,473			6,903				0.089	712 (2)
1981	20,226			5,537				0.036	77 (5)
1982	47,422			6,466				0.026	879 (2)
1983	52,579			12,784				0.051	589 (4)
1984	39,025		618,732	5,056			0.035	0.018	1,331 (2)
1985	42,302		466,190	5,226			0.041	0.060	224 (1)
1986	40,756		481,628	6,716			0.055	0.024	1,484 (1)
1987	41,050		523,022	6,082			0.064	0.024	1,098 (1)
1988	30,800		528,940	5,548			0.066	0.033	831 (2)
1989	30,919		643,367	5,394			0.039	0.027	2,009 (2)
1990	21,762		624,922	5,657			0.039	0.020	1,171 (1)
1991	34,923		593,185	10,268			0.050	0.032	1,223 (3)
1992	39,952		604,898	9,266			0.038	0.031	540 (3)
1993	29,847		819,700	12,497			0.030	0.026	693 (2)
1994	47,976		738,011	12,163			0.038	0.028	786 (2)
1995	67,517		637,293	13,308			0.056	0.035	285 (2)
1996	58,091		907,267	14,182			0.036	0.028	1,364 (3)
1997	52,716		1,164,791	16,376			0.035	0.030	2,270 (2)
1998	70,533		865,896	16,810			0.047	0.028	1,407 (2)
1999	63,805		850,597	15,933	32,090 (0.12)		0.040	0.041	934 (2)
2000	32,694		636,837	13,555	38,047 (0.20)		0.029	0.075	1,174 (3)
2001	41,285		878,205	11,570	39,778 (0.21)		0.023	0.041	691 (2)
2002	40,085		830,263	11,371	32,873 (0.27)	6,390 (0.05)	0.023	0.067	2,087 (2)
2003	49,507		747,091	10,730	44,764 (0.28)	4,890 (0.06)	0.023	0.049	982 (2)

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Year	Harvest Below Sonar[a]	Proportion of Copper Stocks in Harvest below sonar	Miles Lake Sonar Count	Harvest above sonar[b]	Inriver abundance (CV)	Gulkana Counting Tower Escapement (CV)	Proportion in Personal Use Harvest	Proportion in Subsistence Harvest	Gulkana Aerial Index (Quality Score[c])
2004	39,841		684,103	9,919	40,564 (0.11)	4,734 (0.06)	0.022	0.052	2,014 (2)
2005	35,747	0.97	855,125	8,805	30,333 (0.05)	2,718 (0.06)	0.016	0.029	822 (2)
2006	31,850	0.86	959,706	9,335	67,789 (0.07)	4,846 (0.06)	0.021	0.041	1,183 (1)
2007	41,329	0.94	919,601	11,784	46,349 (0.07)	4,422 (0.06)	0.021	0.045	1,182 (2)
2008	12,495	0.92	718,344	8,856	41,343 (0.05)	3,678 (0.07)	0.024	0.053	No survey
2009	10,595		709,748	4,614	32,401 (0.07)	2,720 (0.07)	0.002	0.048	701 (1)
2010	10,858		923,811	5,559	22,323 (0.11)	2,267 (0.07)	0.005	0.028	728 (1)
2011	20,000		914,231	5,895	33,889 (0.1)	3,804 (0.07)	0.008	0.039	515 (2)
2012	12,860		1,294,400	3,617	31,452 (0.17)	1,730 (0.09)	0.004	0.026	512 (2)
2013	10,299	0.80	1,267,060	3,569	32,581 (0.14)	3,936 (0.05)	0.004	0.028	2,220 (1)
2014	11,164	0.70	1,218,418	3,449	24,158 (0.09)	3,478 (0.08)	0.005	0.018	944 (2)
2015	23,868	0.64	1,346,100	5,542	32,306 (0.12)	3,738 (0.07)	0.007	0.023	1,523 (1)
2016	13,234	0.86	801,593	3,524	16,009 (0.07)	1,122 (0.15)	0.004	0.030	No survey
2017	15,406	0.93	723,426	7,839	40,725 (0.10)	3,336 (0.09)	0.014	0.056	768 (NA)
2018	9,099		701,577	10,320	52,524 (0.08)	5,174 (0.07)	0.017	0.120	No survey

Note: NA = not available; blank cells mean there is no data for that year and estimate.

[a] Harvest below sonar includes commercial, subsistence, home pack, donated, educational, and confiscated Chinook salmon in the Copper River District.

[b] Harvest above sonar includes personal use, sport, and federal and state subsistence Chinook salmon.

[c] Quality scale of 1 through 5, where 1 equals clear skies and water and 5 equals cloudy and turbulent water.

Appendix B2.–Age composition estimates from the Copper River District commercial fishery, 1980–2018.

Year	Age-4	Age-5	Age-6	Age-7	Sample Size
1980	0.01	0.29	0.63	0.07	219
1981	0.09	0.42	0.42	0.07	135
1982	No data collected				
1983	0.04	0.64	0.32	0.00	3,165
1984	0.02	0.34	0.60	0.03	2,387
1985	0.07	0.29	0.62	0.02	2,830
1986	0.06	0.54	0.38	0.02	2,766
1987	0.02	0.24	0.67	0.06	2,576
1988	0.04	0.26	0.64	0.07	1,752
1989	0.03	0.25	0.64	0.08	1,545
1990	0.07	0.26	0.56	0.11	1,594
1991	0.04	0.58	0.36	0.02	1,596
1992	0.05	0.14	0.76	0.06	1,996
1993	0.07	0.64	0.27	0.02	2,043
1994	0.05	0.39	0.55	0.01	1,999
1995	0.06	0.54	0.39	0.01	2,118
1996	0.07	0.47	0.45	0.01	1,729
1997	0.10	0.58	0.32	0.01	1,805
1998	0.07	0.64	0.28	0.01	1,920
1999	0.10	0.52	0.37	0.01	1,694
2000	0.06	0.70	0.24	0.01	1,830
2001	0.12	0.65	0.23	0.00	1,845
2002	0.13	0.62	0.25	0.01	2,143
2003	0.07	0.63	0.30	0.00	1,931
2004	0.07	0.50	0.42	0.01	1,865
2005	0.07	0.57	0.35	0.01	2,103
2006	0.16	0.62	0.21	0.00	1,568
2007	0.09	0.64	0.26	0.00	2,290
2008	0.11	0.58	0.31	0.00	1,365
2009	0.20	0.49	0.28	0.03	1,457
2010	0.28	0.49	0.21	0.01	725
2011	0.16	0.76	0.09	0.00	1,760
2012	0.11	0.72	0.17	0.00	1,565
2013	0.21	0.64	0.15	0.00	916
2014	0.31	0.46	0.23	0.00	1,876
2015	0.23	0.55	0.21	0.01	2,505
2016	0.21	0.58	0.20	0.01	1,775
2017	0.17	0.44	0.38	0.01	1,913
2018	0.14	0.77	0.09	0.00	189

Appendix B3.–RJAGS code for the state-space model of Copper River Chinook salmon data, 1980–2018.

```
mod=function(){
 for (y in (A+a.min):(Y+A-1)) {
  log.R[y] ~ dt(log.R.mean2[y],tau.white,500)
  R[y] <- exp(log.R[y])
  log.R.mean1[y] <- log(S[y-a.max]) + lnalpha - beta * S[y-a.max]
  log.resid[y] <- log(R[y]) - log.R.mean1[y]
  lnalpha.y[y] <- lnalpha + log.resid[y]
 }
 log.resid.vec <- log.resid[(A+a.min):(Y+A-1)]
 lnalpha.vec <- lnalpha.y[(A+a.min):(Y+A-1)]
 log.R.mean2[A+a.min] <- log.R.mean1[A+a.min] + phi * log.resid.0
 for (y in (A+a.min+1):(Y+A-1)) {
  log.R.mean2[y] <- log.R.mean1[y] + phi * log.resid[y-1]
 }
 lnalpha ~ dnorm(0,1.0E-6)%_%T(0,)
 beta ~ dnorm(0,1.0E-2)%_%T(0,)
 phi ~ dnorm(0,1.0E-4)%_%T(-1,1)
 tau.white ~ dgamma(0.001,0.001)
 log.resid.0 ~ dnorm(0,tau.red)%_%T(-3,3)
 alpha <- exp(lnalpha)
 tau.red <- tau.white * (1-phi*phi)
 sigma.white <- 1 / sqrt(tau.white)
 sigma.red <- 1 / sqrt(tau.red)
 lnalpha.c <- lnalpha + (sigma.white * sigma.white / 2 / (1-phi*phi) )
 S.max <- 1 / beta
 S.eq <- lnalpha.c * S.max
 S.msy <- S.eq * (0.5 - 0.07*lnalpha.c)
 U.msy <- lnalpha.c * (0.5 - 0.07*lnalpha.c)
```

-continued-

```
# BROOD YEAR RETURNS W/O SR LINK DRAWN FROM COMMON LOGNORMAL
DISTN
 mean.log.R ~ dnorm(0,1.0E-4)%_%T(0,)
 tau.R ~ dgamma(0.001,0.001)
 R.0 <- exp(mean.log.R)
 sigma.R0 <- 1 / sqrt(tau.R)
 for (y in 1:a.max) {
  log.R[y] ~ dt(mean.log.R,tau.R,500)
  R[y] <- exp(log.R[y])
 }

 # GENERATE Y+A-1 MATURITY SCHEDULES, ONE PER BROOD YEAR
 D.scale ~ dunif(0,1)
 D.sum <- 1 / (D.scale * D.scale)

 # MULTIVARIATE LOGISTIC DIRICHLET MODEL FOR TRENDING AGE AT
MATURITY
 eta1[A] <- 1
 eta2[A] <- 0
 for (a in 1:(A-1)) {
  eta1[a] ~ dnorm(0,0.0001)
  eta2[a] ~ dnorm(0,0.0001)
 }

 for (y in 1:(Y+A-1)) {
  for (a in 1:A) {
   logistic.a[y,a] <- exp(eta1[a] + eta2[a] * y)
   pi.y[y,a] <- logistic.a[y,a] / sum(logistic.a[y,])
   Dirch_gamma_shape[y,a] <- D.sum * pi.y[y,a]
   g[y,a] ~ dgamma(Dirch_gamma_shape[y,a],0.1)
   p[y,a] <- g[y,a]/sum(g[y,])
  }
```

-continued-

```
}


# ASSIGN PRODUCT OF P AND R TO ALL CELLS IN N MATRIX
# y SUBSCRIPT INDEXES BROOD YEAR
# y=1 IS THE BROOD YEAR OF THE OLDEST FISH IN YEAR 1 (upper right cell)
# y=Y IS THE BROOD YEAR OF THE YOUNGEST FISH IN YEAR Y (lower left cell,
forecast year)
# ASSIGN PRODUCT OF P AND R TO ALL CELLS IN N MATRIX
for (a in 1:A) {
  for (y in a:(Y + (a - 1))) {
    N.ta[y - (a - 1), (A + 1 - a)] <- p[y, (A + 1 - a)] * R[y]
  }
}

# OBSERVE AGE COMPOSITION
for (t in 1:Y) {
  N[t] <- sum(N.ta[t,1:A])
  for (a in 1:A) {
    q[t,a] <- N.ta[t,a] / N[t]
  }
}
# MULTINOMIAL SCALE SAMPLING ON TOTAL ANNUAL RETURN N
# INDEX t IS CALENDAR YEAR
# OVERLAP IS MUCH LARGER THAN IN PREVIOUS VERSIONS
for (t in 1:Y) {
  x[t, 1:A] ~ dmulti(q[t, ], n.a[t])
}

# INRIVER RUN OBSERVED, AS WELL AS HARVESTS BELOW AND ABOVE
ASSESSMENT SITE
```

-continued-

```
for (y in 1:Y) {
  mu.Hbelow[y] ~ dbeta(0.1,0.1)
  H.below[y] <- mu.Hbelow[y] * N[y]
  H.below.all[y] <- H.below[y] / prop.copper[y
  log.Hba[y] <- log(H.below.all[y])
  tau.log.Hba[y] <- 1 / log(cv.Hb[y]*cv.Hb[y] + 1)
  Hhat.below.all[y] ~ dlnorm(log.Hba[y],tau.log.Hba[y])

  InriverRun[y] <- max(N[y] - H.below[y], 1)
  log.IR[y] <- log(InriverRun[y])

  mu.Habove[y] ~ dbeta(0.1,0.1)
  H.above[y] <- mu.Habove[y] * InriverRun[y]
  log.Ha[y] <- log(H.above[y])
  tau.log.Ha[y] <- 1 / log(cv.Ha[y]*cv.Ha[y] + 1)
  Hhat.above[y] ~ dlnorm(log.Ha[y],tau.log.Ha[y])

  mu[y] <- (H.below[y] + H.above[y]) / N[y]
  S[y] <- max(InriverRun[y] - H.above[y], 1)
  log.S[y] <- log(S[y])
}

# HIERARCHICAL PROPORTIONS COPPER IN CHINOOK HARVEST BELOW
ASSESSMENT SITE
zeta1 ~ dunif(1,1000)
zeta2 ~ dunif(1,1000)
for (y in 1:Y) {
  prop.copper[y] ~ dbeta(zeta1,zeta2)
  count.copper[y] ~ dbin(prop.copper[y],N.copper[y])
}
```

-continued-

```
# OBSERVE MARK RECAP ESTIMATE OF INRIVER RUN
for (y in 1:Y) {
  MR[y] ~ dlnorm(log.IR[y],tau.log.mr[y])
  tau.log.mr[y] <- 1 / log(cv.mr[y]*cv.mr[y] + 1)
}

# PRIORS FOR INDEX PARAMS
q.subas ~ dnorm(0,1.0E-1)%_%T(0,1)
q.dnas1 ~ dnorm(0,1.0E-1)%_%T(0,1)
q.dnas2 ~ dnorm(0,1.0E-1)%_%T(0,1)
q.dnas3 ~ dnorm(0,1.0E-1)%_%T(0,1)
q.air ~ dnorm(0,1.0E-1)%_%T(0,1)
q.tower ~ dnorm(0,1.0E-1)%_%T(0,1)
tau.log.subas ~ dgamma(0.01,0.01)
tau.log.dnas1 ~ dgamma(0.01,0.01)
tau.log.air ~ dgamma(0.01,0.01)
tau.log.tower ~ dgamma(0.01,0.01)
sigma.subas <- 1 / sqrt(tau.log.subas)
sigma.dnas1 <- 1 / sqrt(tau.log.dnas1)
sigma.air   <- 1 / sqrt(tau.log.air)
sigma.tower <- 1 / sqrt(tau.log.tower)

# OBSERVE MILES LAKE SONAR APPORTIONED BY CHINOOK PROPORTION IN
SUBSISTENCE FISHERY AS INDEX OF INRIVER RUN
for (y in 1:Y) {
  log.qIRsubmean[y] <- log(q.subas * InriverRun[y])
  subas[y] ~ dlnorm(log.qIRsubmean[y],tau.log.subas)
}
```

-continued-

```
# OBSERVE MILES LAKE SONAR APPORTIONED BY CHINOOK PROPORTION IN PU
FISHERY AS INDEX OF INRIVER RUN
# PROPORTIONALITY CONSTANT ALLOWED TO DIFFER 1980-1999 VS 2000-2018
for (y in 1:20) {
  log.qIRmean[y] <- log(q.dnas1 * InriverRun[y])
  dnas[y] ~ dlnorm(log.qIRmean[y],tau.log.dnas1)
}

for (y in 21:29) {
  # for (y in 21:Y) {
  log.qIRmean[y] <- log(q.dnas2 * InriverRun[y])
  dnas[y] ~ dlnorm(log.qIRmean[y],tau.log.dnas1)
}

for (y in 30:Y) {
  log.qIRmean[y] <- log(q.dnas3 * InriverRun[y])
  dnas[y] ~ dlnorm(log.qIRmean[y],tau.log.dnas1)
}

# OBSERVE GULKANA TOWER COUNTS AND AIR SURVEYS AS INDICES OF
ESCAPEMENT
for (y in 1:Y) {
  log.qtSmean[y] <- log(q.tower * S[y])
  gka.tower[y] ~ dlnorm(log.qtSmean[y],tau.log.tower)
  log.qaSmean[y] <- log(q.air * S[y])
  gka.air[y] ~ dlnorm(log.qaSmean[y],tau.log.air)
}

# MEAN LNA FOR 5 MOST RECENT BROOD YEARS
lnalpha.recent    <- mean(lnalpha.y[(Y+A-5):(Y+A-1)])
lnalpha.c.recent <- lnalpha.recent + (sigma.white * sigma.white / 2 / (1-phi*phi) )
```

-continued-

```
  U.msy.recent <- lnalpha.c.recent * (0.5 - 0.07*lnalpha.c.recent)
  S.eq.recent <- lnalpha.c.recent * S.max
  S.msy.recent <- S.eq.recent * (0.5 - 0.07*lnalpha.c.recent)
}
```

APPENDIX C: ESCAPEMENT GOALS RELATIVE TO ESTIMATES OF SPAWNING ABUNDANCE PROVIDING MAXIMUM SUSTAINED YIELD FOR 23 ALASKA CHINOOK SALMON STOCKS

Appendix C1.–Escapement goal lower and upper bounds for 23 Alaska Chinook salmon stocks and the recommended SEG range for Copper River Chinook, plotted as multiples of S_{MSY}.