Fishery Data Series No. 22-26

Historical Run and Escapement Estimates for Chinook Salmon Returning to the Nushagak River, 1968–2020

by

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and

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

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Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

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

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, 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
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ABSTRACT

A maximum likelihood model was developed to estimate the 1968–2020 drainagewide run size and escapement of Nushagak River Chinook salmon (*Oncorhynchus tshawytscha*). The model simultaneously combined information by direct observations of escapement at 8 locations (1 tower and 7 aerial surveys); harvest of fish from commercial, subsistence, and sport fisheries; inriver abundance indices from the Nushagak River sonar project; and inriver abundance estimates from acoustic tag and mark–recapture studies. Results showed that reconstructed total run size ranged from 74,000 to 629,000 Chinook salmon with an average run size of 282,000 fish, and escapement ranged from 49,000 to 476,000 fish with an average of 210,000 fish. The model estimated total run and escapement appeared to be reasonable and tracked well with previous estimates. The major deficiency of this model is the absence of overlapping, long-term escapement and run monitoring data.

Keywords: Chinook salmon *Oncorhynchus tshawytscha*, run reconstruction model, total run, escapement, Nushagak River

INTRODUCTION

The Nushagak River supports one of the largest Chinook salmon (*Oncorhynchus tshawytscha*) runs in Alaska. Historically, this run was utilized by the Yup'ik people and has more recently sustained local subsistence, commercial, and sport fisheries. In 1884, the first commercial fishery began in Nushagak Bay, but was primarily focused on sockeye salmon (Nelson, 1987). As this fishery developed, commercial harvest of Chinook salmon advanced rapidly, eventually reaching harvests of just under 200,000 fish in early 1980s (Nelson, 1987). Since 2000, Chinook salmon commercial harvest has ranged from 10,213 to 100,846 (Appendix A1). The first reports of guided Chinook salmon sport fishing in the Nushagak River occurred in 1963 (Paddock 1964), and the sport fishery rapidly grew during the 1970s and 1980s after guided sport fishing operators discovered the river could be successfully fished (Nelson 1987). Over the past 30 years, the popularity of the Nushagak River as a sport fishing destination has remained steady. Based on freshwater logbook data from 2006 to 2016, the Nushagak River saw an average of 53 guide businesses, 211 guides, and 2,500 clients annually, with Chinook salmon as the main target species.

Although escapement of Nushagak River Chinook salmon has been assessed since before statehood, the large geographic size of the drainage has made estimating Chinook salmon total run and spawning escapement challenging despite the methods that have been employed. From the mid-1960s to the late 1970s, the Alaska Department of Fish and Game (ADF&G) estimated escapement Nushagak River Chinook salmon using various combinations of tower counts and aerial surveys (Nelson 1987). In 1979, the department deployed a Bendix sonar to assess sockeye salmon on the lower Nushagak River near Portage Creek (river kilometer 40). At the time, the department acknowledged the potential of the sonar project to estimate Chinook salmon escapement, but elected to continue the aerial survey program until the Portage Creek sonar could provide reliable inseason and total estimates of escapement for Chinook salmon (Nelson 1987). By the mid-1990s, the department believed that the sonar project was providing reliable Chinook salmon escapement estimates. Subsequently, the aerial survey program was discontinued in 1995, and Chinook salmon passage was assessed solely by Bendix sonar. In the early 2000s, Bendix sonar technology was becoming increasingly less reliable and harder to service, and in 2005, the department began transitioning the Nushagak sonar project to Sound Metrics technology (i.e., Dual-frequency Identification Sonar [DIDSON] and Adaptive Resolution Imaging Sonar [ARIS]). During this transition, the department found the estimates based on Bendix soar were smaller than estimates based on DIDSON sonar. A Bendix-DIDSON conversion study was undertaken in 2011 to address this issue (Buck et al. 2012).

A drainagewide sustainable escapement goal (SEG) for Nushagak River Chinook salmon was established by the department in 2007 and revised in 2012 to the current SEG range of 55,000–120,000 fish (Fair et al. 2012). This SEG was based on the historical sonar counts and an assumption that the annual Chinook salmon sonar count was accurate. However, the Nushagak River sonar project does not ensonify the entire river channel. Results from a 2011–2014 acoustic tagging study estimated the proportion of Chinook salmon traveling outside the sonar beam range was 47–65% with a mean of 57% (Maxwell et al. 2020). Similarly, a 2014–2016 mark–recapture study estimated the abundance of adult Chinook salmon in the Nushagak River independently from the sonar estimate. Preliminary results from the 2014–2016 mark–recapture study estimated that the Portage Creek sonar project enumerated 76–81% of the adult Chinook salmon passing the sonar (data on file with Central Region Research Group, ADF&G, Division of Commercial Fisheries, Soldotna). These studies prompted the escapement goal review committee to recommend the creation of a run reconstruction model so the Nushagak Chinook salmon SEG can be based on the total run and escapement of Chinook salmon returning to the Nushagak River, rather than the relatively unreliable index count provided by the sonar assessment project (Erickson et al. 2018).

This report describes a newly developed model that reconstructs the annual total run and escapement of Chinook salmon that returned to the Nushagak River from 1968 through 2020. The model developed follows a general run reconstruction modeling approach that has been applied for reconstructing and setting escapement goals for salmon stocks throughout Alaska (Larson 2020; Hamazaki and Conitz 2015; Hamazaki 2021). The model provides an approach to combine and consider available information about Nushagak River Chinook salmon abundance and 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.

OBJECTIVES

Estimate spawning escapement and total run size of Chinook salmon in the Nushagak River from 1968 through 2020 using a statistical model for combining multiple data sources.

METHODS

MODEL OVERVIEW

The Nushagak Chinook salmon run reconstruction model follows an approach developed by Shotwell and Adkison (2004) and further extended by Bue et al. (2012) for data-limited situations. The model requires 2 datasets: tributary escapement observation timeseries (e.g., aerial, tower, weir, and sonar escapement surveys) and several years of accurate drainagewide inriver run or escapement observations. Under the maximum likelihood modeling framework, the model extracts an index of drainagewide escapement timeseries from tributary escapement observations, and simultaneously scales the index with drainagewide inriver run or escapement observations. The model was written in AD Model Builder (Appendix B; Fournier et al. 2012).

CRITICAL MODELING ASSUMPTIONS

For the Nushagak Chinook salmon run reconstruction modeling, tributary escapement observations consist of 7 aerial surveys (Nushagak River [from Nuyakuk to King Salmon River], Iowithla River, Klutispaw River, King Salmon River, Stuyahok River, Koktuli River, and Mulchatna River [from Koktuli River to Mosquito Creek]), 1 tower survey (Nuyakuk tower), and drainagewide inriver run consists of acoustic tagging and mark–recapture (Table 1, Figure 1). Additionally, inriver sonar counts (Bendix, DIDSON) are treated as indices of inriver run. Drainagewide run is a sum of inriver run and harvest occurred downriver of the inriver run observation site.

The following assumptions were made.

1. Inriver and escapement counts as a whole are indices of total inriver and escapement of Nushagak Chinook salmon.

This assumption was tested by examining the mutual correlation across various surveys (Figure 2). Correlations of determination (R^2) ranged from 0.01 to 0.82 among aerial surveys, of these the majority of the R^2 values are greater than 0.30 suggesting a high degree of consistency across escapement and inriver surveys (Figure 2). The wide range of R^2 values is partially due to outlier data, such as Bendix sonar counts in 1979 and 1980, Nushagak and King Salmon River aerial counts in 1997, and Klustipaw River aerial counts in 1998. Removing those data increased correlations.

2. There is no enroute mortality above the inriver run assessment site.

The model assumes Nushagak River Chinook salmon drainagewide escapement is inriver run minus harvest above the sonar, which ignores potential enroute mortality. Although enroute mortality is known to occur, it is considered minor. Radiotelemetry studies of Yukon River Chinook salmon showed that 7–8% of fish were unaccounted for (presumed as inriver mortality) during mainstem migration (Spencer et al. 2005, 2006, 2007).

MODEL DESCRIPTION

Chinook salmon annually returning to the Nushagak River (N_y) follow 4 stages from entry into the fishery to the spawning grounds (Figure 3).

1. Returning fish are harvested in the bay and lower river downstream of the sonar site ($C_{y,L}$).
2. Passage of fish at the sonar site ($N_{y,L}$), where abundance and stock proportions are estimated.
3. Fish passing upriver of sonar site which are harvested in sport and subsistence fisheries ($C_{y,U}$).
4. Fish escaped from the fishery (E_y) migrate to spawning tributaries ($e_{y,i}$) and are monitored by tributary escapement surveys.

The above 4 stages were modeled as follows.

1. Retuning fish are harvested in the bay and lower river downstream of sonar counting site ($C_{y,L}$).

Harvest at the mouth of river is a fraction ($U_{y,L}$: fishing harvest rate) of the run,

$$C_{y,L} = U_{y,L} \cdot N_y \text{ , where } U_{y,L} = 1 - \exp(-F_{y,L}). \quad (1)$$

where $F_{y,L}$ is instantaneous fishing mortality.

2. Passage of the remaining fish are monitored by sonar ($N_{y,L}$), where abundance and stock proportions are estimated.

$$N_{y,L} = N_y - C_{y,L} \text{ ,} \quad (2)$$

3. Fish passing upriver of sonar site are harvested ($C_{y,U}$).

Harvest upriver of sonar site is a fraction ($U_{y,U}$: fishing harvest rate) of those passing at sonar site.

$$C_{y,U} = U_{y,U} \cdot N_{y,L} \text{ , where } U_{y,U} = 1 - \exp(-F_{y,U}). \quad (3)$$

4. Fish escape from the fishery (E_y) migrate to spawning tributaries.

Drainagewide escapement (E_y) of Nushagak River Chinook salmon are those fish that escaped from the upriver fisheries. Observed escapement at each individual tributary (i) ($e_{y,i}$) is a fraction of the drainagewide escapement.

$$E_y = N_{y,L} - C_{y,U} \text{ ,}$$
$$e_{y,i} = E_y / K_i \quad (4)$$

where K_i is a model parameter and $K_i > 1$.

Observation Model and Likelihoods

For the Nushagak River, observation data consists of inriver run assessment (sonar, acoustic, and mark–recapture) and tributary escapements (aerial and tower counts). For this run reconstruction, all data were sourced from published reports or databases and were deemed sufficiently accurate for this analysis.

Inriver Run Assessments

Inriver run assessment data consists of Bendix, DIDSON, and ARIS sonar estimates, along with acoustic and mark–recapture surveys. Of those, inriver run assessment by acoustic and mark–recapture surveys were deemed accurate, whereas counts by Bendix and DIDSON sonar were considered indices (Maxwell et al. 2020).

Acoustic and mark–recapture

Assuming observations follow lognormal distributions, negative log-likelihoods of lower inriver surveys were constructed as:

$$l(\theta | data : Inriver) = +\sum_i \sum_y \frac{[\ln(\hat{N}_{y,L,i}) - \ln(N_{y,L})]^2}{2 \cdot \sigma^2_{r,y,i}} \quad (5)$$

where $\sigma^2_{r,y,i} = \ln(CV^2_{r,y,i} + 1) + \sigma^2_{r,i}$: $CV_{r,y,i}$ was observed or assumed inriver survey coefficient of variation (CV) of i^{th} method (acoustic, mark–recapture), whichever was larger, and $\sigma^2_{r,i}$ was an additional variance associated with i^{th} inriver survey. In the above equations, the inriver run was considered log-normally distributed. For the acoustic and mark–recapture estimates, the observed CV (6–12% for acoustic, 16–22% for mark–recapture) was considered too small. To correct those, the model specifies assumed CV and additional variance.

Bendix and DIDSON sonar

Assuming observations follow lognormal distributions, negative log-likelihood of inriver estimates by Bendix, DIDSON, and ARIS sonar consists of the following:

$$l\left(\theta \middle| data:Sonar\right) = +\sum_{i}\sum_{y}^{n} \ln(\sigma_{s,y,i}) + \frac{[\ln(N_{s,y,i}) - \ln(q_i \cdot N_{y,L})]^2}{2 \cdot \sigma^2_{s,y,i}} \quad (6)$$

where q_i is a survey coefficient of i^{th} equipment ($0 < q_i < 1$), indicating that sonar estimates are underestimates. $\sigma^2_{s,y,i} = \ln(CV^2_{s,y.i} + 1) + \sigma^2_{s,i}$: $CV_{s,y,i}$ is observed or assumed hydroacoustic survey CV of i^{th} equipment (Bendix, DIDSON), whichever larger, $\sigma^2_{s,i}$ is an additional variance associated with i^{th} equipment.

The observed CV of (1–10% for Bendix, 4–14% for DIDSON/ARIS) does not include uncertainties associated with the proportion of offshore migrating Chinook salmon. To correct those, the model includes minimum assumed CV and additional variance.

Escapement Counts

Escapement of Nushagak Chinook salmon has been historically observed at several locations throughout the drainage (Figure 1). Aerial surveys are conducted on 5 tributary streams that include the Iowithla, Klutispaw, King Salmon, Stuyahok, and Koktuli Rivers. In addition, aerial surveys are conducted on 2 sections of the mainstem of the Nushagak River: the section from Nuyakuk to the King Salmon River, and the Mulchatna section between the Koktuli and Mosquito Rivers. Escapement was historically observed via a tower survey on the Nuyakuk River.

Assuming observations follow lognormal distributions, negative log-likelihood of escapement estimates consists of the following:

$$l\left(\theta \middle| data:esc\right) = +\sum_{i}\sum_{y} \ln(\sigma_{e,i}) + \frac{[\ln(e_{y,i}) - \ln(\hat{e}_{y,i})]^2}{2 \cdot \sigma^2_{e,i}} \quad (6)$$

where $\sigma^2_{e,i} = \ln(CV^2_{e,i} + 1) + \sigma^2_{e,a,i}$: $CV_{e,i,j}$ is an assumed escapement survey CV of i^{th} drainage, $\sigma^2_{e,a,i}$ is an additional variance associated with the i^{th} drainage. Recorded aerial and tower surveys had no information about the survey CV. Accuracy and precisions of those surveys are highly influenced by survey conditions (e.g., weather, water condition). Thus, the CV was set to 0.5.

Harvests

Fishery harvests are separated into 2 geographic areas: (1) at the mouth below sonar, and (2) upriver of sonar (Figure 1).

Negative log-likelihood of the harvests consists of following:

$$l\left(\theta \middle| data : Harv\right) = +\sum_{i}\sum_{y}\frac{[\ln(C_{y,i}) - \ln(\hat{C}_{y,i})]^2}{2 \cdot \sigma_{c,i}^2} \quad (7)$$

$\sigma_{c,i}^2 = \ln(CV_{c,i}^2 + 1)$: $CV_{c,i}$ is an assumed harvest cv of i^{th} location (lower and upper). Harvest of Nushagak River Chinook salmon is considered accurate; thus, CV was set to 0.1.

MODEL DATA INPUTS AND DATA SOURCES

Large amounts of data were available to inform the model and estimate total run and escapement. Escapement and sonar estimates were obtained from reports and ADF&G databases (Table 1) were assumed to be final and sufficiently accurate. Nushagak River Chinook salmon harvest data in commercial, subsistence, and sport fisheries were obtained through ADF&G databases (Table 1). The model was scaled using 6 years of inriver run estimates from 2 methodologies (Appendix A4). Acoustic tag estimates of inriver abundance are considered final at this time (Maxwell et al. 2020), whereas mark–recapture estimates are still preliminary (data on file with Central Region Research Group, ADF&G, Division of Commercial Fisheries, Anchorage).

The Nushagak commercial fishery occurs in the Nushagak District located in Nushagak Bay. Catches from the commercial fishery probably include spawners from the Nushagak, Wood, and Igushik Rivers. However, for this model, all Chinook salmon commercial harvest from Nushagak Bay were assumed to be of Nushagak River origin. Harvest estimates for the Nushagak District were obtained through the ADF&G Fish Ticket Database and include fish that were taken in a commercial fishery but kept for personal use.

The Nushagak Area subsistence and sport fisheries takes place throughout Nushagak Bay and the Wood, Igushik, Snake, and Nushagak Rivers. Chinook salmon harvest in these fisheries that took place within the Nushagak River were assumed to be of Nushagak River origin and were split into *above sonar harvest* or *below sonar harvest* based on the reporting area (Figure 1, Appendix A1). The model assumed no Nushagak origin Chinook salmon were harvested in sport fisheries outside of the Nushagak River drainage. Chinook salmon harvest that occurred outside of the Nushagak River in the subsistence fishery was reviewed based on reporting area of where the harvest took place. Areas that were thought to primarily harvest Nushagak River bound fish were added to the *below sonar harvest* group (Figure 1, Appendix A1).

Model input data for the summer of 2020 is in various stages of finalization. All harvest data for the summer of 2020 is preliminary. Commercial harvest data is based on the daily harvest reports, whereas sport and subsistence harvest are based on the 5-year harvest average. Harvest data will not be finalized and available for the run reconstruction model again until the fall of 2021. All harvest data prior to 2020 is considered final. Escapement data used in the 2020 run reconstruction is considered final and fully vetted at this time (Appendices A2 and A3).

RESULTS

MODEL FITS TO DATA

A total of 177 model parameters were estimated, of which 10 parameters related to sonar and escapement were reported (Table 2). Except for DIDSON/ARIS, the CV of most parameters ranged from 0.24 to 0.34. Standard errors estimated by the model ranged from 0.00 to 0.70, which indicates that model estimated escapement CVs were higher than assumed (CV = 0.25). The root mean square error (RMSE) for acoustic survey was the lowest (0.07) followed by DIDSON/ARIS sonar (0.14), indicating that the model assumed those 2 datasets were more reliable (Figure 4). RMSE of escapement surveys ranged from 0.46 to 0.82, indicating great uncertainty. The main causes of high RMSEs were due to the model predicting high escapements during times of low drainagewide escapement estimates (Figure 4). Many of those occurred during the 1990s when aerial escapements were low despite Bendix estimates being high (Appendices A2 and A3). Those data disagreements resulted in high CV (0.09–0.40) of total run and escapement (Table 3).

RUN AND ESCAPEMENT

Reconstructed total run size ranged from 74,000 (2020) to 629,000 (1981) Chinook salmon with an average run size of 282,000 fish, and escapement ranged from 49,000 (2020) to 476,000 (1980) fish with an average of 210,000 fish (Table 3). Coefficient of variation of run size ranged from 0.09 to 0.40, indicating high uncertainty about historical run and escapement size (Table 3). Model estimated harvest rate was 27%, ranging from 9% to 50% with no obvious trends. The model suggests that Nushagak Chinook salmon run size increased from 1972 (128,000 fish) to 1989 (629,000 fish), declined sharply to less than 200,000 fish in the mid-1980s, then continued at approximately 300,000 fish during the 1990–2000s, and further declined during 2000–2020 (Table 3, Figure 5).

The largest runs occurred between 1978 and 1983, and the lowest runs occurred in 1972, 2010, 2017, and 2019–2020 (range 73,571–629,071; Table 3; Figure 5). Escapement estimates ranged from lows in 1972, 1986, 2007, and 2017–2020 to highs in early 1980s and early 2000s (range 49,227–475,580; Table 3; Figure 5). Coefficients of variation for the annual escapement estimates ranged from 0.09 to 0.55.

DISCUSSION

This is the first Nushagak Chinook salmon run reconstruction model to incorporate all existing historical escapement and inriver run size surveys within a single run reconstruction modeling framework. The model estimated total run and escapement and appeared to be reasonable and tracked well with previous estimates (Buck et al. 2012). The previous Nushagak River Chinook salmon run reconstruction was developed in 2012 prior to the acoustic tag and mark–recapture studies that occurred from 2012 to 2017, and thus considered sonar estimates as accurate (Buck et al. 2012). This model estimated that the survey coefficient (q) of DIDSON/ARIS to be 0.7, or that DIDSON sonar survey counts 70% of Chinook salmon in the river. Predictably, total run and escapement estimated by the model were larger than those produced by Buck et al. (2012), with an average percent difference of 25% (range -26–53%); and escapement estimates by the model were on average larger than those produced by Buck et al. (2012), with an average percent difference of 43% (range 38–65%; Table 4, Figures 6 and 7).

The major deficiency of this model is the absence of overlapping, long-term escapement and run monitoring data (Figure 8). Of the 53 years from 1968 to 2020, 16 years (1989, 1991–1994, 2000–2002, 2005–2010, and 2017–2018) of Chinook salmon escapement/run were assessed by only one survey instrument. True inriver run size of Nushagak River Chinook salmon was assessed by both acoustic tagging (2011–2014) and mark–recapture (2014–2016); however, the 2 methods resulted in different run size estimates. Estimates of total inriver run size derived from DIDSON sonar passage estimates differ greatly from the acoustic tag and mark–recapture estimates (Maxwell et al. 2020). The ratio of DIDSON sonar estimates to inriver run is 1:1.75 for acoustic and 1:1.23 for mark–recapture (Maxwell et al. 2020). These issues made it extremely difficult to reconstruct historical run size and escapement of Nushagak Chinook salmon. Consequently, estimates of run size were greatly affected by assumptions about precision of escapement and inriver surveys (e.g., observed and assumed survey CV, input sample size). Exploration of historical data, such as commercial catch CPUE or CPUE of inriver sport fisheries may improve model fit. Despite the challenges, we believe this methodology did an acceptable job of describing the pattern of abundance and provided reasonable estimates of the time series of total run size and escapement. Although the level of uncertainty in this model is relatively high, it is currently the best available method to reconstruct total run and escapement of Nushagak River Chinook salmon because it incorporates all available data and the uncertainty surrounding each survey methodology.

RECOMMENDATIONS

We recommend review and refinement of the input data used in this run reconstruction. Much of the historical aerial survey data is not documented and has not been validated. Moreover, several critical data are undocumented and have not received rigorous scientific review. These include the Bendix-DIDSON conversion (2003–2004), and the acoustic tag (2011–2014) and mark–recapture (2014–2016) inriver total passage estimates. Of these studies, documentation of Bendix-DIDSON conversion is inadequate to be included in the model. A reevaluation of Bendix-DIDSON conversion, and a better understanding of the differences between the acoustic tag and mark–recapture estimates, could significantly improve model performance.

Furthermore, a crucial flaw in the history of assessing Nushagak Chinook salmon is the absence of alternative assessment surveys. From 1999 to 2018, inriver run and escapement estimates were assessed solely by inriver sonar (DIDSON/ARIS) survey which is known to underestimate Chinook salmon abundance (Maxwell et al. 2020). The proportion of Chinook salmon migrating outside of the ensonified zone is inconsistent and possibly affected by environmental conditions and abundance of other fish migrating in the river. Adding tributary assessment projects such as weirs and aerial surveys may help assess the accuracy of sonar estimates on an annual basis. In 2019, the Nushagak River Chinook salmon aerial survey program was reinstated and had immediate benefits. The 2019 aerial surveys provided evidence that the sonar was probably undercounting Chinook salmon at a higher rate in 2019 than in previous years. Additionally, when both assessment methods (sonar and aerial survey) are operated in tandem, the paired data provides additional information about historical run size in years assessed only by aerial surveys. Since the 2 additional years of aerial survey data have not yet significantly increased model performance, we recommend the aerial surveys be conducted annually as they may improve model estimates in the future.

Last, we recommend performing a full review of the Nushagak sonar project. The Nushagak sonar project started in 1979 and the project was originally designed to enumerate sockeye salmon. Enumeration of other species was first started to determine which of the sonar echoes were not sockeye, but over time these non-sockeye counts began to be used for management. Assessing the current sonar protocols and improving them to better enumerate Chinook salmon could greatly improve model performance as the sonar project is the most influential and timely data source to estimating Chinook salmon abundance.

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REFERENCES CITED

Buck, G. B., C. B. Brazil, F. West, L. F. Fair, X. Zhang, and S. L. Maxwell. 2012. Stock assessment of Chinook, sockeye, and chum salmon in the Nushagak River. Alaska Department of Fish and Game, Fishery Manuscript Series No. 12-05, Anchorage

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 and Game, Fishery Data Series No. 12-49, Anchorage.

Cunningham, C. J., T. A. Branch, T. H. Dann, M. Smith, J. E. Seeb, L. W. Seeb, and R. Hilborn. 2016. A general model for salmon run reconstruction that accounts for interception and differences in availability to harvest. Canadian Journal of Fisheries and Aquatic Sciences 75(3):439–451.

Daigneault, M. J., J. J. Smith, and M. R. Link. 2007. Radiotelemetry monitoring of adult Chinook and sockeye salmon in the Nushagak River, Alaska, 2006. Report prepared by the Bristol Bay Science and Research Institute, Dillingham, AK 99576 http://dx.doi.org/10.13140/RG.2.2.21902.05449 (accessed October 13, 2022).

Erickson, J. W., G. B. Buck, T. R. McKinley X. Zhang, T. Hamazaki, and A.B. St. Saviour. 2018. Review of salmon escapement goals in Bristol Bay, Alaska, 2018. Alaska Department of Fish and Game, Fishery Manuscript No. 18-06, Anchorage.

Fair, L. F., C. E. Brazil, X. Zhang, R. A. Clark, and J. W. Erickson. 2012. Review of salmon escapement goals in Bristol Bay, Alaska, 2012. Alaska Department of Fish and Game, Fishery Manuscript Series No. 12-04, Anchorage.

Fournier, D. A., H. J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M. N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software 27:233–249.

Hamazaki, T. 2021. Stock-specific run and escapement of Yukon River Chinook salmon 1981–2019. Alaska Department of Fish and Game, Fishery Data Series No. 21-15, Anchorage.

Hamazaki, T., and J. M. Conitz. 2015. Yukon River summer chum salmon run reconstruction, spawner-recruitment analysis, and escapement goal recommendation. Alaska Department of Fish and Game, Fishery Manuscript Series No. 15-07, Anchorage.

Larson, S. 2020. 2019 Kuskokwim River Chinook salmon run reconstruction and 2020 forecast. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 3A20-02, Anchorage.

Maxwell, S. L., G. B. Buck, and A. V. Faulkner. 2020. Expanding Nushagak River Chinook salmon escapement indices to inriver abundance estimates using acoustic tags, 2011–2014. Alaska Department of Fish and Game, Fishery Manuscript Series No. 20-04, Anchorage.

Nelson, M. L. 1987. History and management of the Nushagak Chinook salmon fishery. Bristol Bay Data Report No. 87-1. Alaska Department of Fish and Game, Dillingham, Alaska.

Paddock, D. 1964. Inventory and cataloging of the sport fish and sport fish waters in the Bristol Bay and Lower Kuskokwim drainages. [*In*] Sport fish investigations of Alaska, 1963–64. Alaska Department of Fish and Game. Annual Report of Progress, Federal Aid in Fish Restoration Project 5(4):63–93.

Power, S. J. H., S. E. Burril, M. R. Link, S. T. Crawford, and G. Buck. *In prep*. Mark–recapture estimates of abundance and the size, sex, and age composition of Chinook salmon on the Nushagak River, Alaska, 2016. Alaska Department of Fish and Game, Fishery Data Series, Anchorage.

Shotwell, S. K., and M. D. Adkison. 2004. Estimating indices of abundance and escapement of Pacific salmon for data-limited situations. Transactions of the American Fisheries Society 133:538–558.

Spencer, T. R., T. Hamazaki, and J. H. Eiler. 2005. Mark–recapture abundance estimates for Yukon River Chinook salmon in 2002. Alaska Department of Fish and Game, Fishery Data Series No. 05-75, Anchorage.

Spencer, T. R., T. Hamazaki, and J. H. Eiler. 2006. Mark–recapture abundance estimates for Yukon River Chinook salmon in 2003. Alaska Department of Fish and Game, Fishery Data Series No. 06-31, Anchorage.

Spencer, T. R., and J. H. Eiler. 2007. Movements of summer chum salmon radiotagged in the lower Yukon River in 2004. Alaska Department of Fish and Game, Fishery Data Series No. 07-71, Anchorage.

TABLES AND FIGURES

Table 1.–Available Nushagak River Chinook salmon data.

Escapement	Description	Years	Citation
Aerial survey index streams	Composed of 7 index areas: Nushagak River (from Nuyakuk to King Salmon R.), Iowithla R., Klutispaw R., King Salmon R., Stuyahok R., Koktuli R., and Mulchatna R. (from Koktuli R. to Mosquito Creek).	1968–1988, 1990, 1995, 1996–1999, 2019–2020	Nelson (1987); Daigneault et al. (2006); ADF&G data (unpublished)
Nuyakuk tower	Tower counts on the Nuyakuk River.	1979–1983, 1985–2004	ADF&G data (unpublished)
Inriver run index			
Bendix Sonar	Older sonar technology installed at river kilometer (RKM) 40.	1979–1983, 1985–2004	ADF&G data (unpublished)
DIDSON Sonar	Current sonar technology installed at RKM 40.	2006–2020	ADF&G data (unpublished)
Inriver run estimate			
Acoustic tagging	DIDSON sonar counts expanded through the use of acoustic tagging. (Tagging provided an estimate of Chinook salmon passage beyond the ensonified area.)	2011–2014	Maxwell et al. (2020)
Mark–recapture	Independent estimate of inriver run done near the RKM 40 sonar site.	2014–2016	Power et al. (*In prep*)
Harvest			
Commercial	Annual commercial harvest in the Nushagak District.	1968–2020	ADF&G Fish Ticket Database
Sport	Annual estimates of harvest above and below the RKM 40 sonar site.	1968–2020	ADF&G Statewide Harvest Survey Database
Subsistence	Annual estimates of subsistence harvest in Nushagak Bay, the Nushagak River below the RKM 40 sonar, and in the Nushagak River above the RKM 40 sonar.	1968–2020	ADF&G data (unpublished)
Age composition data			
Commercial	Annual commercial harvest age composition in the Nushagak District.	1968–2020	ADF&G Age, Sex and Length (ASL) Database
Inriver run	Annual inriver age composition from Nuyakuk tower and Portage Creek sonar.	1968–2020	ADF&G ASL Database
Data not used			
Total escapement	Estimated from aerial survey counts and towers. Estimation method and data is undocumented.	1968–1985	Nelson et al. (1987)
Expanded total escapement	Historical total escapement that has been expanded to fit sonar.	1968–2011	Buck et al. (1998)
Bendix-DIDSON conversion	Historical Bendix sonar counts were converted to DIDSON equivalents from a partial Bendix-DIDSON side-by-side study. (Little documentation on the conversion methodology and data is reported.)	2002, 2005–2011	Buck et al. (2012)

Table 2.–Parameter estimates derived from the 2020 run reconstruction model.

	Parameter estimate (*k*)	95% Bound		CV
		Lower	Upper	
Sonar projects (*k*)				
Portage Creek (DIDSON)	0.39	0.26	0.52	0.13
Portage Creek (Bendix)	1.05	0.81	1.29	0.24
Aerial survey (*k*)				
Nushagak River	4.65	4.36	4.94	0.29
Iowithla River	5.68	5.40	5.95	0.28
Klutispaw River	5.76	5.49	6.03	0.27
King Salmon River	4.60	4.33	4.86	0.27
Stuyahok River	4.84	4.57	5.12	0.27
Koktuli River	4.29	4.01	4.56	0.27
Mulchatna River	5.42	5.08	5.77	0.34
Tower Project (*k*)				
Nuyakuk River	5.15	4.84	5.45	0.31

Table 3.–Annual drainagewide run and escapement of Nushagak River Chinook salmon from the 2020 run reconstruction model.

Year	Total run estimate	Lower 95% CI	Upper 95% CI	Total esc. estimate	Lower 95% CI	Upper 95% CI	Total run CV	Esc. CV
1968	253,216	160,008	400,721	167,570	52,546	282,594	0.24	0.35
1969	171,442	118,404	248,237	82,809	21,683	143,935	0.19	0.38
1970	236,807	154,384	363,233	142,080	42,490	241,670	0.22	0.36
1971	176,310	101,488	306,294	88,263	-7,545	184,071	0.30	0.55
1972	127,516	84,660	192,067	76,653	25,355	127,951	0.21	0.34
1973	157,787	91,248	272,845	119,850	33,760	205,940	0.29	0.37
1974	276,786	155,780	491,787	235,980	77,094	394,866	0.31	0.34
1975	288,659	156,987	530,768	259,300	83,566	435,034	0.33	0.35
1976	443,299	251,999	779,821	375,010	124,910	625,110	0.30	0.34
1977	304,980	188,973	492,200	213,740	68,866	358,614	0.25	0.35
1978	571,489	339,497	962,010	445,770	149,230	742,310	0.28	0.34
1979	477,347	307,491	741,033	310,560	103,140	517,980	0.23	0.34
1980	552,937	295,434	1,034,884	475,580	129,200	821,960	0.34	0.37
1981	629,071	426,011	928,922	423,140	181,160	665,120	0.20	0.29
1982	602,595	409,364	887,035	393,210	163,870	622,550	0.20	0.30
1983	560,733	369,217	851,590	409,800	177,320	642,280	0.22	0.29
1984	325,136	194,939	542,292	251,710	85,884	417,536	0.27	0.34
1985	402,721	253,972	638,591	325,250	140,146	510,354	0.24	0.29
1986	160,813	117,581	219,942	77,577	29,397	125,757	0.16	0.32
1987	177,726	119,690	263,904	115,790	46,388	185,192	0.21	0.31
1988	205,459	125,445	336,509	176,470	75,256	277,684	0.26	0.29
1989	248,451	141,603	435,923	219,340	79,750	358,930	0.30	0.32
1990	169,906	104,604	275,973	140,000	57,700	222,300	0.26	0.30
1991	327,748	185,736	578,342	291,360	105,332	477,388	0.31	0.33
1992	296,559	179,897	488,874	231,280	83,584	378,976	0.27	0.33
1993	359,331	220,735	584,949	273,030	98,658	447,402	0.26	0.33
1994	409,217	267,994	624,858	264,610	93,544	435,676	0.22	0.33
1995	292,143	197,166	432,873	193,990	80,642	307,338	0.21	0.30
1996	238,232	159,220	356,454	147,390	52,908	241,872	0.21	0.33
1997	247,707	166,748	367,971	165,560	68,694	262,426	0.21	0.30
1998	395,933	264,459	592,769	259,930	102,244	417,616	0.21	0.31
1999	238,709	142,389	400,184	213,310	90,076	336,544	0.28	0.29

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Table 3.–Page 2 of 2.

Year	Total run estimate	Lower 95% CI	Upper 95% CI	Total esc. estimate	Lower 95% CI	Upper 95% CI	Total run CV	Esc. CV
2000	181,861	104,588	316,228	154,440	53,938	254,942	0.30	0.33
2001	284,930	159,931	507,626	255,950	91,446	420,454	0.31	0.33
2002	297,152	175,993	501,721	242,350	87,000	397,700	0.28	0.33
2003	312,388	206,757	471,984	245,050	116,678	373,422	0.22	0.27
2004	445,076	304,236	651,114	322,340	154,510	490,170	0.20	0.27
2005	448,651	261,670	769,241	365,040	123,500	606,580	0.29	0.34
2006	278,173	180,741	428,129	176,770	58,258	295,282	0.23	0.34
2007	154,199	105,251	225,912	79,768	22,274	137,262	0.20	0.37
2008	175,080	103,113	297,277	137,740	45,226	230,254	0.28	0.34
2009	156,686	95,399	257,347	113,610	36,156	191,064	0.26	0.35
2010	122,884	76,909	196,343	84,770	27,562	141,978	0.25	0.34
2011	203,822	177,134	234,530	160,630	132,956	188,304	0.07	0.09
2012	334,369	282,379	395,931	307,600	251,202	363,998	0.09	0.09
2013	196,811	168,753	229,534	168,940	138,848	199,032	0.08	0.09
2014	155,593	131,020	184,775	123,270	96,920	149,620	0.09	0.11
2015	161,297	129,247	201,294	92,763	59,173	126,353	0.11	0.18
2016	219,916	173,581	278,619	172,840	121,388	224,292	0.12	0.15
2017	126,880	82,385	195,407	79,440	25,294	133,586	0.23	0.35
2018	190,995	117,407	310,705	137,420	44,992	229,848	0.26	0.34
2019	118,184	81,730	170,898	80,310	37,208	123,412	0.19	0.27
2020	73,571	50,395	107,405	49,227	21,623	76,831	0.20	0.29
Avg. (2010–2019)	183,075			140,798				

Note: The run reconstruction model produces estimates for all years every time the model is updated with new information.

Table 4.–Comparison of Nushagak River Chinook salmon annual drainagewide run and escapement estimates performed by Buck et al. (2012) and model.

	Total run estimate			Spawning escapement estimate		
Year	Buck et al. method	Model estimate	Percent difference	Buck et al. method	Model estimate	Percent difference
1968	228,551	253,216	10%	142,951	167,570	16%
1969	158,672	171,442	8%	69,970	82,809	17%
1970	196,081	236,807	19%	101,435	142,080	33%
1971	169,206	176,310	4%	81,237	88,263	8%
1972	101,001	127,516	23%	50,156	76,653	42%
1973	107,999	157,787	37%	70,130	119,850	52%
1974	183,287	276,786	41%	142,535	235,980	49%
1975	172,144	288,659	51%	142,791	259,300	58%
1976	273,657	443,299	47%	205,273	375,010	59%
1977	224,104	304,980	31%	132,907	213,740	47%
1978	393,636	571,489	37%	268,046	445,770	50%
1979	361,210	477,347	28%	194,335	310,560	46%
1980	366,555	552,937	41%	289,040	475,580	49%
1981	513,708	629,071	20%	307,527	423,140	32%
1982	509,867	602,595	17%	300,656	393,210	27%
1983	482,196	560,733	15%	331,270	409,800	21%
1984	237,104	325,136	31%	163,544	251,710	42%
1985	314,434	402,721	25%	236,899	325,250	31%
1986	165,950	160,813	3%	82,777	77,577	6%
1987	231,453	177,726	26%	169,562	115,790	38%
1988	141,908	205,459	37%	133,006	176,470	28%
1989	187,644	248,451	28%	158,551	219,340	32%
1990	156,663	169,906	8%	126,747	140,000	10%
1991	246,718	327,748	28%	210,346	291,360	32%
1992	232,103	296,559	24%	166,965	231,280	32%
1993	283,385	359,331	24%	197,098	273,030	32%
1994	334,604	409,217	20%	190,121	264,610	33%
1995	271,126	292,143	7%	173,014	193,990	11%
1996	193,029	238,232	21%	102,348	147,390	36%
1997	247,097	247,707	0%	165,062	165,560	0%
1998	370,883	395,933	7%	235,845	259,930	10%
1999	148,963	238,709	46%	123,906	213,310	53%

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Table 4.–Page 2 of 2.

Year	Total run estimate			Spawning escapement estimate		
	Buck et al. method	Model estimate	Percent difference	Buck et al. method	Model estimate	Percent difference
2000	137,979	181,861	27%	110,682	154,440	33%
2001	213,128	284,930	29%	184,317	255,950	33%
2002	228,919	297,152	26%	174,704	242,350	32%
2003	224,724	312,388	33%	158,307	245,050	43%
2004	351,928	445,076	23%	233,475	322,340	32%
2005	307,245	448,651	37%	223,950	365,040	48%
2006	218,031	278,173	24%	117,364	176,770	40%
2007	125,077	154,199	21%	50,960	79,768	44%
2008	128,445	175,080	31%	91,364	137,740	40%
2009	117,530	156,686	29%	74,781	113,610	41%
2010	93,677	122,884	27%	56,088	84,770	41%
2011	144,795	203,822	34%	102,258	160,630	44%
2012	194,523	334,369	53%	167,618	307,600	59%
2013	132,705	196,811	39%	104,794	168,940	47%
2014	95,075	155,593	48%	62,678	123,270	65%
2015	159,695	161,297	1%	91,090	92,763	2%
2016	165,189	219,916	28%	118,077	172,840	38%
2017	99,777	126,880	24%	52,298	79,440	41%
2018	144,597	190,995	28%	91,089	137,420	41%
2019	78,876	118,184	40%	41,017	80,310	65%
2020	61,202	73,571	18%	36,876	49,227	29%
Average	219,397	282,364	25%	147,355	209,739	35%

Note: Buck et al. (2012) method uses the Nushagak sonar count and adds or subtracts harvest to come up with total run and escapement estimates.

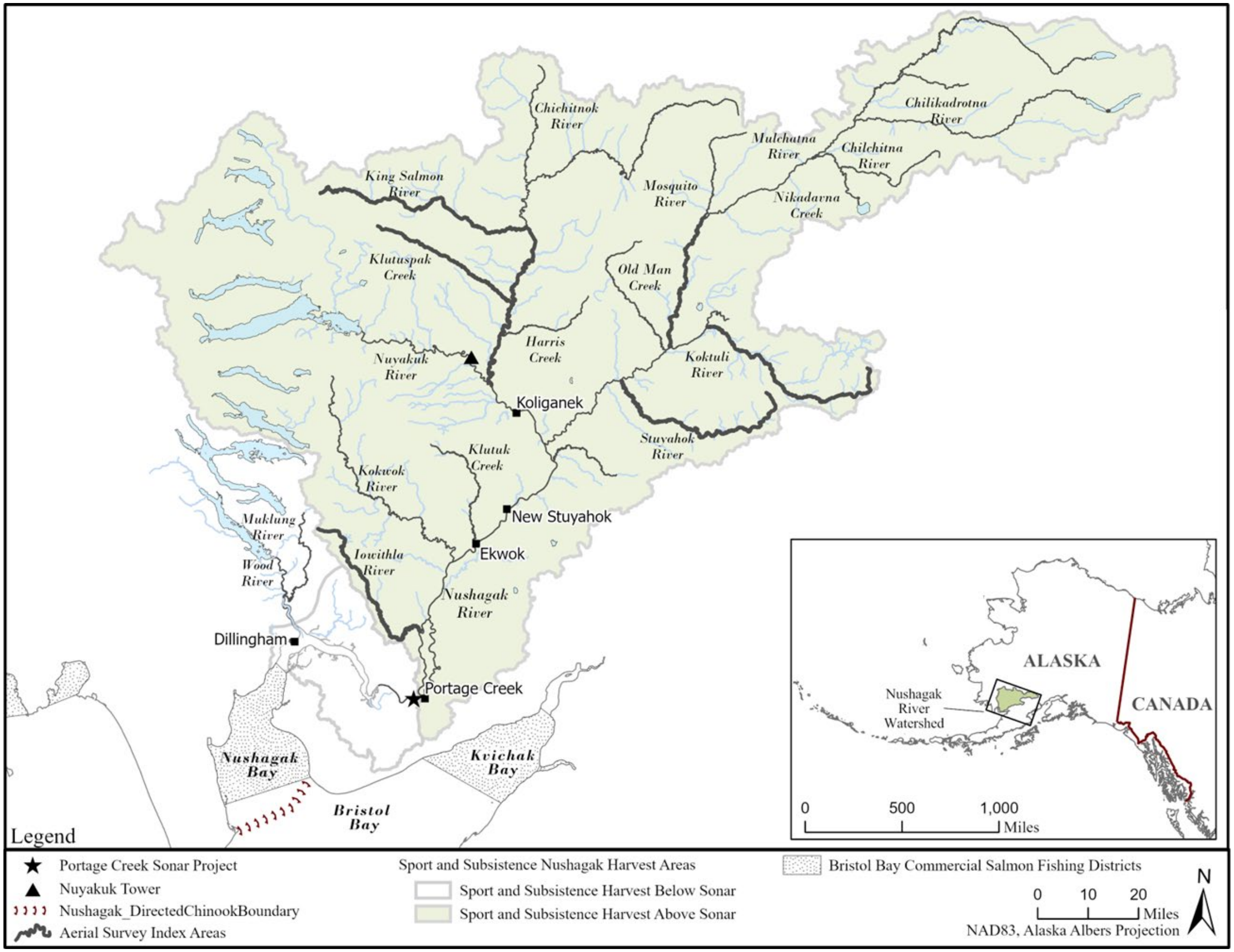

Figure 1.–Map of the study area from which data were obtained for the Nushagak River Chinook salmon run reconstruction model.

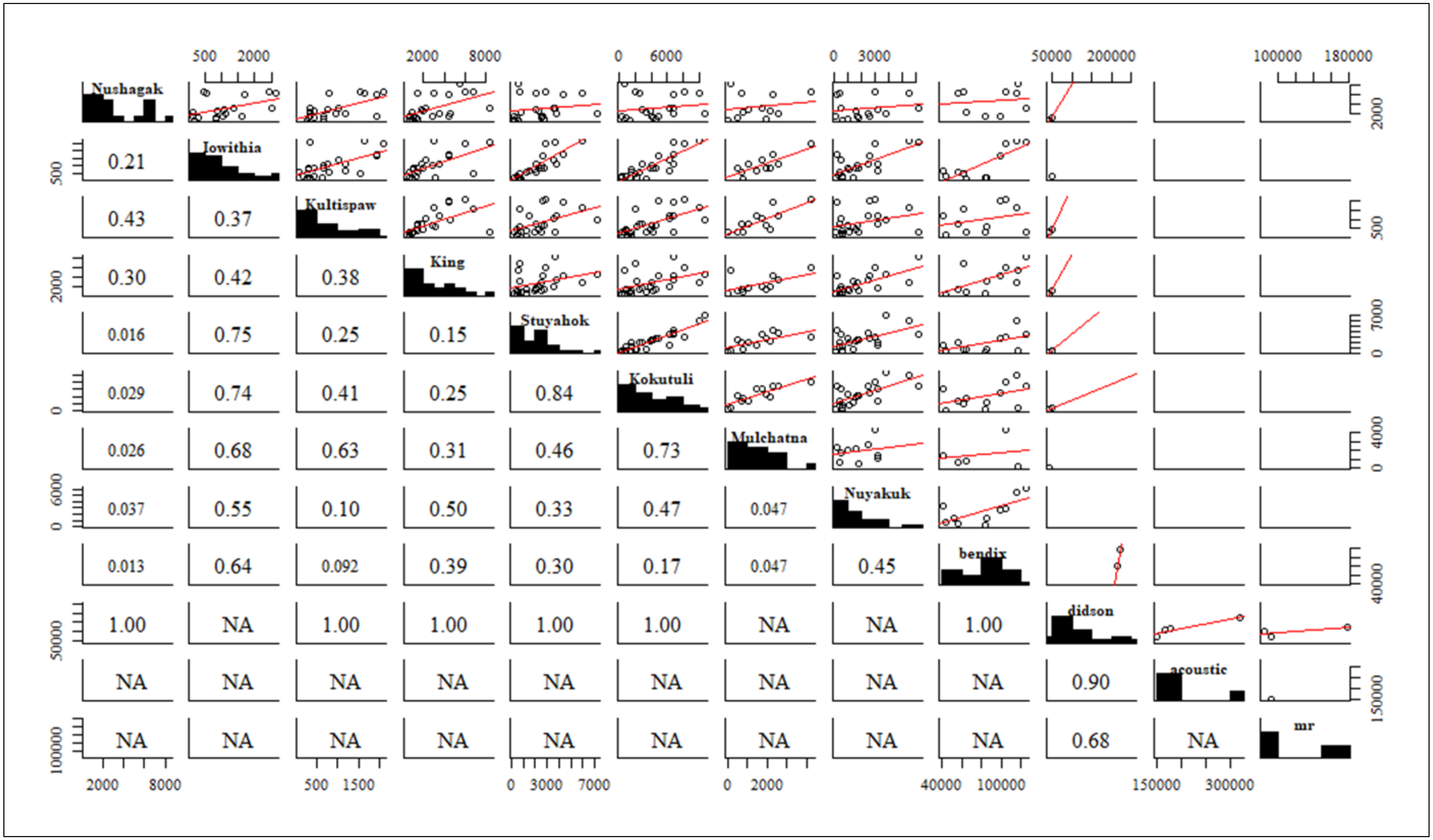

Figure 2.–Mutual correlation amongst historical surveys of Nushagak River Chinook salmon abundance.

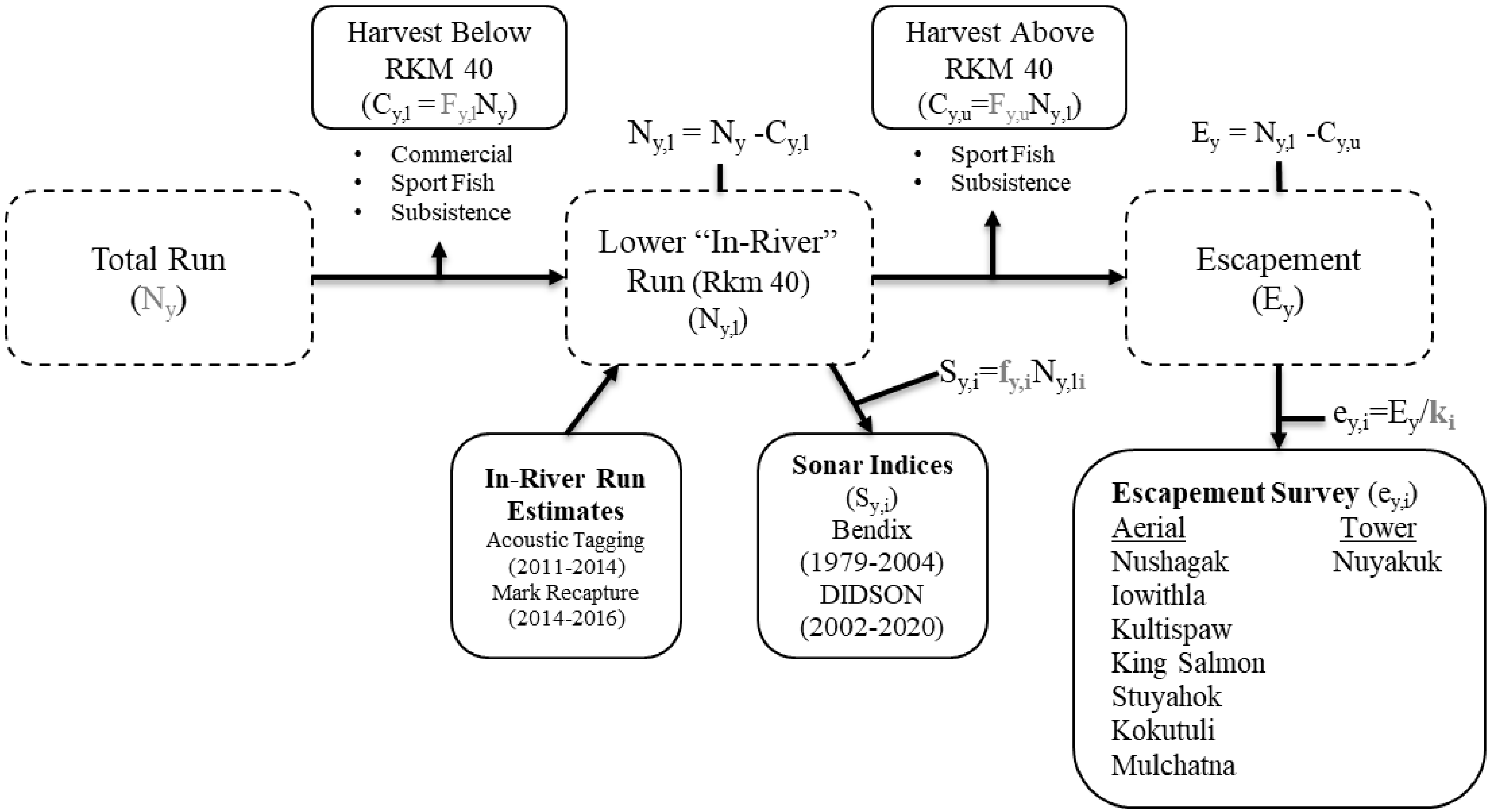

Figure 3.–Simple model diagram of the 2020 Nushagak Chinook Run Reconstruction Maximum Likelihood model.

Note: Black outside boarders represent available data, grey variables represent what is estimated, and dashed outlines represent what is being modeled.

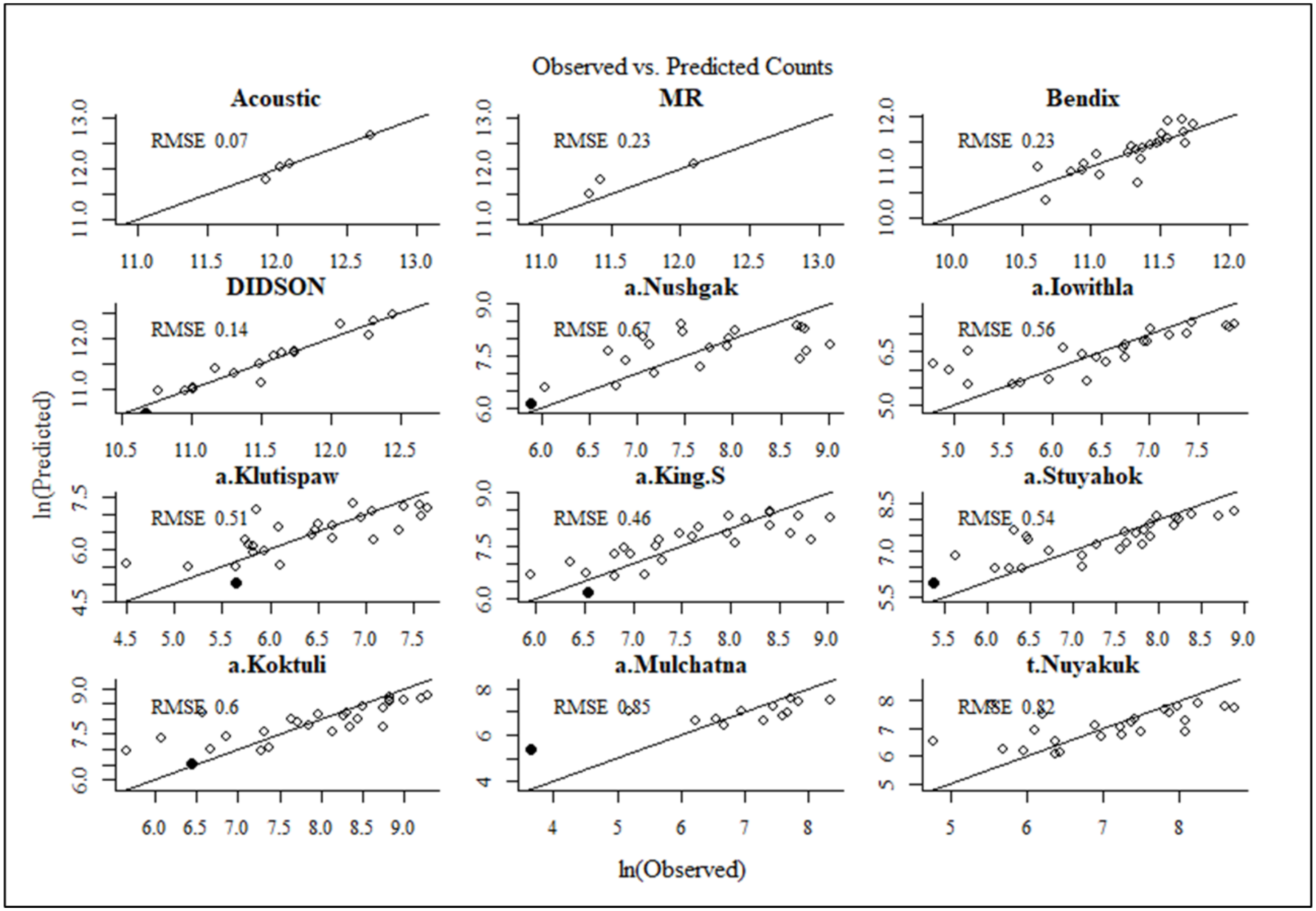

Figure 4.–Observed versus model estimated escapement counts.

Note: The diagonal line within each subplot represents the 1:1 line, which is the point at which observed and estimated escapements are equal. Dots that fall below the 1:1 line indicate that the observed counts are higher than the model estimates, and the opposite is also true. The top 2 left subplots titled "Acoustic and MR" represent the 2011–2014 Hydroacoustic and 2014–2016 mark–recapture total run estimates used to scale the model. A lower case "a" indicates aerial survey while a lower case "t" indicates tower counts.

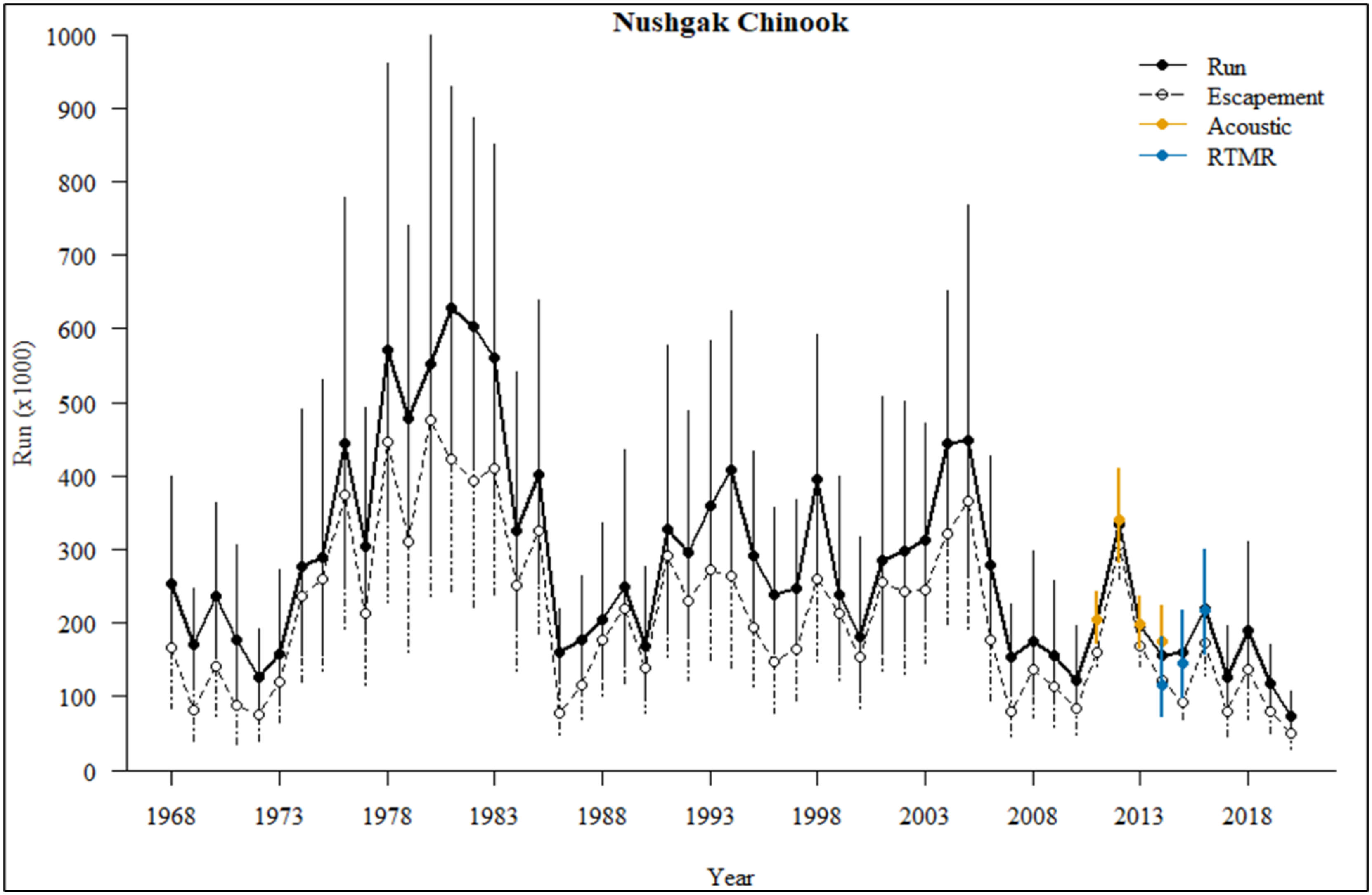

Figure 5.–Annual run (black circles/line) and escapement (open circles/hatched line) estimates with 95% confidence intervals estimated from the 2020 run reconstruction model. Yellow dots are hydroacoustic drainagewide run size estimates and 95% confidence intervals for years 2011–2014 and blue dots are mark–recapture drainagewide run size estimates and 95% confidence intervals for years 2014–2016 used to scale the model.

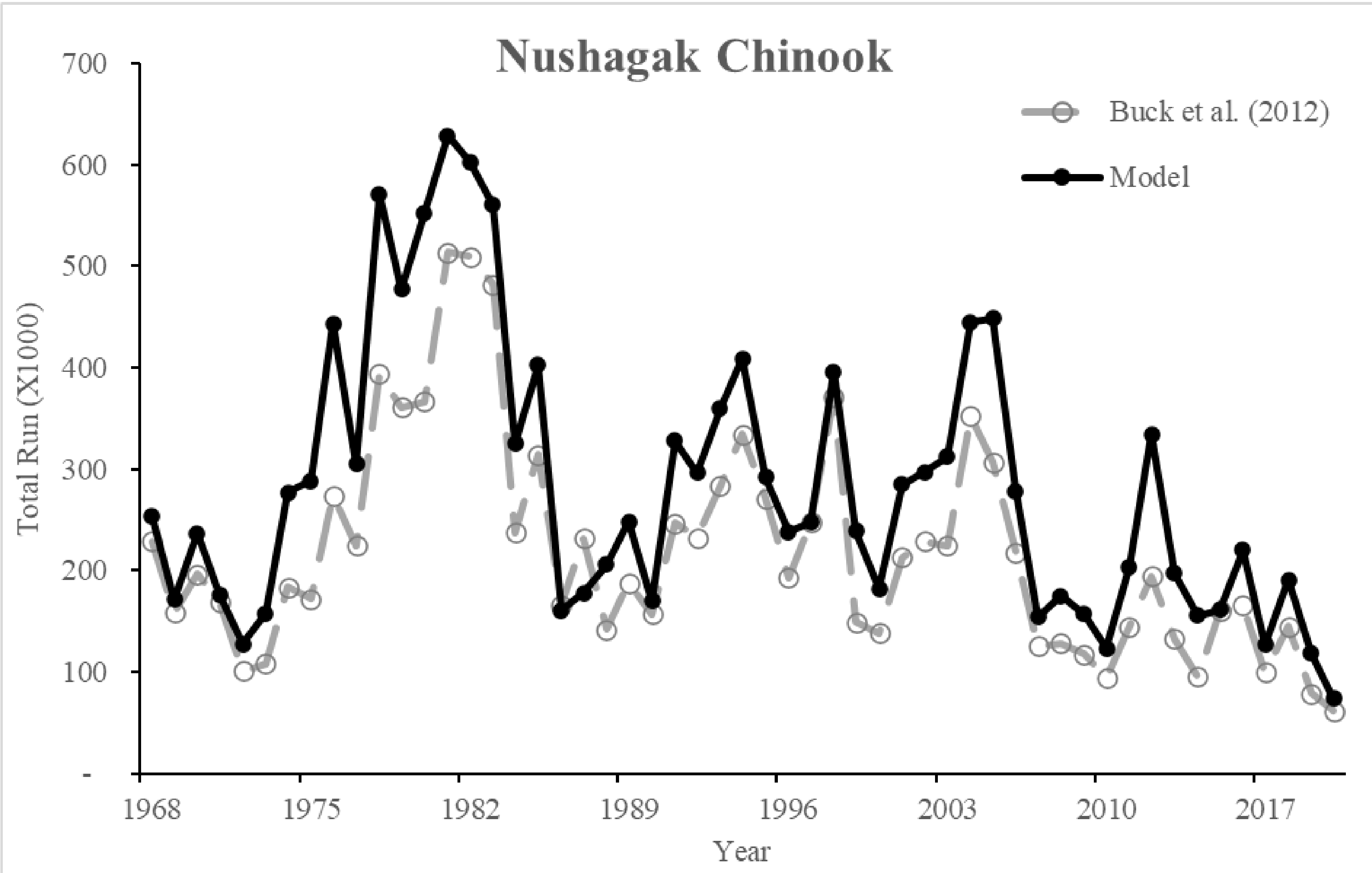

Figure 6.–Comparison of annual estimates of total run of Chinook salmon to the Nushagak River performed by the run reconstruction model (black circles/line) and the Buck et al. (2012) method (open circles/grey line).

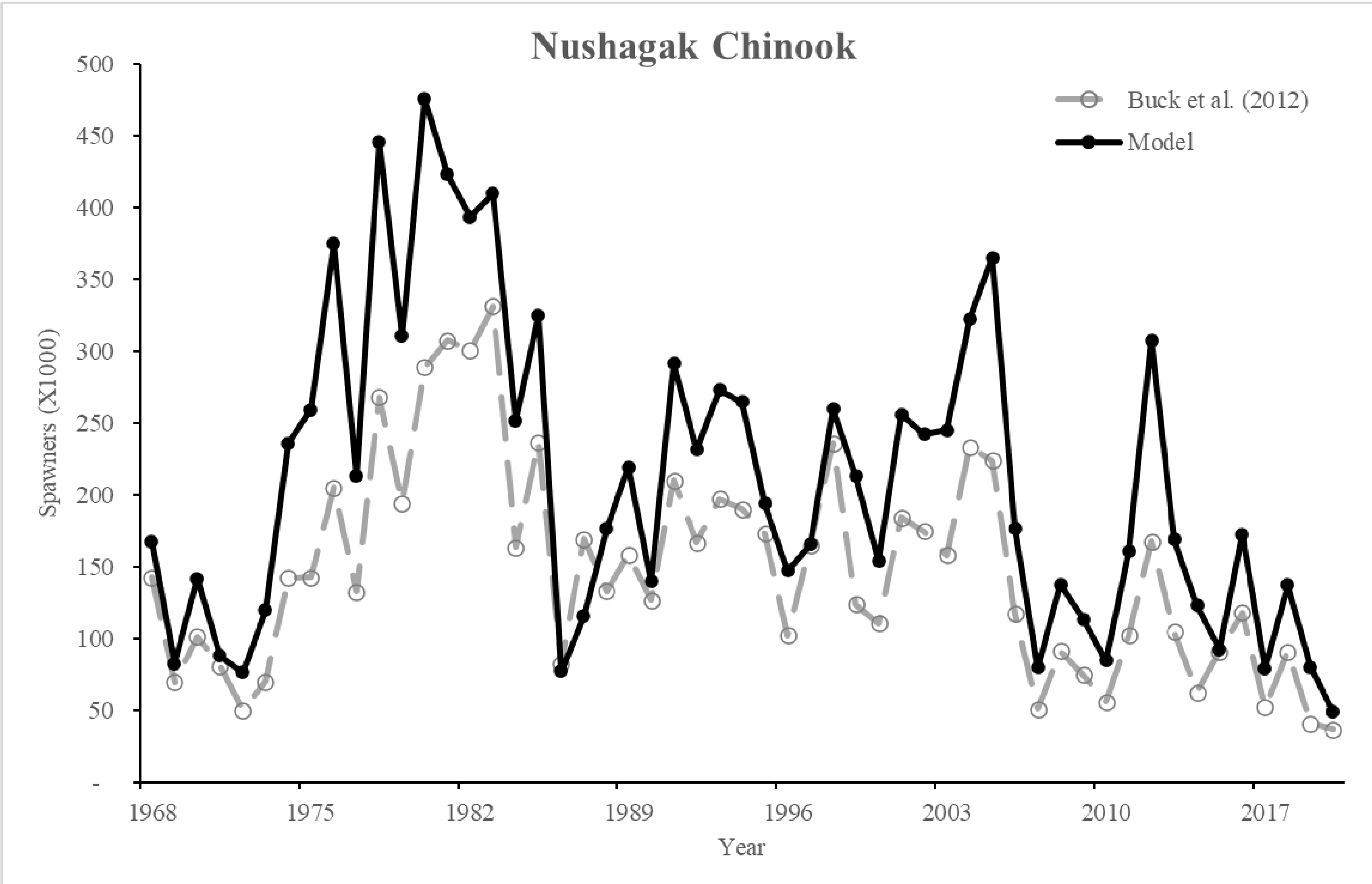

Figure 7.–Comparison of annual escapement estimates of Chinook salmon to the Nushagak River performed by the run reconstruction model (black circles/line) and the Buck et al. (2012) method (open circles/grey line).

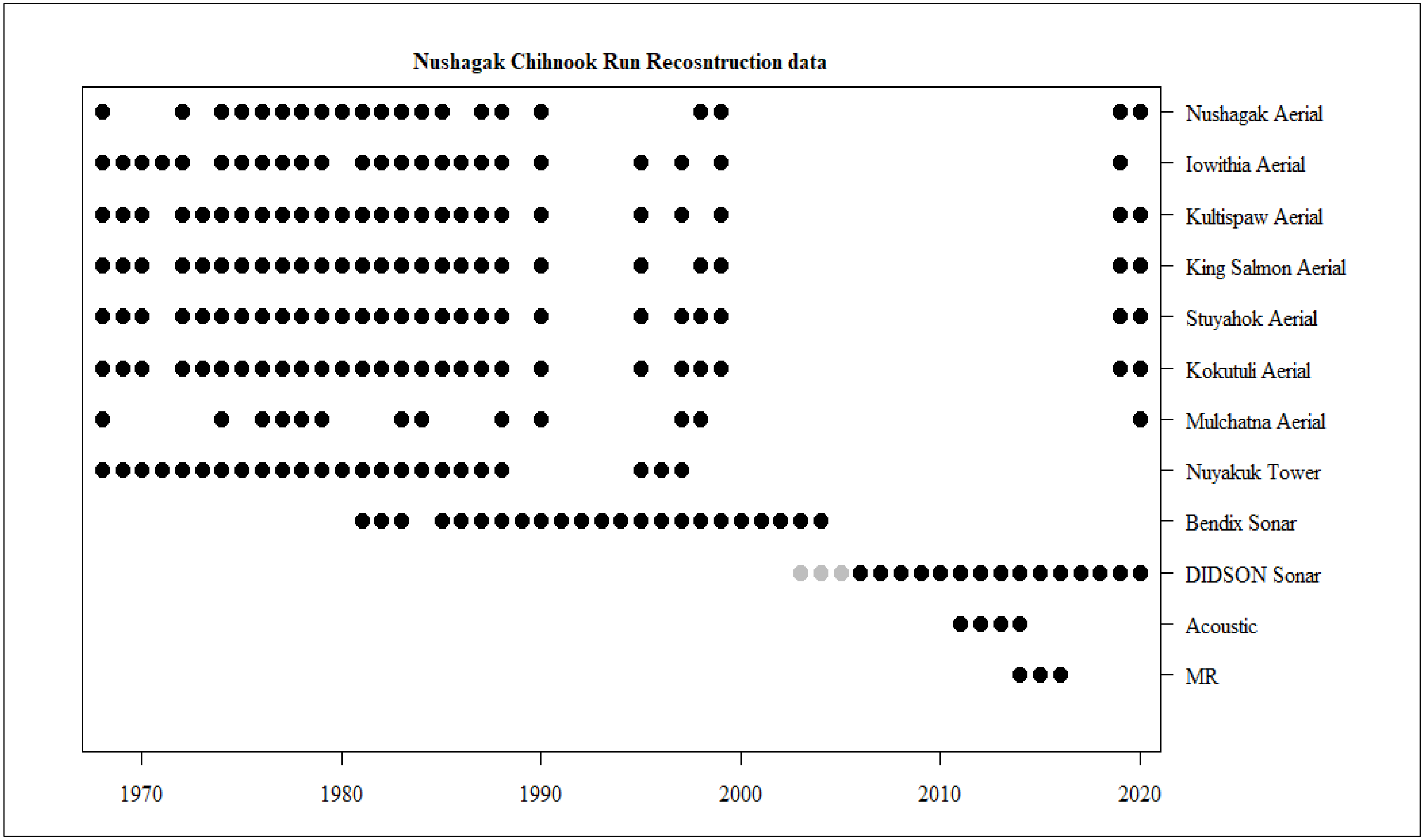

Figure 8.–Available Nushagak River Chinook salmon data used in the 2020 run of the run reconstruction model.

APPENDIX A: NUSHAGAK RIVER CHINOOK SALMON HARVEST, ABUNDANCE, AND ESCAPEMENT DATA

Appendix A1.–Harvest of Nushagak River Chinook Salmon.

	Harvest below the sonar			Harvest above the sonar	
Year	Commercial	Subsistence[a]	Sport	Subsistence[b]	Sport
1968	78,201	4,487	221	2,113	578
1969	80,803	4,826	221	2,274	578
1970	87,547	4,283	221	2,017	578
1971	82,769	2,991	221	1,409	578
1972	46,045	2,719	221	1,281	578
1973	30,470	4,487	221	2,113	578
1974	32,053	5,370	221	2,530	578
1975	21,454	4,826	221	2,274	578
1976	60,684	4,691	221	2,209	578
1977	85,074	3,535	256	1,665	667
1978	118,548	4,487	122	2,113	320
1979	157,321	6,050	181	2,850	473
1980	64,958	8,021	210	3,779	547
1981	193,461	7,818	338	3,682	882
1982	195,287	8,225	505	3,875	1,319
1983	137,123	8,021	555	3,779	1,448
1984	61,378	6,662	659	3,138	1,723
1985	67,783	5,370	513	2,530	1,339
1986	65,783	7,875	628	4,725	4,162
1987	45,983	8,770	1,286	2,680	3,173
1988	16,648	5,671	1,192	3,766	1,626
1989	17,637	5,688	1,404	2,155	2,210
1990	14,812	7,989	797	3,629	2,689
1991	19,709	8,093	1,793	3,010	3,758
1992	47,563	10,322	1,844	2,498	2,911
1993	62,979	14,498	2,408	2,919	3,492
1994	119,476	11,048	4,436	3,331	6,191
1995	79,936	10,800	2,238	2,419	2,713
1996	72,123	10,217	2,346	3,063	3,045
1997	64,390	11,397	931	2,981	2,567
1998	117,820	7,717	1,640	4,429	4,188
1999	11,178	7,450	934	2,477	3,304
2000	12,120	7,247	1,389	1,979	4,628
2001	11,746	7,972	1,600	3,372	4,299
2002	40,039	6,946	1,193	4,103	2,500
2003	43,485	13,399	2,203	4,448	3,752
2004	100,846	10,644	2,567	4,422	4,339
2005	62,764	7,951	2,863	4,471	5,702
2006	84,881	6,131	3,166	3,012	4,307
2007	51,831	9,564	3,581	3,411	6,088
2008	18,968	9,149	3,305	2,571	3,395
2009	24,693	9,312	2,451	2,796	3,903

-continued-

	Harvest below the sonar			Harvest above the sonar	
Year	Commercial	Subsistence[a]	Sport	Subsistence[b]	Sport
2010	26,056	6,345	1,659	1,845	2,248
2011	26,927	8,485	1,542	2,981	3,302
2012	11,952	6,653	1,833	2,369	4,098
2013	10,213	6,812	1,971	4,201	4,714
2014	11,868	10,378	2,369	3,890	3,892
2015	50,675	8,487	2,514	2,209	4,720
2016	24,937	11,831	3053	1,933	5,358
2017	33,374	6,606	2834	1,826	2,837
2018	36,554	7,344	3450	1,408	4,742
2019	21,509	7,001	3600	3,040	2,706
2020[c]	6,826	8,254	3,090	2,083	4,073
Average (2000–2020)	33,917	8,405	2,487	2,970	4,076

[a] Pre 2012, below sonar includes the following reporting areas: Black Point, City Dock/Beach, Clarks Point, Coffee Point, Ekuk, Grassy Island, Igushik, Kanakanak, Lewis Point, Lower Wood River Nushagak Point, Queen's Slough, Scandanavia, Scandanavian, Skinner, Snag Point, Squaw Creek, and Tulie Point. 2012–2019 below sonar includes the following reporting areas: Across from Dragnet, Black Point, Black Slough, City Dock/Beach, Clarks Point, Coffee Point, Dragnet, Ekuk, Grassy Island, Hansen Point, Icicle, Kanakanak, Lewis Point, Lower Wood River, Nushagak Point, Queens Slough, Scandinavian, Site Location Unknown, Skinner, Snag Point, Squaw Creek, Tulie Point, Wood River Outlet, and Wood River Site (unknown).

[b] Pre 2012, above sonar includes following reporting areas: Ekwok, Iowithla, Kokwok, Koliginek, New Stuyahok, Portage Creek, Klutuk. 2012–2019 above sonar includes the following reporting areas: Ekwok Area, Iowithla River, King Salmon River, Kokwok River, Koliganek Area, Mulchatna River, New Stuyahok Area, Portage Creek Area.

Appendix A2.–Ground-based inriver abundance indices and escapement counts of Nushagak River Chinook salmon.

Year	Portage Creek sonar		Nuyakuk
	Bendix	DIDSON	tower
1968	–	–	1,824
1969	–	–	390
1970	–	–	1,080
1971	–	–	300
1972	–	–	594
1973	–	–	588
1974	–	–	1,590
1975	–	–	1,686
1976	–	–	2,490
1977	–	–	996
1978	–	–	258
1979	32,751	–	504
1980	55,957	–	3,814
1981	115,105	–	5,460
1982	124,939	–	6,198
1983	103,765	–	2,958
1984	–	–	3,246
1985	99,037	–	2,628
1986	43,434	–	624
1987	84,309	–	120
1988	56,905	–	450
1989	78,302	–	–
1990	63,955	–	–
1991	104,351	–	–
1992	82,848	–	–
1993	97,812	–	–
1994	95,954	–	–
1995	85,622	–	1,380
1996	52,127	–	1,404
1997	40,705	–	3,246
1998	117,495	–	–
1999	62,331	–	–
2000	56,372	–	–
2001	92,275	–	–
2002	87,141	–	–
2003	80,028	214,724	–
2004	116,400	222,105	–
2005	–	254,123	–
2006	–	124,683	–
2007	–	60,459	–
2008	–	97,330	–
2009	–	81,480	–

-continued-

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	Portage Creek sonar		Nuyakuk
Year	Bendix	DIDSON	tower
2010	–	60,185	–
2011	–	108,278	–
2012	–	174,085	–
2013	–	113,709	–
2014	–	70,460	–
2015	–	98,019	–
2016	–	125,368	–
2017	–	56,961	–
2018	–	97,239	–
2019	–	46,763	–
2020	–	43,032	–

Note: En dash (–) = no data available

Appendix A3.–Peak aerial survey index counts of Nushagak River Chinook salmon.

Year	Nushagak	Iowithla	Klutispaw	King Salmon	Stuyahok	Koktuli	Mulchatna
1968	970	850	310	1,000	2,470	4,220	510
1969	–	580	90	670	1,220	1,600	–
1970	–	700	320	1,060	1,900	1,500	–
1971	–	390	–	–	–	–	–
1972	420	170	280	900	610	1,450	–
1973	–	–	380	1,470	1,220	950	–
1974	2,340	860	440	2,000	2,300	3,920	2,160
1975	1,260	1,040	670	2,900	2,530	4,080	–
1976	1,760	1,110	1,180	3,510	3,750	6,710	2,580
1977	820	840	650	1,420	2,700	4,630	1,980
1978	5,850	1,700	1,940	4,450	4,400	6,730	2,280
1979	2,880	1,350	1,040	2,150	3,570	6,260	1,730
1980	1,736	–	970	4,500	7,200	10,620	–
1981	6,090	2,630	1,650	2,950	5,980	9,960	–
1982	3,050	2,520	350	8,390	3,640	6,780	–
1983	6,330	2,430	2,090	5,990	2,910	8,060	4,260
1984	2,800	1,080	770	1,780	2,010	2,860	1,060
1985	1,180	1,610	1,950	4,460	2,690	4,940	–
1986	–	270	170	380	520	290	–
1987	1,314	140	340	570	280	440	–
1988	6,066	550	780	1,380	2,040	2,580	710
1989	–	–	–	–	–	–	–
1990	2,123	120	340	900	830	3,390	800
1991	–	–	–	–	–	–	–
1992	–	–	–	–	–	–	–
1993	–	–	–	–	–	–	–
1994	–	–	–	–	–	–	–
1995	–	170	630	3,150	660	2,230	–
1996	–	–	–	–	–	–	–
1997	–	640	1,190	8,900	1,460	6,220	1,496
1998	8,300	–	2,620	5,510	550	720	180
1999	6,467	450	1,545	6,825	645	2,075	–
2000	–	–	–	–	–	–	–
2001	–	–	–	–	–	–	–
2002	–	–	–	–	–	–	–
2003	–	–	–	–	–	–	–
2004	–	–	–	–	–	–	–
2005	–	–	–	–	–	–	–
2006	–	–	–	–	–	–	–
2007	–	–	–	–	–	–	–
2008	–	–	–	–	–	–	–
2009	–	–	–	–	–	–	–

-continued-

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Year	Nushagak	Iowithla	Klutispaw	King Salmon	Stuyahok	Koktuli	Mulchatna
2010	–	–	–	–	–	–	–
2011	–	–	–	–	–	–	–
2012	–	–	–	–	–	–	–
2013	–	–	–	–	–	–	–
2014	–	–	–	–	–	–	–
2015	–	–	–	–	–	–	–
2016	–	–	–	–	–	–	–
2017	–	–	–	–	–	–	–
2018	–	–	–	–	–	–	–
2019	881	291	447	1,235	441	787	–
2020	361		284	688	218	626	38

Note: En dash (–) = no data available. Nushagak Aerial Survey Index includes multiple index areas combined (Nuyakuk to King Salmon).

Appendix A4.–Independent estimates of Nushagak River Chinook salmon abundance used to scale the run reconstruction model.

	Hydroacoustic		Mark–recapture	
Year	Inriver run	Standard error	Inriver run	Standard error
2011	167,528	14,364	–	–
2012	320,494	29,976	–	–
2013	178,765	15,653	–	–
2014	151,259	18,204	91,727	20,541
2015	–	–	84,358	16,738
2016	–	–	178,707	28,540

Note: En dash (–) = no data available.

APPENDIX B: AD MODEL BUILDER CODES

Appendix B1.–AD Model Builder code with annotations.

```
/=====================================================================
// Nush_Chinook_reconst.TPL
// This model is the latest version of the
// Nushagak River Chinook Salmlon Run Reconstruction model
// Written by: Toshihide "Hamachan" Hamazaki
// Date: 06/10/2019
//=====================================================================

//=====================================================================
// 1.0 Data Entry
//=====================================================================
DATA_SECTION
 init_int fyear;  // First year
 init_int lyear;  // Last year
 init_int fage;   // First age
 init_int lage;   // Last age
 init_int D;      // Multiplier
 init_vector h_low(fyear,lyear); // Sum of all Catches below Sonar Site
 init_vector h_up(fyear,lyear);  // Sum of all Catches Above sonar site
// Read Bendix data
 init_vector bendix(fyear,lyear);         // Bendix Sonar Passage at Portage Creek
 init_vector bendix_sd(fyear,lyear);      // Bendix Sonar Passage SD
// Read DIDSON Sonar data
 init_vector didson(fyear,lyear);         // DIDSON Sonar Passage at Portage Creek
 init_vector didson_sd(fyear,lyear);      // DIDSON Sonar Passage SD
// Read Accoustic data
 init_vector ac(fyear,lyear);                  // Accoustic  Estimates
 init_vector acsd(fyear,lyear);           // Accoustic  SD
// Read Mark-Recapture data
 init_vector mr(fyear,lyear);                  // MR Estimates
 init_vector mrsd(fyear,lyear);           // MR SD
// Read Aerial data
 init_matrix obescs(1,8,fyear,lyear);     // escapement survey data
```

-continued-

```
// Read Age data
  init_matrix age_p_h(fage,lage,fyear,lyear);  //Annual harv age composition: Unused
  init_matrix age_p_e(fage,lage,fyear,lyear);        //Annual esc age composition: Unused
  init_vector efN_h(fyear,lyear);            //Input effective sample size harvest: Unused
  init_vector efN_e(fyear,lyear);                       //Input effective sample size Escapement: Unused
  init_number SDRec;                                    //SD Recruitment: Unused
  init_number SDma;                                     //SD age composition: Unused
  init_int phiz;                                         // AR1: Unused
  init_int inrz;                                        // Assumed inriver sd
  init_int rbdz;                             // Assumed inriver sd
// Read contorl parameters
//  !! ad_comm::change_datafile_name("proj.ctl");
  init_vector cvesc(1,8);                    // Escapement survey assumed CV
  init_vector cvh(1,2);                                 // Harvest assumed CV
  init_vector cvbd(1,2);                     // Harvest assumed CV
  init_vector cvr(1,2);                                 // Harvest assumed CV
  init_vector bdlike(1,2);                   // Weir likelihood weights
  init_vector rlike(1,2);                    // Weir likelihood weights
  init_vector elike(1,8);                    // Weir likelihood weights
  init_vector tflike(1,6);                   // Age comp, variation likelihoood weights
 // Read contorl parameters
//  !! ad_comm::change_datafile_name("proj.ctl");
  init_vector maxsel(1,4);                    // Age at which Selectivity is 1.0
  init_vector sy(1,3);                                  // Com fis selectivity cut-off years

  !! cout << "Data Section Completed" << endl;
  !! cout << "sy"  << sy << endl;


//=====================================================================
// 2.0  Define parameters
//=====================================================================
PARAMETER_SECTION
```

-continued-

```
  init_bounded_vector log_trun(fyear,lyear,10.0,14.5,1);      //log drainage-wise run
  init_bounded_vector log_bd(1,2,0.0,3.0,1);                  //log slope for Bendix and DIDSON
  init_bounded_vector rbd(1,2,0.0,6.0,rbdz);                  //log slope for Bendix and DIDSON
  init_bounded_vector log_escs(1,8,1.0,8.0,1);                 //log slope for Aerial Survey
  init_bounded_vector rescs(1,8,0.0,6.0,2);                   //log addvar for Aerial Survey
  init_bounded_vector log_fl(fyear,lyear,0.0,3.0,1);          // annual harvest rate Lower
  init_bounded_vector log_fu(fyear,lyear,0.0,3.0,1);          // annual harvest rate Upper
  init_bounded_vector rinr(1,2,0.0,6.0,inrz);                 //Inriver additional variance

//== Run and Escapement ============================================
  vector N(fyear,lyear);                                      // Total run:
  vector low_run(fyear,lyear);                          // Run at Sonar site
  sdreport_vector S(fyear,lyear);                             // Total escapement
//== Escapement slope and sd ================================================
//===================== Escapement slope and sd ===========================
  vector bd(1,2);                                             // slope for bendix-didson
  vector escs(1,8);                                           // slope for escapement survey
//== Harvests =========================================================
  vector eh_low(fyear,lyear);                                 // Lower river harvest
  vector eh_up(fyear,lyear);                            // Upriver harvest

//==== Likelihood Parameters ============================================
  number fpen;
  vector tfbd(1,2);                                           // bendix-didson likelihood
  vector tfescs(1,8);                                         // Aerial likelihood
  vector tfh(1,2);                                            // Harvest likelihood
  vector tfr(1,2);                                            // Run likelihood

  objective_function_value f;
  !! cout << "Parameter Section Completed" << endl;

//==================================================================
// 3.0  Initialization
```

-continued-

```
//===========================================================================
INITIALIZATION_SECTION
  log_trun  12;
  log_bd   0.6;
  log_escs  2.0;
  rescs  0.1;
  log_fl   0.2;
  log_fu   0.2;
  rinr     0.0000000000001;
  rbd     0.0000000000001;
//===========================================================================
// 4.0  Preliminary Calculation Harvest CPUE
//===========================================================================
PRELIMINARY_CALCS_SECTION
  int i,j,k;
  double  tt0,n0,tt1,n1;                    // Calculated working variables nondefferentiated
  tt0=0.0;
  n0 = 0.0;
  tt1 = 0.0;
  n1 = 0.0;


//---------------------------------------------------------------------------
// 4.5  Calculate Winter subsistence discards (twsd)
//      For early years, total number of crab caught is not available.
//      Estimate discards based on average proportion of discards
//---------------------------------------------------------------------------
// Calculate Average cv bendix
 for (i=fyear;i<=lyear;i++)
  {
  if (bendix_sd(i) > 0)
      {
       tt0 += bendix_sd(i)/bendix(i);             // Sum cv of bendisx
       n0 += 1;                                   // Number of sample
```

```
      }
   }
// For early unknown discards, estimate by average discards rate.
  for (i=fyear;i<=lyear;i++)
   {
   if (bendix_sd(i)== 0)
      {
       bendix_sd(i) = bendix(i)*(tt0/n0);
      }
   }

// Calculate Average cv didson
 for (i=fyear;i<=lyear;i++)
  {
  if (didson_sd(i) > 0)
      {
       tt1 += didson_sd(i)/didson(i);          // Sum cv of didson
       n1 += 1;                                // Number of sample
      }
   }
// For early unknown discards, estimate by average discards rate.
  for (i=fyear;i<=lyear;i++)
   {
   if (didson_sd(i)== 0)
      {
       didson_sd(i) = didson(i)*(tt1/n1);
      }
   }

         cout << "Prelimary Calc Section Completed" << endl;
   cout << "bendix_sd " << bendix_sd << endl;
//=====================================================================
//  Procedure Section
```

```
//======================================================================
PROCEDURE_SECTION

  f=0.0;
  convert_parameters_into_rates();
//  cout <<"OK for convert_parameters..."<<endl;
  model_harvest_passage_escapement();
//  cout <<"OK for passage_escapement..."<<endl;
  evaluate_the_objective_function();
//  cout <<"OK for evaluate objective function ..."<<endl;

   if (mceval_phase())
    {
     ofstream MCMCreport("post_samp_r.csv", ios::app);
              MCMCreport << bd(1) << N << S << endl;
              MCMCreport.close();
            }
RUNTIME_SECTION
  maximum_function_evaluations 200000000
  convergence_criteria 1.e-20

//======================================================================
//  Function convert_parameters_into_rates
//======================================================================
FUNCTION convert_parameters_into_rates
  N=exp(log_trun);                                          //Total run
  bd=exp(log_bd);                                           // slope for bendix-didson
  escs=exp(log_escs);                                   // slope for aerial

//======================================================================
//  model_harvest_passage_escapement
//======================================================================
FUNCTION model_harvest_passage_escapement
```

```
// Loewr River Harvest
  eh_low = elem_prod(1-exp(-log_fl),N);
// Run at Portage Creek
  low_run = N - eh_low;
// Harvest above Portage Creek
  eh_up = elem_prod(1-exp(-log_fu),low_run);
// Run at Below Lower River Escapement
  S =  low_run - eh_up;
//==========================================================================
FUNCTION evaluate_the_objective_function
  int i,j;
  dvariable var0, var00, var1, var2, var3, var4, var5, var6, var7, var8;
  tfescs = 0.0;                                                   // initialilze to 0
  tfbd = 0.0;
  tfr = 0.0;                                                      // initialilze to 0
  tfh = 0.0;

  for (i=fyear;i<=lyear;i++)
   {
// ==========================================================================
//   eh_low(i) = t_run(i)*exp(-log_fl(i));
//   cout << eh_low << endl;
//   low_run(i) = t_run(i) - eh_low(i);
//   cout << low_run << endl;
//==========================================================================
//  Lower river likelihood
//==========================================================================
// Mark-Recapture
   if(mr(i)>0)
    {
          if(mrsd(i)/mr(i)< cvr(1))
          {
    var00 = log(square(cvr(1))+1)+square(rinr(1));
```

```
            }
            else
            {
             var00 = log(square(mrsd(i)/mr(i))+1)+ square(rinr(1));
            }
   tfr(1) += log(sqrt(var00))+0.5*square(log(mr(i))-log(low_run(i)))/var00;
    }
// Accoustic
  if(ac(i)>0)
    {
            if(acsd(i)/ac(i)< cvr(2))
            {
     var0 = log(square(cvr(2))+1)+square(rinr(2));
            }
            else
            {
             var0 = log(square(acsd(i)/ac(i))+1)+square(rinr(2));
            }
   tfr(2) += log(sqrt(var0))+ 0.5*square(log(ac(i))-log(low_run(i)))/var0;
           }
//======================================================================
// DIDSON Counts
          if(didson(i)>0)
    {
            if(didson_sd(i)/didson(i)< cvbd(1))
            {
     var1 = log(square(cvbd(1))+1)+square(rbd(1));
            }
            else
            {
            var1 = log(square(didson_sd(i)/didson(i))+1)+square(rbd(1));
            }
     tfbd(1) += log(sqrt(var1))+0.5*square(log(didson(i))-log(low_run(i)/bd(1)))/var1;
```

-continued-

```
    }
// Bendix Counts
        if(bendix(i)>0)
    {
         if(bendix_sd(i)/bendix(i)< cvbd(2))
         {
    var2 = log(square(cvbd(2))+1)+square(rbd(2));
         }
         else
         {
         var2 = log(square(bendix_sd(i)/bendix(i))+1)+square(rbd(2));
         }
    tfbd(2) += log(sqrt(var2))+0.5*square(log(bendix(i))-log(low_run(i)/bd(2)))/var2;
    }
//  eh_up(i) = low_run(i)*exp(-log_fu(i));
//  esc(i) = low_run(i) - eh_up(i);
// Upriver Escapement Surveys
  for(j=1;j<=8;j++)
   {
  if(obescs(j,i)>0)
    {
     var3 = log(square(cvesc(j))+1)+square(rescs(j));
              tfescs(j) += log(sqrt(var3))+0.5*square(log(obescs(j,i))-log(S(i)/escs(j)))/var3;
    }
   }


  }

//==================================================================
// 7.6  Calculate Harvest
//==================================================================
// Likelihood Harvest
// Lower River
```

-continued-

```
  tfh(1) = 0.5*norm2((log(h_low)-log(eh_low))/sqrt(log(square(cvh(1))+1)));
// Upriver Harvest
  tfh(2) = 0.5*norm2((log(h_up)-log(eh_up))/sqrt(log(square(cvh(2))+1)));

// Sum all likelihood ===================================================
  f = sum(elem_prod(tfr,rlike))+sum(elem_prod(tfbd,bdlike))+sum(elem_prod(tfescs,elike))+sum(tfh);
//  cout << tfbd << endl;
//  cout << f << endl;
// ======================================================================
REPORT_SECTION
// ======================================================================
    report <<"Total Run"<< endl;
    report << N << endl;
    report << "Escapement" << endl;
    report << S <<endl;
    report << "low_run" << endl;
    report << low_run <<endl;
    report << "f" << endl;
    report << f << endl;
    report << "tfescs" << endl << tfescs << endl;                    // Aerial
    report << "tfr" << endl << tfr << endl;                                // Acoustic MR
    report << "tfbd" << endl << tfbd <<endl;                             // Bendix-Didson
    report << "tfh" << endl << tfh << endl;                              // Harvest


//======================================================================
// Globals section
//======================================================================
GLOBALS_SECTION
  #include <math.h>
  #include <time.h>
  #include <statsLib.h>
  #include <df1b2fun.h>
```

-continued-

```
  #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;
```