Regional Information Report 4K20-01

Kodiak Archipelago Sockeye Salmon Stocking: A Review of Program History and Methods

by

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and

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February 2020

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

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Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

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

Mathematics, statistics

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

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by

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ABSTRACT

This report serves to describe the historical and present scope of sockeye salmon stocking projects in the Kodiak archipelago and document the current methods used to provide stocking recommendations to Kodiak Regional Aquaculture Association (KRAA), who has undertaken enhancement and rehabilitation projects since the state's Fisheries Rehabilitation, Enhancement and Development Division merged with the Division of Commercial Fisheries in 1993. Of the 44 main lakes across the archipelago, presently Big Waterfall, Crescent, Hidden, Little Kitoi, Little Waterfall, Lower Jennifer, Ruth, Spiridon, and Upper Jennifer lakes are stocked with juvenile sockeye salmon by KRAA. Stocking recommendations are determined by modeling lake area, zooplankton biomass, and other limnological data relative to lake carrying capacity and available forage at the time of stocking.

Key words: sockeye salmon, stocking recommendations, enhancement, limnology, zooplankton

INTRODUCTION

Fisheries are vital to the people of Kodiak. They support local economies via commercial, sport, and subsistence opportunities that engage and sustain the community. Kodiak salmon fisheries have been monitored by either industry or government (with varying accuracy and precision) to identify trends in productivity since the 1820s, well before Alaska's statehood (Barnaby 1944; White 1986). These early observations led to rehabilitation projects and eventually expanded into enhancement, developing new runs in barren systems to increase harvest potential (Roys et al. 1973; Sheridan et al. 1961). Of the roughly 44 lakes across the archipelago, 19 (Figure 1) have been stocked with sockeye salmon since 1908. This report will present the history of the sockeye salmon stocking program in the Kodiak archipelago over 3 notable eras: stocking before statehood, following statehood, and after the inception of the Kodiak Regional Aquaculture Association (KRAA). This report will also focus on the current methodology for determining sockeye salmon stocking densities.

EARLY STOCKING HISTORY

Karluk sockeye salmon were first commercially harvested in 1882 (Gilbert and Rich 1927). Following the inaugural season, canneries blossomed on the Karluk Spit and continued to heavily exploit the watershed's abundance of salmon. With those nascent fisheries lacking any regulation or management, productivity noticeably declined by the late 1890s. Some canneries and the U. S. government recognized a need to repopulate those runs to sustain the fisheries (Gilbert and Rich 1927; NOAA 2018; Roys et al. 1973). While observing the decline, the federal government responded with the Fisheries Act in 1889 that required the establishment of hatcheries near fishing operations and for them to yield 4-fold the mature salmon harvested during a season (NOAA 2018). This created 1 of the earliest and largest rehabilitation programs in the Kodiak archipelago. Initially, several cannery companies with plants in Karluk united to build 1 hatchery in 1891; however, it closed the following year because of disputed fishing rights (Cobb 1921). Between 1896 and 1917, the Alaska Packers' Association founded and operated a salmon hatchery along the eastern end of Karluk Lagoon to bolster production. This hatchery released roughly 3 million fry into the lagoon in its first year and upwards of 45 million fry in its last year of operation (Gilbert and Rich 1927). Unfortunately, the Alaska Packers' Association hatchery utilized poor release strategies, causing high mortality and negligible returns (Hunt 1976; Schmidt et al. 1998).

Six years after the Fisheries Act, the U.S. Bureau of Fisheries was appropriated $50,000 from Congress to build and run new salmon hatcheries in Alaska with the intent to create a reserve for salmon (NOAA 2018).With hatcheries already operating in Karluk, Klawock, and near Ketchikan, 2 new sites were chosen: Yes Bay in Southeast Alaska and Afognak Lake (Figure 1), in the Kodiak archipelago. The Afognak Lake hatchery was constructed in 1907 (Cobb 1921; Jones 1915). During the course of its operation, production would reach over 50 million eggs incubated annually between 1917 and 1922. Fry from this facility were released back into Afognak Lake and also shipped to other facilities in Alaska and out of state. The hatchery closed in 1932 after repeated years of marginal returns, some caused by disease epidemics, storm damage to the hatchery, and ash deposition from the 1912 and 1913 Mount Katmai eruptions (Cobb 1921; Hunt 1976; Honnold and Schrof 2001; NOAA 2018). More so, the Fisheries Act could not be monitored and enforced to ensure achievement of hatchery production objectives; ultimately, following Franklin Roosevelt's presidential election, federal hatchery programs were considered wasteful spending and were closed (Hunt 1976). The Yes Bay hatchery was also closed at this time and the last remaining private hatchery at Boca de Quadra Bay near Ketchikan, Alaska, closed 2 years later (Hunt 1976).

With the 1889 Fisheries Act failing to improve salmon production, the White Act was passed by Congress in 1924: it designated half of salmon returns as escapement to reduce overexploitation (Gilbert and Rich 1927). The U.S. Fish and Wildlife Service, in its various incarnations from the 1920s to the 1940s, struggled with enforcing fishery regulations in Alaska, which exacerbated declines in salmon productivity. Subsequently, in 1949 the Alaska Fisheries Board and Alaska Department of Fisheries (ADF) were established when the Territorial Legislature passed House Bill 37 initially to assist the U.S. Fish and Wildlife Service manage Alaska fisheries, and—pending Alaska's statehood—to position the ADF to assume the conservation and regulation of those fisheries (ADF 1949). Inaugural ADF director C. L. Anderson was pivotal in emphasizing the importance and need for research to determine maximum sustainable yield (ADF 1950). In his vision to understand what caused declines in Alaska salmon runs, he tasked the department with studying the freshwater phases of salmon life histories, which stressed "increasing the available habitat for red and silver salmon" and the use of barren lakes and streams (ADF 1950; 1951).

Study sites were chosen in the Kodiak archipelago because of the abundance of barren lakes and streams (Tait 1962). Selection criteria for individual systems included having a critically depleted fishery and the potential for improvement (ADF 1951). In 1951, fishways were built between Pauls, Laura, and Gretchen lakes on Afognak Island (Figure 1) to bypass barrier falls blocking the upstream passage of returning adult sockeye salmon (ADF 1952). That same year, Gretchen Lake was stocked with sockeye salmon eggs from Southeast Creek that feeds Perenosa Lake (now called Portage Lake; Figure 2) and Karluk Lake, and Frazer Lake was stocked with Karluk eggs. Laura, Little Waterfall, and Little Kitoi lakes (Figure 1) were also surveyed for potential stocking. The following year, Gretchen and Frazer lakes were again stocked and construction began on a small research station and experimental hatchery at Kitoi Bay on Afognak Island (ADF 1953; Tait 1962).

The Kitoi Bay Research Station (KBRS; Figure 2) was fully operational by 1953. Kitoi Bay was selected as a camp site because of its close proximity to numerous barren lakes capable of supporting sockeye salmon production (ADF 1954). Of the objectives for the research station, 1 was to determine the number of fry or eggs to be planted in a given system that would enhance the optimum return of adults; up until this point, stocking densities were subjective, experimental, and often wasteful (ADF 1953). In pursuit of these goals, research staff commenced a comparative stocking study between Ruth (treated with rotenone and stocked) and Midarm (control) lakes, stocked Little Kitoi Lake in 1955 (Figure 1; ADF 1955, 1956, 1958), and began reconnaissance of

Hidden, Spiridon, Upper Jennifer and Lower Jennifer lakes (Figure 1) for rehabilitation in 1956 (ADF 1956).

By 1957, the Division of Commercial Fisheries was established and the department was renamed to its present moniker, which addressed the added management of game (ADF 1957). The KBRS continued to develop sockeye salmon runs in Frazer, Gretchen, Ruth, and Little Kitoi lakes with relatively successful returns to Little Kitoi and Ruth lakes (roughly 3,000 fish for each lake) in 1959 and growing returns to Frazer Lake, which were still manually carried over the barrier waterfall roughly half a mile downstream of the lake (ADF 1958, 1959). Upper and Lower Jennifer lakes were also added to the stocking program in 1959. Stocking levels of the Afognak barren lakes were generally proportional to lake volume (ADF 1957).

THE FRED DIVISION YEARS

After statehood in 1959, the newly minted Alaska Department of Fish and Game (ADF&G) continued to grow its research and management operations while maintaining stocking projects at Frazer Lake and at the KBRS through the 1960s. One monumental project was the 1962 installation of the Frazer fish pass to allow escaping sockeye salmon to bypass the barrier waterfall on their return to Frazer Lake (Eaton and Meehan 1966). During 1970 and 1971, substantial reorganization occurred within the department: research projects once managed by the Division of Commercial Fisheries were transferred to the new Fisheries Rehabilitation, Enhancement and Development (FRED) Division or the Hatchery Services Section (ADF&G 1971). The FRED Division monitored all stocking projects in the state, which were widespread in the 1970s (Roys 1977; Roys et al. 1973; Van Hulle and Murray 1975). Within the Westward Region, feasibility studies were conducted on the enhancement of Horse Marine Lake and establishment of a sockeye salmon run to Silver Salmon Lake (also known as Uyak Lake) at this time (Figure 2; Roys et al. 1973).

Stocking eggs and fry in the Frazer watershed was discontinued after 1971 (Burger et al. 2000); by 1972, the Frazer sockeye salmon run was considered established with returns of 66,000 adult fish that year (ADF&G 1972; Blackett 1984; Meehan et al. 1965), although improvements to the fish ladder would continue (ADF&G 1973). Over the course of establishing the run, Frazer Lake was seeded with donor stocks mainly collected from Karluk and Red lakes on Kodiak Island and, to a lesser extent, Ruth Lake in the Becharof watershed; these stocks encompassed life history traits of early and late run timing and shoal and tributary spawners (Burger et al. 2000).

Following the success at Frazer Lake, the FRED Division had outlined other projects in Kodiak including a 3-phase plan to rehabilitate Karluk and Akalura lakes (Figures 1 and 2) sockeye salmon stocks to historical levels in addition to fish ladder and preliminary habitat assessment projects. The KBRS also changed its name and shifted its focus to solely hatchery production of pink salmon broodstock—refining and developing incubation and rearing techniques to improve juvenile survival such that by 1975, Kitoi Bay Hatchery (KBH) had returns of over 18,000 pink salmon (ADF&G 1976). Also aiding in the rehabilitation of Alaska's salmon stocks, the 1976 Alaska State Legislature passed SB 688, which allowed the establishment of regional aquaculture associations to jointly develop comprehensive salmon plans with the department (ADF&G 1976)

With declines and fluctuating catches of sockeye salmon along the Pacific coast, the FRED Division began to research the effects of reduced carcass contributions upon the food webs of freshwater nursery lakes (ADF&G 1978). To help facilitate this, in 1979 a limnology laboratory was established in Soldotna; the lab was geared towards maximizing salmon production by using fertilization to replace nutrients lost to low escapement. The lab was also tasked with analyzing the quality and suitability of hatchery water for stocking projects and matching the water quality of incubation sites to that of donor stocks to improve egg survival (McMullen and Kissel 1979).

By 1980, KBH took more than 70 million pink salmon eggs with a return of almost 800,000 pink salmon that year. By 1981, midway through the Karluk sockeye salmon rehabilitation project that started in 1978, 4.2 million sockeye salmon were back stocked in the Thumb River tributary (Figure 2) from a streamside incubation facility. At the same time, over 100,000 chum salmon were stocked in the Sturgeon River (Figure 2) by KBH. Commensurate with increased hatchery production, FRED biologists were refining enhancement techniques from assessments of fish food to drafting methods manuals such as the "Lake Stocking Guidelines" (McMullen and Kissel 1981).

Within the division, however, there was acknowledgement that very little research had been conducted beyond counting escapement to identify carrying capacities for lake-rearing fishes (McCullen et al. 1983). FRED limnologists hypothesized that broad manipulations of lake ecosystems would provide the cause-and-effect data to identify a lake's ability to produce fish. Namely, increased stocking densities or fertilization could be used as tools to challenge or increase rearing capacity. Numerous studies were conducted in lakes across the state to gather data and test these theories (Koenings and Kyle 1982; Koenings et al. 1984; Lebida 1984). Eventually, Koenings and Kyle (1987) would publish a study that found correlations between adult sockeye salmon production, euphotic volume, and smolt biomass.

Locally, the Kodiak Fisheries Advisory Committee recognized the needs for a comprehensive salmon plan to guide the development of the area's salmon fisheries and a qualified aquaculture association (ADF&G 1984). With the help of legislative seed money and the FRED Division, the Kodiak Regional Aquaculture Association (KRAA) was formally certified by the commissioner of ADF&G in 1983 and Phase I of the Kodiak Regional Comprehensive Salmon Plan (KRCSP) was approved in 1984 (ADF&G 1984). One outcome of creating the KRCSP was that its public survey data indicated that all user groups preferred increasing sockeye salmon production by stocking of barren lakes. Subsequently, the KRCSP established a target of enhancing sockeye salmon harvest by 900,000 fish in 2002 (ADF&G 1984).

By 1987, KRAA and the FRED Division were conducting prestocking assessments of Akalura, Afognak, Hidden, and Crescent lakes in addition to the Pillar Creek Hatchery feasibility study. Spiridon Lake was also identified as a being a potential candidate for new sockeye salmon projects (Holland 1988). Alternatively, the rehabilitation of Karluk Lake sockeye salmon was considered successful, and the streamside incubation facility was deconstructed and removed by Department of Corrections' minimal security prisoners (Holland 1988).

During the 1980s, the FRED Division was under gubernatorial scrutiny as their project costs increased annually (Hansen 1986; Holland 1988) and declines in the price of oil reduced petroleum dividends to the state, tightening legislative funding (Hansen 1987). To maintain production, the private sector was assuming the operation of well-established hatcheries to help reduce the FRED Division's funding woes. KRAA agreed to operate KBH cooperatively with the FRED Division and provide 50% of the operational funding in 1988 by employing the cost-recovery harvest of salmon returning to the hatchery to generate revenue (Holland 1990). More notably, Kodiak commercial fishermen approved a 2% assessment to support salmon projects.

Despite the FRED Division's financial limitations, the Pillar Creek Hatchery was constructed in 1989 (Holland 1990), incubating roughly 5.1 million eggs in 1990. With Pillar Creek Hatchery operational, the stocking of barren Spiridon Lake would be possible in 1991 (Holland and McKean 1992; Kyle et al. 1990). Lake surveys were also conducted in Jennifer, Hidden, Summit, Red Fox, Crescent, Uyak, and Waterfall lakes (Figures 1 and 2) to determine optimal stocking densities of sockeye salmon fry (McKean 1991).

Ultimately, budget shortfalls forced the merger of the FRED Division with the Division of Commercial Fisheries in 1993. This subsequently ended the state-run enhancement of commercial production by 1995. To maintain important stocking programs, state-run hatcheries were transferred to private nonprofit hatchery associations. For Kodiak, this meant KRAA would assume all financial responsibilities for enhancement and rehabilitation projects; however, ADF&G would still provide guidance on those projects.

KRAA STOCKING

The long-term goal of KRAA has been to increase fishing opportunities for Kodiak Island purse seine and set gillnet fishermen and—to a lesser extent—rehabilitate depleted runs (Honnold and Clevenger 1995; Honnold and Joyce 1995). Since 1990, KRAA has stocked 13 lakes with over 111 million juvenile sockeye salmon on Kodiak and Afognak islands to realize this goal (Tables 1 and 2).

Of the KRAA stocked lakes, Afognak Lake was fertilized between 1990 and 2000 and Malina Lake was fertilized between 1991 and 2001 to rehabilitate depressed runs. Supplemental to fertilization, Afognak and Malina lakes were back stocked pending sufficient escapement of adult returns and fry survival (Table 1; McCullough and Clevenger 2002). Similarly, Laura Lake, which also experienced poor returns, was fertilized (1993–2000) but inadequate escapement precluded back stocking in some years. Big Waterfall, Crescent, Hidden, Lower Jennifer, Little Kitoi, Little Waterfall, Malina, Ruth, Sorg, and Upper Jennifer lakes were stocked to varying extents between 1990 and 1999 as supplements to the common property fishery (Table 1). Notably, Little Kitoi Lake has been consistently stocked to develop a brood source of sockeye salmon at the KBH; however, this has proved more challenging than anticipated due in part to low zooplankton abundance and a short water residence time negating the effects of fertilization (Schrof and Aro 2010).

Within the last 2 decades, Big Waterfall, Crescent, Hidden, Little Kitoi, Lower Jennifer, Ruth, Spiridon, and Upper Jennifer lakes have been assessed annually for stocking of juvenile sockeye salmon (Table 1). Of these lakes, Big Waterfall, Crescent, Hidden, and Little Waterfall lakes are stocked primarily with juvenile sockeye salmon from Afognak Lake broodstock, whose progeny have early run timing. Little Kitoi, Lower Jennifer, Ruth, Spiridon, and Upper Jennifer lakes have been stocked with fish that have late run timing; Olga lakes late-run sockeye salmon were initially used as broodstock until 1997, after which the Saltery Lake (Figure 2) stock was determined to have better late-run timing characteristics (Schrof and Aro 2010).

ADF&G has provided stocking recommendations each summer to KRAA prior to their egg takes to allow them to determine the number of fish needed for broodstock. These recommendations are lake specific and vary from year to year and are dependent upon ecological conditions in each lake.

METHODS

Stocking recommendations are developed relative to several environmental factors. This section will outline the order and general analyses used to determine the number of fry or smolt to be released into a lake. Overall, there are 3 steps to estimating a stocking recommendation. The first step is to predict the zooplankton biomass that the juvenile fish will utilize as forage after release. The second step is to estimate the number of juvenile fish that will fully utilize the lake-rearing capacity (i.e., smolt-rearing capacity). Finally, the third step is to adjust the juvenile fish estimate to account for the stocking density relative to a targeted size and the number of fish that remain in the lake from the prior year's stocking event that have not yet outmigrated from the system (holdover). Variance may be calculated for all estimates to provide a representation of the distribution of the data.

ZOOPLANKTON BIOMASS PREDICTION

Zooplankton are an important prey item for rearing juvenile sockeye salmon (Koenings and Kyle 1997; Kyle 1992). Zooplankton biomass data are incorporated into stocking recommendations to gauge the availability of forage needed to sustain a population of stocked fish. Zooplankton samples are usually collected annually from May to September from the targeted lakes following the methods outlined in Hopkins (2017). Samples are analyzed for abundance, species composition, biomass, and length. These samples estimate the current year's zooplankton biomass, which is used to predict the biomass estimate the following year at the time of stocking. The prediction for any particular system uses a time series of current and lagged biomass estimates to develop the simple linear regression equation which may be represented as

$$\widehat{ZB}_{t+1} = m \cdot \widehat{ZB}_t + b\,, \tag{1}$$

where $\widehat{ZB}_t$ is the estimated zooplankton biomass of year t, m is the slope of the relationship, and b is the intercept. The variance of $\widehat{ZB}_{t+1}$, $var\left(\widehat{ZB}_t\right)$ is the canonical variance for a simple linear regression, in this case at the point on the line that contains $\widehat{ZB}_t$.

SMOLT REARING CAPACITY ESTIMATION

Through a series of lake and fry density manipulations, Koenings and Burkett (1987) estimated a smolt threshold size of 2.0 g and 60 mm across a variety of Alaska sockeye salmon lakes. Their study showed that as stocking densities increased, mean smolt size decreased, and age structure also trended towards freshwater-age-1 fish when density dependence was a factor. They also found significant relationships between aerial primary productivity and euphotic zone depth (EZD; the depth at which 1% of the subsurface photosynthetically active light penetrates the water column). Following a hypothesis that a quantifiable relationship should exist between both variables, they subsequently determined that both total smolt biomass and total number of smolt were highly correlated with euphotic volume (EV; the depth to which primary production occurs in the area of lake that boundaries that depth).

Building on the relationship between EV and smolt production, Koenings and Kyle (1997) determined that smolt biomass becomes a function of zooplankton biomass when rearing conditions are taxed. That is, somatic growth will suffer after 1 rearing season when intraspecific competition is strong enough to limit food. Assuming that the rearing area is fully utilized and at capacity, Koenings and Kyle (1997) assessed 18 lakes for the relationship between seasonal mean zooplankton biomass and smolt biomass ($r^2 = 0.92$, $P < 0.001$). The relationship was calculated as

$$Y = 2.11X, \tag{2}$$

where Y is the smolt biomass in kg/km^2 and X is the seasonal mean zooplankton biomass in mg/m^2.

For stocking recommendations, we estimate the biomass of sockeye salmon smolt (kg/km^2) that the predicted zooplankton biomass $\widehat{ZB}_{t+1}$ (mg/m^2) can support (rearing capacity) for a given lake of surface area *SA* (km^2) and of a targeted release size *G* in grams. Using equation (2) we multiply the per m^2 zooplankton biomass by the surface area of the lake and divide by the smolt target size in kg. The result is the following equation:

$$S_G = \frac{SA \cdot 2.11 \cdot \widehat{ZB}_{t+1}}{G \cdot 1{,}000}. \qquad (3)$$

It should be noted that the conversions from mg to kg between zooplankton biomass and targeted smolt size and m^2 to km^2 between zooplankton biomass and lake area cancel out, as each is 1:1,000,000. The constant of 1,000 converts the targeted release size value from grams to kg. This yields a biomass of smolt that meets the rearing capacity of the lake (S_G) in kg/km^2. For estimating a range of release sizes, S_G is converted to an equivalent number of spring fry (*SF*) by dividing by an assumed fry-to-smolt survival rate of 20%. The variable *SF* also assumes fry weigh 0.2 g.

The variance of S_G is equal to

$$var(S_G) = \left(\frac{SA \cdot 2.11}{G \cdot 1{,}000}\right)^2 var\left(\widehat{ZB}_{t+1}\right). \qquad (4)$$

TARGET SIZE AND HOLDOVER ESTIMATION

To help minimize the risk of overstocking a system, it is important to account for the number of fish that have remained in the lake since the last stocking event. The percentage of holdover fish can be estimated from the percentage of fry or presmolt that survive the winter and the age-at-outmigration for smolt from a system. Based on historical data, it is assumed that when fry are stocked, 20% of those fry that survive to the spring will survive to the smolt stage and, similarly, 50% of presmolt fish will survive to the smolt stage. Of those fish that survive the winter after being stocked, it is then generally assumed that 10% of the fish will not leave the system. This relationship is expressed as

$$S_H = \left(SF_t \cdot SV_{SF_t} + PS_t \cdot SV_{PS_t}\right) \cdot P_H\ , \qquad (5)$$

where S_H is the number of smolt that hold over until the next year, SF_t is the number of spring fry stocked in the current year, SV_{SF_t} is the assumed survival rate of spring fry stocked = 0.2, PS_t is the number of presmolt stocked in the current year, SV_{PS_t} is the assumed survival rate of presmolt stocked = 0.5, and P_H is the proportion of fish that will not leave the system = 0.1.

It should be noted for some systems, that presmolt are not stocked. Additionally, for systems where smolt enumeration studies have been conducted, historical age composition and outmigration data may be used to tailor holdover estimates that better reflect population dynamics.

The variance for the individual variables on the right-hand side of equation 5 are

$var(SF_t) =$ the variance surrounding the estimated number of spring fry stocked in the current year as estimated by the stocking program,

$$var\left(SV_{SF_t}\right) \text{ is } (0.2)(0.8) = 0.16, \qquad (6)$$

$var(PSt) =$ the variance surrounding the estimated number of presmolt stocked in the current year as estimated by the stocking program,

$var(SV_{PS_t})$ is (0.5)(0.5) = 0.25, and (7)

$var(P_H)$ is (0.1)(0.9) = 0.09, (8)

given that all the terms on the righthand side of the equation above are independent, the variance of S_H can be found by using 3 iterations of Goodman's (1960) variance of products equation, which is

$$var(x \cdot y) = x^2 var(y) + y^2 var(x) - var(x) var(y). \quad (9)$$

We first find the $var(SF_t \cdot SV_{SF_t})$ and then the $var(PS_t \cdot SV_{PS_t})$, each using Goodman's equation, and after adding those independent terms together which represent the variance of the fish that survived to the smolt stage, $var(SV_{S_t})$, then $var(S_H) = var(SV_{S_t} \cdot P_H)$ is also found using Goodman's equation.

Once the holdover estimate S_H is calculated, it is subtracted from S_G to yield the number of 0.2 g spring fry to be stocked ($S_{0.2g}$).

$$S_{0.2g} = S_G - S_H, \quad (10)$$

where the variance is equal to

$$var(S_{0.2g}) = var(S_G) + var(S_H). \quad (11)$$

This value can then be converted into kilograms of fish to allow the estimation of a targeted release size such that

$$S_{kg} = \frac{0.2 \cdot S_{0.2g}}{1000}, \quad (12)$$

with a variance of

$$var(S_{kg}) = \left(\frac{0.2}{1000}\right)^2 var(S_{0.2g}), \quad (13)$$

and

$$S_{TS} = \frac{1000 \cdot S_{kg}}{w}, \quad (14)$$

where S_{kg} is the biomass of 0.2 g fry estimated for stocking and S_{TS} is the number of fish of target size w in grams, with a variance of

$$var(S_{TS}) = \left(\frac{1000}{w}\right)^2 var(S_{kg}). \quad (15)$$

DISCUSSION

Although the general objective behind stocking recommendations is to approach the carrying capacity of a system, many individualized strategies exist to achieve that. Johnson (1961) observed that when freshwater-age-0 sockeye salmon exceeded over 5,000 fish per ha in the Babine River, British Columbia, Canada, growth became increasingly depressed. Rainbow trout densities stocked into Matanuska-Susitna Valley, Alaska, landlocked lakes were determined by experiments that assessed survival over a range of densities (Havens et al. 1995). The number of salmonids stocked in the Great Lakes considers public demand, biological parameters, and cost-effectiveness (WDNR 1999). In another assessment of population dynamics, Luecke et al. (1996) utilized limnological sampling, *in-situ* rearing experiments, and bioenergetic-trophic transfer models to simulate lake management strategies for sockeye salmon. Thus, stocking rates can be tailored specifically to a given system and a given agency.

Comparisons of methodologies can also prove informative. For example, the Luecke et al. study compared their models to the EV (Koenings and Burkett 1987) and smolt biomass (Schmidt et al. 1994) regression models described in this report. Although the authors indicated that their smolt were 2 to 4 times larger than Alaska smolt, their results suggested that the EV and smolt biomass models may yield stocking densities that exceed rearing capacity. Similarly, Carpenter et al. (2010) stressed the inherent lack of control or predictability in food webs that is encountered empirically. Thus, these observations may suggest that EV and smolt biomass estimates should err on the conservative side.

Beyond the point estimate of the number of fish to stock, other considerations include when and where to stock fish. Some stocking events use release timing to minimize encounters with predators and competitors (Havens et al. 1995; Luecke et al. 1996; WDNR 1999), and others attempt to stock during peak zooplankton blooms when forage is abundant (Koenings and Burkett 1987). Releasing fish in barren or geographically isolated locations to avoid outbreeding depression or negative impacts upon wild stocks is also an important component of stocking programs for maintaining genetic fitness (WDNR 1999).

Regardless of the method, annual stocking events may be foregone due to management constraints or ecological conditions. For example, sockeye salmon brood stock systems of Kodiak maintain escapement goals to ensure the sustainability of the run as they also support commercial fisheries. In years when the lower bound of the goal will not be met, broodstock will not be collected in order to provide as much escapement as possible. Similarly, if the zooplankton biomass of a system is depressed (<100 mg/m^2) for multiple consecutive years, it may be recommended to not stock the system to allow the zooplankton population to recover to sustain stocking of future populations.

Specific to Kodiak sockeye salmon stocking, several other caveats also exist. Several of the lakes that are stocked have limited monthly zooplankton data: when systems lack complete time series of zooplankton data, other parameters such as phosphorous concentration or physical data may be substituted for ZB_t as indicated by exploratory data analysis and regression diagnostics. Additionally, the target size w in grams is in part determined by hatchery rearing capacity, as some facilities lack the raceway capacity to rear all sockeye salmon at healthy densities to presmolt size. Further, for shallow lakes that are stocked in the Kodiak archipelago, a recent study has shown that aquatic insects are a vital forage of rearing sockeye salmon; however, because of gape limitation, insects were more prevalent in stomachs of juvenile fish greater than 0.6 g, indicating a size threshold (Richardson et al. 2016). Thus, for shallow systems (average depth <10 m), it may be advantageous to target stocking 0.7 g juvenile sockeye salmon to allow them greater foraging opportunity on energy-dense insects.

Considerations should also be given to the assumptions applied to the model formulae. The value of 2.11 from Equation 3 is considered a constant because no estimates of variance are available from the literature describing the derivation of the value. For any sockeye salmon enhancement or rehabilitation project, monitoring and evaluation are vital for determining success and improving survivals; all lakes in Kodiak stocked with sockeye salmon are annually monitored for water quality during the ice-free season and these data are assumed to accurately represent lake conditions for supporting rearing sockeye salmon. However, survival rates of fry and presmolt are assumed to remain static from year to year; apart from Spiridon Lake, no outmigration data are available to gauge the survival to a given size. For most systems, the lack of stock-specific harvest data also confounds any measure of survival to adulthood—the ultimate determination of the effectiveness of lake stocking. Thus, there are many sources of variability inherent in generating stocking recommendations. However, it should be noted that the available smolt outmigration, limnological, and stocking data are assessed periodically to examine potential effects of stocking on lake health.

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TABLES AND FIGURES

Table 1.–Historical lake stocking levels of juvenile sockeye salmon by KRAA from 1990 to 2018.

	Lake stocked (number of juvenile sockeye salmon)											
Year stocked	Afognak[a]	Big Waterfall	Crescent	Hidden	Jennifers	Laura[a]	Little Kitoi	Little Waterfall	Malina[a]	Ruth	Sorg	Spiridon
1990							578,932					249,346
1991												3,480,000
1992	464,000	96,000	399,000	260,000				493,000	85,000			2,200,000
1993			202,000	554,600	180,000		52,418	205,000	318,000			4,245,000
1994	311,000		314,000	250,000	370,000	117,000	183,000	150,000	547,000			5,676,000
1995			90,200	98,650	200,000	16,000	477,652	197,800	53,500			4,599,000
1996	528,000		427,000	390,800		182,000	50,600	82,300	426,300	150,000	146,000	4,844,000
1997	328,300		432,000	455,200	458,000		125,800		390,400	147,000		6,700,000
1998	422,700		571,000	340,400			173,200		350,500	100,000		3,340,000
1999		42,000	371,700	310,000		172,000	205,400	273,000	406,000	66,500		3,564,000
2000		124,000	206,000	504,400			228,539	310,000		78,700		4,397,100
2001		224,300	331,500	315,500			282,089	224,600				1,700,600
2002		44,300	33,600	51,600			212,418	46,100				1,182,000
2003			36,500	31,000			299,468	72,500				1,417,500
2004			22,600	70,700			311,644	32,100		111,400		2,800,000
2005		49,100	54,000	188,300			359,562	78,700		35,000		1,380,000
2006		75,100	238,000	421,700	22,900		586,571	184,600	80,800	46,800		3,196,500
2007		100,000	309,000	500,300	342,300		536,444	249,500		72,600		1,810,100
2008		46,600	345,200	353,800			530,835	252,400				1,049,800
2009		59,500	202,900	254,600			518,249	162,400				1,475,160
2010		45,351	117,689	344,782								3,006,265
2011			136,639	200,998	159,997		113,313	45,011		154,204		2,000,000
2012			122,450	279,463			142,717					1,836,794
2013			187,365	274,886								2,101,690
2014			107,785	200,000	55,200					55,200		2,000,000
2015		54,660		178,271	95,000		69,000			45,000		1,857,479
2016				99,969			106,273			62,000		2,174,494
2017			132,200	214,900						65,100		2,118,200
2018		50,200	101,500	204,300	152,100		76,600	75,000		74,500		3,252,800

[a] Back stocked (juvenile fish released back into the same lake as their eggs were collected from).

Table 2.–Morphometric properties and historical limnological data for Kodiak stocked lakes.

Lake	Surface area (km^2)	Mean depth (m)	Fertilization	Water residence time (years)	Years of nutrient data	1 m TP[a]	10-yr avg. zooplankton biomass (mg/m^2)
Afognak	5.5	9.2	1990–2000	0.4	1987–2018	4.35	123
Big Waterfall	0.3	5.8	None	0.1	None	ND	185
Crescent	0.6	10.3	None	ND	None	ND	442
Hidden	1.9	10.8	None	2.8	1987–2018	2.72	360
Laura	4.2	12.0	1993–2000	1.2	1990–2003	7.65[b]	93[b,c]
Little Kitoi	0.4	11.1	2000–2001	0.4	1990–2003	7.11[b]	143[b]
Little Waterfall	1.0	6.8	1993–2001	0.5	1990–2003, 2010–2018	4.23	132[b]
Lower Jennifer	0.2	9.8	None	ND	None	ND	453
Lower Malina	0.7	6.9	1996–2001	ND	1989–2003	6.92[b]	63[b,d]
Ruth	0.2	7.1	None	ND	None	ND	469
Spiridon	9.2	34.7	None	7.1	1988–2018	2.13	673
Upper Jennifer	0.4	10.6	None	2.2	None	ND	260
Upper Malina	1.2	15.3	1991–2001	0.6	None	ND	122[b]

[a] TP = Total phosphorous.

[b] For data sets ending in 2003, the average is that of the whole data set.

[c] No samples collected in 2017.

[d] Only sampled in 2003.

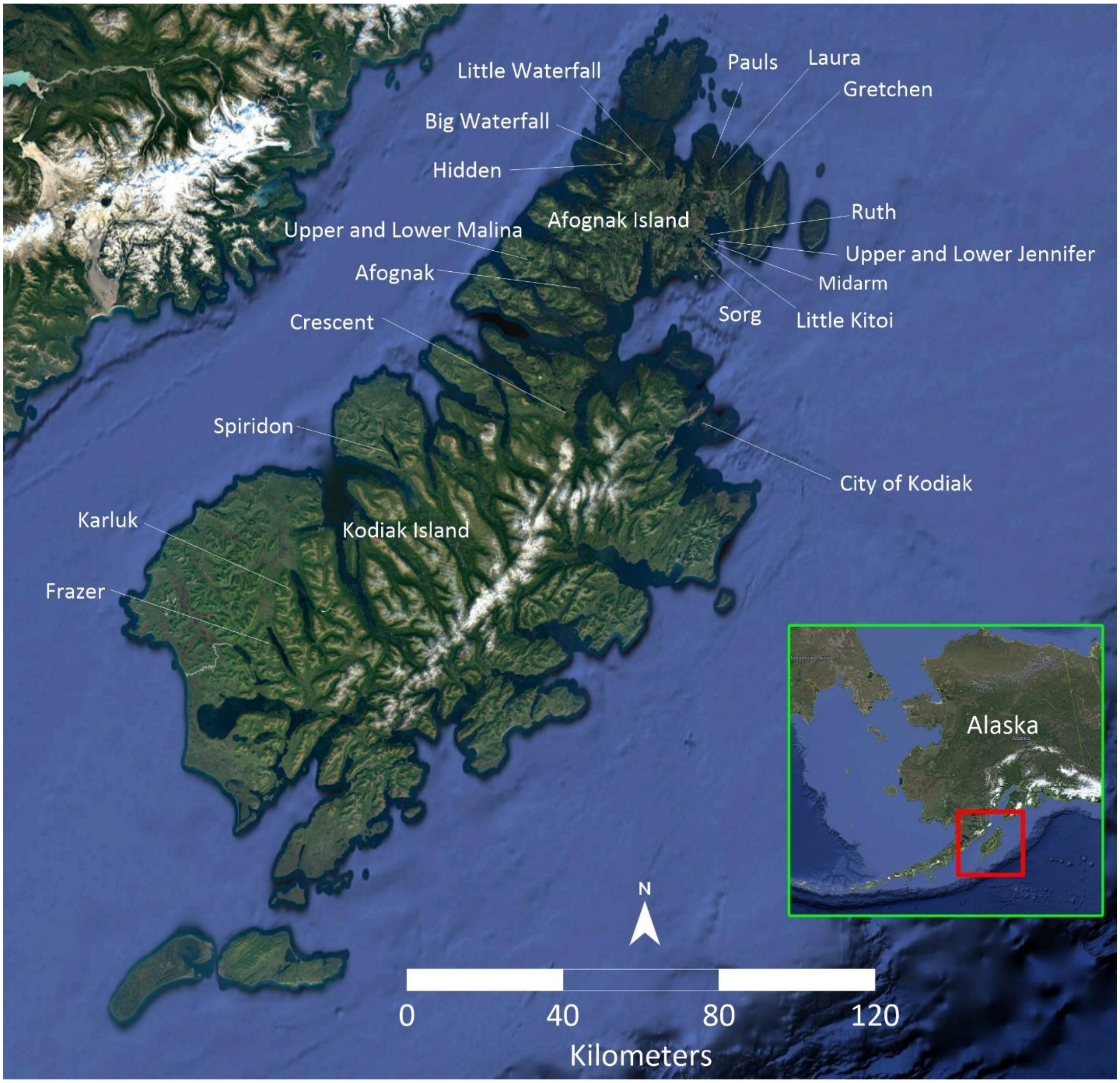

Figure 1.–Map showing the locations of historically stocked lakes on Kodiak and Afognak islands.

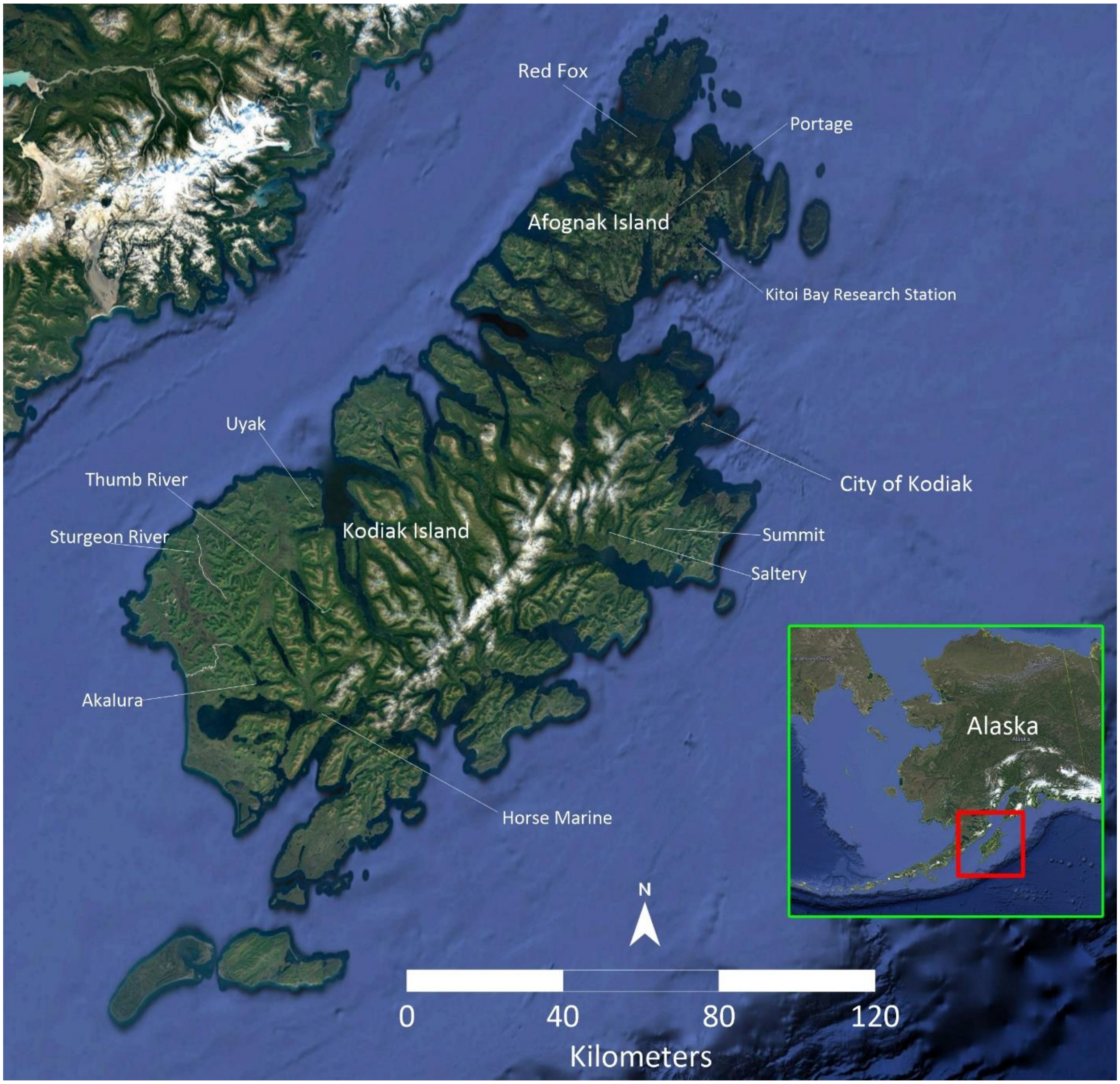

Figure 2.–Other locations assessed for, or vital to, historical stocking projects in the Kodiak archipelago.