Regional Information Report 3A18-04

Kuskokwim River Chinook Salmon Run Reconstruction Model Revisions – Executive Summary

by

Zachary W. Liller

Hamachan Hamazaki

Gary Decossas

William Bechtol

Matthew Catalano

and

Nicholas J. Smith

September 2018

Alaska Department of Fish and Game **Division of Commercial Fisheries**

Symbols and Abbreviations

The following symbols and abbreviations, and others approved for the Système International d'Unités (SI), are used without definition in the following reports by the Divisions of Sport Fish and of Commercial Fisheries: Fishery Manuscripts, Fishery Data Series Reports, Fishery Management Reports, and Special Publications. All others, including deviations from definitions listed below, are noted in the text at first mention, as well as in the titles or footnotes of tables, and in figure or figure captions.

Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

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

Mathematics, statistics

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

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by
Zachary W. Liller, Hamachan Hamazaki, and Nicholas J. Smith,
Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage

Gary Decossas,
U.S. Fish and Wildlife Service, Office of Subsistence Management, Anchorage

William Bechtol,
Bechtol Research
and

Matthew Catalano
Auburn University, School of Fisheries, Aquaculture and Aquatic Sciences

Alaska Department of Fish and Game
Division of Commercial Fisheries
333 Raspberry Road, Anchorage, Alaska, 99518-1565

September 2018

The Regional Information Report Series was established in 1987 and was redefined in 2007 to meet the Division of Commercial Fisheries regional need for publishing and archiving information such as area management plans, budgetary information, staff comments and opinions to Alaska Board of Fisheries proposals, interim or preliminary data and grant agency reports, special meeting or minor workshop results and other regional information not generally reported elsewhere. Reports in this series may contain raw data and preliminary results. Reports in this series receive varying degrees of regional, biometric and editorial review; information in this series may be subsequently finalized and published in a different department reporting series or in the formal literature. Please contact the author or the Division of Commercial Fisheries if in doubt of the level of review or preliminary nature of the data reported. Regional Information Reports are available through the Alaska State Library and on the Internet at: http://www.adfg.alaska.gov/sf/publications/.

Zachary W. Liller, Hamachan Hamazaki, and Nicholas J. Smith,
Alaska Department of Fish and Game, Division of Commercial Fisheries,
333 Raspberry Rd. Anchorage, AK, USA

Gary Decossas,
U.S. Fish and Wildlife Service, Office of Subsistence Management,
1011 E. Tudor, Anchorage, AK, USA

William Bechtol,
Bechtol Research
P.O. Box 3426, Homer, AK, USA

and

Matthew Catalano
Auburn University, School of Fisheries, Aquaculture and Aquatic Sciences
203 Swingle Hall, Auburn, Alabama, USA

This document should be cited as follows:
Liller, Z. W., H. Hamazaki, G. Decossas, W. Bechtol, M. Catalano, and N. J. Smith. 2018. Kuskokwim River Chinook salmon run reconstruction model revision – executive summary. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 3A.18-04, Anchorage.

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ABSTRACT

The Alaska Department of Fish and Game (ADF&G) has made revisions to the statistical model and associated input data used to estimate total annual run size and drainagewide escapement of Kuskokwim River Chinook salmon. A final report detailing the model revisions and revised total run and drainagewide escapement estimates has been planned, but has not been published at this time. An executive summary of the model revisions and revised estimates was drafted for general distribution. A version of the summary was also provided to the North Pacific Fishery Management Council. This report presents both versions of the executive summary for archival purposes and to facilitate referencing revised total run and escapement estimates until such time that a final report is available.

Key words: Chinook salmon, *Oncorhynchus tshawytscha*, run reconstruction model, model review, model revision, Kuskokwim River.

INTRODUCTION

The Alaska Department of Fish and Game (ADF&G) has made revisions to the statistical model and associated input data used to estimate total annual run size and drainagewide escapement of Kuskokwim River Chinook salmon (*Oncorhynchus tshawytscha*). Model revisions were agreed to by the Kuskokwim River Interagency Model Development Team (KRIMDT) which was comprised of salmon stock assessment analysts from ADF&G, U.S. Fish and Wildlife Service, Bechtol Research, and Auburn University working in collaboration with an expert review panel commissioned by the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYKSSI). Full reports detailing the model review process and recommendations will be forthcoming from both the KRIMDT and AYKSSI review teams. In the interim, an executive summary was drafted which 1) highlighted the model review process, 2) summarized specific changes to the model structure and input data, and 3) presented revised total run and escapement estimates. In addition, the executive summary contained a memo from the AYKSSI Expert Panel which summarized their preliminary review results and recommendations. The full model code and input data was also included in the executive summary.

ADF&G distributed 2 versions of the executive summary as part of a broader effort to notify fisheries management agencies and stakeholders of the model changes and make revised total run and escapement estimates available for salmon management and research purposes. One version was drafted for general distribution and was emailed by ADF&G to the Kuskokwim River Salmon Management Working Group list serve on May 16, 2018. That distribution list included members from state, federal, and tribal fishery management organizations; state and federal fishery advisory groups; various non-profit groups; state government representatives; media representatives; and individual stakeholders. The other version was drafted for the North Pacific Fishery Management Council (Council). Since 2015, ADF&G has provided the Council with annual estimates of Kuskokwim River Chinook salmon run abundance as part of a broader index of Chinook salmon abundance to Western Alaska. The Council has used that information to inform Chinook salmon bycatch management in the Bering Sea pollock (*Gadus chalcogrammus*) fishery. ADF&G was required to notify the Council of any changes to the methods used to estimate Kuskokwim River Chinook salmon abundance[1].

[1] ADF&G provided the summary document to the Council on May 15, 2018. The Council and associated Scientific Steering Committee (SSC) discussed the model revisions at their June 2018 meeting held in Kodiak, AK. Based on recommendations from the SSC, the Council approved the use of the revised Kuskokwim River model for the purpose of the 3-river index under amendment 110. All documents regarding the Council decision can be found here: https://npfmc.legistar.com/LegislationDetail.aspx?ID=3486558&GUID=81056FD0-C9E8-4376-BD59-C2F6084C82E9&Options=ID|Text|&Search=Kuskokwim.

Both summary documents are presented herein for archival purposes and to facilitate referencing the details of the model review process, model revisions, and revised estimates until such time subsequent reports are published. With few exceptions, both documents are identical. The version drafted for general distribution (Appendix A) included revised estimates of total run and drainagewide escapement estimates. The version drafted for the Council (Appendix B) presented only revised total run estimates because only those estimates were relevant to Council process. However, the Council version contained additional background which explained the connection between the Kuskokwim River Run Reconstruction model and the Council process.

ACKNOWLEDGEMENTS

We thank the members of the AYKSSI Expert Panel (Daniel Schindler, Timothy Walsworth, Milo Adkinson, Randall Peterman, and André Punt) for their independent review of the Kuskokwim River Run Reconstruction Model. Their willingness to collaborate with the Kuskokwim River Interagency Model Development Team, share preliminary recommendations, and contribute model code dramatically improved the quality and efficiency of the model review. Their written memo detailing key preliminary finding proved to be an invaluable addition to the executive summary documents contained in this report. We also thank Mr. Joseph Spaeder, AYK SSI Research Coordinator, for his efforts to facilitate the independent review and ensure collaboration with the interagency team.

APPENDIX A: SUMMARY OF MODEL REVISIONS, PREPARED FOR GENERAL DISTRIBUTION

Executive Summary

Revisions to the Kuskokwim River Chinook Salmon Run Reconstruction Model

Drafted by:

Alaska Department of Fish and Game[1]

On behalf of the

Kuskokwim River Interagency Model Development Team

- Hamachan Hamazaki – Alaska Department of Fish and Game
- Gary Decossas – U.S. Fish and Wildlife Service, Office of Subsistence Management
- Dr. William Bechtol – Bechtol Research
- Dr. Matthew Catalano – Auburn University, Assistant Professor, School of Fisheries, Aquaculture and Aquatic Sciences

Prepared for general distribution

May 15, 2018

[1] Corresponding author – Zachary Liller, Research Coordinator, Arctic-Yukon-Kuskokwim Region, Division of Commercial Fisheries, Anchorage, AK. zachary.liller@alaska.gov. 907-267-2135

ADF&G is making changes to the model used to estimate total inriver abundance of Kuskokwim River Chinook salmon. This document summarizes the review process which led to the model revisions, presents the revised model, and presents revised total run and escapement estimates of Kuskokwim River Chinook salmon for years 1976–2017. Revised estimates presented here supersede previously published estimates. A full report will be published by the Kuskokwim River Interagency Model Development Team and made available by ADF&G.

For the purpose of this document, the model currently in use by ADF&G to estimate total run size of Kuskokwim River Chinook salmon will be referred to as the "current model". The revised model will be referred to as the "revised model".

Overview of Current Model

The Kuskokwim River Chinook salmon run reconstruction was published in 2012 (Bue et al. 2012) with subsequent revisions in 2014 (Hamazaki and Liller 2015). Estimates of annual inriver abundance and escapement are made using a maximum likelihood model developed for use in data-limited situations. The model combines information on subsistence harvest, commercial catch and effort, sport harvest, test fishery harvest and catch per unit of effort at Bethel, mark–recapture estimates of inriver abundance, counts of salmon at six weirs, and peak aerial counts from 14 tributaries spread throughout the Kuskokwim River drainage (Figure 1). Each of these data sources provides an index of total abundance. The model provides an approach to combine and weight available information about Kuskokwim River Chinook salmon abundance to arrive at a scientifically defensible estimate of total run size and escapement. Estimates produced by the model represent the most likely run size given the observed data. At the time of publication, the run reconstruction model represented a substantial advancement for Kuskokwim River salmon management by producing total run and escapement estimates for all years 1976–present. Since that time, ADF&G has endeavored to review model performance and make improvements as warranted.

Rationale for Model Updating

- ADF&G undertook a four-year effort (2014–2017) to generate independent estimates of drainagewide run size. Incorporation of these new data nearly doubles the amount of information used for model scaling and represents both record high and record low run sizes.
- The 2003–2005 independent estimates of total run size used to scale the current model were suspected to be biased high. ADF&G conducted validation studies in 2014–2016 and new information is available to improve model scaling.
- In recent years, there have been changes in the fishery management which affected salmon spawning distribution relative to the conditions upon which the model was originally based.
- The current model is highly sensitive to starting values and can produce multiple estimates of total run size depending on the starting values used in the model fitting process.
- Agency and independent expert panels have reviewed the current model and recommended changes to improve model stability and reduce complexity.

The following narrative provides more detailed information regarding the summary points highlighted above.

The current model is scaled using a relatively small number of independent estimates of run size from a narrow window of time (2003–2007) which corresponded to above average and record high abundance. In 2010, shortly after the data used to scale the current model was collected, Chinook salmon runs throughout much of Alaska, including the Kuskokwim, experienced a pronounced downturn in productivity resulting in record low abundances. In 2012, the ADF&G Chinook Salmon Research Team was formed and developed a plan with recommended studies to address questions that arose from the statewide decline in the abundance of Chinook salmon (ADF&G Chinook Salmon Research Team 2013). Specific to the Kuskokwim River, the Chinook Salmon Research Team recommended additional independent estimates of total abundance to evaluate performance of the current model during years of low abundance, which could be used if necessary to rescale the current model for improved estimation. This recommendation was consistent with the expectation by the original authors that the current model be periodically updated with new independent estimates of total run size (Bue et al. 2012).

Beginning in 2014, ADF&G undertook a three-year (2014–2016) effort to evaluate performance of the current model during years of low run abundance and develop additional independent estimates of the total run for model scaling purposes. Funding for this work was provided by the State of Alaska through the Chinook Salmon Research Initiative. An additional year of funding was provided in 2017 through Chinook Salmon Disaster Funds administered by the Pacific States Marine Fisheries Commission, which allowed for up to four consecutive years of evaluation and independent run estimates. In each of the four years, preliminary mark–recapture estimates aligned closely with the lower bound of the 95% confidence range surrounding the current model estimate (Liller and Hamazaki 2016; Liller 2017; Smith and Liller 2018). Over time, this consistent trend clearly indicated that the current model overestimated total run size in each of the four years, 2014–2017. On average, the annual preliminary mark–recapture estimates were 27% (42,000 fish) smaller compared to estimates produced from the current model in years 2014–2017 (Smith and Liller 2018). As such, rescaling the current model to improve performance during low abundance years was warranted.

Reduced performance of the current model in recent years was, in part, caused by changes in the fishery management which affected salmon spawning distribution relative to the conditions upon which the model was originally based. Low run sizes in recent years resulted in low escapement and stakeholder concerns about equitability of harvest. Since 2014, all salmon fishing in the mainstem Kuskokwim River has been closed during the early portion of the run in response to preceding years of low run abundance and subsequent year forecasts for below average run sizes.[1] The effect was a notable shift in historical harvest timing, reduced exploitation on early migrating Chinook salmon bound for upriver reaches of the drainage, and above average escapements recorded by the subset of weir and aerial survey projects used to index escapement to headwater tributaries. The current model assumes that the spatial distribution of spawning is stable over time, yet telemetric mark–recapture studies highlighted that headwater tributaries have received proportionally more escapement in recent years, likely due to changes in harvest timing (Head et al. 2017; Smith and Liller 2017a, 2017b, 2018). As a result, additional scaling was needed to address changes to fishery harvest.

The 2014–2017 mark–recapture experiments provided an opportunity to evaluate potential bias in the data from 2003–2007 used to scale the current model. In those years, total run scalars were developed by

[1] In 2016, the Alaska Board of Fisheries formalized the front end closure in regulation (5AAC 07.365) for the purpose of meeting escapement goals and providing harvest opportunity for upriver communities.

adding estimates of abundance from mark–recapture experiments conducted upriver from where the majority of the harvest occurs to all harvest and escapement downriver from the tag site. That approach required that ADF&G make an informed guess about escapement to three unmonitored tributaries in the lower river (Schaberg et al. 2012). The habitat-based methods used to estimate escapement to those unmonitored tributaries has long been suspected of overestimating true escapement to those systems. ADF&G combined telemetric and aerial survey methods to evaluate escapement distribution in the lower river. Results of this work showed that the habitat-based methods used by ADF&G likely overestimated escapement to unmonitored tributaries nearly two-fold. As such, revision to the 2003–2007 model scalars was warranted.

In addition to the above, ADF&G biometric staff, USFWS biometric staff, academic entities, and non-profit research organizations have had considerable opportunity to work with the model since it was published in 2012, share performance observations, and make recommendations to improve model performance. Data weighting (Staton et al. 2015) and model stability (Hamazaki and Liller 2015; Smith and Liller 2018) have been identified as issues that needed to be addressed. The current model estimates an over-dispersion parameter for each escapement index which acts as a way to weight data such that the most "reliable" projects have more influence on the model results. Staton et al. 2015 identified that this approach leads to the undesirable behavior that, at times, the current model will perfectly fit to a single index dataset and ignore all others. The authors demonstrated that pooling over-dispersion parameters by data type (i.e., air surveys, weirs) eliminated the potential extreme and undesirable behavior of the current model. The current model has also been shown to be sensitive to starting values and often does not converge to a single solution (Hamazaki and Liller 2015; Smith and Liller 2018). The source of this behavior is associated with the commercial catch and effort component of the current model and adjustments have been recommended to improve stability.

Model Review Process

Three complimentary model review efforts led to a set of recommended changes to the current model.

First, ADF&G staff from Division of Commercial Fisheries, Kuskokwim Area, carried out four consecutive years of telemetric mark–recapture studies and spawning ground surveys to evaluate model performance relative to independent estimates of abundance. Results showed that the current model scaling for years 2003–2007 was likely biased high and new information is now available to improve model scaling in those years. Furthermore, results showed that the current model has overestimated total run size in recent years. New independent estimates of total run size and associated uncertainties are now available to improve model scaling during years of low run abundance.

Second, in 2016, the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYKSSI) commissioned an independent expert review of the current model. The Panel's research questions were guided by some chief concerns about the current model that have either been reported by ADF&G or have been raised by stakeholders and previous explorations of the current model. A final review document will be drafted. The review panel summarized their research questions, approach, and recommendations in a memo to ADF&G (Appendix A).

The third step involved convening a Kuskokwim River Interagency Model Development Team (KRIMDT) to consider options for incorporating new abundance data from ADF&G, Division of Commercial Fisheries, and pending recommendations from the AYKSSI expert review panel. The KRIMDT consists of representatives from ADF&G, U.S. Fish and Wildlife Service Office of Subsistence Management, Bechtol Research, and Auburn University. The KRIMDT met with the AYKSSI review panel in Anchorage, AK in March 2018 to discuss preliminary review findings and recommendations for model improvement. The KRIMDT provided the AYKSSI review team with a revised model in April 2018. AYKSSI provided a cursory review of the revised model and a summary of basic performance metrics in Appendix A[2].

Data Updates and Model Changes

Changes to the current model include 1) changes to the data input, 2) software changes, and 3) structural changes. Changes were intended to ensure the most complete and accurate data were used, improve estimation of model parameters, improve model stability, and reduce complexity by reducing the number of estimated parameters. See Table 1 for more information about how the revised model differs from the current model.

Data Changes

1. An additional 4 years (2014–2017) of independent estimates of total run abundance were added. The revised model is now scaled with nine independent estimates of total run abundance representing both record high and record low run sizes.
2. Independent estimates of drainagewide run size from years 2003–2007 were adjusted to account for new information about the likely escapement to unmonitored tributaries in the lower river (Table 2).
3. Estimates of variance for the mark–recapture component of the annual model scalars (2003–2007) were recalculated using a closed-form solution.
4. Variance estimates for the annual scalars (2003–2007 and 2014–2017) were recalculated to account for additional uncertainty associated with tributary escapement monitoring and subsistence harvest estimation.
5. Annual estimates of total Chinook salmon escapement past the Kwethluk and Tuluksak weirs (used as model input) were recalculated using a hierarchical Bayesian estimation framework (e.g., Head and Smith 2018).
6. All weir and aerial survey data used as model input were reviewed and minor edits were made to ensure consistency with the ADF&G database (Smith and Liller 2018).
7. Annual CPUE from commercial harvest opportunities using restricted mesh 1976–1984 was removed from the model.

Software Changes

8. Modeling software changed from R (Optim) to ADMB.

[2] The “current model” as identified in the AYKSSI memo under Appendix A refers to a model format consistent with the current model described in this executive summary and used by ADF&G to estimate Kuskokwim River run size in 2014–2017. AYKSSI, however, used the updated data set and revised model scaling for years 2003–2007 as presented in this executive summary. As such, the estimates of annual run size presented in the AYKSSI memo do not match those presented by ADF&G in this or prior total run reports. For example, Smith and Liller (2018) presented notably higher estimates of total run size for 2017 because the old and uncorrected scalars were used.

Structural Changes

9. Lognormal likelihood was assumed for all data.
10. Variance was combined within each data type (weir, aerial, and commercial CPUE).
11. The revised model assumes a linear relationship between catch and effort. The model was fit to annual CPUE for each type of commercial fishery opportunity (Unrestricted and Restricted Mono filament 1985–2017).

Revised Model

Model code is provided in Appendix B. Model input data is provided in Appendix C.

Escapement Counts

Assuming that annual escapement of Chinook salmon returning to each tributary and observed by a weir or aerial survey is a constant fraction of drainagewide escapement (E_y), the expected escapement ($\hat{e}$) in year (y) to tributary (j) observed by method (i; weir or aerial) is:

$$\hat{e}_{ijy}=E_y/k_{ij}, \tag{2}$$

where k_{ij} is a scaling parameter estimated by the model.

Commercial Catch and Effort

Assuming that commercial catch per unit of effort (CPUE) occurring each week is proportional to the drainagewide run migrating during that week, the expected commercial catch CPUE ($CPUE_{wky}$) in week (w) with net configuration (k) is:

$$\widehat{CPUE}_{wky}=c_{wky}/f_{wky} = q_k\left(p_{wy}N_y\right). \tag{3}$$

Summing for all weeks and adjusting by the proportion of fish migrating during the weeks of fisheries, expected annual cumulative CPUE ($CPUE_{ky}$) is:

$$\widehat{CPUE}_{ky}=\frac{\sum_w (c_{wky}/f_{wky})}{\sum_w p_{wy}} = q_k N_y \text{ ,} \tag{4}$$

where:

$CPUE_{wky}$: commercial catch CPUE at week (w) of net configuration (k),
c_{wky}: commercial catch at week (w) of net configuration (k),,
f_{wky}: commercial efforts at week (w) of net configuration (k),,
p_{wy}: proportion of Chinook salmon available at week (w) observed at Bethel test fishery, and
q_k: catchability coefficient of net configurations (k) (i.e., unrestricted, restricted).

The proportion of Chinook salmon available for harvest each week and observed at Bethel Test Fishery included weeks 3–10. Data from weeks 8–10 were combined. Commercial catch and effort by week and net configuration included weeks 3–9. Data from weeks 8 and 9 were combined.

Likelihood Model

Assuming that all observations follow lognormal distributions, negative log likelihoods with omissions of constants were constructed as

$$L(\theta|data) = \begin{array}{l} \text{Escapement Counts} \\ +\sum_{y}\sum_{i}\sum_{j}\left(ln(\sigma_j) + 0.5\left(\frac{ln(\hat{e}_{ijy}) - ln(e_{ijy})}{\sigma_j}\right)^2\right) \\ \text{Adjusted Commercial CPUE} \\ +\sum_{y}\sum_{k}\left(ln(\sigma_k) + 0.5\left(\frac{ln(\widehat{CPUE}_{ky}) - ln(CPUE_{ky})}{\sigma_k}\right)^2\right) \\ \text{Drainagewide Run} \\ +\sum_{y}\left(0.5\left(\frac{ln(\hat{N}_y) - ln(N_y)}{\sigma_y}\right)^2\right). \end{array} \tag{5}$$

where $\sigma_j^2 = \ln(CV_j^2 + 1)$, $\sigma_k^2 = \ln(CV_k^2 + 1)$, and $\sigma_y^2 = \ln(CV_y^2 + 1)$.

CV_j and CV_k were estimated from the model, and CV_y was the observed CV of drainagewide run sizes of 2003–2007 and 2014–2017.

The model was written in AD Model Builder (Fournier et al. 2012).

Effect on Historical Time Series

Overall, the revised model resulted in smaller annual estimates of Kuskokwim River Chinook salmon run size compared to the current model (Table 3). Revised estimates decreased in 34 (81%) of 42 years (1976–2017) and increased in eight years (19%; Figure 2). The largest percent decrease (38%) occurred in 2014 and the largest percent increase occurred in 1980 (19%). On average, annual estimated abundance decreased by approximately 11% or about 14,800 fish. Historical trends in abundance were similar between the two models, showing three distinct periods of high abundance followed by periods of low abundance (Figure 3). Overall, drainagewide escapement estimates decreased on average by 14,800 (17%) across all years 1976–2017 (Table 4).

The most pronounced difference between the two models is specific to the most recent years, 2014–2017 (Figure 3). The revised model produced total run size estimates that are on average 45,000 fish (28%) smaller. The revised model includes additional independent estimates of total run size for each year 2014–2017 and, therefore, nearly double the information upon which to scale the total run estimate. Reduced performance of the current model in recent years was attributed to a combination of record low run sizes and resulting changes to the fishery management beyond the conditions upon which the current model was originally based. By incorporating new model scalars for years 2014–2017, the revised model is more informed for making historical estimates and is expected to perform better under the current run size and fishery management regime moving forward. In addition, the revised model is expected to perform better in the face of possible future shifts in productivity (Appendix A).

Regardless of the model used, runs to the Kuskokwim River in 2015–2016 showed signs of poor performance. While, escapement goals were generally achieved at the drainage and tributary levels, these results were largely due to substantial reductions in harvest (Table 5 and Figure 4). In each year, subsistence fisheries were heavily restricted, commercial fisheries did not occur, and sport fishing for Chinook salmon was closed.

ADF&G and the Kuskokwim River Interagency Salmon Model Development Team plan to continue to evaluate and improve the revised model. Initial discussions about timelines for subsequent reviews centered around a three-year cycle consistent with the Alaska Board of Fisheries process and the ADF&G escapement goal review. Kuskokwim Area stakeholders would be notified of any subsequent changes.

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Table 1. – Summary of 2018 model changes with rationales and comparative reference to the 2014 model.

Change Type	Revised Model	Current Model	Rationale
Data			
1	An additional 4 years (2014–2017) of independent estimates of total run abundance were added.	The model is currently scaled with 5 years (2003–2007) of independent estimates of total run abundance representing above average run sizes.	Additional scalars were added to improve model performance during years of low run size and to improve parameter estimation following recent changes to fishery harvest timing.
2	Independent estimates of drainagewide run size from years 2003–2007 were adjusted to account for new information about the likely escapement to unmonitored tributaries in the lower river.	As described in Schaberg et al. (2012), model scalars were developed as the sum of upriver mark–recapture estimates of abundance, harvest downriver of the tag site, and escapement downriver of the tag site. A total of 3 tributaries downriver of the tag site are not monitored and escapement to these systems was approximated using a habitat (drainage area) expansion.	Validation studies conducted in 2014–2016 indicated that the habitat expansion method likely overestimated escapement to unmonitored tributaries. As a result model scalars for years 2003–2007 were biased high by an average of 25,600 fish
3	Estimates of variance for the mark–recapture component of the annual model scalars (2003–2007) were recalculated using a closed-form solution. The closed form solution was also used for new mark–recapture estimates, 2014–2017.	Bootstrap methods (1,000 simulations) were used to estimate variance for the mark–recapture component of the annual model scalars.	Variance calculations differed over time for published mark–recapture estimates of total abundance. Bootstrap methods used in 2003–2007 overestimated variance; conversely, bootstrap methods used in 2014–2017 underestimate variance. The closed-form solution was recommended by the AYKSSI expert panel and was chosen as the most appropriate method to calculate variance for all years.
4	Variance estimates for the annual scalars (2003–2007 and 2014–2017) were recalculated to account for additional uncertainty associated with tributary escapement monitoring and subsistence harvest estimation.	Previous estimates incorporated weir counts and harvest without error.	
5	Standardized annual estimates of total Chinook salmon escapement past the Kwethluk and Tuluksak weirs (used as model input) were recalculated using a hierarchical Bayesian estimation framework.	Standardized annual estimates of missed passage were estimated using a variety of methods.	This change was to be consistent with the methods used by all other weirs project used to inform the model (e.g., Head and Smith 2018).

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Table 1. – Page 2 of 2.

Change Type		Revised Model	Current Model	Rationale
	6	All weir and aerial survey data used as model input were reviewed and minor edits were made to ensure consistency with the ADF&G database (Smith and Liller 2018).		Three errors were associated with aerial survey counts which were transposed upon entry. Five errors were new data entries of aerial survey counts from prior year data forms that had not been previously entered.
	7	Annual CPUE from commercial harvest opportunities using restricted mesh 1976–1984 was removed from the model.	Data were included.	These data were removed because, the model fit the restricted mesh data poorly; these data disagreed with other more reliable indices in the model; run timing proportions for this time period were unavailable and thus were assumed to follow the long-term average; and they were overly influential on the 1977 and 1980 run size estimates.
Software				
	8	Coded in ADMB	Coded in R (Optim)	The software change was intended to improve estimation of maximum likelihood parameters, mitigate extreme sensitivity to starting values, and reduce time needed for model convergence.
Structural				
	9	Lognormal likelihood was assumed for all data.	Previously, escapement data was assumed to follow a negative binomial distribution, drainagewide run size was assumed to follow a normal distribution, and commercial effort was assumed to follow a lognormal distribution (i.e., no change).	The lognormal distribution appropriately describes the residual variability in the model and there are no concern with obtaining zero observations. As such, the lognormal distribution is more appropriate for these types of data. Assuming a lognormal distribution for all data facilitated computation and interpretation of model parameters.
	10	Variance was combined within each data type (weir, aerial, and commercial CPUE).	A separate dispersion parameter was estimated for each escapement assessment location and the concentrated likelihood function was used or commercial effort to eliminate the need for estimation of variance.	This change reduced model complexity and was intended to prevent the model from potentially overfitting to a single assessment project.
	11	The revised model assumes a linear relationship between catch and effort. The model was fit to annual CPUE for each type of commercial fishery opportunity (Unrestricted and Restricted Mono filament 1985–2017).	The current model assumed a nonlinear relationship between catch and effort. In addition, the current model assumes and that commercial catch and weekly run proportions indexed at the Bethel Test Fishery are known without error.	Fitting to annual CPUE assumes errors in catch, effort, and run proportion, and are thus more true to the nature of the observations. This change mitigated the extreme sensitivity to starting values.

Table 2. – Independent estimates of total abundance of Kuskokwim River Chinook salmon used to scale the maximum likelihood model.

	Current Scalars				Revised Scalars						Absolute Percent
Year	Abundance	95% CI		CV	Abundance	95% CI		CV		Difference	Difference
2003	241,617	182,710	326,202	15%	222,145	194,022	256,158	7%		-19,472	8%
2004	422,657	298,728	577,993	17%	381,958	317,206	459,919	10%		-40,699	10%
2005	345,814	270,560	453,516	13%	312,353	273,580	356,522	7%		-33,461	10%
2006	396,248	281,847	528,218	16%	376,291	320,175	441,427	8%		-19,957	5%
2007	266,219	211,280	340,445	12%	251,781	221,515	284,956	6%		-14,438	5%
									Avg.	-25,605	8%
2014					80,399	64,782	98,931	11%			
2015					124,421	107,672	144,367	8%			
2016					131,090	107,907	157,543	10%			
2017					133,292	105,765	166,967	12%			

Note: Independent estimates are based on a combination of mark–recapture estimates of abundance, harvest downriver from the tag site, and escapement downriver from the tag site. Scalar revisions for years 2003–2007 incorporate new information about escapement to select tributaries downriver from the tag site. Prior methods were shown to overestimate escapement and total run.

Table 3. – Comparison of published and revised total run size estimates for Kuskokwim River Chinook salmon based on the current model (Bue et al. 2012; Hamazaki and Liller 2015) and the revised model.

	Current Model		Revised Model			Absolute Percent
Year	Total Run	CV	Total Run	CV	Difference	Difference
1976	233,967	13%	187,584	13%	-46,383	20%
1977	295,559	13%	348,824	18%	53,265	18%
1978	264,325	12%	241,781	12%	-22,544	9%
1979	253,970	16%	233,787	17%	-20,183	8%
1980	300,573	15%	357,950	25%	57,377	19%
1981	389,791	14%	308,660	16%	-81,131	21%
1982	187,354	9%	173,072	9%	-14,282	8%
1983	166,333	12%	148,278	10%	-18,055	11%
1984	188,238	14%	171,853	12%	-16,385	9%
1985	176,292	14%	143,568	10%	-32,724	19%
1986	129,168	11%	123,452	15%	-5,716	4%
1987	193,465	15%	186,184	13%	-7,281	4%
1988	207,818	9%	204,824	7%	-2,994	1%
1989	241,857	9%	214,081	10%	-27,776	11%
1990	264,802	9%	266,353	8%	1,551	1%
1991	218,705	10%	210,525	9%	-8,180	4%
1992	284,846	10%	259,154	7%	-25,692	9%
1993	269,305	11%	274,830	10%	5,525	2%
1994	365,246	14%	411,724	14%	46,478	13%
1995	360,513	11%	371,079	11%	10,566	3%
1996	302,603	14%	307,072	12%	4,469	1%
1997	303,189	13%	295,259	10%	-7,930	3%
1998	213,873	13%	184,356	13%	-29,517	14%
1999	189,939	12%	158,770	11%	-31,169	16%
2000	136,618	9%	129,138	7%	-7,480	5%
2001	223,707	11%	205,152	9%	-18,555	8%
2002	246,296	10%	226,106	8%	-20,190	8%
2003	248,789	9%	232,282	6%	-16,507	7%
2004	388,136	10%	366,725	6%	-21,411	6%
2005	366,601	9%	326,904	5%	-39,697	11%
2006	307,662	10%	326,067	6%	18,405	6%
2007	273,060	8%	244,754	5%	-28,306	10%
2008	237,074	9%	219,709	6%	-17,365	7%
2009	204,747	10%	189,370	7%	-15,377	8%
2010	118,507	8%	112,975	5%	-5,532	5%
2011	133,059	10%	113,749	6%	-19,310	15%
2012	99,807	14%	79,238	10%	-20,570	21%
2013	94,166	7%	84,311	5%	-9,855	10%
2014	135,749	15%	84,326	8%	-51,423	38%
2015	172,055	16%	125,058	6%	-46,997	27%
2016	176,916	16%	128,855	7%	-48,061	27%
2017	166,863	13%	133,267	8%	-33,596	20%
				Average	-14,775	11%

Source: Bue et al. 2012; Hamazaki and Liller 2015; Liller and Hamazaki 2016; Liller 2017; Smith and Liller 2018.

Table 4. – Comparison of published and revised total escapement estimates for Kuskokwim River Chinook salmon based on the current model (Bue et al. 2012; Hamazaki and Liller 2015) and the revised model.

	Current Model	Revised Model		Absolute Percent
Year	Total Escapement	Total Escapement	Difference	Difference
1976	143,420	97,037	-46,383	32%
1977	201,852	255,117	53,265	26%
1978	180,853	158,309	-22,544	12%
1979	157,668	137,485	-20,183	13%
1980	203,605	260,982	57,377	28%
1981	279,392	198,261	-81,131	29%
1982	80,353	66,071	-14,282	18%
1983	84,188	66,133	-18,055	21%
1984	99,062	82,677	-16,385	17%
1985	94,365	61,641	-32,724	35%
1986	58,556	52,840	-5,716	10%
1987	89,222	81,941	-7,281	8%
1988	80,055	77,061	-2,994	4%
1989	115,704	87,928	-27,776	24%
1990	100,614	102,167	1,553	2%
1991	105,589	97,377	-8,212	8%
1992	153,573	127,881	-25,692	17%
1993	169,816	175,319	5,503	3%
1994	242,616	289,094	46,478	19%
1995	225,595	236,161	10,566	5%
1996	197,092	201,561	4,469	2%
1997	211,247	203,878	-7,369	3%
1998	113,627	84,140	-29,487	26%
1999	112,082	80,940	-31,142	28%
2000	65,180	60,905	-4,275	7%
2001	145,232	126,677	-18,555	13%
2002	164,635	144,445	-20,190	12%
2003	180,687	164,180	-16,507	9%
2004	287,178	266,084	-21,094	7%
2005	275,598	235,901	-39,697	14%
2006	214,004	232,409	18,405	9%
2007	174,943	146,637	-28,306	16%
2008	128,978	111,613	-17,365	13%
2009	118,478	103,101	-15,377	13%
2010	49,073	43,541	-5,532	11%
2011	72,097	49,718	-22,379	31%
2012	76,074	55,746	-20,329	27%
2013	47,315	36,823	-10,492	22%
2014	123,987	72,560	-51,427	41%
2015	155,464	108,454	-47,010	30%
2016	145,718	97,640	-48,078	33%
2017	150,193	116,597	-33,596	22%
			-14,761	17%

Source: Bue et al. 2012; Hamazaki and Liller 2015; Liller and Hamazaki 2016; Liller 2017; Smith and Liller 2018.

Table 5.– Summary of Kuskokwim River Chinook salmon escapement and harvest, 2008–2017. Grey shading indicates escapements or harvests which were below established goal ranges.

	Goal Range [a]		Escapement / harvest									
System	Lower	Upper	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Escapement												
Kuskokwim River (Current model)	65,000	120,000	128,978	118,478	49,073	72,097	76,074	47,315	123,987	155,464	145,718	150,193
Kuskokwim River (Revised Model)	65,000	120,000	111,613	103,101	43,541	49,718	55,746	36,823	72,560	108,454	97,640	116,597
Kogrukluk River	4,800	8,800	9,750	9,528	5,812	6,731	NA	1,819	3,732	8,081	7,056	9,992
Kwethluk River	4,100	7,500	5,275	5,744	1,669	4,079	NA	845	3,187	8,162	7,619	7,429
George River	1,800	3,300	2,563	3,663	1,498	1,547	2,201	1,292	2,993	2,282	1,663	3,685
Kisaralik River	400	1,200	1,074	NS	235	NS	588	599	622	709	622	NS
Aniak River	1,200	2,300	3,222	NS	NS	NS	NS	754	3,201	NS	718	1,781
Salmon River (Aniak R)	330	1,200	589	NS	NS	79	49	154	497	810	NS	423
Holitna River	970	2,100	NS	NS	NS	NS	NS	532	NS	662	1,157	676
Cheeneetnuk River (Stony R)	340	1,300	290	323	NS	249	229	138	340	NS	217	660
Gagaryah River (Stony R)	300	830	177	303	62	96	178	74	359	19	135	453
Salmon River (Pitka Fork)	470	1,600	1,033	632	135	767	670	469	1,865	2,016	1,578	687
Harvest												
Subsistence	67,200	109,800	98,103	78,231	66,056	62,368	22,544	47,113	11,234	16,124	30,693	16,380
Commercial	NA		8,865	6,664	2,732	747	627	174	35	8	0	0
Sport	NA		708	904	354	579	0	0	0	0	0	0

[a] Refers to established escapement goal ranges for the entire Kuskokwim River drainage and select spawning tributaries. The Kuskokwim River drainagewide escapement goal was established in 2013.Subsistence harvest range refers to the Amounts Reasonably Necessary for Subsistence uses (ANS) as defined by the Alaska Board of Fisheries 5AAC 01.286. The ANS range was 64,500–83,000 during 2001–2012, but revised in 2013 to the range shown.

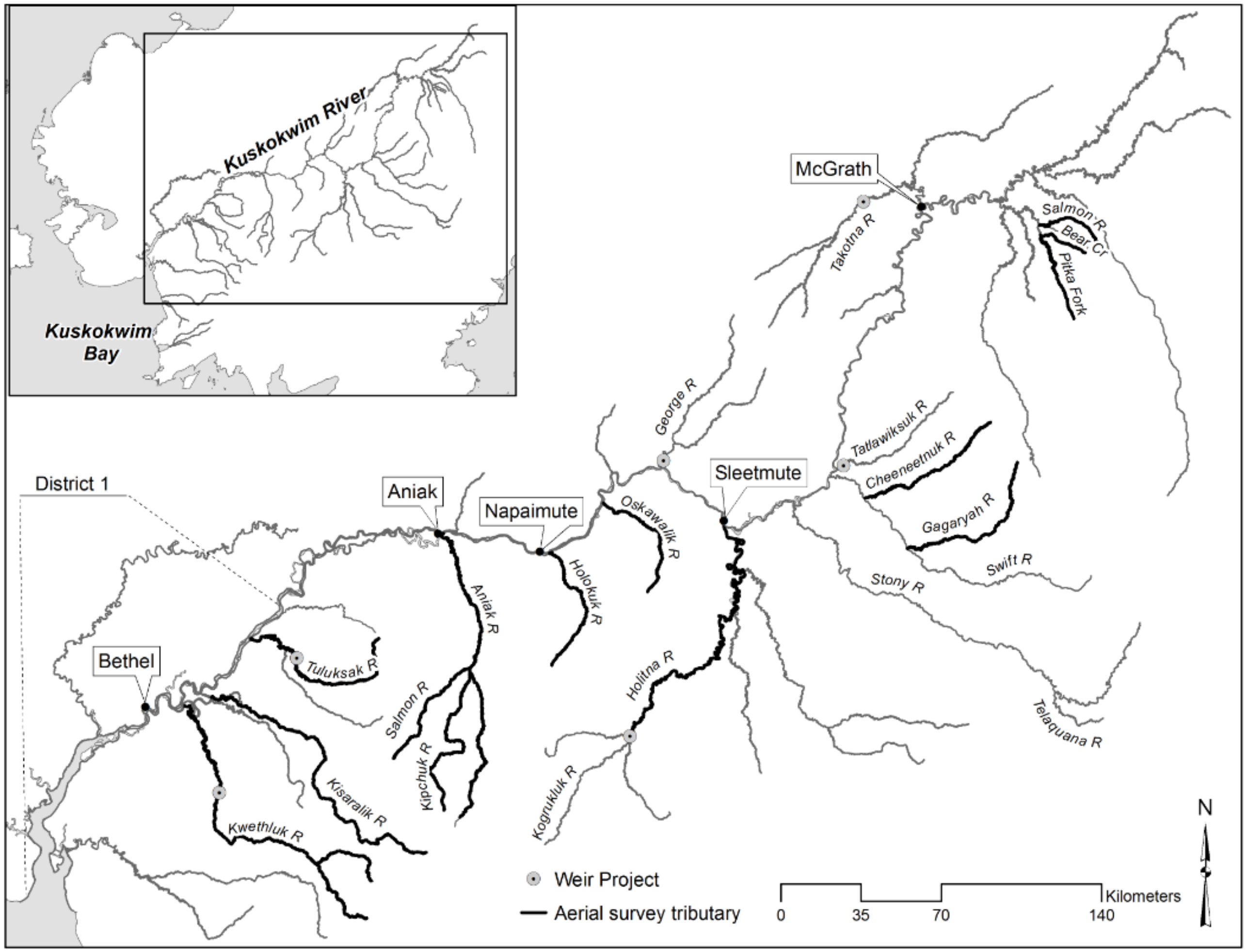

Figure 1.–Kuskokwim River drainage and location of major communities, commercial fishing district, and monitored tributaries. Estimates of total annual inriver abundance and escapement are made using a maximum likelihood model developed for use in data-limited situations. The model combines information on subsistence harvest, commercial catch and effort, sport harvest, test fish harvest and catch per unit of effort at Bethel, counts of salmon at 6 weirs, and peak aerial counts from 14 tributaries spread throughout the Kuskokwim River drainage, and independent estimates of total inriver abundance.

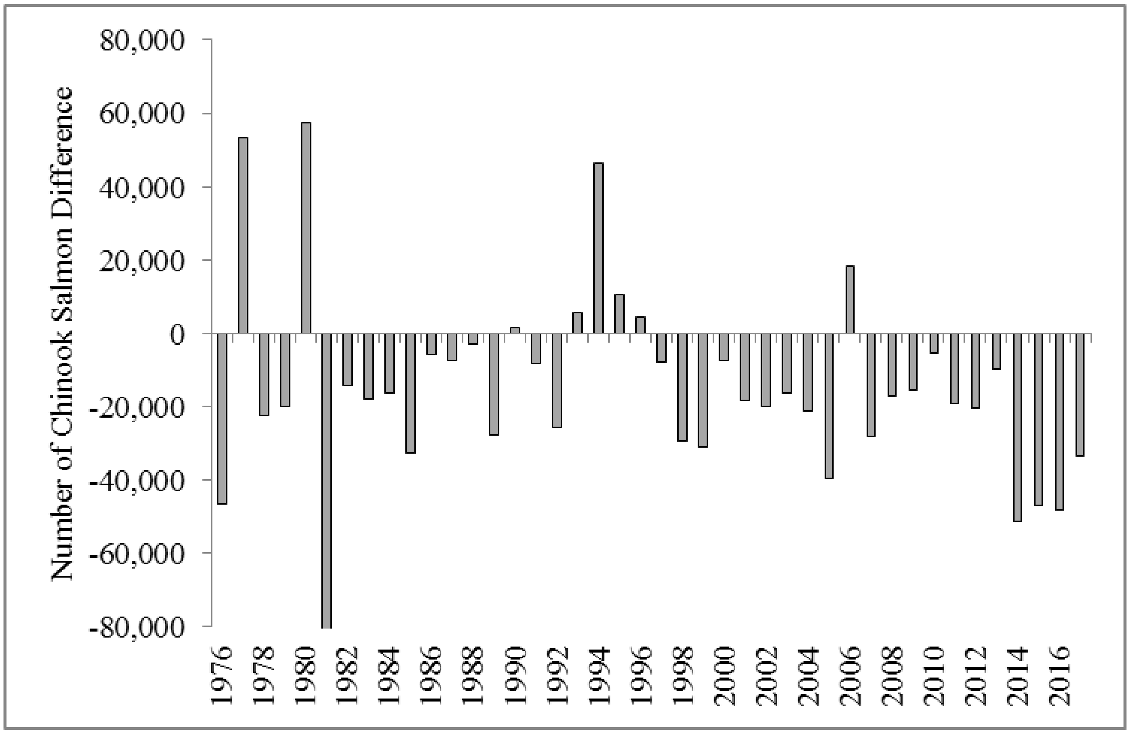

Figure 2. –Difference in the number of Chinook salmon estimated using the revised model compared to the current model.

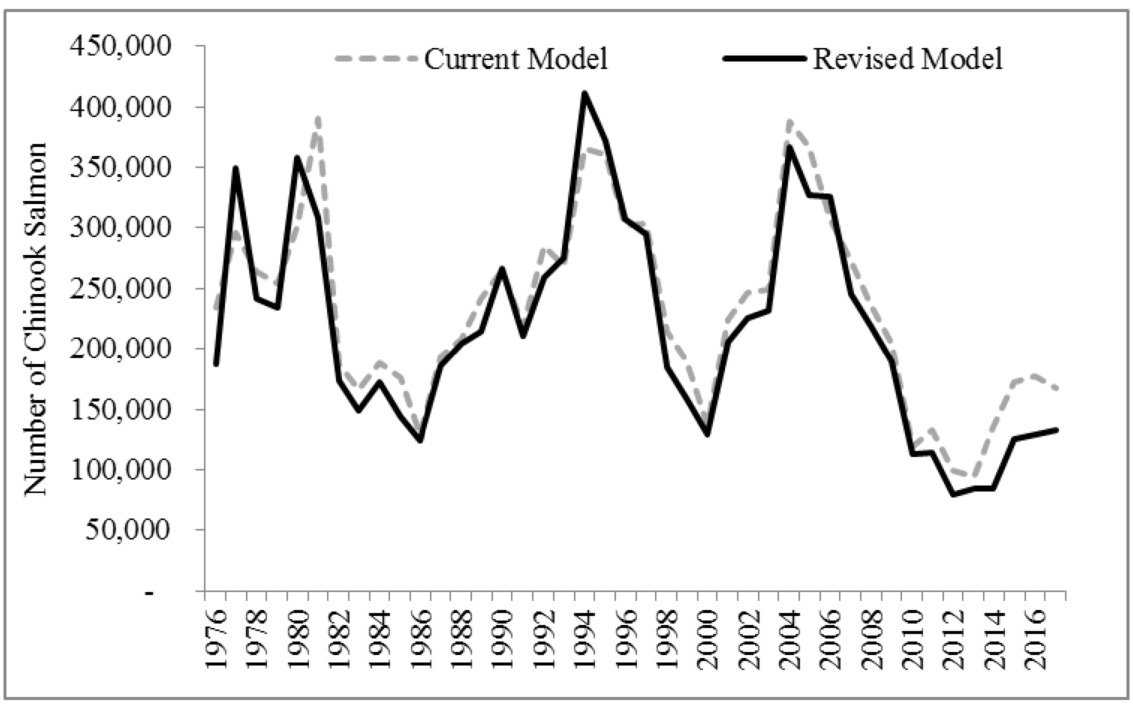

Figure 3.– Total abundance of Kuskokwim River Chinook salmon estimated using the revised model and current model.

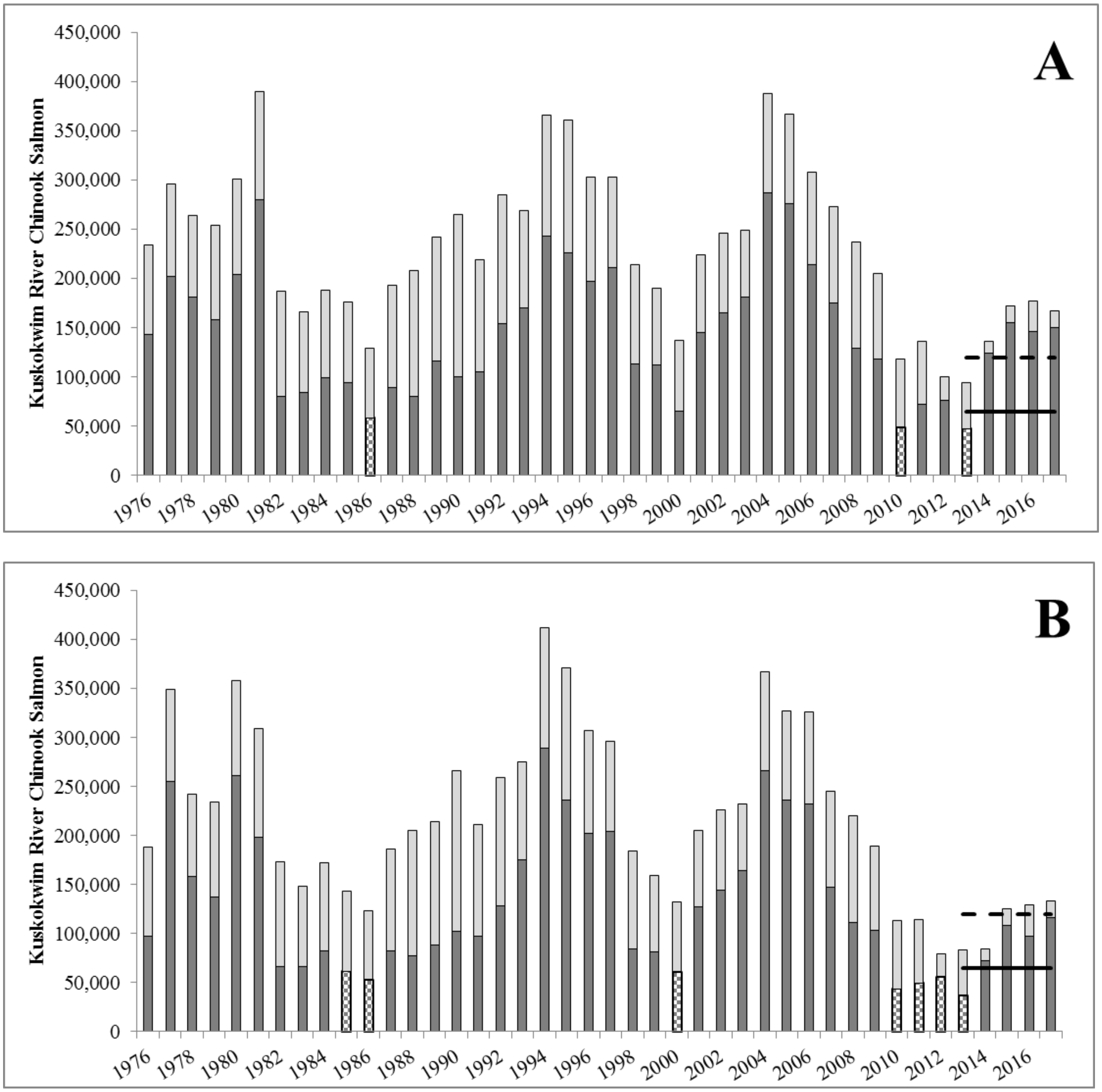

Figure 4.– Total run size of Kuskokwim River Chinook salmon based on the A) current model and B) revised model. Total run size is the sum of drainagewide escapement (dark gray bars) and total harvest (light gray bars). The drainagewide escapement goal of 65,000 (black solid line) to 120,000 (black dashed line) was established in 2013 using estimates produced by the current model. Escapements smaller than 65,000 fish are highlighted with a checkered pattern.

Appendix A.

Memo

The following memo was submitted by an independent expert review panel commissioned by the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYKSSI). Numbers presented in this memo do not match exactly those presented in this executive summary or past ADF&G reports. Results of the “current” model as presented by the AYKSSI expert panel are based on the updated dataset for all years and the revised model scalars for years 2003–2007. As such, the estimates are different than those presented in the executive summary and recent publications which used uncorrected data. Results of the “revised” model as presented by the AYKSSI expert panel differ slightly from those presented in the executive summary. The AYKSSI expert panel was provided with a preliminary version of the revised input dataset and model code. The input data was later corrected by ADF&G; specifically, the 2005 model scalar was changed from 311,516 (sd = 21,428) to 312,353 (sd = 21,083). The model code was updated to correct a typo in the variance term of the inriver likelihood, from square(log(square(inriv_sd(i)/inriv(i))+1)) to log(square(inriv_sd(i)/inriv(i))+1). This typo had little effect on the point estimates, but caused the model to fit the inriver abundance estimates almost exactly and underrepresented the model variance for years when mark-recapture data were available.

MEMO

DATE: May 10, 2018

TO: Zachary Liller, Research Coordinator, Arctic-Yukon-Kuskokwim Region, Alaska Department of Fish & Game, Division of Commercial Fisheries, Anchorage, Alaska

FROM: Expert Panel to evaluate Kuskokwim River Chinook salmon run reconstruction and stock-recruit models commissioned by the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYK-SSI).

Daniel Schindler, Professor, University of Washington, School of Aquatic and Fishery Sciences

Timothy Walsworth, Post-Doctoral Researcher, University of Washington, School of Aquatic and Fishery Sciences

Milo Adkison, Professor, College of Fisheries and Ocean Sciences, University of Alaska Fairbanks

Randall Peterman, Professor School of Resource and Environmental Management, Simon Fraser University

André Punt, Professor, University of Washington, School of Aquatic and Fishery Sciences

SUBJECT: Preliminary assessment of revised run reconstruction model for Chinook salmon in the Kuskokwim River

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Introduction

Stocks of Chinook salmon returning to the Kuskokwim River are among the most abundant in Alaska but have shown downturns in the recent decade, resulting in closed commercial fisheries and hardship for subsistence fisheries in communities throughout the watershed. Stock assessments are particularly challenging in this large and remote river system because it is expensive and logistically difficult to detect and enumerate adult fish migrating from the ocean back to a complex network of spawning habitat distributed among the many tributaries of this river. A run reconstruction model is used by the Alaska Department of Fish & Game (ADF&G) to integrate among a variety of indices of abundance, including: aerial surveys of spawning fish in headwater tributaries, counts of fish passing weirs on tributaries, and commercial catch rates in the lower river. Additionally, in some years, mark-recapture experiments are performed to estimate river-wide population abundance and provide a means for scaling from abundance indices to whole-system estimates in years where mark-recapture studies have not been done.

In response to concerns from a variety of stakeholders about the performance of the ADF&G run reconstruction model, the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYK-SSI) commissioned an independent panel of experts (hereafter Expert Panel), with considerable experience in salmon ecology and stock assessment, to review the structure and performance of the ADF&G's current published run reconstruction model (Bue et al 2012; hereafter 'current model'). The Expert Panel was assembled in 2016 and, combined with the work of a statistical analyst, initiated a collaborative review with the ADF&G to assess the performance of the current ADF&G run reconstruction model.

The Expert Panel used two approaches to assess the performance of the ADF&G run reconstruction model for Chinook salmon on the Kuskokwim River: (1) fitting the run reconstruction model to the observed data supplied by ADF&G, but with various modifications to that model's structure, and (2) fitting ADF&G's current run reconstruction model, including modified versions of it, to simulated data sets where the parameter values and run sizes are specified to simulate alternative plausible states of nature for the Kuskokwim River. A limitation of examining model performance on observed data is that the true state of the system is never known, and so there is no way to assess whether the model is actually capturing the true underlying dynamics in the system. Simulations allow for testing the model under various scenarios while being able to compare model fits to true values (Hilborn and Walters 1992).

The Expert Panel tested the current run reconstruction model in several ways to assess its sensitivity to the starting values for the parameters, to underlying assumptions about Chinook salmon population dynamics, and to the types and amounts of data used to estimate the model parameters. A thorough summary of these results will be available in a forthcoming Expert Panel Review expected to be completed in late May 2018. However, the primary conclusions of the Expert Panel were communicated at a collaborative workshop with ADF&G staff and their Kuskokwim River Interagency Chinook Salmon Run Reconstruction Model Development Team in March 2018, and a list of primary recommendations were made to improve model performance. In particular, the Expert Panel was concerned with:

a) <u>Lack of stability of the current run reconstruction model</u> as demonstrated by its tendency to arrive at multiple solutions for the best values for the parameters of the model, depending on the starting values used in the model fitting process. Further investigation by the Expert Panel suggested that this instability derived from (1) an improperly specified harvest sub-model, and (2) over-parameterization of the escapement indices used to inform the model.

b) <u>Sensitivity of model estimates to inclusion of recent (2014-2017) mark-recapture data</u>. The run reconstruction model produced substantially different estimates of historical run sizes when recent mark-recapture estimates were either used, or not, to anchor the run reconstruction effort.

c) <u>Error structure</u>. The current model assumed a normal distribution for errors associated with the total run estimate derived from the mark-capture data and the Panel thought this would be better assumed to be log-normally distributed. The current model assumed that errors associated with the individual escapement indices were distributed according to a negative binomial distribution, and each individual index site was assigned its own over-dispersion parameter. The Panel concluded that these errors should instead be assumed to be log-normally distributed and that the variances should be pooled by index type (i.e., one describing weirs and one describing aerial survey sites) to reduce the model complexity.

Following the Expert Panel's collaborative workshop in March 2018, ADF&G revised the run reconstruction model to account for several mutually agreed-upon revisions that the Panel suggested for improving model performance (Table 1).

Table 1. Comparison between current and revised model structures for ADF&G Kuskokwim River Chinook salmon run reconstruction model, as of May 1, 2018.

Component	Current Model	Revised Model
Total Run Error Structure	Normal	Log-normal
Escapement Index Error Structure	Negative Binomial	Log-normal
Number of Escapement Error Parameters	One for each index site (20 total)	One for each type of index (2 total)
Harvest Component	Saturating relationship with effort: Catch ~ Run * (1-exp(-Effort*catchability))	Linear relationship with effort: Catch ~ Effort * catchability * Run

At the request of ADF&G, the Expert Panel performed a preliminary assessment of the performance of the revised run reconstruction model that was provided by ADF&G to the Panel on May 1, 2018. The purpose of this memo is to describe the results of this preliminary assessment. Given the short time frame, the Expert Panel was not able to perform an exhaustive assessment of the revised model but, instead, focused on a manageable number of critical concerns that emerged from the review of the current model as described above. For the purposes of this memo, we refer to the original model as the 'current model' and the revised model as the 'revised model'. In reality, the core structure of these two models is fundamentally the same, but certain components have been revised in the new model provided on May 1, 2018.

Assessment of the revised model with historical observed data

Model stability

The revised model showed substantially improved stability compared to the current model as shown by less sensitivity to starting values for the initial run size (inset panels in Figure 1). While the current model settled on several local minima across the run reconstruction times-series (Figure 1 bottom panels), with and without the recent (2014-2017) mark-recapture data, the new model produced a single solution when all recent mark-recapture data were integrated into the run reconstruction (Figure 1, top right panel). The new model produced one renegade solution when the recent mark-recapture data were not used in the run reconstruction model (Figure 1, top left panel), but otherwise converged on a single solution.

Based on these preliminary analyses, it appears that model stability was substantially improved by the combination of simplifying the error structure by pooling many of the parameters and changing the harvest component of the model. While the revised model still showed some worrisome local minima when recent mark-recapture data were not included (Fig. 1 top, left panel), the revisions seem to have distinctly improved model stability, particularly when recent (2014-207) mark-recapture data are used in the run reconstruction. For future revisions to the model, the Expert Panel strongly recommends that ADF&G conduct simulation tests such as these to determine whether the run reconstruction model is sensitive to starting conditions. That procedure would examine model fits across a range of starting parameter values to ensure that a global minimum is found.

Influence of recent mark-recapture data

Mark-recapture estimates of river-wide abundance are needed to scale up from the miscellaneous escapement indices (i.e., weirs and aerial surveys of tributaries), which are assumed to quantify relative trends in abundance, to river-wide estimates of abundance. The Expert Panel noted that the run reconstruction estimates derived from using the current model were highly sensitive to the inclusion of recent (2014-2017) mark-recapture estimates of total river-wide abundance. The revised model remains sensitive to the inclusion of these data (Figure 2), though to a lesser degree than the current model. While the historical changes in abundance estimated from the current and revised models, with differing numbers of years of mark-recapture data, all generally followed the same coarse-scale changes through time, there were some notable discrepancies produced in certain years. In particular, the revised model generally tended to estimate lower total abundance of Chinook salmon between 2014-2017 than the current model did without using recent mark-recapture data for those years, but about the same as when the current model was fit using those data (Figure 2). Regardless, these differences in estimates were relatively small. The revised model also estimated the peak abundance observed in 1990s at more than 400,000 Chinook salmon while the current model estimated abundances almost 50,000 fish lower.

We further explored the sensitivity of the revised run reconstruction model to the inclusion of recent mark-recapture data by varying the number of years of mark-recapture data between 2014 and 2017 used in the run reconstruction. Given that there are no mark-recapture studies planned for 2018 and the following few years, this exercise is one way to assess how robust future estimates might be in years immediately following a series of mark-recapture estimates of river-wide abundance.

From 2010 – 2017, the revised model using all mark-recapture estimates during 2014-2017 estimated between a high of 133.3 thousand fish in 2017 to a low of 79.4 thousand fish in 2012 (Table 2a, right panel). When all four years of recent mark-recapture data were used in the run reconstruction, the deviations of the current model from the revised model estimates tended to be <5%, except for in 2014 when the current model estimated about 12% more fish in the river than was estimated by the revised model (Table 2, right panels).

By comparison, when no new mark-recapture data were used, the current model tended to overestimate the number of fish in the river from 2010-2017 compared to estimates produced by the revised model with all mark-recapture data. The estimates produced from the current model without new mark-recapture data tended to be <10% different from estimates with the revised model and all mark-recapture data. The one exception was 2014 when the current model estimated > 30% more fish than the revised model with all mark-recapture data. By comparison, the revised model without mark-recapture data produced estimates of total abundance that tended to be <5% different from estimates of the revised model fit with all of the mark-recapture data, except for in 2014 where the revised model without mark-recapture data estimated about 14% more fish than the revised model with all the mark-recapture data. The large error in 2014 appears to have been produced by abnormally high counts at two of the weir sites.

Assuming that run-size estimates from the revised model with all recent mark-recapture data are the closest to the true values, estimation accuracy of ADF&G's revised model decreased as fewer years of mark-recapture data were included in the run reconstruction (Table 3). However, these deviations tended to be small, and were typically <5% different from estimates generated by the revised model with all years of mark-recapture data (Table 3b). The one exception to this pattern was in the revised model's estimates of total run size for 2014, when produced without using any mark-recapture data, or when only the most recent (2015-2017) three years of data were used. These estimates were about 13% higher (>10,000 fish) than the estimates produced by the revised model based on all the recent (2014-2017) mark-recapture data. When mark-recapture data were used starting in 2014 (Table 3, three right-most columns), deviations from the situation where all years of mark-recapture data were used were negligible (<3%). Thus, the revised model remains sensitive to the inclusion of recent mark-recapture data, but less so than the current model. The model is particularly sensitive to exclusion of mark-recapture from years with unusual escapement patterns (which drive large estimation errors, e.g., 2014), but these years are more likely to be captured when mark-recapture studies are undertaken with increasing frequency. Further, the model appears to provide robust estimates of river-wide abundance in the years immediately following a mark-recapture experiment, although the analyses we have used to quantify this are very preliminary

Assessment of the revised model performance based on simulated data

We used a simulation model (documented in detail in the Expert Panel's upcoming final report) to generate data that would produce a reasonable approximation to the dynamics observed in Chinook salmon in the Kuskokwim River. The simulation model assumed that there was considerable population structure such that the aggregate dynamics were composed of the sum of the dynamics of 40 individual stocks, 20 of which were monitored for escapement. Covariation among stocks was assumed to be relatively weak, as demonstrated by the lack of synchrony among annual weir counts and among aerial surveys. The model also simulated 'productivity regimes', whereby the per capita productivity at low population sizes could increase by 500% (or decrease by 80%) roughly every 20 years. The model then 'sampled' the data at the intensity that has actually been performed in the Kuskokwim River over the last four decades (data become more sparse farther back in time; see Figure 4 x-axis).

Because we know what the 'real' abundances are in the model simulations, we can assess how well ADF&G's revised and current run reconstruction models perform in capturing these values under a variety of assumptions about the nature of the population dynamics and the intensity of sampling. In particular, we were interested in the influence of mark-recapture studies on model performance, and how the presence of regime shifts in population productivity affected model performance.

The revised model performed better than the current model in estimating the true abundance of Chinook salmon in simulated data (Figure 3); these improvements were particularly prominent in simulations where no new mark-recapture data were included in the run reconstructions. In the absence of regime dynamics and when no mark-recapture data were included, model performance (measured by the normalized root mean squared error, NRMSE) was substantially better for the revised model compared to the current model. However, with new mark-recapture data included, the difference in the NRMSE produced by the two models was negligible. In simulations with regime changes, the revised model performed about as well (as indicated by the NRMSE), regardless of whether new mark-recapture data were included, and the frequency distributions of errors were only slightly wider in situations with regime shifts than without those shifts, regardless of whether new mark-recapture data were included in the run reconstructions (Figure 3).

Inspection of time-series of the relative errors produced by the current and the revised model through time reinforces the conclusion that the performance of the revised model still depends on inclusion of recent mark-recapture data in the run reconstructions, but less so than the current model (Figure 4). As expected, the magnitude of the errors of model predictions increases as you proceed backwards through time and the coverage of escapement sampling decreases. Inclusion of recent mark-recapture data tended to reduce errors in the most recent decade of the analysis, though the revised model had distinctly smaller errors than the current model during the last decade for simulations where new mark-recapture data were not included in the run reconstruction.

Summary

Revisions to the ADF&G run reconstruction model for Chinook salmon on the Kuskokwim River appear to have remedied several of the primary concerns of the AYK-SSI Expert Panel. In particular, the revised model is far more stable than the current model, though its stability still depends on the inclusion of recent mark-recapture data for scaling up from individual abundance indices to river-wide abundance estimates. The revised model also appears to provide more accurate run estimates than the current model, particularly for years when no mark-recapture data are available for scaling up to river-wide abundances. More analyses are required to further assess how robust the model is, particularly in situations where abundance indices from tributary weirs or aerial surveys are omitted from the Kuskokwim monitoring program.

References

Bue, B. G., K. L. Schaberg, Z. W. Liller, and D. B. Molyneaux. 2012. Estimates of the historic run and escapement for the Chinook salmon stock returning to the Kuskokwim River, 1976–2011. Alaska Department of Fish & Game, Fishery Data Series No. 12-49, Anchorage.

Hilborn, R., and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics, and Uncertainty. Chapman Hall. New York.

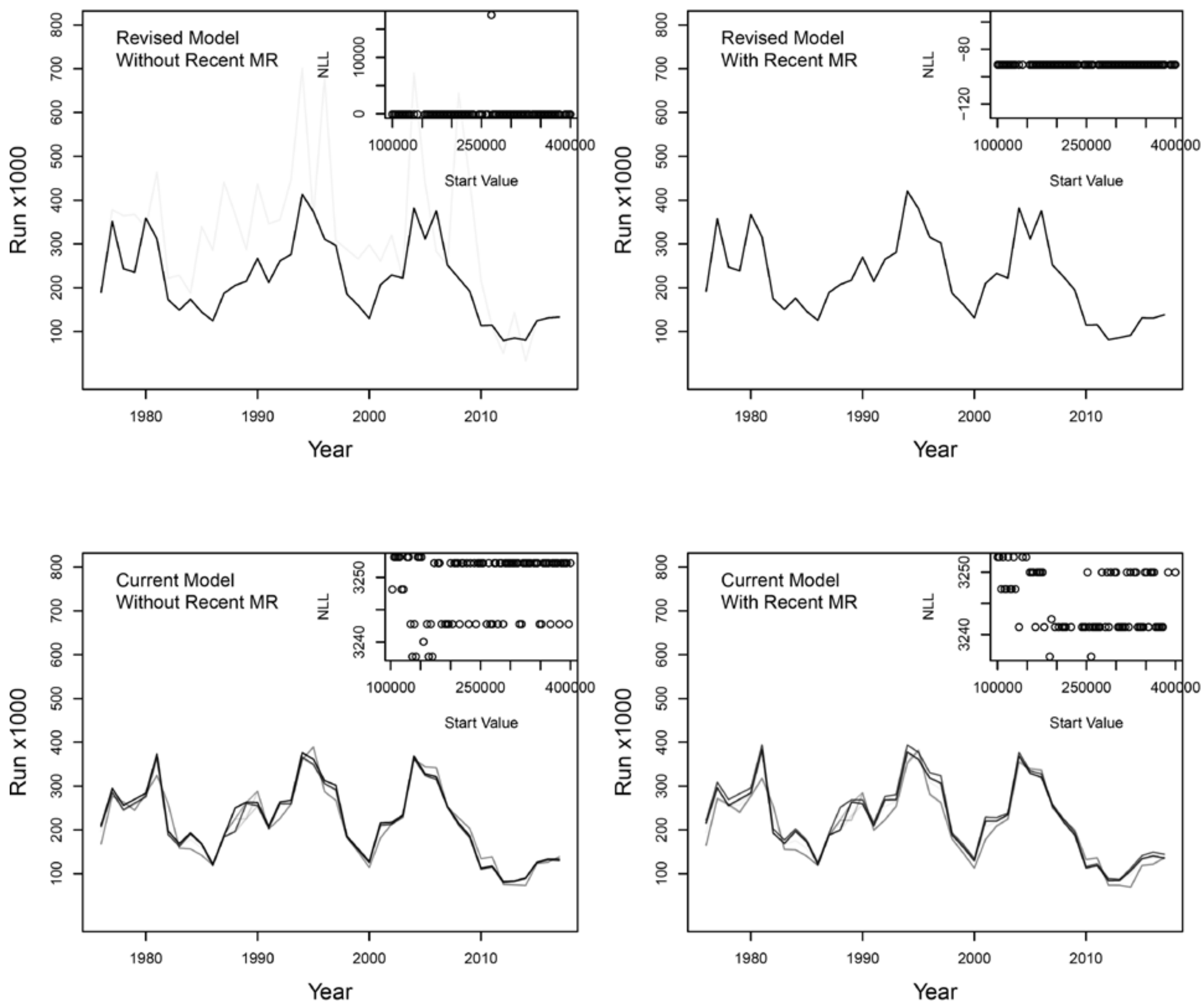

Figure 1. Run size estimates for Chinook salmon in the Kuskokwim River across a range of starting values from the revised run reconstruction model (top row) and current run reconstruction model (bottom row), and with different amounts of mark-recapture data available (no recent (2014-2017) estimates in left column, all recent estimates in right column). Semi-transparent grey lines represent individual model fits (out of 100 total). Black lines indicate stacked grey lines, representing repeated model convergence on the same values. Inset figures represent the negative log-likelihood values of model fits across the range of starting values of the run-size examined for the initial run size.

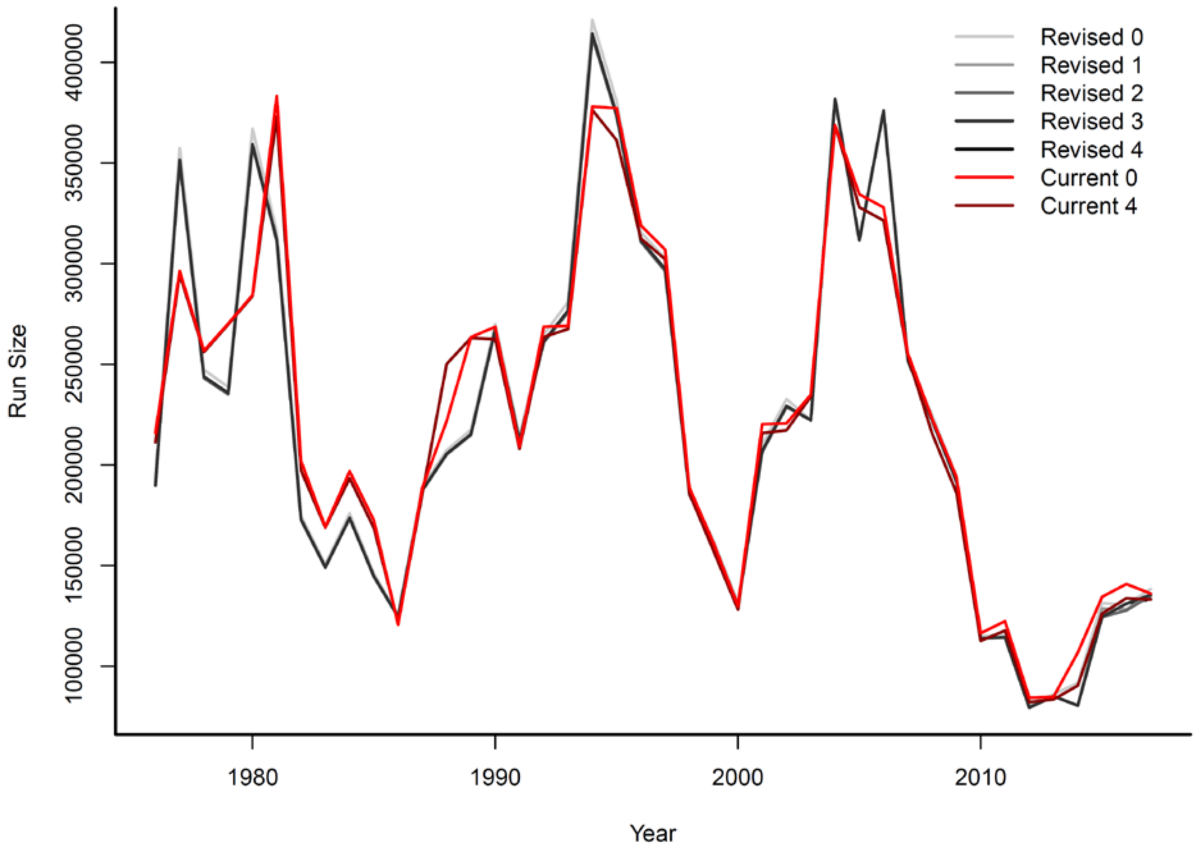

Figure 2. Point estimates of Kuskokwim River Chinook salmon run size using the current model (red and purple lines) and revised model (grey-scale lines) structures. The numbers in the legend following the model structure indicate the number of recent mark-recapture values used to fit the model (i.e., 'Revised 0' is the revised model fit without any mark-recapture data from 2014-2017. 'Revised 4' is the revised model fit with mark-recapture data for four years, 2014-2017. 'Revised 1' used only 2014 mark-recapture data, 'Revised 2' used only 2014 and 2015 mark-recapture data, and so on up through 'Revised 4'.

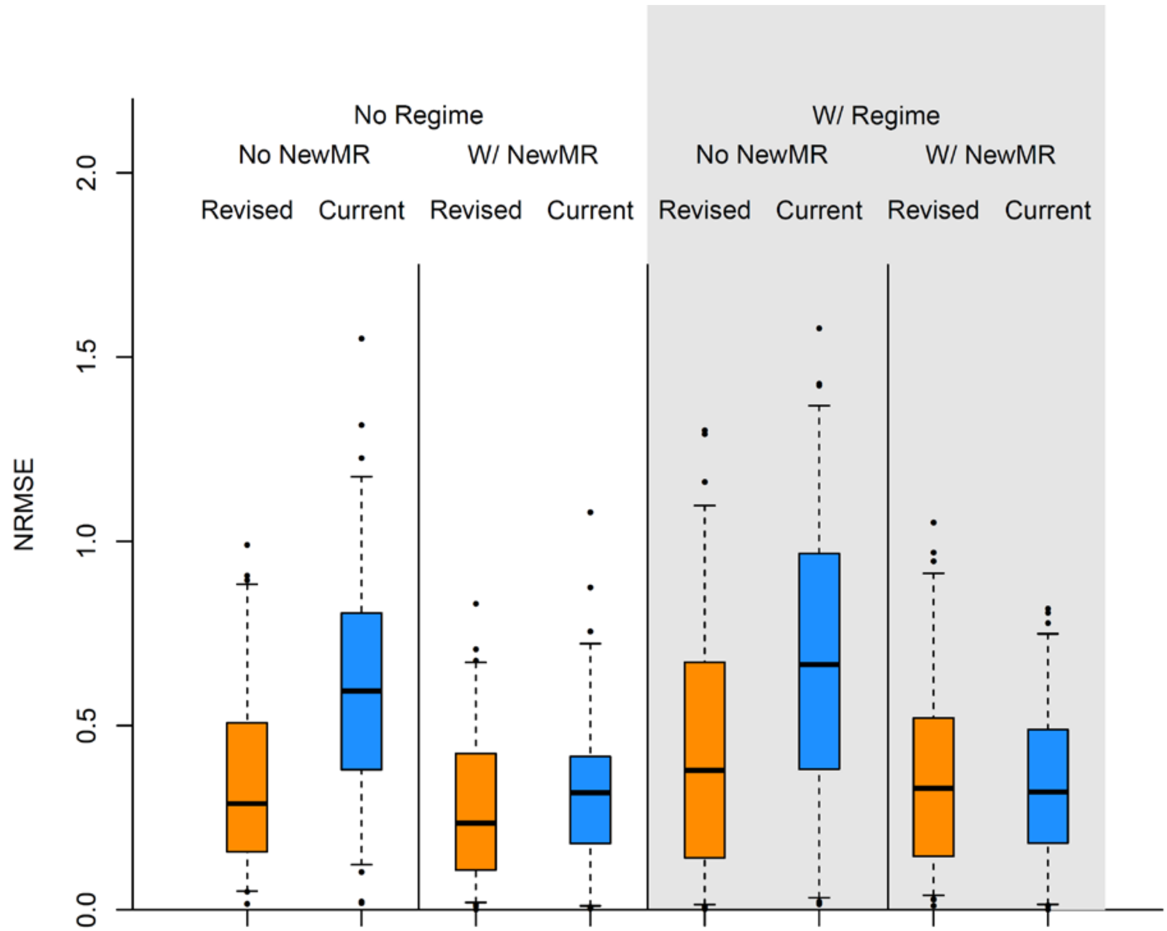

Figure 3. Boxplots of normalized root mean squared error (NRMSE) for Kuskokwim River Chinook salmon run reconstruction model fits to simulated data from an operating model under various biological scenarios and model structures. Box plots show the distribution from 100 simulations. The colors represent model estimates from the revised model structure (orange, left-most of each pair) and current model structure (blue, right-most). Column labels describe which model was used (Revised, Current), whether or not new (2014-2017) mark-recapture estimates were used to fit the models (No NewMR, W/ NewMR), and whether or not the underlying population dynamics were subject to regime shifts (also indicated by grey background).

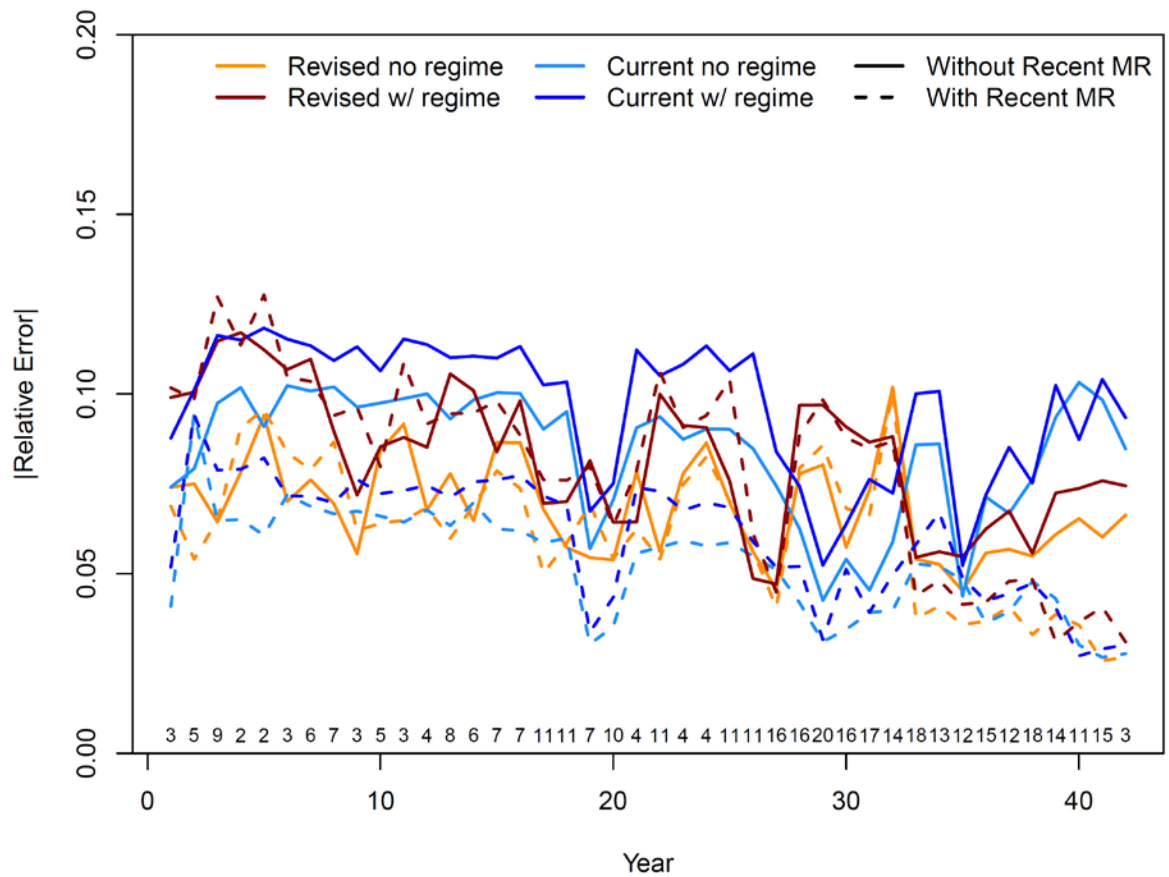

Figure 4. Median absolute values of relative error (expressed as proportional difference from the true value) through time in run reconstruction model estimates for 100 simulated time-series. Solid lines represent those in which the recent (2014-2017) mark-recapture estimates were not used in the run reconstruction model. Dashed lines represent scenarios in which the recent mark-recapture estimates were used in the run reconstruction model. Lines in orange shades represent results from the revised run reconstruction model, while blue shaded lines represent those from the current run reconstruction model. Darker shades of each color represent scenarios with population dynamics subject to regime shifts, while lighter shades represent scenarios without regime shifts. Numbers above x-axis indicate the number of escapement indices available each year, which are the same as in the real data set available for the Kuskokwim River.

Table 2. Comparisons of estimates of Kuskokwim River Chinook salmon abundance (run size in thousands of fish) from run reconstruction models using the revised and current model structures, and mark-recapture estimates of river-wide abundances. (a) Point estimates of Chinook salmon abundance from each of the two models when there are no recent mark-recapture estimates used and when there are all four recent mark-recapture estimates used. Grey boxes indicate years in which mark-recapture estimates are available. (b) Proportional differences between model estimates from part (a) compared to the revised model estimates when all recent mark-recapture estimates are used in the run reconstruction. Proportional differences were calculated as [(run size$_{model\ i}$ - run size$_{model\ j}$)/(run size$_{model\ j}$)], where model j is the analogous 'revised model' fit with all (2014-2017) mark-recapture data.

a)	No Recent Mark-Recapture		All Recent Mark-Recapture	
Year	Revised Model	Current Model	Revised Model	Current Model
2010	114.9	116.4	113.7	112.6
2011	115.7	122.3	114.3	117.7
2012	81.2	84.3	79.4	82.2
2013	86.0	84.8	85.0	83.5
2014	91.6	106.8	80.5	90.3
2015	131.3	134.4	124.4	126.1
2016	130.6	140.8	131.1	133.7
2017	138.3	136.1	133.3	133.1

b)	No Recent Mark-Recapture		All Recent Mark-Recapture	
Year	Revised Model	Current Model	Revised Model	Current Model
2010	0.010	0.023	0.000	-0.010
2011	0.012	0.071	0.000	0.030
2012	0.022	0.061	0.000	0.035
2013	0.011	-0.003	0.000	-0.018
2014	0.139	0.327	0.000	0.123
2015	0.055	0.080	0.000	0.014
2016	-0.004	0.074	0.000	0.020
2017	0.037	0.021	0.000	-0.001

Table 3. Comparisons of Kuskokwim River Chinook salmon run reconstruction estimates using the revised model structure and observed data, with different numbers of recent mark-recapture estimates available. (a) Point estimates of run size (thousands of fish) from the model fits with different numbers and arrangements of recent mark-recapture estimates used. Grey cells indicate years in which mark-recapture estimates were included in the run reconstruction. (b) Proportional differences (calculated as in Table 2) between all model estimates from (a) compared to the new model estimates when all recent mark-recapture estimates were used in the run reconstruction. Blue shading indicates underestimates; red shading indicates overestimates.

a)

	Number of Recent Mark-Recapture Estimates Used							
	No Estimates	Later Estimates			All Estimates	Earlier Estimates		
Year	0	1	2	3	4	3	2	1
2010	114.9	114.5	114.6	114.3	113.7	113.8	113.7	113.9
2011	115.7	115.2	115.3	115.0	114.3	114.4	114.2	114.4
2012	81.2	80.7	80.8	80.4	79.4	79.6	79.3	79.6
2013	86.0	85.7	85.7	85.5	85.0	85.1	85.0	85.1
2014	91.6	91.1	91.2	90.8	80.5	80.5	80.5	80.5
2015	131.3	130.4	130.6	124.4	124.4	124.4	124.4	128.6
2016	130.6	129.7	131.1	131.1	131.1	131.1	127.7	128.2
2017	138.3	133.3	133.3	133.3	133.3	135.5	135.0	135.5

b)

	Number of Recent Mark-Recapture Estimates Used							
	No Estimates	Later Estimates			All Estimates	Earlier Estimates		
Year	0	1	2	3	4	3	2	1
2010	0.010	0.007	0.008	0.005	0.000	0.001	-0.001	0.001
2011	0.012	0.008	0.009	0.006	0.000	0.001	-0.001	0.001
2012	0.022	0.015	0.017	0.012	0.000	0.002	-0.002	0.002
2013	0.011	0.008	0.009	0.006	0.000	0.001	-0.001	0.001
2014	0.139	0.132	0.134	0.128	**0.000**	**0.000**	**0.000**	**0.000**
2015	0.055	0.048	0.050	**0.000**	**0.000**	**0.000**	**0.000**	0.033
2016	-0.004	-0.010	**0.000**	**0.000**	**0.000**	**0.000**	-0.026	-0.022
2017	0.037	**0.000**	**0.000**	**0.000**	**0.000**	0.016	0.012	0.017

Appendix B.

ADMB Code

```
//==========================================================================
// Converting Alaska Department of Fish and Game
// Kuskokwim River Chinook salmon Run-reconstruction model
// Underlying Model Structure by Hamachan Hamazaki
// Major Changes to the model from original R
// 1. Model Structure Changed to use log-normal likelihoods on escapement
//    and drainagewide run
// 2. Common variance parameter for Weir and Aerial Escapement
// 3. Commercial fishery likelihood Changed from weekly effort (Concentrated
//    likelihood) to annual passage adjusted CPUE (log-normal likelihood with
//     common variance)
// 4. Removed Commercial fisery CPUE during the restricted fishery period
//    (Creg=2)
//==========================================================================
//DATA SECTION
//==========================================================================
DATA_SECTION
  init_int nyear; // number of years with datae
  init_int nweek; // number of weeks for harvest data
  init_int nweir; // number of weir sites
  init_int nair;  // number of aerial survey sites

  init_matrix testf(1,nyear,1,nweek); //Estimates of run proportion by week

  init_matrix ceff(1,nyear,1,nweek);  // Weekly effort commercial fishery
  init_matrix ccat(1,nyear,1,nweek);  // Weekly catch commercial fishery
  init_matrix creg(1,nyear,1,nweek);  // Weekly indicator of fishery regulation

  init_vector inriv(1,nyear);         // Annual in-river run estimate
  init_vector inriv_sd(1,nyear);      // SD of annual in-river run estimate

  init_vector tcatch(1,nyear);          // Total harvest across all fishery sectors
  init_matrix esc_w(1,nyear,1,nweir);   // Weir escapement indices
  init_matrix esc_a(1,nyear,1,nair);    // Aerial escapement indices

  init_vector minesc(1,nyear);            // Minimum annual escapement
  init_vector minrun(1,nyear);            // Minimum annual run size
```

```
  init_vector ubrun(1,nyear);             // Upper bounds for annual run size estimation
//=====================================================
// Parameter Section
//=====================================================
PARAMETER_SECTION
  init_bounded_number_vector log_trun(1,nyear,minrun,ubrun,1);  // log drainage-wide run
  init_bounded_vector log_wesc(1,nweir,0,7,1);   // log slope for weir counts
  init_bounded_vector log_aesc(1,nair,0,7,1);    // log slope for aerial counts
  init_bounded_vector log_q(1,2,-12,-9,1);       // log Catchability for different fishery sectors
  init_bounded_number log_cvw(-10,1,1);    // log cv for weir counts
  init_bounded_number log_cva(-10,1,1);     // log cv for aerial counts
  init_bounded_number log_cvq(-10,1,1);     // log cv for commercial cpue
  vector t_run(1,nyear);              // storage for untransformed total runs
  vector wesc(1,nweir);               // storage for untransformed weir escapement slopes
  vector aesc(1,nair);               // storage for untransformed aerial escapement slopes
  vector q(1,2);                     // storage for untransformed catchabilities
  number cvw;                  // storage for untransformed weir cv parameters
  number cva;                  // storage for untransformed aerial cv parameters
  number cvq;                                     // storage for untransformed fishery cv parameters
  matrix wk_est(1,nyear,1,nweek);      // storage matrix for the estimated number of fish available for
harvest each week
  number tfw;                      // likelihood for weir counts
  number tfa;                      // likelihood for aerial counts
  vector tfc(1,3);                 // likelihood for commercial CPUE
  number tft;                      // likelihood for in-river run estimates
  vector esc(1,nyear);               // vector of total escapement estimates
  number var1;                     // storage for Weir Escapement variance parameter
  number var2;                     // storage for Aerial Escapement variance parameter
  number var3;                                     // storage for CPUE variance parameter
  matrix cpue(1,3,1,nyear);                        // storage matrix for annual CPUE by fishery
  matrix testp(1,3,1,nyear);                  // testfish weekly run proportion

  objective_function_value objf;

INITIALIZATION_SECTION
  log_trun  12.5;
  log_wesc  5.0;
  log_aesc  4.0;
  log_q  -11.0;
  log_cvw  1.0;
  log_cva  1.0;
  log_cvq  1.0;
//=====================================================
// Calculate Annual run adjusted CPUE
```

```
//=========================================================
PRELIMINARY_CALCS_SECTION
   int i,j,k;
  for (i=1;i<=nyear;i++)
  {
  for (j=1;j<=nweek;j++)
        {
// Unrestricted mesh catch
    if(creg(i,j)==1)
          {
                    cpue(1,i) += ccat(i,j)/ceff(i,j);
                    testp(1,i) += testf(i,j);
          }
// Restricted mesh catch
    if(creg(i,j)==2)
          {
                    cpue(2,i) += ccat(i,j)/ceff(i,j);
                    testp(2,i) += testf(i,j);
                    }
// Mono-filament mesh catch
    if(creg(i,j)==3 or creg(i,j)==5)
          {
                    cpue(3,i) += ccat(i,j)/ceff(i,j);
                    testp(3,i) += testf(i,j);
                          }
        }
  }

//============================================================
// Procedure Section
//===========================================================
PROCEDURE_SECTION

  objf = 0.0;

  convert_parameters_into_rates();

  evaluate_obj_func();

RUNTIME_SECTION
  maximum_function_evaluations 200000000
  convergence_criteria 1.e-30  //was 1.e-20 //low converge was .000001

//============================================================
```

```
// Function convert_parameters_into_rates
//==========================================================
FUNCTION convert_parameters_into_rates

  t_run=exp(log_trun);
  wesc=exp(log_wesc);
  aesc=exp(log_aesc);
  q=exp(log_q);
  cvw=exp(log_cvw);
  cva=exp(log_cva);
  cvq=exp(log_cvq);
  var1 = log(square(cvw)+1);
  var2 = log(square(cva)+1);
  var3 = log(square(cvq)+1);
//==========================================================
// Function evaluate_obj_func
//==========================================================
FUNCTION evaluate_obj_func
  int i,j,k,l,ctr1,ctr2,ctr3;

  tfw= 0.0;
  tfa= 0.0;
  tft= 0.0;
  tfc=0.0;


  for (i=1;i<=nyear;i++)
  {
   esc(i)=t_run(i)-tcatch(i);

   if(inriv(i)>0)
   {
    tft+= 0.5*square(log(inriv(i))-log(t_run(i)))/log(square(inriv_sd(i)/inriv(i))+1);
          // In-River run estimate likelihood
   }

   // Weir likelihoods
   for(j=1;j<=nweir;j++)
   {
     if(esc_w(i,j)>0)
     {
       tfw += log(sqrt(var1))+0.5*square(log(esc_w(i,j))-log(esc(i)/wesc(j)))/var1;
     }
   }
```

```
// Aerial likelihoods
    for(k=1;k<=nair;k++)
    {
     if(esc_a(i,k)>0)
     {
      tfa += log(sqrt(var2))+0.5*square(log(esc_a(i,k))-log(esc(i)/aesc(k)))/var2;
     }
    }

//===  Calculate annual run adjusted CPUE ==================================

            if(cpue(1,i)>0)
            {
            tfc(1) += log(sqrt(var3))+0.5*square(log(cpue(1,i)/testp(1,i))-log(q(1)*t_run(i)))/var3;
            }
// Remove CPUE during the Restricted Period
//          if(cpue(2,i)>0)
//          {
//          tfc(2) += log(sqrt(var3))+0.5*square(log(cpue(2,i)/testp(2,i))-log(q(2)*t_run(i)))/var3;
//          }
            if(cpue(3,i)>0)
            {
            tfc(3) += log(sqrt(var3))+0.5*square(log(cpue(3,i)/testp(3,i))-log(q(2)*t_run(i)))/var3;
            }

   }

   objf+= tft+tfw+tfa+sum(tfc);
//============================================================================
// Report Section
//============================================================================
REPORT_SECTION
   report<<"Total Run"<< endl << t_run << endl;
   report<<"ObjFunc"<< endl << objf << endl;
   report<<"tfc"<<endl<< tfc <<endl;
   report<<"tft"<<endl<< tft <<endl;
   report<<"tfa"<<endl<< tfa <<endl;
   report<<"tfw"<<endl<< tfw <<endl;
   report<<"cvw"<<endl<< cvw << endl;
   report<<"cva"<<endl<< cva << endl;
   report<< "q" << endl << q << endl;
   report<< "wesc" <<endl<< wesc << endl;
   report<< "aesc" <<endl<< aesc << endl;
```

```
   report<<"tcatch"<<endl<< tcatch<<endl;
   report<<"TotalEscapement"<<endl<< esc << endl;
//=============================================================================
// Globals Section
//=============================================================================
GLOBALS_SECTION
  #include <df1b2fun.h>
  #include <math.h>
  #include <time.h>
  #include <statsLib.h>
  #include <adrndeff.h>
  #include <admodel.h>
  time_t start,finish;
  long hour,minute,second;
  double elapsed_time;

TOP_OF_MAIN_SECTION
  arrmblsize = 100000000;
  gradient_structure::set_MAX_NVAR_OFFSET(30000000);
  gradient_structure::set_GRADSTACK_BUFFER_SIZE(3000000);
  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;
```

Appendix C
Data Input

Appendix C1. –Independent estimates of Kuskokwim River Chinook salmon abundance, used to scale the run reconstruction model.

Conventional name:	Year	Total Run	Standard Error
	2003	222,145	16,055
	2004	381,958	36,322
	2005	312,353	21,083
	2006	376,291	31,094
	2007	251,781	16,315
	2014	80,399	8,605
	2015	124,421	9,362
	2016	131,090	12,632
	2017	133,292	15,702

Appendix C2. –Harvest of Kuskokwim River Chinook Salmon.

Conventional name:	Year	Commercial	Subsistence	Sport	Testfish	Total
	1976	30,735	58,606		1,206	90,547
	1977	35,830	56,580	33	1,264	93,707
	1978	45,641	36,270	116	1,445	83,472
	1979	38,966	56,283	74	979	96,302
	1980	35,881	59,892	162	1,033	96,968
	1981	47,663	61,329	189	1,218	110,399
	1982	48,234	58,018	207	542	107,001
	1983	33,174	47,412	420	1,139	82,145
	1984	31,742	56,930	273	231	89,176
	1985	37,889	43,874	85	79	81,927
	1986	19,414	51,019	49	130	70,612
	1987	36,179	67,325	355	384	104,243
	1988	55,716	70,943	528	576	127,763
	1989	43,217	81,175	1,218	543	126,153
	1990	53,502	109,778	394	512	164,186
	1991	37,778	74,820	401	149	113,148
	1992	46,872	82,654	367	1,380	131,273
	1993	8,735	87,674	587	2,515	99,511
	1994	16,211	103,343	1,139	1,937	122,630
	1995	30,846	102,110	541	1,421	134,918
	1996	7,419	96,413	1,432	247	105,511
	1997	10,441	79,381	1,227	332	91,381
	1998	17,359	81,213	1,434	210	100,216
	1999	4,705	72,775	252	98	77,830
	2000	444	67,620	105	64	68,233
	2001	90	78,009	290	86	78,475
	2002	72	80,982	319	288	81,661
	2003	158	67,134	401	409	68,102
	2004	2,305	96,788	857	691	100,641
	2005	4,784	85,090	572	557	91,003
	2006	2,777	90,085	444	352	93,658
	2007	179	96,155	1,478	305	98,117
	2008	8,865	98,103	708	420	108,096
	2009	6,664	78,231	904	470	86,269
	2010	2,732	66,056	354	292	69,434
	2011	747	62,368	579	337	64,031
	2012	627	22,544	0	321	23,492
	2013	174	47,113	0	201	47,488
	2014	35	11,234	0	497	11,766
	2015	8	16,124	0	472	16,604
	2016	0	30,693	0	522	31,215
	2017	0	16,380	0	290	16,670

Appendix C3. –Weir escapement counts of Kuskokwim River Chinook salmon.

Conventional name:	Year	Kwethluk	Tuluksak	George	Kogrukluk	Tatlawiksuk	Takotna
	1976				5,638		
	1977						
	1978				14,533		
	1979				11,393		
	1980						
	1981				16,089		
	1982				13,126		
	1983						
	1984				4,922		
	1985				4,442		
	1986						
	1987						
	1988				8,028		
	1989						
	1990				10,093		
	1991		697		6,835		
	1992	9,675	1,083		6,563		
	1993		2,218		12,377		
	1994		2,916				
	1995				20,662		
	1996			7,770	13,771		423
	1997			7,810	13,190		1,197
	1998						
	1999				5,543	1,484	
	2000	3,547		2,959	3,242	807	345
	2001		954	3,277	7,475	1,978	718
	2002	8,963	1,346	2,443	10,025	2,237	316
	2003	14,474	1,064		12,008		390
	2004	29,111	1,475	5,488	19,819	2,833	461
	2005		2,653	3,845	21,819	2,864	499
	2006	19,899	1,033	4,355	20,205	1,700	541
	2007	14,438	377	4,011		2,032	412
	2008	6,300	683	2,563	9,750	1,075	413
	2009	5,828	362	3,663	9,528	1,071	311
	2010	1,772	207	1,498	5,812	546	181
	2011	4,217	287	1,547	6,731	992	136
	2012		542	2,201		1,116	228
	2013		194	1,292	1,819	495	97
	2014	3,213	338	2,993	3,732	1,904	
	2015	8,163	711	2,282	8,081	2,104	
	2016		909	1,663	7,056	2,494	
	2017	7,345	645	3,685	9,992	2,156	301

Appendix C4. –Peak aerial survey index counts of Kuskokwim River Chinook salmon.

Conventional name:	Year	Kwethluk	Kisaralik	Tuluksak	Salmon (Aniak)	Kipchuk	Aniak	Holokuk	Oskawalik	Holitna	Cheeneetnuk	Gagaryah	Pitka	Bear	Salmon (Pitka)
	1976									2,571				182	
	1977	2,075		424							2,407	897			1,930
	1978	1,722	2,417		289					2,766	268	504		227	1,100
	1979														682
	1980			975	1,186										
	1981						9,074							93	
	1982		81		126					521				127	413
	1983	471		186	231		1,909			1,069	173				572
	1984										1,177				545
	1985		63	142							1,002				620
	1986				336		424			650					
	1987				516	193			193		317				
	1988	622	869	195	244		954		80						474
	1989	1,157	152		631	1,598	2,109								452
	1990		631	200	596	537	1,255		113						
	1991		217	358	583	885	1,564								
	1992				335	670	2,284		91	2,022	1,050	328			2,536
	1993				1,082	1,248	2,687	233	103	1,573	678	419			1,010
	1994		1,243		1,218	1,520					1,206	807			1,010
	1995		1,243		1,446	1,215	3,171		326	1,887	1,565	1,193			1,911
	1996				985										
	1997		439		980	855	2,187		1,470	2,093	345	364			
	1998		457		425	443	1,930								
	1999								98	741					
	2000				238	182	714			301			151		362
	2001				598			52		4,156		143		175	1,033
	2002	1,795	1,727		1,236	1,615		513	295	733	730	452	165	211	1,255
	2003	2,661	654	94	1,242	1,493	3,514	1,096	844		810	1,095	197	176	1,242
	2004	6,801	5,157	1,196	2,177	1,868	5,362	539	293	4,051	918	670	290	206	1,138
	2005	5,059	2,206	672	4,097	1,679		510	582	1,760	1,155	788	744	367	1,801
	2006		4,734			1,618	5,639	705	386	1,866	1,015	531	170	347	862
	2007		692	173	1,458	2,147	3,984					1,035	131	165	943
	2008	487	1,074		589	1,061	3,222	418	213		290	177	242	245	1,033
	2009							565	379		323	303	187	209	632
	2010		235					229		587		62	67	75	135
	2011				79	116		61	26		249	96	85	145	767
	2012		588		49	193		36	51		229	178			670

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Appendix C4. – Page 2 of 2.

Conventional name:	Year	Kwethluk	Kisaralik	Tuluksak	Salmon (Aniak)	Kipchuk	Aniak	Holokuk	Oskawalik	Holitna	Cheeneetnuk	Gagaryah	Pitka	Bear	Salmon (Pitka)
	2013	1,165	599	83	154	261	754		38	532	138	74		64	469
	2014		622		497	1,220	3,201	80	200		340	359			1,865
	2015		709		810	917		77		662					2,016
	2016		622			898	718	100	47	1,157	217	135		580	1,578
	2017				423	889	1,781	140	136	676	660	453	234	492	687

Note: Only surveys rated good or fair were used. Only surveys flown between July 17 and August 5, inclusive were used.

Appendix C5.– Proportion of total annual Chinook salmon run in District W-1 by week, as estimated by Bethel Test Fishery.

		Week 3	Week 4	Week 5	Week 6
Conventional name:	Year	6/10/ - 6/16	6/17 - 6/23	6/24 - 6/30	7/1 - 7/7
	1976				
	1977				
	1978				
	1979				
	1980				
	1981				
	1982				
	1983				
	1984	0.2243	0.2903	0.1488	0.1633
	1985	0.0000	0.0930	0.2427	0.4306
	1986	0.1503	0.4039	0.1656	0.1399
	1987	0.1988	0.3070	0.2368	0.1137
	1988	0.2080	0.3086	0.1786	0.0852
	1989	0.1769	0.2780	0.3474	0.0976
	1990	0.1434	0.2095	0.3325	0.1492
	1991	0.0593	0.2965	0.2942	0.1994
	1992	0.3466	0.1791	0.2132	0.1085
	1993	0.2148	0.4172	0.1270	0.0328
	1994	0.2883	0.3098	0.1396	0.1009
	1995	0.1566	0.3066	0.3005	0.0988
	1996	0.4007	0.2138	0.0963	0.0288
	1997	0.1913	0.5295	0.1196	0.0533
	1998	0.1166	0.2199	0.3866	0.1513
	1999	0.1360	0.1349	0.2469	0.1462
	2000	0.2089	0.3896	0.1530	0.0461
	2001	0.0791	0.4157	0.2510	0.1036
	2002	0.3547	0.2245	0.1601	0.1034
	2003	0.2764	0.2748	0.1433	0.0662
	2004	0.2130	0.2927	0.2513	0.0693
	2005	0.2335	0.2851	0.1876	0.1601
	2006	0.1299	0.3054	0.2935	0.1675
	2007	0.0996	0.2000	0.3114	0.2472
	2008	0.1524	0.2931	0.3057	0.1183
	2009	0.1955	0.2830	0.3460	0.0753
	2010	0.2190	0.3755	0.1517	0.1335
	2011	0.1188	0.2976	0.1996	0.1695
	2012	0.0508	0.2964	0.3308	0.2114
	2013	0.1681	0.3708	0.2654	0.0963
	2014	0.2834	0.2370	0.1217	0.0771
	2015	0.1859	0.2292	0.1520	0.1316
	2016	0.1696	0.1830	0.2085	0.1385
	2017	0.0899	0.2067	0.3202	0.1459

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Appendix C5.– Page 2 of 2.

Conventional name:	Year	Week 7 7/8 - 7/14	Week 8 7/15 - 7/21	Week 9 7/22 - 7/28	Week 10 7/29 - 8/26
	1976				
	1977				
	1978				
	1979				
	1980				
	1981				
	1982				
	1983				
	1984	0.0509	0.0522	0.0090	0.0173
	1985	0.1504	0.0247	0.0175	0.0410
	1986	0.0488	0.0097	0.0241	0.0000
	1987	0.0210	0.0344	0.0130	0.0094
	1988	0.0218	0.0419	0.0145	0.0192
	1989	0.0258	0.0190	0.0119	0.0112
	1990	0.0609	0.0136	0.0266	0.0256
	1991	0.0337	0.0430	0.0000	0.0000
	1992	0.0542	0.0554	0.0000	0.0118
	1993	0.0273	0.0097	0.0000	0.0000
	1994	0.0138	0.0122	0.0000	0.0061
	1995	0.0300	0.0050	0.0097	0.0050
	1996	0.0214	0.0000	0.0066	0.0033
	1997	0.0357	0.0119	0.0079	0.0059
	1998	0.0378	0.0116	0.0055	0.0000
	1999	0.1903	0.0297	0.0754	0.0297
	2000	0.0205	0.0410	0.0000	0.0183
	2001	0.0528	0.0367	0.0000	0.0156
	2002	0.0337	0.0137	0.0089	0.0132
	2003	0.0351	0.0255	0.0112	0.0042
	2004	0.0406	0.0537	0.0160	0.0021
	2005	0.0768	0.0062	0.0000	0.0168
	2006	0.0535	0.0114	0.0142	0.0105
	2007	0.0754	0.0316	0.0095	0.0032
	2008	0.0431	0.0334	0.0083	0.0139
	2009	0.0323	0.0164	0.0000	0.0049
	2010	0.0556	0.0185	0.0113	0.0103
	2011	0.0818	0.0130	0.0000	0.0031
	2012	0.0627	0.0201	0.0088	0.0127
	2013	0.0743	0.0108	0.0000	0.0000
	2014	0.0148	0.0146	0.0000	0.0029
	2015	0.0625	0.0591	0.0338	0.0238
	2016	0.0722	0.0296	0.0197	0.0112
	2017	0.1117	0.0473	0.0266	0.0265

Appendix C6. – Chinook Salmon catch and effort (permit-hours) by week for Kuskokwim River District W-1.

		Week 3 6/10 - 6/16			Week 4 6/17 - 6/23		
Conventional name:	Year	Catch	Effort	Net	Catch	Effort	Net
	1976	0	0	0	20,010	5,724	1
	1977	12,458	2,802	1	16,227	2,904	1
	1978	18,483	3,972	1	10,066	2,004	1
	1979	24,633	6,432	1	5,651	3,012	2
	1980	9,891	2,814	1	21,698	5,364	4
	1981	29,882	6,180	1	3,830	3,066	2
	1982	4,912	2,784	1	24,628	5,970	1
	1983	13,406	5,634	1	8,063	5,544	2
	1984	0	0	0	17,181	5,562	1
	1985	0	0	0	6,519	2,538	3
	1986	0	0	0	0	0	0
	1987	0	0	0	19,126	4,734	3
	1988	12,640	4,816	3	11,708	3,672	3
	1989	0	0	0	15,215	5,208	3
	1990	0	0	0	16,690	3,780	3
	1991	0	0	0	13,813	3,606	3
	1992	0	0	0	24,334	9,488	3
	1993	0	0	0	0	0	0
	1994	0	0	0	0	0	0
	1995	0	0	0	6,895	2,276	3
	1996	0	0	0	4,091	1,056	3
	1997	0	0	0	10,023	2,118	3
	1998	0	0	0	0	0	0
	1999	0	0	0	0	0	0
	2000	0	0	0	0	0	0
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	0	0	0	0	0	0
	2005	0	0	0	0	0	0
	2006	0	0	0	0	0	0
	2007	0	0	0	0	0	0
	2008	0	0	0	6,415	1,026	3
	2009	0	0	0	3,003	668	3
	2010	0	0	0	0	0	0
	2011	0	0	0	0	0	0
	2012	0	0	0	0	0	0
	2013	0	0	0	0	0	0
	2014	0	0	0	0	0	0
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0
	2017	0	0	0	0	0	0

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Conventional name:	Year	Week 5 6/24 - 6/30 Catch	Effort	Net	Week 6 7/1 - 7/7 Catch	Effort	Net
	1976	4,143	2,088	2	1,550	2,490	2
	1977	1,841	4,722	2	673	4,194	2
	1978	3,723	5,346	2	2,354	8,676	2
	1979	3,860	6,438	2	1,233	3,252	2
	1980	1,460	2,448	2	498	2,298	2
	1981	4,563	5,952	2	2,795	5,520	2
	1982	12,555	5,176	4	1,970	3,968	2
	1983	4,925	5,958	2	2,415	5,634	2
	1984	5,643	5,616	2	3,206	5,454	2
	1985	19,204	5,880	3	9,942	5,844	3
	1986	11,986	6,540	3	5,029	6,852	3
	1987	0	0	0	9,606	6,948	3
	1988	15,060	7,518	3	5,871	6,954	3
	1989	11,094	6,144	3	7,911	7,092	3
	1990	25,459	7,536	3	4,071	3,546	3
	1991	12,612	3,696	3	8,068	7,308	3
	1992	16,307	8,628	3	3,250	4,696	3
	1993	8,184	4,976	3	0	0	0
	1994	14,221	4,608	3	0	0	0
	1995	14,424	4,532	3	4,368	3,824	3
	1996	666	360	3	861	836	3
	1997	0	0	0	0	0	0
	1998	12,771	4,584	3	2,277	1,780	3
	1999	4,668	2,454	3	0	0	0
	2000	0	0	0	357	896	3
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	520	104	3	1,107	446	3
	2005	3,531	1,189	3	874	604	3
	2006	2,493	1,038	3	0	0	0
	2007	0	0	0	0	0	0
	2008	2,362	783	3	19	4	3
	2009	2,539	752	3	762	519	3
	2010	1,724	1,324	5	290	522	3
	2011	0	0	0	361	634	5
	2012	0	0	0	0	0	0
	2013	0	0	0	0	0	0
	2014	0	0	0	0	0	0
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0
	2017	0	0	0	0	0	0

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Conventional name:	Year	Week 7 7/8 - 7/14 Catch	Effort	Net	Week 8 7/15 - 7/21 Catch	Effort	Net
	1976	1,238	4,548	2	236	1,590	2
	1977	153	2,310	2	0	0	0
	1978	987	7,668	2	0	0	0
	1979	470	3,120	2	0	0	0
	1980	445	2,586	2	0	0	0
	1981	941	2,640	2	0	0	0
	1982	1,055	4,734	2	0	0	0
	1983	633	2,796	2	0	0	0
	1984	2,069	5,592	2	744	2,238	2
	1985	0	0	0	0	0	0
	1986	1,156	3,192	3	0	0	0
	1987	1,910	3,582	3	2,758	6,720	3
	1988	5,270	10,794	3	1,728	6,636	3
	1989	6,043	10,962	3	868	2,622	3
	1990	4,931	8,534	3	0	0	0
	1991	904	3,426	3	452	3,408	3
	1992	0	0	0	0	0	0
	1993	0	0	0	0	0	0
	1994	578	1,984	3	441	3,000	3
	1995	1,452	3,716	3	568	3,488	3
	1996	408	896	3	251	1,195	3
	1997	0	0	0	0	0	0
	1998	1,127	1,668	3	0	0	0
	1999	0	0	0	0	0	0
	2000	0	0	0	0	0	0
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	0	0	0	0	0	0
	2005	0	0	0	0	0	0
	2006	0	0	0	0	0	0
	2007	0	0	0	0	0	0
	2008	1	6	3	0	6	0
	2009	113	436	3	83	672	3
	2010	271	686	3	186	958	3
	2011	227	996	5	129	1,226	5
	2012	45	604	5	195	1,616	5
	2013	0	0	0	139	2,018	5
	2014	14	584	5	14	2,276	5
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0
	2017	0	0	0	0	0	0

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		Week 9 7/22-7/28		
Conventional name:	Year	Catch	Effort	Net
	1976	0	0	0
	1977	0	0	0
	1978	0	0	0
	1979	0	0	0
	1980	0	0	0
	1981	0	0	0
	1982	0	0	0
	1983	0	0	0
	1984	0	0	0
	1985	0	0	0
	1986	0	0	0
	1987	0	0	0
	1988	662	6,276	3
	1989	210	3,372	3
	1990	0	0	0
	1991	419	7,522	3
	1992	0	0	0
	1993	0	0	0
	1994	538	6,348	3
	1995	0	0	0
	1996	307	6,398	3
	1997	0	0	0
	1998	816	4,296	3
	1999	0	0	0
	2000	0	0	0
	2001	0	0	0
	2002	0	0	0
	2003	0	0	0
	2004	127	360	3
	2005	0	0	0
	2006	0	0	0
	2007	0	0	0
	2008	0	12	0
	2009	58	752	3
	2010	176	1,632	3
	2011	24	1,668	5
	2012	39	1,464	5
	2013	21	1,556	5
	2014	0	0	0
	2015	0	0	0
	2016	0	0	0
	2017	0	0	0

Key to column Net: 1= unrestricted mesh size, 2 = restricted to 6” or less (old gear), 3 = restricted to 6” or less new gear, 4 = unrestricted and restricted mesh periods in same week, and 5 = Personal Use harvest included.

APPENDIX B: SUMMARY OF MODEL REVISIONS, PREPARED FOR THE NORTH PACIFIC FISHERY MANAGEMENT COUNCIL

Executive Summary

Revisions to the Kuskokwim River Chinook Salmon Run Reconstruction Model

Drafted by:

Alaska Department of Fish and Game[1]

On behalf of the

Kuskokwim River Interagency Model Development Team

- Hamachan Hamazaki – Alaska Department of Fish and Game
- Gary Decossas – U.S. Fish and Wildlife Service, Office of Subsistence Management
- Dr. William Bechtol – Bechtol Research
- Dr. Matthew Catalano – Auburn University, Assistant Professor, School of Fisheries, Aquaculture and Aquatic Sciences

Prepared for the North Pacific Fishery Management Council

Submitted May 15, 2018

[1] Corresponding author – Zachary Liller, Research Coordinator, Arctic-Yukon-Kuskokwim Region, Division of Commercial Fisheries, Anchorage, AK. zachary.liller@alaska.gov. 907-267-2135

ADF&G is recommending changes to the model used to estimate total inriver abundance of Kuskokwim River Chinook salmon. This document summarizes the review process which led to the recommended model revisions, presents the revised model, and presents revised total run estimates of Kuskokwim River Chinook salmon for years 1976–2017.

Background

In April 2015, the North Pacific Fishery Management Council (Council) adopted Amendment 110 to the Fishery Management Plan for Groundfish of the Bering Sea and Aleutian Islands management area. Among other actions, Amendment 110 lowers Chinook salmon bycatch caps in the Bering Sea pollock fishery when Chinook salmon abundance in Western Alaska is at historically low levels.[1] The Council's action identifies historically low Western Alaskan Chinook salmon abundance using a 3-system index of inriver adult Chinook salmon run sizes from the Unalakleet, Upper Yukon, and Kuskokwim rivers combined at or below the threshold level of 250,000 fish. The Council's action also specified a process by which the Alaska Department of Fish and Game (ADF&G) would provide preliminary postseason abundance estimates for the three indexed stocks to the National Marine Fisheries Service (NMFS) by October 1 each year.

Since 2015, ADF&G has generated postseason abundance estimates using methods consistent with those referenced in the Council's public review analysis.[2] It has been understood that ADF&G would report to the Council any changes to the estimation methods upon which the 3-system index was based, such that the Council may make a determination of whether or not to adopt the changes or continue using existing methods. **ADF&G is recommending changes to the data and model used to estimate total inriver abundance of Kuskokwim River Chinook salmon**.

For the purpose of this document, the model currently in use by ADF&G to estimate total run size of Kuskokwim River Chinook salmon will be referred to as the "current model". The revised model, which is being recommended to the Council, will be referred to as the "revised model".

Overview of Current Model

The Kuskokwim River Chinook salmon run reconstruction was published in 2012 (Bue et al. 2012) with subsequent revisions in 2014 (Hamazaki and Liller 2015). Estimates of annual inriver abundance and escapement are made using a maximum likelihood model developed for use in data-limited situations. The model combines information on subsistence harvest, commercial catch and effort, sport harvest, test fishery harvest and catch per unit of effort at Bethel, mark–recapture estimates of inriver abundance, counts of salmon at six weirs, and peak aerial counts from 14 tributaries spread throughout the Kuskokwim River drainage (Figure 1). Each of these data sources provides an index of total abundance. The model provides an approach to combine and weight available information about Kuskokwim River Chinook salmon abundance to arrive at a scientifically defensible estimate of total run size and

[1] https://npfmc.legistar.com/LegislationDetail.aspx?ID=2237783&GUID=89E4DA9C-19B8-4BDE-8643-B19D68DD9EE3

[2] Public Review draft Environmental Assessment/ Regulatory Impact Review/ Initial Regulatory Flexibility Analysis for Proposed Amendment to the Fishery Management Plan for Bering Sea Aleutian Islands Groundfish Bering Sea Chinook and Chum salmon bycatch management measures, March 2015.

escapement. Estimates produced by the model represent the most likely run size given the observed data. At the time of publication, the run reconstruction model represented a substantial advancement for Kuskokwim River salmon management by producing total run and escapement estimates for all years 1976–present. Since that time, ADF&G has endeavored to review model performance and make improvements as warranted.

Rationale for Model Updating

- ADF&G undertook a four-year effort (2014–2017) to generate independent estimates of drainagewide run size. Incorporation of these new data nearly doubles the amount of information used for model scaling and represents both record high and record low run sizes.
- The 2003–2005 independent estimates of total run size used to scale the current model were suspected to be biased high. ADF&G conducted validation studies in 2014–2016 and new information is available to improve model scaling.
- In recent years, there have been changes in the fishery management which affected salmon spawning distribution relative to the conditions upon which the model was originally based.
- The current model is highly sensitive to starting values and can produce multiple estimates of total run size depending on the starting values used in the model fitting process.
- Agency and independent expert panels have reviewed the current model and recommended changes to improve model stability and reduce complexity.

The following narrative provides more detailed information regarding the summary points highlighted above.

The current model is scaled using a relatively small number of independent estimates of run size from a narrow window of time (2003–2007) which corresponded to above average and record high abundance. In 2010, shortly after the data used to scale the current model was collected, Chinook salmon runs throughout much of Alaska, including the Kuskokwim, experienced a pronounced downturn in productivity resulting in record low abundances. In 2012, the ADF&G Chinook Salmon Research Team was formed and developed a plan with recommended studies to address questions that arose from the statewide decline in the abundance of Chinook salmon (ADF&G Chinook Salmon Research Team 2013). Specific to the Kuskokwim River, the Chinook Salmon Research Team recommended additional independent estimates of total abundance to evaluate performance of the current model during years of low abundance, which could be used if necessary to rescale the current model for improved estimation. This recommendation was consistent with the expectation by the original authors that the current model be periodically updated with new independent estimates of total run size (Bue et al. 2012).

Beginning in 2014, ADF&G undertook a three-year (2014–2016) effort to evaluate performance of the current model during years of low run abundance and develop additional independent estimates of the total run for model scaling purposes. Funding for this work was provided by the State of Alaska through the Chinook Salmon Research Initiative. An additional year of funding was provided in 2017 through Chinook Salmon Disaster Funds administered by the Pacific States Marine Fisheries Commission, which allowed for up to four consecutive years of evaluation and independent run estimates. In each of the four years, preliminary mark–recapture estimates aligned closely with the lower bound of the 95% confidence range surrounding the current model estimate (Liller and Hamazaki 2016; Liller 2017; Smith and Liller

2018). Over time, this consistent trend clearly indicated that the current model overestimated total run size in each of the four years, 2014–2017. On average, the annual preliminary mark–recapture estimates were 27% (42,000 fish) smaller compared to estimates produced from the current model in years 2014–2017 (Smith and Liller 2018). As such, rescaling the current model to improve performance during low abundance years was warranted.

Reduced performance of the current model in recent years was, in part, caused by changes in the fishery management which affected salmon spawning distribution relative to the conditions upon which the model was originally based. Low run sizes in recent years resulted in low escapement and stakeholder concerns about equitability of harvest. Since 2014, all salmon fishing in the mainstem Kuskokwim River has been closed during the early portion of the run in response to preceding years of low run abundance and subsequent year forecasts for below average run sizes.[3] The effect was a notable shift in historical harvest timing, reduced exploitation on early migrating Chinook salmon bound for upriver reaches of the drainage, and above average escapements recorded by the subset of weir and aerial survey projects used to index escapement to headwater tributaries. The current model assumes that the spatial distribution of spawning is stable over time, yet telemetric mark–recapture studies highlighted that headwater tributaries have received proportionally more escapement in recent years, likely due to changes in harvest timing (Head et al. 2017; Smith and Liller 2017a, 2017b, 2018). As a result, additional scaling was needed to address changes to fishery harvest.

The 2014–2017 mark–recapture experiments provided an opportunity to evaluate potential bias in the data from 2003–2007 used to scale the current model. In those years, total run scalars were developed by adding estimates of abundance from mark–recapture experiments conducted upriver from where the majority of the harvest occurs to all harvest and escapement downriver from the tag site. That approach required that ADF&G make an informed guess about escapement to three unmonitored tributaries in the lower river (Schaberg et al. 2012). The habitat-based methods used to estimate escapement to those unmonitored tributaries has long been suspected of overestimating true escapement to those systems. ADF&G combined telemetric and aerial survey methods to evaluate escapement distribution in the lower river. Results of this work showed that the habitat-based methods used by ADF&G likely overestimated escapement to unmonitored tributaries nearly two-fold. As such, revision to the 2003–2007 model scalars was warranted.

In addition to the above, ADF&G biometric staff, USFWS biometric staff, academic entities, and non-profit research organizations have had considerable opportunity to work with the model since it was published in 2012, share performance observations, and make recommendations to improve model performance. Data weighting (Staton et al. 2015) and model stability (Hamazaki and Liller 2015; Smith and Liller 2018) have been identified as issues that needed to be addressed. The current model estimates an over-dispersion parameter for each escapement index which acts as a way to weight data such that the most “reliable” projects have more influence on the model results. Staton et al. 2015 identified that this approach leads to the undesirable behavior that, at times, the current model will perfectly fit to a single index dataset and ignore all others. The authors demonstrated that pooling over-dispersion parameters by data type (i.e., air surveys, weirs) eliminated the potential extreme and undesirable behavior of the current model. The current model has also been shown to be sensitive to starting values and often does not

[3] In 2016, the Alaska Board of Fisheries formalized the front end closure in regulation (5AAC 07.365) for the purpose of meeting escapement goals and providing harvest opportunity for upriver communities.

converge to a single solution (Hamazaki and Liller 2015; Smith and Liller 2018). The source of this behavior is associated with the commercial catch and effort component of the current model and adjustments have been recommended to improve stability.

Model Review Process

Three complimentary model review efforts led to a set of recommended changes to the current model.

First, ADF&G staff from Division of Commercial Fisheries, Kuskokwim Area, carried out four consecutive years of telemetric mark–recapture studies and spawning ground surveys to evaluate model performance relative to independent estimates of abundance. Results showed that the current model scaling for years 2003–2007 was likely biased high and new information is now available to improve model scaling in those years. Furthermore, results showed that the current model has overestimated total run size in recent years. New independent estimates of total run size and associated uncertainties are now available to improve model scaling during years of low run abundance.

Second, in 2016, the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYKSSI) commissioned an independent expert review of the current model. The Panel's research questions were guided by some chief concerns about the current model that have either been reported by ADF&G or have been raised by stakeholders and previous explorations of the current model. A final review document was not available from AYKSSI in time for the June, 2018 Council meeting; however, the review panel summarized their research questions, approach, and recommendations (Appendix A).

The third step involved convening a Kuskokwim River Interagency Model Development Team (KRIMDT) to consider options for incorporating new abundance data from ADF&G, Division of Commercial Fisheries, and pending recommendations from the AYKSSI expert review panel. The KRIMDT consists of representatives from ADF&G, U.S. Fish and Wildlife Service Office of Subsistence Management, Bechtol Research, and Auburn University. The KRIMDT met with the AYKSSI review panel in Anchorage, AK in March 2018 to discuss preliminary review findings and recommendations for model improvement. The KRIMDT provided the AYKSSI review team with a revised model in April 2018. AYKSSI provided a cursory review of the revised model and a summary of basic performance metrics in Appendix A[4].

Data Updates and Model Changes

Changes to the current model include 1) changes to the data input, 2) software changes, and 3) structural changes. Changes were intended to ensure the most complete and accurate data were used, improve estimation of model parameters, improve model stability, and reduce complexity by reducing the number of estimated parameters. See Table 1 for more information about how the revised model differs from the current model.

[4] The “current model” as identified in the AYKSSI memo under Appendix A refers to a model format consistent with the current model described in this executive summary and used by ADF&G to estimate Kuskokwim River run size in 2014–2017. AYKSSI, however, used the updated data set and revised model scaling for years 2003–2007 as presented in this executive summary. As such, the estimates of annual run size presented in the AYKSSI memo do not match those presented by ADF&G in this or prior total run reports. For example, Smith and Liller (2018) presented notably higher estimates of total run size for 2017 because the old and uncorrected scalars were used.

Data Changes

1. An additional 4 years (2014–2017) of independent estimates of total run abundance were added. The revised model is now scaled with nine independent estimates of total run abundance representing both record high and record low run sizes.
2. Independent estimates of drainagewide run size from years 2003–2007 were adjusted to account for new information about the likely escapement to unmonitored tributaries in the lower river (Table 2).
3. Estimates of variance for the mark–recapture component of the annual model scalars (2003–2007) were recalculated using a closed-form solution.
4. Variance estimates for the annual scalars (2003–2007 and 2014–2017) were recalculated to account for additional uncertainty associated with tributary escapement monitoring and subsistence harvest estimation.
5. Annual estimates of total Chinook salmon escapement past the Kwethluk and Tuluksak weirs (used as model input) were recalculated using a hierarchical Bayesian estimation framework (e.g., Head and Smith 2018).
6. All weir and aerial survey data used as model input were reviewed and minor edits were made to ensure consistency with the ADF&G database (Smith and Liller 2018).
7. Annual CPUE from commercial harvest opportunities using restricted mesh 1976–1984 was removed from the model.

Software Changes

8. Modeling software changed from R (Optim) to ADMB.

Structural Changes

9. Lognormal likelihood was assumed for all data.
10. Variance was combined within each data type (weir, aerial, and commercial CPUE).
11. The revised model assumes a linear relationship between catch and effort. The model was fit to annual CPUE for each type of commercial fishery opportunity (Unrestricted and Restricted Mono filament 1985–2017).

Revised Model

Model code is provided in Appendix B. Model input data is provided in Appendix C.

Escapement Counts

Assuming that annual escapement of Chinook salmon returning to each tributary and observed by a weir or aerial survey is a constant fraction of drainagewide escapement (E_y), the expected escapement ($\hat{e}$) in year (y) to tributary (j) observed by method (i; weir or aerial) is:

$$\hat{e}_{ijy}=E_y/k_{ij}, \tag{2}$$

where k_{ij} is a scaling parameter estimated by the model.

Commercial Catch and Effort

Assuming that commercial catch per unit of effort (CPUE) occurring each week is proportional to the drainagewide run migrating during that week, the expected commercial catch CPUE ($CPUE_{wky}$) in week (w) with net configuration (k) is:

$$\widehat{CPUE}_{wky} = c_{wky}/f_{wky} = q_k\left(p_{wy}N_y\right). \tag{3}$$

Summing for all weeks and adjusting by the proportion of fish migrating during the weeks of fisheries, expected annual cumulative CPUE ($CPUE_{ky}$) is:

$$\widehat{CPUE}_{ky} = \frac{\sum_w (c_{wky}/f_{wky})}{\sum_w p_{wy}} = q_k N_y\ , \tag{4}$$

where:

$CPUE_{wky}$: commercial catch CPUE at week (w) of net configuration (k),
c_{wky}: commercial catch at week (w) of net configuration (k),,
f_{wky}: commercial efforts at week (w) of net configuration (k),,
p_{wy}: proportion of Chinook salmon available at week (w) observed at Bethel test fishery, and
q_k: catchability coefficient of net configurations (k) (i.e., unrestricted, restricted).

The proportion of Chinook salmon available for harvest each week and observed at Bethel Test Fishery included weeks 3–10. Data from weeks 8–10 were combined. Commercial catch and effort by week and net configuration included weeks 3–9. Data from weeks 8 and 9 were combined.

Likelihood Model

Assuming that all observations follow lognormal distributions, negative log likelihoods with omissions of constants were constructed as

$$L(\theta|data) = \begin{aligned} &\text{Escapement Counts} \\ &+\sum_y\sum_i\sum_j\left(ln(\sigma_j) + 0.5\left(\frac{ln(\hat{e}_{ijy}) - ln(e_{ijy})}{\sigma_j}\right)^2\right) \\ &\text{Adjusted Commercial CPUE} \\ &+\sum_y\sum_k\left(ln(\sigma_k) + 0.5\left(\frac{ln(\widehat{CPUE}_{ky}) - ln(CPUE_{ky})}{\sigma_k}\right)^2\right) \\ &\text{Drainagewide Run} \\ &+\sum_y\left(0.5\left(\frac{ln(\hat{N}_y) - ln(N_y)}{\sigma_y}\right)^2\right). \end{aligned} \tag{5}$$

where $\sigma_j^2 = \ln(CV_j^2 + 1)$, $\sigma_k^2 = \ln(CV_k^2 + 1)$, and $\sigma_y^2 = \ln(CV_y^2 + 1)$.

CV_j and CV_k were estimated from the model, and CV_y was the observed CV of drainagewide run sizes of 2003–2007 and 2014–2017.

The model was written in AD Model Builder (Fournier et al. 2012).

Effect on Historical Time Series

Overall, the revised model resulted in smaller annual estimates of Kuskokwim River Chinook salmon run size compared to the current model (Table 3). Revised estimates decreased in 34 (81%) of 42 years (1976–2017) and increased in eight years (19%; Figure 2). The largest percent decrease (38%) occurred in 2014 and the largest percent increase occurred in 1980 (19%). On average, annual estimated abundance decreased by approximately 11% or about 14,800 fish. Historical trends in abundance were similar between the two models, showing three distinct periods of high abundance followed by periods of low abundance (Figure 3).

Considering the time series 1994–2012 used by the Council to develop the 3-system index, the revised Kuskokwim River estimates decreased in all but four years (1994–1996, 2006). The revised model produced estimates that were about 11,500 fish (9%) smaller on average compared to the current model. The largest percent decrease (21%) was in 2012, and the largest increase (13%) was in 1994. Historical trends in abundance during this time period were similar, showing two distinct periods of high abundance followed by periods of low abundance.

The most pronounced difference between the two models is specific to the most recent years, 2014–2017 (Figure 3). The revised model produced total run size estimates that are on average 45,000 fish (28%) smaller. The revised model includes additional independent estimates of total run size for each year 2014–2017 and, therefore, nearly double the information upon which to scale the total run estimate. Reduced performance of the current model in recent years was attributed to a combination of record low run sizes and resulting changes to the fishery management beyond the conditions upon which the current model was originally based. By incorporating new model scalars for years 2014–2017, the revised model is more informed for making historical estimates and is expected to perform better under the current run size and fishery management regime moving forward. In addition, the revised model is expected to perform better in the face of possible future shifts in productivity (Appendix A).

Since the Council adopted Amendment 110, ADF&G has provided NMFS with estimates of Kuskokwim River Chinook salmon run size as a part of the 3-system index in 2015–2017. In each of those years, the current model used by ADF&G and approved by the Council produced total run size estimates of Kuskokwim River Chinook salmon that were 43,000 fish larger compared to the revised model. The combined 3-system index reported by ADF&G in 2015–2017 was greater than the threshold value of 250,000 using the current model; however, if the revised model estimates were available and used, the index value would have been below the threshold.

Regardless of the model used, runs to the Kuskokwim River in 2015–2016 showed signs of poor performance. While, escapement goals were generally achieved at the drainage and tributary levels, these results were largely due to substantial reductions in harvest (Table 4 and Figure 4). In each year, subsistence fisheries were heavily restricted, commercial fisheries did not occur, and sport fishing for Chinook salmon was closed.

ADF&G and the Kuskokwim River Interagency Salmon Model Development Team plan to continue to evaluate and improve the revised model. Initial discussions about timelines for subsequent reviews centered around a three-year cycle consistent with the Alaska Board of Fisheries process and the ADF&G escapement goal review. The Council would be notified of any subsequent changes.

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Table 1. – Summary of 2018 model changes with rationales and comparative reference to the 2014 model.

Change Type	Revised Model	Current Model	Rationale
Data			
1	An additional 4 years (2014–2017) of independent estimates of total run abundance were added.	The model is currently scaled with 5 years (2003–2007) of independent estimates of total run abundance representing above average run sizes.	Additional scalars were added to improve model performance during years of low run size and to improve parameter estimation following recent changes to fishery harvest timing.
2	Independent estimates of drainagewide run size from years 2003–2007 were adjusted to account for new information about the likely escapement to unmonitored tributaries in the lower river.	As described in Schaberg et al. (2012), model scalars were developed as the sum of upriver mark–recapture estimates of abundance, harvest downriver of the tag site, and escapement downriver of the tag site. A total of 3 tributaries downriver of the tag site are not monitored and escapement to these systems was approximated using a habitat (drainage area) expansion.	Validation studies conducted in 2014–2016 indicated that the habitat expansion method likely overestimated escapement to unmonitored tributaries. As a result model scalars for years 2003–2007 were biased high by an average of 25,600 fish
3	Estimates of variance for the mark–recapture component of the annual model scalars (2003–2007) were recalculated using a closed-form solution. The closed form solution was also used for new mark–recapture estimates, 2014–2017.	Bootstrap methods (1,000 simulations) were used to estimate variance for the mark–recapture component of the annual model scalars.	Variance calculations differed over time for published mark–recapture estimates of total abundance. Bootstrap methods used in 2003–2007 overestimated variance; conversely, bootstrap methods used in 2014–2017 underestimate variance. The closed-form solution was recommended by the AYKSSI expert panel and was chosen as the most appropriate method to calculate variance for all years.
4	Variance estimates for the annual scalars (2003–2007 and 2014–2017) were recalculated to account for additional uncertainty associated with tributary escapement monitoring and subsistence harvest estimation.	Previous estimates incorporated weir counts and harvest without error.	
5	Standardized annual estimates of total Chinook salmon escapement past the Kwethluk and Tuluksak weirs (used as model input) were recalculated using a hierarchical Bayesian estimation framework.	Standardized annual estimates of missed passage were estimated using a variety of methods.	This change was to be consistent with the methods used by all other weirs project used to inform the model (e.g., Head and Smith 2018).

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Change Type		Revised Model	Current Model	Rationale
	6	All weir and aerial survey data used as model input were reviewed and minor edits were made to ensure consistency with the ADF&G database (Smith and Liller 2018).		Three errors were associated with aerial survey counts which were transposed upon entry. Five errors were new data entries of aerial survey counts from prior year data forms that had not been previously entered.
	7	Annual CPUE from commercial harvest opportunities using restricted mesh 1976–1984 was removed from the model.	Data were included.	These data were removed because, the model fit the restricted mesh data poorly; these data disagreed with other more reliable indices in the model; run timing proportions for this time period were unavailable and thus were assumed to follow the long-term average; and they were overly influential on the 1977 and 1980 run size estimates.
Software				
	8	Coded in ADMB	Coded in R (Optim)	The software change was intended to improve estimation of maximum likelihood parameters, mitigate extreme sensitivity to starting values, and reduce time needed for model convergence.
Structural				
	9	Lognormal likelihood was assumed for all data.	Previously, escapement data was assumed to follow a negative binomial distribution, drainagewide run size was assumed to follow a normal distribution, and commercial effort was assumed to follow a lognormal distribution (i.e., no change).	The lognormal distribution appropriately describes the residual variability in the model and there are no concern with obtaining zero observations. As such, the lognormal distribution is more appropriate for these types of data. Assuming a lognormal distribution for all data facilitated computation and interpretation of model parameters.
	10	Variance was combined within each data type (weir, aerial, and commercial CPUE).	A separate dispersion parameter was estimated for each escapement assessment location and the concentrated likelihood function was used or commercial effort to eliminate the need for estimation of variance.	This change reduced model complexity and was intended to prevent the model from potentially overfitting to a single assessment project.
	11	The revised model assumes a linear relationship between catch and effort. The model was fit to annual CPUE for each type of commercial fishery opportunity (Unrestricted and Restricted Mono filament 1985–2017).	The current model assumed a nonlinear relationship between catch and effort. In addition, the current model assumes and that commercial catch and weekly run proportions indexed at the Bethel Test Fishery are known without error.	Fitting to annual CPUE assumes errors in catch, effort, and run proportion, and are thus more true to the nature of the observations. This change mitigated the extreme sensitivity to starting values.

Table 2. – Independent estimates of total abundance of Kuskokwim River Chinook salmon used to scale the maximum likelihood model.

	Current Scalars				Revised Scalars						Absolute Percent
Year	Abundance	95% CI		CV	Abundance	95% CI		CV		Difference	Difference
2003	241,617	182,710	326,202	15%	222,145	194,022	256,158	7%		-19,472	8%
2004	422,657	298,728	577,993	17%	381,958	317,206	459,919	10%		-40,699	10%
2005	345,814	270,560	453,516	13%	312,353	273,580	356,522	7%		-33,461	10%
2006	396,248	281,847	528,218	16%	376,291	320,175	441,427	8%		-19,957	5%
2007	266,219	211,280	340,445	12%	251,781	221,515	284,956	6%		-14,438	5%
									Avg.	-25,605	8%
2014					80,399	64,782	98,931	11%			
2015					124,421	107,672	144,367	8%			
2016					131,090	107,907	157,543	10%			
2017					133,292	105,765	166,967	12%			

Note: Independent estimates are based on a combination of mark–recapture estimates of abundance, harvest downriver from the tag site, and escapement downriver from the tag site. Scalar revisions for years 2003–2007 incorporate new information about escapement to select tributaries downriver from the tag site. Prior methods were shown to overestimate escapement and total run.

Table 3. – Comparison of published and revised total run size estimates for Kuskokwim River Chinook salmon based on the published (old) model (Bue et al. 2012; Hamazaki and Liller 2015) and the revised (new) model.

	Current Model		Revised Model			Absolute Percent
Year	Total Run	CV	Total Run	CV	Difference	Difference
1976	233,967	13%	187,584	13%	-46,383	20%
1977	295,559	13%	348,824	18%	53,265	18%
1978	264,325	12%	241,781	12%	-22,544	9%
1979	253,970	16%	233,787	17%	-20,183	8%
1980	300,573	15%	357,950	25%	57,377	19%
1981	389,791	14%	308,660	16%	-81,131	21%
1982	187,354	9%	173,072	9%	-14,282	8%
1983	166,333	12%	148,278	10%	-18,055	11%
1984	188,238	14%	171,853	12%	-16,385	9%
1985	176,292	14%	143,568	10%	-32,724	19%
1986	129,168	11%	123,452	15%	-5,716	4%
1987	193,465	15%	186,184	13%	-7,281	4%
1988	207,818	9%	204,824	7%	-2,994	1%
1989	241,857	9%	214,081	10%	-27,776	11%
1990	264,802	9%	266,353	8%	1,551	1%
1991	218,705	10%	210,525	9%	-8,180	4%
1992	284,846	10%	259,154	7%	-25,692	9%
1993	269,305	11%	274,830	10%	5,525	2%
1994	365,246	14%	411,724	14%	46,478	13%
1995	360,513	11%	371,079	11%	10,566	3%
1996	302,603	14%	307,072	12%	4,469	1%
1997	303,189	13%	295,259	10%	-7,930	3%
1998	213,873	13%	184,356	13%	-29,517	14%
1999	189,939	12%	158,770	11%	-31,169	16%
2000	136,618	9%	129,138	7%	-7,480	5%
2001	223,707	11%	205,152	9%	-18,555	8%
2002	246,296	10%	226,106	8%	-20,190	8%
2003	248,789	9%	232,282	6%	-16,507	7%
2004	388,136	10%	366,725	6%	-21,411	6%
2005	366,601	9%	326,904	5%	-39,697	11%
2006	307,662	10%	326,067	6%	18,405	6%
2007	273,060	8%	244,754	5%	-28,306	10%
2008	237,074	9%	219,709	6%	-17,365	7%
2009	204,747	10%	189,370	7%	-15,377	8%
2010	118,507	8%	112,975	5%	-5,532	5%
2011	133,059	10%	113,749	6%	-19,310	15%
2012	99,807	14%	79,238	10%	-20,570	21%
2013	94,166	7%	84,311	5%	-9,855	10%
2014	135,749	15%	84,326	8%	-51,423	38%
2015	172,055	16%	125,058	6%	-46,997	27%
2016	176,916	16%	128,855	7%	-48,061	27%
2017	166,863	13%	133,267	8%	-33,596	20%
				Average	-14,775	11%

Source: Bue et al. 2012; Hamazaki and Liller 2015; Liller and Hamazaki 2016; Liller 2017; Smith and Liller 2018.

Table 4.– Summary of Kuskokwim River Chinook salmon escapement and harvest, 2008–2017. Grey shading indicates escapements or harvests which were below established goal ranges.

	Goal Range [a]		Escapement / harvest									
System	Lower	Upper	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Escapement												
Kuskokwim River (Current model)	65,000	120,000	128,978	118,478	49,073	72,097	76,074	47,315	123,987	155,464	145,718	150,193
Kuskokwim River (Revised Model)	65,000	120,000	111,613	103,101	43,541	49,718	55,746	36,823	72,560	108,454	97,640	116,597
Kogrukluk River	4,800	8,800	9,750	9,528	5,812	6,731	NA	1,819	3,732	8,081	7,056	9,992
Kwethluk River	4,100	7,500	5,275	5,744	1,669	4,079	NA	845	3,187	8,162	7,619	7,429
George River	1,800	3,300	2,563	3,663	1,498	1,547	2,201	1,292	2,993	2,282	1,663	3,685
Kisaralik River	400	1,200	1,074	NS	235	NS	588	599	622	709	622	NS
Aniak River	1,200	2,300	3,222	NS	NS	NS	NS	754	3,201	NS	718	1,781
Salmon River (Aniak R)	330	1,200	589	NS	NS	79	49	154	497	810	NS	423
Holitna River	970	2,100	NS	NS	NS	NS	NS	532	NS	662	1,157	676
Cheeneetnuk River (Stony R)	340	1,300	290	323	NS	249	229	138	340	NS	217	660
Gagaryah River (Stony R)	300	830	177	303	62	96	178	74	359	19	135	453
Salmon River (Pitka Fork)	470	1,600	1,033	632	135	767	670	469	1,865	2,016	1,578	687
Harvest												
Subsistence	67,200	109,800	98,103	78,231	66,056	62,368	22,544	47,113	11,234	16,124	30,693	16,380
Commercial	NA		8,865	6,664	2,732	747	627	174	35	8	0	0
Sport	NA		708	904	354	579	0	0	0	0	0	0

[a] Refers to established escapement goal ranges for the entire Kuskokwim River drainage and select spawning tributaries. The Kuskokwim River drainagewide escapement goal was established in 2013.Subsistence harvest range refers to the Amounts Reasonably Necessary for Subsistence uses (ANS) as defined by the Alaska Board of Fisheries 5AAC 01.286. The ANS range was 64,500–83,000 during 2001–2012, but revised in 2013 to the range shown.

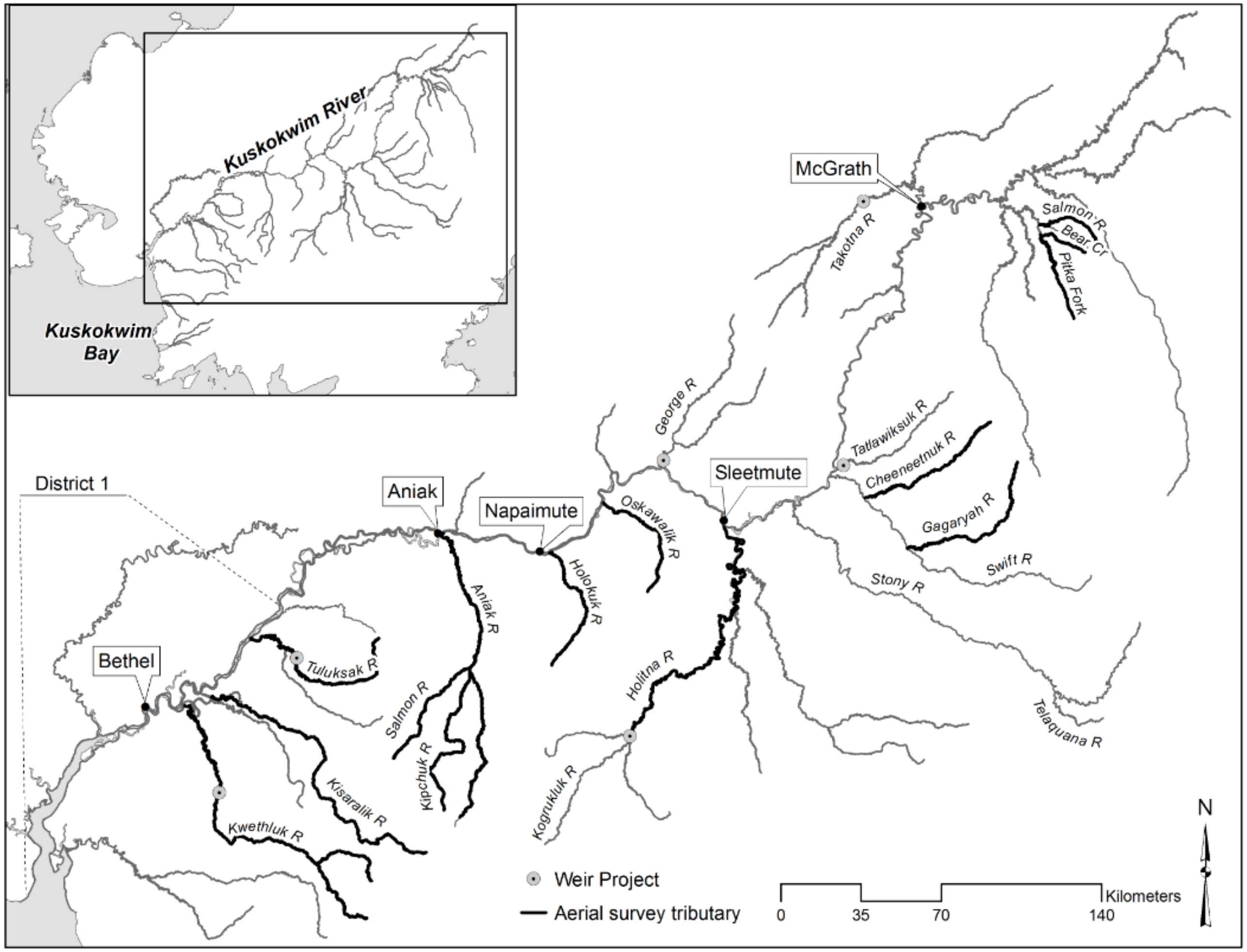


Figure 1.–Kuskokwim River drainage and location of major communities, commercial fishing district, and monitored tributaries. Estimates of total annual inriver abundance and escapement are made using a maximum likelihood model developed for use in data-limited situations. The model combines information on subsistence harvest, commercial catch and effort, sport harvest, test fish harvest and catch per unit of effort at Bethel, counts of salmon at 6 weirs, and peak aerial counts from 14 tributaries spread throughout the Kuskokwim River drainage, and independent estimates of total inriver abundance.

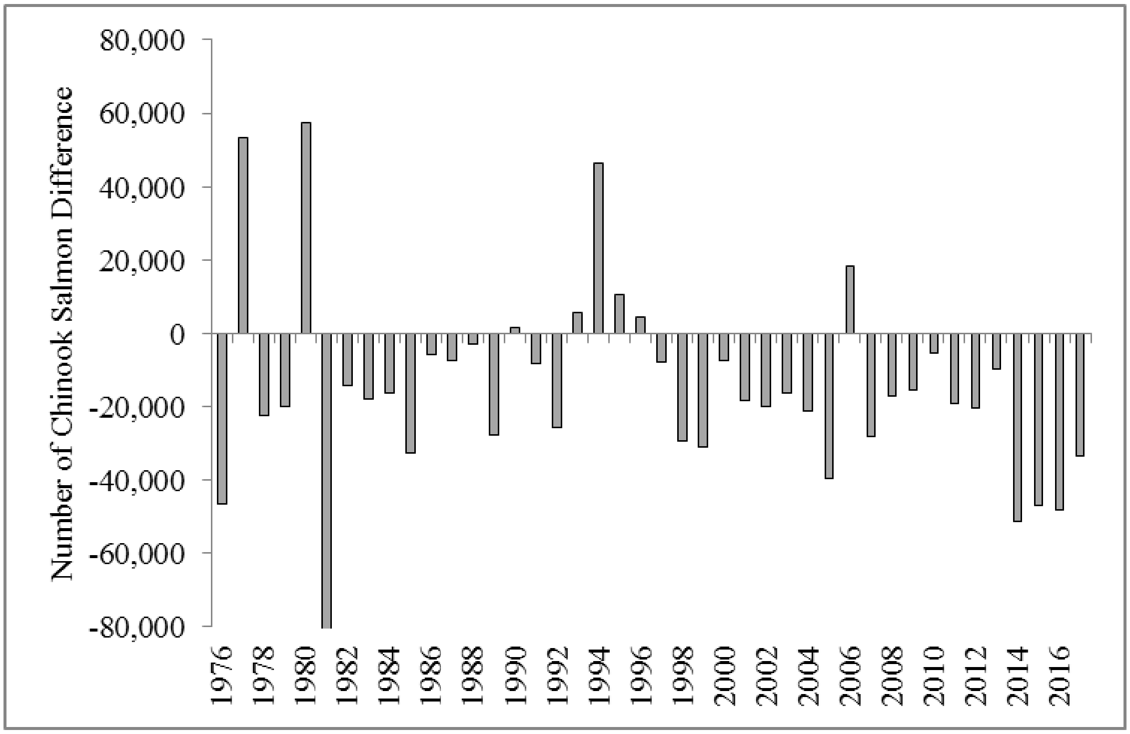


Figure 2. –Difference in the number of Chinook salmon estimated using the revised model compared to the current model.

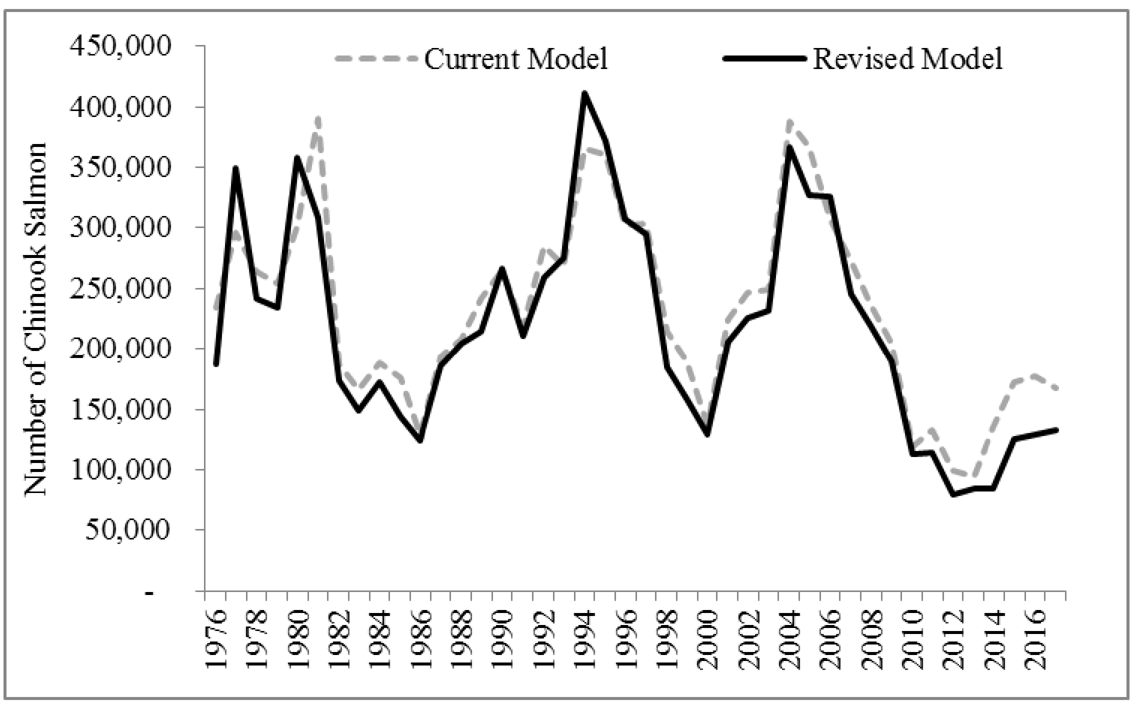
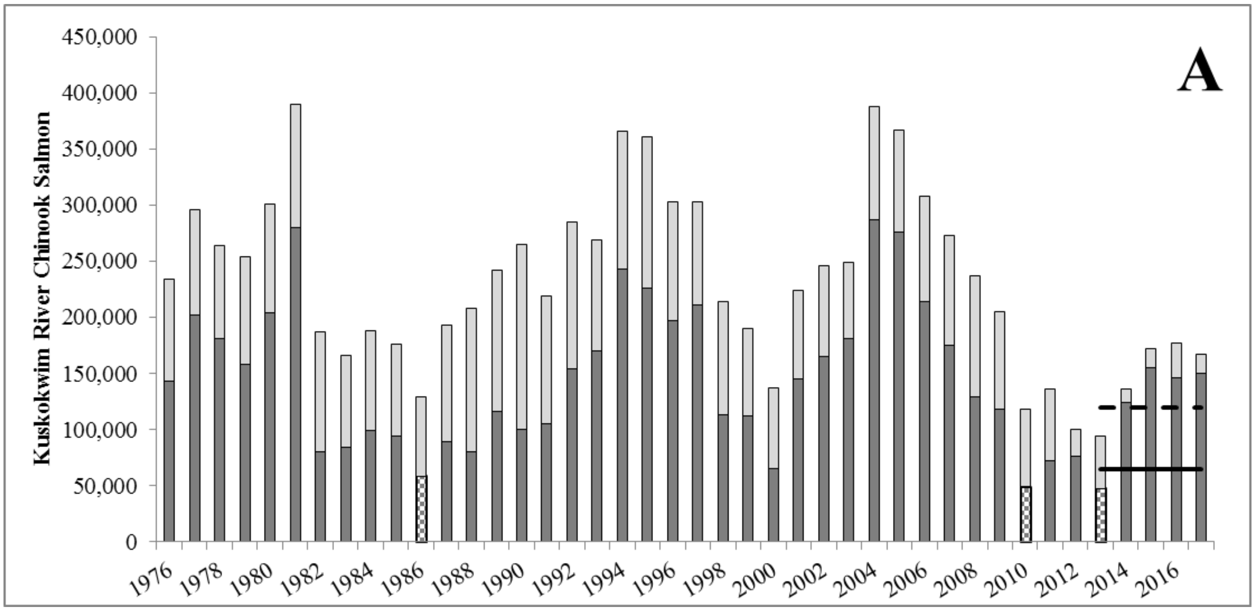


Figure 3.– Total abundance of Kuskokwim River Chinook salmon estimated using the revised model and current model.



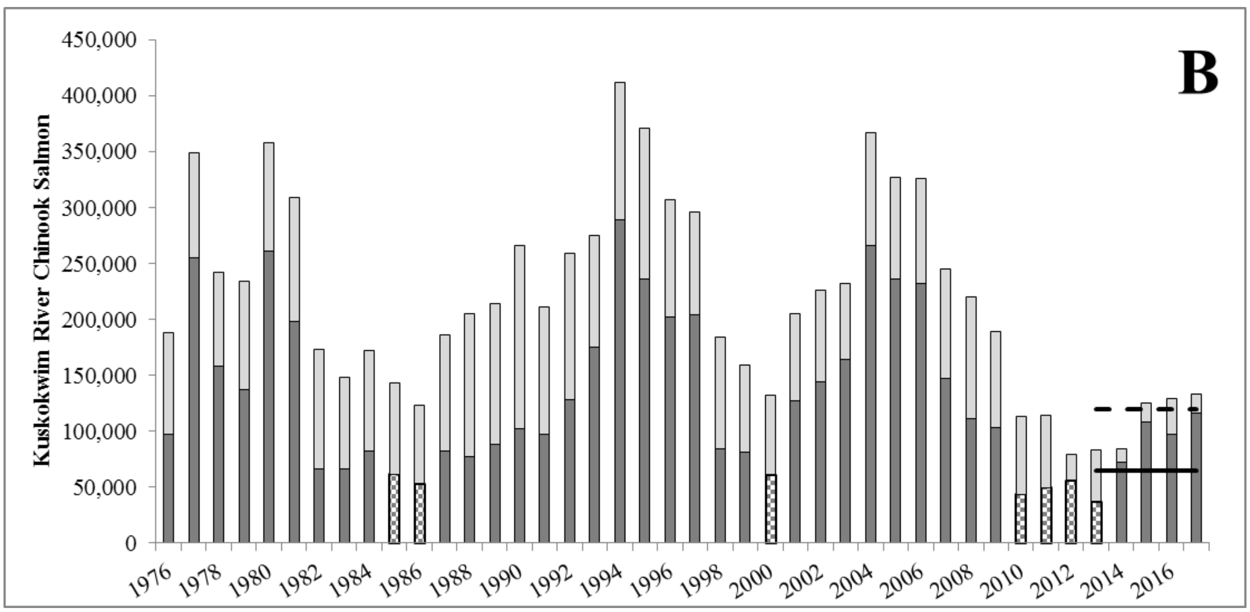


Figure 4.– Total run size of Kuskokwim River Chinook salmon based on the A) current model and B) revised model. Total run size is the sum of drainagewide escapement (dark gray bars) and total harvest (light gray bars). The drainagewide escapement goal of 65,000 (black solid line) to 120,000 (black dashed line) was established in 2013 using estimates produced by the current model. Escapements smaller than 65,000 fish are highlighted with a checkered pattern.

Appendix A.

Memo

The following memo was submitted by an independent expert review panel commissioned by the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYKSSI). Numbers presented in this memo do not match exactly those presented in this executive summary or past ADF&G reports. Results of the "current" model as presented by the AYKSSI expert panel are based on the updated dataset for all years and the revised model scalars for years 2003–2007. As such, the estimates are different than those presented in the executive summary and recent publications which used uncorrected data. Results of the "revised" model as presented by the AYKSSI expert panel differ slightly from those presented in the executive summary. The AYKSSI expert panel was provided with a preliminary version of the revised input dataset and model code. The input data was later corrected by ADF&G; specifically, the 2005 model scalar was changed from 311,516 (sd = 21,428) to 312,353 (sd = 21,083). The model code was updated to correct a typo in the variance term of the inriver likelihood, from square(log(square(inriv_sd(i)/inriv(i))+1)) to log(square(inriv_sd(i)/inriv(i))+1). This typo had little effect on the point estimates, but caused the model to fit the inriver abundance estimates almost exactly and underrepresented the model variance for years when mark-recapture data were available.

MEMO

DATE: May 10, 2018

TO: Zachary Liller, Research Coordinator, Arctic-Yukon-Kuskokwim Region, Alaska Department of Fish & Game, Division of Commercial Fisheries, Anchorage, Alaska

FROM: Expert Panel to evaluate Kuskokwim River Chinook salmon run reconstruction and stock-recruit models commissioned by the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYK-SSI).

Daniel Schindler, Professor, University of Washington, School of Aquatic and Fishery Sciences

Timothy Walsworth, Post-Doctoral Researcher, University of Washington, School of Aquatic and Fishery Sciences

Milo Adkison, Professor, College of Fisheries and Ocean Sciences, University of Alaska Fairbanks

Randall Peterman, Professor School of Resource and Environmental Management, Simon Fraser University

André Punt, Professor, University of Washington, School of Aquatic and Fishery Sciences

SUBJECT: Preliminary assessment of revised run reconstruction model for Chinook salmon in the Kuskokwim River

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Introduction

Stocks of Chinook salmon returning to the Kuskokwim River are among the most abundant in Alaska but have shown downturns in the recent decade, resulting in closed commercial fisheries and hardship for subsistence fisheries in communities throughout the watershed. Stock assessments are particularly challenging in this large and remote river system because it is expensive and logistically difficult to detect and enumerate adult fish migrating from the ocean back to a complex network of spawning habitat distributed among the many tributaries of this river. A run reconstruction model is used by the Alaska Department of Fish & Game (ADF&G) to integrate among a variety of indices of abundance, including: aerial surveys of spawning fish in headwater tributaries, counts of fish passing weirs on tributaries, and commercial catch rates in the lower river. Additionally, in some years, mark-recapture experiments are performed to estimate river-wide population abundance and provide a means for scaling from abundance indices to whole-system estimates in years where mark-recapture studies have not been done.

In response to concerns from a variety of stakeholders about the performance of the ADF&G run reconstruction model, the Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYK-SSI) commissioned an independent panel of experts (hereafter Expert Panel), with considerable experience in salmon ecology and stock assessment, to review the structure and performance of the ADF&G's current published run reconstruction model (Bue et al 2012; hereafter 'current model'). The Expert Panel was assembled in 2016 and, combined with the work of a statistical analyst, initiated a collaborative review with the ADF&G to assess the performance of the current ADF&G run reconstruction model.

The Expert Panel used two approaches to assess the performance of the ADF&G run reconstruction model for Chinook salmon on the Kuskokwim River: (1) fitting the run reconstruction model to the observed data supplied by ADF&G, but with various modifications to that model's structure, and (2) fitting ADF&G's current run reconstruction model, including modified versions of it, to simulated data sets where the parameter values and run sizes are specified to simulate alternative plausible states of nature for the Kuskokwim River. A limitation of examining model performance on observed data is that the true state of the system is never known, and so there is no way to assess whether the model is actually capturing the true underlying dynamics in the system. Simulations allow for testing the model under various scenarios while being able to compare model fits to true values (Hilborn and Walters 1992).

The Expert Panel tested the current run reconstruction model in several ways to assess its sensitivity to the starting values for the parameters, to underlying assumptions about Chinook salmon population dynamics, and to the types and amounts of data used to estimate the model parameters. A thorough summary of these results will be available in a forthcoming Expert Panel Review expected to be completed in late May 2018. However, the primary conclusions of the Expert Panel were communicated at a collaborative workshop with ADF&G staff and their Kuskokwim River Interagency Chinook Salmon Run Reconstruction Model Development Team in March 2018, and a list of primary recommendations were made to improve model performance. In particular, the Expert Panel was concerned with:

a) Lack of stability of the current run reconstruction model as demonstrated by its tendency to arrive at multiple solutions for the best values for the parameters of the model, depending on the starting values used in the model fitting process. Further investigation by the Expert Panel suggested that this instability derived from (1) an improperly specified harvest sub-model, and (2) over-parameterization of the escapement indices used to inform the model.

b) Sensitivity of model estimates to inclusion of recent (2014-2017) mark-recapture data. The run reconstruction model produced substantially different estimates of historical run sizes when recent mark-recapture estimates were either used, or not, to anchor the run reconstruction effort.

c) Error structure. The current model assumed a normal distribution for errors associated with the total run estimate derived from the mark-capture data and the Panel thought this would be better assumed to be log-normally distributed. The current model assumed that errors associated with the individual escapement indices were distributed according to a negative binomial distribution, and each individual index site was assigned its own over-dispersion parameter. The Panel concluded that these errors should instead be assumed to be log-normally distributed and that the variances should be pooled by index type (i.e., one describing weirs and one describing aerial survey sites) to reduce the model complexity.

Following the Expert Panel's collaborative workshop in March 2018, ADF&G revised the run reconstruction model to account for several mutually agreed-upon revisions that the Panel suggested for improving model performance (Table 1).

Table 1. Comparison between current and revised model structures for ADF&G Kuskokwim River Chinook salmon run reconstruction model, as of May 1, 2018.

Component	Current Model	Revised Model
Total Run Error Structure	Normal	Log-normal
Escapement Index Error Structure	Negative Binomial	Log-normal
Number of Escapement Error Parameters	One for each index site (20 total)	One for each type of index (2 total)
Harvest Component	Saturating relationship with effort: Catch ~ Run * (1-exp(-Effort*catchability))	Linear relationship with effort: Catch ~ Effort * catchability * Run

At the request of ADF&G, the Expert Panel performed a preliminary assessment of the performance of the revised run reconstruction model that was provided by ADF&G to the Panel on May 1, 2018. The purpose of this memo is to describe the results of this preliminary assessment. Given the short time frame, the Expert Panel was not able to perform an exhaustive assessment of the revised model but, instead, focused on a manageable number of critical concerns that emerged from the review of the current model as described above. For the purposes of this memo, we refer to the original model as the 'current model' and the revised model as the 'revised model'. In reality, the core structure of these two models is fundamentally the same, but certain components have been revised in the new model provided on May 1, 2018.

Assessment of the revised model with historical observed data

Model stability

The revised model showed substantially improved stability compared to the current model as shown by less sensitivity to starting values for the initial run size (inset panels in Figure 1). While the current model settled on several local minima across the run reconstruction times-series (Figure 1 bottom panels), with and without the recent (2014-2017) mark-recapture data, the new model produced a single solution when all recent mark-recapture data were integrated into the run reconstruction (Figure 1, top right panel). The new model produced one renegade solution when the recent mark-recapture data were not used in the run reconstruction model (Figure 1, top left panel), but otherwise converged on a single solution.

Based on these preliminary analyses, it appears that model stability was substantially improved by the combination of simplifying the error structure by pooling many of the parameters and changing the harvest component of the model. While the revised model still showed some worrisome local minima when recent mark-recapture data were not included (Fig. 1 top, left panel), the revisions seem to have distinctly improved model stability, particularly when recent (2014-207) mark-recapture data are used in the run reconstruction. For future revisions to the model, the Expert Panel strongly recommends that ADF&G conduct simulation tests such as these to determine whether the run reconstruction model is sensitive to starting conditions. That procedure would examine model fits across a range of starting parameter values to ensure that a global minimum is found.

Influence of recent mark-recapture data

Mark-recapture estimates of river-wide abundance are needed to scale up from the miscellaneous escapement indices (i.e., weirs and aerial surveys of tributaries), which are assumed to quantify relative trends in abundance, to river-wide estimates of abundance. The Expert Panel noted that the run reconstruction estimates derived from using the current model were highly sensitive to the inclusion of recent (2014-2017) mark-recapture estimates of total river-wide abundance. The revised model remains sensitive to the inclusion of these data (Figure 2), though to a lesser degree than the current model. While the historical changes in abundance estimated from the current and revised models, with differing numbers of years of mark-recapture data, all generally followed the same coarse-scale changes through time, there were some notable discrepancies produced in certain years. In particular, the revised model generally tended to estimate lower total abundance of Chinook salmon between 2014-2017 than the current model did without using recent mark-recapture data for those years, but about the same as when the current model was fit using those data (Figure 2). Regardless, these differences in estimates were relatively small. The revised model also estimated the peak abundance observed in 1990s at more than 400,000 Chinook salmon while the current model estimated abundances almost 50,000 fish lower.

We further explored the sensitivity of the revised run reconstruction model to the inclusion of recent mark-recapture data by varying the number of years of mark-recapture data between 2014 and 2017 used in the run reconstruction. Given that there are no mark-recapture studies planned for 2018 and the following few years, this exercise is one way to assess how robust future estimates might be in years immediately following a series of mark-recapture estimates of river-wide abundance.

From 2010 – 2017, the revised model using all mark-recapture estimates during 2014-2017 estimated between a high of 133.3 thousand fish in 2017 to a low of 79.4 thousand fish in 2012 (Table 2a, right panel). When all four years of recent mark-recapture data were used in the run reconstruction, the deviations of the current model from the revised model estimates tended to be <5%, except for in 2014 when the current model estimated about 12% more fish in the river than was estimated by the revised model (Table 2, right panels).

By comparison, when no new mark-recapture data were used, the current model tended to overestimate the number of fish in the river from 2010-2017 compared to estimates produced by the revised model with all mark-recapture data. The estimates produced from the current model without new mark-recapture data tended to be <10% different from estimates with the revised model and all mark-recapture data. The one exception was 2014 when the current model estimated > 30% more fish than the revised model with all mark-recapture data. By comparison, the revised model <u>without</u> mark-recapture data produced estimates of total abundance that tended to be <5% different from estimates of the revised model fit <u>with</u> all of the mark-recapture data, except for in 2014 where the revised model <u>without</u> mark-recapture data estimated about 14% more fish than the revised model <u>with</u> all the mark-recapture data. The large error in 2014 appears to have been produced by abnormally high counts at two of the weir sites.

Assuming that run-size estimates from the revised model with all recent mark-recapture data are the closest to the true values, estimation accuracy of ADF&G's revised model decreased as fewer years of mark-recapture data were included in the run reconstruction (Table 3). However, these deviations tended to be small, and were typically <5% different from estimates generated by the revised model with all years of mark-recapture data (Table 3b). The one exception to this pattern was in the revised model's estimates of total run size for 2014, when produced without using any mark-recapture data, or when only the most recent (2015-2017) three years of data were used. These estimates were about 13% higher (>10,000 fish) than the estimates produced by the revised model based on <u>all</u> the recent (2014-2017) mark-recapture data. When mark-recapture data were used starting in 2014 (Table 3, three right-most columns), deviations from the situation where all years of mark-recapture data were used were negligible (<3%). Thus, the revised model remains sensitive to the inclusion of recent mark-recapture data, but less so than the current model. The model is particularly sensitive to exclusion of mark-recapture from years with unusual escapement patterns (which drive large estimation errors, e.g., 2014), but these years are more likely to be captured when mark-recapture studies are undertaken with increasing frequency. Further, the model appears to provide robust estimates of river-wide abundance in the years immediately following a mark-recapture experiment, although the analyses we have used to quantify this are very preliminary

Assessment of the revised model performance based on simulated data

We used a simulation model (documented in detail in the Expert Panel's upcoming final report) to generate data that would produce a reasonable approximation to the dynamics observed in Chinook salmon in the Kuskokwim River. The simulation model assumed that there was considerable population structure such that the aggregate dynamics were composed of the sum of the dynamics of 40 individual stocks, 20 of which were monitored for escapement. Covariation among stocks was assumed to be relatively weak, as demonstrated by the lack of synchrony among annual weir counts and among aerial surveys. The model also simulated ‘productivity regimes’, whereby the per capita productivity at low population sizes could increase by 500% (or decrease by 80%) roughly every 20 years. The model then ‘sampled’ the data at the intensity that has actually been performed in the Kuskokwim River over the last four decades (data become more sparse farther back in time; see Figure 4 x-axis).

Because we know what the ‘real’ abundances are in the model simulations, we can assess how well ADF&G's revised and current run reconstruction models perform in capturing these values under a variety of assumptions about the nature of the population dynamics and the intensity of sampling. In particular, we were interested in the influence of mark-recapture studies on model performance, and how the presence of regime shifts in population productivity affected model performance.

The revised model performed better than the current model in estimating the true abundance of Chinook salmon in simulated data (Figure 3); these improvements were particularly prominent in simulations where no new mark-recapture data were included in the run reconstructions. In the absence of regime dynamics and when no mark-recapture data were included, model performance (measured by the normalized root mean squared error, NRMSE) was substantially better for the revised model compared to the current model. However, with new mark-recapture data included, the difference in the NRMSE produced by the two models was negligible. In simulations with regime changes, the revised model performed about as well (as indicated by the NRMSE), regardless of whether new mark-recapture data were included, and the frequency distributions of errors were only slightly wider in situations with regime shifts than without those shifts, regardless of whether new mark-recapture data were included in the run reconstructions (Figure 3).

Inspection of time-series of the relative errors produced by the current and the revised model through time reinforces the conclusion that the performance of the revised model still depends on inclusion of recent mark-recapture data in the run reconstructions, but less so than the current model (Figure 4). As expected, the magnitude of the errors of model predictions increases as you proceed backwards through time and the coverage of escapement sampling decreases. Inclusion of recent mark-recapture data tended to reduce errors in the most recent decade of the analysis, though the revised model had distinctly smaller errors than the current model during the last decade for simulations where new mark-recapture data were not included in the run reconstruction.

Summary

Revisions to the ADF&G run reconstruction model for Chinook salmon on the Kuskokwim River appear to have remedied several of the primary concerns of the AYK-SSI Expert Panel. In particular, the revised model is far more stable than the current model, though its stability still depends on the inclusion of recent mark-recapture data for scaling up from individual abundance indices to river-wide abundance estimates. The revised model also appears to provide more accurate run estimates than the current model, particularly for years when no mark-recapture data are available for scaling up to river-wide abundances. More analyses are required to further assess how robust the model is, particularly in situations where abundance indices from tributary weirs or aerial surveys are omitted from the Kuskokwim monitoring program.

References

Bue, B. G., K. L. Schaberg, Z. W. Liller, and D. B. Molyneaux. 2012. Estimates of the historic run and escapement for the Chinook salmon stock returning to the Kuskokwim River, 1976–2011. Alaska Department of Fish & Game, Fishery Data Series No. 12-49, Anchorage.

Hilborn, R., and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics, and Uncertainty. Chapman Hall. New York.

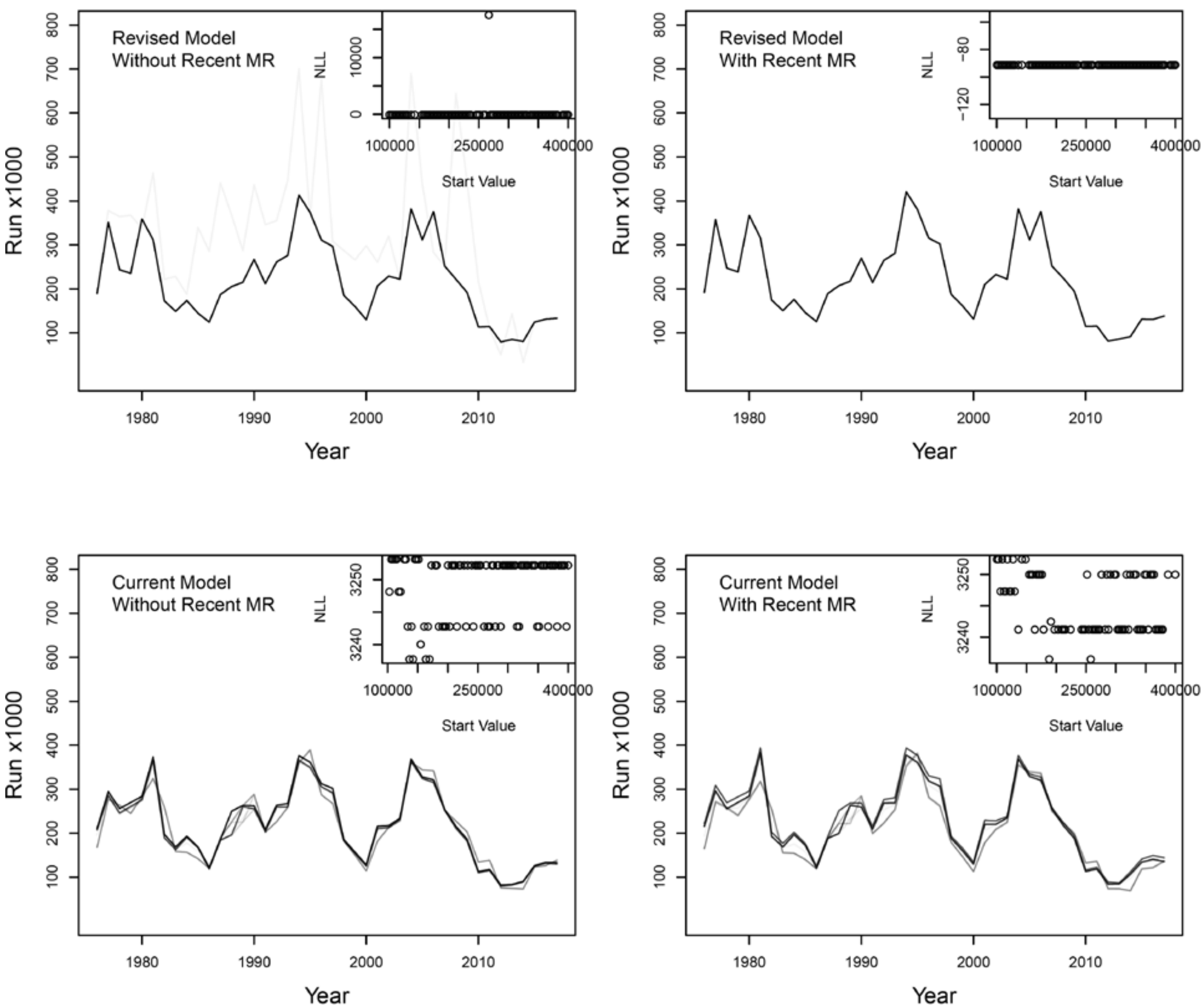

Figure 1. Run size estimates for Chinook salmon in the Kuskokwim River across a range of starting values from the revised run reconstruction model (top row) and current run reconstruction model (bottom row), and with different amounts of mark-recapture data available (no recent (2014-2017) estimates in left column, all recent estimates in right column). Semi-transparent grey lines represent individual model fits (out of 100 total). Black lines indicate stacked grey lines, representing repeated model convergence on the same values. Inset figures represent the negative log-likelihood values of model fits across the range of starting values of the run-size examined for the initial run size.

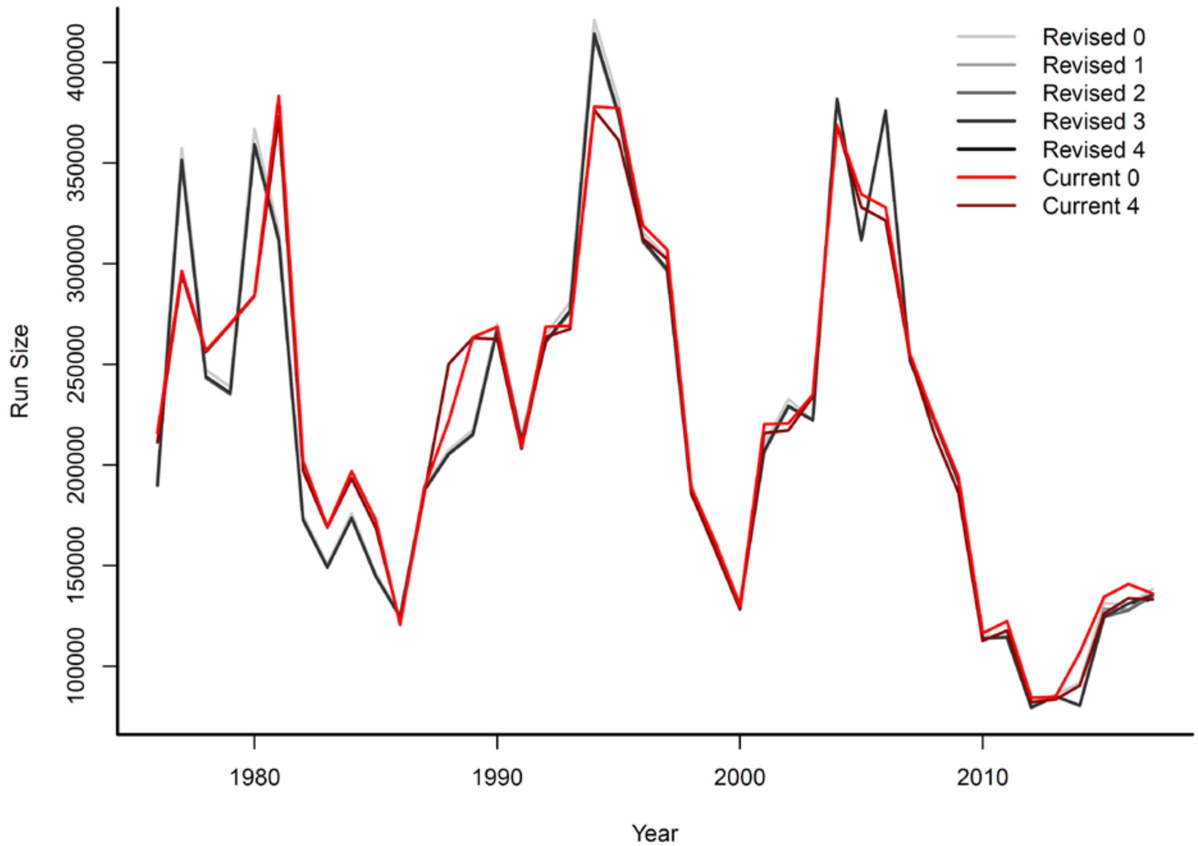

Figure 2. Point estimates of Kuskokwim River Chinook salmon run size using the current model (red and purple lines) and revised model (grey-scale lines) structures. The numbers in the legend following the model structure indicate the number of recent mark-recapture values used to fit the model (i.e., 'Revised 0' is the revised model fit without any mark-recapture data from 2014-2017. 'Revised 4' is the revised model fit with mark-recapture data for four years, 2014-2017. 'Revised 1' used only 2014 mark-recapture data, 'Revised 2' used only 2014 and 2015 mark-recapture data, and so on up through 'Revised 4'.

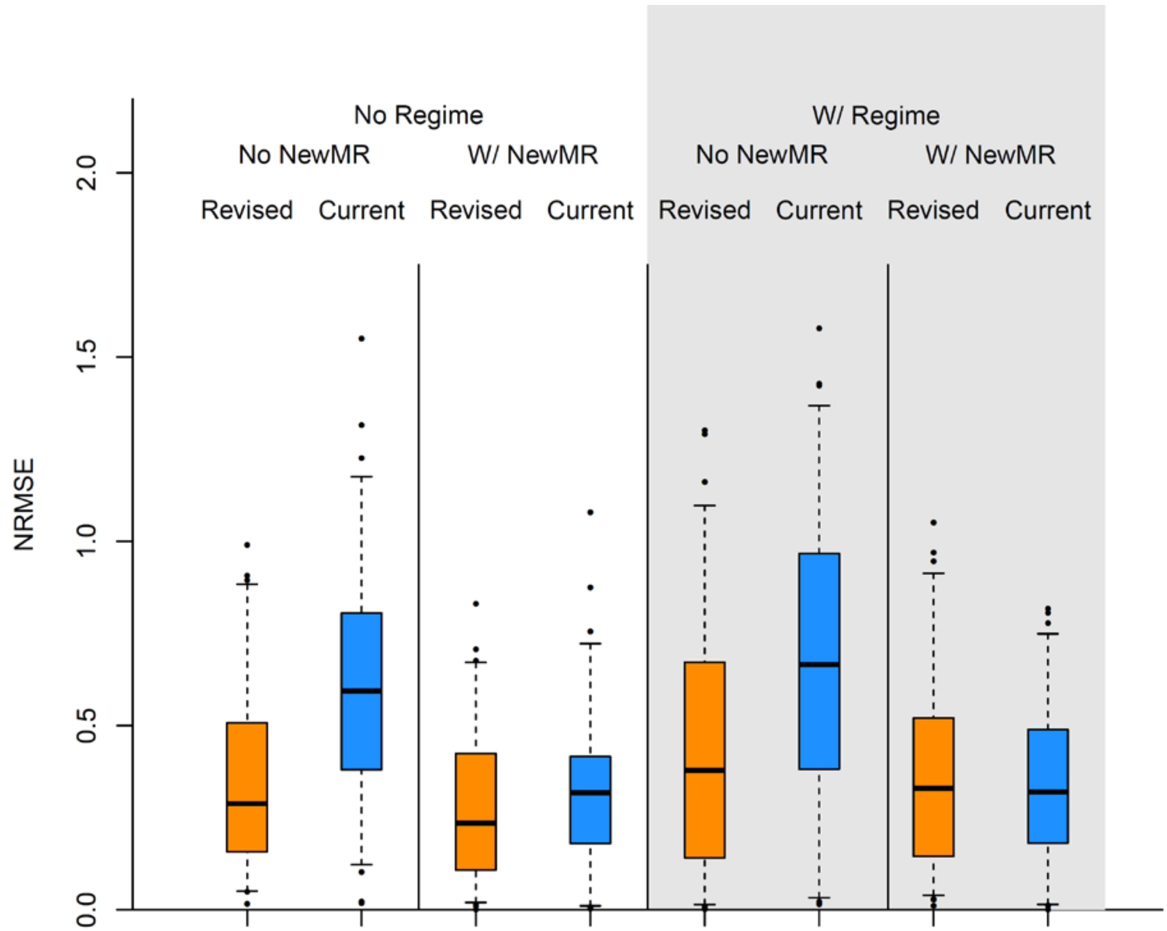

Figure 3. Boxplots of normalized root mean squared error (NRMSE) for Kuskokwim River Chinook salmon run reconstruction model fits to simulated data from an operating model under various biological scenarios and model structures. Box plots show the distribution from 100 simulations. The colors represent model estimates from the revised model structure (orange, left-most of each pair) and current model structure (blue, right-most). Column labels describe which model was used (Revised, Current), whether or not new (2014-2017) mark-recapture estimates were used to fit the models (No NewMR, W/ NewMR), and whether or not the underlying population dynamics were subject to regime shifts (also indicated by grey background).

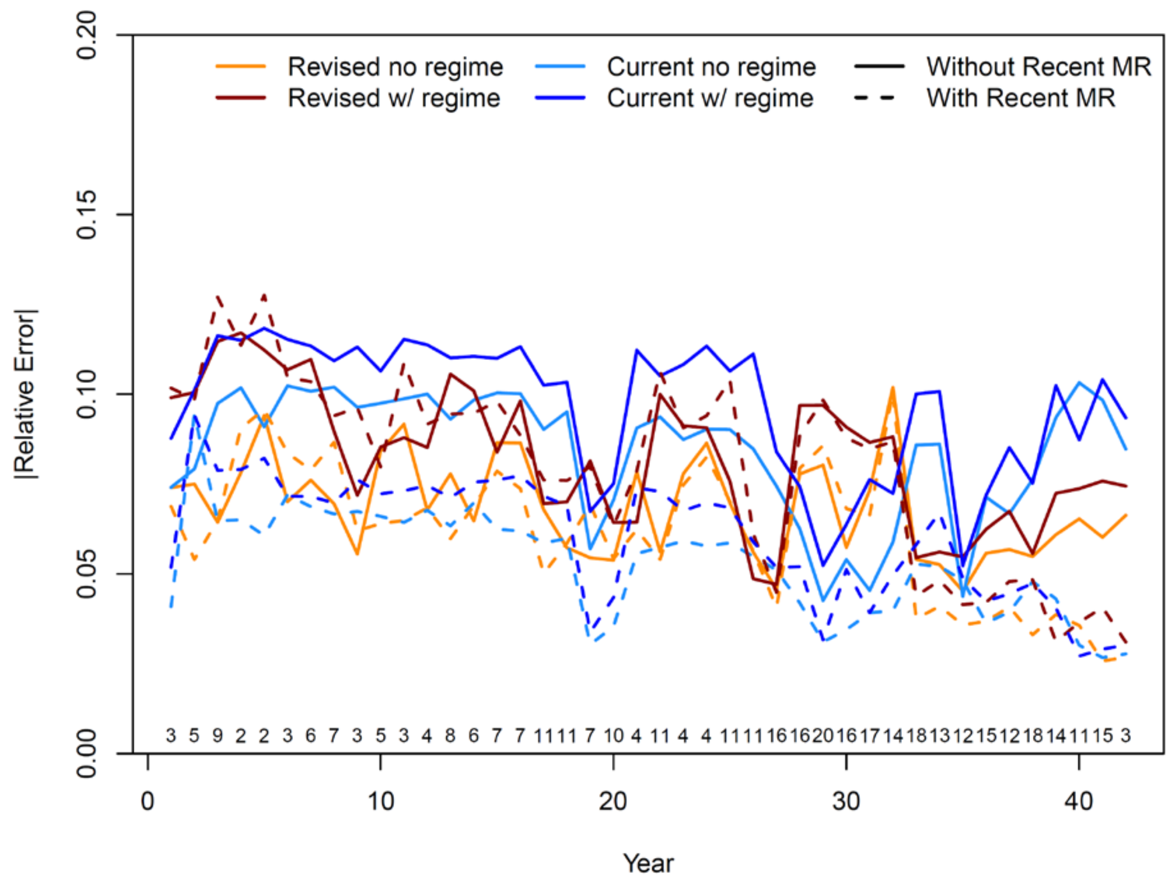

Figure 4. Median absolute values of relative error (expressed as proportional difference from the true value) through time in run reconstruction model estimates for 100 simulated time-series. Solid lines represent those in which the recent (2014-2017) mark-recapture estimates were not used in the run reconstruction model. Dashed lines represent scenarios in which the recent mark-recapture estimates were used in the run reconstruction model. Lines in orange shades represent results from the revised run reconstruction model, while blue shaded lines represent those from the current run reconstruction model. Darker shades of each color represent scenarios with population dynamics subject to regime shifts, while lighter shades represent scenarios without regime shifts. Numbers above x-axis indicate the number of escapement indices available each year, which are the same as in the real data set available for the Kuskokwim River.

Table 2. Comparisons of estimates of Kuskokwim River Chinook salmon abundance (run size in thousands of fish) from run reconstruction models using the revised and current model structures, and mark-recapture estimates of river-wide abundances. (a) Point estimates of Chinook salmon abundance from each of the two models when there are no recent mark-recapture estimates used and when there are all four recent mark-recapture estimates used. Grey boxes indicate years in which mark-recapture estimates are available. (b) Proportional differences between model estimates from part (a) compared to the revised model estimates when all recent mark-recapture estimates are used in the run reconstruction. Proportional differences were calculated as [(run size$_{model\ i}$ - run size$_{model\ j}$)/(run size$_{model\ j}$)], where model j is the analogous 'revised model' fit with all (2014-2017) mark-recapture data.

a)	No Recent Mark-Recapture		All Recent Mark-Recapture	
Year	Revised Model	Current Model	Revised Model	Current Model
2010	114.9	116.4	113.7	112.6
2011	115.7	122.3	114.3	117.7
2012	81.2	84.3	79.4	82.2
2013	86.0	84.8	85.0	83.5
2014	91.6	106.8	80.5	90.3
2015	131.3	134.4	124.4	126.1
2016	130.6	140.8	131.1	133.7
2017	138.3	136.1	133.3	133.1

b)	No Recent Mark-Recapture		All Recent Mark-Recapture	
Year	Revised Model	Current Model	Revised Model	Current Model
2010	0.010	0.023	0.000	-0.010
2011	0.012	0.071	0.000	0.030
2012	0.022	0.061	0.000	0.035
2013	0.011	-0.003	0.000	-0.018
2014	0.139	0.327	0.000	0.123
2015	0.055	0.080	0.000	0.014
2016	-0.004	0.074	0.000	0.020
2017	0.037	0.021	0.000	-0.001

Table 3. Comparisons of Kuskokwim River Chinook salmon run reconstruction estimates using the revised model structure and observed data, with different numbers of recent mark-recapture estimates available. (a) Point estimates of run size (thousands of fish) from the model fits with different numbers and arrangements of recent mark-recapture estimates used. Grey cells indicate years in which mark-recapture estimates were included in the run reconstruction. (b) Proportional differences (calculated as in Table 2) between all model estimates from (a) compared to the new model estimates when all recent mark-recapture estimates were used in the run reconstruction. Blue shading indicates underestimates; red shading indicates overestimates.

a) Number of Recent Mark-Recapture Estimates Used

	No Estimates	Later Estimates			All Estimates	Earlier Estimates		
Year	0	1	2	3	4	3	2	1
2010	114.9	114.5	114.6	114.3	113.7	113.8	113.7	113.9
2011	115.7	115.2	115.3	115.0	114.3	114.4	114.2	114.4
2012	81.2	80.7	80.8	80.4	79.4	79.6	79.3	79.6
2013	86.0	85.7	85.7	85.5	85.0	85.1	85.0	85.1
2014	91.6	91.1	91.2	90.8	80.5	80.5	80.5	80.5
2015	131.3	130.4	130.6	124.4	124.4	124.4	124.4	128.6
2016	130.6	129.7	131.1	131.1	131.1	131.1	127.7	128.2
2017	138.3	133.3	133.3	133.3	133.3	135.5	135.0	135.5

b) Number of Recent Mark-Recapture Estimates Used

	No Estimates	Later Estimates			All Estimates	Earlier Estimates		
Year	0	1	2	3	4	3	2	1
2010	0.010	0.007	0.008	0.005	0.000	0.001	-0.001	0.001
2011	0.012	0.008	0.009	0.006	0.000	0.001	-0.001	0.001
2012	0.022	0.015	0.017	0.012	0.000	0.002	-0.002	0.002
2013	0.011	0.008	0.009	0.006	0.000	0.001	-0.001	0.001
2014	0.139	0.132	0.134	0.128	**0.000**	**0.000**	**0.000**	**0.000**
2015	0.055	0.048	0.050	**0.000**	**0.000**	**0.000**	**0.000**	0.033
2016	-0.004	-0.010	**0.000**	**0.000**	**0.000**	**0.000**	-0.026	-0.022
2017	0.037	**0.000**	**0.000**	**0.000**	**0.000**	0.016	0.012	0.017

Appendix B.

ADMB Code

```
//================================================================================
// Converting Alaska Department of Fish and Game
// Kuskokwim River Chinook salmon Run-reconstruction model
// Underlying Model Structure by Hamachan Hamazaki
// Major Changes to the model from original R
// 1. Model Structure Changed to use log-normal likelihoods on escapement
//    and drainagewide run
// 2. Common variance parameter for Weir and Aerial Escapement
// 3. Commercial fishery likelihood Changed from weekly effort (Concentrated
//    likelihood) to annual passage adjusted CPUE (log-normal likelihood with
//     common variance)
// 4. Removed Commercial fisery CPUE during the restricted fishery period
//    (Creg=2)
//================================================================================
//DATA SECTION
//================================================================================
DATA_SECTION
  init_int nyear; // number of years with datae
  init_int nweek; // number of weeks for harvest data
  init_int nweir; // number of weir sites
  init_int nair;  // number of aerial survey sites

  init_matrix testf(1,nyear,1,nweek); //Estimates of run proportion by week

  init_matrix ceff(1,nyear,1,nweek);  // Weekly effort commercial fishery
  init_matrix ccat(1,nyear,1,nweek);  // Weekly catch commercial fishery
  init_matrix creg(1,nyear,1,nweek);  // Weekly indicator of fishery regulation

  init_vector inriv(1,nyear);         // Annual in-river run estimate
  init_vector inriv_sd(1,nyear);      // SD of annual in-river run estimate

  init_vector tcatch(1,nyear);          // Total harvest across all fishery sectors
  init_matrix esc_w(1,nyear,1,nweir);   // Weir escapement indices
  init_matrix esc_a(1,nyear,1,nair);    // Aerial escapement indices

  init_vector minesc(1,nyear);            // Minimum annual escapement
  init_vector minrun(1,nyear);            // Minimum annual run size
```

```
  init_vector ubrun(1,nyear);             // Upper bounds for annual run size estimation
//=========================================================
// Parameter Section
//=========================================================
PARAMETER_SECTION
  init_bounded_number_vector log_trun(1,nyear,minrun,ubrun,1);  // log drainage-wide run
  init_bounded_vector log_wesc(1,nweir,0,7,1);   // log slope for weir counts
  init_bounded_vector log_aesc(1,nair,0,7,1);    // log slope for aerial counts
  init_bounded_vector log_q(1,2,-12,-9,1);       // log Catchability for different fishery sectors
  init_bounded_number log_cvw(-10,1,1);    // log cv for weir counts
  init_bounded_number log_cva(-10,1,1);     // log cv for aerial counts
  init_bounded_number log_cvq(-10,1,1);     // log cv for commercial cpue
  vector t_run(1,nyear);              // storage for untransformed total runs
  vector wesc(1,nweir);               // storage for untransformed weir escapement slopes
  vector aesc(1,nair);               // storage for untransformed aerial escapement slopes
  vector q(1,2);                     // storage for untransformed catchabilities
  number cvw;                // storage for untransformed weir cv parameters
  number cva;                // storage for untransformed aerial cv parameters
  number cvq;                                  // storage for untransformed fishery cv parameters
  matrix wk_est(1,nyear,1,nweek);      // storage matrix for the estimated number of fish available for
harvest each week
  number tfw;                      // likelihood for weir counts
  number tfa;                      // likelihood for aerial counts
  vector tfc(1,3);                 // likelihood for commercial CPUE
  number tft;                      // likelihood for in-river run estimates
  vector esc(1,nyear);              // vector of total escapement estimates
  number var1;                      // storage for Weir Escapement variance parameter
  number var2;                      // storage for Aerial Escapement variance parameter
  number var3;                                     // storage for CPUE variance parameter
  matrix cpue(1,3,1,nyear);                        // storage matrix for annual CPUE by fishery
  matrix testp(1,3,1,nyear);                 // testfish weekly run proportion

  objective_function_value objf;

INITIALIZATION_SECTION
  log_trun  12.5;
  log_wesc  5.0;
  log_aesc  4.0;
  log_q  -11.0;
  log_cvw  1.0;
  log_cva  1.0;
  log_cvq  1.0;
//=========================================================
// Calculate Annual run adjusted CPUE
```

```
//=========================================================
PRELIMINARY_CALCS_SECTION
   int i,j,k;
  for (i=1;i<=nyear;i++)
  {
  for (j=1;j<=nweek;j++)
        {
// Unrestricted mesh catch
    if(creg(i,j)==1)
            {
                        cpue(1,i) += ccat(i,j)/ceff(i,j);
                        testp(1,i) += testf(i,j);
            }
// Restricted mesh catch
    if(creg(i,j)==2)
            {
                        cpue(2,i) += ccat(i,j)/ceff(i,j);
                        testp(2,i) += testf(i,j);
                        }
// Mono-filament mesh catch
    if(creg(i,j)==3 or creg(i,j)==5)
            {
                        cpue(3,i) += ccat(i,j)/ceff(i,j);
                        testp(3,i) += testf(i,j);
                                }
        }
  }

//============================================================
// Procedure Section
//==========================================================
PROCEDURE_SECTION

  objf = 0.0;

  convert_parameters_into_rates();

  evaluate_obj_func();

RUNTIME_SECTION
  maximum_function_evaluations 200000000
  convergence_criteria 1.e-30  //was 1.e-20 //low converge was .000001

//============================================================
```

```
// Function convert_parameters_into_rates
//===========================================================
FUNCTION convert_parameters_into_rates

   t_run=exp(log_trun);
   wesc=exp(log_wesc);
   aesc=exp(log_aesc);
   q=exp(log_q);
   cvw=exp(log_cvw);
   cva=exp(log_cva);
   cvq=exp(log_cvq);
   var1 = log(square(cvw)+1);
   var2 = log(square(cva)+1);
   var3 = log(square(cvq)+1);
//===========================================================
// Function evaluate_obj_func
//===========================================================
FUNCTION evaluate_obj_func
   int i,j,k,l,ctr1,ctr2,ctr3;

   tfw= 0.0;
   tfa= 0.0;
   tft= 0.0;
   tfc=0.0;


   for (i=1;i<=nyear;i++)
   {
    esc(i)=t_run(i)-tcatch(i);

    if(inriv(i)>0)
    {
     tft+= 0.5*square(log(inriv(i))-log(t_run(i)))/log(square(inriv_sd(i)/inriv(i))+1);
            // In-River run estimate likelihood
    }

    // Weir likelihoods
    for(j=1;j<=nweir;j++)
    {
      if(esc_w(i,j)>0)
      {
        tfw += log(sqrt(var1))+0.5*square(log(esc_w(i,j))-log(esc(i)/wesc(j)))/var1;
      }
    }
```

```
// Aerial likelihoods
    for(k=1;k<=nair;k++)
    {
     if(esc_a(i,k)>0)
     {
      tfa += log(sqrt(var2))+0.5*square(log(esc_a(i,k))-log(esc(i)/aesc(k)))/var2;
     }
    }

//===  Calculate annual run adjusted CPUE =================================

            if(cpue(1,i)>0)
            {
            tfc(1) += log(sqrt(var3))+0.5*square(log(cpue(1,i)/testp(1,i))-log(q(1)*t_run(i)))/var3;
            }
// Remove CPUE during the Restricted Period
//          if(cpue(2,i)>0)
//          {
//          tfc(2) += log(sqrt(var3))+0.5*square(log(cpue(2,i)/testp(2,i))-log(q(2)*t_run(i)))/var3;
//          }
            if(cpue(3,i)>0)
            {
            tfc(3) += log(sqrt(var3))+0.5*square(log(cpue(3,i)/testp(3,i))-log(q(2)*t_run(i)))/var3;
            }

   }

   objf+= tft+tfw+tfa+sum(tfc);
//==========================================================================
// Report Section
//==========================================================================
REPORT_SECTION
   report<<"Total Run"<< endl << t_run << endl;
   report<<"ObjFunc"<< endl << objf << endl;
   report<<"tfc"<<endl<< tfc <<endl;
   report<<"tft"<<endl<< tft <<endl;
   report<<"tfa"<<endl<< tfa <<endl;
   report<<"tfw"<<endl<< tfw <<endl;
   report<<"cvw"<<endl<< cvw << endl;
   report<<"cva"<<endl<< cva << endl;
   report<< "q" << endl << q << endl;
   report<< "wesc" <<endl<< wesc << endl;
   report<< "aesc" <<endl<< aesc << endl;
```

```
   report<<"tcatch"<<endl<< tcatch<<endl;
   report<<"TotalEscapement"<<endl<< esc << endl;
//==============================================================================
// Globals Section
//==============================================================================
GLOBALS_SECTION
  #include <df1b2fun.h>
  #include <math.h>
  #include <time.h>
  #include <statsLib.h>
  #include <adrndeff.h>
  #include <admodel.h>
  time_t start,finish;
  long hour,minute,second;
  double elapsed_time;

TOP_OF_MAIN_SECTION
  arrmblsize = 100000000;
  gradient_structure::set_MAX_NVAR_OFFSET(30000000);
  gradient_structure::set_GRADSTACK_BUFFER_SIZE(3000000);
  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;
```

Appendix C
Data Input

Appendix C1. –Independent estimates of Kuskokwim River Chinook salmon abundance, used to scale the run reconstruction model.

Conventional name:	Year	Total Run	Standard Error
	2003	222,145	16,055
	2004	381,958	36,322
	2005	312,353	21,083
	2006	376,291	31,094
	2007	251,781	16,315
	2014	80,399	8,605
	2015	124,421	9,362
	2016	131,090	12,632
	2017	133,292	15,702

Appendix C2. –Harvest of Kuskokwim River Chinook Salmon.

Conventional name:	Year	Commercial	Subsistence	Sport	Testfish	Total
	1976	30,735	58,606		1,206	90,547
	1977	35,830	56,580	33	1,264	93,707
	1978	45,641	36,270	116	1,445	83,472
	1979	38,966	56,283	74	979	96,302
	1980	35,881	59,892	162	1,033	96,968
	1981	47,663	61,329	189	1,218	110,399
	1982	48,234	58,018	207	542	107,001
	1983	33,174	47,412	420	1,139	82,145
	1984	31,742	56,930	273	231	89,176
	1985	37,889	43,874	85	79	81,927
	1986	19,414	51,019	49	130	70,612
	1987	36,179	67,325	355	384	104,243
	1988	55,716	70,943	528	576	127,763
	1989	43,217	81,175	1,218	543	126,153
	1990	53,502	109,778	394	512	164,186
	1991	37,778	74,820	401	149	113,148
	1992	46,872	82,654	367	1,380	131,273
	1993	8,735	87,674	587	2,515	99,511
	1994	16,211	103,343	1,139	1,937	122,630
	1995	30,846	102,110	541	1,421	134,918
	1996	7,419	96,413	1,432	247	105,511
	1997	10,441	79,381	1,227	332	91,381
	1998	17,359	81,213	1,434	210	100,216
	1999	4,705	72,775	252	98	77,830
	2000	444	67,620	105	64	68,233
	2001	90	78,009	290	86	78,475
	2002	72	80,982	319	288	81,661
	2003	158	67,134	401	409	68,102
	2004	2,305	96,788	857	691	100,641
	2005	4,784	85,090	572	557	91,003
	2006	2,777	90,085	444	352	93,658
	2007	179	96,155	1,478	305	98,117
	2008	8,865	98,103	708	420	108,096
	2009	6,664	78,231	904	470	86,269
	2010	2,732	66,056	354	292	69,434
	2011	747	62,368	579	337	64,031
	2012	627	22,544	0	321	23,492
	2013	174	47,113	0	201	47,488
	2014	35	11,234	0	497	11,766
	2015	8	16,124	0	472	16,604
	2016	0	30,693	0	522	31,215
	2017	0	16,380	0	290	16,670

Appendix C3. –Weir escapement counts of Kuskokwim River Chinook salmon.

Conventional name:	Year	Kwethluk	Tuluksak	George	Kogrukluk	Tatlawiksuk	Takotna
	1976				5,638		
	1977						
	1978				14,533		
	1979				11,393		
	1980						
	1981				16,089		
	1982				13,126		
	1983						
	1984				4,922		
	1985				4,442		
	1986						
	1987						
	1988				8,028		
	1989						
	1990				10,093		
	1991		697		6,835		
	1992	9,675	1,083		6,563		
	1993		2,218		12,377		
	1994		2,916				
	1995				20,662		
	1996			7,770	13,771		423
	1997			7,810	13,190		1,197
	1998						
	1999				5,543	1,484	
	2000	3,547		2,959	3,242	807	345
	2001		954	3,277	7,475	1,978	718
	2002	8,963	1,346	2,443	10,025	2,237	316
	2003	14,474	1,064		12,008		390
	2004	29,111	1,475	5,488	19,819	2,833	461
	2005		2,653	3,845	21,819	2,864	499
	2006	19,899	1,033	4,355	20,205	1,700	541
	2007	14,438	377	4,011		2,032	412
	2008	6,300	683	2,563	9,750	1,075	413
	2009	5,828	362	3,663	9,528	1,071	311
	2010	1,772	207	1,498	5,812	546	181
	2011	4,217	287	1,547	6,731	992	136
	2012		542	2,201		1,116	228
	2013		194	1,292	1,819	495	97
	2014	3,213	338	2,993	3,732	1,904	
	2015	8,163	711	2,282	8,081	2,104	
	2016		909	1,663	7,056	2,494	
	2017	7,345	645	3,685	9,992	2,156	301

Appendix C4. –Peak aerial survey index counts of Kuskokwim River Chinook salmon.

Conventional name:	Year	Kwethluk	Kisaralik	Tuluksak	Salmon (Aniak)	Kipchuk	Aniak	Holokuk	Oskawalik	Holitna	Cheeneetnuk	Gagaryah	Pitka	Bear	Salmon (Pitka)
	1976									2,571				182	
	1977	2,075		424							2,407	897			1,930
	1978	1,722	2,417		289					2,766	268	504		227	1,100
	1979														682
	1980			975	1,186										
	1981						9,074							93	
	1982		81		126					521				127	413
	1983	471		186	231		1,909			1,069	173				572
	1984										1,177				545
	1985		63	142							1,002				620
	1986				336		424			650					
	1987				516	193			193		317				
	1988	622	869	195	244		954		80						474
	1989	1,157	152		631	1,598	2,109								452
	1990		631	200	596	537	1,255		113						
	1991		217	358	583	885	1,564								
	1992				335	670	2,284		91	2,022	1,050	328			2,536
	1993				1,082	1,248	2,687	233	103	1,573	678	419			1,010
	1994		1,243		1,218	1,520					1,206	807			1,010
	1995		1,243		1,446	1,215	3,171		326	1,887	1,565	1,193			1,911
	1996				985										
	1997		439		980	855	2,187		1,470	2,093	345	364			
	1998		457		425	443	1,930								
	1999								98	741					
	2000				238	182	714			301			151		362
	2001				598			52		4,156		143		175	1,033
	2002	1,795	1,727		1,236	1,615		513	295	733	730	452	165	211	1,255
	2003	2,661	654	94	1,242	1,493	3,514	1,096	844		810	1,095	197	176	1,242
	2004	6,801	5,157	1,196	2,177	1,868	5,362	539	293	4,051	918	670	290	206	1,138
	2005	5,059	2,206	672	4,097	1,679		510	582	1,760	1,155	788	744	367	1,801
	2006		4,734			1,618	5,639	705	386	1,866	1,015	531	170	347	862
	2007		692	173	1,458	2,147	3,984					1,035	131	165	943
	2008	487	1,074		589	1,061	3,222	418	213		290	177	242	245	1,033
	2009							565	379		323	303	187	209	632
	2010		235					229		587		62	67	75	135
	2011				79	116		61	26		249	96	85	145	767
	2012		588		49	193		36	51		229	178			670

--continued--

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Conventional name:	Year	Kwethluk	Kisaralik	Tuluksak	Salmon (Aniak)	Kipchuk	Aniak	Holokuk	Oskawalik	Holitna	Cheeneetnuk	Gagaryah	Pitka	Bear	Salmon (Pitka)
	2013	1,165	599	83	154	261	754		38	532	138	74		64	469
	2014		622		497	1,220	3,201	80	200		340	359			1,865
	2015		709		810	917		77		662					2,016
	2016		622			898	718	100	47	1,157	217	135		580	1,578
	2017				423	889	1,781	140	136	676	660	453	234	492	687

Note: Only surveys rated good or fair were used. Only surveys flown between July 17 and August 5, inclusive were used.

Appendix C5.– Proportion of total annual Chinook salmon run in District W-1 by week, as estimated by Bethel Test Fishery.

		Week 3	Week 4	Week 5	Week 6
Conventional name:	Year	6/10/ - 6/16	6/17 - 6/23	6/24 - 6/30	7/1 - 7/7
	1976				
	1977				
	1978				
	1979				
	1980				
	1981				
	1982				
	1983				
	1984	0.2243	0.2903	0.1488	0.1633
	1985	0.0000	0.0930	0.2427	0.4306
	1986	0.1503	0.4039	0.1656	0.1399
	1987	0.1988	0.3070	0.2368	0.1137
	1988	0.2080	0.3086	0.1786	0.0852
	1989	0.1769	0.2780	0.3474	0.0976
	1990	0.1434	0.2095	0.3325	0.1492
	1991	0.0593	0.2965	0.2942	0.1994
	1992	0.3466	0.1791	0.2132	0.1085
	1993	0.2148	0.4172	0.1270	0.0328
	1994	0.2883	0.3098	0.1396	0.1009
	1995	0.1566	0.3066	0.3005	0.0988
	1996	0.4007	0.2138	0.0963	0.0288
	1997	0.1913	0.5295	0.1196	0.0533
	1998	0.1166	0.2199	0.3866	0.1513
	1999	0.1360	0.1349	0.2469	0.1462
	2000	0.2089	0.3896	0.1530	0.0461
	2001	0.0791	0.4157	0.2510	0.1036
	2002	0.3547	0.2245	0.1601	0.1034
	2003	0.2764	0.2748	0.1433	0.0662
	2004	0.2130	0.2927	0.2513	0.0693
	2005	0.2335	0.2851	0.1876	0.1601
	2006	0.1299	0.3054	0.2935	0.1675
	2007	0.0996	0.2000	0.3114	0.2472
	2008	0.1524	0.2931	0.3057	0.1183
	2009	0.1955	0.2830	0.3460	0.0753
	2010	0.2190	0.3755	0.1517	0.1335
	2011	0.1188	0.2976	0.1996	0.1695
	2012	0.0508	0.2964	0.3308	0.2114
	2013	0.1681	0.3708	0.2654	0.0963
	2014	0.2834	0.2370	0.1217	0.0771
	2015	0.1859	0.2292	0.1520	0.1316
	2016	0.1696	0.1830	0.2085	0.1385
	2017	0.0899	0.2067	0.3202	0.1459

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Conventional name:	Year	Week 7 7/8 - 7/14	Week 8 7/15 - 7/21	Week 9 7/22 - 7/28	Week 10 7/29 - 8/26
	1976				
	1977				
	1978				
	1979				
	1980				
	1981				
	1982				
	1983				
	1984	0.0509	0.0522	0.0090	0.0173
	1985	0.1504	0.0247	0.0175	0.0410
	1986	0.0488	0.0097	0.0241	0.0000
	1987	0.0210	0.0344	0.0130	0.0094
	1988	0.0218	0.0419	0.0145	0.0192
	1989	0.0258	0.0190	0.0119	0.0112
	1990	0.0609	0.0136	0.0266	0.0256
	1991	0.0337	0.0430	0.0000	0.0000
	1992	0.0542	0.0554	0.0000	0.0118
	1993	0.0273	0.0097	0.0000	0.0000
	1994	0.0138	0.0122	0.0000	0.0061
	1995	0.0300	0.0050	0.0097	0.0050
	1996	0.0214	0.0000	0.0066	0.0033
	1997	0.0357	0.0119	0.0079	0.0059
	1998	0.0378	0.0116	0.0055	0.0000
	1999	0.1903	0.0297	0.0754	0.0297
	2000	0.0205	0.0410	0.0000	0.0183
	2001	0.0528	0.0367	0.0000	0.0156
	2002	0.0337	0.0137	0.0089	0.0132
	2003	0.0351	0.0255	0.0112	0.0042
	2004	0.0406	0.0537	0.0160	0.0021
	2005	0.0768	0.0062	0.0000	0.0168
	2006	0.0535	0.0114	0.0142	0.0105
	2007	0.0754	0.0316	0.0095	0.0032
	2008	0.0431	0.0334	0.0083	0.0139
	2009	0.0323	0.0164	0.0000	0.0049
	2010	0.0556	0.0185	0.0113	0.0103
	2011	0.0818	0.0130	0.0000	0.0031
	2012	0.0627	0.0201	0.0088	0.0127
	2013	0.0743	0.0108	0.0000	0.0000
	2014	0.0148	0.0146	0.0000	0.0029
	2015	0.0625	0.0591	0.0338	0.0238
	2016	0.0722	0.0296	0.0197	0.0112
	2017	0.1117	0.0473	0.0266	0.0265

Appendix C6. – Chinook Salmon catch and effort (permit-hours) by week for Kuskokwim River District W-1.

		Week 3 6/10 - 6/16			Week 4 6/17 - 6/23		
Conventional name:	Year	Catch	Effort	Net	Catch	Effort	Net
	1976	0	0	0	20,010	5,724	1
	1977	12,458	2,802	1	16,227	2,904	1
	1978	18,483	3,972	1	10,066	2,004	1
	1979	24,633	6,432	1	5,651	3,012	2
	1980	9,891	2,814	1	21,698	5,364	4
	1981	29,882	6,180	1	3,830	3,066	2
	1982	4,912	2,784	1	24,628	5,970	1
	1983	13,406	5,634	1	8,063	5,544	2
	1984	0	0	0	17,181	5,562	1
	1985	0	0	0	6,519	2,538	3
	1986	0	0	0	0	0	0
	1987	0	0	0	19,126	4,734	3
	1988	12,640	4,816	3	11,708	3,672	3
	1989	0	0	0	15,215	5,208	3
	1990	0	0	0	16,690	3,780	3
	1991	0	0	0	13,813	3,606	3
	1992	0	0	0	24,334	9,488	3
	1993	0	0	0	0	0	0
	1994	0	0	0	0	0	0
	1995	0	0	0	6,895	2,276	3
	1996	0	0	0	4,091	1,056	3
	1997	0	0	0	10,023	2,118	3
	1998	0	0	0	0	0	0
	1999	0	0	0	0	0	0
	2000	0	0	0	0	0	0
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	0	0	0	0	0	0
	2005	0	0	0	0	0	0
	2006	0	0	0	0	0	0
	2007	0	0	0	0	0	0
	2008	0	0	0	6,415	1,026	3
	2009	0	0	0	3,003	668	3
	2010	0	0	0	0	0	0
	2011	0	0	0	0	0	0
	2012	0	0	0	0	0	0
	2013	0	0	0	0	0	0
	2014	0	0	0	0	0	0
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0
	2017	0	0	0	0	0	0

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		Week 5 6/24 - 6/30			Week 6 7/1 - 7/7		
Conventional name:	Year	Catch	Effort	Net	Catch	Effort	Net
	1976	4,143	2,088	2	1,550	2,490	2
	1977	1,841	4,722	2	673	4,194	2
	1978	3,723	5,346	2	2,354	8,676	2
	1979	3,860	6,438	2	1,233	3,252	2
	1980	1,460	2,448	2	498	2,298	2
	1981	4,563	5,952	2	2,795	5,520	2
	1982	12,555	5,176	4	1,970	3,968	2
	1983	4,925	5,958	2	2,415	5,634	2
	1984	5,643	5,616	2	3,206	5,454	2
	1985	19,204	5,880	3	9,942	5,844	3
	1986	11,986	6,540	3	5,029	6,852	3
	1987	0	0	0	9,606	6,948	3
	1988	15,060	7,518	3	5,871	6,954	3
	1989	11,094	6,144	3	7,911	7,092	3
	1990	25,459	7,536	3	4,071	3,546	3
	1991	12,612	3,696	3	8,068	7,308	3
	1992	16,307	8,628	3	3,250	4,696	3
	1993	8,184	4,976	3	0	0	0
	1994	14,221	4,608	3	0	0	0
	1995	14,424	4,532	3	4,368	3,824	3
	1996	666	360	3	861	836	3
	1997	0	0	0	0	0	0
	1998	12,771	4,584	3	2,277	1,780	3
	1999	4,668	2,454	3	0	0	0
	2000	0	0	0	357	896	3
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	520	104	3	1,107	446	3
	2005	3,531	1,189	3	874	604	3
	2006	2,493	1,038	3	0	0	0
	2007	0	0	0	0	0	0
	2008	2,362	783	3	19	4	3
	2009	2,539	752	3	762	519	3
	2010	1,724	1,324	5	290	522	3
	2011	0	0	0	361	634	5
	2012	0	0	0	0	0	0
	2013	0	0	0	0	0	0
	2014	0	0	0	0	0	0
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0
	2017	0	0	0	0	0	0

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Conventional name:	Year	Week 7 7/8 - 7/14 Catch	Effort	Net	Week 8 7/15 - 7/21 Catch	Effort	Net
	1976	1,238	4,548	2	236	1,590	2
	1977	153	2,310	2	0	0	0
	1978	987	7,668	2	0	0	0
	1979	470	3,120	2	0	0	0
	1980	445	2,586	2	0	0	0
	1981	941	2,640	2	0	0	0
	1982	1,055	4,734	2	0	0	0
	1983	633	2,796	2	0	0	0
	1984	2,069	5,592	2	744	2,238	2
	1985	0	0	0	0	0	0
	1986	1,156	3,192	3	0	0	0
	1987	1,910	3,582	3	2,758	6,720	3
	1988	5,270	10,794	3	1,728	6,636	3
	1989	6,043	10,962	3	868	2,622	3
	1990	4,931	8,534	3	0	0	0
	1991	904	3,426	3	452	3,408	3
	1992	0	0	0	0	0	0
	1993	0	0	0	0	0	0
	1994	578	1,984	3	441	3,000	3
	1995	1,452	3,716	3	568	3,488	3
	1996	408	896	3	251	1,195	3
	1997	0	0	0	0	0	0
	1998	1,127	1,668	3	0	0	0
	1999	0	0	0	0	0	0
	2000	0	0	0	0	0	0
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	0	0	0	0	0	0
	2005	0	0	0	0	0	0
	2006	0	0	0	0	0	0
	2007	0	0	0	0	0	0
	2008	1	6	3	0	6	0
	2009	113	436	3	83	672	3
	2010	271	686	3	186	958	3
	2011	227	996	5	129	1,226	5
	2012	45	604	5	195	1,616	5
	2013	0	0	0	139	2,018	5
	2014	14	584	5	14	2,276	5
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0
	2017	0	0	0	0	0	0

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Conventional name:	Year	Week 9 7/22-7/28 Catch	Effort	Net
	1976	0	0	0
	1977	0	0	0
	1978	0	0	0
	1979	0	0	0
	1980	0	0	0
	1981	0	0	0
	1982	0	0	0
	1983	0	0	0
	1984	0	0	0
	1985	0	0	0
	1986	0	0	0
	1987	0	0	0
	1988	662	6,276	3
	1989	210	3,372	3
	1990	0	0	0
	1991	419	7,522	3
	1992	0	0	0
	1993	0	0	0
	1994	538	6,348	3
	1995	0	0	0
	1996	307	6,398	3
	1997	0	0	0
	1998	816	4,296	3
	1999	0	0	0
	2000	0	0	0
	2001	0	0	0
	2002	0	0	0
	2003	0	0	0
	2004	127	360	3
	2005	0	0	0
	2006	0	0	0
	2007	0	0	0
	2008	0	12	0
	2009	58	752	3
	2010	176	1,632	3
	2011	24	1,668	5
	2012	39	1,464	5
	2013	21	1,556	5
	2014	0	0	0
	2015	0	0	0
	2016	0	0	0
	2017	0	0	0

Key to column Net: 1= unrestricted mesh size, 2 = restricted to 6” or less (old gear), 3 = restricted to 6” or less new gear, 4 = unrestricted and restricted mesh periods in same week, and 5 = Personal Use harvest included.