Fishery Data Series No. 08-64

Kuskokwim River Chum Salmon Run Reconstruction

Final Report for Study 07-302
USFWS Office of Subsistence Management
Fisheries Resource Monitoring Program

by

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

Symbols and Abbreviations

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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)

Measures (fisheries)

fork length	FL
mideye to fork	MEF
mideye to tail fork	METF
standard length	SL
total length	TL

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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ABSTRACT

The goal of this project was to reconstruct the chum salmon *Oncorhynchus keta* run to the Kuskokwim River for the years 1976 to 2007 with sufficient accuracy and precision to allow for the estimation of productivity on a drainage-wide basis. Previous work by Shotwell and Adkison (2004) showed a great deal of promise, but the resulting estimates were thought to be biased low, largely because of their reliance on estimates of inriver abundance obtained from a sonar project at Bethel. In addition, Shotwell and Adkison (2004) had to rely on a single location in the Kuskokwim River drainage for an assessment of escapement. A great deal of effort has been directed towards expanding the coverage and the quality of the escapement estimates in the drainage in recent years, with a time series of eight years or more now being available for seven tributaries. In addition, a large scale mark–recapture study in 2002 and 2003 produced estimates of escapement for the entire drainage upstream of Kalskag. It was thought that given this large infusion of new information, it would be a good time to revisit the estimation of historical runs to the system. Upon closer examination of the data, we found that the total abundance estimates generated in more recent years still greatly underestimate the true number of chum salmon in the Kuskokwim River drainage. This underestimate prevented an accurate scaling of the run reconstruction, which ultimately produced estimates of total abundance that are again biased low. Consequently, it was decided to close out the study, report the work performed, and make recommendations for the successful completion of similar projects in the future.

Key words: chum salmon, *Oncorhynchus keta*, Kuskokwim River, historical run sizes, historical abundance, inriver abundance, run reconstruction, mark–recapture.

INTRODUCTION

The subsistence salmon fishery of the Kuskokwim Area is one of the largest and most important in Alaska, accounting for approximately 20% of the annual statewide subsistence harvest of chum salmon *Oncorhynchus keta* (Brown et al. 2005; Fall et al. 2007a, b). This fishery competes directly with the commercial fishery of the lower Kuskokwim River, with the average harvests for the recent 10-years being approximately 54,000 and 40,000 chum salmon from the subsistence and commercial fisheries, respectively. While the commercial harvest has ranged as high as 1.4 million chum salmon (Whitmore et al. 2005), low returns during the mid-1990s through 2000 prompted the Alaska Board of Fisheries to declare Kuskokwim River chum salmon a stock of concern (Burkey et al. 2000; Bergstrom and Whitmore 2004). This declaration impacted subsistence users by both reducing the time available for subsistence fishing, and through a reduction in income obtained from commercial fishing; money needed, among other things, to purchase supplies for subsistence harvest activities. The chum salmon runs to the Kuskokwim River have been improving in recent years with levels sufficient to allow for the opportunity to achieve subsistence needs (Linderman and Bergstrom 2006).

Identifying the reason for the wide swing in chum salmon abundance has been elusive. A major shortcoming has been the lack of estimates of historical abundance upon which to base an analysis of productivity and to evaluate the effectiveness of fisheries management actions. In response to this need, Shotwell and Adkison (2004) developed a statistical model that utilized the majority of the datasets available at that time to estimate historical annual chum salmon abundance for the Kuskokwim River. While their methodology was innovative and valid, we believe their estimates were low. Some of the annual exploitation rates estimated from their abundance estimates exceeded 75%, a number exceptionally high given the fishing schedule and capacity of the fishing fleet at that time (Figure 1). In addition, recently revised estimates of chum salmon escapement into the Aniak River (McEwen 2007) averaged 89% of the Shotwell and Adkison (2004) estimates of total Kuskokwim River escapement. While the Aniak River estimates include some fraction of species other than chum salmon, the remaining balance is likely not sufficient to account for chum salmon escapement to other Kuskokwim River tributaries, especially the Holitna River sub-basin where chum salmon production is of the same magnitude as the Aniak River sub-basin. In 2002 and 2004, for example, abundance estimates for the Holitna River sub-basin were 542,172 and 996,216 chum salmon based on radio telemetry studies (Stroka and Brase 2004, Stroka and Reed 2005), compared to 472,346 and 672,931 counts from Aniak River sonar for those same years.

The problems with the Shotwell and Adkison (2004) work point to their reliance on whole-river abundance estimates generated in 1993, 1994, and 1995, from a configurable sonar project operated near Bethel. The reliability of these estimates has long been questioned. While no formal documentation of "no confidence" has been made, it is firmly implied both by the fact that the whole-river sonar program has been discontinued and that fisheries managers do not use these estimates. Unfortunately, these three years of estimates were the only data available to Shotwell and Adkison (2004) for scaling their abundance model. They recognized the problem and recommended that their model would benefit from a few years of improved estimates of total abundance.

Subsequent to the work of Shotwell and Adkison (2004), efforts were made to address this information gap primarily through the use of mark–recapture studies to estimate total inriver abundance upstream of Kalskag (Kerkvliet et al. 2003, 2004). Chum salmon were captured using fishwheels and drift gillnets near Kalskag, and fitted with spaghetti or anchor tags. The tags were later recovered at a recapture site in the mainstem of the Kuskokwim River near Aniak and at the salmon counting weirs located on the George, Kogrukluk, Tatlawiksuk, and Takotna rivers. Radio telemetry studies were also implemented in the Holitna River drainage in 2001 through 2004 to determine the number of chum salmon spawning in that system (Stroka and Brase 2004; Stroka and Reed 2005).

Considerably more information on chum salmon escapement into the Kuskokwim River tributaries is available today. A great deal of effort has been exerted since the late 1990s to count salmon escapement into several Kuskokwim River tributaries providing eight or more years of counts for the Kwethluk, Tuluksak, George, Tatlawiksuk and Takotna rivers (Appendix A). In addition, the sonar technology used in the Aniak River has progressed from a single-beam, echo-counting system (Bendix[1]), to a dual-beam system (Biosonics), to a dual-frequency identification sonar system (DIDSON; McEwen 2007), with the historical data now being standardized to the more accurate DIDSON counts. Paired comparison of the dual beam and DIDSON units demonstrated that DIDSON counts were much closer to the true escapement. Consequently, all sonar counts pre-dating the use of DIDSON technology were adjusted to account for the difference. This provided an additional time series of escapement information, 23 years in length, for use in the run reconstruction model. The inclusion of these additional data sources should, at a minimum, bring the index of escapement closer to the actual total chum salmon escapement.

[1] Product names used in this report are included for scientific completeness but do not constitute a product endorsement.

OBJECTIVES

Objectives of the Kuskokwim River Chum Salmon Run Reconstruction (FIS 07-302) were to:

1. Estimate spawning and total abundance of chum salmon in the Kuskokwim River from 1976 through 2007 using a statistical model for combining multiple data sources;
2. Develop brood tables for Kuskokwim River chum salmon for the years 1976 through 2007 by combining the abundance estimates with estimates of age composition obtained from the subsistence and commercial fisheries as well as escapement enumeration projects; and,
3. Estimate the stock-recruitment relationship for the Kuskokwim River chum salmon population using the brood table developed in Objective 2 and the Ricker and Beverton-Holt stock-recruitment models.

It was determined in early January 2008 that there was insufficient information to achieve the project objectives. The total inriver estimates of chum salmon abundance obtained from the mark–recapture project at Kalskag in 2002 and 2003 were low and, as such, any estimates of the historical run abundance would be biased low (Objective 1). Achievement of Objectives 2 and 3 depend on the successful completion of Objective 1. Biologists from the USFWS Office of Subsistence Management directed us to (1) examine the 2002 and 2003 mark–recapture studies with the purpose of suggesting possible solutions for a successful outcome in the future, (2) perform an initial run reconstruction using readily available information to determine if the proposed version of the Shotwell-Adkison model showed promise, and (3) to extract the pattern of total return and escapement if possible.

METHODS

The available information on total run abundance was insufficient to achieve the project objectives; thus, the model demonstration was limited to the years 1988–2007, where data on run abundance were easily available. We elected to not spend the time and money required to attempt to rectify, if possible, inconsistencies with information from the earlier years. For instance, prior to 1988, chum, coho, and sockeye salmon harvested in the subsistence fishery were grouped into a single classification called "small salmon".

The AYK Salmon Database Management System maintained by the Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage, was the source of the escapement information collected at the weirs (http://sf.adfg.state.ak.us/cfprojects/aykdbms/). Escapement data for the Aniak River sonar came from McEwen (2007; personal communication) and was standardized to DISDON units. Subsistence harvest data were obtained from Dave Koster (ADF&G, Division of Subsistence; personal communication) and commercial harvest and effort information was obtained from Whitmore et al. (2005) and John Linderman (ADF&G, Division of Commercial Fisheries; personal communication) (Appendices A and B). Information for the Bethel test fishery was provided by Kuskokwim River research staff of ADF&G, Division of Commercial Fisheries. Data from the commercial fishery and Bethel test fishery were grouped into weekly intervals to facilitate the estimation of run timing (Appendix C).

RUN RECONSTRUCTION MODEL

Maximum likelihood methodology (MLE) was used to estimate total run and ultimately total escapement of chum salmon into the Kuskokwim River for the years 1988 through 2007. The model simultaneously combined information on subsistence harvest, commercial harvest and effort, test-fish indices of abundance at Bethel, mark–recapture estimates of inriver abundance, counts of salmon at six weirs spread throughout the drainage (Kwethluk, Tuluksak, George, Kogrukluk, Tatlawiksuk, and Takotna rivers), and estimates of chum salmon escapement obtained using sonar (Aniak River). To simplify the description of the estimation process, the methodology was divided into three logical components based on the type of data used in the model: (1) escapement assessment, (2) commercial harvest and effort, and (3) total inriver abundance. The model simultaneously combined input from all three components to estimate total run to the Kuskokwim River. A listing and description of the variables used for the model formulation can be found in Appendix D.

The escapement assessment component used total counts of chum salmon by year from six weirs and a sonar project operating in the Kuskokwim drainage (Figure 2). For each escapement assessment project (i) it was assumed that the annual measurement of escapement (I_{iy}) for year y was related to the total annual escapement into the Kuskokwim River drainage (E_y) by:

$$E_y = \hat{k}_{iy} I_{iy} \quad , \tag{1}$$

where $\hat{k}_{iy}$ is a scaling factor for assessment project i.

The estimated annual escapement into the Kuskokwim River drainage ($\hat{E}_y$) was related to total estimated abundance ($\hat{N}_y$) by:

$$\hat{E}_y \quad = \quad \left(\hat{N}_y - S_y - C_y\right) e^{\hat{\sigma}_y} \quad , \hat{\sigma}_y \sim N\left(0, \sigma_\delta^2\right) \quad , \tag{2}$$

where the annual subsistence and commercial catches are represented by S_y and C_y. The random error about $\hat{E}_y$ is assumed to be lognormal with mean zero and standard deviation σ_δ.

The commercial catch component relates weekly (j) commercial catch and effort data from commercial fishing district W1 (C_{yj}; Figure 2) to total estimated abundance by week ($\hat{N}_{yj}$) by converting the annual abundance estimates to weekly estimates using the observed run timing at the Bethel test fishery. The proportion of the run present in commercial fishing district W1 by week and year (p_{yj}) was defined by:

$$p_{yj} \quad = \quad \frac{CPUE_{yj}}{\sum_{j=1}^{n} CPUE_{yj}} \quad , \tag{3}$$

and the number of chum salmon present in commercial fishing district W1 by year and week ($\hat{N}_{yj}$) was estimated by:

$$\hat{N}_{yj} = \hat{N}_y p_{yj} \quad , \tag{4}$$

where $CPUE_{yj}$ is the total catch per unit effort during week *j*, year *y* in the Bethel test fishery and *n* is the number of weeks that significant numbers of chum salmon are present in the Kuskokwim River at Bethel. Catch by year and week ($\hat{C}_{yj}$) can be estimated by:

$$\hat{C}_{yj} = \hat{N}_{yj} \left[1 - e^{-\hat{q}B_{yj}}\right] e^{\varepsilon_{yj}} \quad , \qquad \varepsilon_{yj} = N\left(0, \sigma_\varepsilon^2\right) \quad , \tag{5}$$

which is the Baranov catch equation where $\hat{q}$ is the estimated catchability coefficient and B_{yj} is the observed effort for year *y* and week *j*. The random error about $\hat{C}_{yj}$ was assumed to be lognormal with mean zero and standard deviation σ_ε.

An intensive stock assessment program designed to estimate the total inriver run is essential for the successful completion of this modeling effort. An accurate estimate of the number of chum salmon migrating upstream of Kalskag, combined with accurate estimates of escapement for the tributaries downstream of Kalskag, and estimates of the subsistence and commercial catches, allows for a comparison of the observed total return (N_y) to the estimated total return ($\hat{N}_y$), where:

$$N_y = E_{(Downstream)y} + E_{(Upriver)y} + S_y + C_y \quad , \tag{6}$$

and:

$$\hat{N}_y = \hat{N}_y \; e^{\lambda_y} \quad , \qquad \lambda_y \sim N\left(0, \sigma_\lambda^2\right) \quad . \tag{7}$$

The random error about $\hat{N}_y$ is assumed to be lognormal with mean zero and standard deviation σ_λ.

The escapement, catch, and total inriver components were combined into a single model that simultaneously estimated the total run to the Kuskokwim drainage for each year. A maximum likelihood model that allowed for the weighting (w_i, w_c, and w_N) of individual datasets was used,

$$L(\theta \mid data) = \prod_i \prod_y \left[\frac{1}{E_{iy}\sigma_\delta w_i \sqrt{2\pi}} \; e^{\frac{-\left(\ln E_{iy} - \ln \hat{E}_y\right)^2}{2\sigma_\delta^2 w_i^2}} \right] \bullet$$

$$\prod_y \prod_j \left[\frac{1}{C_{yj}\sigma_\varepsilon w_C \sqrt{2\pi}} \; e^{\frac{-\left(\ln C_{yj} - \ln \hat{C}_{yj}\right)^2}{2\sigma_\varepsilon^2 w_C^2}} \right] \bullet \tag{8}$$

$$\prod_y \left[\frac{1}{N_y \sigma_\lambda w_N \sqrt{2\pi}} \; e^{\frac{-\left(\ln N_y - \ln \hat{N}_y\right)^2}{2\sigma_\lambda^2 w_N^2}} \right] ,$$

and the concentrated negative log likelihood form,

$$-\ln L(\theta \mid data) \quad = \quad \frac{T}{2} \ln \left[\sum_i \sum_y \frac{\left(\ln E_{iy} - \ln \hat{E}_y\right)^2}{w_i^2} + \sum_y \sum_j \frac{\left(\ln C_{yj} - \ln \hat{C}_{yj}\right)^2}{w_C^2} + \sum_y \frac{\left(\ln N_y - \ln \hat{N}_y\right)^2}{w_N^2} \right], \tag{9}$$

was minimized to arrive at the best estimates of the model parameters (Deriso et al. 2007; Hilborn and Mangel 1997). For this expression, T is the total number of observations from all data sets.

The confidence region about the estimates of total run can be calculated using the negative log-likelihood profiles for $\hat{N}_y$ for each year. For this method, the negative log-likelihood profile for an estimate of total abundance for a selected year will be estimated by calculating the negative log-likelihood for individual levels of possible run size within a wide range of possible run abundances while searching over all possible values of the other parameters in the model. The confidence bounds for $\hat{N}_y$ can then be estimated using the negative log-likelihood ($\mathbf{L}(N)$) for a total return of abundance N by:

$$2\left[\mathbf{L}(N) - \mathbf{L}(N)_{\min}\right] \;, \tag{10}$$

which is chi-square distributed with 1 df (Venzon and Moolgavkar 1988; Hilborn and Mangel 1997).

RESULTS AND DISCUSSION

We determined early in this study that the independent estimates of total drainage abundance that are critical for the successful completion of this project were biased low, and that the bias would influence all estimates of total run in the reconstructed time series. Because of this data gap, we elected to terminate the project and report the findings to date.

Accurate estimates of drainage-wide chum salmon abundance independent of the run reconstruction model are required to scale the run reconstruction model (Shotwell and Adkison 2004). When this project was proposed, there were two published estimates of abundance for chum salmon upstream of Kalskag based on large-scale mark–recapture studies (Kerkvliet et al. 2003, 2004). We anticipated that these mark–recapture estimates could be combined with subsistence and commercial catch numbers and counts of escapement for the Kwethluk and Tuluksak Rivers to provide accurate estimates of drainage-wide abundance for the Kuskokwim River for 2002 and 2003. After further investigation, however, we found that the mark–recapture estimates were not supported by the total of the information gathered from other independent estimates of abundance upstream of Kalskag.

A comparison of the 2002 and 2003 estimates of chum salmon abundance upstream of Kalskag based on mark–recapture estimates to the sum of all chum salmon enumerated at counting weirs, Aniak sonar, and an independent mark–recapture estimate of the Holitna River drainage indicated that the estimates at Kalskag were low by hundreds of thousands of fish (Table 1). While the major chum salmon spawning areas in the Kuskokwim River are the Aniak and Holitna rivers, the true value of the underestimate is very likely to be much larger than we have described here since chum salmon are known to spawn throughout the Kuskokwim River drainage, including numerous tributary streams and other major sub-basins such as the Stony River, Swift River, Middle Fork, Big River, and South Fork Kuskokwim River.

Kerkvliet et al. (2003) concluded that their estimate of chum salmon abundance upstream of Kalskag in 2002 was not low; rather, they suspected that the mark–recapture estimate to the Holitna River (Chythlook and Evenson 2003) was biased high. Since that time, however, the escapement estimates to the Aniak River have been revised upward (McEwen 2007) and the number of chum salmon unaccounted for in the Kuskokwim River drainage when the Holitna River mark–recapture estimate is ignored is less than 117 thousand fish (Table 1). This is an unrealistically low number, especially when one considers that the number of chum salmon in the Holitna River downstream of the Kogrukluk River weir appears to be large and that there are numerous unmonitored populations of chum salmon in the Kuskokwim River drainage. While the Chythlook and Evenson (2003) estimate may be high, it would need to overestimate the Holitna River population by a factor of at least five (Table 1) for the Kerkvliet et al. (2003) estimate to make sense; a degree of bias that is highly unlikely. It is very likely that the true 2002 escapement level upstream of Kalskag is larger than that estimated by Kerkvliet et al. (2003).

Kerkvliet et al. (2004) did conclude, however, that their estimate of chum salmon escapement upstream of Kalskag in 2003 was low, and suspected that one explanation may have been high densities of fish in the fish wheel live boxes prior to tagging. They demonstrated an increased probability of recapture of tagged fish when the fish had been held in high densities and stated that an increase in the probability of recapture of tagged fish would have resulted in an underestimate. Holding time in fish wheel live boxes has also been implicated to delayed mortality in fall chum salmon on the Yukon River (Burek and Underwood 2002; Underwood et al. 2002). This delayed mortality may explain the decrease in the proportion of tags in the escapement as distance from the tagging site increased in both 2002 and 2003 (Table 2; Kerkvliet et al. 2003, 2004), although the investigators assumed the decrease to be due to differential tagging rates associated with differences in stock specific run timing. This disproportionate tag recovery at the weirs violates the equal probability of recapture assumption for mark–recapture experiments and led investigators to select the wheel-to-wheel method for calculating abundance rather than wheel-to-weir. The wheel-to-wheel estimates may have been compromised by the incomplete mixing of tagged fish among all stocks between the Kalskag tag deployment site and Aniak tag recovery site. Evidence of inadequate mixing can be seen in the tag recovery data where in 2002, 60% of the fish tagged at the Kalskag site were recaptured upstream at the Aniak site on the same bank they were tagged instead of the expected 50% occurrence (Kerkvliet et al. 2003).

RUN RECONSTRUCTION MODELING

An evaluation of the proposed model for use in reconstructing the Kuskokwim River chum salmon runs was undertaken using easily assessable data and the model framework already developed for a comparable study for Chinook salmon in the Kuskokwim River (http://www.aykssi.org/Research/project_profile.cfm?project_id=123). Since estimates of total inriver abundance were required, subjective estimates for the 2000, 2002, 2003, and 2006 runs were developed using available information and subjective estimates of run magnitude made by the ADF&G staff (Table 3). The subjective estimates were based on observations of the Kuskokwim River salmon populations acquired through numerous years of experience working in the drainage. While our estimates are also most likely not accurate, we believed they were sufficient to allow for an evaluation of how well the model might work if appropriate total abundance data were available. The 2000 and 2006 estimates were included to provide contrast for the model as well as to provide future researchers an estimate of the possible range of run abundance. This evaluation was limited to 1988 through 2007 returns because of the lack of easily assessable subsistence harvest data prior to 1988.

Twenty-eight parameters were estimated for the run reconstruction model: 20 total runs ($\hat{N}_y$; 1988–2007), 7 scaling factors ($\hat{k}_{iy}$; 6 weirs and Aniak Sonar), and a catchability coefficient ($\hat{q}$). While the number of parameters is high, there were 257 observations fit to the model (Appendices A and B) in addition to the run timing curves developed from the Bethel test fishery data (Figure 3). The parameter weighting scheme used for the demonstration was 0.5 for the inriver component, 1.0 for the weir and sonar counts, and 2.0 for the catch-effort model. These parameter weights are the opposite of what the casual reader might expect, with smaller numbers indicating more weight and larger values indicating less weight. All analyses were performed using Microsoft Excel and the solver add-in for optimization.

The model converged readily with the optimizer being constrained to (1) values of total run ($\hat{N}_y$) greater than the number of fish already accounted for in the catch and escapement and (2) values for the escapement scaling factor ($\hat{k}_{iy}$) were constrained to 1.0 or greater. Both of these constraints reflect the assumption that there were more fish in the river system than were counted by the catch and escapement programs already in operation in the drainage. Finally, catchability was constrained to be greater than or equal to 1×10^{-13} to protect against obtaining negative values. It was not felt that this constraint adversely influences parameter estimation in the model since the value of catchability that minimizes the negative log likelihood is approximately $1.0x10^{-4}$.

An ad hoc examination of model stability was undertaken wherein a wide range of values were used for initial parameter settings and the optimizer was allowed to seek the combination of parameters that minimized the negative log likelihood. The model converged to approximately the same values for nearly all scenarios with the exception of when the starting catchability was greater than 0.05.

Negative log likelihood profiles for the escapement scaling factors and catchability can be found in Figures 4 and 5. All model parameters displayed a pronounced "U-shaped" profile across a wide range of possible values, although the profile for the catchability coefficient was not as steep as for the other parameters as the coefficient increased. This pattern in the likelihoods indicates that there is a unique solution for the model for the range of possible parameter values examined.

A comparison of the escapement estimates obtained from the run reconstruction model to the estimates obtained using tributary counts scaled by a constant (Equation 1) generally showed strong agreement (Figure 6), although there was some evidence that the model did not capture the signal from the large 2005 and 2006 escapements into the Kogrukluk River. Comparison of the modeled and actual harvests indicates that the Baranov catch per unit effort model also did a reasonable job of estimating the harvest (Figure 7). Shotwell and Adkison (2004) broke the catch and effort dataset into two strata because of changes in how the fishery was managed, and estimated separate catchability coefficients for each stratum. We did not pursue stratification for this study and would recommend that any future researcher working on the Kuskokwim River chum salmon dataset consider changes in fishery management and examine the appropriateness of using multiple strata.

While acknowledging that our independent estimates of total inriver abundance are subjective and most likely inaccurate, and that any estimates of the historical time series of total inriver abundance obtained from the run reconstruction model based on these estimates would also be inaccurate, we estimated the historical time series of inriver estimates for 1988 through 2007. A comparison of our estimates to those of Shotwell and Adkison (2004) indicated that both studies identified the same pattern of abundance (Figure 8). We believe that our methodology did an acceptable job of describing the actual pattern of abundance and should be able to provide reasonable estimates of the time series of total inriver abundance and escapement if good independent estimates of total inriver abundance were available. Confidence in a time series of abundance estimates will depend on the number and accuracy of the independent estimates of total inriver abundance, and the range the independent estimates. Generally, a wide range of independent abundance estimates and a large number of reliable estimates will make for a stronger model.

A weakness of the model is the reliance upon a relatively small number of estimates of total inriver abundance from a narrow window of time. Hilborn et al. (2003) demonstrated for Bristol Bay sockeye salmon that distinct geographic and life history components of a stock contribute differently to the stock's abundance through time, with some stocks being minor producers under one climatic regime but dominating during the next. If this pattern is also present in the Kuskokwim River drainage, our reconstruction model will perform well for the years close in time to the total inriver estimates with accuracy decreasing with time both before and after the total inriver estimates. Because of this it will be important to periodically update the model with new estimates of total inriver abundance. We do not feel this weakness will decrease the value of estimating the historical time series. More useful fisheries management information will be obtained from a reasonably accurate estimate of abundance than from no estimate at all.

RECOMMENDATIONS

ASSESSMENT OF ABUNDANCE INDEPENDENT OF THE RECONSTRUCTION MODEL

Total inriver abundance estimates of Kuskokwim River chum salmon independent of the run reconstruction model are critical to the success of this methodology. While an evaluation has not been made of how the number of independent estimates influences the time series of reconstructed estimates, it is obvious that the more accurate the independent estimates, the more independent estimates available, and the more evenly the independent estimates are distributed through time and across run abundances, the more confidence can be placed in the resulting run reconstruction.

It appears at this time that the most efficient and accurate method of independently assessing the size of the total Kuskokwim River chum salmon population is through the use of a large scale mark–recapture study. Furthermore, given the difficulties encountered by Kerkvliet et al. (2003, 2004), resources may be best invested in a mark–recapture study that includes the use of radio telemetry. Radio tags provide a means for testing more of the underlying assumptions than the use of anchor tags or spaghetti tags alone. This being stated, researchers should continue to look for better ways to enumerate or estimate the population.

The studies by Kerkvliet et al. (2003, 2004) were the first large-scale mark–recapture estimates made on the Kuskokwim River. A great deal of experience with this type of project has been gained on both the Kuskokwim and Yukon Rivers since then, and it is imperative that any future investigations take into account the drainage-specific knowledge and sampling techniques that have proven successful for other studies. Care should be taken to only tag healthy fish that have not been held for an extended period of time or crowded in a live box. All attempts should be made to tag proportional to the run abundance and to tag throughout the run. Marked to unmarked ratios should be assessed at all escapement assessment projects, including the Aniak River. The use of radio tags is strongly encouraged. As with all studies, time spent on operational planning, including the calculation of tagging levels where considerations are made for potential problems with tag application and recovery, is time well spent. We have provided an assessment of approximate run magnitude for 2000 and 2006 runs to aid the design of future mark–recapture projects (Table 3). These two years represent the smallest and largest runs in the recent 15 years (Figure 8).

RUN RECONSTRUCTION MODELING

The historical management of the commercial fishery should be examined to determine where major changes in fishing patterns and fishing gear were made. The date of these changes should then be considered for stratifying the commercial catch and effort for use in the model. Care needs to be taken to not create too many strata since there will be a reduction in the degrees of freedom for every additional strata created.

A sensitivity analysis should be performed to determine how the pattern and magnitude of the time series of estimated historical run abundance is affected by the model assumptions, stratification of the catch and effort data, and the independent estimates of total inriver abundance.

An evaluation of whether data prior to 1988 can be included in the model should be pursued. Only data that were easily obtained were used for this study.

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TABLES AND FIGURES

Table 1.–Comparison of the estimates of total chum salmon abundance using mark–recapture methods to independent assessments of abundance for the Kuskokwim River drainage upstream of Kalskag, Alaska.

Assessment Project	Year of Run 2002	2003
Abundance estimate at Kalskag using mark–recapture [a, b]	675,659	412,443
Abundance estimates from tributaries upstream of Kalskag [c]		
Aniak River sonar (adjusted to DIDSON) [d]	472,346	477,544
Holitna River mark–recapture [e]	542,172	NA
Kogrukluk River weir (Holitna River tributary)	51,570	23,411
George River weir	6,543	33,666
Tatlawiksuk River weir	24,542	NA
Takotna River weir	4,366	3,393
Sum excluding Kogrukluk River weir [f]	1,049,969	NA
Sum excluding Holitna River mark–recapture [f]	559,367	538,014
Abundance estimate at Kalskag minus the sum of measured abundance from tributaries upstream of Kalskag		
Excluding Kogrukluk River weir [f]	-374,310	NA
Excluding Holitna River mark–recapture [f]	116,292	-125,571

[a] Kerkvliet et al. 2003.
[b] Kerkvliet et al. 2004.
[c] This list of tributaries represents a subset of the streams known to support spawning chum salmon upstream of Kalskag.
[d] McEwen 2007.
[e] Chythlook and Evenson 2003.
[f] The Holitna River mark–recapture estimate includes escapement past the Kogrukluk River weir and, as such, it is inappropriate to include the mark–recapture estimate and the weir count in the same total.

Table 2.–Proportion of chum salmon passing the counting weirs that were tagged in relation to the distance from the tagging location near Kalskag, Alaska.

Weir project	Distance [a]	2002	2003
George River	183	0.0102	0.0096
Tatlawiksuk River	298	0.0024	NA
Kogrukluk River	440	0.0004	0.0021
Takotna River	565	0.0005	0.0003

[a] Distance is from the fish wheel site located above Kalskag.

Table 3.–Total inriver abundance estimates used to test the run reconstruction model for chum salmon returning to the Kuskokwim River, Alaska.

	Year of Run			
Abundance Assessment Project	2000	2002	2003	2006
Subsistence harvest	51,696	69,019	43,320	54,839
Commercial harvest	11,570	1,900	2,760	44,070
Tributaries downstream of Kalskag				
Eek River [a]	11,000	35,000	40,000	46,000
Kwethluk River weir	11,691	35,854	41,812	47,490
Kisaralik-Kasigluk River [a]	12,000	36,000	42,000	47,500
Tuluksak River weir	NA	9,958	11,724	25,648
Total	34,384	116,812	135,536	166,638
Tributaries upstream of Kalskag [b]				
Aniak River sonar	177,384	472,346	477,544	1,108,626
Holitna River mark–recapture		542,172		
Estimated return to Holitna River [c]	204,000		548,000	1,273,000
George River weir	3,492	6,543	31,300	41,467
Tatlawiksuk River weir	6,965	24,542	28,400 [d]	32,301
Takotna River weir	1,254	4,366	3,393	12,598
Stony River sub-basin [e]	18,000	47,000	48,000	111,000
Swift River sub-basin [e]	18,000	47,000	48,000	111,000
Tributaries upstream of McGrath [e]	18,000	47,000	48,000	111,000
Other tributaries [e]	18,000	47,000	48,000	111,000
Total	465,095	1,237,969	1,280,637	2,911,992
Total inriver estimate	563,052	1,425,700	1,462,253	3,177,539

[a] Estimated as approximately the same as the Kwethluk River weir.

[b] This list of tributaries represents a subset of the streams known to support spawning chum salmon upstream of Kalskag.

[c] Estimated using the ratio of observed fish in 2002 at the Aniak sonar project and the Holitna River mark–recapture estimate.

[d] Tatlawiksuk River weir did not operate in 2003; count was estimated as the average of the weir counts in 2001, 2002, 2004, and 2005.

[e] Estimated as approximately 10% of Aniak River sonar.

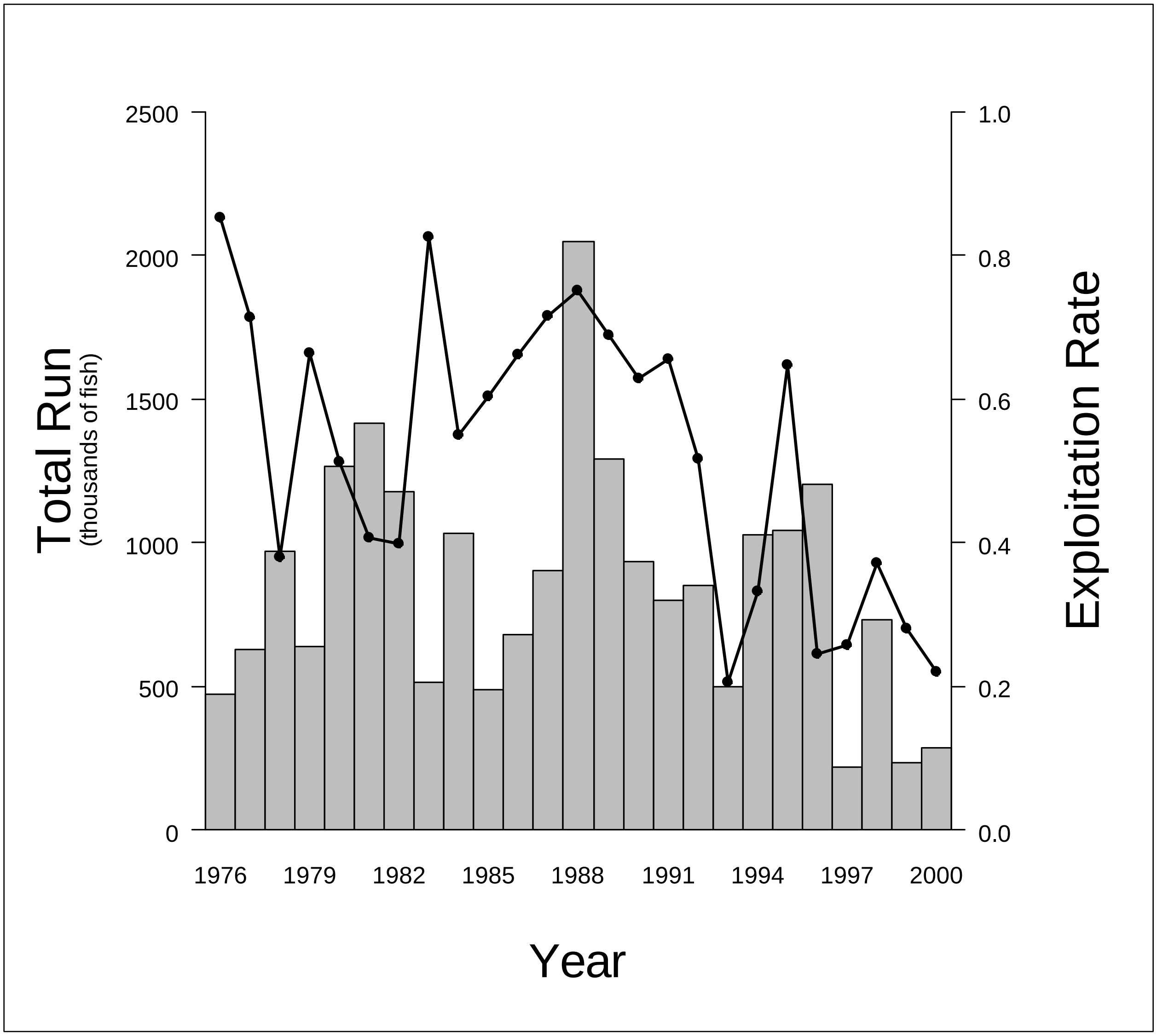

Figure 1.–Estimated historical chum salmon abundance in the Kuskokwim River (columns) and the resulting exploitation rate (line) as estimated by Shotwell and Adkison (2004).

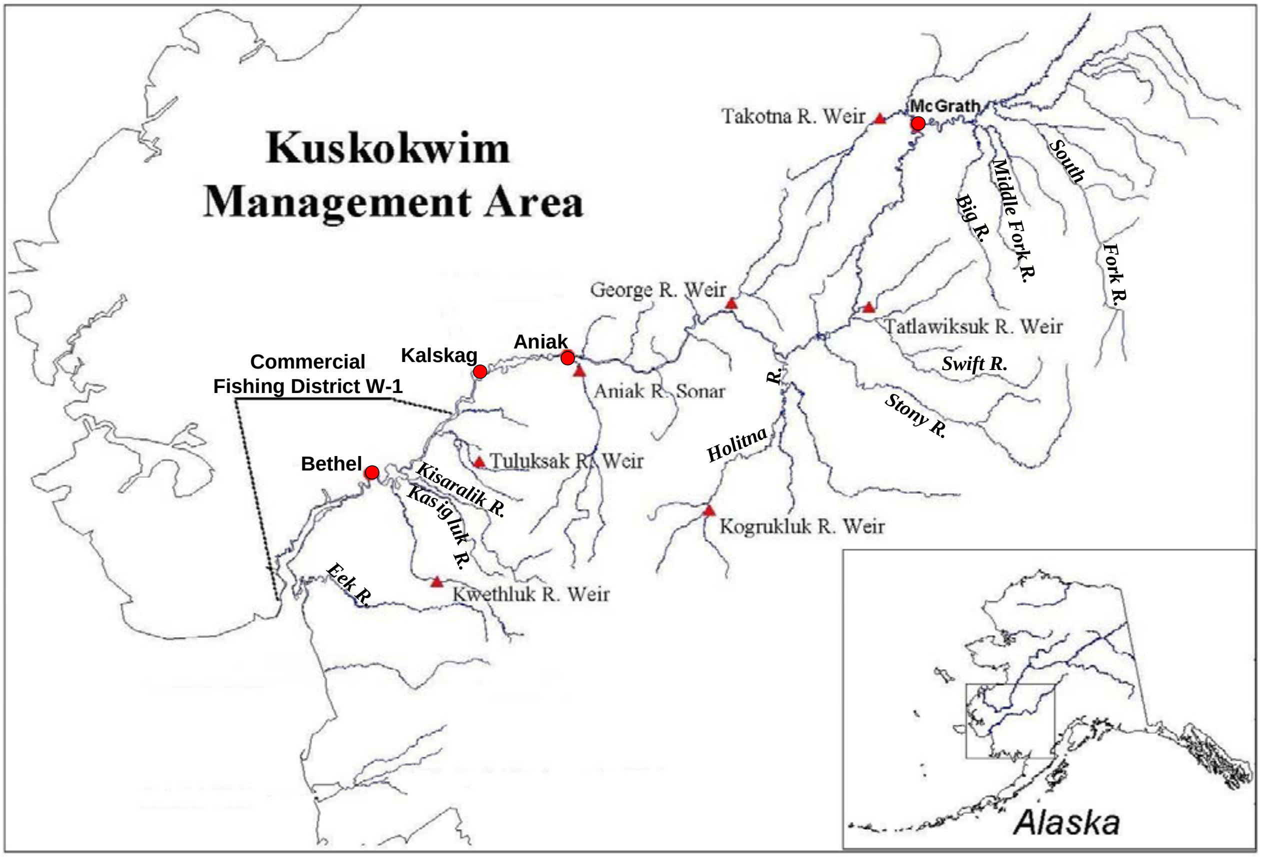

Figure 2.–Location of the stock assessment projects for chum salmon in the Kuskokwim River drainage.

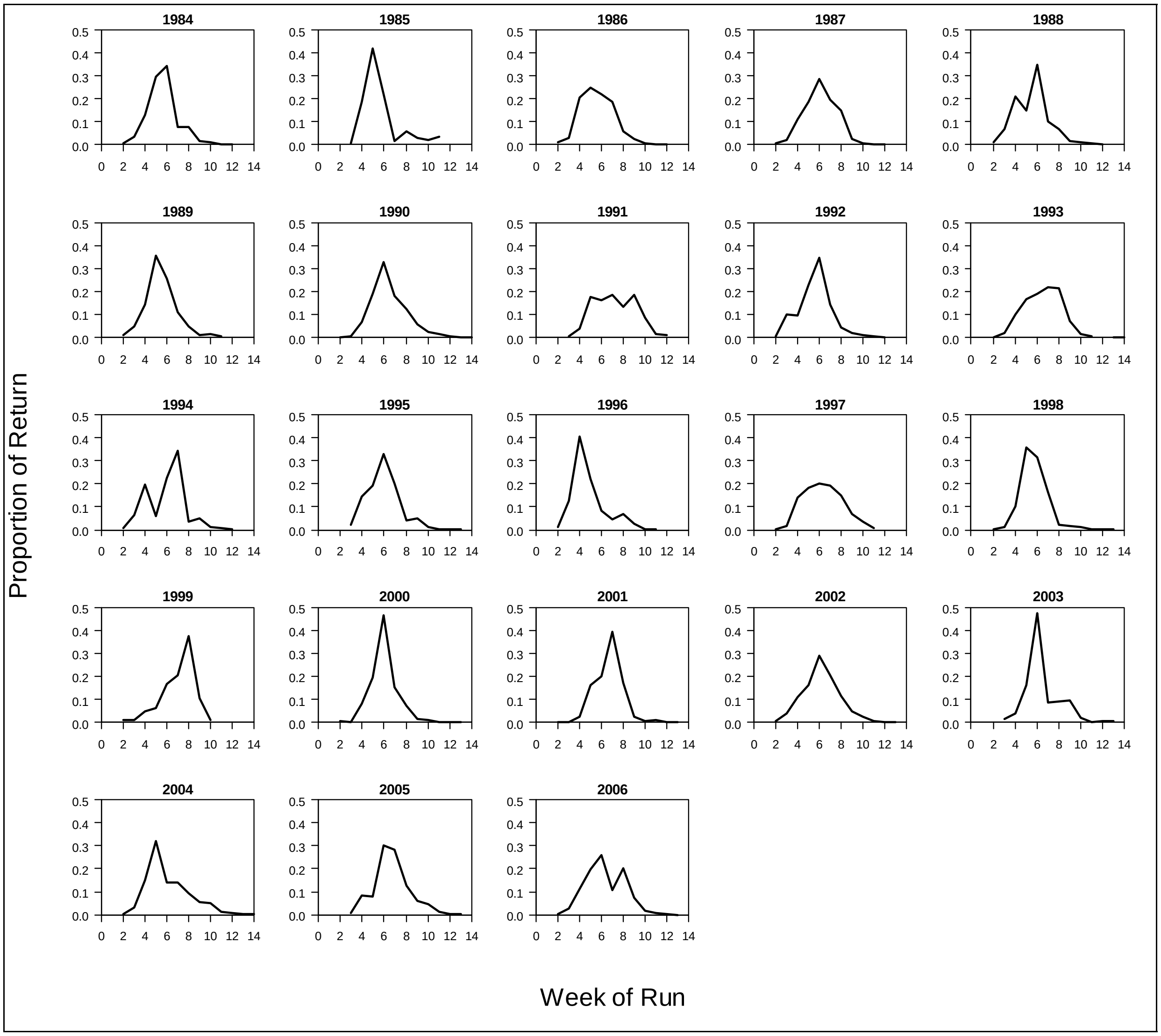

Figure 3.–Run timing of chum salmon into the W1 commercial fishing district of the Kuskokwim River as estimated by the Bethel test fishery for the years 1984-2006.

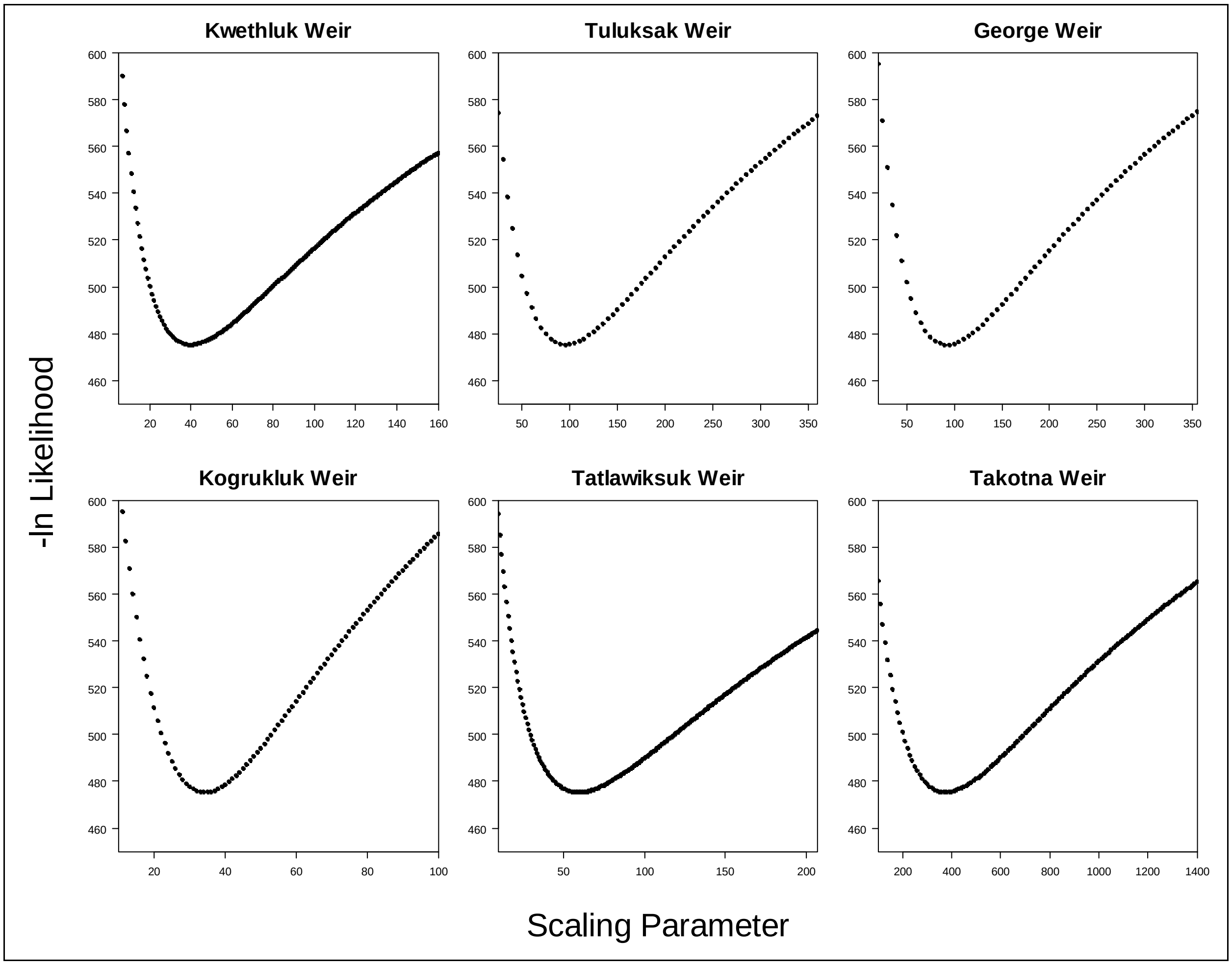

Figure 4.–Negative log likelihood profiles for the escapement scaling factor ($\hat{k}_i$) for each of the systems with weirs.

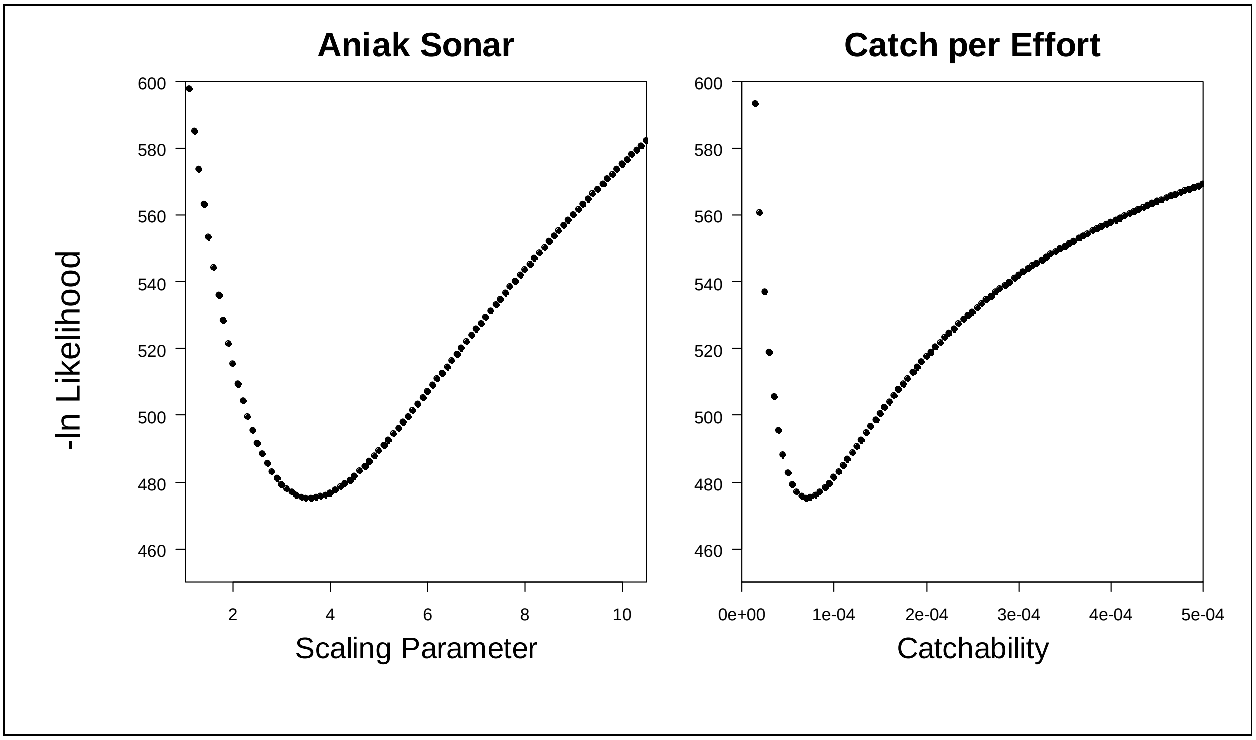

Figure 5.–Negative log likelihood profiles for the escapement scaling factor ($\hat{k}_i$) for Aniak River sonar and the catchability coefficient ($\hat{q}$) for the Baranov catch effort model.

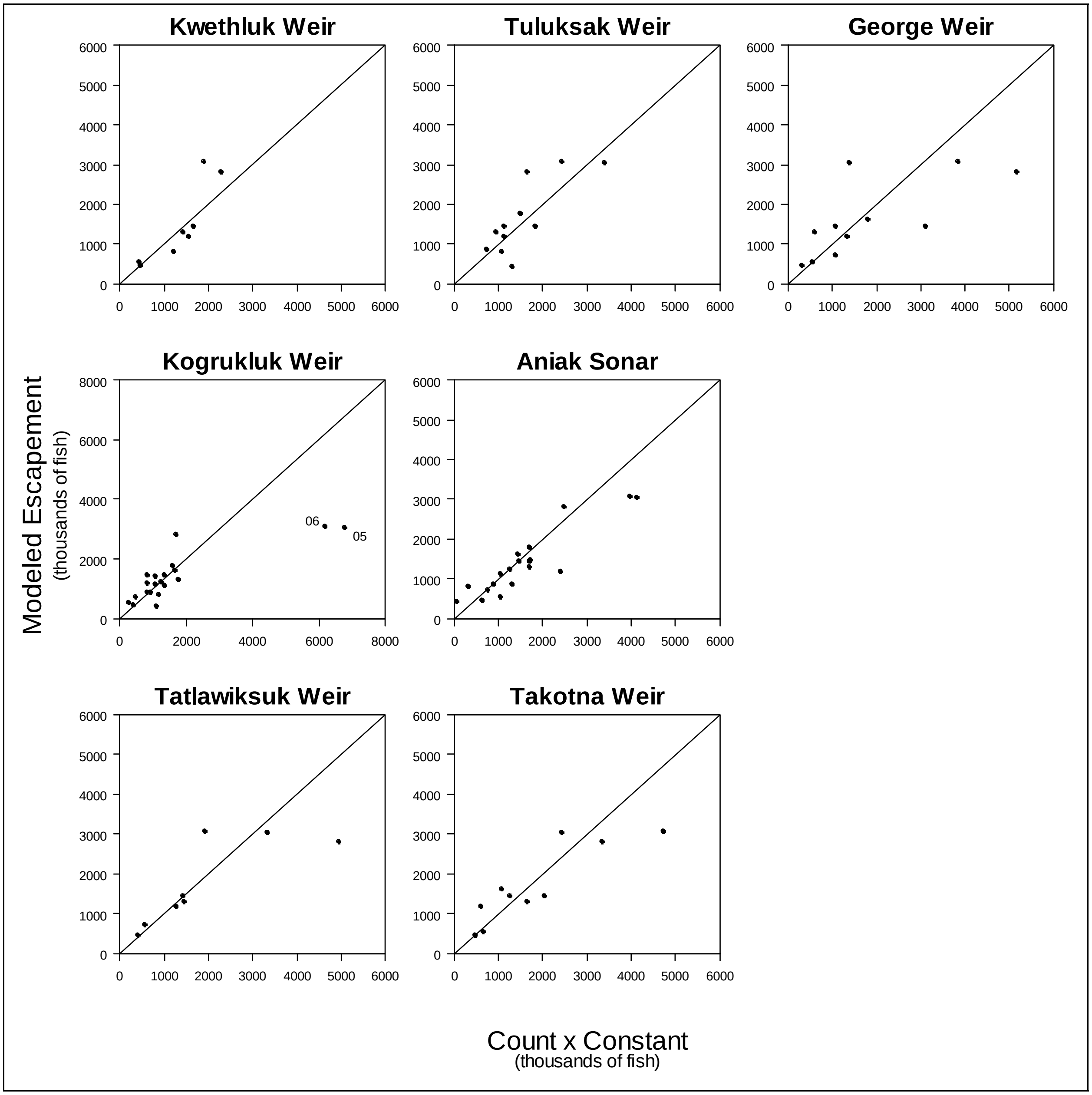

Figure 6.–Comparison of the chum salmon escapement estimates based on the run reconstruction model to the escapement estimate based on a tributary observation for the Kuskokwim River, Alaska. Estimates were made for the purpose of illustrating the potential use of the run reconstruction model and are not actual estimates of escapement.

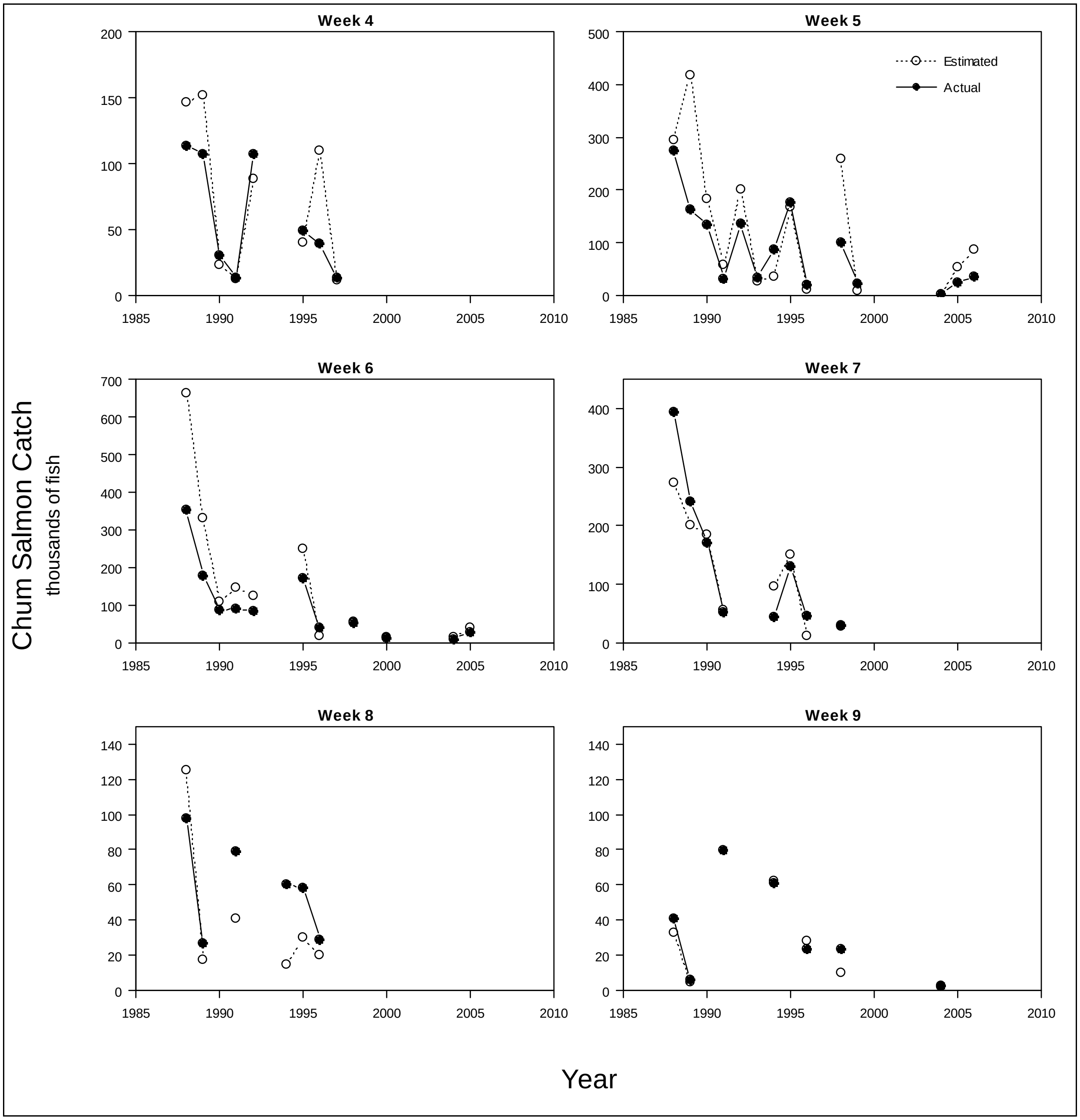

Figure 7.–Comparison of the estimated chum salmon harvest from the Baranov catch per unit effort model to the actual harvest by week and year, Kuskokwim River, Alaska.

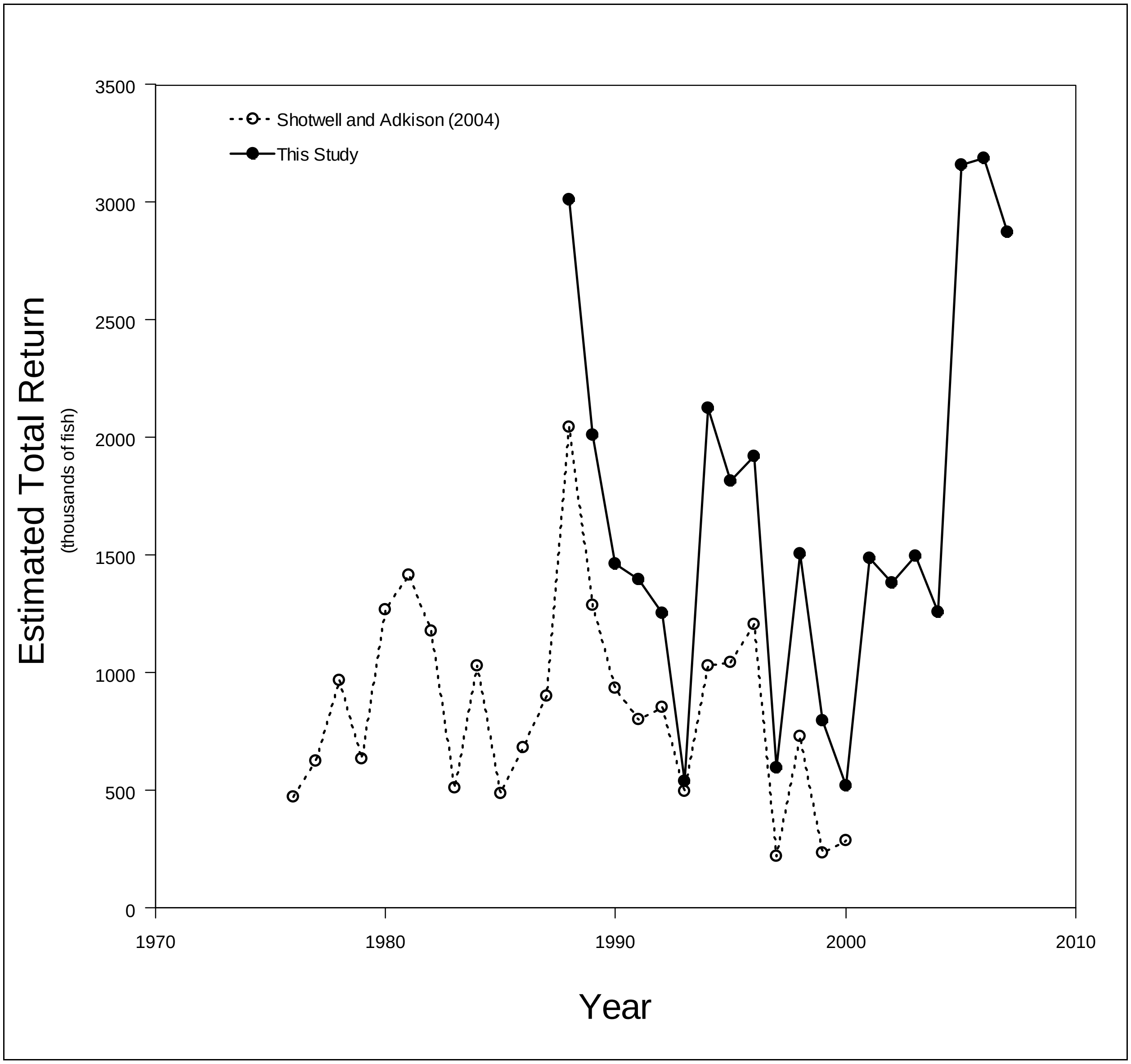

Figure 8.–Comparison of the time series of total run estimates for chum salmon returning to the Kuskokwim River obtained by Shotwell and Adkison (2004) and total run estimates from this study. The estimates made by this study were for the purpose of illustrating the performance of the run reconstruction model and are not actual estimates of total run.

APPENDIX A

Appendix A1.–Harvests and escapements of chum salmon returning to the Kuskokwim River 1976 to 2007.

	Harvest		Escapement						
Year	Commercial	Subsistence	Kwethluk weir	Tuluksak weir	George weir	Kogrukluk weir	Tatlawiksuk weir	Takotna weir	Aniak sonar
1976	177,864					8,117			
1977	248,721								
1978	248,656					48,125			
1979	261,874					18,599			
1980	483,751								1,601,790
1981	418,677					57,374			649,849
1982	278,306					64,077			529,758
1983	276,698								166,452
1984	423,718					41,484			317,688
1985	199,478					15,005			273,306
1986	309,213					14,693			219,770
1987	574,336								204,834
1988	1,381,674	151,967				39,543			485,077
1989	749,182	139,672				39,547			295,993
1990	461,624	126,509				26,765			246,813
1991	431,802	93,077		7,675		24,188			366,687
1992	344,603	96,491	30,595	11,183		34,104			87,467
1993	43,337	59,394		13,804		31,901			15,278
1994	271,115	72,022		15,724		46,635			474,356
1995	605,918	67,861				31,265			
1996	207,877	88,966			19,393	48,494		2,872	402,168
1997	17,026	39,970	10,659		5,907	7,958		1,839	289,654
1998	207,809	63,537				36,441			351,792
1999	23,006	43,601			11,552	13,820	9,599		214,429
2000	11,570	51,696	11,691		3,492	11,491	6,965	1,254	177,384
2001	1,272	49,874		19,321	11,601	30,570	23,718	5,414	408,830
2002	1,900	69,019	35,854	9,958	6,543	51,570	24,542	4,377	472,346
2003	2,760	43,320	41,812	11,724	33,666	23,413		3,393	477,544
2004	20,248	52,374	38,646	11,796	14,409	24,201	21,245	1,630	672,931
2005	68,977	46,036		35,696	14,828	197,723	55,720	6,467	1,151,505
2006	44,070	54,839	47,490	25,648	41,467	180,594	32,301	12,598	1,108,626
2007	10,783	54,839	57,230	17,286	55,842	49,505	83,246	8,900	696,801

APPENDIX B

Appendix B1.–Harvest and effort data for chum salmon in commercial fishing district W1 by week and year, Kuskokwim River, Alaska. Effort is estimated as the number of permits fished times the number of hours the fishery was open.

	Week 3		Week 4		Week 5		Week 6		Week 7		Week 8		Week 9	
	6/10 - 6/16		6/17 - 6/23		6/24 - 6/30		7/1 - 7/7		7/8 - 7/14		7/15 - 7/21		7/22 - 7/28	
Year	Harvest	Effort	Harvest	Effort	Harvest	Effort	Harvest	Effort	Harvest	Effort	Harvest	Effort	Harvest	Effort
1979	2,517	12,864	32,295	3,012	102,291	12,876	83,164	3,252	32,434	3,120	0	0	0	0
1980	711	2,814	111,765	10,728	131,945	2,448	122,613	2,298	90,233	2,586	0	0	0	0
1981	14,124	12,360	78,168	3,066	133,373	11,904	114,393	11,040	66,138	2,640	0	0	0	0
1982	2,532	2,784	14,697	11,940	119,209	15,528	68,233	8,060	49,651	9,468	0	0	0	0
1983	1,805	11,268	53,540	11,088	100,011	11,916	83,141	11,268	20,560	2,796	0	0	0	0
1984	0	0	27,897	11,124	158,893	11,232	124,878	10,908	60,709	11,184	18,613	2,238	0	0
1985	0	0	19,762	2,538	90,221	11,760	76,052	11,688	0	0	0	0	0	0
1986	0	0	0	0	129,727	13,080	121,822	13,704	48,990	3,192	0	0	0	0
1987	0	0	14,137	4,734	167,417	21,078	169,842	13,896	72,118	3,582	137,058	13,440	0	0
1988	72,219	4,816	113,628	3,672	273,835	15,036	351,833	13,908	393,152	32,382	97,392	13,272	40,921	12,552
1989	0	0	107,439	10,416	164,002	12,288	177,072	14,184	241,520	32,886	26,407	2,622	5,716	3,372
1990	0	0	30,306	3,780	133,855	15,072	86,835	3,546	171,214	16,996	0	0	0	0
1991	0	0	13,266	3,606	30,632	3,696	90,181	14,616	52,552	3,426	78,797	3,408	79,871	15,064
1992	0	0	107,124	18,976	135,327	17,206	84,196	4,696	0	0	0	0	0	0
1993	0	0	0	0	34,123	4,976	0	0	0	0	0	0	0	0
1994	0	0	0	0	87,214	4,608	0	0	43,585	1,984	60,104	3,000	60,609	12,696
1995	0	0	49,157	2,276	176,732	9,064	170,673	7,648	129,505	7,432	58,333	7,040	0	0
1996	0	0	39,002	2,112	19,438	360	38,566	1,672	45,269	1,792	28,582	2,320	23,528	12,656
1997	0	0	13,090	2,118	0	0	0	0	0	0	0	0	0	0
1998	0	0	0	0	99,256	9,168	51,471	1,780	29,407	1,668	0	0	23,163	8,592
1999	0	0	0	0	22,700	2,454	0	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	11,026	896	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	2,798	104	9,438	1,320	0	0	0	0	2,343	360
2005	0	0	0	0	24,048	3,410	27,901	604	0	0	0	0	0	0
2006	0	0	0	0	36,006	2,076	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX C

Appendix C1.–Dates used for grouping commercial and test fishery data into weekly intervals for the estimation of run timing.

Week Number	Date Range
1	May 27 – June 2
2	June 3 – June 9
3	June 10 – June 16
4	June 17 – June 23
5	June 24 – June 30
6	July 1 – July 7
7	July 8 – July 14
8	July 15 – July 21
9	July 22 – July 28
10	July 29 – August 4
11	August 5 – August 11
12	August 12 – August 18
13	August 19 – August 25
14	August 26 – September 1

APPENDIX D

Appendix D1.–Variable and parameter definitions used for the formulation of the chum salmon run reconstruction model.

Variable	Description
y	Year
i	Escapement data set. For example, Kwethluk weir count or Aniak sonar count
j	Week of run
I_{iy}	Escapement count for data set *i* and year *y*
E_{iy}	Escapement for data set *i* and year *y*
$\hat{E}_y$	Estimated escapement for year *y*
$\hat{k}_i$	Scaling constant for escapement data set *i*
N_y	Total run for year *y*
$\hat{N}_y$	Estimated total run for year *y*
$\hat{N}_{yj}$	Estimated total run for year *y* present in commercial fishery during week *j*
S_y	Observed subsistence catch for year *y*
C_y	Observed commercial catch for year *y*
$\hat{C}_{yj}$	Estimated commercial catch for year *y* during week *j*
$\hat{q}$	Catchability coefficient
B_{yj}	Observed commercial fishing effort for year *y* during week *j*
p_{yj}	Observed proportion of run *y* present during week *j*
δ_y	Lognormal random error about the estimated escapement ($\hat{E}_y$) for year *y*
ε_{yj}	Lognormal random error about the estimated catch ($\hat{C}_{yj}$) for year *y* week *j*
λ_y	Lognormal random error about the estimated total run ($\hat{N}_y$) for year *y*
w_i	Weight applied to escapement data set *i*
w_C	Weight applied to the catch and effort data set
w_N	Weight applied to the total inriver data set