Fishery Data Series No. 23-17

Estimating Fish Abundance in the Kuskokwim River Using Sonar, 2021

by

Keegan O. Birchfield

August 2023

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)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	′
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	″
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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by
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ABSTRACT

Sonars were operated on the Kuskokwim River in 2021 to estimate the inseason abundance of Pacific salmon *Oncorhynchus* and nonsalmon species. After identifying a location with a suitable bottom profile, split-beam and imaging sonar were deployed on the gentle sloping left bank, and an imaging sonar was deployed on the steep right bank. Species-specific fish passage abundance estimates were generated using a 3-step process. All fish passing the site were estimated without regard to species. Species composition was estimated and adjusted using net selectivity parameters. Species composition estimates were then applied to total passage estimates to create species-specific abundance estimates. An estimated 2,704,816 fish passed the sonar site between June 1 and August 26. The Chinook salmon *O. tshawytscha* passage estimate was 102,552 fish (95% CI 84,438–120,666). The sockeye salmon *O. nerka* passage estimate was 745,037 fish (95% CI 696,241–793,833). The chum salmon *O. keta* passage estimate was 25,689 fish (95% CI 14,550–36,828). The coho salmon *O. kisutch* passage estimate was 237,285 fish (95% CI 209,320–265,250). The pink salmon *O. gorbuscha* passage estimate was 41,912 fish (95% CI 30,758–53,066). All nonsalmon species totaled 1,552,341 fish (95% CI 1,415,098–1,689,584).

Keywords: Pacific salmon *Oncorhynchus*, Chinook salmon *Oncorhynchus tshawytscha*, sockeye salmon *Oncorhynchus nerka*, chum salmon *Oncorhynchus keta*, coho salmon *Oncorhynchus kisutch*, pink salmon *Oncorhynchus gorbuscha,* whitefish, hydroacoustics, sonar, split-beam, ensonification, long range dual-frequency identification sonar, DIDSON, adaptive resolution imaging sonar, ARIS, gillnet, apportionment, Kuskokwim River, Alaska.

INTRODUCTION

The Kuskokwim River supports runs of all 5 Pacific salmon species *Oncorhynchus*. Chinook salmon *O. tshawytscha*, sockeye salmon *O. nerka*, chum salmon *O. keta*, and several whitefish species historically supported a modest commercial fishery. Kuskokwim River salmon are staples of one of the largest subsistence fisheries in Alaska. Most subsistence and all commercial harvests occur in the first 200 km of the Kuskokwim River, and harvest opportunity is managed inseason (Figure 1). A test fishery operated by the Alaska Department of Fish and Game (ADF&G) near Bethel uses CPUE indices to inform run strength and timing and assist inseason management (Tiernan and Gray 2020). Weir projects and aerial surveys provide postseason escapement estimates to key spawning tributaries (e.g., Dickerson et al. 2019). In addition, several tagging projects have been conducted to assess the run size and timing of Chinook, chum, and coho salmon *O. kisutch* (Clark and Smith 2019; Schaberg et al. 2010; Liller et al. 2014).

The Kuskokwim River has a long history of sonar projects operating in the lower river. In 1980 and 1981, a feasibility study was conducted at a site 8 km upstream from Bethel, but the results were inconclusive, and a full-scale project was not developed (Nickerson and Gaudet 1983). From 1988 to 1990, a feasibility project was operated near the same location, and from 1991 to 1995, the project produced daily passage estimates (Vaught and Molyneaux 1995). Early operations encountered problems, including suboptimal left-bank profiles while using 1 transducer, surface ensonification due to a wide beam that resulted in low signal-to-noise ratios, and no access to low-frequency sonar, which limited horizontal range due to attenuation (Vaught and Molyneaux 1995). A 3-year feasibility study was initiated in 1999 at a new site 26 km upstream from Bethel, but it only operated for a single season due to staffing shortages. Improvements in sonar technology over the last 2 decades, and the continuing need for additional inseason management tools, prompted renewed interest in using sonar to estimate salmon abundance in the lower Kuskokwim River.

From 2014 to 2017, a feasibility study used sonar and drift gillnets to estimate salmon abundance in the Kuskokwim River. The study determined that sonar could provide timely inseason abundance estimates for salmon migrating through the lower river during typical environmental conditions (Brodersen et al. 2016; Birchfield and Smith 2019; Birchfield et al. 2019). Sites were reviewed in 2014 and 2015 based on bottom profiles and historical sonar locations. A preferred site near the upper confluence of Church Slough was selected based on proximity to Bethel (20 river km), location downstream from most major salmon spawning tributaries, and historical site stability. A combination of split-beam and imaging sonar was optimal to enumerate fish passage, and drift gillnet fishing within 3 corresponding horizontal zones was used to apportion counts. Depending on site conditions, sonar could ensonify up to 400 m of the 425 m span at the Church Slough site (measured between the right bank and the leading edge of the left-bank fish lead). Consistent bottom profiles, successful drift gillnetting, and clear sonar images year to year indicated this site would remain a viable option to estimate fish passage (Brodersen et al. 2016; Birchfield et al. 2019). Sonar at this site has produced at least partial estimates of fish passage since 2016. The sonar project has been considered fully operational since 2018.

This report presents results from the Kuskokwim River sonar in 2021. This included a 1-month project extension funded by the Office of Subsistence Management (OSM) to estimate the abundance of coho salmon and better index whitefish runs.

OBJECTIVES

The primary project objective was as follows:

1) Provide managers with timely estimates and associated confidence intervals of the daily and seasonal passage of adult Chinook, sockeye, coho, and chum salmon between June 1 and August 26.

The secondary project objectives were as follows:

1) Index daily and seasonal abundance of whitefish between June 1 and August 26.
2) Collect daily water temperature measurements representative of the study area from June 1 through August 26.

METHODS

STUDY DESIGN

Study Area

The Kuskokwim River is the second largest drainage in Alaska, flowing west approximately 730 km from the confluence of its east and north forks near Medfra to the Bering Sea. The glacially fed north fork originates northwest of Denali in the Kuskokwim Mountains and Alaska Range, bringing the total length to 1,130 km, whereas the south fork flows out of the Alaska Range west of Mount Gerdine (Figure 1; Benke and Cushing 2005). The sonar project was located just upriver from the confluence of the Kuskokwim River and Church Slough at river km 130 (20 river km upriver from Bethel). The river forms a single channel with a 450 m bankfull width at the sonar site (Figure 2). The right bank substrate was predominantly coarse silt, with a slope of approximately 25°. The left bank gradually slopes approximately 2.6°, and the substrate was muddy to fine silt.

River Bottom Surveys

Fish detection by sonar required a suitable bottom profile with minimal relief. A series of bottom profiles were produced using a Hummingbird 998C SI fathometer with GPS and side-scan sonar to determine viable sonar deployment locations. A preseason survey was analyzed using a depth profiling program to produce river cross-section summaries. Profiles were reviewed to determine optimal slope and bottom curvature. Optimal conditions were defined as smooth, slightly concave, and with consistent left- and right-bank slopes.

Sonar Deployment and Operation

A long-range dual-frequency identification sonar (DIDSON-LR) manufactured by Sound Metrics Corporation (SMC) was deployed on the left bank to ensonify the 0–20 m nearshore region (stratum 1 [LS1]; Table 1). Immediately adjacent to the DIDSON-LR, a digital split-beam echosounder system manufactured by Hydroacoustic Technology Inc. (HTI; model 244), operated at 120 kHz, was used with a split-beam transducer (HTI 1.5° x 8°) to ensonify the 20–100 m (stratum 2 [LS2]) and 100–350 m (stratum 3 [LS3]) ranges (Table 2). A 1.75-inch mesh net and aluminum panel lead were deployed approximately 2 m downriver from shore and extended up to 3 m beyond the transducers to prevent fish from passing behind the sonar. The lead was angled approximately 20° upriver, marked with buoys, and secured with steel conduit, Nurail joints, Voile quick release straps, galvanized strainers, steel cable, leadline, and anchors. At its greatest length, the lead extended approximately 25 m from shore.

An adaptive resolution imaging sonar (ARIS; SMC model 1200) was deployed on the steep right bank. The ARIS operated at 0.7 MHz to ensonify the 0–20 m range (stratum 1 [RS1]) and 20–50 m range (stratum 2 [RS2]). A 28° spreader lens was required to ensonify a greater height of the water column (Table 3). No lead was deployed on the right bank due to a very narrow (~5 m) and shallow (<1 m) shelf behind the sonar during most of the season.

Sonar equipment required aiming after each deployment or pod movement, or if bottom profiles degraded. The split-beam transducer was aimed remotely using a pair of rotators (HTI model 661) in conjunction with a rotator controller (HTI model 660) for remote tilt and pan settings. The ARIS was linked directly to a rotator (SMC model 1200-AR2) for remote tilt and roll settings, and the DIDSON-LR was manually tilted and panned using a custom aluminum mount. Aiming procedures were the same between all systems, with a few exceptions. Echograms were recorded from the sonar while an operator tilted or panned the transducer in small increments (0.5–2.0° for HTI, 1.0–2.0° for ARIS), and a manual crank was used to adjust the DIDSON-LR. Each aim was selected based on the prevalence of bottom returns throughout the stratum, which indicated consistent coverage across the full horizontal range. All settings were recorded on a paper form, and sonar systems were updated to reflect new aims. Repositioning sonar occurred regularly in 2021 due to changing water levels throughout most of the season (Table 4).

Sonar equipment was operated daily and recorded 30 minutes of data during even hours in each ensonified zone. Starting at 0000 each day, RS1, LS1, and LS2 recorded for 30 minutes. At the bottom of the hour, RS2 and LS3 recorded for 30 minutes. Sonar recording periods were expanded to produce daily estimates of abundance. Previous research has shown a minimal difference between abundance estimates from data collected at discrete intervals throughout the day and data collected continuously over 24 hours (Xie and Martens 2014; Melegari 2015). However, continuous data collections cost significantly more than discrete-time sampling methods.

Technicians processed 30-minute sonar samples using custom software Echotastic 3 developed by ADF&G (Carl Pfisterer, Commercial Fisheries Biologist, ADF&G, Fairbanks; personal communication) during 3 scheduled shifts: 0500 to 0830, 1430 to 1800, and 2100 to 0030 hours. Only upstream fish were marked. Each mark was saved as an individual record (including time and range from the transducer) in a text file (*.txt) by bank and stratum. The total number of marks was recorded on a paper count form. A subset of counts was reviewed postseason for quality assurance. This involved a systematic review of counts every other day. Each 30-minute sample was reviewed for accuracy, and individual counter accuracy was summarized to improve future count training.

Drift Gillnet Fishing

A drift gillnet test fishery was used to apportion daily passage estimates by species (Table 5). Drift zones corresponded to overlapping sonar strata: right bank nearshore (zone 1 [Z1]), left bank nearshore (zone 2 [Z2]), and left bank offshore (zone 3 [Z3]; Figure 3). A suite of 6 gillnet mesh sizes was used throughout the season, hung at a 2:1 ratio. Gillnets were 25 fathoms in length (45.7 m) and 4.2–8.0 m in depth to match river depth. The 4.2 m deep nets were used in Z2, but Z1 and Z3 required at least 8.0 m deep nets to sample the full water column. Three 25-fathom, 11.0 m deep nets were tested daily in 2021 to ascertain how many fish may be passing below the current suite of 8.0 m deep nets in Z3. Because these 3 nets only include 4.0-, 5.25-, and 6.5-inch mesh, results from these nets were omitted from daily estimates. Test fishing occurred during 2 fishing periods. Drift period 1 (P1) was 0900–1330, and period 2 (P2) was 1530–2000 hours. During each period, 3 different mesh sizes were fished once per zone for a total of 9 drifts of varying durations. In addition, 1 drift was conducted daily using each of the 11.0 m deep nets. Mesh groupings changed systematically throughout the season and cycled between fishing periods daily (Table 6). Zone 1 was fished for 6 minutes, including half of set-out and pull-in times (~4-minute drift). Total drift times in Z2 were 8 minutes. Depending on fish passage, slow river velocity and lower overall passage in Z3 required total drift times between 10 and 14 minutes.

Biological Sampling

Drift gillnetting was used to collect species, sex, and length data. Fish were removed from gillnets during net retrieval and placed in a tote filled with fresh river water until the net was fully retrieved. All captured fish were identified to species. Species identification was accomplished using morphological and meristic traits. Common identifiers included mouth position, fin coloration, gum coloration, gill raker counts, scale coloration, size, and spotting (Mecklenburg et al. 2002). Fish length was measured using a fabric tape measure affixed to a wooden measuring cradle. Salmon species were measured to the nearest mm from the middle of the eye to tail fork (METF), and all nonsalmon species were measured using fork length. Morphological features, including girth, kype development, and ovipositor presence/absence, were examined to externally determine the sex of all salmon species sampled. All test fishery data, including drift information and biological data, were recorded on printed test fishery forms and entered into a database. Fish were released at the discretion of samplers based on physical condition. Excessive bleeding, lethargy, ambient temperature, or time out of the water contributed to fish retention. Retained fish were distributed from the field site dock using a “Free Fish” sign, and the remaining retentions were delivered to the community of Kwethluk and nearby fish camps.

Data Analysis

Daily passage estimates were produced from a multi-component process as follows:

1. Undifferentiated hydroacoustic estimates of all fish targets passing the site.
2. Estimates of species proportions using CPUE from the test fishing data and adjusted by a model to account for net selectivity.

3. Estimates of species proportions combined with undifferentiated hydroacoustic estimates to compute passage by species and associated variance.

This process was completed for Chinook, chum, sockeye, coho, and pink salmon *O. gorbuscha*, whitefish species, and other species. Whitefish species included humpback whitefish *Coregonus pidschian*, broad whitefish *C. nasus*, Bering cisco *C. laurettae*, least cisco *C. sardinella*, and inconnu *Stenodus leucichthys*. Unless otherwise specified, other species refers to burbot *Lota lota*, Dolly Varden *Salvelinus malma*, northern pike *Esox lucius*, and longnose sucker *Catostomus catostomus*.

Sonar Passage Estimates

Fish passage was estimated separately for each sonar stratum. Let y_{dsk} be defined as 30-minute subsampling acoustic counts (k) at stratum (s), during the day (d). Hourly passage per stratum and sample was calculated as:

$$r_{dsk} = \frac{y_{dsk}}{h_{dsk}}, \tag{1}$$

where h_{dpsk} was the number of hours actively reviewed for the sample (k). Daily passage was then estimated as:

$$\hat{y}_{ds} = 24\frac{\sum_k r_{dsk}}{n_{ds}}, \tag{2}$$

where n_{ds} was the number of samples during the day (d) in the stratum (s).

Treating the systematically sampled sonar counts as a simple random sample could yield an overestimate of the total variance because sonar counts were highly autocorrelated. To accommodate these data characteristics, a variance estimator, based on the squared differences of successive observations, was employed (Wolter 1985). Variance for passage estimates ($\hat{y}_{ds}$) was estimated as:

$$\widehat{Var}(\hat{y}_{ds}) = 24^2\left(\frac{s^2}{n_{ds}}\right)\left(1 - \frac{h_{is}}{24}\right), \tag{3}$$

where s^2 was the variance of the passage rate per sample:

$$s^2 = \left(\frac{\sum_{k=2}^{n_{ds}}\left(r_{dsk} - r_{ds,k\text{-}1}\right)^2}{2(n_{ds} - 1)}\right). \tag{4}$$

Species Proportions

To estimate species proportions, test fishery sampling was conducted in 3 zones. The right bank had only 1 zone (Z1), and the left bank was divided into 2 zones: Z2 (0–100 m) and Z3 (100–350 m). In relation to acoustic sampling, Z1 corresponded to sonar strata RS1 and RS2, Z2 corresponded to LS1 and LS2, and Z3 corresponded to LS3 (Figure 4). Test fishing was conducted twice daily during drift P1 and drift P2. This was considered 2-stage systematic sampling, in which CPUE of species (i) passing at zone (z) during period (p) of day (d) (C_{dzpi}) was considered the primary sampling unit of measurement.

The duration of the test fishing drift (j) in minutes (t) was calculated as:

$$t_j = \left(SI_j - FO_j\right) + \frac{\left(FO_j - SO_j\right)}{2} + \frac{\left(FI_j - SI_j\right)}{2}, \tag{5}$$

where:

SO = the time the net was initially set out,

FO = the time the net was fully set out,

SI = the time the net started back in, and

FI = the time the net was fully retrieved in.

CPUE (C_{dzpi}) was calculated by dividing the sum of the number of species (i) of length (l) caught by meshes (m) (c_{dzpilm}) by the sum of length selectivity adjusted efforts by meshes (m) (f_{dzpilm}) and then summing across all lengths:

$$C_{dzpi} = \sum\nolimits_l \left(\frac{\sum_m c_{dzpilm}}{\sum_m f_{dzpilm}}\right), \tag{6}$$

where length selectivity adjusted effort f_{dzpilm} was calculated as:

$$f_{dzpilm} = S_{ilm} \cdot e_{dzpm}, \tag{7}$$

and S_{ilm} was the net selectivity of the species (i) of length (l) caught by mesh (m), and e_{dzpm} was the effort (in fathom-hours) calculated by multiplying the drift time (t) (in minutes) by 25 fathoms and dividing by 60 minutes per hour as (Appendix A1; Bromaghin 2005):

$$e_{dzpm} = \frac{25 \cdot t_{dzpm}}{60}. \tag{8}$$

To prevent individual fish with extremely low selectivity from inflating the CPUE unreasonably, a threshold was applied such that:

$$S_{ilm} = \begin{cases} S_{ilm} & S_{ilm} \geq 0.1 \\ 0.1 & \text{otherwise} \end{cases}. \tag{9}$$

The proportion of species (i) passing zone (z) during period (p) of day (d) ($\hat{p}_{dzpi}$) and the proportion for day ($\hat{p}_{dzi}$) were estimated as:

$$\hat{p}_{dzpi} = \frac{C_{dzpi}}{\sum_i C_{dzpi}} \text{ and } \hat{p}_{dzi} = \frac{\sum_p C_{dzpi}}{\sum_p \sum_i C_{dzpi}}. \tag{10}$$

The variance of $\hat{p}_{dzi}$ was estimated from the squared differences between the proportion for each test fishing period within the day ($\hat{p}_{dzpi}$) and the proportion of the entire day ($\hat{p}_{dzi}$) as:

$$\widehat{Var}\left(\hat{p}_{dzi}\right) = \frac{\sum_p \left(\hat{p}_{dzi} - \hat{p}_{dzpi}\right)^2}{n_p\left(n_p - 1\right)}, \tag{11}$$

where n_p was the number of test fishing sampling periods within the day.

In order to estimate variance accurately, zones during days with missing test fishing periods were pooled with adjacent days such that there were at least 2 complete test fishing periods. There were 2 options available when there was a large span of days with insufficient catches. First, test fishing periods could be pooled across multiple days; second, a different test fishery zone could be used to apportion sonar strata. Long spans of insufficient catches generally only occurred in Z3 (used to apportion LS3), in which case, Z1 was used to apportion LS3 (Table 7).

Fish Passage by Species

The final step in the estimation process was combining sonar passage estimates with estimates of species proportions to compute passage by species. To estimate passage by species within each sonar stratum, passage within each stratum (Equation 2) was multiplied by the species proportions (Equation 10) for the test fishing zones as follows: Z1 was applied to the entire right-bank counting range (RS1 and RS2 approximately 0–50 m from the right-bank sonar). Zone 2 was applied to counting ranges LS1 and LS2 (approximately 0–100 m from the left-bank sonar). Zone 3 was applied to the counting range corresponding to LS3 (approximately 100–350 m from the left-bank sonar; Figure 4). The passage of species (i) at stratum (s) for each day was estimated by multiplying total passage ($\hat{y}_{ds}$) and proportion ($\hat{p}_{dzi}$) as:

$$\hat{y}_{dsi} = \hat{y}_{ds} \cdot \hat{p}_{dzi}. \tag{12}$$

Except for the timing of sonar and gillnet sampling periods, sonar-derived estimates of total fish passage were independent of gillnet-derived estimates of species proportions. Therefore, the variance of their product was estimated as the variance of the product of 2 independent random variables (Goodman 1960) as:

$$\widehat{Var}(\hat{y}_{dsi}) = \hat{y}_{ds}^2 \cdot \widehat{Var}(\hat{p}_{dzi}) + \hat{p}_{dzi}^2 \cdot \widehat{Var}(\hat{y}_{ds}) - \widehat{Var}(\hat{y}_{ds}) \cdot \widehat{Var}(\hat{p}_{dzi}). \tag{13}$$

Daily passage and variance of each species were summed across sonar strata as:

$$\hat{y}_{di} = \textstyle\sum_s \hat{y}_{dsi} \text{ and } \widehat{Var}(\hat{y}_{di}) = \textstyle\sum_s \widehat{Var}(\hat{y}_{dsi}). \tag{14}$$

Likewise, total passage and variance for the season of each species were the sum of the daily passage as:

$$\hat{y}_i = \textstyle\sum_d \hat{y}_{di} \text{ and } \widehat{Var}(\hat{y}_i) = \textstyle\sum_d \widehat{Var}(\hat{y}_{di}). \tag{15}$$

Assuming normally distributed errors, 95% CI were calculated as:

$$95\% \text{ CI} = \hat{y}_i \pm 1.96\sqrt{\widehat{Var}(\hat{y}_i)}. \tag{16}$$

Extra Deep Net Analysis

To compare the proportions of species caught in nets of similar mesh (4.0, 5.25, and 6.5 inches) but differing depths (8.0 m and 11.0 m), Pearson's chi-square test of independence was performed. The expected catch frequency (E) for each species (i) in net depth (q) was calculated as the total catch (c) by species (i), times the sum of catch by net depth and divided by the sum of all catch as:

$$E_i = \frac{c_i \cdot \sum_q c_{iq}}{\sum c}. \tag{17}$$

Species with expected values less than 5 were removed due to insufficient sample size. The chi-square test statistic X^2 was then calculated as the sum of squared differences between observed catch by species and depth (c_{id}) and the expected frequency E_i divided by the expected frequency E_i as:

$$X^2 = \sum \frac{(c_{id} - E_i)^2}{E_i}. \tag{18}$$

All statistical analyses were conducted using the computing environment R[1].

CLIMATOLOGIC AND HYDROLOGIC OBSERVATIONS

Daily water temperature measurements were reported from June 4 through August 26 due to delayed HOBO meter deployment in 2021. Water temperature was sampled using a HOBO meter installed at the base of the right-bank sonar tripods at a depth of approximately 1 m. Daily air temperature measurements were reported from June 1 through August 26. Air temperature was approximated using National Oceanographic and Atmospheric Administration (NOAA) atmospheric data at Bethel[2] (Appendices B1 and B2).

RESULTS

River Bottom Surveys

Bottom profiles indicated acceptable conditions for sonar operation. Initial surveys showed the best profiles had moved approximately 25 m downriver from previous years (Figure 5; Birchfield and Kastning 2023). A midseason review on August 1 indicated a stable profile (Figure 6). There was sufficient evidence to conclude bottom profiles will probably remain stable at the Church Slough sonar site.

Sonar Deployment and Estimates

The Kuskokwim River sonar project operated from June 1 through August 26, and sonar uptime was measured as the total duration for which each unit was fully functional and running. The ARIS uptime was 85.9 days, the DIDSON uptime was 84.7 days, and the HTI split-beam uptime was 82.3 days out of approximately 87 days of project operations. There were no full days of downtime following deployment (Table 4).

An estimated 2,704,816 fish passed the sonar site from June 1 through August 26. The combined right-bank count was 1,679,244 fish (47.5% RS1 and 14.5% RS2), the combined left-bank nearshore count was 745,377 fish (10.0% LS1 and 17.6% LS2), and the left-bank offshore count was 280,195 fish (10.4% LS3; Table 8). The median range of fish passage along the left bank was 45.69 m. The median range of passage along the right bank was 12.56 m (Figure 7).

Drift Gillnet Fishing

A total of 5,421 fish were caught during drift gillnet fishing, including 295 Chinook salmon, 2,295 sockeye salmon, 66 chum salmon, 542 coho salmon, 51 pink salmon, and 2,172 nonsalmon species. Of captured fish, 45.9% were retained as mortalities and distributed to residents to help meet subsistence needs (Table 9). There were no interruptions of net coverage in 2021.

Species Passage Estimates

Salmon

Summaries of cumulative passage estimates, daily passage estimates, passage by bank, and run timing quartiles were produced for each salmon species (Tables 10 and 11). The Chinook salmon

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[1] The R Project for statistical computing. R version 4.0.0. [Released: April 24, 2020; Accessed: June 5, 2020]. Available for download from https://www.r-project.org/.

[2] NOAA (National Oceanic and Atmospheric Administration). NOWData – NOAA Online Weather Data – Bethel Area. https://www.weather.gov/wrh/climate (Accessed: December 2, 2021).

passage estimate was 102,552 fish (95% CI 84,438–120,666; Figure 8), and median run timing was June 29. The sockeye salmon passage estimate was 745,037 fish (95% CI 696,241–793,833; Figure 9), and median run timing was July 6. The chum salmon passage estimate was 25,689 fish (95% CI 14,550–36,828; Figure 10), and median run timing was July 19. The coho salmon passage estimate was 237,285 (95% CI 209,320–265,250; Figure 11). The average coho salmon daily passage during the final 3 days of operations was 2.2% of total passage, indicating incomplete coho salmon passage and run timing estimates. The pink salmon passage estimate was 41,912 fish (95% CI 30,758–53,066; Figure 12), and median run timing was July 22.

Nonsalmon

Summaries of cumulative passage estimates, daily passage estimates, passage by bank, and run timing quartiles were produced for most nonalmon species (Tables 10 and 12). All nonsalmon species totaled 1,552,341 fish (95% CI 1,415,098–1,689,584; Figure 13). The combined Bering and least cisco passage estimate was 823,091 fish (95% CI 728,049–918,133), and median run timing was August 5. The broad whitefish passage estimate was 22,859 fish (95% CI 8,647–37,071), and median run timing was August 6. The humpback whitefish passage estimate was 667,285 fish (95% CI 570,118–764,452), and median run timing was July 17. The sheefish passage estimate was 20,731 fish (95% CI 9,351–32,111), and median run timing was July 19. Other species (including burbot, Dolly Varden, northern pike, and longnose sucker) totaled 18,375 fish (95% CI 12,938–23,812).

Historical

Summaries of annual cumulative passage estimates by species and mean historical passage were produced for the first time in 2021(Table 13). Meaningful comparisons between passage estimates in 2021 and historical passage were only possible for species that complete migratory passage prior to the historical operational end date of July 26 (Chinook, sockeye, and chum salmon). The Chinook salmon passage estimate (102,552 fish) was below the 2018–2020 average (133,969 fish). The sockeye salmon estimate (745,037 fish) was near the 2018–2020 average (726,381 fish). The chum salmon estimate (25,689 fish) was far below the 2018–2020 average (339,101 fish).

Extra Deep Net Analysis

Pearson's chi-square test of independence was performed to compare cumulative catch by species between nets of the same mesh size but different depths using a 2-way 2x6 contingency table. The test indicated a significant difference between catch frequencies by species of the 2 depths of net X^2 (df = 5, N = 68.17, p <0.001; Appendix C1).

Climatologic and Hydrologic Observations

Water and air temperatures were collected at the sonar site in 2021. Daily mean water temperatures ranged between 9.6°C and 17.8°C and were slightly below average in June (13.5°C) and August (13.9°C) and slightly above average in July (15.0°C; Appendix B1). Air temperatures collected in Bethel indicated below-average air temperatures in all 3 months (Appendix B2). Mean seasonal (June–August) discharge in 2021 was near the 20-year average[3] (Appendix B3), and 2021 had near average water clarity (Appendix B4).

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[3] USGS (United States Geological Survey). Surface water for USA: USGS surface–water annual statistics. https://waterdata.usgs.gov/nwis/annual (Accessed: March 7, 2022).

DISCUSSION

The Kuskokwim River sonar was successfully operated in 2021. There were no periods of sonar downtime exceeding 1 calendar day, and the sonar continued to ensonify 400 m of the approximately 420 m span of the river. Sonar pod deployment and bottom profiles in 2021 were similar to 2020 with a continuing trend of downstream deployment. Increased boat traffic and high water at the sonar site have created bank stability issues since 2018. Coir logs, natural reinforcement, wake breaks, and sandbags were deployed near the right bank sonar to prevent large bank loss from 2019 to 2021. The right bank showed signs of sediment deposition and stabilization in 2021 despite high water and a season of high-velocity southerly wind. Shoreline GPS tracks were collected in 2020 and 2021 to track bank erosion progression. There were 2 narrow deployment options in 2021, but bank stabilization has resulted in fewer right-bank adjustments (Table 4). Right-bank erosion and left-bank deposition may shift optimal profiles slightly downriver and continued monitoring is necessary.

Drift gillnet apportionment experienced no interruptions in 2021; however, chum salmon apportionment continues to be a challenge. The sonar apportionment fishery has indicated chum salmon dominate offshore passage and swim near the bottom at the sonar site (Birchfield et al. 2019). When comparing sonar passage with escapement monitoring projects from 2018 to 2021, there was evidence the sonar site near Bethel underestimated chum salmon by an unknown margin. George River weir and Kogrukluk River weir chum salmon escapement from 2018 to 2021 made up a combined 18–37% of the chum salmon passage estimate at the sonar site[4]. However, historical tagging estimates from 2002 to 2005 indicated the George and Kogrukluk Rivers only contributed 5–15% of combined assessment projects (Pawluk et al. 2006). If productivity has remained the same, and historical distribution estimates are accurate, sonar estimates would be an underestimate of chum salmon passage. In addition, the Bethel test fishery captured chum salmon approximately 4 miles downriver, up to 1 week prior to the first sonar estimations of daily chum salmon passage (further indicating missed passage at the sonar site)[3]. To test if species were distributed unequally in the water column, deeper nets were deployed systematically during offshore drifts in 2021 to test for differences in catch compositions (Tables 5 and 6). Pearson's chi-square test of independence indicated a significant difference between catch frequencies by species of the 2 depths of net X^2 (df = 5, N = 68.17, p <0.001; Appendix C1). However, given the small contribution of offshore passage to total passage, it is unlikely a new suite of deeper nets will fully account for the chum salmon bias. In addition, without an independent estimate of chum salmon abundance, it is impossible to precisely quantify chum salmon abundance bias. For now, sonar estimates of chum salmon abundance are being treated as an index of total abundance past the sonar site. The issue of chum salmon bias raises a second problem; as chum salmon estimates are considered low, it must be assumed estimates of at least 1 other species are biased high. If the chum salmon bias is distributed proportionally among the remaining species, the difference between estimates and the actual population is probably small. However, if the chum salmon bias is concentrated in any single species, that species estimate could be significantly inflated.

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[4] Arctic–Yukon–Kuskokwim Database Management System (AYKDBMS). 2006– . Alaska Department of Fish and Game, Division of Commercial Fisheries. Juneau, AK. https://www.adfg.alaska.gov/CF_R3/external/sites/aykdbms_website/Default.aspx (Accessed: March 28, 2022).

Although there is no clear path to further improving confidence in sonar estimates at this time, there are 2 independent studies that may be conducted to better quantify chum salmon bias:

- A concurrent mark–recapture project could provide an independent comparison of drainagewide chum salmon abundance.
- An acoustic tagging study like the Chinook salmon study on the Nushagak River, with a hydrophone array at the sonar site, could provide insight to chum salmon distribution as they pass the sonar (Maxwell et al. 2020).

Sonar was operated through August for a second year in 2021 to provide an estimate of coho salmon abundance and a more complete index of whitefish abundance. Despite extending operations through August 26, daily coho salmon passage averaged more than 2% of total passage during the final 3 days of operations, indicating an incomplete coho salmon abundance estimate (Table 11 and Figure 11). In order to consistently estimate total abundance in light of later run timing during the last 20 years[5], operations would probably need to extend into mid-September. Without a test of extended operations, it is impossible to predict exactly how much of the coho salmon run is missed by ending operations in August. In the meantime, sonar estimates of abundance will be compared with escapement monitoring projects to examine their utility as an index. This will require at least 1 more year of August data.

Kuskokwim River sonar's fitness as a management tool has been under close scrutiny since it began full operations in 2018. Environmental conditions at the site have been highly variable since the project's inception, making comparisons year to year difficult. However, in 2021, Kuskokwim River environmental conditions (water levels, air and water temperatures, seasonal discharge, and water clarity) were closer to historical averages than 2015–2018. Ongoing inconsistencies between sonar estimates of chum salmon abundance and monitored escapement, coupled with later coho salmon run timing, continue to detract from confidence in abundance estimates for some species in 2021. However, sonar methods continue to describe inseason passage of Chinook, sockeye, chum, and coho salmon to a standard that can provide managers with useful passage information. Chum and coho salmon estimates continue to be considered indices of abundance in 2021. A simple linear regression model was used to describe the relationship between sonar estimates of chum salmon abundance and weir passage estimates, which indicated a relationship from 2018 to 2021 ($R^2 = 0.862$, $n = 4$, $p = 0.072$; Appendix C2). Additional years of data will clarify if this relationship persists over time. Drainagewide Chinook salmon escapement is estimated annually using a run reconstruction model that incorporates harvests, test fisheries, and tributary escapements (Larson 2021). Estimates of Chinook salmon passage at the sonar combined with upriver harvest estimates consistently agree with estimated drainagewide escapement using the Kuskokwim River run reconstruction model. Furthermore, the Chinook salmon run reconstruction model and Chinook salmon estimates of abundance at the sonar were nearly identical in 2021.

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5 Bethel test fishery and inseason catch per unit effort; Kuskokwim management area commercial fisheries. https://www.adfg.alaska.gov/index.cfm?adfg=commercialbyareakuskokwim.btf (Accessed: November 18, 2022).

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TABLES AND FIGURES

Table 1.–Technical specifications for the long-range dual-frequency identification sonar (DIDSON-LR) on the Kuskokwim River left-bank nearshore stratum (LS1), 2021.

		Value
Nominal settings		
	Mode	Identification
	Operating frequency (MHz)	0.7
	Beam dimensions (height x width)	14° x 0.6°
	Number of beams	48
	Field of view (horizontal)	29°
Sample settings		
	Start range (m)	0.83
	Window length (LS1; m)	20.01
	Range bin size (mm)	39
	Pulse length (µs)	46
	Frame rate (f/s)	7

Table 2.–Technical specifications for the split-beam sonar in the Kuskokwim River left-bank midrange and offshore strata (LS2 and LS3), 2021.

Component	Setting	Stratum	Setting
Transducer	Beam dimensions (h x w)		1.5° x 8.0°
Echosounder	Transmit power (dB)		20.0
	Receiver gain (dB)		-6.0
	Source Level (dB)		216.5
	Through-system gain (dB)		-172.4
	Pulse width (ms)		0.4
	Start range (m)		2
	Time varied gain (TVG)		40 log(R)
	Ping rate (pps)	LS2	6.0
		LS3	1.8
	Range (m)	LS2	20–100
		LS3	100–350

Table 3.–Technical specifications for the adaptive resolution imaging sonar (ARIS) in the Kuskokwim River right bank nearshore and offshore strata (RS1 and RS2), 2021.

Setting	Stratum	Value
Beam dimensions (h x w)		28° x 0.6°
Field of view (horizontal)		28°
Frequency (MHz)		0.7
Transmit power (dB re 1 µPa at 1 m)		216.6
Receiver gain (dB)		20.0
Samples/beam		1,024
Frame rate (f/s)	RS1	10.0
	RS2	4.8
Range (m)	RS1	0.7–20.1
	RS2	20.1–50.0

Table 4.–Kuskokwim sonar aiming log, 2021.

Date	Sonar	Event
5/31	ARIS/DIDSON/HTI	Initial aim
6/3	ARIS/DIDSON/HTI	Aim review
6/5	ARIS	Aim review
6/9	DIDSON/HTI	Moved sonar offshore
6/10	DIDSON	Aim review
6/16	ARIS	Removed debris from pod
6/20	DIDSON/HTI	Extended weir and moved offshore
6/22	HTI	Aim review
6/23	DIDSON/HTI	Re-aim to reduce surface noise
6/28	ARIS	Moved sonar upstream for aim higher in the water column
7/3	DIDSON	Cleaned unit
7/19	DIDSON/HTI	Extended weir and moved offshore
7/20	ARIS	Re-aimed down to reduce multipath traces
7/25	DIDSON/ARIS	Cleaned units
7/28	DIDSON/HTI	Reduced weir and moved inshore
8/1	ARIS	Moved slightly offshore
8/4	DIDSON/HTI	Extended weir and moved offshore
8/6	ARIS	Re-aimed down to reduce multipath traces
8/17	DIDSON/HTI	Cleaned units and moved inshore
8/23	DIDSON/HTI	Moved units offshore

Note: Adaptive resolution imaging sonar (ARIS), dual-frequency identification sonar (DIDSON), Hydroacoustic Technology Inc. (HTI).

Table 5.–Specifications for drift gillnets used for test fishing at the Kuskokwim River sonar project, 2021.

Stretch mesh size		Twine size	Meshes deep	Depth	Length
(in)	(mm)		(md)	(m)	(fathom)
2.75	70	50	131	7.9	25
2.75	70	50	67	4.1	25
4.00 [a]	102	50	125	11.0	25
4.00	102	50	90	7.9	25
4.00	102	50	45	4.0	25
5.25 [a]	133	63	95	11.0	25
5.25	133	63	69	7.9	25
5.25	133	63	35	4.0	25
6.50 [a]	165	73	77	11.0	25
6.50	165	73	56	8.0	25
6.50	165	73	28	4.0	25
7.50	191	83	48	7.9	25
7.50	197	83	25	4.3	25
8.50	216	93	43	8.0	25
8.50	216	93	22	4.1	25

[a] In 2021, extra deep nets (11.0 m) were used to test sampling depth apportionment bias in Zone 3. Fish caught in extra deep nets were omitted from estimates of passage because they do not represent the full range of mesh sizes.

Table 6.–Alternating daily schedule for drift gillnets used for test fishing by period and day at the Kuskokwim River sonar project, 2021.

Period	First day mesh size (in)	Second day mesh size (in)	Third day mesh size (in)	Fourth day mesh size (in)
1	4.00	5.25	6.50	4.00 XD
	6.50	7.50	5.25 XD	6.50 XD
	8.50	4.00 XD	8.50	7.50
	5.25 XD	6.50 XD	4.00	2.75
		2.75		5.25
2	7.50	5.25 XD	2.75	4.00
	4.00 XD	8.50	5.25	6.50
	6.50 XD	4.00	7.50	5.25 XD
	2.75	6.50	4.00 XD	8.50
	5.25		6.50 XD	

Note: The apportionment fishery stopped deploying 8.50-inch mesh nets on August 1. XD means extra deep nets (11.00 m).

Table 7.–Summary of zones pooled or substituted at the Kuskokwim River sonar project, 2021.

	Right bank	Left bank	
Date	Nearshore (zone 1)	Offshore (zone 3)	Nearshore (zone 2)
6/1	IC		
6/2	IC	ICZ	IC
6/3	IC	ICZ	IC
6/4		ICZ	IC
6/5	IC	ICZ	IC
6/6	ICZ		IC
6/7	ICZ		IC
6/8	ICZ		IC
6/9	ICZ		IC
6/10	IC	ICZ	IC
6/11	IC	ICZ	IC
6/12	IC	ICZ	IC
6/13		IC	IC
6/14		IC	IC
6/15		IC	IC
6/16		IC	IC
6/17		IC	
6/18		IC	
6/19	ICZ		IC
6/20		IC	IC
6/21		IC	IC
6/22		IC	
6/23			
6/24			
6/25			
6/26		IC	
6/27			
6/28			
6/29			
6/30			

-continued-

Table 7.–Page 2 of 3.

	Right bank	Left bank	
Date	Nearshore (zone 1)	Offshore (zone 3)	Nearshore (zone 2)
7/1			
7/2			
7/3			
7/4			
7/5			
7/6			
7/7			
7/8			
7/9			
7/10			
7/11			
7/12			
7/13			
7/14			
7/15			
7/16			
7/17			
7/18		IC	
7/19			
7/20			IC
7/21			
7/22			
7/23		IC	
7/24			
7/25			
7/26		IC	
7/27		IC	
7/28		IC	
7/29		IC	
7/30			

-continued-

Table 7.–Page 3 of 3.

	Right bank	Left bank	
Date	Nearshore (zone 1)	Offshore (zone 3)	Nearshore (zone 2)
7/31		IC	
8/1		IC	
8/2		IC	
8/3			
8/4			
8/5		IC	
8/6			
8/7		IC	
8/8			
8/9		IC	
8/10		IC	
8/11			
8/12		IC	
8/13		IC	
8/14		IC	
8/15		IC	
8/16	ICZ		
8/17	ICZ		
8/18			
8/19		IC	
8/20		IC	
8/21			
8/22		IC	
8/23	IC	IC	
8/24		IC	
8/25		IC	
8/26		IC	

Note: IC denotes each day when there was an insufficient catch in the test fishery for variance estimation, and zones were pooled across days. ICZ denotes each day when a zone had little to no catch, and another zone was substituted for apportionment. Groups of days or zones outlined by a box denotes pooling across days or zones.

Table 8.–Summary of undifferentiated passage by stratum, 2021.

Stratum	LS1	LS2	LS3	RS2	RS1	Total
Passage	269,676	475,701	280,195	393,374	1,285,870	2,704,816
Proportion	10.0%	17.6%	10.4%	14.5%	47.5%	

Note: Left-bank nearshore stratum (LS1), left-bank midrange (LS2), left-bank offshore strata (LS3), right-bank nearshore (RS1), right-bank offshore strata (RS2), and right bank (RS3).

Table 9.–Number of fish captured and retained in the Kuskokwim River sonar test fishery, 2021.

Total catch

	Chinook	Sockeye	Chum	Coho	Pink	Cisco [a]	Broad	Humpback	Sheefish	Others [b]	Total
June	176	617	8	0	1	30	9	96	13	12	962
July	119	1,666	57	161	43	439	8	702	10	2	3,207
August	0	12	1	381	7	731	16	87	9	8	1,252
Total	295	2,295	66	542	51	1,200	33	885	32	22	5,421

Fish retained

	Chinook	Sockeye	Chum	Coho	Pink	Cisco [a]	Broad	Humpback	Sheefish	Others [b]	Total
June	58	398	5	0	1	4	5	70	3	0	544
July	20	901	14	30	10	144	5	358	1	1	1,484
August	0	2	0	103	1	316	6	32	0	1	461
Total	78	1,301	19	133	12	464	16	460	4	2	2,489

Proportion retained

	Chinook	Sockeye	Chum	Coho	Pink	Cisco [a]	Broad	Humpback	Sheefish	Others [b]	Total
June	33.0%	64.5%	62.5%	0.0%	100.0%	13.3%	55.6%	72.9%	23.1%	0.0%	56.5%
July	16.8%	54.1%	24.6%	18.6%	23.3%	32.8%	62.5%	51.0%	10.0%	50.0%	46.3%
August	0.0%	16.7%	0.0%	27.0%	14.3%	43.2%	37.5%	36.8%	0.0%	12.5%	36.8%
Total	26.4%	56.7%	28.8%	24.5%	23.5%	38.7%	48.5%	52.0%	12.5%	9.1%	45.9%

[a] Includes Bering and least cisco.

[b] *Others* refers to burbot, Dolly Varden, northern pike, and longnose sucker.

Table 10.–Summary of cumulative passage by species and bank, 2021.

Species	Left bank	Right bank	Total	SE	CV	Lower 95% CI	Upper 95% CI
Chinook	56,814	45,738	102,552	9,242	9%	84,438	120,666
Sockeye	273,996	471,041	745,037	24,896	3%	696,241	793,833
Chum	18,319	7,370	25,689	5,683	22%	14,550	36,828
Coho	132,402	104,883	237,285	14,268	6%	209,320	265,250
Pink	28,404	13,508	41,912	5,691	14%	30,758	53,066
Cisco	227,141	595,950	823,091	48,491	6%	728,049	918,133
Broad	1,970	20,889	22,859	7,251	32%	8,647	37,071
Humpback	254,907	412,378	667,285	49,575	7%	570,118	764,452
Sheefish	14,224	6,507	20,731	5,806	28%	9,351	32,111
Other [a]	17,395	980	18,375	2,774	15%	12,938	23,812

Note: Coefficient of variation (CV), confidence interval (CI), standard error (SE).

[a] *Other* refers to burbot, Dolly Varden, northern pike, and longnose sucker.

Table 11.–Daily and total passage at the Kuskokwim River sonar project, 2021.

Date	Chinook	Sockeye	Chum	Coho [a]	Pink	Nonsalmon	Total
6/1	249	0	0	0	0	999	1,248
6/2	261	0	0	0	0	1446	1,707
6/3	236	0	0	0	0	1,550	1,786
6/4	747	0	0	0	0	983	1,730
6/5	993	0	0	0	0	844	1,837
6/6	858	0	0	0	0	721	1,579
6/7	792	0	0	0	0	1,646	2,438
6/8	950	303	0	0	0	1,263	2,516
6/9	848	355	320	0	0	1,370	2,893
6/10	1,102	737	0	0	0	1,131	2,970
6/11	1,626	950	0	0	0	1,268	3,844
6/12	1,332	830	0	0	0	1,192	3,354
6/13	2,528	994	0	0	0	372	3,894
6/14	2,667	2,037	0	0	0	0	4,704
6/15	2,731	1,355	0	0	0	981	5,067
6/16	1,019	3,333	0	0	0	1,784	6,136
6/17	1,700	4,342	0	0	0	3,026	9,068
6/18	1,375	6,635	0	0	0	2,716	10,726
6/19	2,585	1,569	0	0	0	9,708	13,862
6/20	2,745	1,674	0	0	0	9,104	13,523
6/21	2,059	7,421	0	0	0	3,859	13,339
6/22	3,125	6,246	300	0	0	7,042	16,713
6/23	1,479	5,071	249	0	0	8,854	15,653
6/24	3,261	6,549	0	0	0	10,985	20,795
6/25	3,788	7,705	1,071	0	0	6,098	18,662
6/26	1,459	10,559	0	0	0	4,568	16,586
6/27	4,330	11,581	0	0	0	2,128	18,039
6/28	2,751	15,908	184	0	185	2,905	21,933
6/29	**4,219**	23,561	0	0	0	3,006	30,786
6/30	2,367	36,415	266	0	0	2,304	41,352

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Table 11.–Page 2 of 3.

Date	Chinook	Sockeye	Chum	Coho [a]	Pink	Nonsalmon	Total
7/1	5,223	32,671	656	0	0	5,705	44,255
7/2	3,101	22,821	819	0	0	8,491	35,232
7/3	3,692	32,673	0	0	0	5,536	41,901
7/4	1,770	56,482	511	0	960	11,648	71,371
7/5	1,500	56,124	1,091	0	0	16,470	75,185
7/6	2,331	**39,890**	579	0	0	6,689	49,489
7/7	3,625	42,628	1,202	0	0	10,823	58,278
7/8	3,647	43,024	385	0	0	7,556	54,612
7/9	3,217	21,250	850	0	675	7,081	33,073
7/10	1,521	21,785	1,336	0	0	4,784	29,426
7/11	1,716	19,520	401	0	0	10,315	31,952
7/12	1,933	21,811	585	0	1,069	9,621	35,019
7/13	273	24,927	316	0	866	16,925	43,307
7/14	0	44,081	0	0	842	21,029	65,952
7/15	966	14,310	0	0	2,189	88,137	105,602
7/16	4,907	20,505	0	0	696	94,307	120,415
7/17	1,585	16,137	1,209	0	1,419	88,287	108,637
7/18	947	7,461	503	0	1,711	86,507	97,129
7/19	1,078	8,041	**3,172**	279	1,028	66,918	80,516
7/20	1,133	14,984	1,800	0	1,641	43,770	63,328
7/21	0	5,516	2,976	1,577	4,881	44,556	59,506
7/22	0	3,166	2,391	5,875	**4,195**	**35,293**	50,920
7/23	0	2,755	0	1,829	1,254	41,905	47,743
7/24	0	1,244	0	3,232	6,487	38,983	49,946
7/25	736	1,752	197	5,768	0	28,895	37,348
7/26	775	1,237	535	8,650	721	15,632	27,550
7/27	0	1,782	1,152	5,863	0	13,799	22,596
7/28	161	2,225	0	6,549	1,009	11,210	21,154
7/29	192	951	423	6,896	2,190	12,583	23,235
7/30	120	130	0	6,356	178	13,381	20,165
7/31	221	687	0	7,501	440	9,361	18,210

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Table 11.–Page 3 of 3.

Date	Chinook	Sockeye	Chum	Coho [a]	Pink	Nonsalmon	Total
8/1	0	793	0	7,677	0	12,240	20,710
8/2	0	1,981	0	8,953	0	13,255	24,189
8/3	0	0	0	6,632	0	27,289	33,921
8/4	0	462	0	11,700	0	34,172	46,334
8/5	0	819	0	15,508	0	59,479	75,806
8/6	0	1,413	0	**8,491**	0	64,282	74,186
8/7	0	0	0	10,287	823	58,040	69,150
8/8	0	0	0	8,900	2,912	47,153	58,965
8/9	0	0	0	6,669	0	37,830	44,499
8/10	0	0	0	8,903	939	34,319	44,161
8/11	0	0	0	11,657	535	26,540	38,732
8/12	0	0	0	5,720	0	21,443	27,163
8/13	0	440	0	3,396	0	15,901	19,737
8/14	0	0	0	3,537	0	13,196	16,733
8/15	0	293	0	2,987	0	12,203	15,483
8/16	0	0	210	4,237	0	9,637	14,084
8/17	0	0	0	4,476	0	12,952	17,428
8/18	0	0	0	3,236	525	9,876	13,637
8/19	0	0	0	3,025	664	8,194	11,883
8/20	0	0	0	8,546	878	8,460	17,884
8/21	0	136	0	9,601	0	6,076	15,813
8/22	0	0	0	4,472	0	9,972	14,444
8/23	0	0	0	2,330	0	10,687	13,017
8/24	0	0	0	8,374	0	5,791	14,165
8/25	0	0	0	2,751	0	11,833	14,584
8/26	0	0	0	4,845	0	11,471	16,316
Total	102,552	745,037	25,689	237,285	41,912	1,552,341	2,704,816
SE	9,242	24,896	5,683	14,268	5,691	70,022	NA
CV	9%	3%	22%	6%	14%	5%	NA
Lower 95% CI	84,438	696,241	14,550	209,320	30,758	1,415,098	NA
Upper 95% CI	120,666	793,833	36,828	265,250	53,066	1,689,584	NA

Note: Coefficient of variation (CV), confidence interval (CI), standard error (SE). The second and third quartile of the run, including the expanded estimate, are outlined by a border and median days of passage are bold.

[a] Coho salmon passage continued beyond operations in 2021, resulting in incomplete passage and run timing estimates.

Table 12.–Daily and total passage of nonsalmon species at the Kuskokwim River sonar project, 2021.

Date	Cisco	Broad	Humpback	Sheefish	Other [a]	Total
6/1	648	0	145	83	123	999
6/2	684	0	315	180	267	1,446
6/3	615	0	387	221	327	1,550
6/4	0	0	297	170	516	983
6/5	0	0	459	125	260	844
6/6	0	0	567	154	0	721
6/7	559	0	722	365	0	1,646
6/8	0	0	170	203	890	1,263
6/9	0	0	0	327	1,043	1,370
6/10	0	0	0	0	1,131	1,131
6/11	0	0	0	0	1,268	1,268
6/12	0	0	0	0	1,192	1,192
6/13	0	0	372	0	0	372
6/14	0	0	0	0	0	0
6/15	0	0	0	981	0	981
6/16	0	0	1,201	0	583	1,784
6/17	585	0	1,320	320	801	3,026
6/18	648	0	1,733	335	0	2,716
6/19	0	0	9,708	0	0	9,708
6/20	857	738	7,509	0	0	9,104
6/21	0	0	3,859	0	0	3,859
6/22	1,083	1,351	4,608	0	0	7,042
6/23	1,292	0	7,562	0	0	8,854
6/24	2,206	1,148	6,999	0	632	10,985
6/25	3,923	291	1,884	0	0	6,098
6/26	1,047	0	3,404	117	0	4,568
6/27	333	0	1,207	229	**359**	2,128
6/28	787	0	764	1,354	0	2,905
6/29	1,089	0	818	0	1,099	3,006
6/30	1,063	0	743	498	0	2,304

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Table 12.–Page 2 of 3.

Date	Cisco	Broad	Humpback	Sheefish	Other [a]	Total
7/1	938	796	3,971	0	0	5,705
7/2	1,472	0	7,019	0	0	8,491
7/3	616	0	4,920	0	0	5,536
7/4	0	0	11,648	0	0	11,648
7/5	1,170	0	15,300	0	0	16,470
7/6	1,445	0	5,244	0	0	6,689
7/7	2,344	0	8,213	266	0	10,823
7/8	0	0	7,556	0	0	7,556
7/9	1,194	0	5,887	0	0	7,081
7/10	599	0	4,185	0	0	4,784
7/11	1,215	0	9,100	0	0	10,315
7/12	4,012	0	4,527	1,082	0	9,621
7/13	379	0	15,233	1,313	0	16,925
7/14	4,965	0	16,064	0	0	21,029
7/15	14,095	0	74,042	0	0	88,137
7/16	51,645	1,375	40,636	651	0	94,307
7/17	23,198	1,581	**62,942**	566	0	88,287
7/18	41,167	0	44,380	0	960	86,507
7/19	21,966	0	42,410	**2,542**	0	66,918
7/20	13,309	1,040	26,596	2,825	0	43,770
7/21	15,144	482	28,930	0	0	44,556
7/22	15,841	0	19,452	0	0	35,293
7/23	13,658	0	27,434	813	0	41,905
7/24	18,709	0	20,274	0	0	38,983
7/25	13,747	0	14,402	0	746	28,895
7/26	7,528	0	8,104	0	0	15,632
7/27	8,783	0	5,016	0	0	13,799
7/28	8,941	0	2,269	0	0	11,210
7/29	8,531	0	4,052	0	0	12,583
7/30	7,514	0	5,867	0	0	13,381
7/31	6,664	0	2,697	0	0	9,361

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Table 12.–Page 3 of 3.

Date	Cisco	Broad	Humpback	Sheefish	Other [a]	Total
8/1	4,818	0	6,373	375	674	12,240
8/2	10,473	259	2,523	0	0	13,255
8/3	20,176	794	4,452	1,342	525	27,289
8/4	27,613	307	5,590	662	0	34,172
8/5	**49,956**	0	9,523	0	0	59,479
8/6	52,274	**2,566**	9,442	0	0	64,282
8/7	42,468	6,565	8,100	0	907	58,040
8/8	42,977	1,626	2,550	0	0	47,153
8/9	33,656	481	2,632	376	685	37,830
8/10	32,690	0	1,629	0	0	34,319
8/11	23,751	395	2,394	0	0	26,540
8/12	21,443	0	0	0	0	21,443
8/13	15,901	0	0	0	0	15,901
8/14	13,196	0	0	0	0	13,196
8/15	11,843	0	0	360	0	12,203
8/16	9,261	0	0	245	131	9,637
8/17	12,840	0	0	0	112	12,952
8/18	7,903	0	987	0	986	9,876
8/19	7,265	0	0	0	929	8,194
8/20	7,231	0	0	0	1,229	8,460
8/21	4,523	464	1,089	0	0	6,076
8/22	9,651	0	0	321	0	9,972
8/23	9,111	0	612	964	0	10,687
8/24	5,791	0	0	0	0	5,791
8/25	8,859	600	2,374	0	0	11,833
8/26	9,213	0	1,892	366	0	11,471
Total	823,091	22,859	667,285	20,731	18,375	1,552,341
SE	48,491	7,251	49,575	5,806	2,774	70,022
CV	6%	32%	7%	28%	15%	5%
Lower 95% CI	728,049	8,647	570,118	9,351	12,938	1,415,098
Upper 95% CI	918,133	37,071	764,452	32,111	23,812	1,689,584

Note: Coefficient of variation (CV), confidence interval (CI), standard error (SE). The second and third quartile of the run, including the expanded estimate, are outlined by a border and median days of passage are bold.

[a] *Other* refers to burbot, Dolly Varden, northern pike, and longnose sucker.

Table 13.–Historical cumulative passage estimates, by species, with historical averages for species with at least 3 years of comparable estimates of passage, 2018–2021.

	Chinook	Sockeye	Chum	Coho	Pink	Cisco	Broad	Humpback	Sheefish	Other
2018	132,970	679,230	555,570	9,144	51,477	286,184	8,758	407,328	12,970	20,501
2019	162,672	924,579	385,409	29,467	32,346	608,122	6,726	697,627	17,984	6,582
2020	106,265	575,334	76,323	163,708	19,793	1,217,611	7,892	633,815	8,236	13,659
2021	102,552	745,037	25,689	237,285	41,912	823,091	22,859	667,285	20,731	18,375
2018–2020 average [a]	133,969	726,381	339,101	NA	NA	NA	NA	NA	NA	NA

Note: *Other* refers to burbot, Dolly Varden, northern pike, and longnose sucker.

[a] Operations ended July 26, 2018, and July 27, 2019, before most coho salmon passage and a large portion of pink salmon and nonsalmon passage occurred. Operations ended August 25, 2020, and August 26, 2021, before some coho, pink, and nonsalmon passage occurred, resulting in incomplete passage estimates.

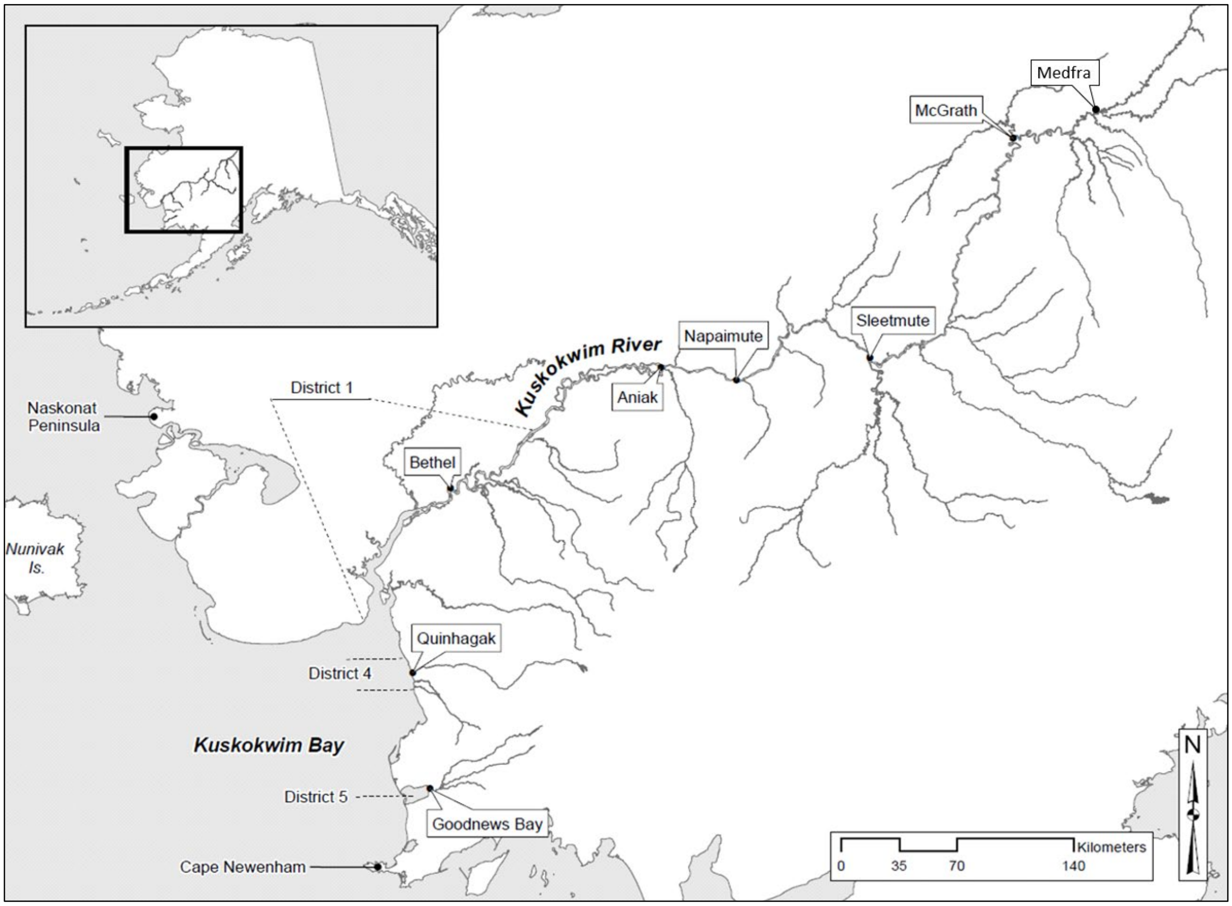


Figure 1.–The Kuskokwim Management Area, including Kuskokwim Bay, the Kuskokwim River, and select commercial fishing districts.

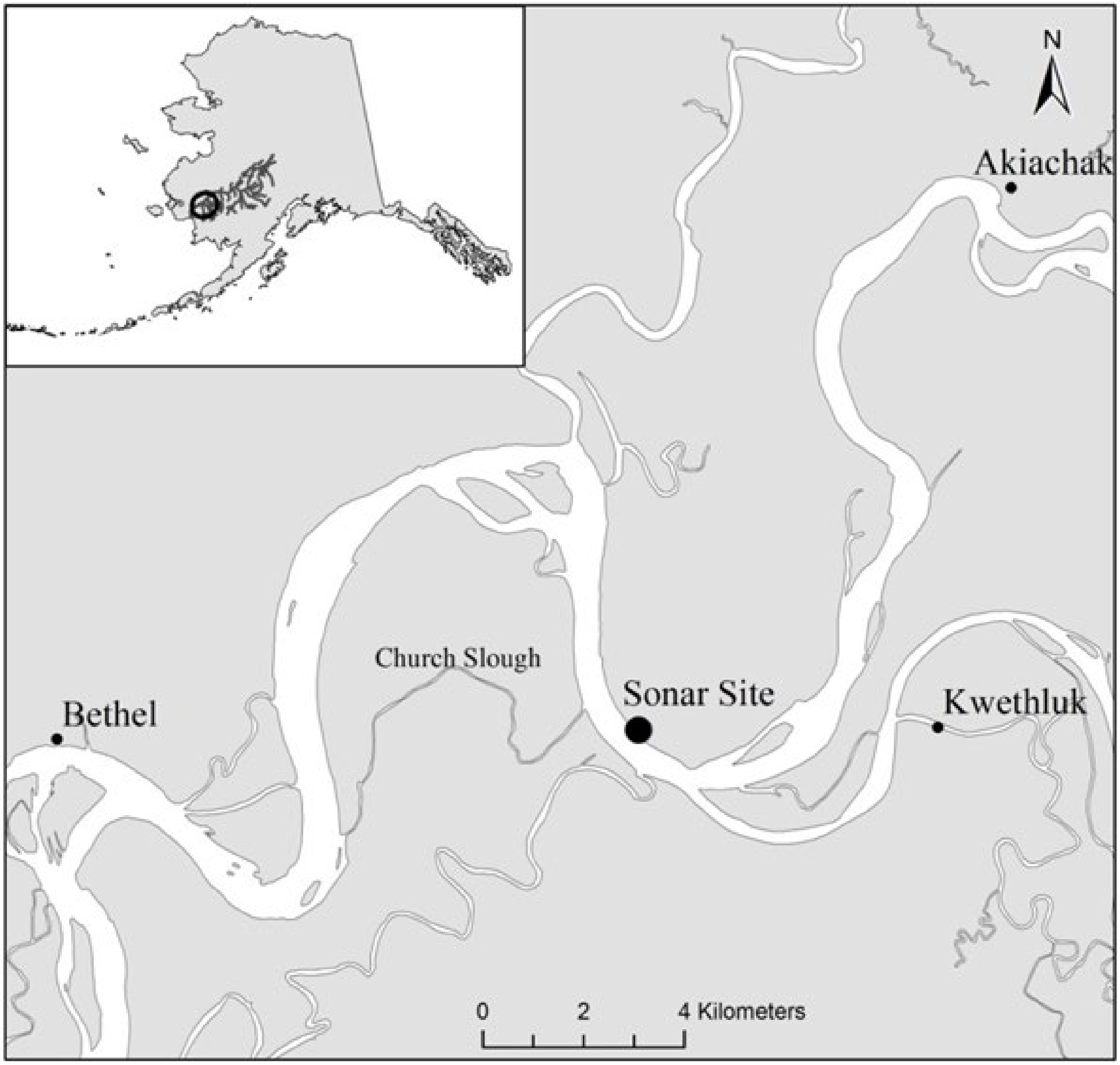


Figure 2.–Kuskokwim River sonar project site (locally referred to as Bethel sonar site).

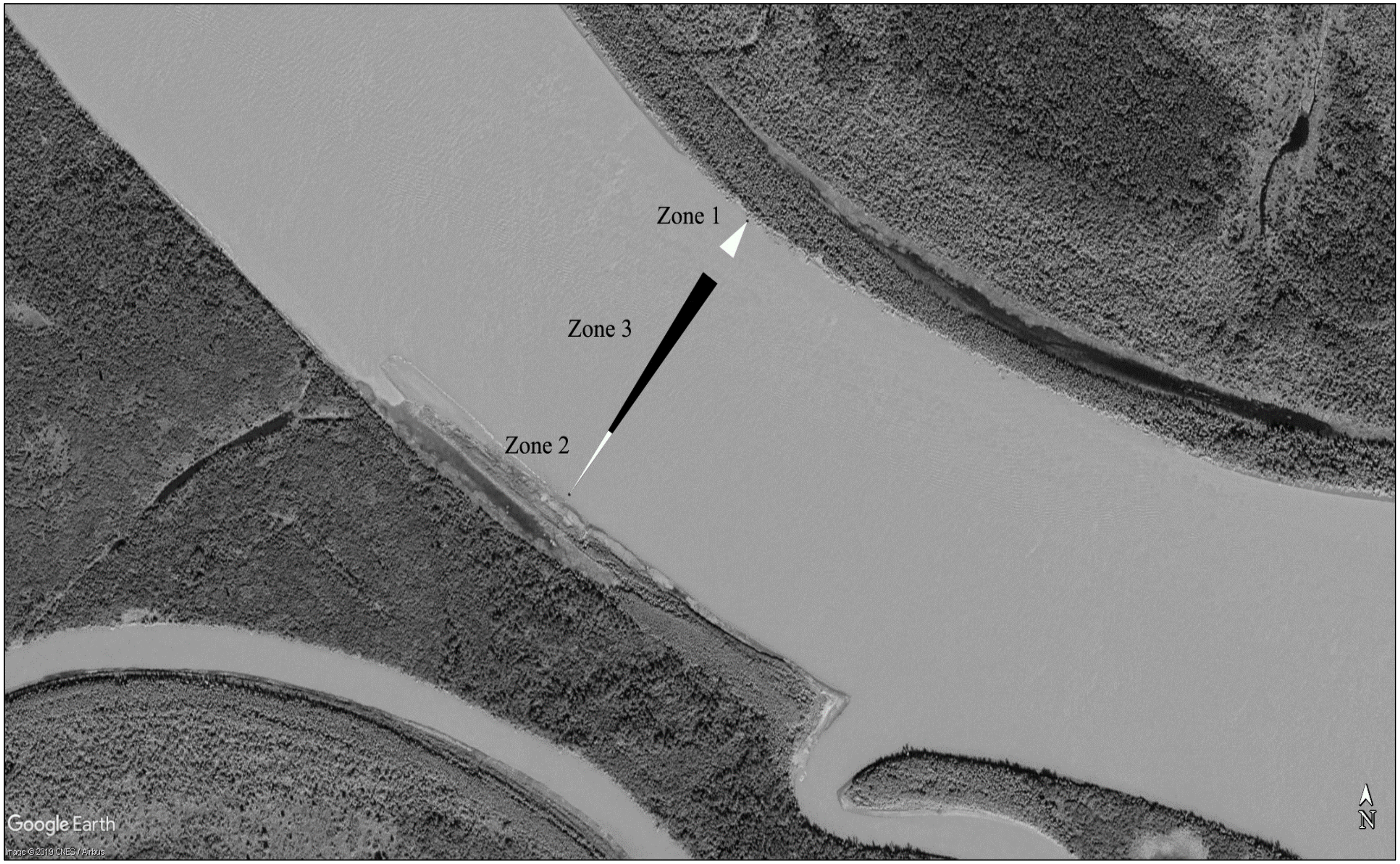


Figure 3.–Test fishing zones overlaying sonar coverage at Kuskokwim River sonar project.

Note: The northern white triangle represents approximate adaptive resolution imaging sonar (ARIS) coverage. The southern white triangles represent nearshore coverage by the dual-frequency identification sonar (DIDSON) and Hydroacoustic Technologies Inc. (HTI). The offshore black wedge represents HTI offshore coverage. Satellite image courtesy of Google Earth, 2019.

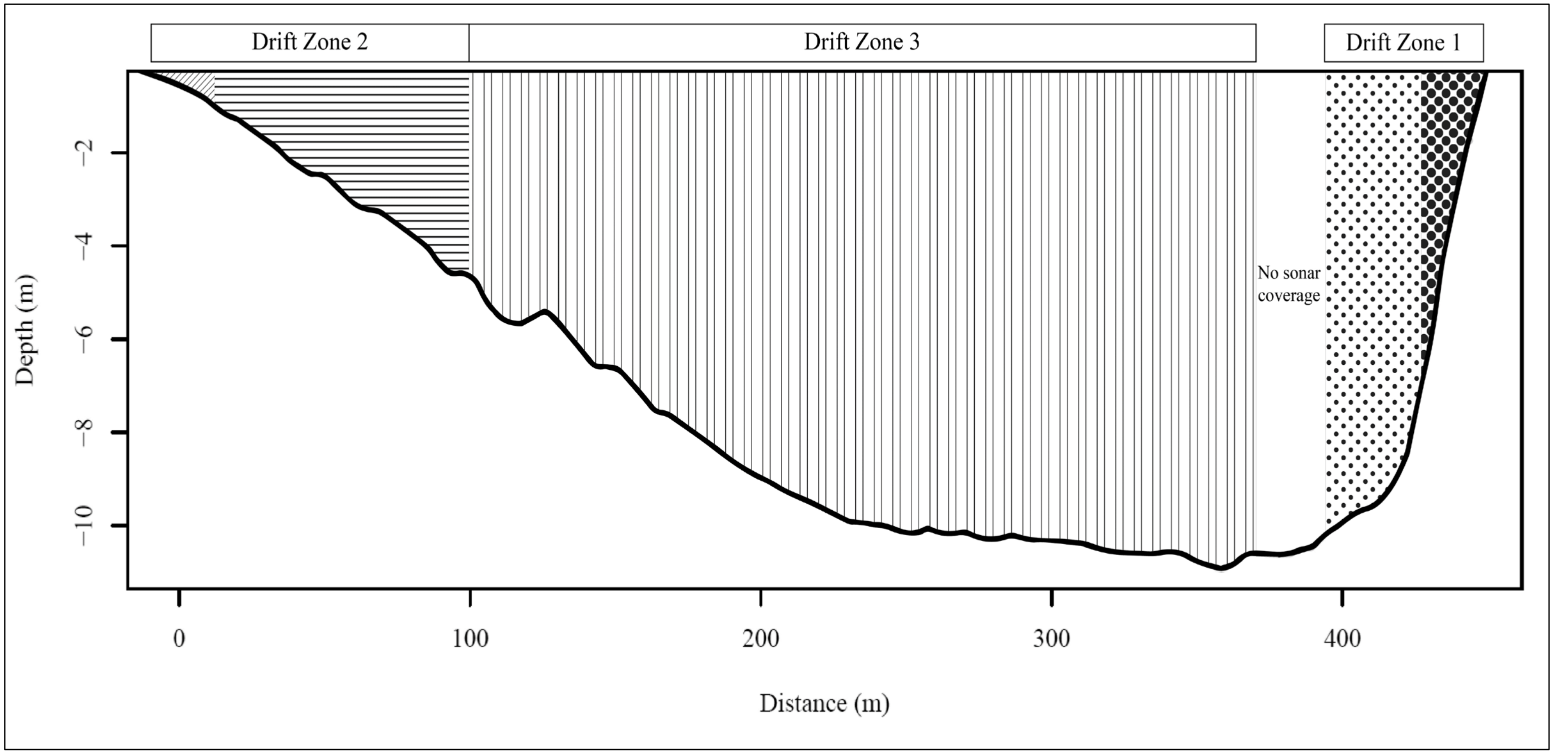


Figure 4.–Representation of the right-bank nearshore stratum RS1 (large dots), right-bank offshore stratum RS2 (small dots), left-bank nearshore stratum LS1 (diagonal lines), left-bank midrange stratum LS2 (horizontal lines), and left-bank offshore stratum LS3 (vertical lines) ensonified areas.

Note: The figure includes 3 gillnet drift zones overlaid on a horizontally compressed Kuskokwim River sonar site channel profile looking downriver.

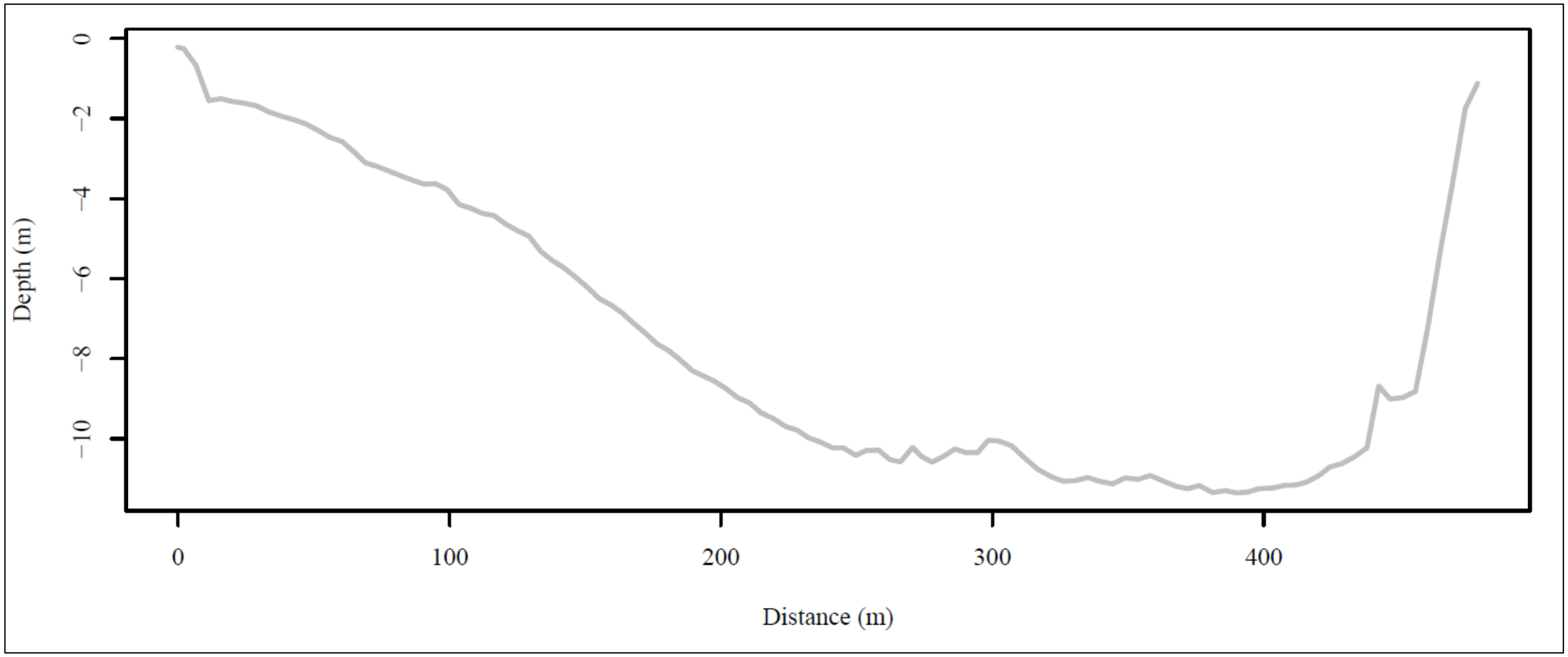


Figure 5.–Site survey looking downriver at the Kuskokwim River sonar site conducted May 30, 2021.

Note: Image is laterally compressed.

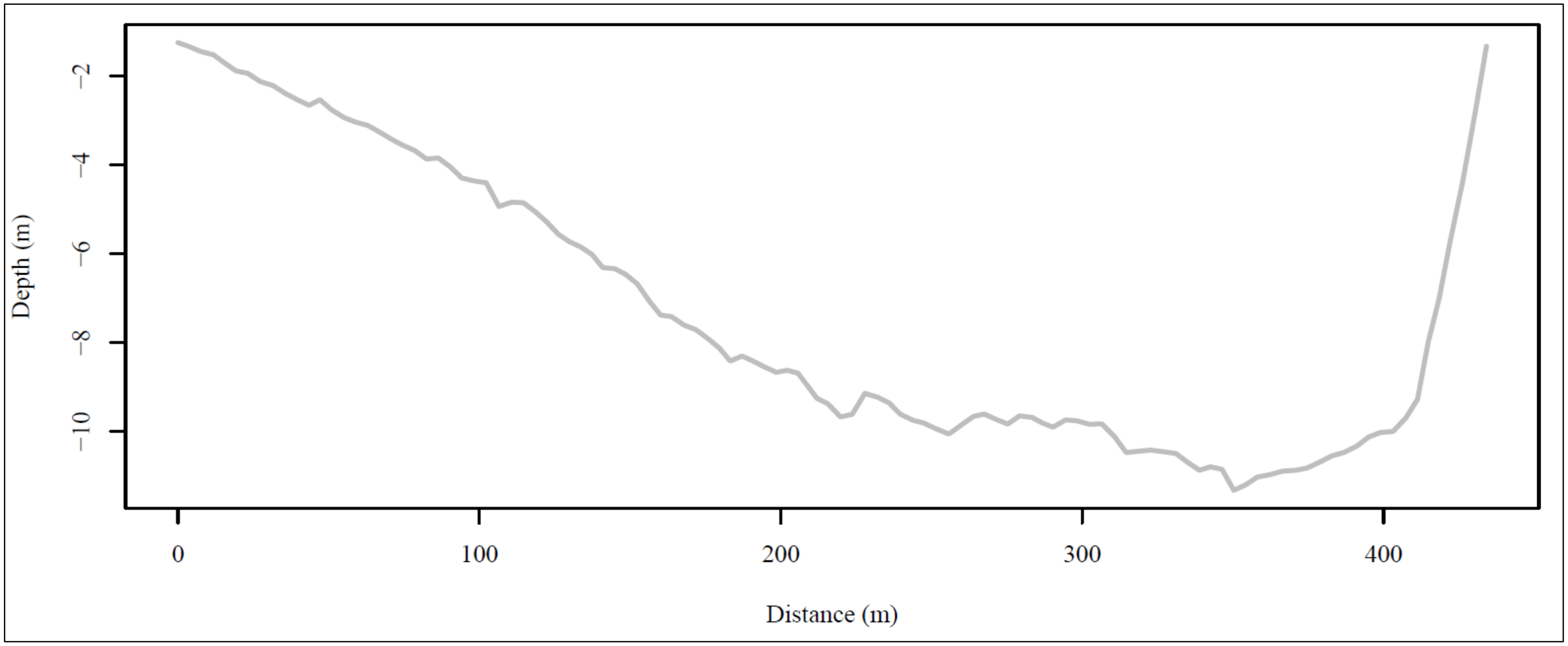


Figure 6.–Site survey looking downriver at the Kuskokwim River sonar site conducted August 2, 2021.

Note: Image is laterally compressed.

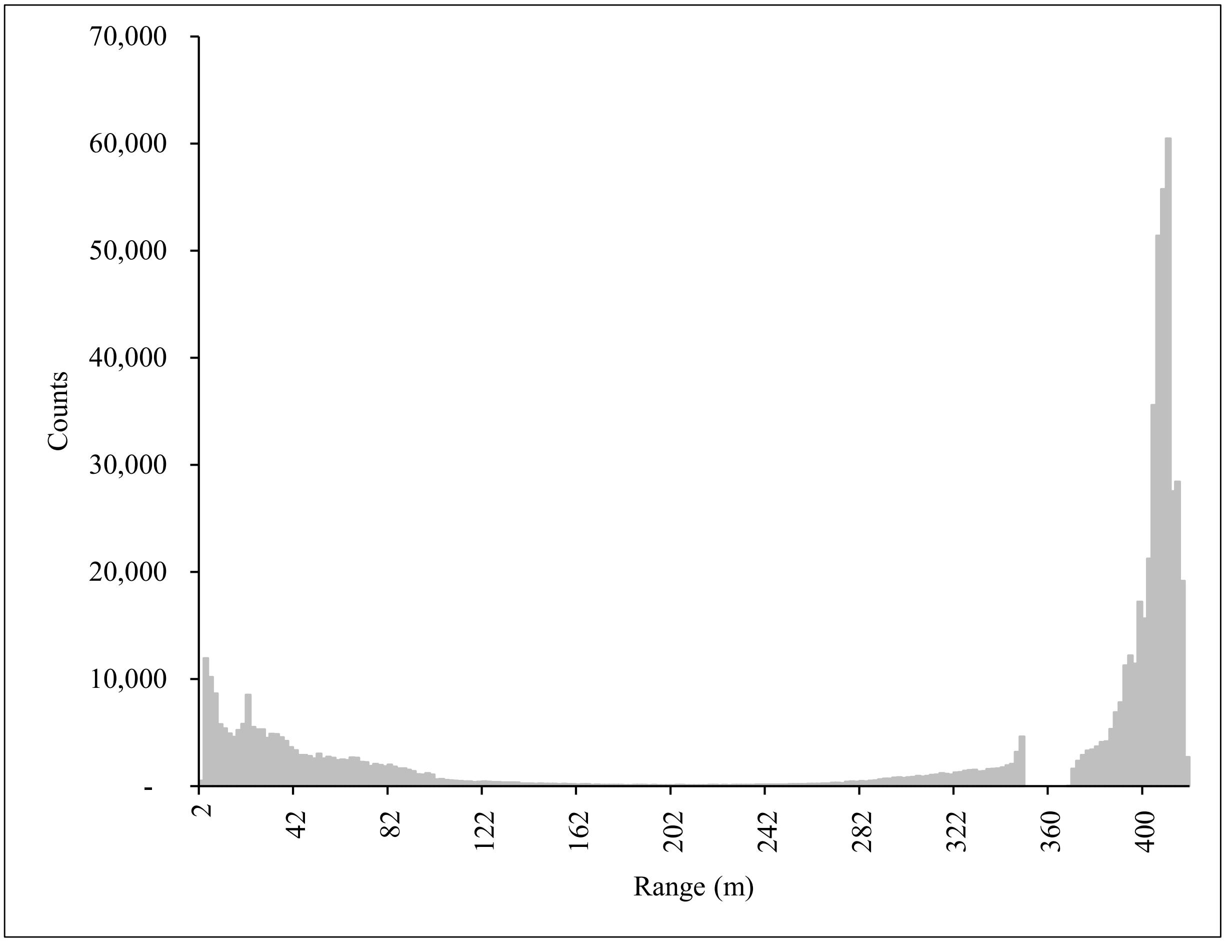


Figure 7.–Horizontal fish distribution in 2.00 m increments, relative to transducers, at the Kuskokwim River sonar project, 2021.

Note: Median range of fish passage from the left-bank transducer was 45.69 m. Median range of fish passage from the right-bank transducer was 12.56 m.

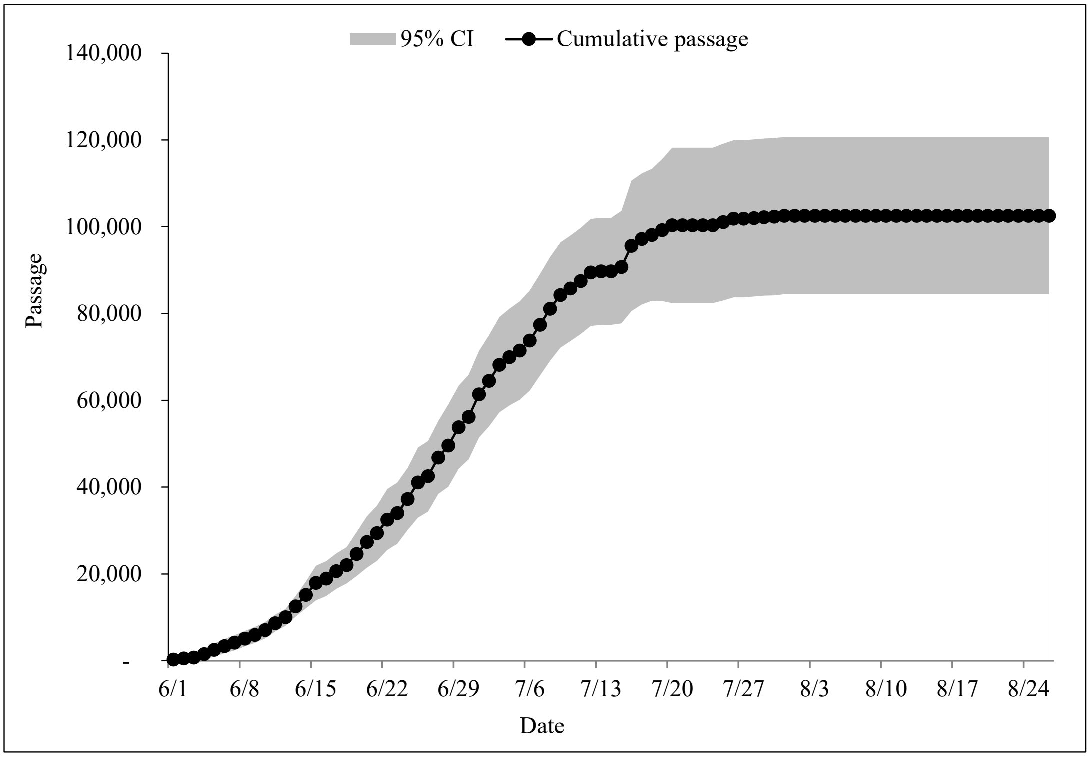


Figure 8.–Cumulative Chinook salmon passage, including 95% CI, at the Kuskokwim River sonar project, 2021.

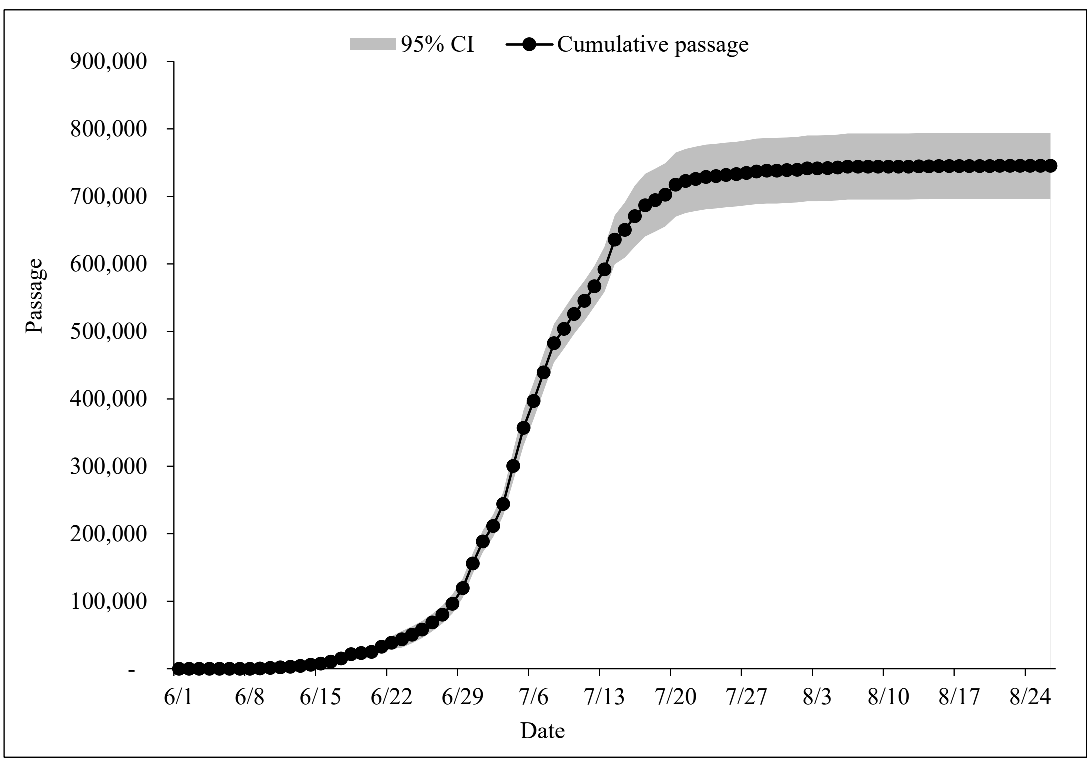


Figure 9.–Cumulative sockeye salmon passage, including 95% CI, at the Kuskokwim River sonar project, 2021.

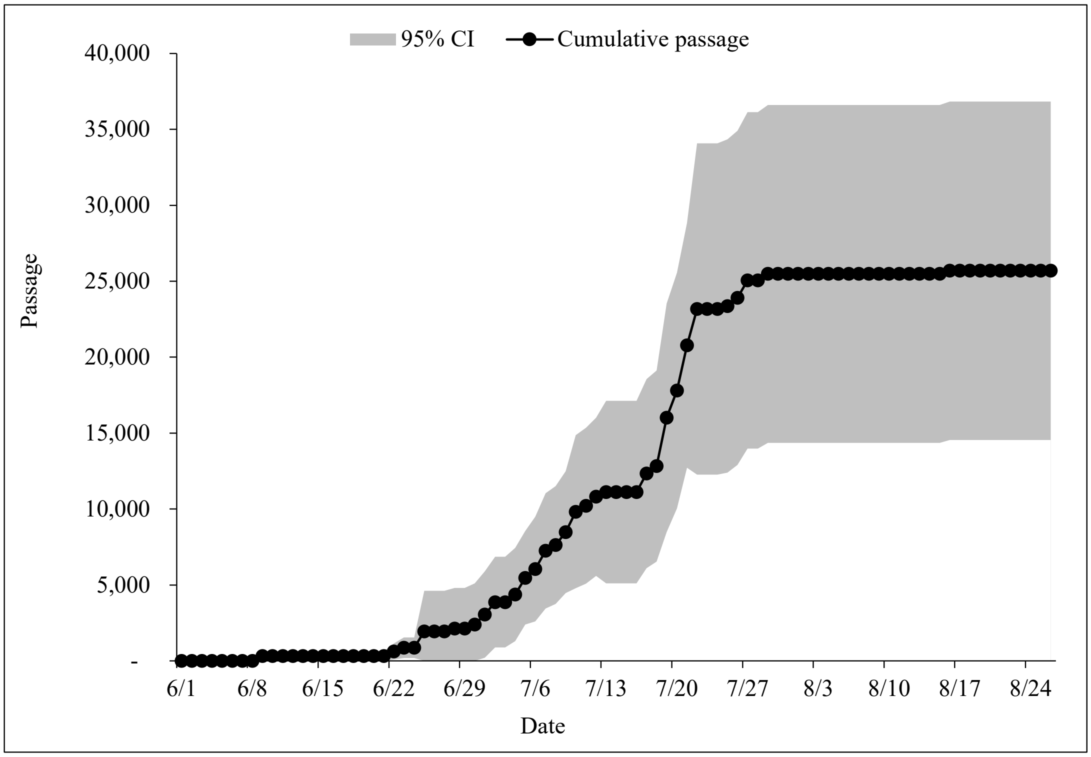


Figure 10.–Cumulative chum salmon passage, including 95% CI, at the Kuskokwim River sonar project, 2021.

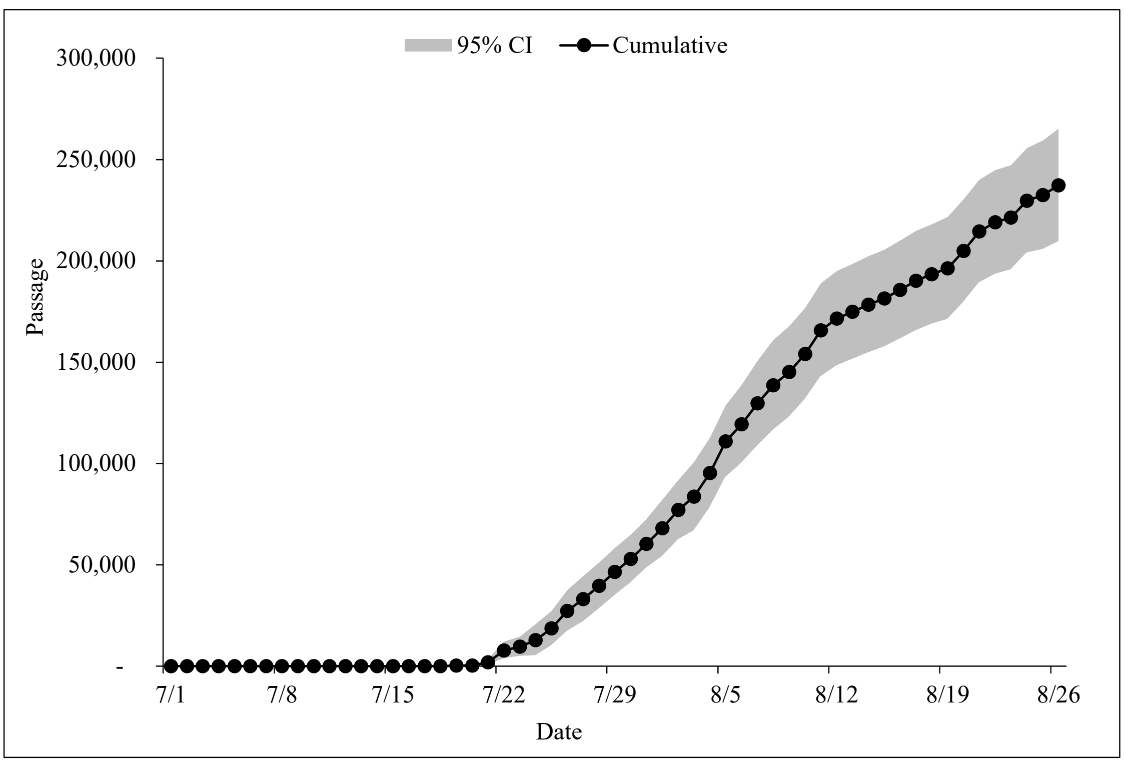


Figure 11.–Cumulative coho salmon passage, including 95% CI, at the Kuskokwim River sonar project, 2021.

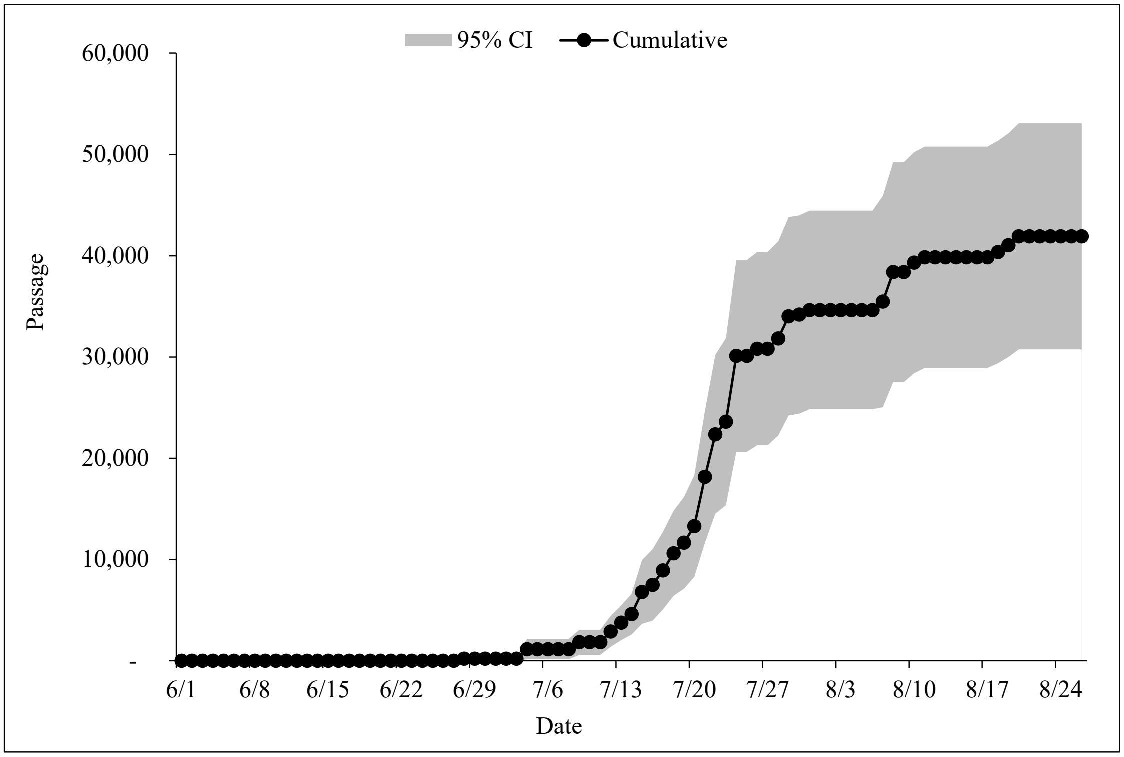


Figure 12.–Cumulative pink salmon passage, including 95% CI, at the Kuskokwim River sonar project, 2021.

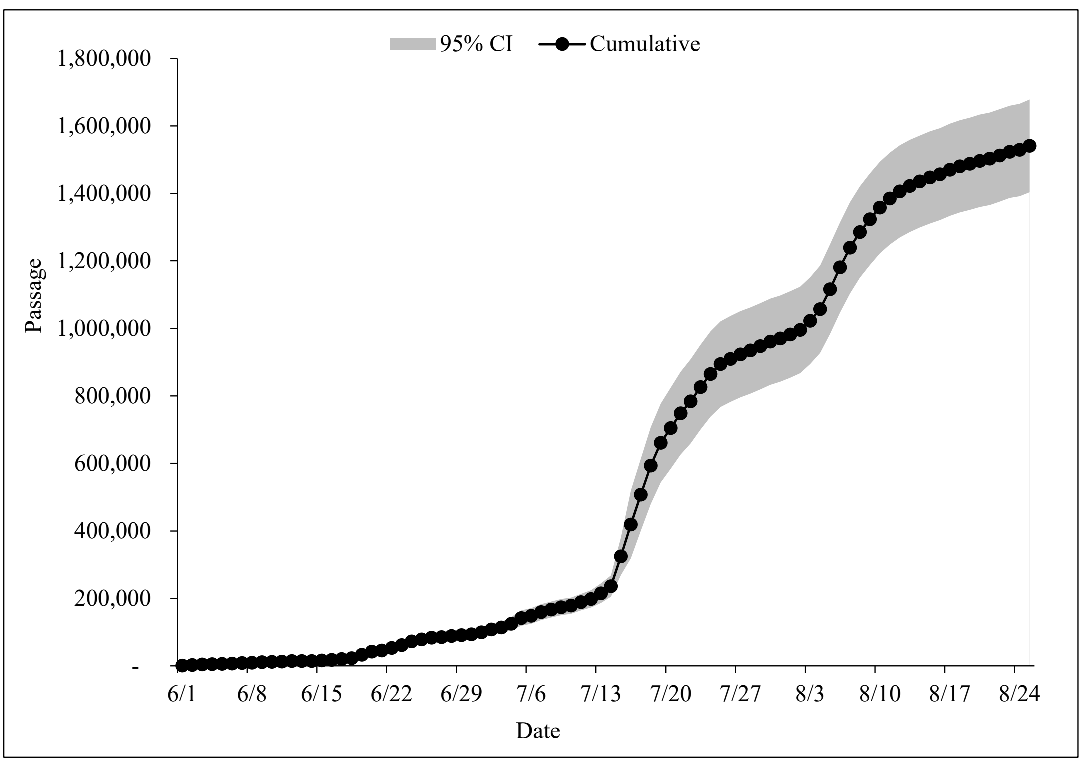


Figure 13.–Cumulative nonsalmon species passage, including 95% CI, at the Kuskokwim River sonar project, 2021.

APPENDIX A: NET SELECTIVITY PARAMETERS

Appendix A1.–Net selectivity parameters derived from Pilot Station (located on the Yukon River) and Kuskokwim River catch data used at Kuskokwim River sonar project, 2021.

Species	Tau	Sigma	Theta	Lambda	Tangle
Chinook salmon	1.9144	0.2464	0.7938	-1.1053	0.0000
Chum salmon	1.8990	0.2745	1.3899	-1.6150	0.0000
Sockeye salmon	1.9860	0.1598	0.4497	-0.6054	0.2016
Coho salmon	2.0570	0.4597	1.3017	-1.6960	0.0863
Pink salmon	1.9595	0.3537	2.5556	3.0157	0.1485
Broad whitefish	1.8037	0.2062	1.0548	-1.8365	0.1299
Humpback whitefish	1.9891	0.2188	1.8197	-2.9699	0.0000
Least cisco	2.1445	0.2875	1.4049	-2.5044	0.2451
Bering cisco	2.1445	0.2875	1.4049	-2.5044	0.2451
Sheefish	2.1730	0.2311	0.7922	-1.6967	0.0000
Other [a]	2.7002	0.5724	1.0164	-3.7235	0.0100

[a] *Other* refers to burbot, Dolly Varden, northern pike, and longnose sucker.

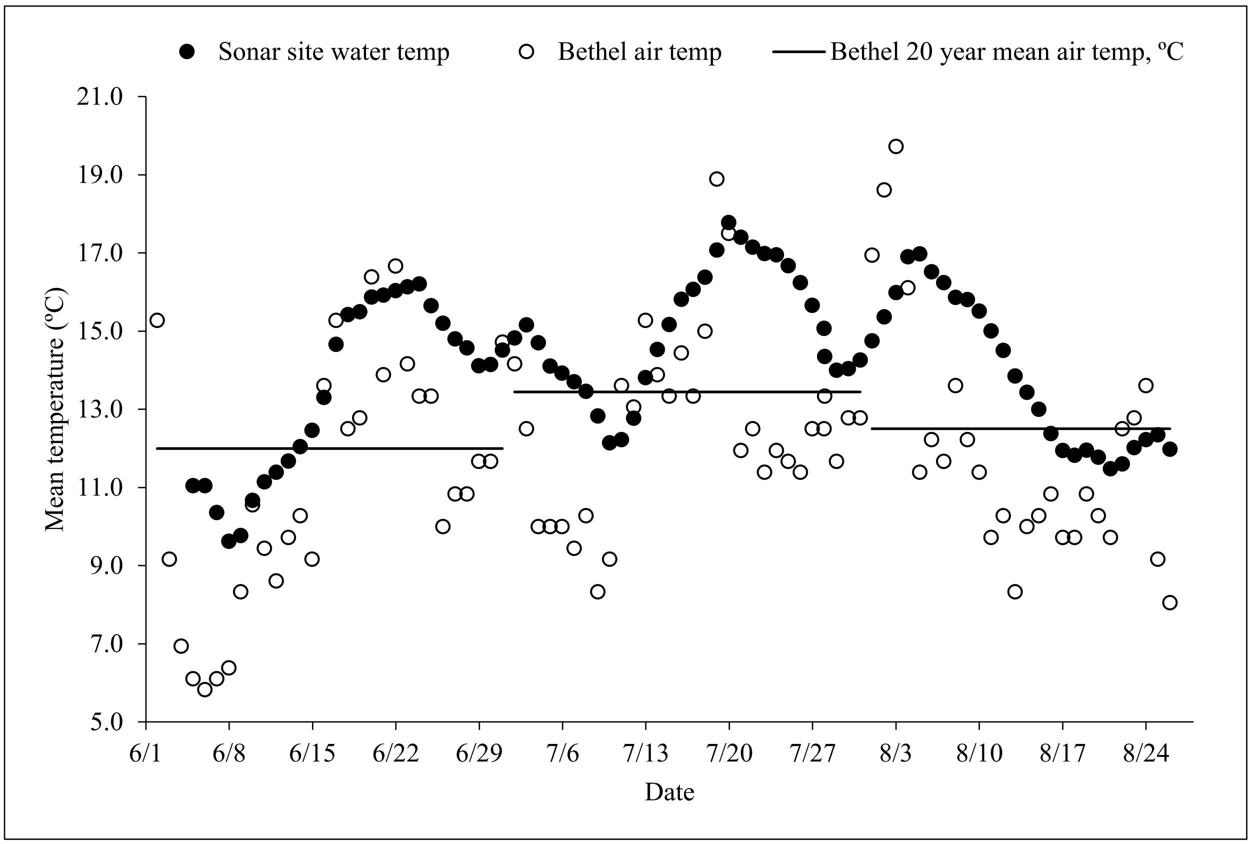
APPENDIX B: ENVIRONMENTAL CONDITIONS

Appendix B1.–Summary of historical mean water temperature data at the sonar site (°C).

	June	July	August	Season
2018	13.0	8.4	ND	10.8
2019	16.2	18.9	ND	17.5
2020	15.0	15.8	15.7	15.6
2021	13.5	15.0	13.9	14.2
Mean	14.4	14.5	14.8	14.5

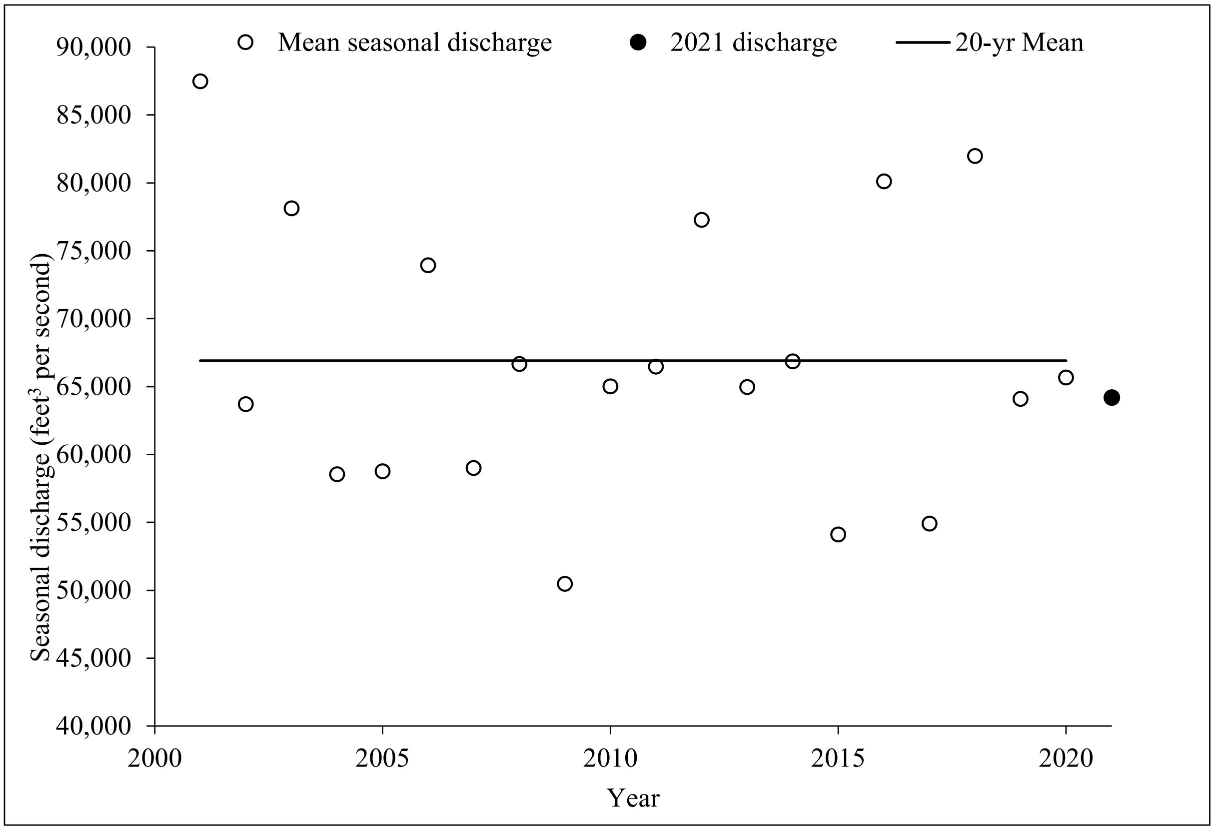
Note: ND means no data. Operations ended in July 2018 and 2019.

Appendix B2.–Daily mean water temperature collected automatically every 4 hours using a HOBOmeter.



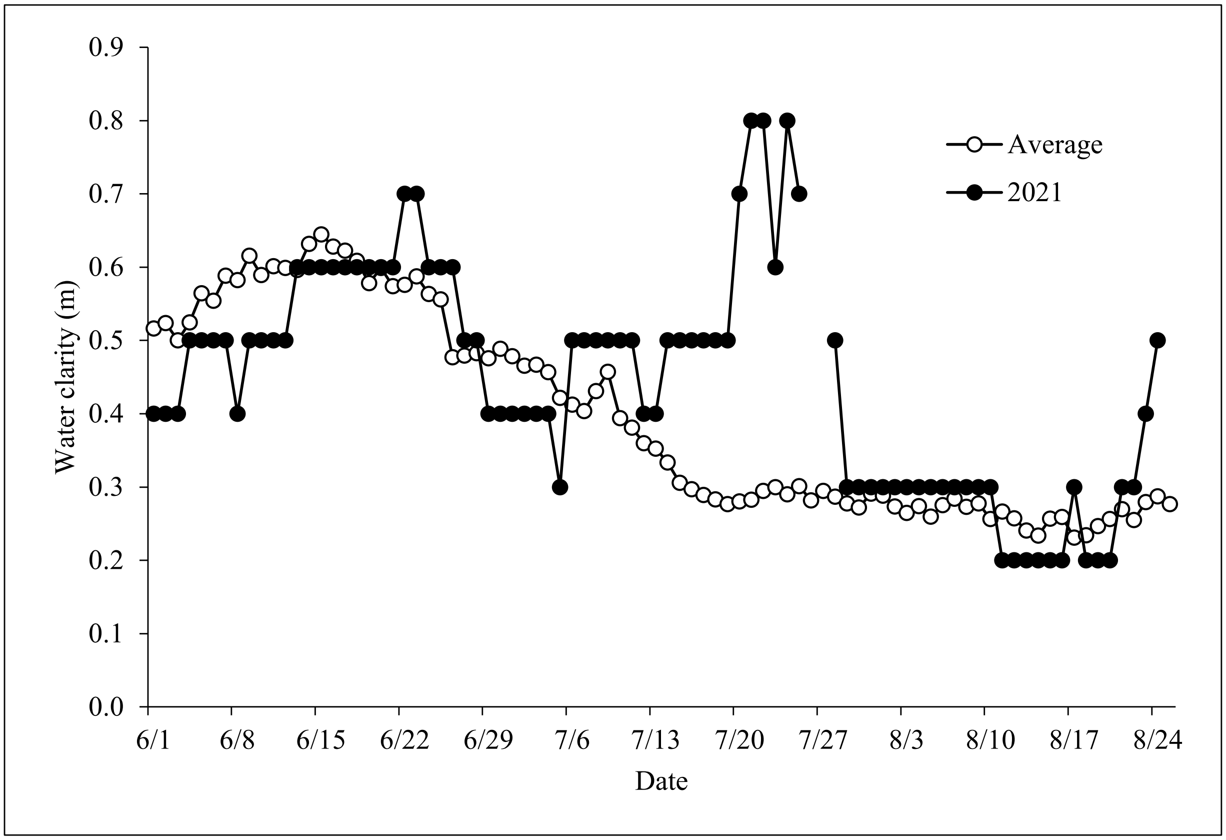
Note: The water temperature logger was attached to the right-bank transducer pod at a depth of approximately 1 m. Seasonal mean water temperature was 14.2ºC at the Kuskokwim River sonar site.

Appendix B3.–Graph displaying mean seasonal (June through August) discharge rates at the Crooked Creek water gauge as an approximation of Kuskokwim River water levels.



Note: Mean seasonal discharge in 2021 was near the previous 20-year mean (NOAA (National Oceanic and Atmospheric Administration). NOWData – NOAA Online Weather Data – Bethel Area. https://www.weather.gov/wrh/climate (Accessed: December 2, 2021).

Appendix B4.–Water clarity measurements collected using a Secchi disk to gauge water transparency (low clarity indicates high turbidity).



Note: Data was collected by the Bethel test fishery. Figure includes 2021 measurements and mean daily measurements from 1984 to 2020.

APPENDIX C: COMPARATIVE ANALYSES

Appendix C1.–Two-way 2x6 contingency table used in Pearson's chi-square test of independence comparing 8.0 m deep CPUE and 11.0 m deep nets CPUE by species with mesh sizes 4.0, 5.25, and 6.5 inch.

Net depth	Chinook	Sockeye	Chum	Coho	Cisco	Humpback whitefish
8.0 m	36	179	17	54	13	37
11.0 m	15	160	20	145	1	78

Note: Pink salmon and several whitefish species were omitted due to low catch of individual species (expected values less than 5).

Appendix C2.–Combined total chum salmon passage estimates at the Kogrukluk and George River weirs, regressed on cumulative chum salmon passage estimates at the sonar site, 2018–2021.