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Estimates of Total Annual Return of Chinook Salmon to the Kuskokwim River, 2002–2007

Final Report for Study 07-304
Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative

by

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

ALASKA DEPARTMENT OF FISH AND GAME

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)

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

Chinook salmon *Oncorhynchus tshawytscha* abundance in the Kuskokwim River drainage from 2002 through 2007 was estimated by combining harvest estimates, escapement estimates in monitored tributaries and expansions to unmonitored drainage areas, and abundance estimates obtained from large-scale mark–recapture studies. Middle and upper Kuskokwim River Chinook salmon abundance was estimated using data from mark–recapture and radiotelemetry studies conducted from 2002 through 2006. We extended the radio telemetry mark–recapture investigation through 2007 and tested assumptions necessary to include recapture data from the Aniak River population in the estimate. Specifically, operation of an escapement monitoring weir on the Salmon River, a tributary of the Aniak River, provided sufficient recapture data to more completely test our mark–recapture assumptions. Estimates of abundance above Birch Tree Crossing (rkm >294) ranged from 125,235 to 245,043 Chinook salmon. Additionally, we estimated escapement in the lower Kuskokwim River tributaries using weirs and a habitat-based model. Estimates of escapement in the lower Kuskokwim River ranged from 46,925 to 105,118 Chinook salmon. Combining these estimates with harvest data provided estimates of the total Chinook salmon run to the Kuskokwim River for the years 2003 through 2007 ranging from 241,617 to 422,657 fish.

Key words: Chinook salmon, *Oncorhynchus tshawytscha*, Kuskokwim River, total run, escapement, subsistence salmon harvest, commercial salmon harvest, habitat model, radiotelemetry, mark–recapture, stock specific run timing.

INTRODUCTION

In 2007, the Alaska Department of Fish and Game (ADF&G), Division of Commercial Fisheries began development of a statistical model to reconstruct total annual returns of Kuskokwim River Chinook salmon *Oncorhynchus tshawytscha* back to 1976. The approach was based on methods presented by Shotwell and Adkison (2004) and subsequent modifications by Bue et al. (2008) for estimating salmon abundance in data limited situations. The success of this modeling initiative is reliant on independent estimates of total abundance for scaling purposes. Estimating drainagewide salmon abundance is challenging due to the large size and remoteness of the Kuskokwim River (Figure 1), coupled with the fact that a direct count of all fish returning to the drainage has not been possible in the lower river because of the width and depth of the river and tidal influence in the areas where a total river count would need to be conducted. Rather an approach that combines direct and indirect methods is required. This report details the methods used to reconstruct total abundance of Kuskokwim Chinook salmon from 2002 to 2007 which could be used to scale more general abundance models.

Efforts to monitor Kuskokwim River Chinook salmon abundance have increased since 1990. Historically, information on Chinook salmon abundance came from harvest statistics of commercial, subsistence, and test fisheries, and an escapement index that combined escapement data from aerial survey counts, and a weir located on the Kogrukluk River, a tributary of the Holitna River (Figure 2). Following several years of low Chinook salmon abundance that occurred in the late 1990s and early 2000s, the Kuskokwim River salmon monitoring platform expanded considerably. Weirs operated by U.S. Fish and Wildlife Service (USFWS) located on the Kwethluk (river kilometer (rkm) 216) and Tuluksak (rkm 248) rivers have been used to monitor escapement to the lower Kuskokwim River since 1999. Weirs operated by Division of Commercial Fisheries, Kuskokwim Native Association, and Takotna Tribal Council located on the Salmon (rkm 404), George (rkm 453), Tatlawiksuk (rkm 568), Kogrukluk (rkm 710), and Takotna (rkm 835) rivers have been used to monitor escapement into the middle and upper portions of the drainage (Figure 2).

This suite of weirs was used for recapture sampling in an extensive multi-year mark–recapture experiment conducted by Division of Sport Fish from 2002 to 2006. Chinook salmon were tagged with radio tags near Kalskag using fish wheels and drift gillnets, and were recaptured at the upriver weirs, resulting in an annual estimate of large (≥450 mm) Chinook salmon that returned to the Kuskokwim River upstream of river kilometer 311 (Stuby 2007). The telemetry information also allowed for identification of the relative contribution of each tributary and included unmonitored systems used for Chinook salmon spawning.

The combination of the abundance data collected from 2002 to 2006 represented all harvested Chinook salmon, partial escapement counts for the lower river tributaries, and partial abundance estimates for middle and upper portions of the drainage. However, the telemetry and abundance estimates still did not account for escapements into several unmonitored lower Kuskokwim River tributaries or fish returning to the Aniak River in 2002–2005.

The mark–recapture study conducted by Division of Sport Fish in 2002–2005 represented only those Chinook salmon that returned to the Kuskokwim River upriver of rkm 311 but excluded returns to the Aniak River, which joins with the Kuskokwim River at rkm 307. The Aniak River is a major Chinook salmon spawning tributary and estimates of the number of Chinook salmon that returned to the Aniak River were needed for reconstructing total annual return of Chinook salmon to the Kuskokwim River. During each year of the 2002–2005 mark–recapture study, efforts were made to sample Chinook salmon in accordance with the necessary conditions to produce an unbiased estimate of abundance with the generalized Petersen model (Stuby 2007). However, the investigators thought that tagged Chinook salmon that returned to the Aniak River were disproportionately tagged on the south-side bank as a result of bank orientation they observed. They could not specifically test whether tagging was unbiased because there was not a recapture site located in the Aniak River drainage, so tagged fish identified in the Aniak River were excluded from the estimates. Their abundance estimates were germane only to waters upstream of the Aniak River (Stuby 2007).

Given the large number of Chinook salmon that return annually to the Aniak River, the inability to account for those fish in the 2002–2005 study was considered a significant limitation. In response, Division of Commercial Fisheries installed a weir in 2006 on the Salmon River (rkm 404), a major tributary of the Aniak River, which functioned as an additional recapture site for Chinook salmon tagged at Kalskag (rkm 270) (Stuby 2007). This site allowed us to test mark–recapture assumptions with Aniak River fish included. In the 2006 mark–recapture data, no evidence of disproportionate tagging was found. As a result, the 2006 mark–recapture abundance estimate was germane to the entire middle and upper drainage upriver of Birch Tree Crossing (rkm 294), including the Aniak River (Stuby 2007). Given that similar mark–recapture tagging methods were used in 2002–2005 and in 2006, we assumed it would be appropriate to reanalyze all the mark–recapture data collected from 2002 to 2005 to produce abundance estimates for the entire middle and upper drainage upriver of Birch Tree Crossing (rkm 294), including the Aniak River, comparable to 2006. Furthermore, we decided to check that assumption by collecting an additional year of data in 2007 to further test the assumption that capture methods used to tag Chinook salmon were not selective for Aniak bound fish.

Differences in the methods used during the 2007 mark–recapture study and those used in 2002–2006 studies required that all prior data be revisited. These changes resulted in small differences to the input data used by Stuby (2003, 2004, 2005, 2006, and 2007) for estimating abundance. In 2007 we included estimated passage at the weirs during inoperable times where the previous investigators only considered fish that passed during times when the weir was fully operational. That change was made because the Division of Commercial Fisheries standardized methods to estimate missed passage, and confidence in those estimates for a variety of purposes is high. The inclusion of the inoperable periods also allowed for the inclusion of radiotagged fish that passed the weir during those times, which increased sample sizes and statistical power for testing mark–recapture assumptions. Additionally, the tracking station located just below the village of Aniak that was used from 2002 to 2006 as the entry point was not operated in 2007. This decision was made because that tower location was upriver from the entrance to Aniak Slough, a potential migration route for Chinook salmon, and fish traveling through the slough could be missed by the tower. The tracking station was also on a high bluff and recorded fish traveling up the Aniak River, which could be confounded with fish traveling in the mainstem Kuskokwim River. In 2007, the tracking station at Birch Tree Crossing (rkm 294) was deemed to be more appropriate and was used as the entry point for that year. The change of entry points in 2007 resulted in an additional 10 rkm of the mainstem included in the study area and required us to reassess all the prior data for consistency with that change.

Lower Kuskokwim River escapement was not accounted for in the mark–recapture estimates from Birch Tree Crossing, and counts are only available for the Kwethluk (Miller et al. 2008) and Tuluksak rivers (Plumb and Harper 2008). However, the Kisaralik, Kasigluk, and Eek rivers also drain the lower Kuskokwim River and are known to support notable numbers of Chinook salmon (Johnson and Daigneault 2008). We present an approach to estimating annual escapement to those unmonitored portions of the lower Kuskokwim River by first assuming that either the Kwethluk or Tuluksak rivers is a suitable surrogate and then scaling the annual observed escapement of the surrogate to account for the expected annual difference in productivity of any unmonitored system. The habitat model presented by Parken et al. (2006) uses basin area to estimate spawners at maximum sustained yield (S_{msy}) and was developed using data from the west coast of the United States and Canada, including Alaska. To our knowledge, this approach has not been used in other studies to estimate Chinook salmon escapement into unmonitored tributaries. Although unconventional, this approach provides a time series of escapement estimates that are reasonable for the purpose of reconstructing total annual return of Chinook salmon to the Kuskokwim River.

OBJECTIVES

1. Conduct a two-sample mark–recapture experiment in 2007 and reanalyze data collected in 2006 to test the assumption that Aniak River Chinook salmon were tagged in proportion to abundance, and use those results to determine if it is appropriate to reanalyze the mark–recapture estimates of abundance produced by Division of Sport Fisheries in 2002–2005 to include tagged fish tracked to the Aniak River.
2. If it is determined to be appropriate given the results of Objective 1, reanalyze all 2002–2006 mark–recapture data based on methods consistent with those used in 2007. Revisions will include revised entry point designating the lower boundary of the study area; inclusion of estimated escapement during periods when recapture weirs were inoperable; inclusion of radiotagged Chinook salmon that passed weirs during inoperable periods; and including radiotagged Chinook salmon recovered in the Aniak River.
3. Estimate abundance of Chinook salmon upriver of Birch Tree Crossing (rkm >294) from 2002 to 2007.
4. Estimate the escapement of Chinook salmon in the lower Kuskokwim River below the Birch Tree Crossing (rkm >294).

5. Reconstruct total annual return of Kuskokwim River Chinook salmon from 2002 to 2007 by combining harvest data with estimates of lower river escapement (rkm <294) and abundance upriver of Birch Tree Crossing (rkm >294).

METHODS

2006 AND 2007 MARK–RECAPTURE DIAGNOSTICS

The focus of this portion of the project was on testing the hypothesis that Chinook salmon bound for the Aniak River had the same probability of being captured and tagged as Chinook salmon bound for other areas upstream of the tag site located near Kalskag (rkm 270; Figure 2). Data from 2006 were reevaluated from those reported in Stuby (2007) because of differences in telemetry tower locations and passage criteria which may have resulted in different diagnostic findings. Failure to reject our hypotheses in 2006 and 2007 was the criterion used to determine if it was appropriate to include data from Aniak River Chinook salmon in a reanalysis of all mark–recapture data collected using similar techniques in 2002–2005.

2007 Tagging and Tracking

Chinook salmon were captured from the mainstem Kuskokwim River using two bank mounted fish wheels and mid-river drift gill nets near Kalskag (rkm 270) as described by Stuby (2007). In 2007, the fish wheels operated 18 hours a day, 6 days a week from June 10 to August 15. Chinook salmon captured with fish wheels where held for no longer than one hour in a live box before being tagged and released. Fish captured with gillnets were tagged and released immediately after capture.

Tags and tag deployment methods were consistent with those used by Stuby (2007). Esophageal-implanted radio transmitters were the primary mark. Radio tags were Model Five pulse encoded transmitters made by ATS[1]. Each radio tag was distinguishable by a unique frequency and encoded pulse pattern. Twenty frequencies spaced approximately 20 kHz apart in the 149–150 MHz range with 25 encoded pulse patterns per frequency were used for a total of 500 uniquely identifiable tags. Fish were selected for tagging following a schedule that attempted to distribute tags in proportion to run strength based on historic run timing (Schaberg et al. 2010). In addition, effort was made to distribute tags proportional to expected length composition, based on data from upriver weirs. Weekly tag goals were such that 20% of tags were deployed in fish measuring between 450 and 650 mm, and the remaining tags were deployed in large fish (i.e., ≥650 mm). Due to the size of the radio transmitters (14.5 x 49 mm), Chinook salmon <450 mm were not tagged (Winter 1983). All radiotagged fish were given a secondary mark of a brightly colored and uniquely numbered anchor tag to aid in recapture and diagnostics.

Radiotagged Chinook salmon were tracked as they migrated up the Kuskokwim River using a network of 18 tracking stations and aerial tracking surveys. Stations were positioned at key locations along the mainstem Kuskokwim River and at each of the upriver weirs (Figure 2). Two aerial tracking flights were conducted following the end of tagging operations. The first flight occurred August 20–27, with the intent of locating earlier tagged fish before they started to die and drift down river. The second flight occurred September 21–27 to target fish tagged later in the season. These flights covered the entire Kuskokwim drainage upstream of rkm 233.

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[1] Advanced Telemetry Systems, Isanti, Minnesota (Product names used in this report are included for scientific completeness but do not constitute product endorsement).

Fate Assignment

We used data from aerial surveys and tracking stations to estimate the number of tagged fish that successfully continued upstream after tagging and entered the "marked" population. The fate assigned to each fish was determined using the following criteria:

1. A tagged fish was determined to have entered the sample population if any of the following was true:
    a. it was recorded at any ground-based tracking station located upstream of the Birch Tree Crossing station (rkm 294) and remained upstream of Birch Tree Crossing for more than 7 days;
    b. it was located upstream of Birch Tree Crossing during aerial tracking; or
    c. it was harvested upstream of Birch Tree Crossing.
2. A tagged fish was determined to have not entered the sample population if any of the following was true:
    a. it was recorded only at the tracking station located downstream of the Kalskag capture site ("High Bluffs", rkm 233);
    b. it remained upstream of the Birch Tree Crossing station for 7 or fewer days;
    c. it was never located during aerial tracking or at tracking stations upstream of Birch Tree Crossing; or
    d. it was harvested below Birch Tree Crossing.

Recapture Sample

The recapture event occurred at weirs located on 5 tributaries upstream of the Kalskag capture site: Salmon (rkm 404; unpublished data on file with the Kuskokwim Research Group, contact Kevin Schaberg, ADF&G Division of Commercial Fisheries; Anchorage), George (rkm 453; Thalhauser et al. 2008), Tatlawiksuk (rkm 568; Stewart et al. 2008), Kogrukluk (rkm 710; Williams and Shelden 2010), and Takotna (rkm 835; Costello et al. 2008) rivers (Figure 2). The capture event (C_i) consisted of all Chinook salmon that where estimated to have passed upstream of weir i (i=1,…,5), including estimates of missed passage during inoperable periods. The number of recaptures (R_i) for weir i (i=1,…,5) consisted of all radiotagged fish that passed upstream of the tracking station located at that weir, including those that passed during inoperable periods.

Conditions for an Unbiased Mark–Recapture Study

Unbiased estimates of abundance from mark–recapture experiments require certain assumptions be met (Seber 1982). The assumptions, expressed in terms of the conditions of this study, respective design considerations, and test procedures are listed below. To produce an unbiased estimate of abundance with the generalized Petersen model, Assumptions I, II, III must be met. In addition, 1 of the 3 "or" conditions under Assumption IV must also be appropriate.

Assumption I: The population was closed to births, deaths, immigration and emigration.

Operational periods of the capture site and recovery weirs were designed to sample the entire return of Chinook salmon upstream of the capture site. Any portion of the Chinook salmon run passing the capture or recapture sites before or after project operations was assumed to be negligible. Modest harvest levels of Chinook salmon occur upriver of the capture site; however, we assumed that marked and unmarked fish were harvested at the same rate. We used radiotelemetry to monitor tagging success, and only tagged Chinook salmon assigned to Fate 1 were included in the marked population. Use of this entrance criterion was intended to mitigate the bias associated with any disproportionate dropout between tagged and untagged Chinook salmon due to tagging effects.

Assumption II: Marking and handling did not affect the catchability of Chinook salmon in the second event.

Based on recommendations from (Bromaghin and Underwood 2004), holding time in the live box and handling time during tagging was minimized in an effort to minimize handling effects. Fish judged to be excessively stressed or injured were not tagged.

Assumption III: Tagged fish did not lose their tags between the capture site and the weirs.

Precautions of tagging appropriately sized fish and reducing holding stress were implemented to reduce the likelihood of tag loss. All tags that were located below the entry point at Birch Tree Crossing (rkm 294) were removed from the marked population, and further tag loss was assumed to be minimal.

Assumption IV: Equal probability of capture, recapture, complete mixing.

One of the following 3 conditions must be met:

1. All Chinook salmon had the same probability of being caught in the marking event; or
2. All Chinook salmon had the same probability of being captured in the recovery event; or
3. Marked fish mixed completely with unmarked fish between the mark and recovery events.

Because the first objective of this study was to assess whether Aniak River bound Chinook salmon were marked proportional to their occurrence in the population, we prioritized the test of the probability of being caught in the marking event. Upon satisfaction of this condition, we would move forward with the incorporation of the 2002–2005 data. If this condition was not met, we would be unable to move forward with the other objectives. Meeting condition 1 satisfied both the mark–recapture assumption IV, and objective 1, therefore, conditions 2 and 3 were not investigated.

It was expected that individual capture gears used at the Kalskag tag site may be selective for a particular component of the population; however, we assumed the aggregate of tagging gears would adequately represent upriver stocks proportional to their abundance past the tag site. Equal probability of capture during the marking event was tested using contingency table analysis as described Appendix A1.

The potential for sex and length selective biases during the capture and recapture events were explored using contingency table analysis and Kolmogorov-Smirnov methods as described in Appendix A2. The tests for differences between the marked and recovered fish (M vs. R in Appendix A2) were straightforward while the tests involving all of the fish examined during the second event (C in Appendix A2) were modified to account for the fact that the age, sex and length (ASL) composition (Molyneaux et al. 2010) of the fish examined for marks during the second event was estimated and the number of samples collected at each site was not proportional to abundance. We approached this problem using a bootstrap resampling design

(Efron 1982) to obtain representative samples from each weir project. It was assumed that the ASL samples from each weir were representative of the fish that passed through the weir, that a random sample of these ASL observations would represent a random sample of the weir population, and combining random samples from all weir projects would represent the total escapement.

The test for differences in sex composition or length distribution for a year was then made by randomly selecting with replacement, ASL_i samples from those collected at weir *i,* combining them into a composite group composed of samples from all weirs examined that year and then calculating the test statistic. The random selection and the calculation of the test statistic was repeated 10,000 times and the expected value or mean of the 10,000 bootstraps was used to estimate the probability of failing to reject the hypothesis of no difference between the groups (p-value).

The number of ASL observations to be included in the bootstrap sample from each weir was determined using a methodology which maximized the number of samples used in the analysis while ensuring that the ratio of ASL samples to weir counts was the same for each weir. The ratio of ASL samples to weir counts was the smallest at the Kogrukluk weir in 2002, and 2004–2007, and the number of ASL samples to be randomly selected for use in the analysis from weir *i* (ASL_i) was determined by,

$$ASL_i = C_i \frac{ASL_{Kog}}{C_{Kog}} , \tag{1}$$

where C_i and C_{Kog} were the number of fish estimated to have passed through weir *i* and Kogrukluk while ASL_{Kog} was the number of ASL samples from Kogrukluk. Similar determinations were made for the remaining weirs and the total number of ASL samples (ASL_{Tot}) to be randomly selected for any year was the sum of the determinations;

$$ASL_{Tot} = ASL_{Kog} + \sum ASL_i . \tag{2}$$

In 2003, the ratio of ASL to weir counts was smallest at the George River weir and values for ASL_{Kog} and C_{Kog} were replaced in equations 1 and 2 by corresponding values from George River.

2002–2005 MARK–RECAPTURE DIAGNOSTICS INCLUDING THE ANIAK RIVER

The criterion used to determine if it was appropriate to include radio tag data for Aniak River Chinook salmon in a reanalysis of Chinook salmon abundance upriver of Birch Tree Crossing in 2002–2005 was a failure to reject the hypotheses that Aniak River Chinook salmon were tagged proportional to abundance in 2006 and 2007. That criterion was considered acceptable given the similarity in tagging methods used across all years. Raw telemetry data from the 2002–2005 tagging efforts conducted by Division of Sport Fish were reanalyzed using fate assignment and escapement passage criteria implemented for the 2006 and 2007 investigation. We then tested mark–recapture assumptions following the same methods described for 2006 and 2007. If mark–

recapture assumptions were satisfied in these years, we proceeded with estimation of abundance upstream of Birch Tree Crossing for 2002–2005.

ABUNDANCE ESTIMATES UPSTREAM OF BIRCH TREE CROSSING

Abundance of Chinook salmon was estimated for each year, *y*, in which mark–recapture assumptions were satisfied using the Chapman modification to the Petersen estimator (Chapman 1951):

$$\hat{N}_y = \frac{\left(\hat{C}_y + 1\right)\left(M_y + 1\right)}{R_y + 1} - 1 \quad , \tag{3}$$

where:

$\hat{N}_y =$ estimated abundance of Chinook salmon;

$M_y =$ the number of radiotagged Chinook salmon known to survive tagging and handling (i.e., Fate 1);

$R_y = \Sigma R_{yi}$ the number of radiotagged Chinook salmon identified moving upstream of all 5 weirs: Salmon River (R_1); George River (R_2), Kogrukluk River (R_3), Tatlawiksuk River (R_4), and Takotna River (R_5), as determined from a combination of tracking stations, and aerial tracking); and,

$\hat{C}_y = \sum \hat{C}_{yi}$ the estimated number of Chinook salmon counted past all the 5 weirs, including visual counts and missed passage during periods when weirs were inoperable or compromised.

Variance Estimates

Parametric bootstrap simulations (1,000 replicates) were used to estimate the variance of the mark–recapture estimate of abundance. The distribution of number of marked and recaptured fish was modeled and separate estimates of abundance were calculated for each of the 1,000 bootstrap samples.

$$N^*_{y(b)} = \frac{(M^*_{y(b)} + 1)(\hat{C}_y + 1)}{R^*_{y(b)}} - 1 \tag{4}$$

where:

(b) = denotes bootstrap simulation replicates.

The estimated variance and estimated relative statistical bias were approximated as:

$$Var(\hat{N}_y) = \frac{\sum_{(b)} (N^*_{y(b)} - \overline{N}^*)^2}{B - 1} \quad , \tag{5}$$

$$\text{Relative Statistical Bias} = \frac{\hat{N} - \overline{N}^*}{\overline{N}^*} \times 100 \ , \tag{6}$$

where:

B = 1,000 and

$\overline{N}^* = (\Sigma N^*_{y(b)}) / B$.

Simulation of the Number of Marked Fish

The number of marked fish (M^*) that moved upstream in the simulation was treated as a random variable, because only a portion of the total available radio tags that were deployed, moved upstream. M^* was assumed to have a binomial distribution with $M' \sim B(T, \ \hat{\pi})$ where T= number of tags available to deploy and $\hat{\pi}$=proportion of radio tags that were deployed and successfully moved upstream.

Simulation of the Number of Recaptured Fish

The tagged fish that passed upstream of Birch Tree Crossing (M^*) were then assigned to mutually exclusive fates with multinomial distribution X_i~multi (π_i, M^*): 1) unknown (π_1); 2) moved to non-terminal area or harvested (π_2); 3) moved upstream of Salmon River (R_1) (π_3); 4) moved upstream of George River (R_2) (π_4), 5) moved upstream of Kogrukluk River (R_3) (π_5); 6) moved upstream of Tatlawiksuk River (R_4) (π_6); 7) moved upstream of Takotna River (R_5) (π_7); and 8) moved upstream of upper Kuskokwim River (π_8).

Probability of each fate was estimated as $\hat{\pi}_i = X_i / M$ where X_i is the number of radiotagged fish assigned to each fate. The simulated number of recaptured fish at 5 streams $(R^*_1, R^*_2, R^*_3, R^*_4, and R^*_5)$ was calculated as ($R^*_i = \pi^*_{i+2} \bullet M^{-1*}$).

Lower Kuskokwim River Chinook Salmon Abundance Estimates

All waters located below Birch Tree Crossing (rkm 294) that support Chinook salmon spawning were identified from the ADF&G Anadromous Waters Catalogue (AWC; Johnson and Daigneault 2008). The Eek, Kasigluk, Kisaralik, Kwethluk, Tuluksak, and Fog rivers were identified as important Chinook salmon spawning habitat (Figure 3). Salmon counting weirs located on the Kwethluk (rkm 216) and Tuluksak (rkm 248) rivers have been used from 1999 to the present to estimate annual spawning escapement into those systems (Miller et al. 2008; Plumb and Harper 2008; Figure 2). These weir-based estimates were not expanded for unmonitored reaches downriver of the weir because local knowledge suggests that Chinook spawning activity in those areas is negligible (Dan Gillikin, Fisheries Biologist, USFWS/Bethel; personal communication).

We estimated escapement for unmonitored tributaries with the aid of a habitat-based model developed by Parken et al. (2006), which estimates spawning abundance necessary to achieve maximum sustained yield (S_{msy}) using watershed area. The model was developed using the allometric relationship between estimates of S_{msy} from systems with adequate spawner recruit data along the West coast of North America (including Alaska) and available habitat area in these systems. The authors identified different relationships between ocean-type and stream-type life histories in Chinook salmon; however, the Kuskokwim River supports only stream-type Chinook salmon, so only the stream-type S_{msy} model developed by Parken et al. (2006) was used.

The log transformed version of the allometric model from Parken et al. (2006) is:

$$\ln y = \ln a + b \ln x + \sigma^2 . \quad (7)$$

Where ln a, b, and σ^2 were estimated using linear regression of habitat area and S_{msy}. To solve for S_{msy} the constants from the regression result in:

$$S_{msy} = \exp(2.917216 + (0.6921884 * \ln(\text{watershed area km}^2) + 0.293/2)) \quad (8)$$

Determination of watershed area was made following specific decision criteria, and utilized the Riverscape Analysis Project (RAP) sub-watershed delineation tool (http://rap.ntsg.umt.edu/). The decision criteria for inclusion in the watershed are as follows:

1. Chinook salmon were identified as present in the tributary watershed by the AWC;
2. The lower watershed boundary was established as the nearest stream junction to the point at which the river becomes primarily palustrine in nature, i.e. gradient < 0.5%, substrate is fine sand and silt, high turbidity and primarily a single meandering channel;
3. The entire watershed from the identified lower boundary was selected using the RAP;
4. Tributaries (and associated catchments) were removed if not identified with the AWC Chinook distribution or the AWC distribution was < 1/3 of the total drainage length for the catchment and couldn't be further divided by another stream junction;
5. Upper watershed boundary was identified by selecting the nearest stream junction in the RAP that encompassed the furthest upstream distribution of Chinook salmon as identified with the AWC and selecting the catchment above that point, with the exception of the Tuluksak which was selected by the furthest point downstream of which past and current mining activity has taken place.

For our analysis, the Kasigluk and Kisaralik rivers were considered one system because they share water through multiple channels in their lower reaches.

We examined the appropriateness of using estimates of S_{msy} for escapement estimation by comparing the estimate of S_{msy} to known escapements for the Kwethluk and Tuluksak rivers. In all years the observed escapement past the Kwethluk River weir exceeded S_{msy} whereas the observed escapement past the Tuluksak River weir was less than estimates of S_{msy}. This pattern made sense given that the Kwethluk River is a largely un-impacted system with limited inriver harvest whereas the Tuluksak River has a history of mining and supports an intensive subsistence fishery near the mouth of the river (Harris and Harper 2010). We assumed that using S_{msy} estimates from the habitat model for Kasigluk/Kisaralik and Eek Rivers would underestimate annual escapement given that these systems are similar to the Kwethluk in habitat integrity and that aerial survey counts of peak spawning abundance in these systems correlates well with Kwethluk River weir counts.

We assumed that the Kwethluk River was a suitable surrogate for the Kasigluk/Kisaralik and Eek rivers and the Tuluksak River was a suitable surrogate for the Fog River. Annual estimates of escapement into unmonitored tributaries were made by adjusting the annual observed escapements for the appropriate surrogate system to account for differences in productivity between the monitored and unmonitored systems. We assumed that a systems' productivity did not change annually, and that the ratio of S_{msy} for any two systems is a reasonable approximation of the relative difference in productivity between those two systems.

The relationship between the abundance and the estimates of S_{msy} from the habitat model should fit:

$$\frac{N_{yU}}{N_{yM}} = \frac{S_U}{S_M}, \tag{9}$$

where:

$\hat{N}_{yU}$ = Unknown escapement of Chinook salmon into watershed of interest in year *y*.

N_{yM} = Number of Chinook salmon observed or estimated into monitored watershed in year *y*.

$\hat{S}_U$ = Estimate of S_{msy} for watershed of interest from Parken et al. (2006) habitat model.

$\hat{S}_M$ = Estimate of S_{msy} for monitored watershed from Parken et al. (2006) habitat model.

Rearranging the above relationship to solve for the estimate of escapement in the unmonitored watersheds yields:

$$\hat{N}_{yU} = \frac{\hat{S}_u}{\hat{S}_M} N_{yM}. \tag{10}$$

Total escapement to the lower Kuskokwim River was estimated as:

$$\hat{N}_{yL} = \sum \hat{N}_{yU} + \sum N_{yM}. \tag{11}$$

The escapements into monitored rivers were measured from weir counts and were assumed to be measured without error. The Kwethluk River escapement was estimated in 2005 using a relationship between weir counts and aerial surveys on the Kwethluk developed by Molyneaux and Brannian (2006), and the values for S_{msy} were also estimated. Variance was assumed to be minimal at monitored systems as the counts are based on observations and was approximated using the Delta Method (Seber 1982) for unmonitored systems:

$$Var(\hat{N}_{yL}) = \sum Var(\hat{N}_{yU}) , \tag{12}$$

$$Var(\hat{N}_{yU}) = (N_{yM})^2 \operatorname{var}(\frac{\hat{S}_U}{\hat{S}_M}) , \tag{13}$$

$$Var(\frac{\hat{S}_U}{\hat{S}_M}) = e^{2\ln(\frac{\hat{S}_u}{\hat{S}_M})} \ln(\frac{A_U}{A_M})^2 \operatorname{var}(b) , \tag{14}$$

where:

A_U = drainage area of unmonitored watershed;

A_M = drainage area of monitored watershed;

var(b) = 0.293; from the Parken et al. (2006) regression.

ESTIMATES OF TOTAL ANNUAL RETURN OF CHINOOK SALMON TO THE KUSKOKWIM

The total annual return of Chinook salmon to the Kuskokwim River ($\hat{R}_{y,total}$) was estimated as the sum of:

- Chinook salmon abundance upstream of Birch Tree Crossing ($\hat{N}_y$);
- Chinook escapement in tributaries in the lower Kuskokwim River ($\hat{N}_{yL}$); and
- Harvest downstream of Birch Tree Crossing ($\hat{H}_y$), or:

$$\hat{R}_{y,total} = \hat{N}_y + \hat{N}_{yL} + \hat{H}_y . \tag{15}$$

Harvest data were inclusive of subsistence, commercial, sport, and test fisheries. Subsistence harvest estimates downstream of Birch Tree Crossing were from Hamazaki (2011; Table 1). The commercial and test fishery data were compiled using annual fish ticket reports, and the sport harvest information came from Chythlook (2009). A small portion of the sport harvest occurred upstream of Birch Tree Crossing and resulted in double accounting. This distinction was ignored because of the small number of fish in the sport harvest and the difficulty in parsing out sport harvest by area.

Each component of the estimated total return was assumed to be independent. Therefore, the variance of the total return estimate was calculated as the sum of the variance estimates from each of the abundance and harvest components:

$$Var(\hat{R}_{y,total}) = Var(\hat{N}_y) + Var(\hat{N}_{yL}) + Var(\hat{H}_y) \quad (16)$$

Subsistence comprised the largest component of harvest, and sport, commercial, and test fishery harvests of Chinook salmon were considered negligible in comparison. Therefore, the variances of the sport, commercial, and test fish harvests were not estimated. Variance of the subsistence harvest was compiled from Hamazaki (2011).

Confidence intervals for the total return estimates were calculated at α= 0.05:

$$95\%CI = \hat{R}_{y,total} \pm 1.96\sqrt{Var(\hat{R}_{y,total})} \quad (17)$$

RESULTS

2006 AND 2007 MARK–RECAPTURE RESULTS AND DIAGNOSTICS

Radio tags were deployed in 506 and 343 Chinook salmon in 2006 and 2007, respectively. Of those, 463 and 327 tagged fish (91.5% and 95.3%) migrated upstream and successfully entered the sample population (Table 2). A total of 61 tags were identified passing weirs in 2006, and 66 passed in 2007 (Table 3). The marked fraction of Chinook salmon at each of the recovery weirs were not significantly different in either year (2006, p= 0.1522; 2007, p= 0.0756; Table 3), indicating that radio tags were distributed proportionately among stocks represented at the weirs.

No statistical difference was detected in sex composition between the first and second event for the tagged fish during either 2006 or 2007 (Table 4; *M* vs. *R*). No statistical difference was found between the sex compositions of the marked fish recovered during the second event and all of the fish examined during the second event in either year (Table 4; *C* vs. *R*). There was evidence of differences in sex composition between the first and second sampling event in 2006 but not in 2007 (Table 4; *M* vs. *C*).

No statistical difference was detected in the length distribution between the first and second event for the tagged fish during 2006 or 2007 (Table 5; *M* vs. *R*). No statistical differences were found between the length distributions of the marked fish recovered during the second event and all of the fish examined during the second event for either year (Table 5; *C* vs. *R*). There was evidence of differences in the length distributions between the first and second sampling event in 2006 but not in 2007 (Table 5; *M* vs. *C*). The results of these tests indicate that mark–recapture results should not be biased with respect to sex or length. The results also suggest using the sex and length composition from the second event would better describe the population than that of the first event compositions.

2002–2005 MARK–RECAPTURE DIAGNOSTICS AND REVISIONS

The hypothesis that Aniak River fish were tagged in proportion to abundance was not rejected in the 2006 and 2007 analyses; therefore we met our criteria for reevaluation of the 2002–2005 data to include Aniak River fish. Final fates of Chinook salmon radiotagged from 2002 to 2005, based on the fate assignment criteria established for 2007, show some spatial variability, specifically tags identified in the Aniak River in 2002 (Table 2), For years 2003–2005 there was no significant difference in the marked fraction of fish examined at the weirs (p=0.1680 to 0.7246; Table 3), indicating Chinook salmon were annually marked proportionately among stocks represented at the weirs. In 2002, however, fish were not tagged proportionally among stocks represented at the weirs (p= 0.023; Table 3).

No statistical difference was detected in sex composition between the first and second event for the tagged fish during any of the years (Table 4; *M* vs. *R*). A statistical difference was found between the sex composition of the marked fish recovered during the second event and all of the fish examined during the second event for 2005 while no difference was detected for the remaining years (Table 4; *C* vs. *R*). There was evidence of differences in sex composition between the first and second sampling event for all years except 2007 (Table 4; *M* vs. *C*).

No statistical difference was detected in the length distribution between the first and second event for the tagged fish during any of the years (Table 5; *M* vs. *R*). Statistical differences were found between the length distribution of the marked fish recovered during the second event and all of the fish examined during the second event for 2003 and 2004 while no difference was detected for the remaining years (Table 5; *C* vs. *R*). There was evidence of differences in the length distributions between the first and second sampling event for all years except 2005 and 2007 (Table 5; *M* vs. *C*).

Results suggest that abundance estimates upstream of Birch Tree Crossing should be unbiased for years 2003–2007. Chinook salmon were not tagged in proportion to abundance in 2002 and an estimate of abundance upriver of Birch Tree Crossing could be biased. Therefore, we did not pursue estimating Chinook salmon abundance upstream of Birch Tree Crossing for 2002.

ABUNDANCE ESTIMATES UPSTREAM OF BIRCH TREE CROSSING, 2003–2007

Chinook salmon abundance upstream of Birch Tree Crossing for 2003–2007 ranged from a minimum of 125,235 fish (95% CI: 83,679–185,292) in 2003 to a maximum of 245,043 fish (95% CI: 163,722–338,966) in 2006 (Table 6). The differences in the estimates from this study to those produced by Division of Sport Fish (22,074–77,680 fish; Stuby 2007) represent the Chinook salmon contribution of the Aniak River in those years. The difference between the two estimates for 2006 (11,910 fish) is likely because of the differences in inclusion criteria used in this study (Table 6).

LOWER KUSKOKWIM RIVER CHINOOK ABUNDANCE ESTIMATES, 2003–2007

The ratios of watershed based estimates of S_{msy} (Equation 9) for the Eek and Kisaralik/Kasigluk Rivers to S_{msy} for the Kwethluk River watershed were 1.102 and 1.464 respectively, and this ratio for Fog River to the Tuluksak River watershed was 1.124 (Table 7). The resulting escapement estimates for Eek River (14,421–31,513 fish), Kisaralik/Kasigluk (18,921–41,868 fish), and Fog River (443–2,981 fish) include the annual variability of escapement during the time period observed at Kwethluk and Tuluksak weirs. The lowest estimate for lower Kuskokwim River

Chinook salmon escapement for 2003–2007 was 46,925 fish (95% CI: 39,137–54,713) in 2007 and the highest estimate was 105,118 fish (95% CI: 87,883–122,353) in 2004 (Table 7).

KUSKOKWIM RIVER CHINOOK SALMON RUN ESTIMATES, 2003–2007

Estimates of the total Kuskokwim River Chinook salmon run for 2003–2007 ranged from a low of 241,617 fish (95% CI: 182,710–326,202) in 2003 to a high of 422,657 fish (95% CI: 298,728–577,993) in 2004 (Table 8). The harvest rate was relatively stable over these years ranging from 22% to 33%, and the escapement to the lower Kuskokwim River during those years was estimated to be between 16% and 25% of the total run (Table 9).

DISCUSSION

The objective of this report was to produce estimates of the total abundance of Chinook salmon to the Kuskokwim River to scale a maximum likelihood model (MLE) for reconstructing historical abundance of Kuskokwim River Chinook salmon (Bue et al.[2]). These estimates were produced using the most complete and accurate data available. Our results suggest that the estimates of abundance presented in this report are unbiased, and precision of our estimates is representative of our uncertainty when estimating total annual return of Chinook salmon to a large and complex system such as the Kuskokwim River. We feel the our estimates of abundance of Chinook salmon for 2003–2007 are appropriate for scaling the MLE model given that the uncertainty in our estimates is incorporated in the model development. These reasonably accurate estimates of abundance allow for more useful fisheries management information than no estimates at all. For example, once scaled using our estimates, the MLE model will result in a time series of abundance and escapement estimates from 1976 to 2011, a brood table, and analysis of the spawner-recruit relationship for Kuskokwim River Chinook salmon. The spawner-recruit model could be used to determine minimum and optimal whole river escapement needs, forecast future returns, and allow for development of new management tools.

Bue et al. (2008) discussed the need for recalibration of MLE models after a period of years to make sure the model isn't drifting. Hilborn et al. (2003) and Schindler et al. (2010) 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 true for Chinook salmon, the MLE model will perform well for the years close in time to the 2003–2007 total run estimates, but accuracy may decrease with time. Bue et al. (2008) suggested that multiple independent estimates of total run would be needed intermittently to assure the model is performing correctly given the uncertainty about shifts in production. It is our recommendation to use the project design described in this report to conduct these additional estimates in the future. We also recommend that other more robust methods be considered to estimate individual components (e.g., escapement and harvest) or the total run of Kuskokwim River Chinook salmon.

The mark–recapture estimates of abundance upriver of Birch Tree Crossing were developed using standard methodologies that have been shown to produce unbiased estimates of salmon abundance. The combination of fish wheels and mid-river drift gill netting as a capture and

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[2] Bue, B. G., K. L. Schaberg, Z. W. Liller, and D. B. Molyneaux. Draft manuscript. Estimates of the historic run size and productivity of the Chinook salmon population returning to the Kuskokwim River, 1976–2011. Alaska Department of Fish and Game, Kuskokwim research group, Anchorage AK.

tagging platform was shown in 2006 and 2007 to capture Chinook salmon returning to select spawning tributaries in proportion to their occurrence in the total escapement. For future mark–recapture studies to estimate abundance of Chinook salmon in the Kuskokwim River, we suggest using a similar tagging platform, and continuing to explore additional means to minimize potential capture and handling effects.

One aspect of this study that we found to be crucial to the success in abundance estimation using mark–recapture methods was the number and distribution of weir projects that served as recapture sites. An adequate number and spatial distribution of recapture sites is required to confidently determine if mark–recapture model assumptions are met. A shortfall to the 2003–2005 estimates was that the Salmon River weir was not operated. The addition of that weir in 2006 and 2007 allowed for inclusion of a very large component of the middle river escapement. Given that model assumptions were met in 2006 and 2007 and the capture methods used in those years were similar to those used from 2003 to 2005, we felt confident that our reanalyzed estimates for those earlier years were also unbiased. Future efforts to estimate abundance using mark–recapture methods should ensure that recapture weir sites are located on major spawning tributaries, and that they are well distributed throughout the drainage. At a minimum, we recommend recapture sites within the Holitna and Aniak rivers. Future studies should also consider using new modeling approaches to estimation of salmon abundance in large systems where ensuring that all components of the run are captured proportionally is very difficult (e.g., Bromaghin et al. 2011).

We consider our methodology for estimating Chinook salmon escapement into the unmonitored tributaries of the lower Kuskokwim River to be the weakest component of the 2003–2007 abundance estimates. Our attempt to account for differences in productivity between watersheds known to support Chinook salmon was based the ratio of S_{msy} as estimated using the Parken et al. (2006) habitat model. That model relies exclusively on watershed area as the predictor variable and we attempted to use the best available data to estimate usable watershed area. Unfortunately, our approach does not take into consideration differences in habitat quality. The Riverscape Analysis Project (RAP) (http://rap.ntsg.umt.edu/) indicates that the Kwethluk River is complex and highly conducive to salmon spawning and rearing; whereas, the larger Eek River is estimated to have considerably less usable habitat. Consequently our approach may overestimate escapement into systems such as the Eek River, especially given that the observed escapements at the Kwethluk River weir from 2003 to 2007 were substantial. We used this method as a reproducible estimate in lieu of subjectively assigning escapements to unmonitored systems. We feel that our estimates of escapement for the unmonitored systems should be used cautiously; however, we feel that are consistent with other information about these systems and therefore useful for our purposes of reconstructing total Chinook salmon abundance. We recommend that escapement into lower Kuskokwim River tributaries be more directly measured to verify our estimates. This could be achieved through the addition of monitoring weirs on the currently unmonitored systems, more frequent aerial surveys, or mark–recapture studies within each tributary.

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TABLES AND FIGURES

Table 1.–Estimates of subsistence harvest by community for the Kuskokwim River below Birch Tree Crossing.

Community	2002	2003	2004	2005	2006	2007
Kipnuk [a]	-	-	323	-	-	-
Kwigillingok [a]	-	-	-	-	-	-
Kongiganak [a]	1,384	1,859	2,808	1,495	1,719	1,806
Tuntutuliak	3,916	2,645	3,878	4,543	4,440	4,578
Eek	2,479	2,049	2,912	3,050	2,651	2,643
Kasigluk	4,725	3,538	7,921	4,389	4,234	4,200
Nunapitchuk	4,589	3,215	4,918	4,110	4,057	4,698
Atmautluak	1,494	539	2,107	1,963	1,438	1,886
Napakiak	2,738	2,539	2,809	3,002	5,227	3,256
Napaskiak	3,953	3,379	4,051	4,441	5,992	7,100
Oscarville	1,110	1,190	1,256	1,069	980	1,293
Bethel	22,991	23,827	29,489	28,293	27,805	30,422
Kwethluk	6,896	4,372	7,302	6,190	7,152	6,617
Akiachak	7,099	2,495	7,402	5,377	5,469	7,569
Akiak	3,630	3,914	3,820	3,865	4,034	4,107
Tuluksak	2,813	3,029	3,764	2,783	2,422	3,599
Lower Kalskag	1,552	1,621	1,975	1,447	3,498	1,896
Upper Kalskag	1,563	1,339	2,437	2,516	1,480	1,383
Kuskokwim River Below Birch Tree Crossing	72,932	61,550	89,172	78,533	82,598	87,053
Lower 95% CI	70,590	58,516	84,114	76,109	78,966	84,301
Upper 95% CI	75,274	64,584	94,230	80,957	86,230	89,804
CV%	2%	3%	3%	2%	2%	2%

Source: Hamazaki 2011.

Note: Communities upriver of the tagging site near Kalskag are not included in this accounting. Subsistence harvest in these communities is accounted for in the mark–recapture abundance estimates.

[a] North Kuskokwim Bay communities that have historically harvested Chinook salmon within the Kuskokwim River.

Table 2.–Final fates of radiotagged Chinook salmon, 2002–2007 determined from aerial tracking, tracking stations, and weir recoveries.

Watershed/Tributary	Project Year					
	2002	2003	2004	2005	2006	2007
Total Tagged						
Fish wheel	187	239	123	215	210	140
Gillnet	274	249	258	234	296	203
Subtotal Tagged	461	488	381	449	506	343
Dropped Downstream of Tagging Site [a]	33	28	63	39	43	16
Tags Available for Recovery	428	460	318	410	463	327
Upriver Destinations						
Aniak River Subtotal	182	81	84	53	109	59
Mainstem [b]	154	53	62	41	82	38
Upper Aniak River [c]	15	11	8	5	8	8
Salmon River (R_1)	10	9	5	4	6	6
Kipchuk River	3	8	9	3	13	7
Oskawalik River	7	7	2	8	7	0
Holokuk River	3	5	10	7	3	11
Holitna River Subtotal	96	176	108	166	169	135
Lower Holitna River [d]	1	3	2	6	3	3
Upper Holitna River [e]	51	79	45	65	94	67
Hoholitna River	26	45	35	44	36	22
Kogrukluk River (R_3)	18	49	26	51	36	43
George River (R_2)	12	10	10	6	10	11
Stony River	3	7	7	23	38	18
Swift River	13	31	17	24	31	25
Tatlawiksuk River (R_4)	4	16 [f]	5	12	8	5
Takotna River (R_5)	1	6	1	2	1	6
Upstream of McGrath	22	32	7	17	22	12
Successful to Spawning Areas	343	371	251	318	398	282
Main Stem	85	89	67	92	65	45
Subtotal to Upriver Locations	428	460	318	410	463	327

[a] Drop out tags are defined as those tags that did not enter the marked population upstream of Birch Tree Crossing.

[b] Mainstem Aniak is defined as the reaches of the Aniak River from the confluence with the Kuskokwim River to the confluence of the Kipchuk River.

[c] Upper Aniak is defined as the reaches of the Aniak River upstream of the Kipchuk River confluences.

[d] Lower Holitna River is defined as the reaches of the Holitna River from the confluence with the Kuskokwim River to the Hoholitna River confluence.

[e] Upper Holitna is defined as the reaches of the Holitna River upstream of the Hoholitna River confluence.

[f] Weir was not operational; tags identified with ground-based tacking station, recaptures not included in mark–recapture estimate.

Table 3.–Chinook salmon passage at weirs, associated radio tag recoveries and Chi-square results testing equal probability of tagging between recovery sites.

Recovery Site	Distance (rkm) [a]	2002 Weir Passage	2002 Recovered Tags Number	2002 Recovered Tags Ratio	2003 Weir Passage	2003 Recovered Tags Number	2003 Recovered Tags Ratio	2004 Weir Passage	2004 Recovered Tags Number	2004 Recovered Tags Ratio	2005 Weir Passage	2005 Recovered Tags Number	2005 Recovered Tags Ratio	2006 Weir Passage	2006 Recovered Tags Number	2006 Recovered Tags Ratio	2007 Weir Passage	2007 Recovered Tags Number	2007 Recovered Tags Ratio
Salmon	404	-- [b]	--		-- [b]	--		-- [b]	--		-- [b]	--		6,732	9	0.0013	6,220	8	0.0013
George	453	2,444	12	0.0049	4,693	10	0.0021	5,207	9	0.0017	3,845	6	0.0016	4,357	9	0.0021	4,883	10	0.0020
Tatlawiksuk	568	2,237	4	0.0018	-- [b]	--		2,833	5	0.0018	2,920	12	0.0041	1,700	7	0.0041	2,061	5	0.0024
Kogrukluk	718	10,104	18	0.0018	11,771	49	0.0042	19,651	24	0.0012	22,000	49	0.0022	19,414	36	0.0019	13,029	43	0.0033
Takotna	835	316	0	0.0000	378	2	0.0053	461	1	0.0022	499	1	0.0020	539	0	0.0000	418	0	0.0000
Total		15,101	34	0.0023	16,842	61	0.0036	28,152	39	0.0014	29,264	68	0.0023	32,742	61	0.0019	26,611	66	0.0025
Chi Square Results:																			
p-value [c]			0.0230			0.2513			0.7246			0.1680			0.1522			0.0756	
H_o Decision [d]			Fail to Reject			Fail to Reject			Fail to Reject			Fail to Reject			Fail to Reject			Fail to Reject	

[a] Distance in river kilometers (rkm) from the mouth of the Kuskokwim River.

[b] Weir not operational.

[c] α=0.05

[d] H_o = no difference in probability of tagging between stocks.

Table 4.–Results of the tests of selective sampling by sex in Marked (M), Captured (C), and Recaptured (R) Chinook salmon, 2002–2007, using contingency table analysis.

		Sample Populations [a]										Expected [e]			
Year	Sex	M [b]		C [c]	R [b]		Sample Size for Tests			M vs. R	C vs. R		M vs. C	
		n	%	%	n	%	M	C	R	p-value [d]	χ^2	p-value	χ^2	p-value
2002	Male	273	62.6	68.6	20	58.8								
	Female	163	37.4	31.4	14	41.2								
	Total	436			34		436	756	34	0.66	1.053	0.305	5.68	0.017
2003	Male	236	51.5	66.9	47	62.7								
	Female	222	48.5	33.1	28	37.3								
		458			75		458	97	75	0.073	0.467	0.494	7.613	0.006
2004	Male	181	56.9	76.7	25	64.1								
	Female	137	43.1	23.3	14	35.9								
		318			39		318	1,155	39	0.391	2.354	0.125	48.202	<0.001
2005	Male	168	41.1	65.1	30	44.1								
	Female	241	58.9	34.9	38	55.9								
		409			68		409	1,099	68	0.637	10.498	0.001	70.198	<0.001
2006	Male	237	53.4	63.6	33	56.9								
	Female	207	46.6	36.4	25	43.1								
		444			58		444	1,336	58	0.613	1.794	0.180	23.330	<0.001
2007	Male	228	73.1	85.1	48	77.4								
	Female	84	26.9	14.9	14	22.6								
		312			62		312	668	62	0.478	0.036	0.850	1.012	0.314

[a] Total number of successfully sexed Chinook salmon. Number of tagged fish reported here do not reflect those used for estimating abundance because not all tagged fish were successfully sexed.

[b] Sexes were included only for fish that remained in the marked population for abundance estimation, and identified in the annual tagging databases maintained in the Anchorage ADF&G office.

[c] Sexes were determined from Molyneaux et al. (2010) and the percent by sex was estimated by weighting the sex composition from each operational weir by the number of fish which passed the weir in a given year.

[d] H_o: No difference in sex composition between the marked (M) and recaptured (R) populations.

[e] Expected $\chi 2$ is the mean of 10,000 bootstrap samples. P-value is calculated using the expected $\chi 2$.

Table 5.–Results of the tests of selective sampling by size in Marked (M), Captured (C), and Recaptured (R) Chinook salmon, 2002-2007, using the Kolmogorov-Smirnov test.

		Length (mm, MEF)			Sample Size for Tests				C vs. R Expected [c]		M vs. C Expected [c]	
Year		M	C [a]	R	M	C	R	p-value [b]	d	p-value	d	p-value
2002	Min	455	450	530								
	Max	1,025	1,015	1,025								
	Mean	748	764	779								
	n	423	1,269	34	423	756	34	0.504	0.225	0.075	0.123	<0.001
2003	Min	455	465	455								
	Max	1,100	1,008	971								
	Mean	724	756	691								
	n	459	556	74	459	97	74	0.977	0.291	0.002	0.176	0.014
2004	Min	470	454	550								
	Max	1,015	1,010	1,000								
	Mean	756	698	773								
	n	319	1,524	39	319	1,155	39	0.800	0.293	0.003	0.251	<0.001
2005	Min	460	451	480								
	Max	1,050	1,250	935								
	Mean	721	721	712								
	n	410	2,039	67	410	1,099	67	0.796	0.108	0.444	0.073	0.087
2006	Min	465	450	480								
	Max	1,025	1,012	965								
	Mean	728	704	704								
	n	444	1,941	58	444	1,336	58	0.504	0.076	0.911	0.11	<0.001
2007	Min	326	450	470								
	Max	1,019	998	972								
	Mean	666	667	656								
	n	311	1,729	62	311	668	62	0.692	0.095	0.694	0.055	0.574

[a] Min and Max were obtained by pooling all samples from all recapture sites while Mean is the weighted average where the weights are the number of fish counted through the appropriate weir.

[b] H_o: No difference in length distribution between the marked (M) and recaptured (R) populations.

[c] Expected d is the mean of 10,000 bootstrap samples. P-value is calculated using the expected d.

Table 6.–Estimates of abundance for Chinook salmon upstream of Birch Tree Crossing, 2003–2007.

	Project Year				
	2003	2004	2005	2006	2007
Abundance from Stuby 2007	103,161 [a]	146,839 [a]	145,373 [a]	233,133 [b]	-
Abundance Estimate above Birch Tree Crossing	125,235	224,519	174,317	245,043	130,279
Lower 95% CI	83,679	136,933	121,499	163,722	91,483
Upper 95% CI	185,292	334,729	250,596	338,966	182,968
CV%	24%	26%	22%	21%	21%

[a] Estimate from Stuby 2007, does not include Aniak River Chinook salmon (rkm >310).

[b] Estimate from Stuby 2007, Includes Aniak River Chinook salmon. Estimate is from Aniak (rkm >307).

Table 7.–Estimates of lower Kuskokwim River escapement, derived from weir counts, and expansion of habitat based estimates of S_{msy}.

	Watershed Area (km^2)	S_{msy} [a]	S_u/S_m	Year 2003	2004	2005	2006	2007
Kwethluk River Escapement	1,439	3,285		14,474	28,605	22,836 [b]	17,619	12,927
Eek River (Above tidal)	1,655	3,619	1.102 [c]	15,945	31,513	25,157	19,410	14,241
Kisaralik/Kasigluk Rivers	2,495	4,808	1.464 [c]	21,185	41,868	33,424	25,788	18,921
Tuluksak River Escapement	316	1,150		1,064	1,475	2,653	1,044	394
Fog River	374	1,293	1.124 [d]	1,196	1,657	2,981	1,173	443
Lower Kuskokwim River Escapement				53,864	105,118	87,051	65,034	46,925
Lower 95% CI				45,142	87,883	73,286	54,418	39,137
Upper 95% CI				62,586	122,353	100,817	75,650	54,713
CV%				8%	8%	8%	8%	8%

[a] S_{msy} was calculated from Parken et al. (2006) based on watershed area. S_{msy}= exp(0.6921884 ln(watershed area km2)+2.917216+(0.293/2)).

[b] The Kwethluk weir was not operated in 2005. The escapement estimate is from Molyneaux and Brannian 2006, which was derived as a conversion from aerial survey estimates.

[c] Su/Sm is the expansion factor used to scale the weir counts from Kwethluk River to the unmonitored system.

[d] Su/Sm is the expansion factor used to scale the weir counts from Tuluksak River to the unmonitored system.

Table 8.–Total inriver abundance for Chinook salmon in the Kuskokwim River 2003–2007 combining harvest and estimates derived from mark–recapture and habitat model techniques.

Component	2003	2004	2005	2006	2007
Abundance Upstream of Birch Tree Crossing	125,235	224,519	174,317	245,043	130,279
Escapment Downstream of Birch Tree Crossing	53,864	105,118	87,051	65,034	46,925
Lower Kuskokwim River Harvest					
Subsistence [a]	61,550	89,172	78,533	82,598	87,053
Commercial [b]	158	2,300	4,784	2,777	179
Bethel Test Fish [b]	409	691	557	352	305
Sport [c]	401	857	572	444	1,478
Total Harvest	62,518	93,020	84,446	86,171	89,015
Total Inriver Abundance	241,617	422,657	345,814	396,248	266,219
Lower 95% CI	182,710	298,728	270,560	281,847	211,280
Upper 95% CI	326,202	577,993	453,516	528,218	340,445
CV%	15%	17%	13%	16%	12%

[a] Subsistence harvest includes all villages from Kalskag downstream to the mouth of the Kuskokwim River, plus the north Kuskokwim Bay village of Kongiganak. Data from Hamazaki (2011).

[b] Commercial and Bethel Test Fish harvest data from Bavilla et al. (2010).

[c] Sport harvest data from John Chythlook, Sport Fish Biologist, ADF&G, Fairbanks; personal communication.

Table 9.–Composition of Kuskokwim River Chinook salmon total run, as proportion of total run for each major component.

	2003	2004	2005	2006	2007
Abundance Upstream of Birch Tree Crossing	52%	53%	50%	62%	49%
Escapement Downstream of Birch Tree Crossing	22%	25%	25%	16%	18%
Total Harvest	26%	22%	24%	22%	33%

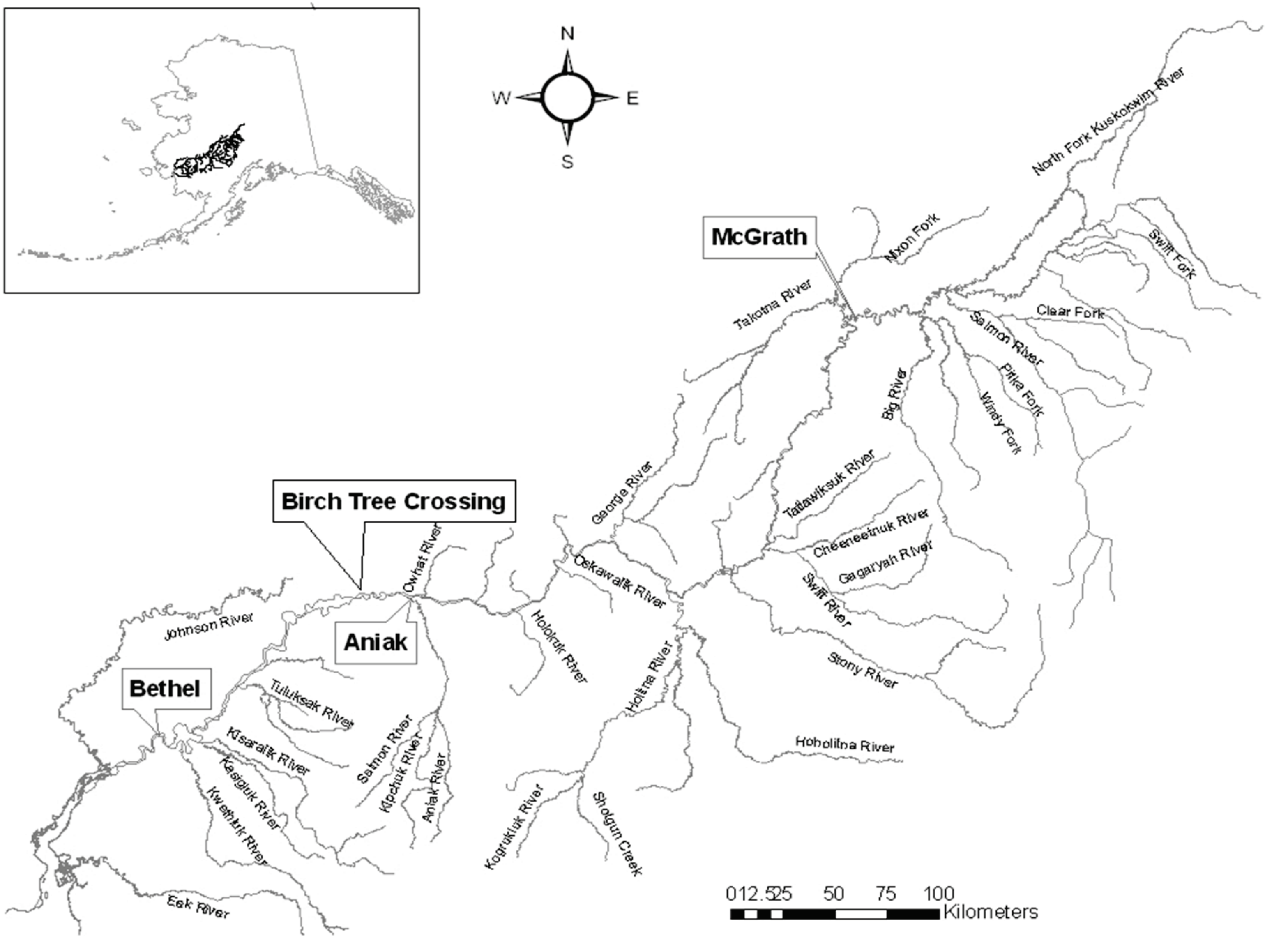

Figure 1.–Kuskokwim River showing major communities, tributary locations, and important reference locations.

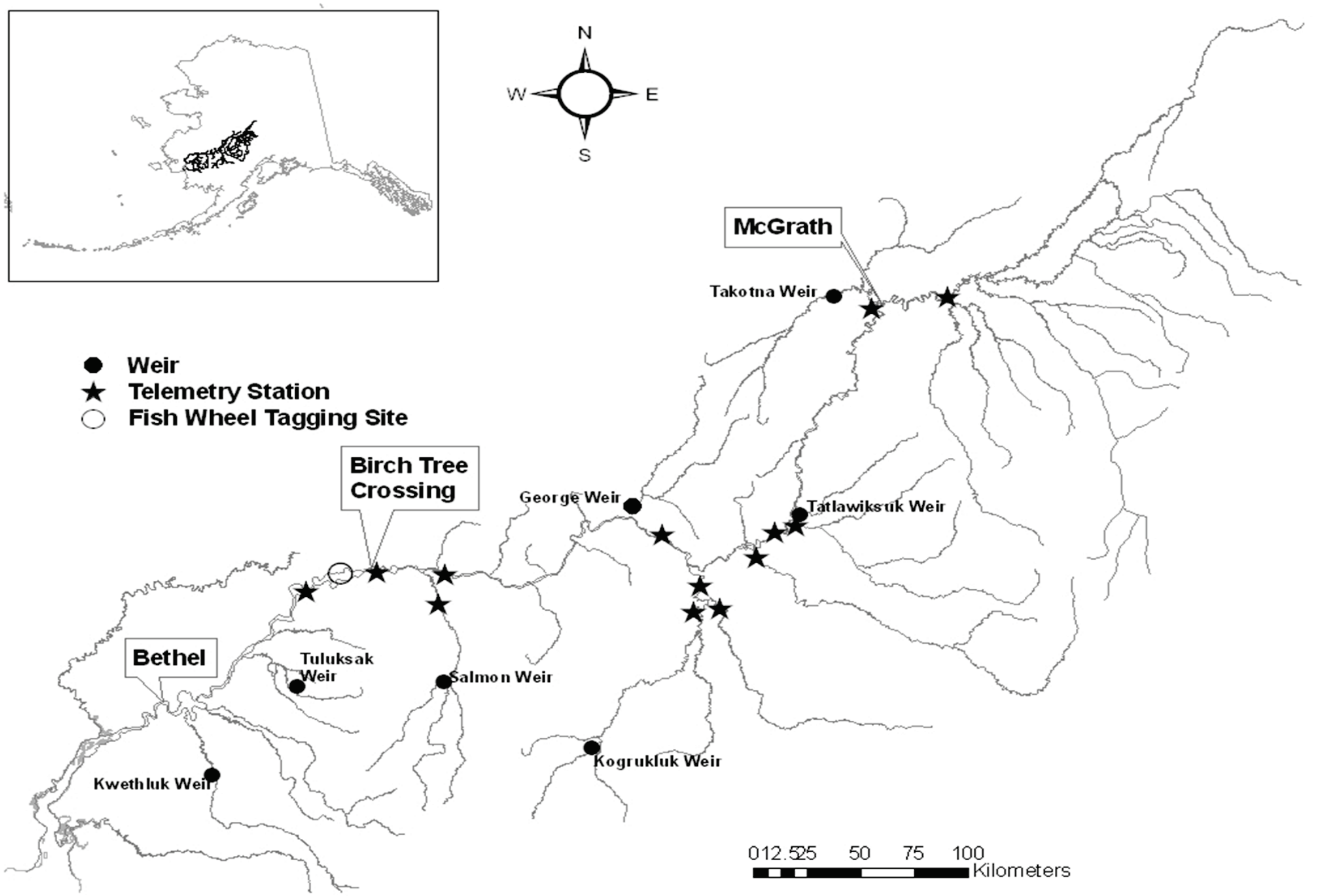

Figure 2.–Kuskokwim River showing location of fish capture event, weirs used for the recapture event, and ground-based telemetry stations.

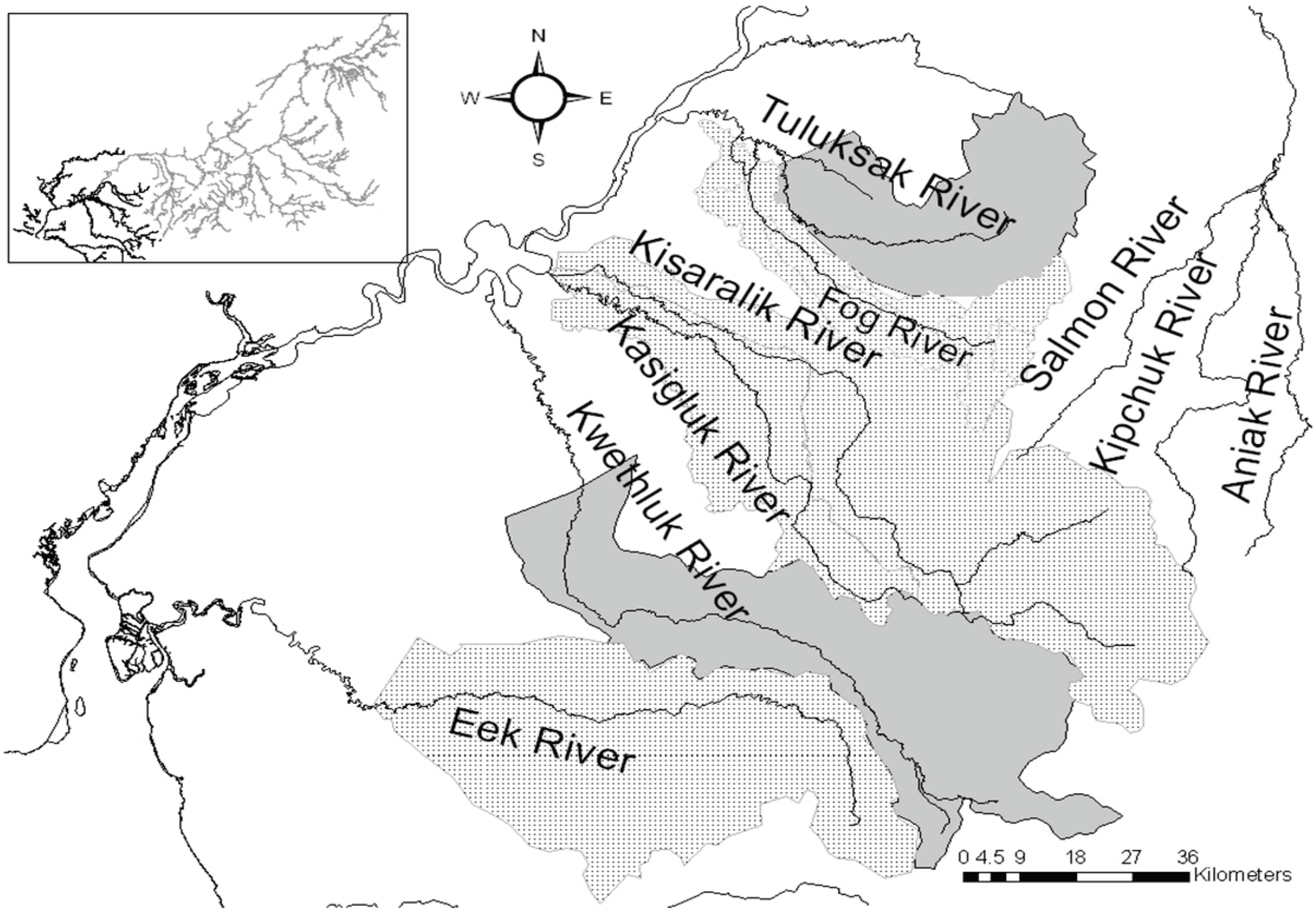

Figure 3.–The lower Kuskokwim River highlighting portions of drainages where Chinook salmon escapement was monitored (dark shaded) and those portions were escapement was estimated (stippled).

APPENDIX A: STATISTICAL TESTS FOR ANALYZING DATA FOR SEX AND SIZE BIAS

Appendix A1.–Tests of consistency for the Petersen estimator (from Seber 1982, page 438).

Tests of consistency for Petersen Estimator

Of the following conditions, at least one must be fulfilled to meet assumptions of a Petersen estimator:

1. Marked fish mix completely with unmarked fish between events;
2. Every fish has an equal probability of being captured and marked during the first event; or,
3. Every fish has an equal probability of being captured and examined during the second event.

To evaluate these three assumptions, the chi-square statistic is used to examine the following contingency tables as recommended by Seber (1982). At least one null hypothesis needs to be accepted for assumptions of the Petersen model (Bailey 1951, 1952 as cited in Seber 1982; Chapman 1951) to be valid. If all three tests are rejected, a temporally or geographically stratified estimator (Darroch 1961 as cited in Seber 1982) will be used to estimate abundance.

I.-Test For Complete Mixing[a]

Area/Time Where Marked	Area/Time Where Recaptured				Not Recaptured
	1	**2**	**…**	**t**	$(n_1\text{-}m_2)$
1					
2					
…					
S					

II.-Test For Equal Probability of Capture During the First Event[b]

	Area/Time Where Examined			
	1	**2**	**…**	**t**
Marked (m_2)				
Unmarked $(n_2\text{-}m_2)$				

III.-Test For Equal Probability of Capture During the Second Event[c]

	Area/Time Where Marked			
	1	**2**	**…**	**s**
Recaptured (m_2)				
Not Recaptured $(n_1\text{-}m_2)$				

[a] This tests the hypothesis that movement probabilities (θ) from area or time i (i = 1, 2, ...s) to section j (j = 1, 2, ...t) are the same among sections: H_0: $\theta_{ij} = \theta_j$.

[b] This tests the hypothesis of homogeneity on the columns of the 2-by-t contingency table with respect to the marked to unmarked ratio among area or time designations: H_0: $\Sigma_i a_i \theta_{ij} = k U_j$, where k = total marks released/total unmarked in the population, U_j = total unmarked fish in stratum j at the time of sampling, and a_i = number of marked fish released in stratum i.

c This tests the hypothesis of homogeneity on the columns of this 2-by-s contingency table with respect to recapture probabilities among area or time designations: H0: Σjθijpj = d, where pj is the probability of capturing a fish in section j during the second event, and d is a constant.

Appendix A2.–Detection of size and/or sex selective sampling (from Stuby 2007).

Size selective sampling: The Kolmogorov-Smirnov two sample test (Conover 1980 as cited in Stuby 2007) is used to detect significant evidence that size selective sampling occurred during the first and/or second sampling events. The second sampling event is evaluated by comparing the length frequency distribution of all fish marked during the first event (M) with that of marked fish recaptured during the second event (R) by using the null test hypothesis of no difference. The first sampling event is evaluated by comparing the length frequency distribution of all fish inspected for marks during the second event (C) with that of R. A third test that compares M and C is then conducted and used to evaluate the results of the first two tests when sample sizes are small. Guidelines for small sample sizes are <30 for R and <100 for M or C.

Sex selective sampling: Contingency table analysis (Chi^2-test) is generally used to detect significant evidence that sex selective sampling occurred during the first and/or second sampling events. The counts of observed males to females are compared between M&R, C&R, and M&C using the null hypothesis that the probability that a sampled fish is male or female is independent of sample. If the proportions by gender are estimated for a sample (usually C), rather an observed for all fish in the sample, contingency table analysis is not appropriate and the proportions of females (or males) are then compared between samples using a two sample test (e.g., Student's t-test).

M vs. R	**C vs. R**	**M vs. C**
Case I:		
Fail to reject H_o	Fail to reject H_o	Fail to reject H_o
There is no size/sex selectivity detected during either sampling event.		
Case II:		
Reject H_o	Fail to reject H_o	Reject H_o
There is no size/sex selectivity detected during the first event but there is during the second event sampling.		
Case III:		
Fail to reject H_o	Reject H_o	Reject H_o
There is no size/sex selectivity detected during the second event but there is during the first event sampling.		
Case IV:		
Reject H_o	Reject H_o	Either result possible
There is size/sex selectivity detected during both the first and second sampling events.		
Evaluation Required:		
Fail to reject H_o	Fail to reject H_o	Reject H_o

Sample sizes and powers of tests must be considered:

A. If sample sizes for M vs. R and C vs. R tests are not small and sample sizes for M vs. C test are very large, the M vs. C test is likely detecting small differences which have little potential to result in bias during estimation. *Case I* is appropriate.

B. If a) sample sizes for M vs. R are small, b) the M vs. R p-value is not large (~0.20 or less), and c) the C vs. R sample sizes are not small and/or the C vs. R p-value is fairly large (~0.30 or more), the rejection of the null in the M vs. C test was likely the result of size/sex selectivity during the second event which the M vs. R test was not powerful enough to detect. *Case I* may be considered but *Case II* is the recommended, conservative interpretation.

-continued-

C. If a) sample sizes for C vs. R are small, b) the C vs. R p-value is not large (~0.20 or less), and c) the M vs. R sample sizes are not small and/or the M vs. R p-value is fairly large (~0.30 or more), the rejection of the null in the M vs. C test was likely the result of size/sex selectivity during the first event which the C vs. R test was not powerful enough to detect. *Case I* may be considered but *Case III* is the recommended, conservative interpretation.

D. If a) sample sizes for C vs. R and M vs. R are both small, and b) both the C vs. R and M vs. R p-values are not large (~0.20 or less), the rejection of the null in the M vs. C test may be the result of size/sex selectivity during both events which the C vs. R and M vs. R tests were not powerful enough to detect. *Cases I, II, or III* may be considered but *Case IV* is the recommended, conservative interpretation.

Case I. Abundance is calculated using a Petersen-type model from the entire data set without stratification. Composition parameters may be estimated after pooling length, sex, and age data from both sampling events.

Case II. Abundance is calculated using a Petersen-type model from the entire data set without stratification. Composition parameters may be estimated using length, sex, and age data from the first sampling event without stratification. If composition is estimated from second event data or after pooling both sampling events, data must first be stratified to eliminate variability in capture probability (detected by the M vs. R test) within strata. Composition parameters are estimated within strata, and abundance for each stratum needs to be estimated using a Petersen-type formula. Overall composition parameters are estimated by combining stratum estimates weighted by estimated stratum abundance according to the formulae below.

Case III. Abundance is calculated using a Petersen-type model from the entire data set without stratification. Composition parameters may be estimated using length, sex, and age data from the second sampling event without stratification. If composition is estimated from first event data or after pooling both sampling events, data must first be stratified to eliminate variability in capture probability (detected by the C vs. R test) within strata. Composition parameters are estimated within strata, and abundance for each stratum needs to be estimated using a Petersen-type type formula. Overall composition parameters are estimated by combining stratum estimates weighted by estimated stratum abundance according to the formulae below.

Case IV. Data must be stratified to eliminate variability in capture probability within strata for at least one or both sampling events. Abundance is calculated using a Petersen-type model for each stratum, and estimates are summed across strata to estimate overall abundance. Composition parameters may be estimated within the strata as determined above, but only using data from sampling events where stratification has eliminated variability in capture probabilities within strata. If data from both sampling events are to be used, further stratification may be necessary to meet the condition of capture homogeneity within strata for both events. Overall composition parameters are estimated by combining stratum estimates weighted by estimated stratum abundance.

If stratification by sex or length is necessary prior to estimating composition parameters, then an overall composition parameters (p_k) is estimated by combining within stratum composition estimates using:

$$\hat{p}_k = \sum_{i=1}^{j} \frac{\hat{N}_i}{\hat{N}_\Sigma} \hat{p}_{ik} \text{ ; and,} \tag{1}$$

$$\hat{V}[\hat{p}_k] \approx \frac{1}{\hat{N}_\Sigma^2} \left(\sum_{i=1}^{j} \hat{N}_i^2 \hat{V}[\hat{p}_{ik}] + \left(\hat{p}_{ik} - \hat{p}_k \right)^2 \hat{V}[\hat{N}_i] \right). \tag{2}$$

where: j = the number of sex/size strata;

$\hat{p}_{ik}$ = the estimated proportion of fish that were age or size k among fish in stratum i;

$\hat{N}_i$ = the estimated abundance in stratum i; and,

$\hat{N}_\Sigma$ = sum of the $\hat{N}_i$ across strata.