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Yukon River Summer Chum Salmon Run Reconstruction, Spawner-Recruitment Analysis, and Escapement Goal Recommendation

by

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and

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December 2015

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

FISHERY MANUSCRIPT SERIES NO. 15-07

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ABSTRACT

Summer chum salmon *Oncorhynchus keta* are the largest of the Yukon River salmon runs and have also sustained the largest subsistence and commercial salmon harvests throughout recorded history. These salmon spawn in numerous tributary and mainstem areas throughout the lower and middle Yukon River drainage but are generally managed as a single stock, especially in the main harvest areas in the lower river. These facts indicated the need for a drainagewide summer chum salmon escapement goal, in accordance with Alaska's Sustainable Salmon Policy. As of 2015, summer chum salmon escapement goals existed only for 2 of the largest spawning tributaries, Anvik and Adreafsky (East Fork) rivers. Assessment of the drainagewide run was greatly improved by full implementation of the mainstem sonar project near Pilot Station in 1995. However, other components of the run have now also been incorporated in a formal, drainagewide run reconstruction, combining all available harvest, run size index, escapement, and age composition data. The run reconstruction was implemented with a spawner-recruit model within a single state-space framework to generate spawner-recruitment parameters and associated reference points germane to determination of an escapement goal. Total run size has been strongly cyclic, ranging from 600,000 to over 4 million summer chum salmon during the 1978–2014 study period. Average harvest rates were around 40% from 1978 to 1990 and 13% from 1991 to 2014. The spawner-recruit relationship indicates a moderately productive population demonstrating strong negative density dependence. A committee of fisheries scientists, managers, and research biologists met to review the analysis and decide upon an appropriate escapement goal recommendation. Fishery stakeholder representatives also participated in these discussions. Based upon consideration of optimal yield profiles, along with typical harvest sizes and rates and the range of observed run sizes, the committee recommended a biological escapement goal of 500,000–1,200,000 summer chum salmon.

Key words: Summer chum salmon *Oncorhynchus keta*, escapement, abundance, harvest rate, escapement goal, biological escapement goal, run reconstruction, spawner-recruit model, state-space model, optimal yield profile, Yukon River.

INTRODUCTION

According to the *Policy for the management of sustainable salmon fisheries* (*Sustainable Salmon Policy*: 5 AAC 39.222) and the *Policy for statewide salmon escapement goals* (*Escapement Goal Policy*; 5 AAC 39.223), assessment of spawning stocks and establishment of escapement goals are required for salmon stocks with large, important, or intensive fisheries. Summer chum *Oncorhynchus keta* salmon in the Yukon River make up spawning groups from numerous tributaries and mainstem areas, but are primarily managed as a single stock. Thus Yukon River summer chum salmon fisheries are large-scale, important, and often intensive, such that a single drainagewide escapement goal is appropriate for management of this collective stock. However, the complexity and cost of monitoring and assessing the drainagewide run and all its component stocks have made development of an escapement goal a challenging long-term task. This report presents the rationale and analytical model for a proposed new summer chum salmon escapement goal for the Yukon River drainage, based on a state-space model incorporating run reconstruction estimates and an age-structured spawner-recruit model.

Chum salmon make up the largest of the salmon spawning migrations in the Yukon River, and can be separated into genetically distinct summer and fall runs (Seeb and Crane 1999; Flannery et al. 2007). These distinct runs have long been recognized by Yukon River fishermen through visual characteristics and timing (Gilbert and O'Malley 1921; ADF&G 1979). Summer chum salmon are generally smaller and mature more rapidly upon entering fresh water, entering the river early in the season, concurrently with Chinook salmon *O. tschawytscha*, from early June through mid-July. They spawn primarily in tributaries of the lower 700 miles of the Yukon River, including the Tanana and Koyukuk rivers and their tributaries, as well as numerous small channels adjacent to the mainstem (Figure 1). Fisheries targeting summer and fall chum salmon are managed separately, by season: the fall season begins by regulation on July 16 (*Yukon River* *drainage fall chum salmon management plan* 5AAC 01.249). Genetic analysis consistently supports this data as the transition between the 2 runs (F. Bue, U.S. Fish and Wildlife Service Subsistence Fisheries Branch Chief, Fairbanks AK; personal communication).

Chum salmon have been the most utilized species in Yukon River subsistence and commercial salmon harvests throughout the recorded history of these fisheries. Early commercial markets for chum salmon were predominately informal and local; fishermen would typically sell any surplus after providing for their subsistence needs. Chum salmon were vital to individual households and the local economy as food for sled dog teams, which were the primary mode of winter transport throughout the area. Declines in chum salmon utilization were noted after the introduction of air transport in the late 1920s (Carey 1980) and with further replacement of dog teams by snowmobiles during the 1960s (Geiger and Anderson 1979). Development of outside commercial markets for chum salmon beginning in the late 1960s and for chum salmon roe in beginning in 1980 resulted in rapid expansion of summer chum salmon commercial harvests. Only 11,000 summer chum salmon were harvested commercially in 1967; in the 2 decades that followed the commercial harvest increased to an average of 700,000 fish in 1977–1986 (ADF&G 1988). Subsistence harvests of summer chum salmon averaged about 276,000 fish from 1978 to 1987 (ADF&G 1988) and about 170,000 fish from 1988 to 1997 (Borba and Hamner 1999). As in the past, some of the harvest supplied food for sled dogs, whose numbers had increased again during this period for recreational travel and racing. Excess chum salmon carcasses from the commercial roe fishery were available for subsistence use and for sled dogs. In the mid-1990s commercial markets declined for both summer chum salmon flesh and roe. Shortly thereafter, run abundance decreased sharply over a several year period, subsistence and commercial harvests were reduced accordingly, and existing escapement goals were generally not met, leading to a “stock of concern” designation by the Alaska Board of Fisheries (ADF&G 2000). Summer chum salmon abundance improved after 2001 and the stock of concern designation was discontinued in 2007 (Bue and Hayes 2007).

Summer chum salmon continue to provide the largest numbers of salmon in both subsistence and commercial harvests. A range for the amount necessary for subsistence (ANS) of 83,500 to 142,192 summer chum salmon was established by the Alaska Board of Fisheries in 2001 (5 AAC 01.236). In recent years (2003–2012), subsistence harvest of summer chum salmon averaged just under 80,000 fish annually, similar to fall chum and exceeding Chinook salmon harvests during this same period (Estensen et al. 2015). Subsistence and commercial fisheries for summer chum salmon have assumed increased importance in the Yukon area since extensive conservation measures for Chinook salmon began. All directed commercial harvest of Chinook salmon has been closed since 2008, and subsistence Chinook salmon catches declined precipitously as a result of unprecedented restrictions, to only about 12,500 fish in 2013 (JTC 2015). At the same time subsistence harvests of summer chum salmon increased above the previous decade average to over 121,000 fish (2012–2013 average; Estensen et al. 2015), as fishing households began shifting their effort to the less restricted species. Commercial markets for summer chum salmon remained weak though the mid-2000s and the market for roe has continued to decline, but increased marketing efforts more recently have assisted in rebuilding the fishery. Average annual commercial harvest of summer chum salmon in 2003–2012 was about 152,000 fish, and in 2013 increased to over 485,000 fish (Estensen et al. 2015).

Management of the summer chum salmon run is guided by the *Yukon River Summer Chum Salmon Management Plan* (5 AAC 05.362), originally adopted in 1990. The intent of this plan is to manage harvests to provide first for escapement needs, then to give priority to subsistence use over other consumptive uses including commercial, sport, and personal use fishing. Harvest opportunity can vary according to expected run size. A directed commercial fishery may be opened in a local area when the run size is projected to be 700,000–1,000,000 fish and escapement goals in that area are expected to be met. When the run size is projected to be between 900,000 and 1,000,000 fish, limited directed commercial fishing may be allowed. When run size is projected to be greater than 1,000,000 fish, directed commercial fishing may be opened more generally to harvest the available surplus. Commercial fishing opportunities have been increasingly constrained by management strategies designed to protect large portions of the Chinook salmon runs (Estensen et al. 2015). A separate plan adopted in 1994 guides management of summer chum salmon returning to the Anvik River (*Anvik River Chum Salmon Fishery Management Plan*, 5 AAC 05.368). This plan was designed to specifically target large surpluses of Anvik River summer chum salmon above escapement needs, and thereby decrease fishing pressure on non-Anvik River stocks migrating further upriver. Commercial harvests were taken in this terminal area only from 1994 to 1997.

Summer chum salmon abundance and escapement have been assessed using a combination of test fishery projects in the lower river, passage estimates from the sonar project near Pilot Station, tributary escapement monitoring projects, and aerial survey spawning escapement indices (Figure 1). No single project provides a complete assessment of the drainagewide population, although the Pilot Station sonar passage estimate has been presumed to represent abundance above that point in the river. The oldest continuous escapement monitoring project for summer chum salmon began in 1971 with establishment of a counting tower project on the Anvik River, the largest producer of summer chum salmon in the Yukon drainage (Trasky 1972). The counting tower was replaced by sonar in 1979, at a point lower in the river where most of the Anvik spawning population could be counted (Buklis 1982). On the Andreafsky River, the lowest major tributary in the drainage, ground based escapement enumeration started with a sonar project in 1981 on the East Fork (Buklis 1982). A counting tower was used for several years in the 1980s, and a weir project was implemented in 1994 and has been operated continuously since then (AYKDBMS)[1]. A number of ground based escapement enumeration projects were implemented in other Yukon tributaries during the 1990s, most lasting for less than 10 years. However, a few of these projects have operated continuously since the 1990s, including weirs on the Gisasa River and Henshaw Creek in the Koyukuk River drainage, and towers, primary for counting Chinook salmon, on the Chena and Salcha rivers in the Tanana River drainage. The mainstem sonar project near Pilot Station began estimating salmon passage, by species, in 1986. Species proportions are estimated by means of test fishery catches. Chum salmon passing the sonar are assumed to be summer run fish through July 18 and fall run fish starting July 19. Fisheries managers have relied on daily abundance estimates generated by this project to manage and regulate fisheries according to management plans, escapement goals, and other objectives.

Escapement goal development proceeded gradually starting in the early 1980s. Following approval of an escapement goal policy in 1992, summer chum salmon escapement goals were documented for the Andreafsky, Anvik, Nulato, Hogatza, and Salcha rivers, of which all except Anvik were based upon aerial surveys (Buklis 1993). More fully developed biological

[1] Data for these and other escapement projects in the Yukon River drainage can be accessed through ADF&G's Arctic–Yukon–Kuskokwim Database Management System (AYKDBMS), http://www.adfg.alaska.gov/CommFishR3/WebSite/AYKDBMSWebsite/Default.aspx.

escapement goals were eventually implemented for the Andreafsky and Anvik rivers, in 2001 (Clark 2001; Clark and Sandone 2001). These 2 goals have been subsequently revised, and have remained the only summer chum salmon escapement goals in the Yukon Area (Conitz et al. 2012). The goal for the East Fork Andreafsky River, based on the weir count, is a lower bound sustainable escapement goal (SEG) of greater than 40,000 fish (Fleischman and Evenson 2010) The goal for the Anvik River is a biological escapement goal (BEG) of 350,000–700,000 fish (ADF&G 2004). Interest in establishing a drainagewide escapement goal for summer chum salmon was advanced by development of the Pilot Station sonar project. Low chum salmon abundance and subsequent economic disaster declarations in the Arctic–Yukon–Kuskokwim region during the late 1990s and early 2000s further motivated interest in estimating drainagewide abundance. Several attempts were made to estimate historical drainagewide run abundance, based on limited data and broad assumptions (for example, Clark and Sandone (2001) suggested drainagewide abundance is about two times the Anvik River passage counts). Formal statistical approaches were developed to address data limitations, essentially combining multiple data sources (harvest, test fishing indices escapement, sonar passage) such that maximum information could be extracted from the combined data to generate plausible historical abundance estimates (Shotwell and Adkison 2004). Similar methods were used subsequently in run reconstruction and escapement goal analysis for fall chum salmon drainagewide (Fleischman and Borba 2009) and for East Fork Andreafsky River summer chum salmon (Fleischman and Evenson 2010).

The model we used in this Yukon summer chum salmon escapement goal analysis combined a run reconstruction and spawner-recruit model within a single state-space framework. State-space models relate unobserved process or "state" variables to observed data and incorporate specification of both stochastic fluctuation inherent in the system (process error) and observation error, allowing for a robust and realistic characterization of uncertainty (Rivot et al. 2004; Su and Peterman 2012; Fleischman 2013). Applied to Pacific salmon, state-space models incorporate serial correlation in recruitment and allow for characterization of variable age structure and time-varying productivity. These comprise the process variation part of the state-space model. Observation error is incorporated by specifying the relationship of observed annual harvest, escapement counts, and run age composition estimates to the modeled, unobserved states (Fleischman et al. 2013).

The purpose of this analysis was to determine appropriate reference points for a BEG for the Yukon River summer chum salmon population. The actual BEG range was selected by a committee of regional and statewide biologists and biometricians based upon the estimated reference points. The committee reviewed and discussed preliminary results from the analysis in a meeting with fishery stakeholders on February 2, 2015, and provided some direction on additional input to the model as well as desired outcomes. They met again on August 21 and September 28, 2015, to review the finished analysis and discuss and select the recommended escapement goal range.

METHODS

DATA SOURCES

Harvest data and estimates were compiled from subsistence and commercial fisheries reports. Escapement data and estimates were obtained from ground-based projects and aerial surveys. Summer chum salmon age data from fisheries and escapement samples were compiled and combined with harvest and escapement estimates to generate estimates of age composition of the total annual run (Appendix A). Most of these data are stored in the ADF&G regional database (AYKDBMS), and documented in ADF&G technical reports, primarily those published by year in the *Yukon Area annual management report* series (e.g., Estensen et al. 2015) or individual project reports (e.g., Jallen et al. 2012; Eaton 2014; Lozori and McIntosh 2014; McEwen 2015). Data were preferentially obtained from the management and project reports, but were also extracted from the database for comparison or when not available in reports. Minor differences in data obtained from these various sources exist due to error correction, updating of estimation methods, or revision of harvest reporting units or methods over time. Care was taken to ensure data and estimates were consistent across various sources, but minor differences were ignored as they would contribute only a small amount of uncertainty to the overall result. Although some escapement data, mostly from aerial survey counts, date back to the 1950s, harvest data collected before 1978, particularly from subsistence fisheries, lacked sufficient detail on species or harvest area to be useful for this analysis. Only data from 1978 through 2014 were included in the analysis.

Harvest Data

Subsistence and personal use harvest data have been collected by ADF&G through a combination of postseason household surveys, telephone interviews, catch calendars, mail-in questionnaires and returned permits where permits are required, since 1961. Although survey and estimation methods have changed and improved over time, the objective for the survey was always to provide annual estimates of harvest size and trends that are as comprehensive and reliable as possible (Bergstrom et al. 1995). Subsistence and personal use harvest data are organized geographically by community, and we subdivided harvest estimates by communities within specific districts and statistical areas, under the assumption that most harvest is taken near the community that reports it (Jallen et al. 2012; Appendix A1). Subsistence and personal use harvest estimates include estimates of sampling error which are typically around 10 percent. Because the estimates are ultimately based on self-reporting, potential for inaccuracy and bias from under- or over-reporting exists. However, incentives for under- or over-reporting are assumed to be minimal and are assumed to be equally offset, since survey participation is voluntary and confidential and no penalties or enforcement are associated with this method of reporting.

Commercial harvest data are recorded on fish tickets by species, location (district and statistical area; Figure 2; Appendix A1) when they are delivered to a buyer or processor, and these records are considered to accurately account for all commercial related harvest. Summer chum salmon are distinguished arbitrarily from fall chum salmon in catches by date when fishing began. Summer chum salmon run end dates, adjusted for estimated fish travel time to upriver districts, are: District 1: July 15; District 2: July 18; District 3: July 20; District 4: July 31; Lower District 5: August 4; Upper District 5: August 8; District 6: August 15. In years before about 1986, summer and fall chum salmon were not always reported separately on fish tickets. In those years, slightly different end dates were used to apportion summer and fall chum salmon harvests in various reports, possibly resulting in some minor variation among summer chum salmon harvest numbers appearing in these sources and in this report.

Changes in statistical area designations within District 4 had to be accounted for in the historical harvest data used in this analysis. In particular, we had to apportion harvest to areas below the Anvik River confluence and areas above, which includes the Anvik River itself. This division corresponds to the boundary between statistical areas 334-44 and 334-45 in Subdistrict 4A. However, these statistical areas were not designated until 1990. In order to apportion commercial harvest before 1990 to these statistical areas, we assumed that actual commercial harvests were apportioned similarly to subsistence harvests. The community of Anvik is in statistical area 334-44, and we attributed all subsistence harvest for Anvik to that statistical area. The remaining communities of Grayling, Kaltag, Nulato, and Koyukuk within Subdistrict 4A are in statistical areas above the Anvik confluence (334-45, 334-46, and 334-47). For each year's harvest between 1978 and 1989, we applied the Anvik proportion of subsistence harvest within Subdistrict 4A to commercial harvest in Subdistrict 4A to estimate commercial harvest in statistical area 334-44. Statistical area 334-47, designated in 1994 (Bergstrom et al. 1996; Estensen et al. 2015), is within the Anvik River and was included with other areas above the Anvik confluence. Commercial harvests occurred in this statistical area only from 1994 through 1997.

Much of the commercial harvest in Yukon Districts 4–6 was directed towards chum salmon roe from the late 1970s through the 1990s. Instead of purchasing whole salmon from fishermen, some processors required fishermen to separate roe for sale, due to weak markets for chum salmon flesh. In these cases, fishermen were expected to retain male chum salmon and carcasses for subsistence use[2]. Data recorded on fish tickets included roe weight along with numbers of any chum salmon purchased in the round; the number of females harvested to produce the roe sold was later estimated using average roe weight per fish. ADF&G biologists also attempted to estimate the total number of male chum salmon that were harvested to produce the roe sold, using average sex ratios from nearby test fishery projects. Thus, these estimates accounted for the total removal of chum salmon to produce the roe and whole fish which were sold, and were variously reported in area management reports as "roe expansion" or "commercial related" catch. However, stripped carcasses and unsold males retained for subsistence use may have also been reported in subsistence harvest surveys, creating the potential for double counting these fish when considering subsistence and commercial harvest together. To minimize this potential, we included only the number of females directly estimated from roe weight plus any fish sold in the round in commercial harvest totals; these data were obtained from annual management reports. Subsistence harvest estimates were assumed to include any "commercial related" or incidentally caught summer chum salmon that were not sold but used for subsistence. Although double counting could still occur if fishermen reported female carcasses they retained for subsistence after selling the roe, subsistence harvest estimates may have underestimated "commercial related" catches. The text and footnotes in annual management reports may resolve these ambiguities and were consulted for this report (Estenson et al. 2015; Bergstrom et al. 1995, 1992, 1991; ADF&G 1988).

Salmon harvested in test fisheries were included through commercial or subsistence harvest reports. Sport fishing harvest of summer chum salmon was assumed to be negligible and was not included.

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[2] At some fish wheels during roe fishery operations, males would be released alive if possible to reduce the burden of large numbers of carcasses on commercial operations. During the peak of the roe fishery, managers monitored sex ratios and found them to be even at locations farthest downstream from Anvik , but the male proportion increased in areas closer Anvik. Clearly, not all males were released, and managers did attempt to account for total fishing mortality the best they could (F. Bue, US Fish and Wildlife Service Subsistence Fisheries Branch Chief, Fairbanks AK; personal communication).

Total Run Size and Escapement Data

Annual escapement counts of summer chum salmon have been recorded from over 30 locations within the US portion of the Yukon River drainage. The Anvik River sonar project, operated since the late 1970s, provided the longest continuous time series of escapement estimates within the Yukon River drainage (McEwen 2015). The mainstem sonar project near Pilot Station, which has been operated since 1986, provided baseline estimates of total summer chum run size above that point in the river (Lozori and McIntosh 2014). Measurement error was estimated with the run size estimates beginning in 1995. For earlier years, a CV of 10% was assigned to the annual run size estimates, which is slightly larger than the average CV for years 1995–2014 (Appendix A2). The Andreafsky River is the lowest major chum salmon spawning tributary in the drainage and escapement there has been monitored since 1981 with sonar, counting tower, and finally a weir beginning in 1994 (Fleischman and Evenson 2010). A weir on the Gisasa River in the Koyukuk River drainage has also provided escapement counts continuously since 1994 (Carlson 2015). Other monitoring projects of shorter duration and numerous aerial surveys of summer chum salmon spawning tributaries contributed information from other parts of the Yukon River drainage throughout this time period (AYKDBMS and Appendices A2–A4). Some of these estimates were known to be incomplete or lower than actual escapement size, such as those from aerial surveys conducted under poor visibility conditions or from counting projects incapacitated by high water before the end of the salmon run. Escapement data were edited before analysis to remove obviously low or incomplete estimates.

Age Composition Data

Salmon age, sex, and length data are collected from commercial fisheries and many of the ground-based escapement projects (Eaton 2014). Summer chum salmon age composition estimates from these samples were obtained from records in the regional database (AYKDBMS). The annual sample age proportions from fisheries or escapement samples were applied to the respective harvests or escapements to estimate total harvest and escapement age compositions. Harvest and escapement age composition estimates were combined, in proportion to the size of each component, to produce total run age proportions used in this analysis (Appendix A5). Subsistence harvests of summer chum salmon were generally not sampled for age data, so commercial age compositions were applied to subsistence harvests within each district. Given low numbers of commercial age samples in Districts 3 and 5 in particular, data from Districts 2 and 3 and from Districts 4 and 5 were pooled. If insufficient data were available to estimate age composition for any given calendar year, an average age composition across all years for that fishing district or escapement project was applied.

PRELIMINARY DATA ANALYSIS

Prior to modeling, escapement and abundance data sets were examined for completeness and consistency. Data from key components of the run, including the East Fork Andreafsky weir, Anvik River sonar, and Pilot Station sonar, were pivotal in the model and were compared using a correlation matrix (Figure 3). For the Andreafsky River, the more accurate and complete East Fork weir, sonar, and tower counts could be extrapolated to the West Fork based upon a relationship between the ground-based and aerial survey counts, if sufficiently well correlated. Reasonable correlations between East Fork weir and aerial survey counts (R^2 = 0.74) and between East and West Fork aerial survey counts were verified (R^2 = 0.60; Figure 3). The relationship between the Anvik River escapement and summer chum salmon passage at Pilot

Station sonar has been monitored informally over time and a decline in the Anvik contribution, starting in the early 2000s, has been observed. Better correlations between the Anvik and Pilot Station estimates were obtained when the data were split into 2 time periods, 1978–2002 and 2003–2014 (R^2 = 0.84 and R^2 = 0.56, respectively). A shift in relative abundance over the same time period also applied to Andreafsky River escapement. In both cases, correlations were better during the earlier period than the more recent, for unknown reasons (Figure 3). Data sets from 7 ground-based (weir, tower) and 6 aerial survey escapement monitoring projects above the Anvik River were also compared using correlation matrices. Correlations among these upriver escapement data series were better in ground-based data (Figure 4) than in aerial survey data (Figure 5). The upriver data sets did not in themselves cover sufficiently large portions of the total escapement, and were often not long enough, to individually characterize drainagewide escapement, but collectively they had potential to inform the model, particularly the weir and tower data.

RUN RECONSTRUCTION AND SPAWNER-RECRUIT ANALYSIS

We employed an integrated stock assessment approach that uses all available data in as raw a form as appropriate in single analysis. Such methods have been widely used for assessment of marine fishery stocks (Maunder and Punt 2013). Traditionally, spawner-recruit analysis has been conducted in 3 steps: (1) reconstructing historical run abundance, escapement, and age composition, (2) constructing a brood table and estimating brood year recruitment, and (3) fitting a spawner-recruit model. More recently, the second and third of these steps have been integrated in a state-space spawner-recruit modeling approach. This approach was applied, with run reconstruction estimates as input, in escapement goal analysis for Yukon River fall chum (Fleischman and Borba 2009), East Fork Andreafsky River summer chum (Fleischman and Evenson 2010), and Kuskokwim River Chinook salmon (Hamazaki et al. 2012). The integrated stock assessment approach employed here combines run reconstruction and state-space spawner-recruit analysis in single analysis, providing a more robust evaluation of uncertainties. See McKinley and Fleischman (2013) for an example of an integrated run reconstruction and spawner-recruit analysis applied to Kenai River Chinook salmon data.

A Ricker spawner-recruit model has been used in the previous examples of escapement goal analyses and many others. A primary assumption in this model, as with any spawner-recruit model, is that recruitment variation is primarily affected by the number of spawners (i.e., density-dependent process). In reality, recruitment is affected by a multitude of factors, such as freshwater and marine physical (e.g., temperature, salinity, turbidity, river discharge, climate change) and biological (e.g., predation, prey availability, parasites, disease) factors, along with anthropogenic factors (e.g., pollutants, bycatch). The magnitude of these effects on recruitment variation is unknown; they were incorporated in this model as an autoregressive lag-1 (AR-1) process and random white noise.

Critical Modeling Assumptions

The following assumptions were made for this model.

1. Recruitment follows a Ricker spawner-recruit formulation (Ricker 1954).
2. Productivity is time-varying, according to an AR-1 time series model (Noakes et al. 1987).

3. No inriver migration mortality other than fishery harvests occurs, and straying (spawning in area other than natal area) is negligible.
4. Harvest was observed accurately without error (see discussion in Data Sources above). Most uncertainty is associated with subsistence harvest estimates, but these harvests are a small enough component of overall run size that any error would have only minimal effects on estimates of spawner-recruit parameters. Likewise, uncertainty associated with commercial roe fishery harvests was considered small enough in relationship to total harvest and run sizes that any influence on parameter estimates would be minor.
5. Returning fish age classes include only ages -3, -4, -5, and -6. Some chum salmon return at age 2 after spending only 1 year in the ocean, and some return at ages greater than 6 after spending more than 5 years in the ocean. Proportions of both these groups, however, are so small that they can reasonably be ignored or included with adjacent age classes.
6. Spawning escapement below Pilot Station occurs only in the Andreafsky River. Summer chum salmon do spawn in other unmonitored tributaries below Pilot Station but these spawning populations were assumed small enough to be ignored.

Population Dynamics: Spawner-Recruit Model

Let S_y be the number of spawners in year y. The number of recruits (R_y) produced from these spawners follows a Ricker (1954) spawner-recruit function with autoregressive lognormal errors (Noakes et al. 1987). Here, ln(α) and β are the productivity and density dependence parameters of the Ricker stock-recruit relationship, ϕ is the autoregressive lag-1 (AR1) coefficient, and the a_y are independent, identically distributed normal random variables, each with mean zero and variance σ_a^2, $a_y \sim N(0,\sigma_a^2)$. Let ω_{y-1} denote a residual starting from ω_0. Then

$$\omega_y = \phi\omega_{y-1} + a_y \ , \tag{1}$$

and

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

Maturity Schedule

Summer chum salmon mature at various ages from 3 to 6 and return to their natal river. Recruits from brood year y will mature and return to their natal river by age a ($3 \le a \le 6$) with cumulative probability $m_{a,y}$, modeled as an asymptotic logistic function where probability reaches 0.99 at the terminal age 6. Denote μ_y as a parameter for mean age at maturity, distributed with mean μ_o and variance σ_μ^2, such that $\mu_y \sim N(\mu_o, \sigma_\mu^2)$. Computationally, the annual variation b_y is modeled as $b_y \sim N(0, \sigma_b^2)$, and $\mu_y = \mu_o + b_y$. Then

$$m_{a,y} = \frac{1}{1 + e^{(\mu_y(6-a) + \ln(1/0.99 - 1))}} \, . \tag{3}$$

The proportion of recruits from brood year y maturing and returning to natal river at age a ($\pi_{y,a}$) is

$$\pi_{y,a} = m_{y,a} - m_{y,a-1} \, . \tag{4}$$

Summer chum salmon of age a recruiting from brood year y return in calendar year $y + a$. Alternatively, the age a summer chum salmon returning in calendar year y are recruits from brood year y - a. The number of age a fish returning to spawn in year y ($N_{y,a}$) is the proportion of age a recruits from brood year y - a multiplied by the total recruitment from brood year y - a (R_{y-a}):

$$N_{y,a} = \pi_{y-a,a} \cdot R_{y-a} \quad . \tag{5}$$

The number of summer chum salmon returning in calendar year y (N_y) is the sum of age a spawners ($3 \le a \le 6$) from brood year y - a:

$$N_y = \sum_{a=3}^{6} \pi_{y-a,a} \cdot R_{y-a} \; . \tag{6}$$

Total Run and Spawning Escapement

Returning summer chum salmon are harvested in subsistence and commercial fisheries with total harvest in calendar year y denoted as H_y. Assuming no other inriver mortality, the escapement or number of chum salmon reaching spawning grounds in calendar year y (S_y) is the difference between the total number of fish returning in calendar year y and the total harvest in calendar year y:

$$S_y = N_y - H_y \; . \tag{7}$$

Observation model

Run Age Composition

The proportion of age class a returning in calendar year y ($p_{y,a}$) is

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

Escapement and Abundance

Summer chum salmon spawning escapement was modeled as 3 stocks or spawning groups within adjacent sections of the Yukon River drainage (Figure 2). The lower river stock $S_{l,y}$ was represented by escapement in the Andreafsky River drainage, and the middle river stock $S_{m,y}$ was represented by escapement in the Anvik River (Appendix A2). All other escapement above Pilot Station was considered part of the upper river stock $S_{u,y}$. Note that in this designation, escapement in tributaries between Pilot Station and the Anvik River, but not in the Anvik itself, was included in the upper river stock. The estimated total summer chum salmon spawning population S_y was the sum of escapements for the 3 stocks:

$$S_y = S_{l,y} + S_{m,y} + S_{u,y} \, . \tag{9}$$

Total abundance or run size, was modeled for the same 3 sections, with demarcations at the Andreafsky River confluence and the Anvik River confluence. Abundance was additionally modeled at the sonar project site near Pilot Station. Abundance at each point in the drainage was estimated as total drainagewide escapement and harvest minus any escapement and harvest below the demarcation point.

Harvests were not separately modeled (based on assumption they were observed without error). Total harvest H, obtained from subsistence and commercial harvest data, was subdivided into 4 sections corresponding to boundaries used to model escapement and abundance (Appendix A1):

H_1 : harvest below Andreafsky confluence (all of District 1 plus statistical areas 334-21 and 334-22 within District 2);

H_2 : harvest between Andreafsky confluence and Pilot Station (statistical area 334-23);

H_3 : harvest between Pilot Station and Anvik confluence (statistical areas 334-24 and 334-25 within District 2 plus all of District 3 and statistical area 334-44 within District 4);

H_4 : harvest above Anvik confluence (statistical areas 334-42, 334-43, 334-45, 334-46, and 334-47 within District 4 plus all of Districts 5 and 6).

Lower River

At the point just below the Andreafsky River confluence, the annual summer chum salmon run $N_{l,y}$ comprises the total spawning population (S_y) and all fish harvested above the Andreafsky River (i.e., total harvest minus harvest below Andreafsky confluence):

$$N_{l,y} = S_y + H_y - H_{1,y} \ . \tag{10}$$

Let $k_{l,t}$ be a scaling parameter with 2 time periods (t = 1: $y \leq 2002$, t = 2: $y \geq 2003$). Andreafsky River escapement ($S_{l,y}$) is modeled as a fraction of $N_{l,y}$ such that

$$S_{l,y} = N_{l,y} / k_{l,t} \tag{11}$$

The East Fork Andreafsky River weir was considered to count all spawners in the tributary, but aerial surveys in East and West Forks were considered to count only a fraction of total spawners. Aerial surveys of both forks were conducted on a single day by the same crew, so efficiency of the survey counts was assumed to be the same for both forks.

Denote East Fork escapement as $S_{le,y}$ and West Fork escapement as $S_{lw,y}$. Let γ be the fraction of Andreafsky River spawners migrating into the East Fork. Then, East and West Fork escapements are fractions of $S_{l,y}$ such that

$$\begin{aligned} S_{le,y} &= \gamma \, S_{l,y} \text{ , and} \\ S_{lw,y} &= (1-\gamma) \, S_{l,y} \ . \end{aligned} \tag{12}$$

Denote i as an index indicating East or West fork, i = (e, w), and k_{la} as a scaling parameter for the Andreafsky aerial survey. The aerial survey escapement count for each fork ($E_{l,i,,y}$) was modeled as

$$E_{l,i,y} = S_{l,i,y} / k_{la} \ . \tag{13}$$

Anvik River

At the point just below the Anvik River confluence, the annual summer chum salmon run $N_{m,y}$ comprises total escapement minus lower river (Andreafsky River) escapement plus harvest above the Anvik confluence:

$$N_{m,y} = S_y - S_{l,y} + H_{4,y} \ . \tag{14}$$

Middle river escapement ($S_{m,y}$), represented by escapement into the Anvik River, is a fraction of $N_{m,y}$. Let $k_{m,t}$ be a scaling parameter for Anvik River escapement with 2 time periods (t = 1: $y \leq 2002$, t = 2: $y \geq 2003$). Then Anvik River escapement is modeled as

$$S_{m,y} = N_{m,y} / k_{m,t} \quad . \tag{15}$$

Upper River

The remaining escapement in the upper river above the Anvik River $S_{u,y}$ makes up the total escapement minus lower and middle river escapements

$$S_{u,y} = S_y - S_{l,y} - S_{m,y} \; . \tag{16}$$

Escapement counts from 7 ground-based projects (weir or tower) and 6 aerial survey projects were used in the analysis (Appendices A3 and A4). Let i be an index denoting individual upper river escapement projects. Escapement counts at each tributary monitoring project $E_{u,i,y}$ represent a fraction of the total upper river spawning population. Denote that $k_{uf,i}$ is a time invariant scaling parameter for each aerial survey escapement monitoring project. Individual tributary spawning populations monitored by aerial survey are then modeled as a fraction of the total upper river spawning population:

$$E_{u,i,y} = S_{u,y} / k_{uf,i} \; , \; i = (1,\ldots,6). \tag{17}$$

Likewise, denote that $k_{ug,i}$ is a time invariant scaling parameter for each ground-based escapement monitoring project, Individual tributary spawning populations monitored by weir or tower are also modeled as a fraction of the total upper river spawning population:

$$E_{u,i,y} = S_{u,y} / k_{ug,i} \text{ for } i = (1,\ldots,7). \tag{18}$$

Total upper river escapement was also estimated as the total summer chum salmon passage estimate at the Pilot Station sonar site minus harvest above Pilot Station and escapement into the Anvik River.

Passage at Pilot Station Sonar

The summer chum salmon run is monitored at the sonar project near Pilot Station (Lozori and McIntosh 2014). The total run past the Pilot Station sonar site, $N_{P,y,}$, comprises the total spawning population (S_y) minus the Andreafsky River spawning population ($S_{l,y}$) and harvest above Pilot Station:

$$N_{P,y} = S_y - S_{l,y} + (H_y - H_{1,y} - H_{2,y}). \tag{19}$$

Pilot Station sonar project started in 1986 as feasibility project, and formal estimation started in 1995. An efficiency parameter q was included to adjust for potential underestimates between 1986 and 1995.

Likelihood components

Assume that measurement errors follow lognormal distribution, and age composition has a multinomial error structure (Fournier and Archibald 1982; Methot 1989). The following constants were designated.

K_y = assumed input sample size of run age compositions in year y, set as 25 for all years.

κ = a constant equal to 0.001.

σ_f = standard deviation for aerial escapement surveys, assumed to be the same across projects.

σ_g = standard deviation for weir and tower escapement counts, assumed to be the same across projects.

σ_m = standard deviation for Anvik sonar escapement count.

q = efficiency constant for Pilot Station sonar estimates before 1995; q = 1 for years 1995–2014.

$CV_{P,y}$ = coefficient of variation for the Pilot Station sonar estimate.

SD_a = standard deviation of ln recruit, used as a weighting factor and assumed to be 0.5.

SD_μ = standard deviation of mean age at maturity, used as a weighting factor and assumed to be 0.5.

The negative log-likelihood function is a sum of the following negative log-likelihood components: (a) run age composition, (b) escapement estimated at Andreafsky weir, (c) escapement aerial survey indices for East and West Fork Andreafsky rivers, (d) run size estimated at Pilot Station sonar site, (e) escapement estimated at Anvik sonar site, (f) upriver aerial escapement surveys, (g) upriver ground escapement surveys, (h) recruitment deviation, and (i) maturity deviation. These are defined as

$$\sum_y K_y \left[\sum_{a=3}^{a=6} p_{a,y} \ln(\hat{p}_{a,y} + \kappa) - \sum_{a=3}^{a=6} p_{a,y} \ln(p_{a,y} + \kappa) \right], \qquad \text{(a)} \qquad (20)$$

$$-\sum_y \ln(\sigma_g) + \frac{[\ln(\hat{S}_{le,y}) - \ln(S_{le,y})]^2}{2 \cdot \sigma_g^2}, \qquad \text{(b)}$$

$$-\sum_{i=e}^{w} \sum_y^{n} \ln(\sigma_f) + \frac{[\ln(\hat{E}_{l,i,y}) - \ln(E_{l,i,y})]^2}{2 \cdot \sigma_f^2}, \qquad \text{(c)}$$

$$-\sum_y \frac{[\ln(q\hat{N}_{P,y}) - \ln(N_{P,y})]^2}{2 \cdot ln(CV_{P,y}^2 + 1)}, \qquad \text{(d)}$$

$$-\sum_y \ln(\sigma_m) + \frac{[\ln(\hat{S}_{m,y}) - \ln(S_{m,y})]^2}{2 \cdot \sigma_m^2}, \qquad \text{(e)}$$

$$-\sum_i \sum_y \ln(\sigma_f) + \frac{[\ln(\hat{E}_{u,i,y}) - \ln(E_{u,i,y})]^2}{2 \cdot \sigma_f^2}, \qquad \text{(f)}$$

$$-\sum_i \sum_y \ln(\sigma_g) + \frac{[\ln(\hat{E}_{u,i,y}) - \ln(E_{u,i,y})]^2}{2 \cdot \sigma_g^2}, \qquad \text{(g)}$$

$$-\sum_{y=1} \frac{a_y^2}{2 \cdot SD_a^2}, \quad \text{(h)}$$

$$-\sum_{y=1} \frac{b_y^2}{2 \cdot SD_\mu^2}. \quad \text{(i)}$$

Reference Points and Profile Analysis

We calculated the following spawner-recruitment reference points: equilibrium spawning population size (S_{eq}), spawning population size generating maximum sustainable yield (S_{msy}), and spawning population size generating maximum recruitment (S_{max}). In these calculations, an adjustment was made to the productivity parameter ln(α), which is a median value based on the modeled lognormal error distribution under an AR1 process (Pacific Salmon Commission 1999). To estimate expected production, a mean value is needed, which differs from the median in a lognormal distribution. The adjusted value of the productivity parameter ln(α') was calculated as

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_a^2}{2(1-\phi^2)}. \quad (21)$$

Equilibrium spawning population size, where the number of recruits equals the number spawners, was calculated as

$$S_{eq} = \ln(\alpha')/\beta. \quad (22)$$

Spawning population size generating maximum sustained yield (S_{msy}) was calculated using Hilborn's (1985)

$$S_{msy} = \ln(\alpha')(0.5\text{-}0.07\ln(\alpha'))/\beta \quad (23)$$

Spawning population size generating maximum recruitment (S_{max}) was calculated as

$$S_{max} = 1/\beta. \quad (24)$$

With each MCMC sample of ln(α') and β and a specified range of escapement (S), expected sustained yield (Y_s) was calculated as

$$Y_S = Se^{\ln(\alpha')-\beta S} - S. \quad (25)$$

Model Implementation and Fitting

The model code was written in ADMB (Fournier et al. 2012; Appendix B). Bounds for all estimated parameters were set using prior information and preliminary data analysis (Table 2). After model convergence, a Bayesian posterior profile analysis of reference points was conducted, in which 1,000,000 MCMC draws were generated and samples were saved every 1,000 simulation.

As a diagnostic check, root mean square error (RMSE) was calculated for each series of annual component estimates, I_y:

$$RMSE = \sqrt{\frac{1}{n}\sum(\ln(I_y) - \ln(\hat{I}_y))^2}.$$

Sensitivity of the model was examined by changing the standard deviation of recruitment and average age of maturity (SD_a and SD_μ) and the effective sample size of run age composition (K).

RESULTS

The model achieved convergence with total negative log-likelihood of 71.57 (Table 3). Higher CVs were observed in annual variation of recruitment (a_y) and mean age at maturity (b_y), some exceeding 100% (Table 4). The model fit well to Pilot Station run estimates (RMSE 0.11), and Anvik sonar escapement estimates (RMSE 0.25). The model fit to other escapement projects was poor (Figure 6). The model fit reasonably well to run age composition; however, it tended to underestimate proportion of age 4 and thus overestimated proportions of other age classes, especially ages 3 and 5 (Figure 7).

In sensitivity analyses, changing standard deviations of recruitment and average age at maturity from 0.5 to 0.25 and 1.0 had little effect on the likelihood of escapement and abundance estimates. Likewise, increasing the effective sample size for run age composition from 25 to 50 made little difference in the overall likelihood (Table 3). However, these changes had a large effect on the estimated AR1 parameter. Nevertheless, estimates of Ricker spawner-recruit parameters α, or α', and β, and thus derived management parameters (e.g., S_{msy}) were similar across all alternative models (Table 3). All remaining results reported here are from the base model configuration.

Annual summer chum run size showed strong cycles between high and low abundance over the 36year study period (Figure 8; Table 5). The early part of this period was characterized by regularly spaced 3–4 year cycles with run sizes ranging from 2 million to 4 million summer chum salmon. Longer and more erratic cycles have been apparent starting in the mid-1990s. In 1995, a record run size of 4.5 million fish was observed, followed by a precipitous drop over the next several years to low runs of less than 600,000 fish in 2000 and 2001. The run cycled to another high of nearly 4 million fish in 2006, followed by a less extreme low (1.7 million fish) in 2006 and another high run (3.3 million fish) in 2013. Uncertainty in estimated run sizes was higher, at 13–17%, in 1978–1985 before Pilot Station sonar project was established, but decreased to only 2–4% after 1995, corresponding with refinement of the sonar project and estimation methods. Escapement cycles have generally paralleled cycles in abundance, as would be expected since capacity to substantially increase harvests during years of high abundance is limited. Estimated harvest rates were high through the late 1970s and the 1980s, averaging about 41%, but declined after 1990, averaging just 12% from 1991 to 2006. Following low rates of fewer than 5% in 2005 and 2006, harvest rates increased to about 25% in 2014. The average rate over the period from 1991 to 2014 was estimated to be just under 14% (Figure 9).

Point estimates of the Ricker spawner-recruit parameters, α and β were 4.08 (95% CI 2.75–6.30) and 6.37×10^{-7} (95% CI: 4.02×10^{-7} - 9.04×10^{-7}), respectively (Table 6). The AR1 parameter ϕ was estimated to be 0.28 (95% CI: 0.02–0.60). Mean log age at maturity was 1.217, or maturity age of 3.38 (Table 4), corresponding to proportions of 3.8%, 49.9%, 43.4%, and 2.8%, for ages -3, -4, -5, and -6, respectively.

The spawner-recruit curve showed strong negative density dependence in which escapements of greater than 2,000,000 resulted in recruitments below replacement (Figure 10). S_{msy} was estimated to be 969,856 (95% CI: 795,349–1,247,588). S_{eq} was estimated to be 2,475,024 (95% CI: 2,149,774–3,033,969; Table 6). Estimated productivity was strongly cyclic, ranging from less than 1 to greater than 5 recruits per spawner (R/S; Figure 11). These cycles were generally opposite of escapement cycles, high escapement producing low relative recruitments and vice versa, reflecting the negative density dependent relationship. Estimated yield at S_{msy} would fall between about 700,000 and 1.6 million summer chum salmon at the 95% confidence interval for S_{msy} (Figure 12).

DISCUSSION AND ESCAPEMENT GOAL RECOMMENDATION

The run reconstruction model fit reflected its dependence upon key data components and certain assumptions (Figure 8). In particular, the tight fit to Pilot Station passage and Anvik escapement estimates was expected, because the model was purposely designed around these estimates (note that fit improved for years after full implementation of Pilot Station sonar in 1995). The Pilot Station passage estimate is the best index of total run size at that point in the river, and Anvik escapement comprises the largest single component of escapement, measured at a point above Pilot Station such that it can be compared with the total passage estimate. The model fit better and thus was weighted more on ground based than aerial survey escapement data in the upper part of the drainage. This was not surprising, despite the generally longer aerial survey data series; aerial survey counts of summer chum salmon are notoriously inconsistent due to fish visibility and difficulty in matching spawn timing with weather conditions for flying.

The sensitivity analysis showed that the estimate of the AR parameter was strongly affected by modeling assumptions. As indicated in equation (2), deviations from the Ricker spawner-recruit model are assigned to either AR1 error process or annual random variation. Increasing the assigned SD for recruitment and average age at maturity assumes greater random annual variation, and should reduce the relative influence of the AR1 process, leading to a lower AR1 parameter estimate. Likewise, lowering the SD assumes less random annual variation and would lead to a higher AR1 parameter estimate, as observed (Table 3). However, because the Ricker model parameters were not strongly influenced by these assumptions, the proposed baseline model appears to be reasonable for establishing an escapement goal, and changing the assumptions would have little effect on the resulting reference point estimates.

PROPOSED ESCAPEMENT GOAL

A biological escapement goal range of 500,000–1,200,000 summer chum salmon is recommended based on Ricker model reference points and optimal yield profiles (Figure 13), along with consideration of historical ranges of harvest and escapement. Steepness of the optimal yield curve depends on the quality of information contained in the data: a steep profile with high maximum probability indicates very good information about sustained yield at different levels of escapement (Fleischman et al 2013). The optimal yield profiles from this analysis are steep and have high maximum probability, reflecting very good information about sustained yield for Yukon River summer chum salmon. The lower bound was determined from the range of escapement that would provide an expectation of sustained yield at 80% of MSY with greater than 70% probability. The upper bound was determined from the range of escapement that would provide an expectation of sustained yield at 90% of MSY with greater than 70% probability (Figure 13). The use of slightly different criteria for the lower and upper bounds was justified by differences in management of subsistence and commercial fisheries, both of which are very important in the Yukon area for summer chum salmon. Considering the 37 year time series of estimated historical escapements (Figure 8; Table 5) in the context of the recommended BEG range, over half (22) of the escapements would have exceeded the upper bound but none were below the lower bound. However, the low escapements of 2000 and 2001 were statistically indistinguishable from the lower bound (500,000 fish) and could have been slightly below the lower bound given the limits of precision of the estimates.

The consensus of escapement goal committee was that the recommended lower bound was consistent with historical escapement and harvest information and probably would not pose a threat to sustainability of the stock, given appropriate precautions specified in the management plan. In practice, the management objective will be escapements in the middle part of the BEG range, which have the highest probability of attaining the maximum sustained yield, rather than escapement near the lower bound. In any case, the reconstruction clearly shows that high recruitments have resulted from low escapements, indicating variability in escapement and recruitment that is likely independent of fishing, or restrictions on fishing. A low to moderate subsistence harvest is not expected to jeopardize sustainability of the run. During the low escapement years of 2000 and 2001 substantial, but below average, subsistence harvests between 58,000 and 65,000 summer chum salmon were taken. This is similar to what may be expected under the new recommended BEG, in the event of future low runs.

Overall, harvest rates have been low, particularly during the most recent 2 decades, and commercial markets and processing capacity are substantially lower now than in the past. Prosecution of the summer chum salmon fishery has been greatly limited by measures taken since 2012 to conserve concurrent Chinook salmon runs (e.g., Estensen et al. 2015; JTC 2015). Maintaining escapements within the upper bound of the BEG will be more difficult if these factors persist. Nevertheless, the size and importance of the summer chum salmon run, the long history of commercial utilization, and the economic need for fishing income in the area indicate that a biological escapement goal is appropriate for this stock. The strong negative density-dependence apparent in the spawner-recruitment relationship further indicates that the recommended upper bound is appropriate.

The committee discussed annual monitoring and assessment of the recommended goal. In practice, managers have been using the Pilot Station passage estimate, along with tributary assessments including escapement goals for Andreafsky and Anvik river summer chum salmon, to ensure sustainable levels of escapement are achieved. The analysis described in this report confirms that informal assessments and managers' long-standing impressions of the drainagewide summer chum salmon run are in alignment with the model-based estimates. Inseason run assessments and projections can be made directly comparable to the new escapement goal range by expressing them in terms of escapement, which is roughly Pilot Station passage plus projected Andreafsky River escapement minus expected harvest above Pilot Station. Postseason, the formal drainagewide run reconstruction will be updated annually, based on Pilot Station passage, harvests, and tributary escapement estimates. With the new run reconstruction and drainagewide goal, independent tributary assessments can serve as a check on the escapement assessed at the drainagewide level. The possibility exists that tributary goals may not be met if drainagewide escapement is near the lower bound of the goal. Nevertheless, the management objective remains to achieve all escapement goals, and management for the drainagewide BEG will also have to accommodate the tributary goals. Maintaining tributary escapement projects and data series is challenging given competing needs for limited monitoring resources. To a point, even if a tributary assessment project is discontinued, the run can still be assessed with the reconstruction, using the remaining assessment information and Pilot Station passage estimates. However, the uncertainty of the reconstruction estimate increases as information decreases, particularly the ability to understand and monitor relationships between drainagewide and tributary escapements and productivity.

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TABLES AND FIGURES

Table 1.–List of data sets used for run reconstruction.

Spawning group	Project
Andreafsky	
East fork	Sonar, tower, weir
	Aerial
West fork	Aerial
Anvik	Tower, sonar
Upriver	
Rodo River	Aerial
Nulato (South fork)	Aerial
Nulato (North fork)	Aerial
Gisasa (Koyukuk)	Aerial
Hogatza (Koyukuk)	Aerial
Tozitna	Aerial
Salcha (Tanana)	Aerial
Chena (Tanana)	Aerial
Kaltag	Tower
Nulato	Tower, weir
Henshaw (Koyukuk)	Tower, weir
Gisasa (Koyukuk)	Weir
Hogatza (Koyukuk)	Weir
Salcha (Tanana)	Tower
Chena (Tanana)	Tower
Run	
Pilot Station	Sonar

Table 2.–List of estimated parameters with bounds.

Parameters	Definition	Parameter bounds
$ln(\alpha)$	Ricker alpha	(0, 3)
β'	Ricker beta = β'/100000	(0, 3)
ϕ	AR1 coeffcient	(-1, 1)
$\ln(R)$	Mean *ln* recruit	(10, 20)
$a_{77,\ldots,10}$	*ln* recruitment deviation	(-10,10)
ω_0	Initial residual for *ln* recruits (y = 0)	(-10,10)
m	Mean age at maturity	(0.6, 2.0)
$b_{77,\ldots,10}$	Age-at-maturity deviation	(-1, 2)
$ln(k_{uf,1\ldots6})$	*ln* upriver aerial escapement scaling parameters	(1, 8)
$ln(k_{ug,1\ldots7})$	*ln* upriver tower/weir escapement scaling parameters	(2, 7)
$ln(\sigma_f)$	*ln* standard deviation for aerial survey	(-3, 10)
$ln(\sigma_g)$	*ln* standard deviation for weir/tower survey	(-3, 5)
$ln(k_{l,t})$	*ln* Andreafsky River scaling parameters	(0, 8)
g	proportion of Andreafsky River spawners to east fork	(0, 1)
$ln(k_{la})$	*ln* Andreafsky River aeruak survey scaling parameters	(0, 7)
$ln(k_{m,t})$	*ln* Anvik River scaling parameters	(0, 3)
$ln(\sigma_m)$	*ln* standard deviation for Anvik sonar survey	(-3, 3)
q	Pilot Station survey coefficient	(0.1,2.0)

Table 3.–Estimated likelihood of model components and total likelihood, and estimated likelihood of Ricker spawner-recruit parameters, for base model and 3 alternative models.

		Alt 1	Alt 2	Alt 3
Negative log-likelihood	Baseline	*K*=50	SD = 1.0	SD = 0.25
Age composition	33.01	61.04	31.23	46.57
Andreafsky weir	0.41	0.01	0.19	0.97
Andreafsky aerial	16.27	16.91	16.88	16.45
Pilot Station passage	0.72	0.98	0.65	1.13
Anvik sonar	-36.31	-33.57	-36.57	-35.89
Ground escapement	11.09	10.77	10.88	11.52
Aerial escapement	30.78	29.93	31.08	30.48
Recruitment deviation	14.45	16.30	4.47	31.04
Maturity deviation	0.66	0.68	0.19	2.55
Total	71.57	103.04	59.01	104.81
$ln(\alpha)$	1.32	1.36	1.33	1.35
$ln(\alpha')$	1.44	1.48	1.46	1.44
$\beta \times (10^{-7})$	5.91	6.23	5.95	5.89
ϕ	0.45	0.36	0.35	0.68
S_{msy}	912,415	886,412	907,885	928,996

Table 4.–Estimated mean values, ranges (2.5 to 97.5% credible intervals), standard deviations, and coefficients of variation for all model parameters.

Parameter	Mean	2.5%	97.5%	SD	CV
$ln(\alpha)$	1.406	1.010	1.840	0.218	0.155
β'	0.637	0.402	0.904	0.124	0.195
ϕ	0.282	0.024	0.598	0.148	0.525
$ln(R\mu)$	14.775	14.272	15.291	0.259	0.018
a_{72}	-0.067	-1.056	0.814	0.483	-7.253
a_{73}	-0.069	-1.087	0.927	0.524	-7.573
a_{74}	0.140	-0.400	0.752	0.299	2.131
a_{75}	-0.215	-0.742	0.314	0.276	-1.280
a_{76}	0.531	-0.013	1.052	0.273	0.514
a_{77}	-0.119	-0.756	0.442	0.305	-2.569
a_{78}	0.108	-0.806	1.000	0.459	4.249
a_{79}	-0.033	-0.468	0.383	0.218	-6.559
a_{80}	0.472	0.078	0.858	0.192	0.408
a_{81}	0.701	0.305	1.103	0.203	0.290
a_{82}	-0.256	-0.692	0.178	0.229	-0.895
a_{83}	0.096	-0.302	0.477	0.203	2.122
a_{84}	0.669	0.317	1.003	0.173	0.259
a_{85}	0.007	-0.520	0.587	0.284	41.040
a_{86}	-0.044	-0.419	0.335	0.190	-4.335
a_{87}	0.189	-0.220	0.586	0.214	1.136
a_{88}	-0.435	-0.879	-0.013	0.225	-0.518
a_{89}	0.313	0.015	0.643	0.162	0.518
a_{90}	0.324	-0.049	0.670	0.180	0.554
a_{91}	0.425	0.059	0.758	0.185	0.436
a_{92}	0.102	-0.316	0.524	0.208	2.049
a_{93}	-0.907	-1.399	-0.498	0.230	-0.254
a_{94}	-0.025	-0.452	0.455	0.229	-9.231
a_{95}	-0.583	-1.078	-0.058	0.263	-0.451
a_{96}	-0.718	-1.108	-0.290	0.210	-0.293
a_{97}	-0.840	-1.294	-0.320	0.248	-0.295
a_{98}	-0.309	-0.869	0.247	0.281	-0.911
a_{99}	-0.227	-0.583	0.148	0.177	-0.780
a_{00}	-0.143	-0.696	0.368	0.272	-1.900
a_{01}	1.280	0.974	1.568	0.159	0.124
a_{02}	-0.454	-1.023	0.028	0.267	-0.587
a_{03}	-0.085	-0.400	0.209	0.159	-1.866

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Table 4.–Page 2 of 3.

Parameter	Mean	2.5%	97.5%	SD	CV
a_{04}	-0.428	-0.775	-0.094	0.178	-0.415
a_{05}	-0.208	-0.665	0.217	0.224	-1.076
a_{06}	0.597	0.114	1.174	0.253	0.424
a_{07}	-0.246	-0.593	0.086	0.175	-0.709
a_{08}	0.482	0.201	0.712	0.129	0.268
a_{09}	0.025	-0.356	0.339	0.180	7.187
a_{10}	0.003	-0.657	0.842	0.384	121.737
a_{11}	0.015	-0.893	0.994	0.483	31.406
ω_0	-0.622	-4.426	3.461	1.996	-3.211
μ_0	1.217	1.187	1.249	0.016	0.014
b_{72}	-0.232	-0.860	0.332	0.308	-1.331
b_{73}	-0.130	-0.459	0.292	0.185	-1.424
b_{74}	-0.177	-0.367	-0.037	0.084	-0.478
b_{75}	-0.070	-0.184	0.033	0.056	-0.800
b_{76}	0.035	-0.052	0.118	0.044	1.239
b_{77}	-0.074	-0.189	0.038	0.057	-0.769
b_{78}	-0.034	-0.149	0.070	0.056	-1.674
b_{79}	-0.038	-0.168	0.068	0.059	-1.583
b_{80}	-0.027	-0.121	0.064	0.047	-1.691
b_{81}	0.026	-0.046	0.103	0.038	1.426
b_{82}	-0.121	-0.219	-0.023	0.052	-0.429
b_{83}	0.099	0.012	0.172	0.041	0.414
b_{84}	0.010	-0.049	0.073	0.031	3.241
b_{85}	-0.049	-0.152	0.050	0.051	-1.040
b_{86}	0.083	0.007	0.163	0.040	0.478
b_{87}	0.073	-0.011	0.159	0.042	0.578
b_{88}	-0.014	-0.132	0.107	0.061	-4.262
b_{89}	0.135	0.066	0.203	0.035	0.258
b_{90}	0.103	0.024	0.185	0.042	0.411
b_{91}	-0.005	-0.090	0.078	0.043	-9.476
b_{92}	-0.060	-0.141	0.024	0.042	-0.695
b_{93}	-0.132	-0.290	0.001	0.074	-0.561
b_{94}	0.040	-0.013	0.100	0.028	0.692
b_{95}	-0.072	-0.164	0.024	0.046	-0.646
b_{96}	0.060	-0.004	0.127	0.032	0.531
b_{97}	0.260	0.173	0.355	0.046	0.178

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Table 4.–Page 3 of 3.

Parameter	Mean	2.5%	97.5%	SD	CV
b_{98}	-0.044	-0.118	0.031	0.039	-0.892
b_{99}	0.024	-0.037	0.087	0.032	1.368
b_{00}	-0.051	-0.172	0.057	0.058	-1.153
b_{01}	0.070	0.025	0.116	0.023	0.330
b_{02}	-0.033	-0.137	0.082	0.056	-1.701
b_{03}	0.016	-0.060	0.092	0.038	2.436
b_{04}	0.003	-0.086	0.089	0.046	15.351
b_{05}	-0.115	-0.218	-0.014	0.052	-0.458
b_{06}	0.018	-0.048	0.082	0.033	1.852
b_{07}	-0.060	-0.160	0.026	0.049	-0.811
b_{08}	0.048	-0.010	0.104	0.029	0.608
b_{09}	0.033	-0.054	0.116	0.042	1.302
b_{10}	0.062	-0.128	0.244	0.102	1.632
b_{11}	0.353	-0.069	0.918	0.271	0.769
$ln(k_{ug,1})$	4.016	3.581	4.415	0.214	0.053
$ln(k_{ug,2})$	2.391	2.036	2.821	0.209	0.087
$ln(k_{ug,3})$	2.401	2.081	2.766	0.175	0.073
$ln(k_{ug,4})$	3.084	2.798	3.386	0.152	0.049
$ln(k_{ug,5})$	3.820	3.438	4.210	0.200	0.052
$ln(k_{ug,6})$	4.650	4.215	5.083	0.223	0.048
$ln(k_{ug,7})$	3.522	3.204	3.868	0.167	0.047
$ln(k_{uf,1})$	5.429	4.820	6.031	0.302	0.056
$ln(k_{uf,2})$	5.653	5.295	6.021	0.188	0.033
$ln(k_{uf,3})$	4.830	4.377	5.268	0.226	0.047
$ln(k_{uf,4})$	5.463	4.990	5.965	0.255	0.047
$ln(k_{uf,5})$	5.163	4.640	5.659	0.264	0.051
$ln(k_{uf,6})$	5.438	4.965	5.894	0.232	0.043
$ln(\sigma_f)$	-0.368	-0.498	-0.206	0.073	-0.199
$ln(\sigma_s)$	-0.088	-0.223	0.058	0.072	-0.812
γ	0.435	0.295	0.563	0.071	0.163
$ln(k_{l,1})$	2.018	1.605	2.392	0.198	0.098
$ln(k_{l,2})$	3.206	2.722	3.630	0.224	0.070
$ln(k_{la})$	1.339	1.019	1.821	0.215	0.161
$ln(k_{m,1})$	0.972	0.841	1.119	0.072	0.074
$ln(k_{m,2})$	1.441	1.267	1.622	0.089	0.061
$ln(\sigma_m)$	-1.238	-1.544	-0.877	0.172	-0.139
q	0.741	0.626	0.868	0.060	0.081

Table 5.–Model estimates of mean annual summer chum run size and escapement, 1978–2014.

Year	Run	CV	Escapement	CV
1978	2,586,420	0.15	1,319,292	0.29
1979	2,025,820	0.15	1,007,894	0.29
1980	2,963,450	0.14	1,620,713	0.26
1981	3,723,550	0.13	2,319,154	0.21
1982	2,279,290	0.17	1,404,105	0.28
1983	2,233,660	0.13	1,098,504	0.27
1984	2,958,690	0.14	1,972,173	0.21
1985	4,121,990	0.14	3,091,530	0.19
1986	3,837,050	0.08	2,552,960	0.13
1987	1,753,050	0.08	918,366	0.15
1988	3,862,670	0.07	2,228,680	0.13
1989	3,395,020	0.08	1,947,570	0.14
1990	1,753,660	0.09	1,207,556	0.12
1991	2,317,060	0.09	1,677,130	0.12
1992	2,289,260	0.15	1,703,919	0.20
1993	1,606,290	0.10	1,377,833	0.11
1994	3,219,690	0.10	2,910,100	0.11
1995	4,385,200	0.04	3,668,090	0.04
1996	3,718,250	0.12	3,119,140	0.15
1997	1,779,350	0.05	1,497,830	0.05
1998	1,037,678	0.04	922,934	0.04
1999	1,190,200	0.04	1,090,398	0.05
2000	584,147	0.04	512,628	0.04
2001	564,893	0.04	506,654	0.04
2002	1,310,060	0.04	1,224,130	0.04
2003	1,254,860	0.03	1,175,790	0.03
2004	1,476,680	0.02	1,380,670	0.02
2005	2,624,870	0.03	2,504,780	0.04
2006	3,994,420	0.03	3,811,290	0.03
2007	2,010,230	0.03	1,735,570	0.03
2008	1,895,350	0.04	1,675,760	0.04
2009	1,669,500	0.02	1,431,850	0.03
2010	1,686,210	0.05	1,387,500	0.06
2011	2,348,040	0.02	1,995,140	0.02
2012	2,479,810	0.02	2,056,350	0.03
2013	3,265,670	0.02	2,688,060	0.03
2014	2,409,760	0.02	1,805,180	0.03

Table 6.–Estimated parameters of the Ricker spawner-recruit model, showing mean and 2.5 and 97.5 percentiles of the model output (MCMC draws).

Parameter	Mean	2.5%	97.5%
$ln(\alpha)$	1.41	1.01	1.84
α	4.08	2.75	6.30
σ_w	0.16	0.12	0.20
β	6.37E-07	4.02E-07	9.04E-07
ϕ	0.28	0.02	0.60
S_{MSY}	969,856	795,349	1,247,588
S_{EQ}	2,475,024	2,149,774	3,033,969

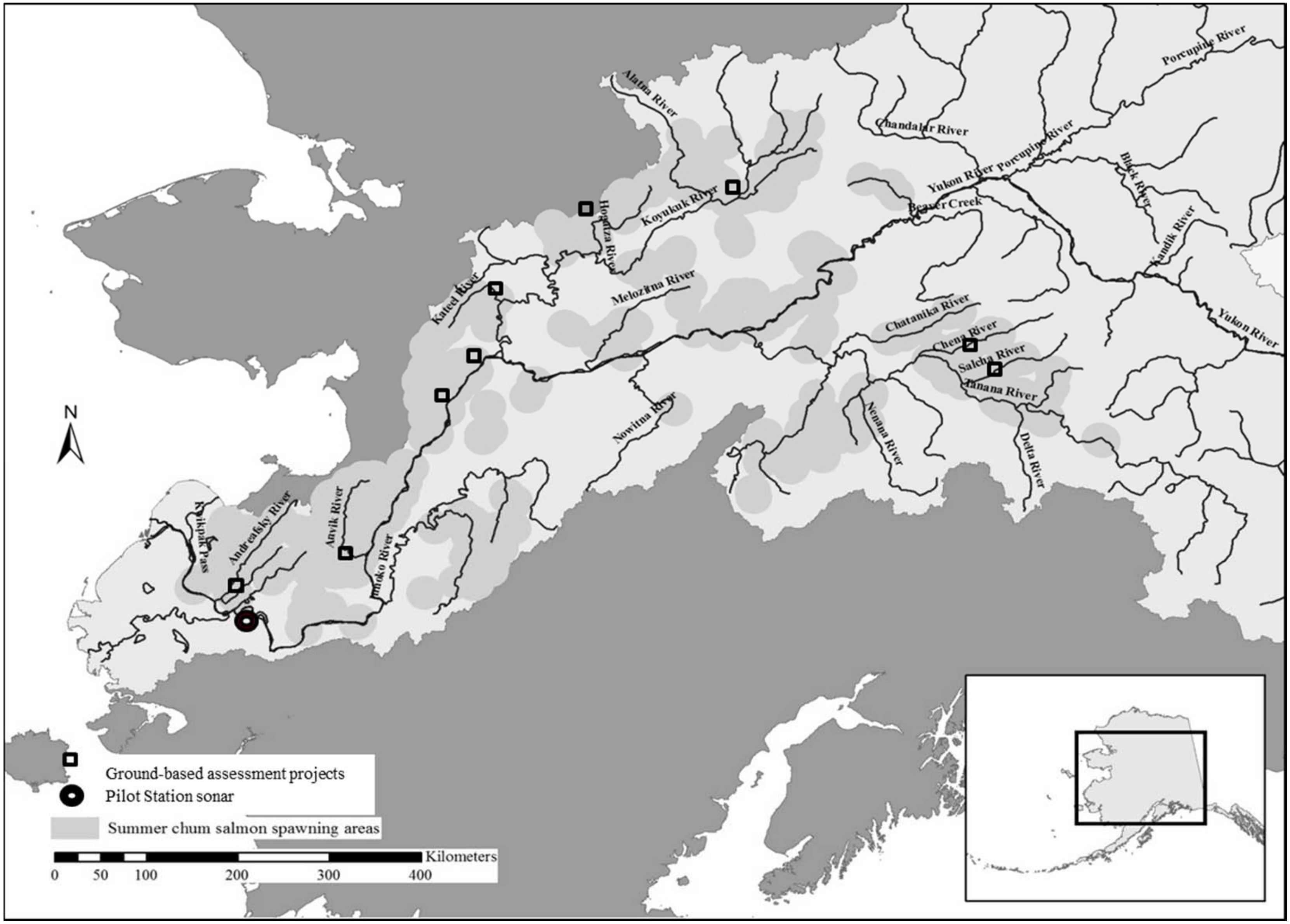

Figure 1.–Map of Yukon River drainage showing summer chum salmon spawning areas and assessment project locations.

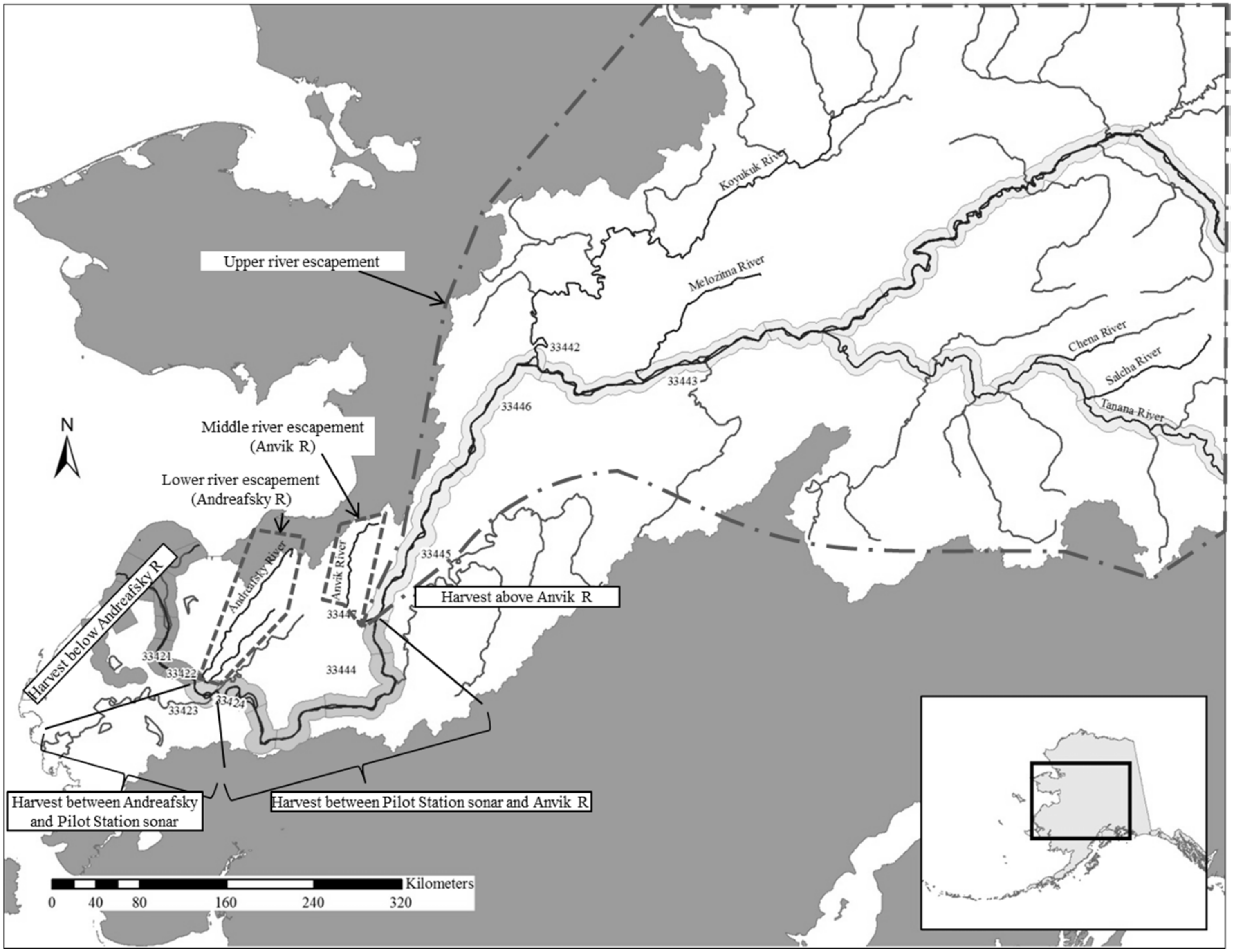

Figure 2.–Map of Yukon River drainage showing commercial fishery statistical areas (indicated by 5-digit codes) and portioning of the study area into 4 harvest sections and lower, middle, and upper escapement groups for the run reconstruction model.

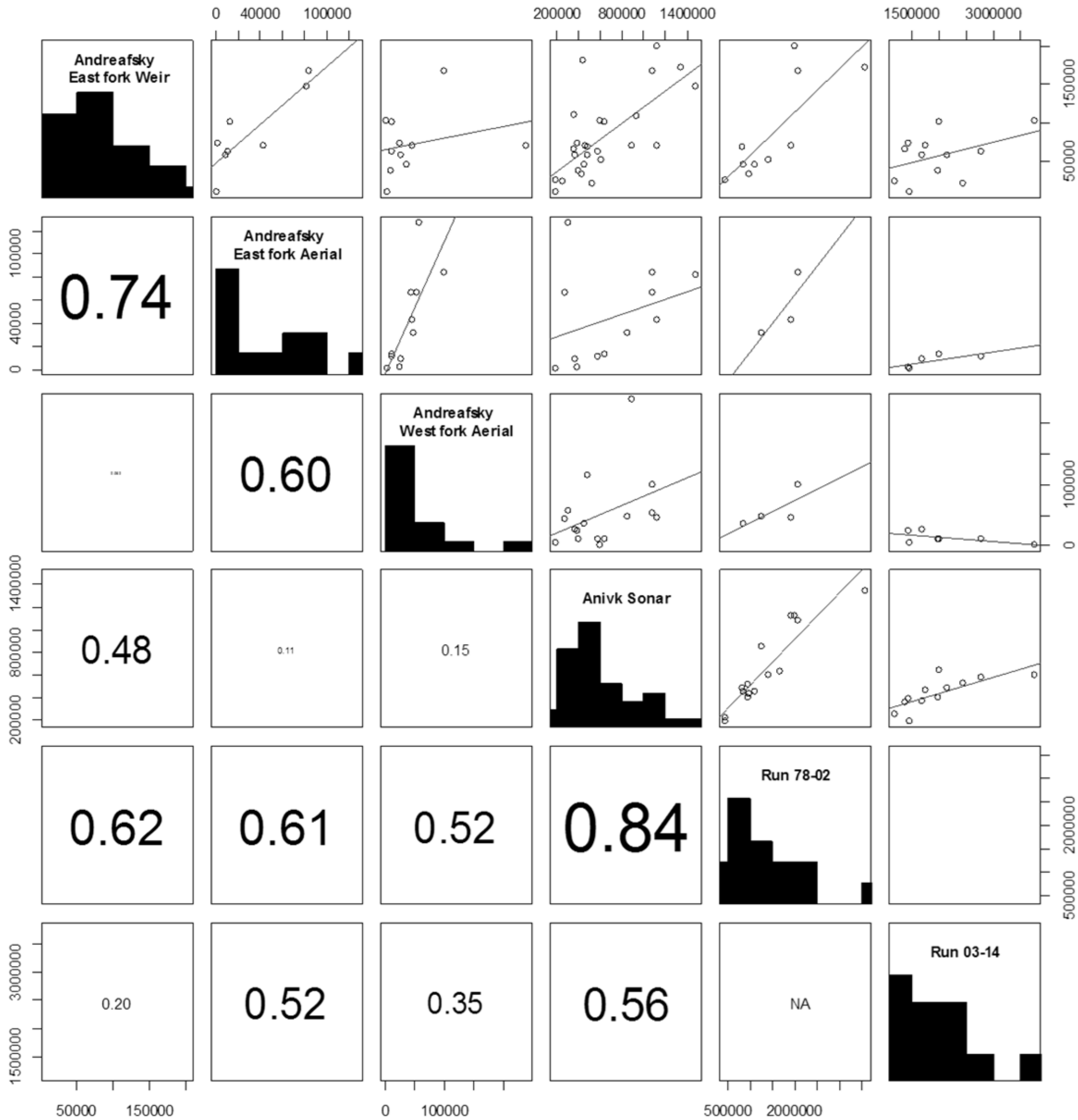

Figure 3.–Correlation matrix among observed escapements (weir, tower, sonar, and aerial survey estimates) from Andreafsky and Anvik rivers, in comparison with total run indices from 2 different time periods.

Note: Histograms along the diagonal show frequencies over the range of each series of estimates. Numbers below the diagonal are *R*-squared values for each correlation.

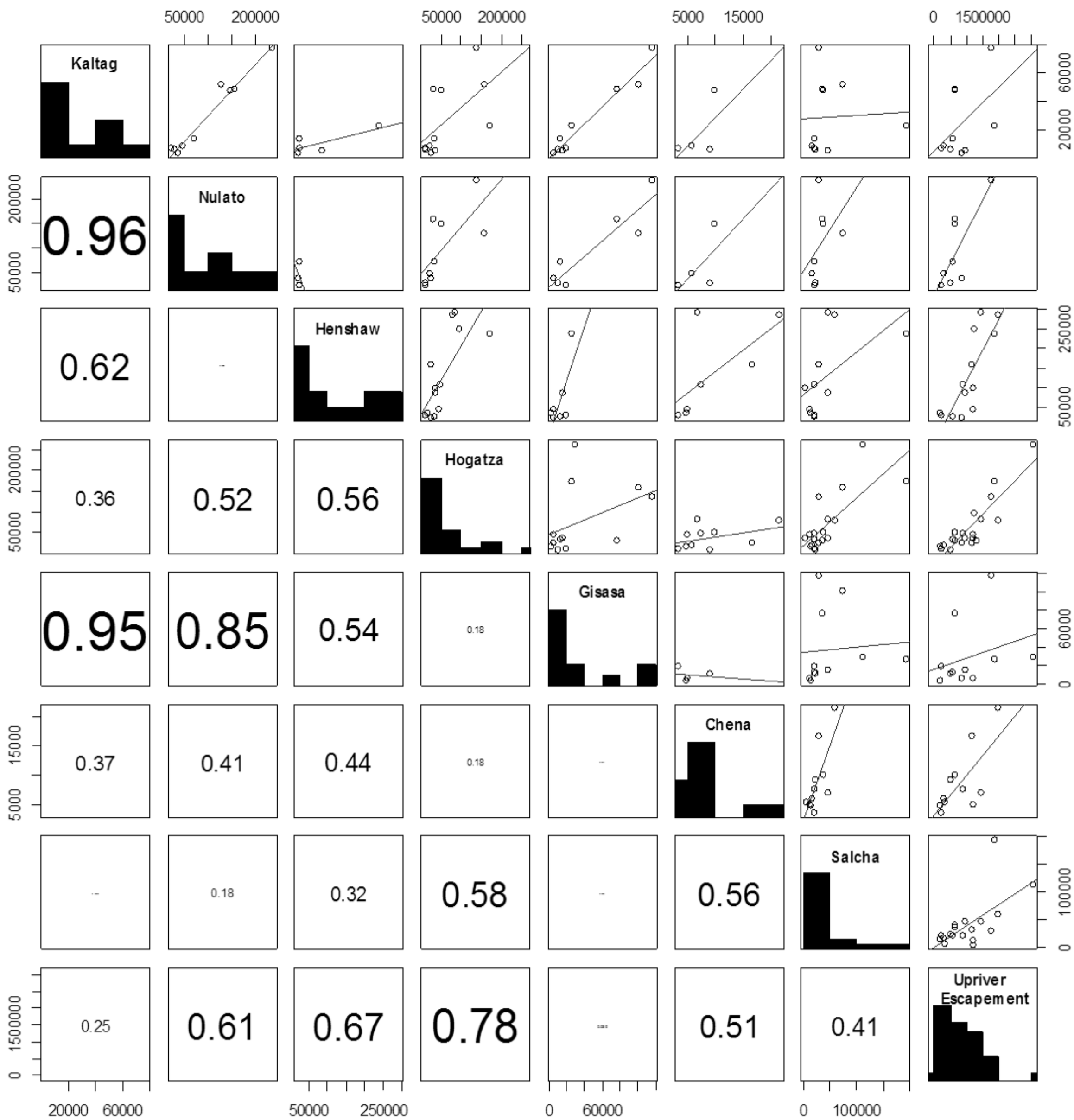

Figure 4.–Correlation matrix among observed escapement estimated from ground based projects (weir, tower) in upper river tributaries, in comparison with total upriver escapement based on passage at Pilot Station sonar minus Anvik River escapement and harvest above Pilot Station.

Note: Histograms along the diagonal show frequencies over the range of each series of estimates. Numbers below the diagonal are R-squared values for each correlation.

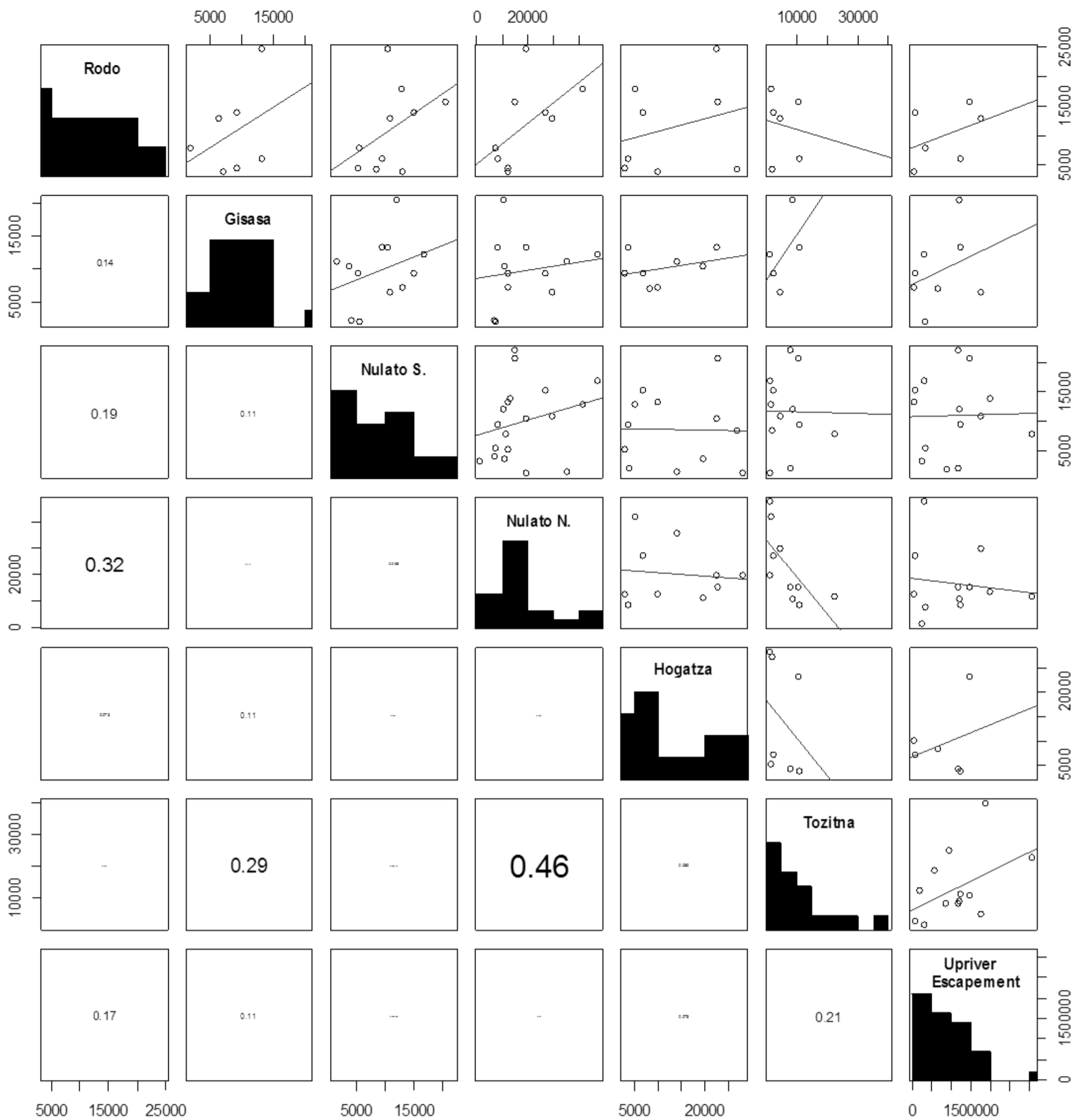

Figure 5.–Correlation matrix among observed upper river aerial survey escapement estimates, in comparison with total upriver escapement based on passage at Pilot Station sonar minus Anvik River escapement and harvest above Pilot Station.

Note: Histograms along the diagonal show frequencies over the range of each series of estimates. Numbers below the diagonal are R-squared values for each correlation.

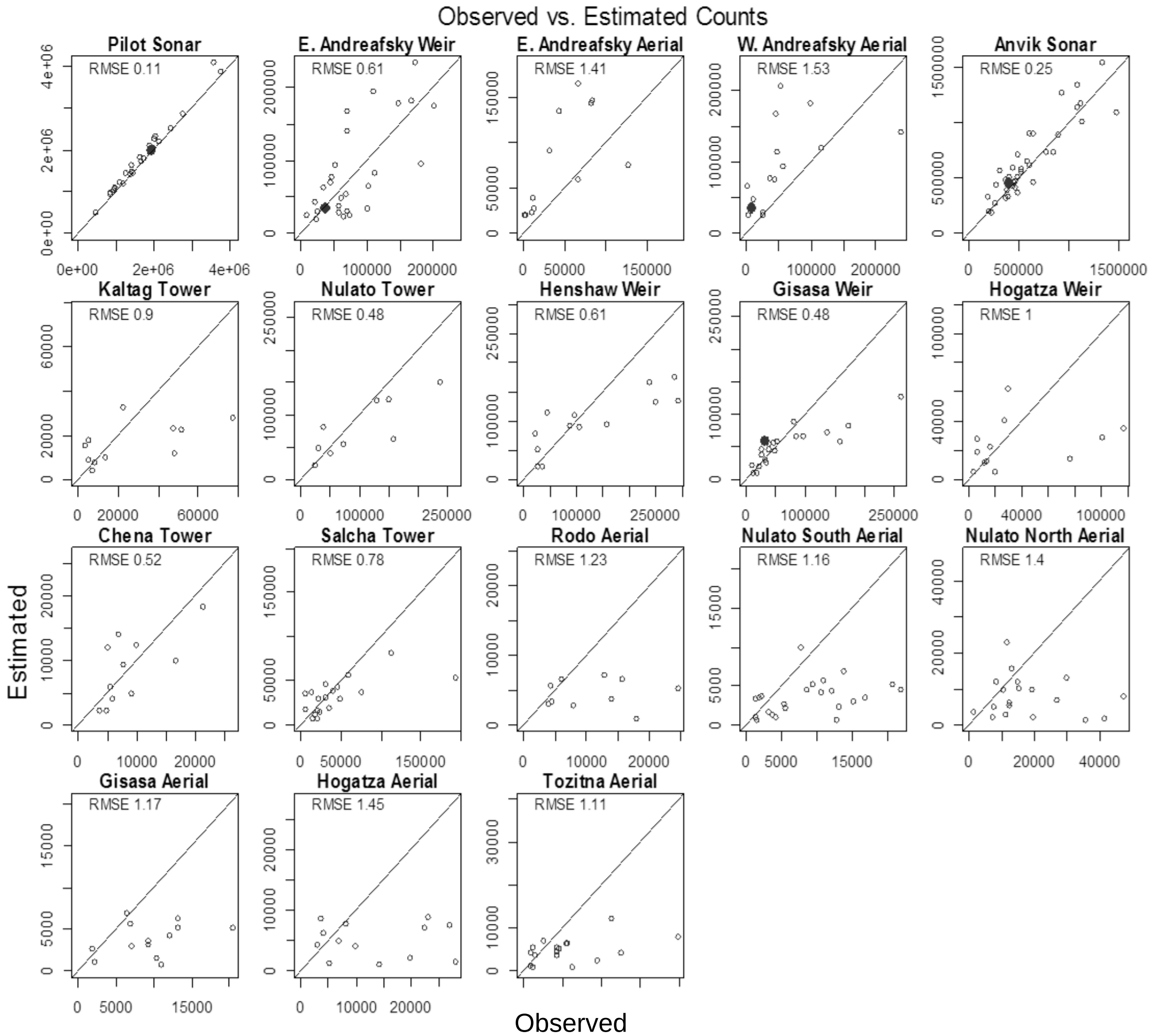

Figure 6.–Correlations between observed and model estimated escapements.

Note: Solid points indicate 2014 estimates.

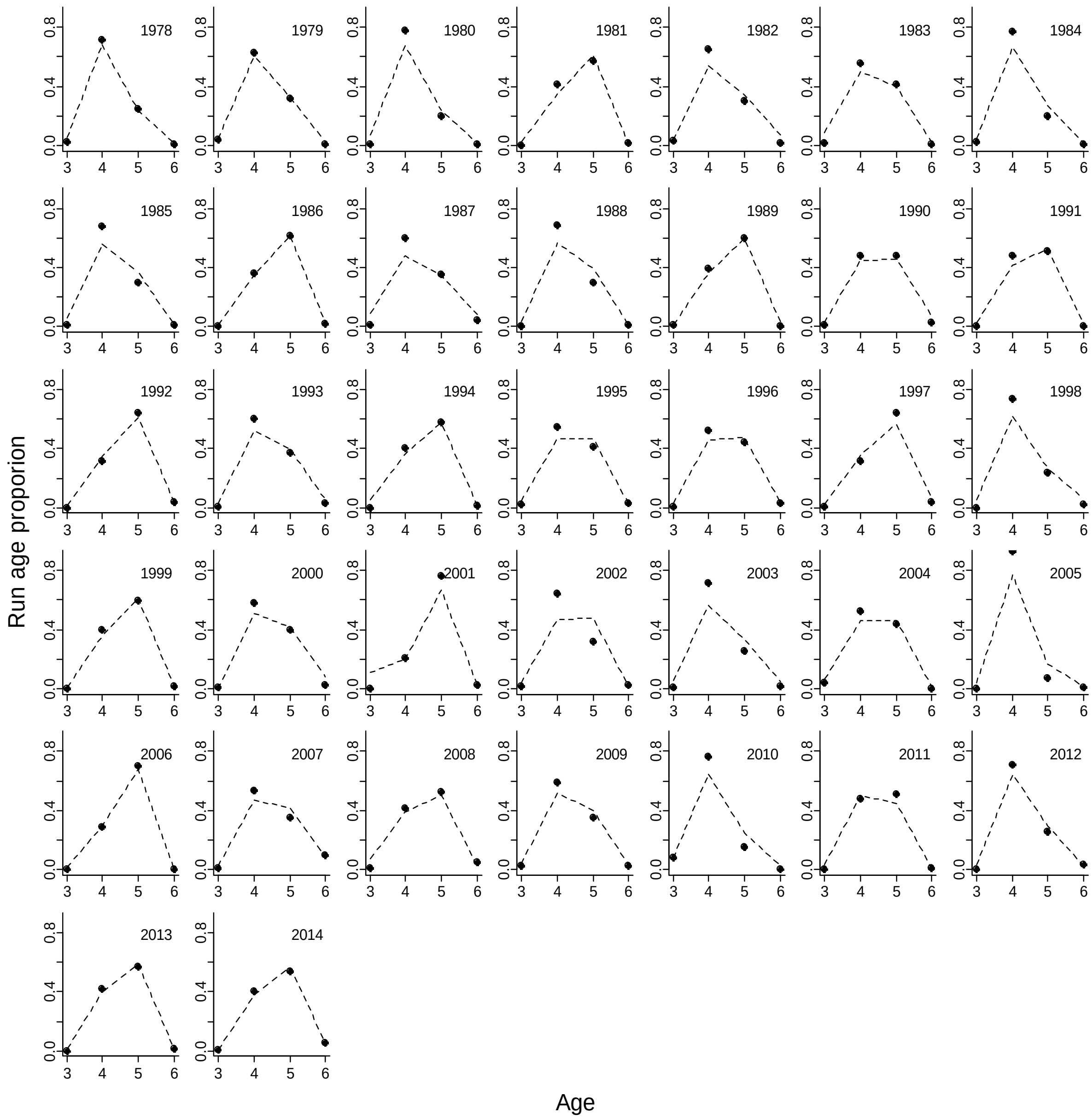

Figure 7.–Observed (black dots) and model estimated (dashed line) run age proportions, 1978–2014.

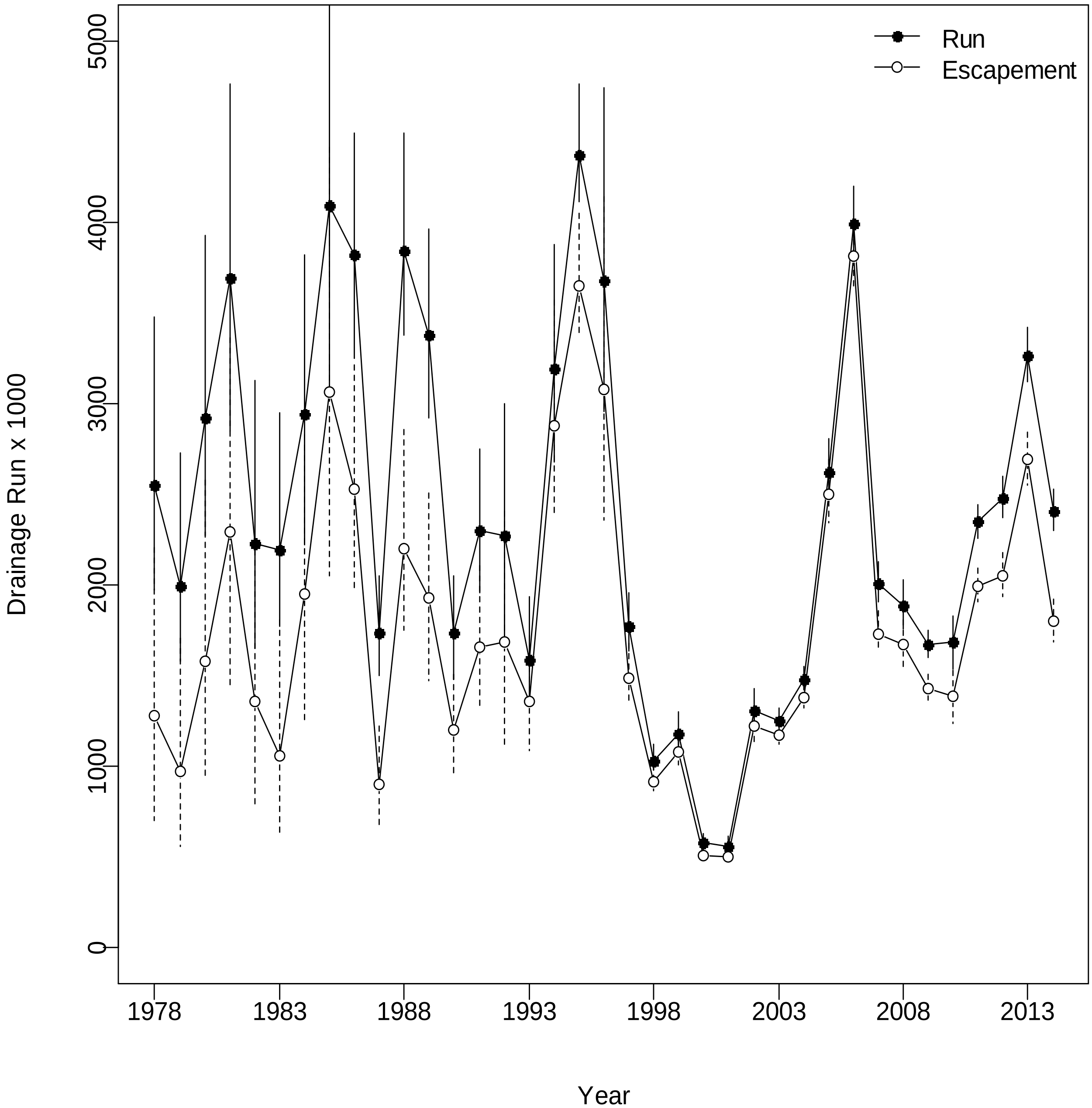

Figure 8.–Estimated summer chum salmon total run size (solid dots) and escapement (open circles), 1978–2014.

Note: Vertical lines indicate the 95% credible interval for each estimate.

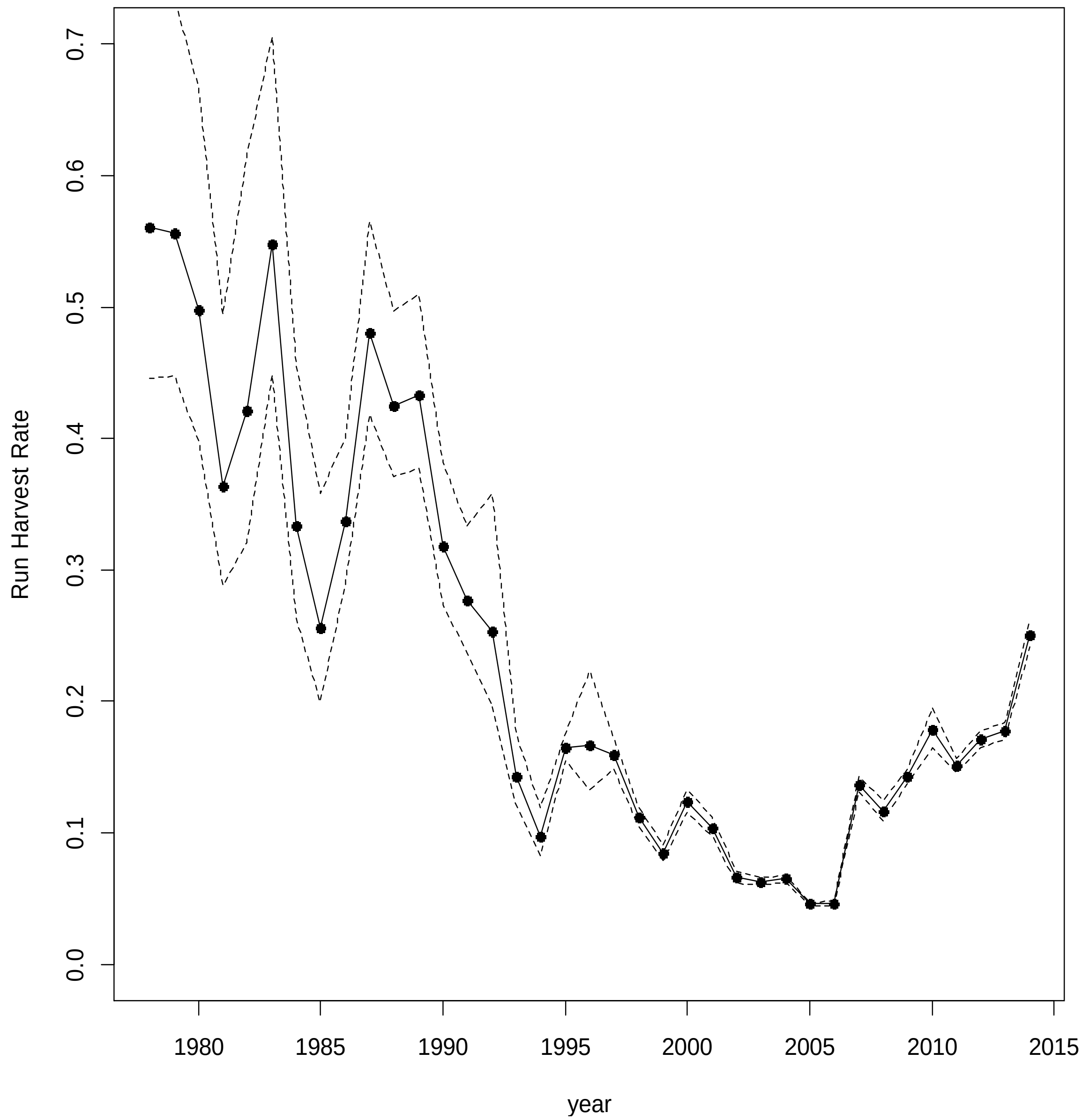

Figure 9.–Estimated summer chum salmon harvest rates, 1978–2014.

Note: Dashed lines indicate bounds of 95% credible interval.

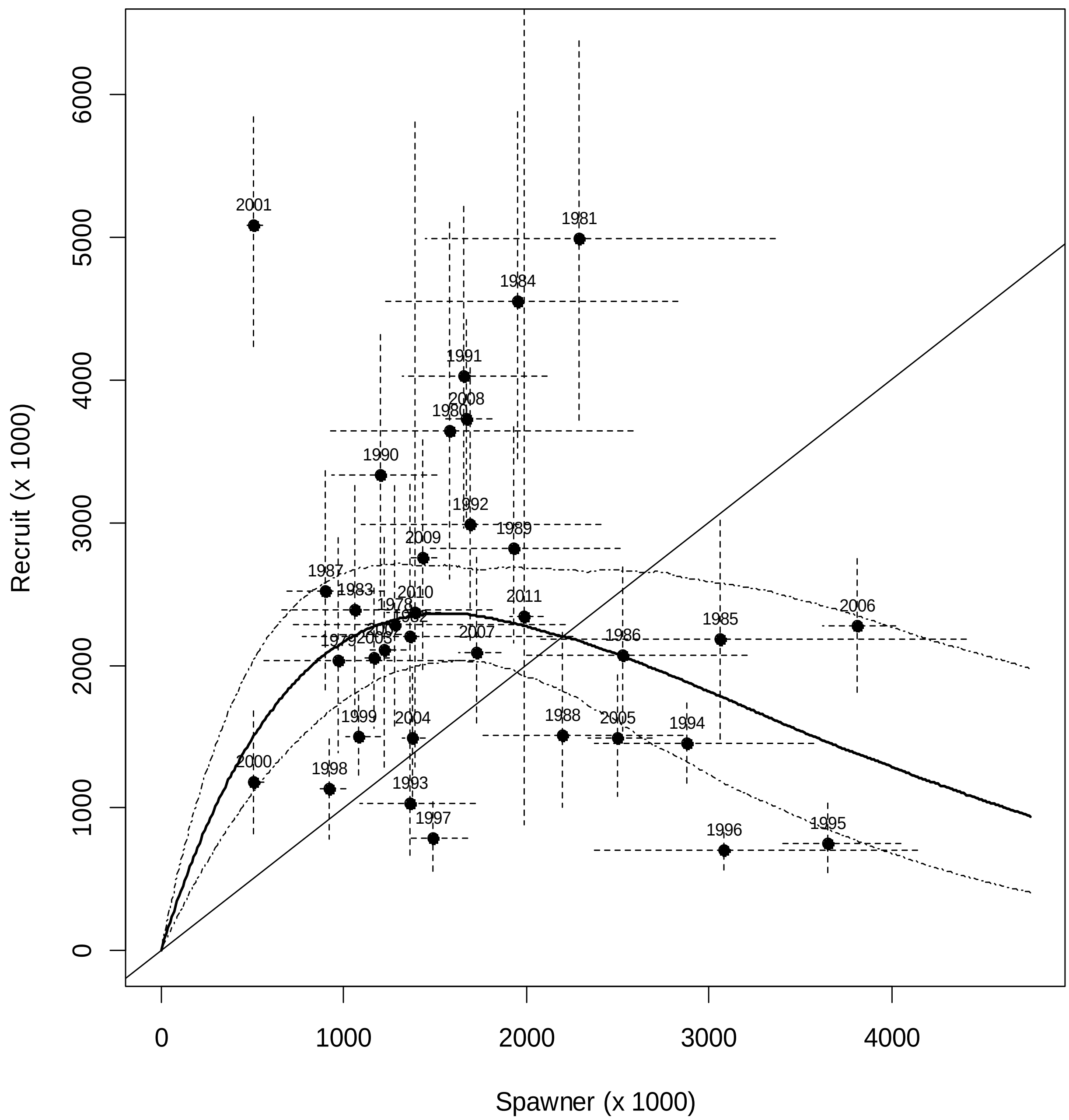

Figure 10.–Spawner-recruitment curve, based on Ricker model.

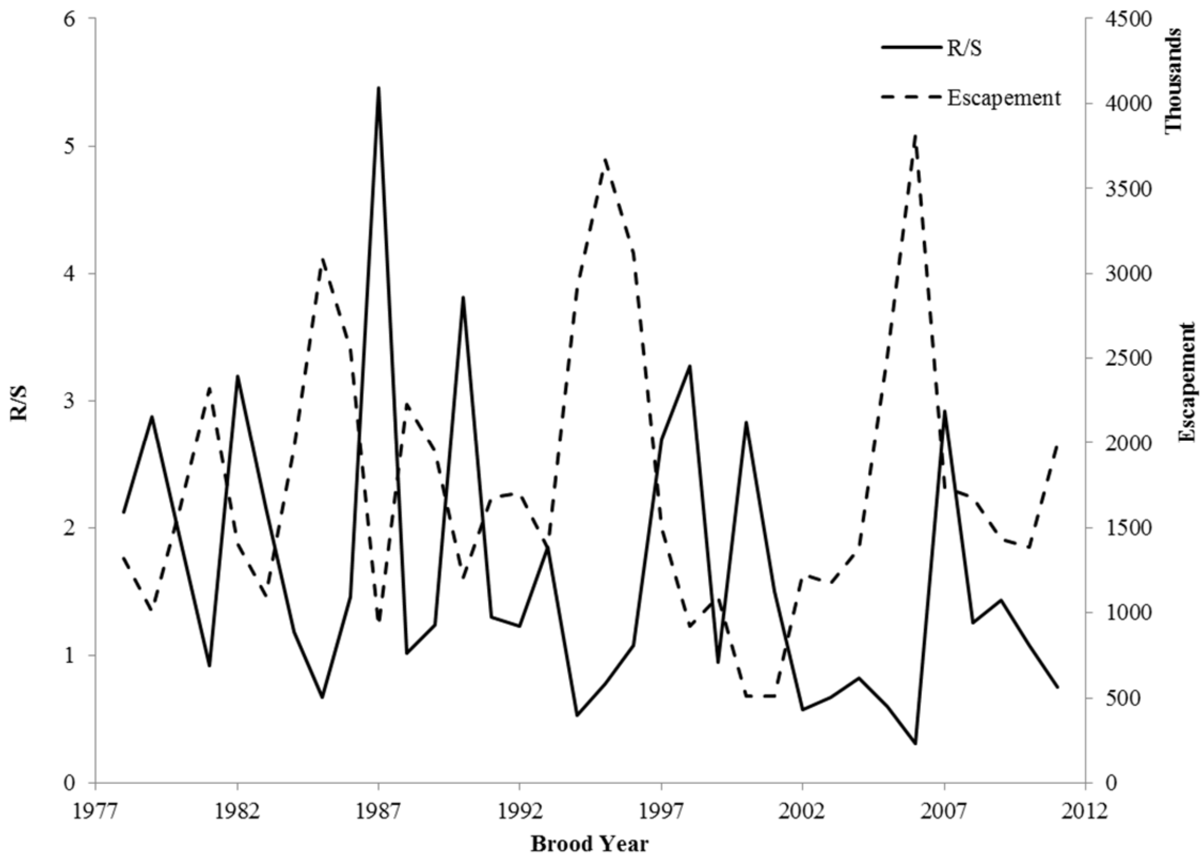

Figure 11.–Recruits-per-spawner ratio (R/S) in comparison with brood year escapement, 1978–2011 brood years.

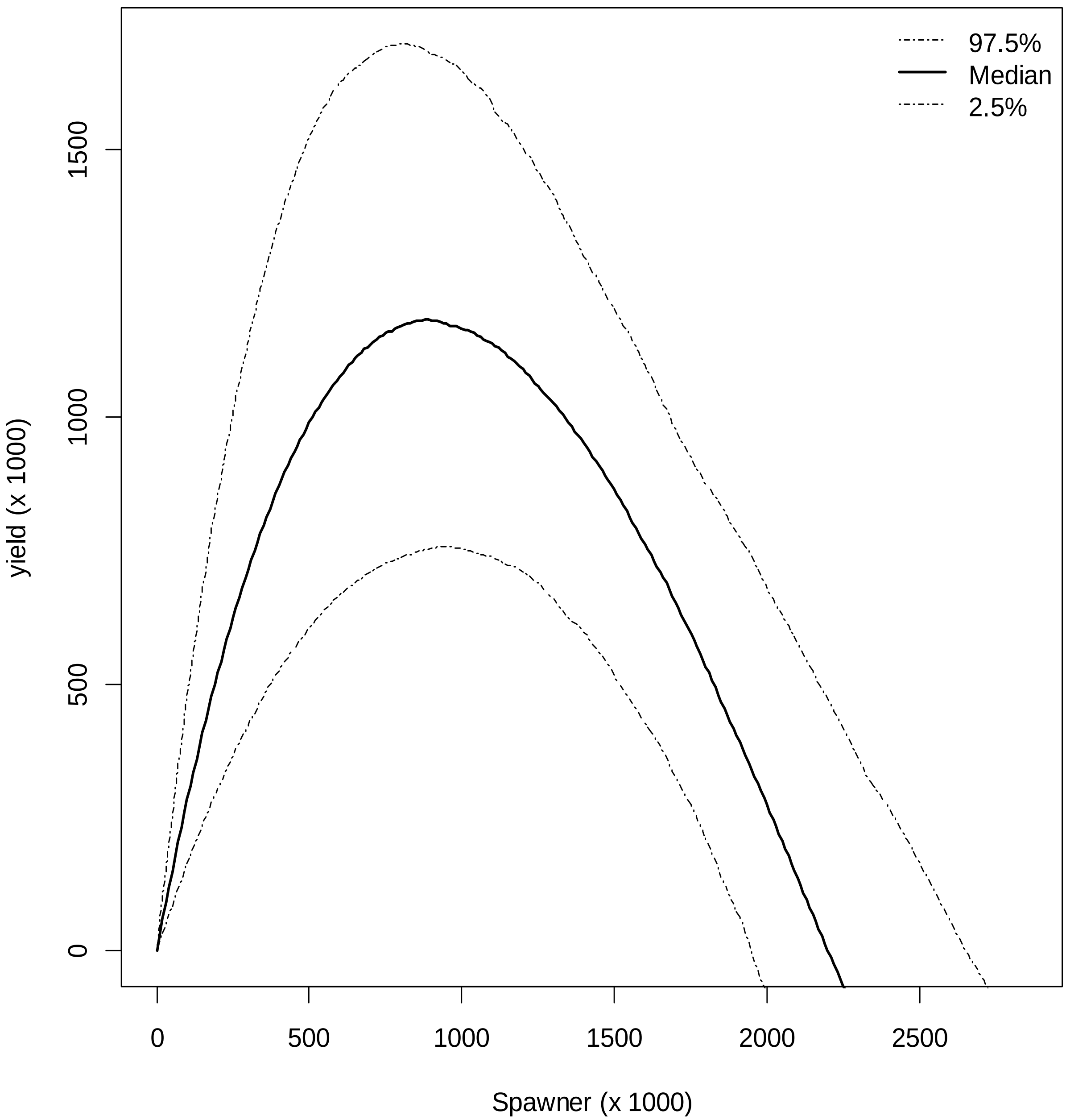

Figure 12.–Expected yield plot, showing yield or surplus above population replacement level (1 recruit per spawner).

Note: Dashed lines indicate 95% credible interval.

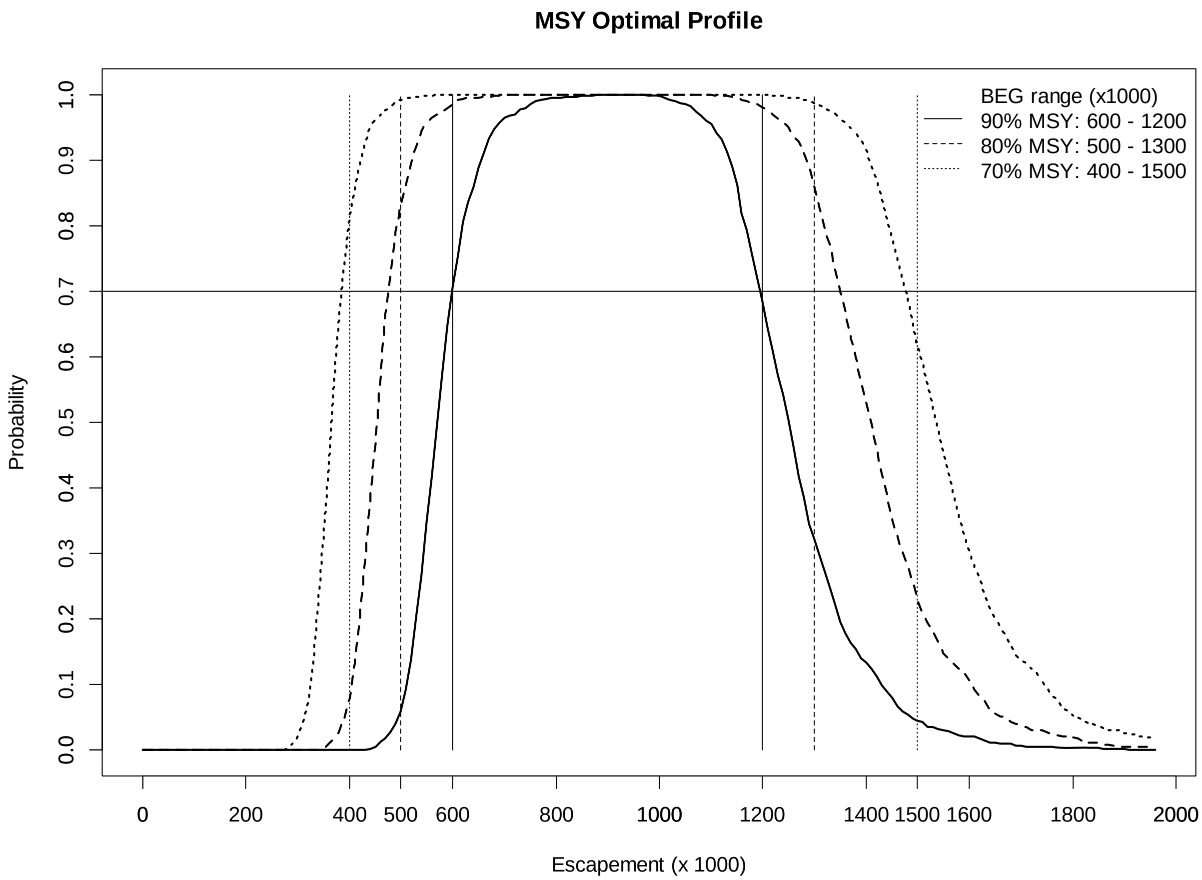

Figure 13.–Optimal yield profiles showing probability of obtaining yield, or surplus, at target levels of 70%, 80%, and 90% of estimated maximum sustained yield (MSY), over a range of possible escapements.

Note: The horizontal line indicates a 70% probability of meeting the targeted level, and vertical lines are projected to show the ranges of escapement corresponding to these target levels.

APPENDIX A: DATA TABLES

Appendix A1.–Yukon summer chum salmon harvest estimates used in run reconstruction and spawner-recruit model.

	Commercial harvests				Subsistence harvests				Total harvest (commercial and subsistence)			
Year	Section 1	Section 2	Section 3	Section 4	Section 1	Section 2	Section 3	Section 4	Section 1	Section 2	Section 3	Section 4
1978	550,054	24,998	144,789	349,894	46,753	3,810	19,607	126,974	596,807	28,808	164,396	476,868
1979	479,641	22,036	120,240	199,746	32,485	3,193	25,987	134,522	512,126	25,229	146,227	334,268
1980	582,952	62,437	142,254	282,725	22,678	2,545	38,208	208,967	605,630	64,982	180,462	491,692
1981	718,643	57,285	199,049	221,097	19,392	2,859	37,295	148,738	738,035	60,144	236,344	369,835
1982	359,288	15,368	86,333	153,180	31,711	2,135	35,975	191,148	390,999	17,503	122,308	344,328
1983	580,725	56,499	105,007	152,638	43,431	4,683	29,162	163,110	624,156	61,182	134,169	315,748
1984	430,727	43,116	114,573	167,405	48,143	3,236	33,860	145,508	478,870	46,352	148,433	312,913
1985	368,084	24,983	99,995	272,560	38,650	3,133	30,998	192,047	406,734	28,116	130,993	464,607
1986	555,089	36,304	161,974	239,793	65,308	7,870	60,991	156,656	620,397	44,174	222,965	396,449
1987	326,091	19,157	94,727	124,231	55,618	4,279	45,060	165,417	381,709	23,436	139,787	289,648
1988	862,732	56,302	238,791	277,665	48,683	4,242	32,012	113,671	911,415	60,544	270,803	391,336
1989	734,426	48,986	123,754	373,110	81,837	6,783	17,161	61,374	816,263	55,769	140,915	434,484
1990	201,910	25,132	86,428	117,009	56,464	6,698	13,843	38,604	258,374	31,830	100,271	155,613
1991	256,013	32,584	82,573	150,217	41,817	4,634	8,463	63,626	297,830	37,218	91,036	213,843
1992	268,098	22,107	56,579	112,826	49,658	6,236	12,817	56,786	317,756	28,343	69,396	169,612
1993	82,814	4,445	13,529	22,735	51,897	5,641	11,018	36,220	134,711	10,086	24,547	58,955
1994	51,746	1,435	24,661	121,862	47,314	5,450	11,687	45,453	99,060	6,885	36,348	167,315
1995	204,868	11,541	55,758	325,923	53,159	4,427	16,746	44,391	258,027	15,968	72,504	370,314
1996	114,739	4,965	38,586	338,409	44,929	6,355	15,984	35,235	159,668	11,320	54,570	373,644
1997	74,979	673	17,623	91,131	48,179	4,532	18,130	26,268	123,158	5,205	35,753	117,399
1998	24,330	1,079	2,709	680	46,833	5,042	9,904	24,225	71,163	6,121	12,613	24,905
1999	21,208	1,457	5,218	1,530	37,829	5,265	7,808	19,421	59,037	6,722	13,026	20,951
2000	5,828	327	469	0	40,975	5,223	7,324	11,373	46,803	5,550	7,793	11,373

-continued-

Appendix A1.–Page 2 of 2.

	Commercial harvests				Subsistence harvests				Total harvest (commercial and subsistence)			
Year	Section 1	Section 2	Section 3	Section 4	Section 1	Section 2	Section 3	Section 4	Section 1	Section 2	Section 3	Section 4
2001	0	0	0		42,143	5,329	3,005	7,762	42,143	5,329	3,005	7,762
2002	8,429	862	1,063	3,224	38,687	6,490	6,079	21,004	47,116	7,352	7,142	24,228
2003	5,587	218	357	4,523	31,519	4,163	7,494	25,128	37,106	4,381	7,851	29,651
2004	17,156	1,350	1,269	6,635	39,007	5,779	4,971	19,915	56,163	7,129	6,240	26,550
2005	30,741	850	633	8,986	44,456	4,333	9,478	20,635	75,197	5,183	10,111	29,621
2006	38,664	2,080	6,731	44,621	49,074	6,070	8,313	27,450	87,738	8,150	15,044	72,071
2007	160,729	9,310	11,543	16,619	40,935	3,711	10,376	21,783	201,664	13,021	21,919	38,402
2008	96,802	16,781	12,015	25,588	38,023	6,012	6,334	18,025	134,825	22,793	18,349	43,613
2009	133,489	19,717	8,590	8,476	38,027	4,888	3,595	21,232	171,516	24,605	12,185	29,708
2010	134,871	14,474	33,870	49,673	40,319	6,196	4,187	15,246	175,190	20,670	38,057	64,919
2011	206,507	20,506	39,497	8,651	45,290	4,182	6,763	21,480	251,797	24,688	46,260	30,131
2012	183,881	12,317	11,651	111,726	56,317	5,716	15,964	25,754	240,198	18,033	27,615	137,480
2013	314,991	29,860	34,292	106,444	51,730	5,299	9,508	25,442	366,721	35,159	43,800	131,886
2014	315,641	50,069	61,637	103,297	38,111	5,728	11,989	18,370	353,752	55,797	73,626	121,667

Note: Harvest sections are designated as follows: Section 1: below Andreafsky River; Section 2: between Andreafsky River and Pilot Station; Section 3: between Pilot Station and Anvik River; Section 4: above Anvik River, including statistical area 334-47 in Anvik River.

Appendix A2.–Summer chum salmon passage estimates and standard deviations at Pilot Station (mainstem Yukon River) sonar, and escapement counts in Andreafsky and Anvik rivers.

Year	Pilot Station sonar passage	SD [Pilot Station sonar passage]	East Fork Andreafsky weir counts[a]	East Fork Andreafsky aerial survey	West Fork Andreafsky aerial survey	Anvik River sonar count[b]
1978				127,050	57,321	307,270
1979				66,471	43,391	277,712
1980				36,823	114,759	482,181
1981			147,312	81,555		1,479,582
1982			181,352	7,501	7,267	444,581
1983			110,608			362,912
1984			70,125	95,200	238,565	891,028
1985				66,146	52,750	1,080,243
1986	2,027,861	202,786	167,614	83,931	99,373	1,085,750
1987	826,384	82,638	45,221	5,587	35,535	455,876
1988	1,870,407	187,041	68,937	43,056	45,432	1,125,449
1989	1,622,327	162,233		21,460		636,906
1990	931,498	93,150		11,519	20,426	403,627
1991	1,232,876	123,288		31,886	46,657	847,772
1992				11,308	37,808	775,626
1993	947,190	94,719		10,934	9,111	517,409
1994	1,997,186	199,719	200,981			1,124,689
1995	3,556,445	65,529	172,148			1,339,418
1996			108,450			933,240
1997	1,415,641	49,672	51,139			605,752
1998	826,385	18,416	67,720			487,301
1999	973,708	25,694	32,587			437,356
2000	456,271	12,185	24,785	2,094	18,989	196,349
2001	441,450	13,488				224,058
2002	1,088,463	31,894	44,194			459,058
2003	1,168,518	37,933	22,461			256,920
2004	1,357,826	31,486	64,883			365,353
2005	2,439,616	50,279	20,127			525,391
2006	3,767,044	96,799	102,260	3,100	617	605,485
2007	1,726,885	53,697	69,642			460,121
2008	1,665,667	83,030	57,259	9,300	25,850	374,928
2009	1,421,646	38,241	8,770	736	3,877	191,566
2010	1,405,533	95,389	72,839	1,982	24,380	396,173
2011	1,977,808	49,361	100,473	12,889	10,020	642,527
2012	2,130,404	51,695	56,680			484,090
2013	2,747,218	72,656	61,234	10,965	9,685	577,877
2014	1,924,425		37,337		9,650	399,223

[a] E. Fk Andreafsky weir counts include sonar (1981–1984) and tower (1986–1988) counts.

[b] Anvik sonar counts include a tower count for 1978.

Appendix A3.–Summer chum salmon escapement counts from ground-based monitoring projects (weir or tower).

Year	Kaltag River tower	Nulato River tower	Henshaw Creek weir	Hogatza River weir	Gisasa River weir	Chena River tower	Salcha River tower
1978							
1979							
1980							
1981							
1982							
1983							
1984							
1985							
1986							
1987							
1988							
1989							
1990							
1991							
1992							
1993						5,400	5,809
1994	47,295	148,762			51,116	9,984	39,450
1995	77,193	236,890		116,735	136,886	3,519	30,784
1996	51,269	129,694		100,912	158,582	12,810	74,827
1997	48,018	157,975		76,454	31,800	9,439	35,741
1998	8,113	49,140			21,142	5,901	17,289
1999	5,339	30,076		11,283	10,155	9,165	23,221
2000	6,727	24,308	27,271	19,376	11,410	3,515	20,516
2001			35,031	3,674	17,946	4,773	14,900
2002	13,583	72,232	25,249	13,150	33,481	1,021	20,837
2003	3,056	19,590	22,556	6,159	25,999	573	
2004	5,247		86,474	15,661	37,851	15,162	47,861
2005	22,093		237,481	26,420	172,259	2,928	193,085
2006				29,166	261,306	35,109	111,869
2007			44,425	6,029	46,257	4,999	13,069
2008			96,731		36,938	1,300	4,636
2009			156,933		25,904	16,516	31,035
2010			105,398		47,669	7,560	22,185
2011			248,247		95,796		
2012			292,082		83,423	6,882	46,251
2013			285,008		80,055	21,385	59,188
2014					32,523		

Appendix A4.–Summer chum salmon escapement index counts from aerial surveys.

Year	Rodo River	Gisasa River	South Fork Nulato River	N Fork Nulato River	Hogatza River	Tozitna River
1978	17,845	9,280	12,821	41,659	5,102	2,262
1979		10,962	1,506	35,598	14,221	
1980		10,388	3,702	11,244	19,786	580
1981			1,348			
1982		334			4,984	874
1983		2,356	1,263	19,749	28,141	1,604
1984						
1985	24,576	13,232	10,494	19,344	22,566	1,030
1986		12,114	16,848	47,417		1,778
1987		2,123	4,094	7,163	5,669	
1988	13,872	9,284	15,132	26,951	6,890	2,983
1989						
1990	1,941	450	3,196	1,419	2,177	36
1991	3,977	7,003	13,150	12,491	9,947	93
1992	4,465	9,300	5,322	12,358	2,986	794
1993	7,867	1,807	5,486	7,698		970
1994		6,827			8,247	
1995	12,849	6,438	10,875	29,949		4,985
1996	4,380		8,490		27,091	2,310
1997	2,775	686			1,821	428
1998					120	7
1999						
2000						480
2001						12,527
2002						18,789
2003						8,487
2004						25,003
2005						39,700
2006		1,000	7,772	11,658		22,629
2007			21,825	15,277		8,470
2008		20,470	12,070	10,715		9,133
2009		1,060	2,120	567	3,981	8,434
2010		1,096	1,891	1,038	840	
2011	6,011	13,228	9,454	8,493	3,665	11,351
2012	15,606		20,600	14,948	23,022	11,045
2013		9,300	13,695	13,230		
2014						

Appendix A5.–Estimated proportions of total annual Yukon River summer chum salmon run, by age class.

Year	Age 3	Age 4	Age 5	Age 6
1978	0.026	0.716	0.249	0.009
1979	0.043	0.627	0.319	0.011
1980	0.010	0.779	0.202	0.010
1981	0.004	0.412	0.572	0.013
1982	0.035	0.647	0.300	0.018
1983	0.015	0.557	0.416	0.012
1984	0.022	0.769	0.203	0.006
1985	0.014	0.678	0.296	0.012
1986	0.004	0.363	0.616	0.016
1987	0.009	0.598	0.349	0.044
1988	0.006	0.684	0.298	0.012
1989	0.008	0.393	0.595	0.005
1990	0.013	0.483	0.478	0.026
1991	0.007	0.476	0.511	0.007
1992	0.001	0.319	0.643	0.037
1993	0.006	0.597	0.367	0.030
1994	0.001	0.405	0.580	0.014
1995	0.021	0.542	0.408	0.028
1996	0.005	0.523	0.439	0.033
1997	0.003	0.318	0.643	0.036
1998	0.001	0.737	0.239	0.023
1999	0.001	0.394	0.592	0.014
2000	0.006	0.578	0.395	0.021
2001	0.002	0.209	0.763	0.026
2002	0.013	0.641	0.320	0.025
2003	0.012	0.714	0.255	0.019
2004	0.038	0.522	0.436	0.004
2005	0	0.926	0.069	0.005
2006	0.007	0.292	0.701	0
2007	0.011	0.538	0.355	0.096
2008	0.013	0.415	0.524	0.049
2009	0.026	0.593	0.355	0.026
2010	0.082	0.762	0.151	0.005
2011	0.007	0.475	0.508	0.009
2012	0.005	0.708	0.254	0.033
2013	0.001	0.420	0.565	0.014
2014	0.004	0.399	0.540	0.056

APPENDIX B: ADMB CODE USED IN MODEL

Appendix B1.–ADMB model code.

```
//===============================================================================
// Reconst_SS_SR.TPL
// This model is Yukon Summer Run reconstruciton Satate-Space model
// Written by: Toshihide "Hamachan" Hamazaki
// Date: 09/18/2015
//===============================================================================

//===============================================================================
// 1.0 Data Entry
//===============================================================================
DATA_SECTION
  init_int fyear;      // First year
  init_int lyear;      // Last year
  init_int tyear;  // Transition year
  init_int fage;       // First age
  init_int lage;       // Last age
  init_int nweir;      // number of Weir projects
  init_int naerial; // number of Aerial projects
  init_matrix obs_H(1,4,fyear,lyear);   // Harvests from 1 to 4

// Read Pilot Sonar data: This is the anchora data
  init_vector obs_plt(fyear,lyear);     // Pilot Sonar Passage estimate
  init_vector obs_plt_sd(fyear,lyear);   // SD of Pilot Sonar Passage estimates
  init_vector obs_w_andr(fyear,lyear);   // Observations Andreafsky Weir
  init_vector obs_a_andr_e(fyear,lyear); // Observations Andreafsky Aerial East
  init_vector obs_a_andr_w(fyear,lyear); // Observations Andreafsky Aerial West
  init_vector obs_anvk(fyear,lyear);     // Observations Anvik Sonar 1973-2002

// Read weir data
  init_matrix obs_wS(1,nweir,fyear,lyear);

// Read Aerial data
  init_matrix obs_aS(1,naerial,fyear,lyear);

// Read Age Compostion data
  init_vector efN(fyear,lyear);              // effective sample size
  init_matrix obs_age_p(fage,lage,fyear,lyear);    //Annual age composition
  init_number SDRec;                               //Weight Recruitment
  init_number SDma;                                //Weight age composition

// Read Control data
  !! ad_comm::change_datafile_name("proj.ctl");
  init_vector lnalpha_lup(1,3);  // Ricker ln alpha
  init_vector s_beta_lup(1,3);   // Ricker beta X 100000
  init_vector phi_lup(1,3);      // AR1 phi
  init_vector ln_mu_R0_lup(1,3); // Mean Recruitment
  init_vector ln_Rdevs_re_lup(1,3); // Recruitment variation
  init_vector resid0_lup(1,3);     // First year residual
  init_vector ln_mu_ma_lup(1,3);                        // Mean maturity years
  init_vector ln_madev_re_lup(1,3); // deviation of maturity years
  init_vector ln_wS_lup(1,3);               // ln transformed slope for upriver weir/tower model
  init_vector ln_aS_lup(1,3);               // ln transformed slope for upriver aerial model
  init_vector ln_rwS_lup(1,3);// ln transformed sd for weir model
  init_vector ln_raS_lup(1,3); // ln transformed sd for aerial model
  init_vector p_east_lup(1,3); // proportion of Andreafsky east fork
  init_vector ln_wandr_lup(1,3);      // ln transformed slope for Andreafsky River:
  init_vector ln_aandr_lup(1,3);     // ln transformed slope for Andreafsky Aerial
  init_vector ln_anvk_lup(1,3);     // ln transformed slope for Anvik Sonar: 1973-2002, 2003-2013
  init_vector ln_ranvk_lup(1,3);     // ln transformed sd for Anvik Sonar
```

```
 !! cout << "Data Section Completed" << endl;
//!!cout<<SDma<<endl;
//!!exit(9);
//===============================================================================
//  Initialization section
//===============================================================================
INITIALIZATION_SECTION
 ln_wS   3.0;       // ln transformed slope for upriver Weir/Tower model
 ln_aS  5.0;        // ln transformed slope for upriver aerial model
 ln_rwS   0.0;       //  for Kwethluk weir model
 ln_raS   0.0;      // log transformed slope for Kwethluk aerial model
 ln_wandr  4.0;      // slope for Anndreafsky
 ln_aandr  5.0;      // slope for Anndreafsky East Aerial
 ln_anvk  1.0;      // slope for Anvik Sonar 1973-2002
 ln_alpha   1.2;    // Ricker ln Alpha
 s_beta    0.7;      // Ricker beta
 phi       0.0;
 ln_mu_ma   1.2;
 ln_mu_R0   15.0;
 p_east    0.5;
 q         1.0;
//  resid0    -0.15;
//===============================================================================
// 2.0  Define Parameters
//===============================================================================
PARAMETER_SECTION
// State-Space Model parameters
 init_bounded_number ln_alpha(lnalpha_lup);                  // Ricker ln alpha
 init_bounded_number s_beta(s_beta_lup);                               // Ricker beta X 10000
 init_bounded_number phi(phi_lup);                                                // AR1 phi
 init_bounded_number ln_mu_R0(ln_mu_R0_lup);                     // Mean Recruitment
 init_bounded_dev_vector ln_Rdevs_re(fyear-lage,lyear-fage,-20.0,20.0,2); // Recruitment variation
 init_bounded_number resid0(-10.0,10.0,1);                             // First year residual
 init_bounded_number ln_mu_ma(0.6,2.0,1);                              // Mean maturity years
 init_bounded_dev_vector ln_madev_re(fyear-lage,lyear-fage,-1.0,1.0,2); // deviation of maturity years

// Run reconstruction parameters
 init_bounded_vector ln_wS(1,nweir,2.0,7.0,1);               // ln transformed slope for upriver weir/tower model
 init_bounded_vector ln_aS(1,naerial,1.0,8.0,1);  // ln transformed slope for upriver aerial model
 init_bounded_number ln_rwS(-3.0,10.0,3);                              // ln transformed sd for weir model
 init_bounded_number ln_raS(-3.0,5.0,3);                               // ln transformed sd for aerial model
 init_bounded_number p_east(0.0,0.6,1);                                // proportion of Andreafsky east fork
 init_bounded_vector ln_wandr(1,2,0.0,5.0,1);                // ln transformed slope for Andreafsky River: 1983-2002
 init_bounded_number ln_aandr(1.0,6.0,1);                              // ln transformed slope for Andreafsky Aerial
 init_bounded_vector ln_anvk(1,2,0.0,3.0,1);      // ln transformed slope for Anvik Sonar: 1973-2002, 2003-2013
 init_bounded_number ln_ranvk(-3.0,3.0,1);                             // ln transformed sd for Anvik Sonar
 init_bounded_number q(0.1,2.0,1);                                     // Pilot Station suvey efficiency 1986-1994

//  init_bounded_vector ln_rwS(1,nweir,-3.0,10.0,2);           // ln transformed sd for weir model
//  init_bounded_vector ln_raS(1,naerial,-3.0,5.0,2);          // ln transformed sd for aerial model

//  Working parameters: Run reconstructin
 vector wS(1,nweir);                                                                  // slope for weir model
 vector aS(1,naerial);                                                    // slope for aerial model
 number rwS;                                                                                  // sd for weir model
 number raS;                                                                                  //    sd    for    aerial
model
//  vector rwS(1,nweir);                    // sd for weir model
//  vector raS(1,naerial);
 vector wandr(1,2);       // log transformed slope for Andreafsky River: 1983-2002
 number aandr;                            // log transformed slope for Andreafsky Aerial
 vector anvk(1,2);                // log transformed slope for Anvik Sonar: 1973-2002, 2003-2013
```

```
  number ranvk;

//  Working parameters: State-Space Model
// Ricker Spawner-Recruit Pamaeters
  number alpha;
  number beta;
  // Expected ln Recruit
  vector ln_R(fyear-lage,lyear-fage);         // Receuit vector
  vector ln_predR1(fyear,lyear-fage);         // Receuit vector2
  vector ma(fyear-lage,lyear-fage);           // Annual mean maturity age
  matrix g(fage,lage,fyear-lage,lyear-fage);  //maturity schedule logistic
  matrix p(fage,lage,fyear-lage,lyear-fage);  //proporion of mature for eage
  matrix N_ta(fage,lage,fyear,lyear);                              // Total Run by age
  matrix est_age_p(fage,lage,fyear,lyear);  // Expected run age proportion

// Estimated paramters size wih SD
  sdreport_vector N(fyear,lyear);                                  //Total Run with SD
  sdreport_vector S(fyear,lyear);                                  //Total Escapement with SD
  sdreport_vector R(fyear-lage,lyear-fage); //Recuritment with SD
  sdreport_vector resid(fyear-1,lyear-fage); //Expected residuals
  vector obs_HT(fyear,lyear);                              //Total Harvest
  vector obs_H24(fyear,lyear);                                     //Sum of Harvests 2 to 4
  vector obs_H34(fyear,lyear);                                     //Sum of Harvests 3 to 4
  vector S_up(fyear,lyear);          //Esc above Anvik
  vector S_adr(fyear,lyear);    // Andreafsky escapement
  vector S_anv(fyear,lyear);    // Anvik escapement
  vector N_plt(fyear,lyear);     // Pilot Station Run

// Likelihoood
  number fpen;
  vector tfw(1,nweir);   // Likelihood for weir model
  vector tfa(1,naerial);  // likelihood for aerial model
  vector tfr(1,5);          // likelihood for inriver model
  vector tf(1,3);
  objective_function_value f;

 !!cout<<"parameter_section Done"<<endl;
//===============================================================================
// 5.0  Calculate sum Harvest data
//===============================================================================
PRELIMINARY_CALCS_SECTION
  int i;
  obs_HT = colsum(obs_H);                   // Harvest Sum
  for (i=fyear;i<=lyear;i++)
   {
    obs_H24(i) = obs_H(2,i)+obs_H(3,i)+obs_H(4,i);
              obs_H34(i) = obs_H(3,i)+obs_H(4,i);
   }

  cout<<"preliminary_calcs_section Done"<<endl;
//===============================================================================
// 5.0  Procedure
//===============================================================================
PROCEDURE_SECTION
  fpen = 0.0;
  convert_parameters_into_rates();
//  cout <<"OK for convert_parameters..."<<endl;

  get_initial_years_recruit();
//  cout <<"OK for get_initial_year..."<<endl;

  get_population_dynamics();
```

```
//  cout <<"OK for get_populaiton_dynamics..."<<endl;


  evaluate_the_objective_function();

   if (mceval_phase())
    {
     ofstream MCMCreport("post_samp.csv", ios::app);
              MCMCreport <<ln_alpha << "," << s_beta << "," << phi << "," <<tf(2) << ","<< N << S<< R <<endl;
              MCMCreport.close();
//             cout << ln_alpha << "," << s_beta << endl;
             }
//===============================================================================
// 6.0  Function:  Convert parameters into rates
//===============================================================================
FUNCTION convert_parameters_into_rates
  int i,j;
  wS=exp(ln_wS);       // slope for weir model
  aS=exp(ln_aS);       // slope for aerial model
  rwS=exp(ln_rwS);       // SD for weir model
  raS = exp(ln_raS);       // SD for aerial model
  wandr = exp(ln_wandr);        // slope for Andreafsky River
  aandr = exp(ln_aandr);       // slope for Andreafsky Aerial
  anvk = exp(ln_anvk);       //  slope for Anvik
  ranvk = exp(ln_ranvk);       //  slope for Anvik

  alpha = exp(ln_alpha);                                    // Ricker alpha
  beta =  s_beta/1000000;                                   // Ricker beta
  resid(fyear-1) = resid0;                                  // First year residual
  ln_R = ln_mu_R0;                    //
  ma = mfexp(ln_mu_ma+ln_madev_re);      // maturity index
// calculate maturity functions
  for (i=fyear-lage;i<=lyear-fage;i++){
    for (j=fage;j<=lage;j++){
// matrutiry probability logistic function
     g(j,i) = 1.0/(1.0+exp(ma(i)*(lage-j)+log(1.0/0.999-1.0)));
                          }
    }
// calculate maturity functions
  p(fage) = g(fage);
  for (i=fyear-lage;i<=lyear-fage;i++){
    for (j=fage+1;j<=lage;j++){
     p(j,i) = g(j,i) - g(j-1,i);
                          }
    }
//===============================================================================
// 7.0  Function:  get_initial_years_abundance
//                        This function estimates previous lyears of recruitment
//      Both abundance and length composition is estimated
//===============================================================================
FUNCTION get_initial_years_recruit
  int i;
// GET RECRUITMENTS FOR YEARS WITH NO SR LINK
  for (i=fyear-lage;i<fyear;i++){
      ln_R(i)=ln_Rdevs_re(i)+ln_mu_R0;
      R(i)=exp(ln_R(i));
  }
//===============================================================================
// 6.0  Function:  generate_maturity_schedule
//===============================================================================
FUNCTION get_population_dynamics
  int i,j;
```

```
// CALCULATE NUMBERS AT AGE
  for (i=fyear;i<=lyear;i++)
  {
    for (j=fage;j<=lage;j++)
                        {
// Assign each year's run by age
          N_ta(j,i) = p(j,i-j)*R(i-j);
                        }
// N is expected run size
    N(i) = colsum(N_ta)(i);
// S is expected Escapement: Expected run size - harvest

// est_age_p is expected age proportion
 for (j=fage;j<=lage;j++)
                        {
// Assign each year's run by age
          est_age_p(j,i) = N_ta(j,i)/N(i);
                        }
    S(i) = N(i) - obs_HT(i);
              S(i) = posfun(S(i), 350000,fpen);

// Calculate Escapement of Andreafsky, Anvik, Pilot Run  =======================
              if(i <= tyear)
                        {
                        S_adr(i) = (S(i)+obs_H24(i))/wandr(1);   // Andreafsky River Escapement
                        S_anv(i) = (S(i)+obs_H(4,i)-S_adr(i))/anvk(1);  // Anvik River Escapement
                        }
              else
                        {
                        S_adr(i) = (S(i)+obs_H24(i))/wandr(2);
                        S_anv(i) = (S(i)+obs_H(4,i)-S_adr(i))/anvk(2);
                        }
              S_up(i) = S(i) - S_anv(i) - S_adr(i);  // Upriver Escapement
              N_plt(i) = S(i) + obs_H34(i) - S_adr(i);  // Run size at Pilot

// Calculte
  if (i<=lyear-fage)
                        {
// Expected log Recruit without AR1 process
                        ln_predR1(i) = ln_alpha - beta*S(i) + log(S(i));
                        resid(i) = phi*resid(i-1) + ln_Rdevs_re(i);
// Expected log Recruit with AR1 process
                        ln_R(i) = ln_predR1(i) + resid(i);
// Expected Recruit with AR1 process
       R(i) = exp(ln_R(i));
                        }
  }
//==============================================================================
// 10.0  Likelihood Calculation
//==============================================================================
FUNCTION evaluate_the_objective_function
  int i,j,k;
//observation model
  f=0.0;
  tfw = 0.0;             // initialilze to 0
  tfa = 0.0;             // initialilze to 0
  tfr = 0.0;             // initialilze to 0
  tf = 0.0;
  for (i=fyear;i<=lyear;i++)
  {
//=============================================================================
// 6.6 Andreafsky Escapement likelihood
```

```
//==========================================================================================
//Andreafsky East Weir
  if(obs_w_andr(i)>0)
    {
       tfr(1) += log(rwS)+0.5*square(log(obs_w_andr(i))-log(S_adr(i)*p_east))/square(rwS);
    }
//Andreafsky Areal East
  if(obs_a_andr_e(i)>0)
             {
       tfr(2) += log(raS)+0.5*square(log(obs_a_andr_e(i))-log(S_adr(i)*p_east/aandr))/square(raS);
             }
//Andreafsky Aerial west
   if(obs_a_andr_w(i)>0)
    {
                         tfr(3) += log(raS)+0.5*square(log(obs_a_andr_w(i))-log(S_adr(i)*(1-p_east)/aandr))/square(raS);
    }
//==========================================================================================
// 6.4  Pilot Station Likelihood
//==========================================================================================
  if(obs_plt(i)>0)
    {
             if(i < 1995)
             {
             tfr(4) += square(log(obs_plt(i))-log(q*N_plt(i)))/log(square(obs_plt_sd(i)/obs_plt(i))+1);
    }
             else
             {
             tfr(4) += square(log(obs_plt(i))-log(N_plt(i)))/log(square(obs_plt_sd(i)/obs_plt(i))+1);
    }
    }
//==========================================================================================
// 6.3 Middle (Anvik) Escapement likelihood
//==========================================================================================
//Anvik Sonar
  if(obs_anvk(i)>0)
   {
       tfr(5) += log(ranvk)+0.5*square(log(obs_anvk(i))-log(S_anv(i)))/square(ranvk);
   }
//============= Weir likelihood Calculation ===================================
  for(j=1;j<=nweir;j++)
   {
  if(obs_wS(j,i)>0)
    {
      tfw(j) += log(rwS)+0.5*square(log(obs_wS(j,i))-log(S_up(i)/wS(j)))/square(rwS);
             }
   }
//===  Aerial survey based likelihood calculation ==============================
  for(k=1;k<=naerial;k++)
   {
  if(obs_aS(k,i)>0)
     {
      tfa(k) += (log(raS)+0.5*square(log(obs_aS(k,i))-log(S(i)/aS(k)))/square(raS));
              }
    }
 }
//Log likelhihood for Run age proportion
  tf(1)                    =                    -(sum(elem_prod(efN,colsum(elem_prod(obs_age_p,log(est_age_p+1.e-3)))))                    -
sum(elem_prod(efN,colsum(elem_prod(obs_age_p,log(obs_age_p+1.e-3))))));
//deviation in recruits
  tf(2) = norm2(ln_Rdevs_re)/(2*SDRec*SDRec);
//deviation in maturity scheduel
  tf(3) = norm2(ln_madev_re)/(2*SDma*SDma);
```

```
// Sum all likelihood ==========================================================
  f = sum(tf)+sum(tfw)+sum(tfa)+sum(tfr)+fpen;

REPORT_SECTION
  report << "f" << endl << f << endl;  // Total likelihood
// Individual likelihood
  report << "tfw" << endl << tfw << endl;            // Weir
  report << "tfa" << endl << tfa << endl;            // Aerial
  report << "tfr" << endl << tfr << endl;   //
  report << "tf" << endl << tf <<endl;               //State-Space
  report << "N_ta" << endl << N_ta << endl;
//==============================================================================
GLOBALS_SECTION
  #include <math.h>
  #include <admodel.h>
  #include <time.h>

  time_t start,finish;
  long hour,minute,second;
  double elapsed_time;
  int header;
// ============================================================================
TOP_OF_MAIN_SECTION
  arrmblsize = 10000000;
  gradient_structure::set_GRADSTACK_BUFFER_SIZE(3000000); // this may be incorrect in
  gradient_structure::set_CMPDIF_BUFFER_SIZE(100000000);
  time(&start);
// ============================================================================
FINAL_SECTION
 // Output summary stuff
 time(&finish);
 elapsed_time = difftime(finish,start);
 hour = long(elapsed_time)/3600;
 minute = long(elapsed_time)%3600/60;
 second = (long(elapsed_time)%3600)%60;
 cout << endl << endl << "Starting time: " << ctime(&start);
 cout << "Finishing time: " << ctime(&finish);
 cout << "This run took: " << hour << " hours, " << minute << " minutes, " << second << " seconds." << endl << endl;
```