Fishery Data Series No. 10-33

Stock Assessment and Restoration of the Afognak Lake Sockeye Salmon Run, 2009

by

Robert T. Baer

May 2010

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

Symbols and Abbreviations

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Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

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

Measures (fisheries)

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

Mathematics, statistics

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

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ABSTRACT

The Afognak Lake sockeye salmon *Oncorhynchus nerka* run severely declined in 2001 and has remained low since. Concerns expressed by local subsistence users to the Alaska Department of Fish and Game and the US Fish and Wildlife Service Office of Subsistence Management prompted an investigation of the lake's rearing environment in 2003 followed by subsequent annual studies. This report provides 2009 project results, a summary of results from 2007 and 2008, and an evaluation of limnology conditions and their effects upon smolt production. Using mark-recapture techniques, it was estimated that 492,998 sockeye salmon smolts (95% CI 417,689 – 568,306) emigrated from Afognak Lake in 2009. The population was estimated to be composed of 427,141 age-1., 64,560 age-2., and 1,296 age-3. smolts. Age-1. smolts had a mean weight of 3.5 g, a mean length of 76.7 mm, and a mean condition factor of 0.76. Age-2. smolts had a mean weight of 5.3 g, a mean length of 88.8 mm, and a mean condition factor of 0.75. Age-3. smolts had a mean weight of 6.6 g, a mean length of 94.0 mm, and a mean condition factor of 0.80. Lake limnology data was collected during five monthly sampling events from May to September in 2009. Compared to 2003-2008 limnology records notable 2009 results included an increase in chlorophyll-*a* concentrations, a continued trend of reduced total phosphorus concentrations, a historical low zooplankton density, and a positive association ($p<.005$, $R^2=.818$) between temperature and the condition of emigrating smolts. Further assessment of photosynthetically active radiation, nutrient availability, phytoplankton population, available forage species vs. actual forage species, and the bioenergetic responses of juvenile salmon will occur over the next four years (2010-2013). This additional information, coupled with annual smolt health and abundance estimates, will provide greater insight into Afognak Lake's freshwater environment and factors affecting smolt production.

Key words: Afognak Lake, Litnik, mark-recapture, age, emigration, escapement, Kodiak Island, *Oncorhynchus nerka*, smolt, sockeye salmon, subsistence harvest, trap, zooplankton.

INTRODUCTION

DESCRIPTION OF STUDY AREA

The Afognak Lake watershed is located on the southeast side of Afognak Island, approximately 50 km northwest of the city of Kodiak (Figure 1). Afognak Lake (58^{o} 07' N, 152^{o} 55' W) lies 21.0 m above sea level, is 8.8 km long, has a maximum width of 0.8 km, and has a surface area of 5.3 km^2 (Schrof et al. 2000; White et al. 1990). The lake has a mean depth of 8.6 m, a maximum depth of 23.0 m, and an estimated lake-water residence time of 0.4 years (Figure 2). Due to shallow depth Afognak Lake is easily influenced and mixed by wind and ice melt (Cole 1983). Runoff from Afognak Lake flows in an easterly direction into the 3.2 km long Afognak River, which in turn flows into Afognak Bay, which is part of the Alaska Maritime National Wildlife Refuge and where most subsistence fishing in the watershed occurs. The Afognak Native Corporation owns the land surrounding the Afognak Lake watershed down to tidewater.

In addition to sockeye salmon *Oncorhynchus nerka*, other fish species in the Afognak Lake drainage include pink salmon *O. gorbuscha*, coho salmon *O. kisutch*, rainbow trout (anadromous and potamodromous) *O. mykiss*, Dolly Varden *Salvelinus malma*, three spine stickleback *Gasterosteus aculeatus*, and coastrange sculpin *Cottus aleuticus* (White et al. 1990). Chinook *O. tshawytscha* and chum *O. keta* salmon have been observed in the Afognak River on occasion but have not established discernable spawning populations (White et. al 1990).

BACKGROUND

Harvest, Management, and Enhancement

Sockeye salmon from Afognak Lake are an important target species for salmon fisheries within the Kodiak region, and there is a long history of assessment projects on this population. A salmon counting weir was first established just below the lake outlet on the upper reaches of the

Afognak River in 1921 and was operated intermittently through 1977 (Roppel 1982). The Alaska Department of Fish and Game (ADF&G) has estimated escapement of sockeye salmon to Afognak Lake annually since 1978. In 1986, the weir was relocated to its current location 200 meters upstream of the mouth of Afognak River. Harvests have been estimated since the 1970's, using ADF&G commercial landing fish ticket system, statewide sport fish surveys, and return of subsistence fishing permits (Dinnocenzo and Caldentey 2008).

Residents of Port Lions, Ouzinkie, Afognak Village, and Kodiak have traditionally harvested salmon in Afognak Bay for subsistence uses (Figure 1). From 1981-2000, the Afognak Lake system, on average, supported the largest subsistence sockeye salmon fishery within the Kodiak Archipelago (Figure 3).

Prior to 2005, the Afognak Lake escapement goal was 40,000 to 60,000 sockeye salmon (Nelson and Lloyd 2001). Escapements in 1987 and 1988 did not reach the lower end of the range, and little commercial fishing effort was directed at this stock through the mid to late 1980s (White et al. 1990). In the mid 1980s, Kodiak Island residents, in response to a survey by the Kodiak Regional Planning Team, indicated that sockeye salmon was the preferred species for both commercial and subsistence fishers (KRPT 1987). These results, coupled with the declining sockeye salmon production from Afognak Lake, led to the Kodiak Regional Planning Team, and Kodiak Regional Aquaculture Association (Aquaculture Association) to list this system as the highest priority sockeye salmon enhancement project for Afognak Island. In 1987, ADF&G, in cooperation with the Aquaculture Association, initiated pre-fertilization fisheries and limnological investigations at Afognak Lake (Honnold and Schrof 2001; Schrof et al. 2000; White et al. 1990). These investigations indicated that sockeye salmon production was limited by juvenile rearing capacity (White et al. 1990). To enhance sockeye salmon rearing capacity in the lake and increase adult returns, ADF&G and the Aquaculture Association fertilized the lake during 1990-2000 to increase primary and secondary production and also stocked juveniles into the lake in 1992, 1994, 1996-1998. As part of the evaluation process, limnological data (phosphorus, nitrogen, chlorophyll-*a*, and zooplankton) were collected three years prior to, during, and three years after fertilization activities.

The Afognak Lake sockeye salmon stock was selected as a brood stock for barren lake stocking projects on Afognak Island, with the first fish stocked in Little Waterfall, Hidden, and Crescent Lakes in 1992 (Duesterloh and Byrne 2008). Hatchery survivals were higher than anticipated in 1992 and resulted in more fry being available than had been planned. Rather than increasing stocking levels into the barren lakes, which had not been stocked previously, the ADF&G allowed the Aquaculture Association to stock the excess fry back into Afognak Lake. Although the escapement in 1992 (and from 1989 to 1991) exceeded the sustainable escapement goal, stocking a fairly small number of juveniles (less than 500,000) was considered acceptable as long as the lake fertilization program continued and zooplankton (primary forage for juvenile sockeye) levels remained stable. Afognak Lake stocking was repeated in 1994 and from 1996 to 1998. Lake fertilization was continued to alleviate concerns of increasing predation by stocked fry on the zooplankton population. In 1999, ADF&G required the Aquaculture Association to follow established egg-take goals in order to avoid stocking excess fry into Afognak Lake (Honnold et al. 1999). The number of sockeye salmon eggs that could be taken from Afognak Lake by the Aquaculture Association was reduced, and fertilization of Afognak Lake was also discontinued after 2000 (Honnold and Schrof 2001).

The Alaska Board of Fisheries (Board of Fish) adopted two policies into regulation in the early 2000s to ensure that the state's salmon stocks would be conserved, managed, and developed using the sustained yield principle. The Board of Fish adopted the Policy for the Management of Sustainable Salmon Fisheries (5 AAC 39.222) in 2000, and the Policy for Statewide Salmon Escapement Goals (5 AAC 39.223) in 2001. The Policy for the Management of Sustainable Salmon Fisheries included definitions for biological escapement goals (BEGs)[1] and sustainable escapement goals (SEGs)[2], both of which were to have important implications for the following board cycle in 2004. Afognak Lake sockeye salmon runs substantially declined in 2001, and subsequent escapements from 2002 through 2004 were below the established SEG of 40,000 to 60,000 sockeye salmon (Baer et al. 2009; Caldentey 2009; Dinnocenzo and Caldentey 2008; Honnold et al. 2007). As a result of these poor runs, the commercial sockeye salmon fishery in Southeast Afognak Section (which includes all of Afognak Bay and surrounding waters; Figure 1) was closed in 2001, and commercial fishing remained closed through 2004. Sport fishing restrictions were also implemented in 2001, and in-season closures and reduced bag limits occurred each year through 2004. In conjunction with commercial and sport fishing closures, State and Federal managers closed subsistence fishing in early June during the 2002 season, and in-season closures occurred in 2003 and 2004 in an attempt to achieve escapement goals for sockeye salmon into Afognak Lake.

For the 2004 Board of Fish regulatory cycle, the ADF&G used the terms defined in the Policy for the Management of Sustainable Salmon Fisheries to revise the Afognak Lake sockeye salmon escapement goal from an SEG (40,000 to 60,000 salmon) to a BEG (20,000 to 50,000 salmon). The Board of Fish adopted the change and it was in effect for the 2005 season. The revised escapement goal was derived from Ricker spawner-recruit model of brood years 1982-1997 and limnology data that excluded data from 1990-2000 which were the years the lake was stocked and fertilized (Nelson et al. 2005).

The sockeye salmon commercial fishery in the Southeast Afognak Section briefly opened for five days in 2005, and 356 sockeye salmon were harvested. The fishery remained closed in both 2006 and 2007. The sport fishery remained open throughout the 2005 and 2006 seasons without any restrictions, but was closed in 2007. The subsistence fishery remained open throughout the 2005 season, although few sockeye salmon were harvested, and closures occurred during July of both 2006 and 2007. Although Afognak subsistence fishing closures restricted harvest of sockeye salmon and caused fishing efforts to shift to other systems, the Afognak subsistence fishery was reopened on August 1 every year to provide harvest opportunities for pink and coho salmon.

In the fall of 2007, the Afognak Lake sockeye salmon BEG was reevaluated with three additional years of data, and a BEG of 20,000 to 50,000 sockeye salmon was maintained (Honnold et al. 2007). The commercial fishery has remained closed since 2005, whereas sport and subsistence

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[1] "*Biological escapement goal* (BEG): the escapement that provides the greatest potential for maximum sustained yield (MSY)"

[2] "*Sustainable escapement goal* (SEG): a level of escapement, indicated by an index or an escapement estimate, that is known to provide for sustained yield over a 5 to 10 year period, used in situations where a BEG cannot be estimated due to the absence of a stock-specific catch estimate"

fisheries have remained open since 2007. Subsistence harvests in Afognak Bay from 1981 through 2008 have ranged from 451 (2006) to 12,412 (1997) sockeye salmon (Table 1). The smallest sockeye salmon subsistence harvests on record are from the most recent seven years of available data (2002-2008).

Escapements during the last nine years have been just below (2002 and 2004) and just above the lower bound (2001, 2003, 2005-2009) of the current BEG, with the largest escapement occurring in 2009 when 31,358 sockeye salmon were counted past the weir (Table 1). Although the lower bound has been met in most years, escapements have not been distributed throughout the range; this lack of distribution throughout the range is inconsistent with the Policy for Sustainable Salmon Management which instructs ADF&G "to maintain evenly distributed salmon escapements within the bounds of the BEG."

Juvenile Production and Limnological Investigations

Juvenile production studies have been conducted in conjunction with limnological investigations at a number of sockeye salmon systems in the Kodiak Archipelago (Barrett et al. 1993a, 1993b; Coggins 1997; Coggins and Sagalkin 1999; Edmundson et al. 1994a, 1994b; Honnold 1997; Honnold and Edmundson 1993; Kyle et al. 1988, 1990; Kyle and Honnold 1991; Sagalkin 1999; Sagalkin and Honnold 2003; Schrof et al. 2000; Swanton et al. 1996; White et al. 1990). Some of these studies estimated smolt abundance and body size by age based on results of trapping and mark-recapture programs. Several studies counted emigrating smolts using a weir and trap. In addition, some studies used a combination of hydroacoustics and trawl surveys in lakes to enumerate rearing juveniles. Smolt abundance and body size studies provide estimates of overall freshwater survival, covering the time between egg deposition in the gravel and smolt emigration to the ocean.

Historically, there is little information available on Afognak Lake juvenile sockeye salmon during their freshwater life history stage, when sockeye salmon mortality rates are usually greatest (Burgner 1991). Prior to 2003, ADF&G efforts to collect juvenile sockeye salmon data from Afognak Lake met with limited success (Schrof and Honnold 2003). Estimates of lake rearing juvenile abundance using hydroacoustics proved inaccurate due to the presence of large numbers of threespine stickleback *Gasterosteus aculeatus*, and hydroacoustic surveys were discontinued after 1995. A mark-recapture project for smolts was conducted in 1990 and 1991, but reliable abundance estimates were not obtained due to low trap efficiencies. In 1992, funding for the mark-recapture project was discontinued, and only the collection of smolt age, weight, and length (AWL) data was continued. After 1995, further funding reductions resulted in smolt AWL data collection being limited to one annual sample. It was not until 2003 that a smolt and lake study was reinitiated (Honnold and Schrof 2004).

After Afognak Lake experienced poor runs and fisheries closures in 2002, local subsistence users, represented by the Kodiak-Aleutians Regional Advisory Council, Kodiak Fish and Game Advisory Committee, and Kodiak Tribal Council, contended that continued closure of the Afognak system had made it more difficult for local residents to harvest sockeye salmon, was shifting fishing effort to small nearby sockeye salmon runs and the Buskin River, and constituted an emergency situation. In response to this problem, ADF&G received funding through the Office of Subsistence Management's Fishery Resources Monitoring Program to determine the feasibility of estimating sockeye salmon smolt production in Afognak Lake. This initial feasibility study, conducted in 2003, showed that sockeye salmon smolts could be effectively trapped in Afognak River and their abundance reliably estimated using mark-recapture techniques (Honnold and Schrof 2004).

In addition to smolt abundance and body size data, additional information on rearing conditions within Afognak Lake was needed to determine the freshwater factors affecting sockeye salmon production. A lake's physical parameters (solar illumination, temperature, and dissolved oxygen) greatly affect nutrient cycling (Schlesinger 1991). Lake nutrients, specifically phosphorous and nitrogen, are prerequisites for photosynthesis, and their concentrations can be used to assess the potential for primary production within a system (Spalinger and Bouwens 2003). Chlorophyll-*a* levels are indicators of the standing crop of primary producers that provide food for zooplankton, which are prey for sockeye salmon. Estimating zooplankton community attributes is crucial to understanding the lacustrine food chain because zooplankton abundance, individual size, and species composition can be regulated either from bottom up pressures, such as phytoplankton availability (Stockner and MacIsaac 1996), or through top down predation pressures, such as grazing by juvenile sockeye salmon (Kyle 1992).

Based on findings from the 2003 feasibility study, the Office of Subsistence Management provided funding for a three-year study (2004-2006) that enabled the continuation of smolt assessment work, examination of rearing and spawning capacity, and estimation of sockeye salmon production potential of Afognak Lake. Sockeye salmon freshwater production is limited by the amount and quality of available spawning habitat as well as by juvenile rearing capacity (Honnold and Edmundson 1993; Willette et al. 1995). In 2005, spawning habitat surveys of Afognak Lake resulted in a total tributary capacity estimate of 15,297 spawners (Baer et al. 2007). The lake shoal spawning capacity was more difficult to assess. Prior studies reported peak shoal spawner counts ranging from 35,811 to 70,853 (White et. al. 1990; from the unpublished 1984 Migratory Timing of the primary Spawning populations of red salmon at Afognak Lake by Mark T. Willette, available at ADF&G Kodiak). The final report for the 2004-2006 study consolidated historical fishery and limnological data, provided results of a sockeye salmon escapement goal review and production analysis conducted from 2004 to 2006, and documented the final results of the project (Baer, Schrof, and Honnold 2007). Results indicated that rearing conditions within Afognak Lake appeared to be stable or improving, and zooplankton abundance did not suggest overgrazing. In addition, the relatively high body condition factor of smolts (>0.75) and the high percentage of age.1 emigrants (86%) indicated favorable rearing conditions.

Continued analysis of Afognak Lake and annual smolt emigration studies were deemed of high importance for evaluating changes in nutrient food web dynamics (for example, to determine whether the structure of consumer communities has modified nutrient transfer along the food web) and assessing how changes may have affected the growth and production of emigrating juvenile sockeye salmon. Recognizing the importance of continued analysis on Afognak Lake sockeye salmon production, the Office of Subsistence Management extended funding to ADF&G for an additional three-years (2007-2009). This report provides results of the third and final year (2009) of that project, consolidates historical fishery and limnological data, and assesses juvenile rearing conditions in the Afognak Lake system.

PROJECT OBJECTIVES

1. Estimate the number, age, and average body size at age of sockeye salmon smolts emigrating from Afognak Lake from 2007 through 2009 as follows:
   - Estimate the number with 25% relative error and 95% confidence,

- Estimate age proportions with 3% absolute error and 95% confidence, and
- Estimate mean body length within 0.5 mm and mean body weight within 0.25 g of the true mean with 95% confidence.

2. Evaluate the water chemistry, nutrient status, and plankton production of Afognak Lake from 2007 to 2009.
3. Assess the rearing conditions for juvenile sockeye salmon in Afognak Lake based upon completion of objectives 1 and 2.

METHODS

SMOLT ASSESSMENT

Trap Deployment and Assembly

An inclined-plane Canadian fan trap (Ginetz 1977; Todd 1994) was installed on 10 May 2009 approximately 32 m upstream from the adult salmon weir site (Figure 4). The trap was positioned towards the middle of the river, where water velocity was great enough to make it difficult for smolts to avoid capture. A live box (1.2 m x 1.2 m x 0.5 m) was attached to the cod end of the trap, and the entire trapping device was connected to cables attached to hand powered cable winches ("come-alongs") fixed to each stream bank. The trap was secured to an aluminum pipe frame, which allowed the vertical trap position to be adjusted in response to water level fluctuations. Perforated (3.2 mm) aluminum sheeting (1.2 m x 2.4 m) supported by a Rackmaster®[3] pipe frame was placed at the entrance of the trap in a "V" configuration to divert smolts into the mouth of the inclined plane trap. Trapping was discontinued and the trap was removed from the river on 3 July after the number of captured smolts dropped to less than 100 per day for three consecutive days. Detailed methods of trap installation, operation, and maintenance are described in Baer (2009).

Smolt Capture and Handling

Smolts were captured in the trapping system and held in the attached live box until they were counted. During the night (2200 to 0800 hours), the live box was checked every one to two hours, depending on smolt abundance. During the day (0801 to 2159 hours), the live box was checked every three to four hours. All smolts were removed from the live box with a dip net, counted, and either released downstream of the trap or transferred to an in-stream holding box for sampling and marking. Species identification was made by visual examination of external characteristics (Pollard et al. 1997). All data, including mortality counts, were entered on a reporting form each time the trap was checked.

Trap Efficiency and Mark-Recapture Abundance Estimation

Total smolt abundance was estimated using a mark-recapture procedures to first estimate trap efficiency. Trap efficiency was then used to estimate the total number of smolts migrating from the watershed.

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

Releases of sockeye salmon smolts marked with Bismarck Brown Y dye were made about once per week, as well as when changes were made to the trapping system. Based on smolt studies at Akalura Lake (Coggins and Sagalkin 1999; Sagalkin and Honnold 2003), an effort was made to achieve trap efficiencies between 15% and 20%. To estimate total smolt abundance each week so that there was only a 5% probability of exceeding a relative error (r) of 25%, would require that 330 (20% trap efficiency) to 440 (15% trap efficiency) smolts had to be marked and released for each experiment (Carlson et al. 1998; Robson and Regier 1964). Therefore, we attempted to mark and release about 500 smolts each week to help ensure that sufficient numbers would be available for recapture even if delayed mortality from handling and marking reached 33%.

Once collected, smolts to be marked were placed in an aerated 33-gallon trashcan filled with water and transported in a trailer pulled by an all-terrain vehicle to the release site approximately 1,240 m upstream. At the release site, smolts were exposed to a continuously oxygenated solution of Bismarck Brown Y dye (1.9 g of dye to 15 gallons of water) for 30 minutes. Dyed smolts that displayed unusual behavior (labored respiration, flared gills, side swimming, etc.) were removed from the experiment and released downstream of the trap. Dyed smolts were then transferred to a holding box at the release site. Between 2100 and 2300 hours, about 500 of the dyed smolts were randomly selected from the holding box, counted, and released across the width of the stream. The remaining dyed smolts (about 100) were counted and left in the holding box for five days to estimate delayed mortality resulting from the capture and marking process. The proportion of smolts that died during the five day holding period was used to estimate the actual number of marked smolts available for recapture in the experiment (M_h).

All dyed smolts recaptured at the trap site were counted and assigned to the recapture period, hereafter referred to as a “stratum”, corresponding to the time period starting the day of their release until the day before the next release and mark-recapture event.

Trap efficiency E_h for stratum h was calculated as

$$E_h = \frac{m_h + 1}{M_h + 1}, \qquad (1)$$

where

m_h = number of marked smolts recaptured in stratum h

A modification of the stratified Petersen estimator (Carlson et al. 1998) was used to estimate the number of unmarked smolts U_h emigrating within each stratum h as

$$\hat{U}_h = \frac{u_h (M_h + 1)}{m_h + 1}, \qquad (2)$$

where

u_h = number of unmarked smolts recaptured in stratum h.

Variance of the smolt abundance estimate was estimated as

$$\hat{\mathrm{var}}\left(\hat{U}_h\right) = \frac{(M_h + 1)(u_h + m_h + 1)(M_h - m_h)u_h}{(m_h + 1)^2 (m_h + 2)}. \qquad (3)$$

Total abundance of *U* of unmarked smolts over all strata was estimated by

$$\hat{U} = \sum_{h=1}^{L} \hat{U}_h , \tag{4}$$

where *L* is the number of strata. Variance for $\hat{U}$ was estimated by

$$\hat{\mathrm{var}}\left(\hat{U}\right) = \sum_{h=1}^{L} v\left(\hat{U}_h\right), \tag{5}$$

and 95% confidence intervals were estimated using

$$\hat{U} \pm 1.96\sqrt{v\left(\hat{U}\right)} , \tag{6}$$

which assumes that $\hat{U}$ is approximately normally distributed.

Within each stratum *h*, the total population size by age class *j* was estimated as,

$$\hat{U}_{jh} = \hat{U}_h \hat{\theta}_{jh} , \tag{7}$$

where $\hat{\theta}_{jh}$ is the observed proportion of age class *j* in stratum *h*. Variance of $\hat{\theta}_{jh}$ was estimated using the standard variance estimate of a population proportion (Thompson 1987). The variance of $\hat{U}_{jh}$ was then estimated by

$$\hat{\mathrm{var}}\left(\hat{U}_{jh}\right) = \hat{U}_h^{\,2} v\left(\hat{\theta}_{jh}\right) + \hat{U}_h v\left(\hat{\theta}_{jh}\right)^2 . \tag{8}$$

The total number of emigrating smolts within each age class was estimated by summing the individual strata estimates, and its variance was likewise estimated by summation over the individual strata estimates.

Inanimate objects were used to test for evidence of passive trap avoidance by juvenile salmon. A minimum of 50 buoyant (pieces of apple), negatively buoyant (olives), and neutrally buoyant (pecans) objects were released evenly across the river approximately 50 meters upstream of the trap. Six recapture trials with inanimate objects were conducted during the first two weeks of the 2009 season. The proportion of captured objects was used to generate a capture efficiency rate for objects that had no ability to either actively avoid or swim into the trap, across a range of object buoyancies.

Age, Weight, and Length Sampling

To ensure proportional abundance sampling, approximately 2% of the daily sockeye salmon smolt catch was sampled to obtain AWL data. For every 100 sockeye salmon smolts counted out of the trap the field crew retained two for AWL sampling the following morning. Smolts were collected throughout the night and held in the in-stream live box. The following day, all smolts from the live box were anesthetized using tricaine methanesulfonate prior to being sampled. After being sampled, all smolts were held in aerated buckets of water until they recovered from the anesthetic, and subsequently released downstream from the trap.

Fork lengths were recorded to the nearest 1 mm and weights to the nearest 0.1 g. Scales were removed from the preferred area (INPFC 1963) and mounted on a microscope slide for age determination. Age was estimated from scales viewed with a microfiche reader at 60X magnification and recorded in European notation (Koo 1962) following the criteria established by Mosher (1968). In addition, the overall health or condition factor of each sampled smolt was assessed by calculating its body condition factor *K* (Bagenal and Tesch 1978) as

$$K = \frac{W}{L^3}10^5 \quad (6)$$

Life History-Based Abundance Estimation

In addition to mark-recapture estimates of actual abundance, the predicted number of smolts expected to emigrate in 2009 was estimated based on a life history model. The history-based estimates, utilized the sex composition data from parental spawning escapements in 2006 (55% females) and 2007 (51% females), average egg deposition based on the average fecundity assessment of females used in egg-takes by Pillar Creek Hatchery crews in 2006 (2,077 per female) and 2007 (2,359 eggs per female), a 7% egg-to-fry survival (Drucker 1970, Bradford 1995 and Koenings and Kyle 1997) and a 21% fry-to-smolt survival (Koenings and Kyle 1997) from rates reported from other clear water system, and a smolt age composition of 79% age 1. and 21% age 2. based on the average age composition of the 2003-2008 smolt emigration.

LIMNOLOGICAL ASSESSMENT

Lake Sampling Protocol

Five limnological surveys of Afognak Lake were conducted at approximately 4-5 week intervals from May to September, 2009. Collected data and water samples were returned to the ADF&G Near Island Laboratory (Kodiak, AK) and analyzed as described in Thomsen (2008). Two stations, marked with anchored mooring buoys and located with Global Positioning System (GPS) equipment, were sampled from a float plane during each survey (Figure 2). Zooplankton samples were collected at both stations, but water samples were only collected at Station 1.

Temperature, Dissolved Oxygen, Light, Water Clarity and Euphotic Volume

Water temperature (°C) and dissolved oxygen (mg L^{-1}) levels were measured with a YSI® meter. Surface temperature readings were calibrated against a hand-held mercury thermometer. Temperature and dissolved oxygen readings were recorded at half-meter intervals to a depth of 5 m and then at one-meter depth intervals to the lake bottom. Results were categorized into spring (May-June), summer (July-August), and fall (September-October) sampling periods.

Water transparency was measured at each station using a Secchi disc as described in Thomsen (2008). Measurements of photosynthetically active radiation (PAR) were taken with a Protomatic® submersible photometer sensitive to the visible spectrum range (400-700 nanometers). Readings were taken above the water surface, at the water surface, and at half-meter intervals below the water surface until reaching a depth of 5 m and then at one-meter intervals to the lake bottom or to a depth at which the reading was (no more than) 1% of the subsurface reading. Measurements were adjusted by linear regression to the Beer-Lambert equation to estimate an integrated vertical extinction coefficient (K_d m^{-1})for PAR within the euphotic zone, the layer of water from the surface down to 1% of subsurface PAR as

$$K_d \ m^{-1} = (1/z) \ln (I_z / I_o) ,$$

where

I_o = light intensity just below the water surface, and

I_z = light intensity at water depth *z* in meters.

Since an integrated vertical extinction coefficient was used, $K_{d\ w}$ was treated as being constant with depth, and mean euphotic zone depth was then given by 4.6/K_d (Kirk 1994). Lake primary production potential for rearing juvenile sockeye salmon was assessed through a euphotic volume calculation as the product of the average euphotic zone depth for the five monthly sampling periods and lake surface area (Koenings and Burkett 1987; Nelson et al. 2005).

Since only limited water temperature data was able to be collected from Afognak Lake additional water temperature data for Big Kitoi Lake (18.3 mi bearing 71 degrees northeast of Afognak Lake) was also collected from Kitoi Bay Hatchery. We used Big Kitoi Lake data as a surrogate for Afognak Lake water temperatures to simulate water temperatures sockeye salmon would have experienced in Afognak Lake from the time they emerged from eggs as sac fry until they emigrated from the lake as smolts. Mean water temperatures about 3 meters below the surface of Big Kitoi Lake were calculated for each 14 month sac fry-to-smolt period (April-May) for Afognak Lake age-1. smolt emigration years 2003-2009. The potential effects of thermal conditions on sockeye salmon juvenile rearing and smolt emigration were explored by looking at correlations between water temperature and various sockeye salmon life history parameters, including condition factor of age-1. smolts.

General Water Chemistry, Phytoplankton and Nutrients

During each survey, water samples were collected at a depth of 1 m below the water's surface using a 4.0 L Van Dorn sampler. Each water sample was emptied into a pre-cleaned polyethylene carboy, which was kept cool and dark, until refrigerated at the Kodiak Island laboratory for no more than 3 days before processing or freezing. Lake water from the carboy was transferred into a 500 ml bottled, refrigerated, and analyzed for alkalinity and pH. A 250 ml bottled was filled with from the carboy, frozen, and later analyzed for total Kjeldahl nitrogen (TKN) and total phosphorus (TP). A total of 2.0 L of water was filtered using the following two different methods. One 1.0 L of water was filtered through a rinsed 4.25 cm diameter Whatman GF/F cellulose fiber filter under 15 psi vacuum pressure for filtrate collection. The filtrate was then analyzed for total filterable phosphorus (TFP), filterable reactive phosphorus (FRP), nitrate + nitrite (NO_3^- + NO_2^-), and ammonia (NH_4^+). The second 1.0 L of lake water was filtered through another Whatman fiber filter pad with the addition of approximately 5 ml of magnesium carbonate ($MgCO_3$) added to the final 50 ml of water near the end of the filtration process to act as a preservative. The filtrate was discarded and the fiber filter was retained and frozen on a petri dish for chlorophyll-*a* (chl-*a*) and phaeophytin (pheo-*a*) analysis.

TP, TFP and FRP were analyzed using a Spectronic Genesys 5 (SG5) spectrophotometer using the potassium persulfate-sulfuric acid digestion method described in Thomsen (2008). Unfiltered frozen water was sent to South Dakota University for the TKN analysis. The pH of water samples was measured with a Corning 430 meter, while alkalinity (mg L^{-1} as $CaCO_3$) was determined from 100 ml of unfiltered water titrated with 0.02 N H_2SO^4 to a pH of 4.5 and measured with a pH meter (Mettler Toledo Seven easy).

Samples for NO_3^- + NO_2^- were analyzed using the cadmium reduction method described in Thomsen (2008). NH_4^+ was analyzed with a SG5 using the phenol-sodium hypochlorite method described in Thomsen (2008). Total nitrogen (TN), the sum of TKN and $NO_3^- + NO_2^-$, and the ratio of TN to TP was calculated for each sample.

Total filterable phosphorus was determined using the same methods as those for TP utilizing filtered water. Filterable reactive phosphorus was determined using the potassium persulfate-sulfuric acid method described in Thomsen (2008).

Chlorophyll-*a* (chl-*a*) is the primary photosynthetic pigment in plants and is commonly used as an index of phytoplankton abundance, Samples of chl-*a* were prepared for analysis by separately grinding each frozen filter containing the filtrate in 90% buffered acetone using a mortar and pestle, and then refrigerating the resulting slurry from each sample in separate 15-ml glass centrifuge tubes for 4 hours to ensure maximum pigment extraction. Pigment extracts were centrifuged, decanted, and diluted to 15 ml with 90% acetone. The extracts were analyzed with a SG5 spectrophotometer using methods described in Thomsen (2008). Concentrations of pheo-*a*, a common degradation product of chl-*a*, were simultaneously estimated during the spectrophotometer analysis of chl-*a*. The ratio of chl-*a* to pheo-*a* was calculated to provide an indicator of phytoplankton physiological condition.

Zooplankton

Vertical zooplankton hauls were made at each station using a 0.2 m diameter conical net with 153 µm mesh. The net was pulled manually at a constant speed (~0.5 m sec^{-1}) from approximately 2 m off the lake bottom to the surface. The contents from each tow were emptied into a 125-ml polyethylene bottle and preserved in 10% buffered formalin. Cladocerans and copepods were identified to genus using taxonomic keys in Edmondson (1959) and Thorp and Covich (2001). Zooplankton lengths were measured in triplicate 1 ml subsamples taken with a Hansen-Stempel pipette and placed in a Sedgewick-Rafter counting chamber. Zooplankton were grouped at the genus level and measured to the nearest 0.01 mm. The standard deviation (SD) of the lengths (L) of up to 15 individuals was estimated. This value was then used to estimate the appropriate sample size (N) by applying it to a T-statistic (t) with a 0.05 significance level and relative to 10% variation from the mean measured length calculated as

$$N=[(t \times SD)/(0.1 \times L)]^2.$$

Biomass was estimated from species-specific linear regression equations of length and dry weight derived by Koenings et al. (1987). For each survey, average density and biomass from the two stations were calculated for each species group.

RESULTS

SMOLT ASSESSMENT

Smolt Capture

The inclined plane trap was fished continuously from 10 May to 3 July 2009 and captured 64,967 sockeye salmon smolts (Table 2; Figure 5). The peak of emigration occurred during a three-day period, 23-25 May, when 23,425 smolts were counted. The 2009 emigration timing was slightly earlier than the average recorded for 2003-2008 (Figure 6).

Trap Efficiency and Mark-Recapture Abundance Estimation

Estimated trap efficiencies from the five mark-recapture experiments ranged from 17.3% in stratum 1 (10 – 22 May) to 6.4% in stratum 5 (22 June – 3 July) (Table 2; Figure 7). The peak of the emigration occurred in stratum 2 (23 May – 1 June) when trap efficiency was estimated to be 14.3%. Mean estimated trap efficiency for all the experiments was 11.4%.

The total number of sockeye salmon smolts estimated to have emigrated from Afognak Lake in 2009 was 492,998 with 95% CI 417,689 – 568,306 (Table 3). The separate recapture trials using inanimate objects (fruits and nuts) yielded a mean 17.1% recapture rate during a 10-day period (19 May-28 May), and overlapped two smolt mark-recapture experiments that produced trap efficiency estimates of 17.3% (stratum 1, 10-22 May) and 14.3% (stratum 2, 23 May-1 June) (Figure 7).

Age, Weight, and Length Sampling

AWL data were obtained from a total of 1,262 smolts collected proportionally throughout the trapping period (Table 2). Summing smolt abundance estimates by age class from all five mark-recapture strata resulted in a total emigration estimate of 427,141 (86.6%) age-1., 64,560 (13.1%) age-2., and 1,296 (0.3%) age-3. smolts (Table 4; Figures 8, 9, and 10). The occurrence of age-3. smolts in the 2009 emigration marks the first time this age class was encountered in the seven years of this project. Age-1. smolts comprised an estimated 54.1% of the emigration within the first (10 - 22 May), 89.4% within the second (23 May - 1 June) and 100% within the last three (2 June – 3 July) strata.

Sampled age-1. smolts had a mean weight of 3.5 g, a mean length of 76.7 mm and a mean condition factor of 0.76. Sampled age-2. smolts had a mean weight of 5.3 g, a mean length of 88.8 mm, and a mean condition factor of 0.75. Sampled age-3. smolts had a mean weight of 6.6 g, a mean length of 94.0 mm, and a mean condition factor of 0.80 (Table 5).

The mean condition factor of age-1. smolts emigrating from Afognak Lake during 2003-2009 strongly correlated to 14 month mean water temperatures about 3 meters below the surface of Big Kitoi Lake (R^2=.82, p<.005) (Figure 11).

Life History-Based Abundance Estimation

Using the life history-based abundance method, the 2006 escapement of 22,933 adults (brood year 2006) was expected to produce 74,990 age-2. smolts, and the 2007 escapement of 21,070 adults (brood year 2007) was expected to produce 317,468 age-1. smolts (Table 6). Combining these two age classes resulted in an expected emigration of 392,458 smolts from Afognak Lake in spring 2009 (Figure 9).

For the seven years of the project, annual differences between life history-based and mark-recapture estimates ranged from 17% to 44% (R^2=.44, p<.11) (Figure 12). Life history-based estimates were greater than mark-recapture estimates in four years (2003, and 2006-2008) and less than mark-recapture estimates in three years (2004, 2005, and 2009). The life history-based estimate was included within the 95% confidence interval for a mark-recapture estimate in only one year (2003). The cumulative 2003-2009 smolt production from annual life history-based estimates (2.81 million smolts) was only 3% greater than that from annual mark-recapture estimates (2.73 million smolts).

LIMNOLOGICAL ASSESSMENT

Temperature, Dissolved Oxygen, Light, Water Clarity and Euphotic Volume

In 2009, water temperatures ranged from 6.9° C near the lake bottom during the spring (May) sampling period to 17.4° C at the surface of the lake during the summer (July) period (Figure 13).

Dissolved oxygen concentrations ranged from 7.9 mg L^{-1} at the bottom in the summer to 10.9 mg L^{-1} at the surface in the spring. The mean vertical light extinction coefficient was -2.08 m^{-1}, mean euphotic zone depth was 9.10 m, and mean Secchi disk reading was 4.4 meters. Estimated euphotic volume for Afognak Lake was 48.21 10^6 m^3.

General Water Chemistry, Phytoplankton and Nutrients

Afognak Lake mean pH was 7.02 and ranged from 6.38 in July to 7.30 in August (Table 7). Mean alkalinity level was 11.7 mg L^{-1} and ranged from 11.0 mg L^{-1} in June to 12.5 mg L^{-1} in August. Mean chl-*a* concentration was 1.92 μg L^{-1} and ranged from 1.28 μg L^{-1} in September to 2.88 μg L^{-1} in May (Table 7). Mean pheo-*a* concentration was 0.63 μg L^{-1} and ranged from 0.19 μg L^{-1} in July to 0.96 μg L^{-1} Mean chl-*a* to pheo-*a* ratio was 1.9:1.0 and ranged from 1.3:1 in September to 8.4:1 in July.

Three different measures of seasonal phosphorus were made (Table 8). Mean TP concentration was 4.8 μg L^{-1} and ranged from 3.6 μg L^{-1} in September to 5.9 μg L^{-1} in both May and August (Table 8). Mean TFP concentration was 1.3 μg L^{-1} and ranged from 0.8 μg L^{-1} in August to 1.6 μg L^{-1} in May. Mean FRP concentration was 1.8 μg L^{-1} and ranged from 0.6 μg L^{-1} in August to 3.0 μg L^{-1} in June.

Three different measures of seasonal nitrogen were made (Table 8). Mean TKN concentration was 130.8 μg L^{-1} and ranged from 80.0 μg L^{-1} in September to 144.0 μg L^{-1} in May. Mean NH_{4+} concentration was 4.2 μg L^{-1} and ranged from 2.9μg L^{-1} in July to 5.2 μg L^{-1} in September. Mean NO_2 + NO_3 concentration was 38.8 μg L^{-1} and ranged from 2.3 μg L^{-1} in August to 92.4 μg L^{-1} in May. Mean TN concentration was 169.6 μg L^{-1} and ranged from 236.4 to 94.3 μg L^{-1} . The overall mean TN to TP ratio, by weight, was 79.1:1.0 and ranged from 54.2:1.0 in August to 106.7:1.0 in June.

Zooplankton

Zooplankton weighted mean density was 61,133 animals m^{-2} in Afognak Lake (Table 9). All zooplankton identified were crustaceans commonly referred to as either cladocerans (*Order* Anomopoda and Ctenopoda) or copepods (*Order* Calanoida, Cyclopoida, and Harpacticoida). Copepods were somewhat more abundant (52.8% of weighted mean density) than cladocerans (47.2%). Among the copepods, the two most abundant groups were a pooled category we called "other copepods" (35.0%), which was made up mostly of the genus *Harpaticus* and various unidentified nauplii (larvae), and the genus *Epischura* (15.2%). The copepod genus *Cyclops*, usually an important component of the zooplankton community in sockeye salmon rearing lakes, was not very abundant (2.5%), and the genus *Diaptomus* was the least abundant copepod (0.1%). Among the cladocerans, the genus *Bosmina* was most abundant (39.0%). Other observed cladoceran genera were *Daphnia* (3.4%), *Holopedium* (1.7%), and a group we called "other cladocerans," which consisted of various unidentified immature cladocerans (3.1%).

Mean total zooplankton biomass was 50.2 mg m^{-2} ', and was mostly comprised (57.4% of mean total biomass) of copepods (Table 9). The copepod genus *Epischura* represented most of the biomass (53.2%), followed by the cladoceran genus *Bosmina* (34.0%). The remaining biomass was composed of *Daphnia* (5.0%), *Cyclops* (4.0%), *Holopedium* (3.6%), *Diaptomus* (0.2%) and "other copepods and cladocerans", which consisted of larvae too small to weigh.

The copepod *Diaptomus* was the largest zooplankton member measured, with a mean length of 0.70 mm (Table 9). Mean lengths of the remaining zooplankton measured, in decreasing size, were 0.83 mm for the copepod *Epischura*, 0.62 mm for the copepod *Cyclops*. 0.53 mm for the cladoceran *Daphnia*, 0.46 mm for the cladoceran *Holopedium*, and 0.28 mm for the cladoceran *Bosmina*.

DISCUSSION

SMOLT ASSESSMENT

This was the seventh consecutive year in which the same methods and materials were used to conduct the Afognak Lake smolt assessment project. Despite different field personnel and variable environmental conditions, mean trap efficiencies for five of the seven years have been very similar (18.0% to 19.9%) (Appendix 1). Mean trap efficiency was below this range in both 2005 (14.9%) and 2009 (11.4%). Lower mean trap efficiencies in 2009 may have been due to low water levels and velocity. The greatest 2009 trap efficiencies (17.3% and 14.3%) were obtained for the first two mark-recapture strata when seasonal water flows were greatest, while the lowest 2009 trap efficiencies (10.2%, 8.2% and 5.4%) were obtained for the last three strata when water flows were much lower. Most of the 2009 emigration (70%) occurred during the first two strata, which had trap efficiencies similar to those from past years. Additionally, the similarity between capture efficiencies of inanimate, passively floating objects and juvenile sockeye salmon documented in 2009 suggests that smolt may not be actively avoiding the trap. All this suggests that the seven annual estimates of smolt production are comparable and probably represent reasonable estimates of actual abundance.

Age-1. smolts emigrating from Afognak Lake in 2009 had a lower mean condition factor (0.76) than age-1 smolts sampled during 2003-2008 (overall mean 0.80) (Appendix 2). This was because age-1. smolts sampled in 2009 had a greater mean length (76.7 mm) but the same mean weight (3.5 g) as age-1. smolts sampled during 2003-2008 (overall mean length: 74.8 mm; overall mean weight: 3.5 g). However, age-2. smolts emigrating from Afognak Lake in 2009 had the same mean condition factor (0.75) as age-2. smolts sampled during 2003-2008. This was because age-2. smolts sampled in 2009 had both a greater mean length (88.8 mm) and weight (5.3 g) than age-2. smolts sampled during 2003-2008 (overall mean length: 79.9; overall mean weight: 3.9 g).

While life history-based estimates were usually outside the 95% CI range of mark-recapture estimates, confidence intervals for life history-based predictions were not calculated because point estimates were used for model inputs. While annual differences between life history-based and mark-recapture estimates ranged from 17% to 44%, the overall difference between cumulative smolt production for all seven years for the two methods was only 3%. This suggests that differences between methods within a year were likely due to variability in annual age composition, and that these differences were modulated when multiple cohort years were considered. Since there also appears to be no consistent directional bias in differences between life history-based and mark-recapture estimates across years, it is believed the life history-based method may provide a reasonable and unbiased estimate of actual smolt abundance. Confidence intervals for the life history-based estimates are intended to be derived in future years, which should allow better comparative results with mark-recapture estimates.

Differences in smolt size, condition factor, age composition, and run timing appear to be related to temperature conditions. Some apparent correlations of Afognak Lake smolt age composition and Kodiak airport air temperature data (1931-2009) from the were previously identified and reported (Baer et al. 2009). Although, surface, middle and bottom water temperatures have been obtained from each sampling station on Afognak Lake since 1989, these data collection periods only represent a few snapshots in time, whereas time series of air temperature data are averages of many recordings made each day. Unfortunately, air temperature data may not be an appropriate proxy for surface water temperature and cannot provide an accurate representation of the actual thermal conditions experienced during the diel vertical migrations made by foraging sockeye salmon juveniles (Edmundson and Mazumder 2001). Efforts to use water temperatures from Big Kitoi Lake to more closely examine this relationship may be more relevant, and it was discovered that average water temperatures at shallow depths (about 3 m) from the time of hatching to smolt emigration was strongly correlated with the condition factor of age-1. smolts from corresponding emigration years. Hatchery studies support the concept that water temperature is a critical factor in fish development (Piper et al. 1982), and lake studies indicate that metabolic rates of age-0. sockeye salmon increase as temperatures increase within threshold levels, as long as food supplies are not limiting (Brett 1971).

The rate of egg development and time of alevin emergence is also largely dependent upon the temperature regimes in the redd (Burgner 1991, Groot and Margolis 1991). In Afognak Lake, late-winter and early-spring (January-May) air temperatures in 2007 through 2009 were on average 1.5°C colder than the previous 76-year historical average for the same 5 month time period. It is likely these colder temperatures not only resulted in later fry emergence and slowed metabolic processes in juveniles, but may have also affected phytoplankton production (Sommer and Lengfellner 2008; Staeher and Sands-Jensen 2006). Lower phytoplankton biomass may have resulted in later growth and development of zooplankton and could have caused copepods, the most abundant zooplankton in this system, to go into diapause. This would have reduced the forage base for juvenile sockeye salmon.

The change from age-1. smolt dominated emigrations during the period 2003-2007 to an age-2. smolt dominated emigration in 2008 may also have been due, at least in part, to colder recent temperatures. The occurrence of age-3. smolts in 2009, the first time this age class was observed in this seven year study, provided some confirmation that the large number of age-2. smolts in 2008 was not just an artifact of sampling. Other studies have shown that colder temperatures are related to later hatching, slower metabolic rates, slower growth, and later smoltification (Brett 1971, Groot and Margolis 1991). Rice et al. (1994) also documented that juvenile sockeye salmon may alter their life history strategies in response to adverse rearing conditions. Therefore, poor rearing conditions in Afognak Lake probably caused more juvenile salmon to extend their rearing time an additional year or two until they achieved a suitable size and condition factor for smoltification.

Smolt emigration from Afognak Lake typically begins in mid-May, peaks in early to mid-June, and ends by early July Appendix 1). Emigration timing in 2009 was earlier than timing of both the 2007 and 2008 emigrations, but similar to the timing of the 2003-2006 emigrations (Baer et al. 2009). However, while smolt emigrations in 2007 and 2008 did begin late (the end of May), they both peaked (mid-June) and ended (early July) at the typical times. Observations from other systems (Barnaby 1944; Burgner 1962; Krogius and Krokhin 1948) indicate that older and larger smolts tend to migrate earlier. Therefore, delayed emigration in 2007 and 2008, along with the lower condition factor and extended freshwater residence times for these smolts, suggest that colder spring conditions are affecting juvenile production as well as freshwater productivity.

LIMNOLOGICAL ASSESSMENT

Although most of the seasonal mean physical properties measured in Afognak Lake during 2009 were consistent with those from past years, water temperatures were a notable exception. Spring (May-June) and summer (July-August) 2009 surface temperatures were 1.7°C and 1.5°C warmer, respectively, than historical (1989-2008) seasonal average readings (Appendix 3). These warmer than average spring and summer 2009 surface temperatures were consistent with expected effects from the strengthening of the El Niño Southern Oscillation (US Department of Commerce 2010). Although the seasonal water temperature readings were obtained from a limited set of sampling events, air temperature data also indicated that spring and summer (April-July) air temperatures were slightly warmer (0.7°C) than the 76-year historical record air temperatures. The important role climate plays in the timing and age structure of Afognak Lake juvenile sockeye salmon was reflected in the earlier emigration and predominance of age-1. smolts in 2009.

As a result of active mixing events, Afognak Lake is typically stratified into warm epilimnion and cool hypolimnion layers for only short periods of time in the middle of the summer, such as in July of 2009 (Figure 11). Recorded dissolved oxygen levels at the surface and the bottom of Afognak Lake in 2009 were high and generally similar to those recorded during 1989-2008 (Appendix 4). Light, euphotic volume and euphotic zone values recorded in 2009 were similar to values for post-fertilization years (2001-2008) and generally higher than values for fertilization years (1990-2000), (Appendix 5). Seasonal mean water chemistry values have not varied greatly, although average pH and alkalinity were both lower during the fertilization period (pH: 6.8; alkalinity: 9.5) than during the post-fertilization period (pH: 6.9; alkalinity: 10.8; Appendix 6). During 2009, average pH (7.0) and alkalinity (11.7 mg L^{-1}) were greater than the 1987-2008 average values (pH: 6.8; alkalinity: 10.0 mg L^{-1}). These observed differences may be explained in part by seasonal fluctuations associated with photosynthesis, temperature, and sampling timing. As daylight increases over the summer sampling season, photosynthetic rates may also increase, thereby increasing pH (Wetzel and Likens 2000). Similarly, increasing temperatures may cause pH to decline. Variability among years may also be caused by the variability in photosynthetic rates and changing temperatures relative to the time samples were collected.

Nutrient and phytoplankton pigment concentrations have also exhibited differences among fertilization years (1990-2000), post-fertilization years (2001-2009), and the three year period just prior to fertilization (1987-1989; Appendix 7). The average TKN, $NH_{4+,}$ chl-*a* and pheo-*a* concentrations were all higher during the fertilization years than during the pre- and post-fertilization years. In 2009, all surface nutrient concentrations were less than the average for the fertilization years, while algal standing crop, as measured by chl-*a*, was greater. When comparing 2009 surface nutrients and algal pigment concentrations to the most recent eight year post-fertilization period (2001-2008), only three measurements were greater in 2009 (TKN: 131 µg L^{-1}, chl-*a* 1.92 µg L^{-1} and pheo-*a* .63 µg L^{-1}) than the overall average for 2001-2008 (TKN:

129 μg L^{-1}, chl-*a* 1.54 μg L^{-1} and pheo-*a* .36 μg L^{-1}) The five remaining nutrient concentrations measured in 2009 (TP: 4.8 μg L^{-1}, TFP: 1.3 μg L^{-1}, FRP: 1.8 μg L^{-1}, NH_{4+}: 4.0 μg L^{-1} and NO_3^- + NO_2^-: 39 μg L^{-1}) were all lower than the overall average concentration for 2001-2008 (TP: 6.6 μg L^{-1}, TFP: 3.8 μg L^{-1}, FRP: 2.8 μg L^{-1}, NH_{4+}: 5.8 μg L^{-1} and NO_3^- + NO_2^-: 46 μg L^{-1}; Appendix 7). These differences may due to changes in the lake's physical processes but could also be an artifact of process and measurement error due to the small number of measurements made each year and the inherent variability of evaluating low concentrations of nutrients.

The largest chl-*a* to pheo-*a* ratio documented in 2009 occurred in July (8.4:1). Although, this larger ratio may be a false indication that the most primary production occurred in July because the chl-*a* level by itself in July was the second lowest observed in 2009. In addition the chl-*a* level was the same in June (1.60 μg L^{-1}) as it was in July, whereas the concentration of pheo-*a* was reduced by more than half from June (0.42 μg L^{-1}) to July (0.19 μg L^{-1}) and was the least amount observed throughout the season. This suggests that pheo-*a* was falling out of the water column due to inactive lake mixing and a well defined thermocline as observed in July as opposed to the other four months when the lake was thermally stratified and actively mixed.

The seasonal mean zooplankton density and biomass estimates at station 2 have historically been less than estimates from station 1 (Appendix 7). However, due to the variability of station 2 samples and the absence of zooplankton sampling during 1998-2003, effort was focused on discussions on data obtained from station 1. The relatively low zooplankton density and biomass in samples from station 2 has been attributed to the closer proximity of that sampling station to the lake outlet (Schrof and Honnold 2005; White et al. 1990). Lake water residence time in Afognak Lake is estimated to be only 0.4 years, and this rapid lake flushing may physically remove zooplankton more quickly than standing stocks can be replenished through reproduction. Rapid flushing may also affect nutrient availability for phytoplankton, which in turn could lower zooplankton production at this site. This effect may be further compounded in times, such as the springs of 2007 and 2008, when there was greater precipitation than normal. Since the zooplankton community is the primary forage base for juvenile sockeye salmon, total zooplankton density and biomass are often used as a measure to assess juvenile sockeye salmon production potential (Koenings et al. 1987). During 2009 at Station 1, weighted mean total zooplankton density (50,424 individuals m^{-2}) and biomass (73 mg m^{-2}) levels were the lowest and second smallest amounts, respectively, ever recorded in the 23 year history of zooplankton collection. Historical averages from 1987-2008 (171,260 individuals m^{-2}, 234 mg m^{-2}) were more than three times the 2009 levels, while the recent post-fertilization averages from 2001-2008 (105,872 individuals m^{-2}, 134 mg m^{-2}) were nearly twice 2009 levels (Appendix 8). However, the high chl-*a* concentrations in 2009 in combination with low TP concentrations suggested that low zooplankton biomass was probably due, at least in part, to overgrazing by juvenile salmon.

Because juvenile sockeye salmon favor cladocerans rather than copepods as a food source, cladoceran abundance has been used as an indicator of juvenile sockeye salmon grazing pressure (Koenings et al. 1987; Kyle 1996). In particular, the presence and abundance of *Daphnia* is considered a very important indicator of grazing pressure since it is a primary prey item for juvenile sockeye salmon, (Honnold and Schrof 2001; Kyle 1996). However, *Daphnia* abundance can be limited in other ways. For example, *Daphnia* require phosphorus-rich diets, and it is possible their phytoplankton forage base in Afognak Lake has been reduced in recent years, which has caused reductions in *Daphnia* populations. Average concentration of TP during the most recent three year period, (2007-2009) has been 4.1μg L^{-1}, which is much less than the average concentration of 7.8μg L^{-1} measured in prior years (1987-2006). In 2009, *Daphnia* mean density (2,866 individuals m^{-2}) and biomass (4 mg m^{-2}) at station 1 were both much less than the overall mean density (4,757 individuals) and biomass (6 mg m^{-2}) for the eight preceding (2001-2008) post-fertilization years (Appendix 8). Along with decreased abundance, the mean body size of *Daphnia* in 2009 (0.54 mm) was smaller than all but the first two post-fertilization years (2001: 0.49 mm; and 2002: 0.51 mm). It is thus unclear whether low *Daphnia* abundance in recent years was due to grazing pressures, nutrient limitations or a combination of these and other factors.

The two other main groups of cladocerans, *Bosmina* and *Holopedium*, exhibited similar differences in abundance and size between 2009 and the eight preceding post-fertilization years at Station 1 (Appendix 8). However, while *Bosmina* was the most abundant cladoceran, comprising 86% of total cladoceran biomass, they may not be a good indicator of available forage because their smaller size (half the size of *Daphnia*) tends to make them a more difficult prey item for juvenile salmon to prey upon (Koenings and Kyle 1997). Nevertheless, the mean size of *Bosmina* (0.29 mm) at Station 1 in 2009 was the smallest ever recorded in Afognak Lake, which could be due to grazing pressure if juvenile sockeye salmon foraged on larger *Bosmina* since *Daphnia* abundance was low.

CONCLUSIONS

Results and analysis of this 3-year study coupled with historical data suggest Afognak Lake continues to be a rearing limited habitat for juvenile sockeye salmon. Direct rearing limitations appear to be from reduced phytoplankton levels resulting in reduced number and size of zooplankton forage. The cause of phytoplankton limitation appears to be a combination of nutrient, temperature, and possibly solar input limitations in conjunction with grazing pressures. However, survival estimates, age structures, and condition of emigrating smolts suggest rearing juvenile salmon are obtaining a threshold size and condition within a time frame that can supply viable and sustainable adult returns provided there is healthy ocean survival.

RECOMMENDATIONS

Water temperature affects juvenile sockeye salmon in variety of ways, both directly and indirectly, and can also be a useful indicator of light intensity or solar input, which ultimately controls primary production through photosynthetic carbon fixation. However, since Afognak Lake is located on the coast at a northern latitude, the effect of solar input on air and water temperatures is reduced by the prevailing maritime weather conditions that commonly bring clouds, overcast, and rain. So, despite having a large annual photoperiodic range (6.5 – 18.0 hrs day), average annual air temperature range for Kodiak is less than a 14.0°C, with January being the coldest month (-0.9°C) and August the warmest month (12.9°C). Future work on Afognak Lake should include measures of light intensity or photoperiod to better assess the relationship between solar input and smolt production.

Although limnological data has indentified potential water chemistry, nutrient, and zooplankton limitations, it has not identified what organisms are taking up nutrients, what organisms are being consumed, and what energetic response rearing salmon have within their habitat. Further studies involving phytoplankton analysis should be applied to help identify limiting and controlling factors associated with primary trophic production and how it interacts with primary consumers. Analyses should also be conducted on stomach contents of rearing juveniles to further understand prey consumption and food energy transfer through the food web. Additional modeling involving bioenergetics should also be applied to further identify juvenile salmon's ability to utilize available prey and habitat. Bioenergetics models, habitat models, and future climate trends coupled with future and historical salmon age and abundance estimates could further elucidate the driving forces of sockeye salmon production within Afognak Lake and better predict future trends under differing rearing and climatic conditions.

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TABLES AND FIGURES

Table 1.–Afognak Lake sockeye salmon escapement, harvest, and total run estimates, 1978-2009.

Year	Escapement	Harvest			Total Run
		Commercial[a]	Subsistence[b]	Total[c]	
1978	52,701	3,414	1,632	5,046	57,747
1979	82,703	2,146	2,069	4,215	86,918
1980	93,861	28	3,352	3,380	97,241
1981	57,267	16,990	3,648	20,638	77,905
1982	123,055	21,622	3,883	25,505	148,560
1983	40,049	4,349	3,425	7,774	47,823
1984	94,463	6,130	3,121	9,251	103,714
1985	53,563	1,980	6,804	8,784	62,347
1986	48,328	2,585	3,450	6,035	54,363
1987	25,994	1,323	2,767	4,090	30,084
1988	39,012	14	2,350	2,364	41,376
1989	88,825	0	3,859	3,859	92,684
1990	90,666	22,149	4,469	26,618	117,284
1991	88,557	47,237	5,899	53,136	141,693
1992	77,260	2,196	4,638	6,834	84,094
1993	71,460	1,848	4,580	6,428	77,888
1994	80,570	17,362	3,329	20,691	101,261
1995	100,131	67,665	4,390	72,055	172,186
1996	101,718	106,141	11,023	117,164	218,882
1997	132,050	10,409	12,412	22,821	154,871
1998	66,869	26,060	4,690	30,750	97,619
1999	95,361	34,420	5,628	40,048	135,409
2000	54,064	14,124	7,572	21,696	75,760
2001	24,271	0	4,720	4,720	28,991
2002	19,520	0	1,279	1,279	20,799
2003	27,766	0	604	604	28,370
2004	15,181	0	567	567	15,748
2005	21,577	356	696	1,052	22,629
2006	22,933	6	451	457	23,390
2007	21,070	0	490	490	21,560
2008	26,874	1,098	594	1,692	28,566
2009	31,358	363	971	1,334	32,692

[a] Statistical fishing section 252-34 (Southeast Afognak Section).

[b] Data from ADF&G subsistence catch database 1978-2008.

[c] Sport harvest data does not have enough respondents to provide reliable estimates.

[d] Not available at time of publication.

Table 2.–Sockeye salmon smolt catch, number of AWL samples collected, mark-recapture releases and recoveries, and trap efficiency estimates from Afognak River by stratum, 2009.

Date	Daily Catch	AWL Samples	Marked releases[a]	Marked recoveries	Trap efficiency
		Stratum 1			
10-May	9				
11-May	0				
12-May	0				
13-May	169	5			
14-May	264	5			
15-May	558	10			
16-May	750	15			
17-May	846	15	381	41	
18-May	1,485	30		17	
19-May	2,596	49		7	
20-May	3,473	70		0	
21-May	1,407	30		0	
22-May	2,781	55		0	
Total Stratum 1	14,338	284	381	65	17.3%
		Stratum 2			
23-May	8,366	170	356	39	
24-May	4,785	90		4	
25-May	10,274	205		7	
26-May	1,809	35		0	
27-May	2,774	55		0	
28-May	1,741	35		0	
29-May	3,232	65		0	
30-May	1,875	40		0	
31-May	1,631	30		0	
1-Jun	1,050	20		0	
Total Stratum 2	37,537	745	356	50	14.3%
		Stratum 3			
2-Jun	584	10	420	35	
3-Jun	307	5		4	
4-Jun	503	10		4	
5-Jun	1,741	35		0	
6-Jun	880	20		0	
7-Jun	875	15		0	
8-Jun	678	10		0	
9-Jun	261	5		0	
Total Stratum 3	5,829	110	420	43	10.5%

-continued-

Table 2.–Page 2 of 2.

Date	Daily Catch	AWL Samples	Marked releases[a]	Marked recoveries	Trap efficiency
		Stratum 4			
10-Jun	265	5	425	23	
11-Jun	154	0		10	
12-Jun	566	10		2	
13-Jun	754	15		0	
14-Jun	911	15		0	
15-Jun	262	5		0	
16-Jun	597	10		0	
17-Jun	237	5		0	
18-Jun	583	10		0	
19-Jun	571	10		0	
20-Jun	326	5		0	
21-Jun	527	10		0	
Total Stratum 4	5,753	100	425	35	8.5%
		Stratum 5			
22-Jun	384	8	93	1	
23-Jun	150	0		4	
24-Jun	180	5		0	
25-Jun	235	0		0	
26-Jun	102	5		0	
27-Jun	179	0		0	
28-Jun	114	0		0	
29-Jun	53	5		0	
30-Jun	65	0		0	
1-Jul	48	0		0	
2-Jul	0	0		0	
3-Jul	0	0		0	
Total Stratum 5	1,510	23	93	5	6.4%
Total Strata 1-5	64,967	1,262	1,674	198	11.4%

[a] Adjusted number released using the delayed mortality methods.

Table 3.–Estimated abundance of sockeye salmon smolts emigrating from Afognak Lake, 2009.

Stratum	Beginning	Ending						95% Confidence Interval	
(h)	Date	Date	Unmarked	Released	Recovered	Estimate	Variance	lower	upper
1	5/10	5/22	14,338	381	65	82,891	8.52E+07	64,799	100,983
2	5/23	6/1	37,537	356	50	262,568	1.14E+09	196,454	328,681
3	6/2	6/9	5,829	420	43	55,727	6.23E+07	40,261	71,192
4	6/10	6/21	5,753	425	35	68,080	1.15E+08	47,025	89,136
5	6/22	7/3	1,510	93	5	23,732	7.56E+07	6,686	40,778
Total						492,998	1.48E+09	417,689	568,306
						SE=	38422.77		

Table 4.–Estimated emigration abundance of Afognak Lake sockeye salmon smolt by time period (stratum) and age class, 2009.

Stratum		Age 1.	2.	3.	Total
1	Number	44,840	37,456	595	82,891
(5/10-5/22)	Percent	54.1%	45.2%	0.7%	100.0%
2	Number	234,762	27,104	701	262,568
(5/23-6/1)	Percent	89.4%	10.3%	0.3%	100.0%
3	Number	55,727	0	0	55,727
(6/2-6/9)	Percent	100.0%	0.0%	0.0%	100.0%
4	Number	68,080	0	0	68,080
(6/10-6/21)	Percent	100.0%	0.0%	0.0%	100.0%
5	Number	23,732	0	0	23,732
(6/22-7/3)	Percent	100.0%	0.0%	0.0%	100.0%
Total	Number	427,141	64,560	1,296	492,998
	Percent	86.6%	13.1%	0.3%	100.0%

Table 5.–Length, weight, and condition of sockeye salmon smolt from the Afognak River, 2009.

Stratum	Dates	Sample Size	Weight (g) Mean	Weight (g) Standard Error	Length (mm) Mean	Length (mm) Standard Error	Condition Mean	Condition Standard Error
Age 1.								
1	5/10-5/22	154	3.4	0.04	76.9	0.28	0.74	0.003
2	5/23-6/1	666	3.2	0.01	75.6	0.11	0.74	0.001
3	6/2-6/9	110	3.6	0.04	77.2	0.26	0.78	0.004
4	6/10-6/21	100	4.5	0.06	81.5	0.31	0.82	0.005
5	6/22-7/3	23	5.3	0.09	84.8	0.64	0.87	0.017
Totals		1,053	3.5	0.02	76.7	0.11	0.76	0.002
Age 2.								
1	5/10-5/22	128	5.4	0.06	89.9	0.31	0.74	0.004
2	5/23-6/1	77	5.0	0.09	87.0	0.50	0.76	0.007
3	6/2-6/9	0						
4	6/10-6/21	0						
5	6/22-7/3	0						
Totals		205	5.3	0.05	88.8	0.29	0.75	0.004
Age 3.								
1	5/10-5/22	2	6.9	0.85	94.5	1.50	0.81	0.062
2	5/23-6/1	2	6.5	0.75	93.5	3.50	0.79	0.003
3	6/2-6/9	0						
4	6/10-6/21	0						
5	6/22-7/3	0						
Totals		4	6.6	0.48	94.0	1.58	0.80	0.026

Table 6.–Theoretical production Afognak Lake sockeye salmon eggs, emergent fry, and smolts by age from brood years 2005 and 2006 and predicted smolt emigration for 2009.

Production		Brood Year		Estimate 2009
Parameter	Assumption	2006	2007	Age-1. and -2. smolt
Escapement		22,933	21,070	
Females spawning	55% (2006) 51% (2007)[a]	11,696	11,589	
Deposited Eggs	2,077 (2006) 2,359 (2007)[b]	24,292,239	27,337,272	
Emergent Fry	7% egg-to-fry survival[c]	1,700,457	1,913,609	
Smolt	21% fry-to-smolt survival[d]	357,096	401,858	
2009 Smolt Emigration	79% age-1., 21% age-2.[e]	74,990	317,468	392,458

[a] Female sex composition derived from 2006 and 2007 sex data obtained from adult sampling (2006 and 2007).

[b] Actual fecundity of Afognak Lake sockeye salmon as reported from Pillar Creek Hatchery (2006 and 2007).

[c] Egg to fry survival assumption from Drucker (1970), Bradford (1995), and Koenings and Kyle (1997).

[d] Fry to smolt survival assumptions from Koenings and Kyle (1997).

[e] Age composition assumptions derived from the average of 2003-2008 smolt age class estimates.

Table 7.–General water chemistry and algal pigment concentrations at 1-m water depth, station 1, Afognak Lake 2009.

Date	pH (units)	Alkalinity (mg L^{-1})	Chlorophyll *a* (μg L^{-1})	Pheophytin *a* (μg L^{-1})
18-May	7.02	11.5	2.88	0.93
15-Jun	7.10	11.0	1.60	0.42
16-Jul	6.38	11.3	1.60	0.19
24-Aug	7.30	12.5	2.24	0.67
22-Sep	7.29	12.0	1.28	0.96
Average	7.02	11.7	1.92	0.63
SD	0.38	0.6	0.64	0.33

Table 8.–Seasonal phosphorus and nitrogen concentrations at 1 m water depth, station 1, Afognak Lake, 2009.

Date	Total filterable-P (μg L^{-1})	Filterable reactive-P (μg L^{-1})	Total-P (μg L^{-1})	Ammonia (μg L^{-1})	Total Kjeldahl Nitrogen (μg L^{-1})	Nitrate + Nitrite (μg L^{-1})	Total Nitrogen (μg L^{-1})	TN:TP ratio
18-May	1.6	1.0	5.9	4.2	144.0	92.4	236.4	88.7
15-Jun	1.5	3.0	4.2	4.2	132.0	70.4	202.4	106.7
16-Jul	1.4	1.7	4.3	2.9	156.0	14.5	170.5	87.8
24-Aug	0.8	0.6	5.9	4.6	142.0	2.3	144.3	54.2
22-Sep	1.3	2.5	3.6	5.2	80.0	14.3	94.3	58.0
Average	1.3	1.8	4.8	4.2	130.8	38.8	169.6	79.1
SD	0.3	1.0	1.1	0.8	29.7	40.0	54.4	22.3

Table 9.–Weighted mean zooplankton density, biomass, and size by station from Afognak Lake, 2009.

Station	*n*		*Epischura*	*Diaptomus*	*Cyclops*	Other Copepods	*Bosmina*	*Daphnia*	*Holopedium*	Other Cladocerans	Total Copepods	Total Cladocerans	Total all zooplankton
1	5	density (no. m^{-2})	13,402	0	1,409	23,061	31,539	2,866	1,208	2,548	37,872	38,161	76,033
		%	17.6%	0.0%	1.9%	30.3%	41.5%	3.8%	1.6%	3.4%	49.8%	50.2%	100.0%
		biomass (mg m^{-2})	42.3	0.0	1.7	–[a]	23.9	3.5	2.1	–[a]	44.0	29.5	73.5
		%	57.5%	0.0%	2.3%	–[a]	32.6%	4.8%	2.8%	–[a]	59.8%	40.2%	100.0%
		size (mm)	0.88	0.00	0.60	–[a]	0.29	0.54	0.45	–[a]			
2	5	density (no. m^{-2})	5,149	106	1,645	19,693	16,189	1,274	902	1,274	26,593	19,639	46,232
		%	11.1%	0.2%	3.6%	42.6%	35.0%	2.8%	2.0%	2.8%	57.5%	42.5%	100.0%
		biomass (mg m^{-2})	11.2	0.2	2.3	–[a]	10.1	1.5	1.5	–[a]	13.7	13.2	26.8
		%	41.7%	0.6%	8.6%	–[a]	37.8%	5.6%	5.7%	–[a]	50.9%	49.1%	100.0%
		size (mm)	0.77	0.70	0.64	–[a]	0.27	0.51	0.46	–[a]			
1 & 2		density (no. m^{-2})	9,276	53	1,527	21,377	23,864	2,070	1,055	1,911	32,233	28,900	61,133
Averaged		%	15.2%	0.1%	2.5%	35.0%	39.0%	3.4%	1.7%	3.1%	52.7%	47.3%	100.0%
		biomass (mg m^{-2})	26.7	0.1	2.0	–[a]	17.0	2.5	1.8	–[a]	28.8	21.3	50.2
		%	53.2%	0.2%	4.0%	–[a]	34.0%	5.0%	3.6%	–[a]	57.5%	42.5%	100.0%
		size (mm)	0.83	0.70	0.62	–[a]	0.28	0.53	0.46	–[a]			

[a] Other copepods and cladocerans are composed of immature species that are too small to measure to generate a biomass estimate.

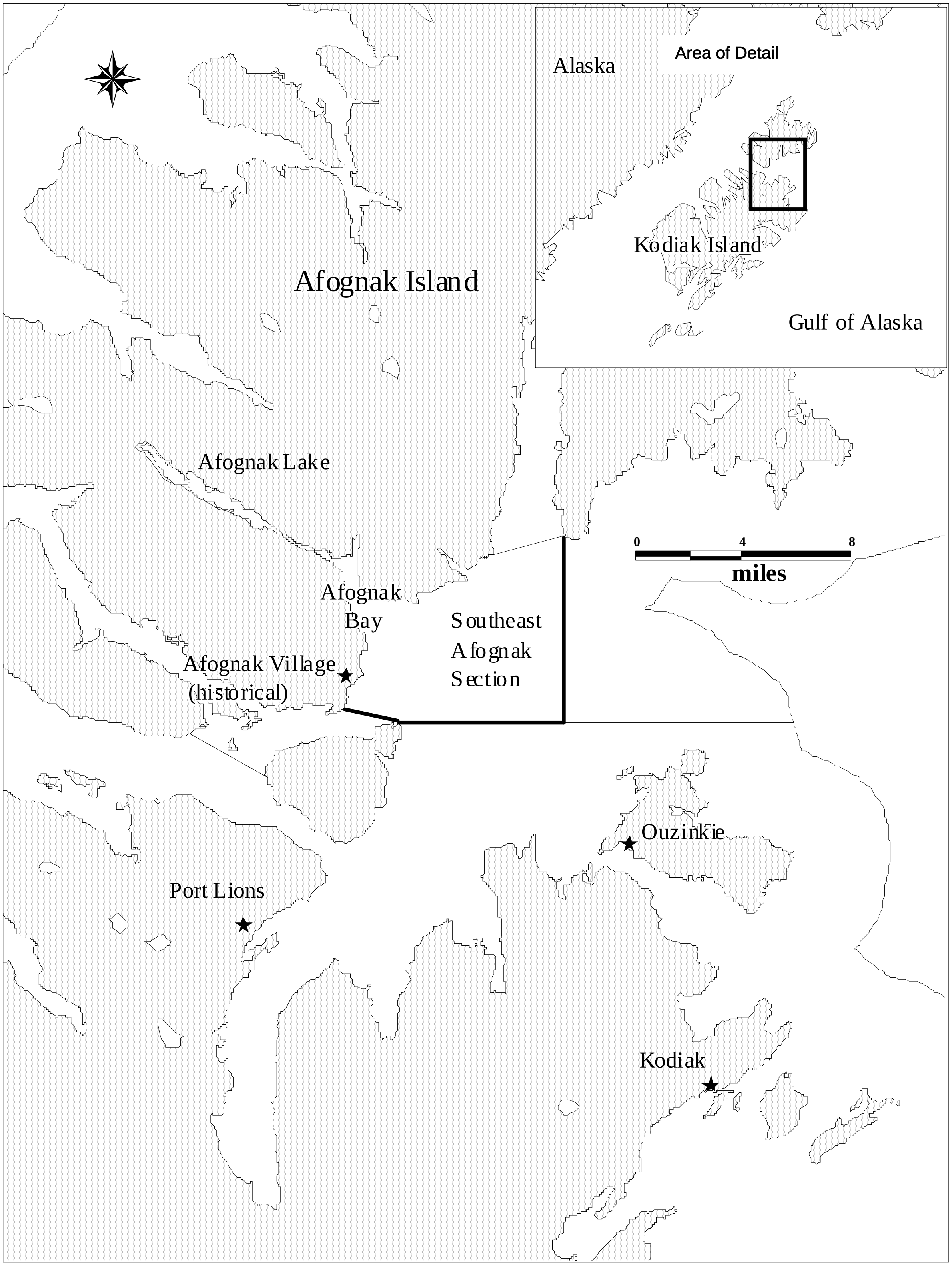

Figure 1.–Map depicting the location of Kodiak City, and the villages of Port Lions, and Ouzinkie and their proximity to the Afognak Lake drainage on Afognak Island.

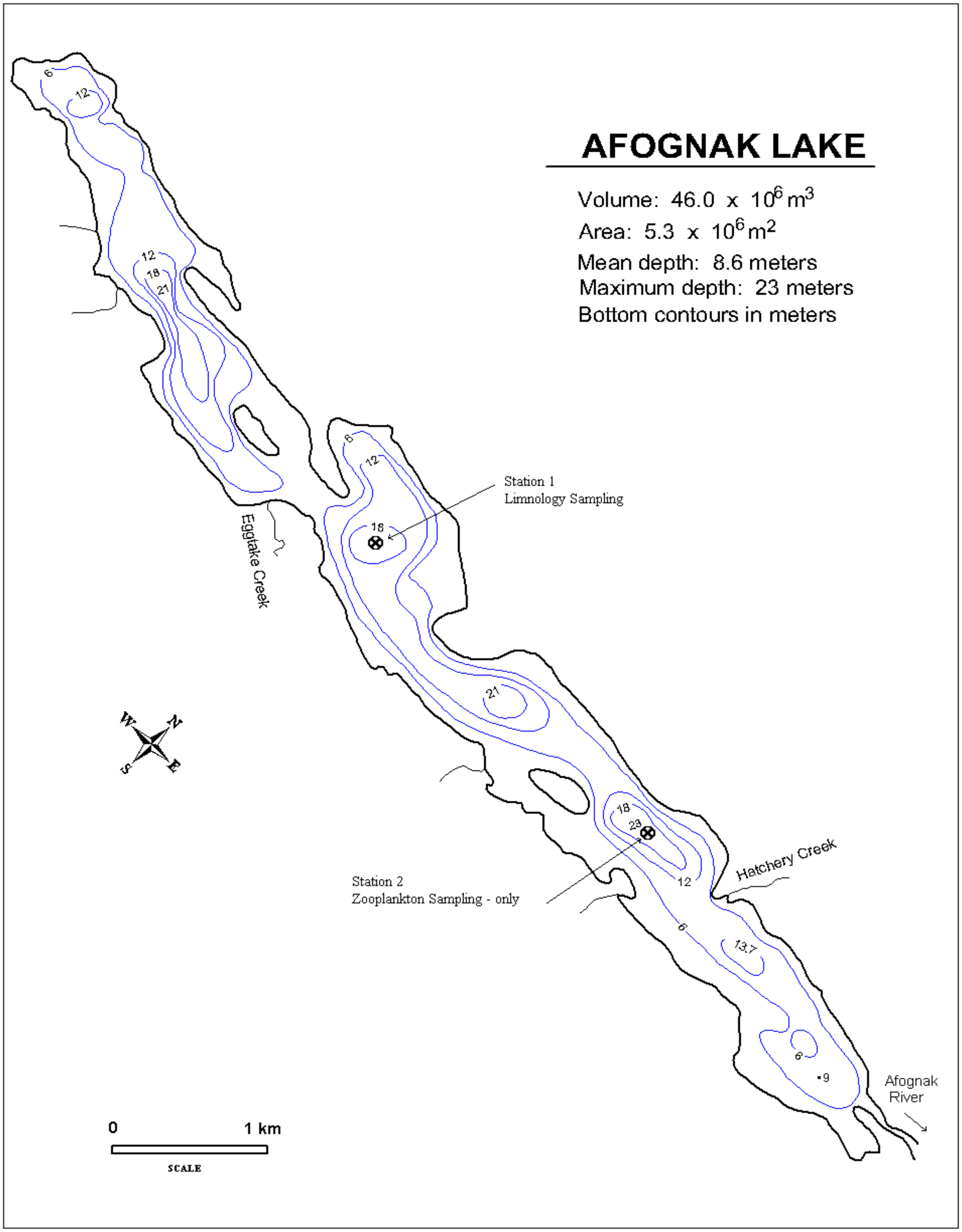

Figure 2.–Bathymetric map showing the limnology and zooplankton sampling stations on Afognak Lake.

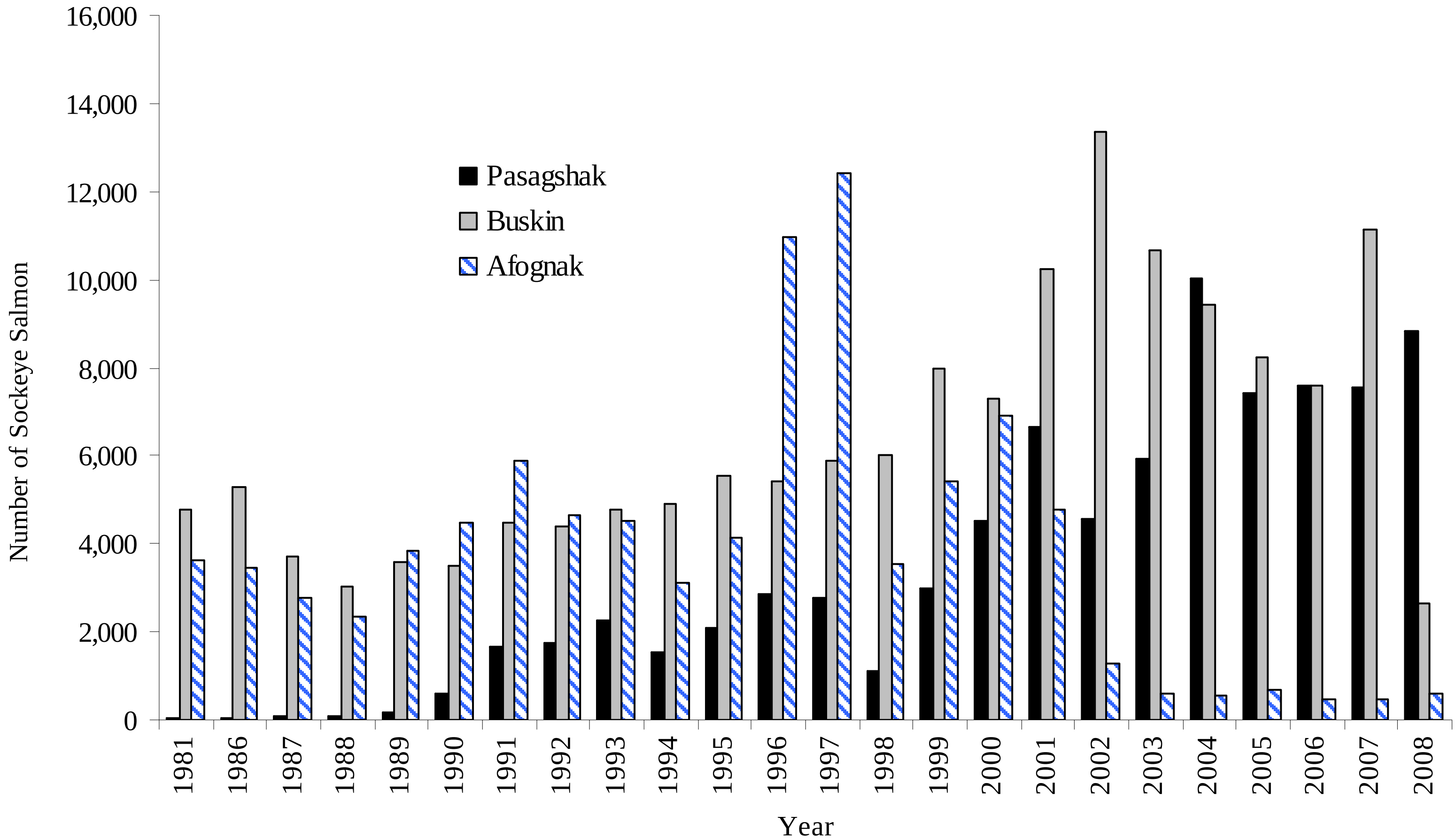

Figure 3.–Sockeye salmon subsistence harvest from the three largest subsistence fisheries within the Kodiak Archipelago, 1981-2008.

Figure 4.–The smolt trapping system in Afognak River, 2009. Water is flowing from left to right of photo.

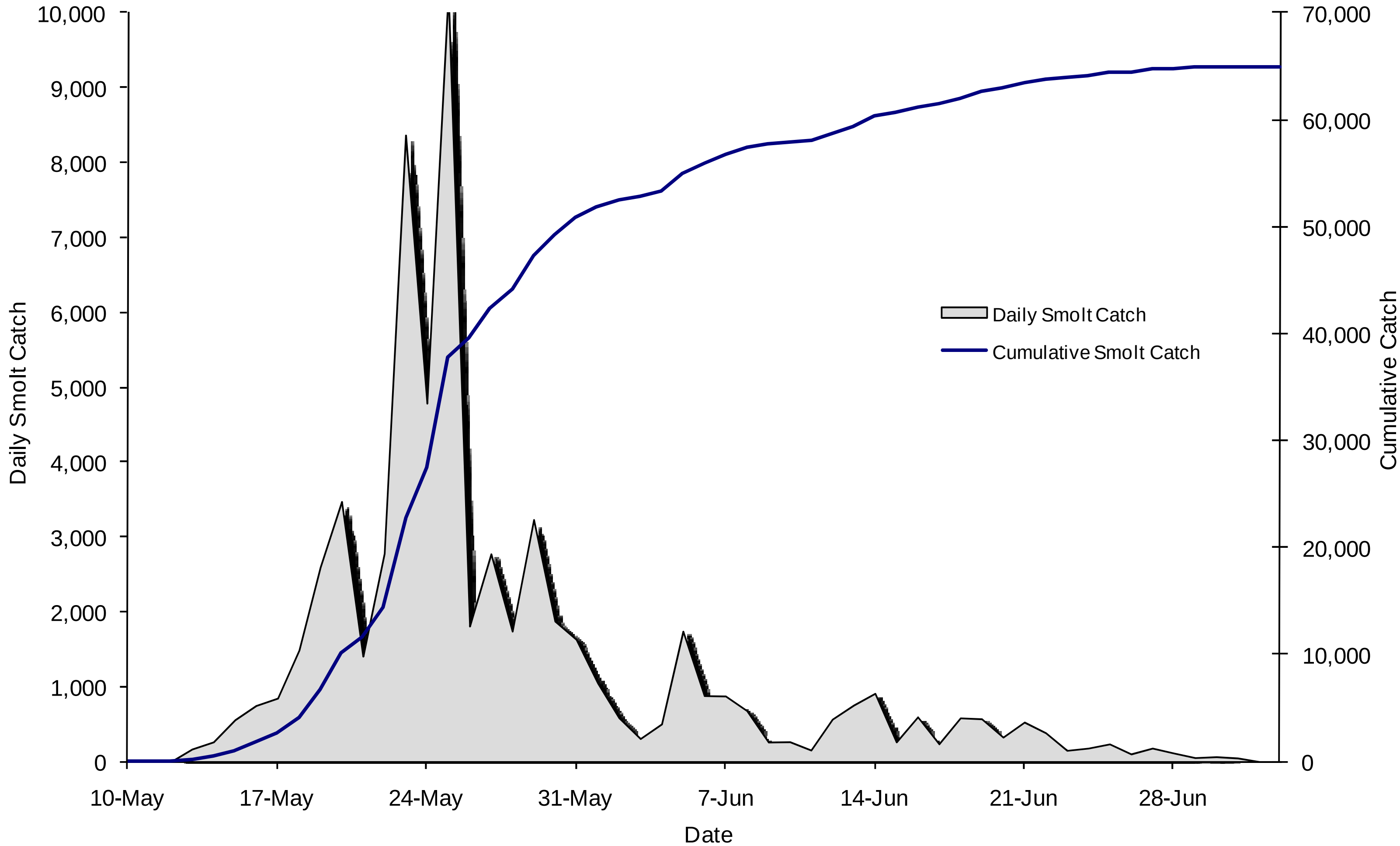

Figure 5.–Daily and cumulative sockeye salmon smolt trap catch from 10 May to 3 July in the Afognak River, 2009.

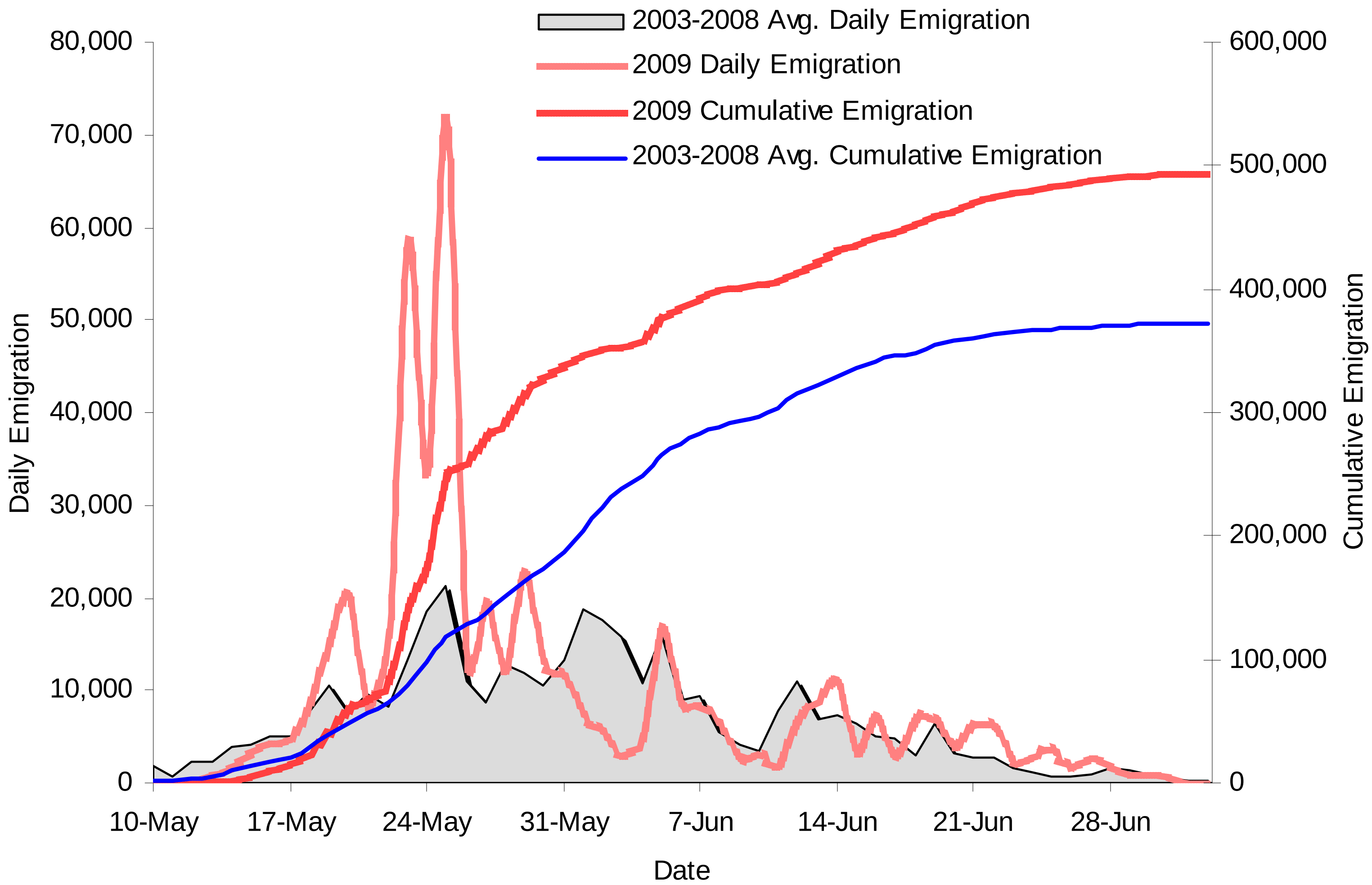

Figure 6.–The 2009 daily and cumulative smolt emigration timing as compared to the average of the 2003-2008 daily and cumulative emigration timing from Afognak Lake.

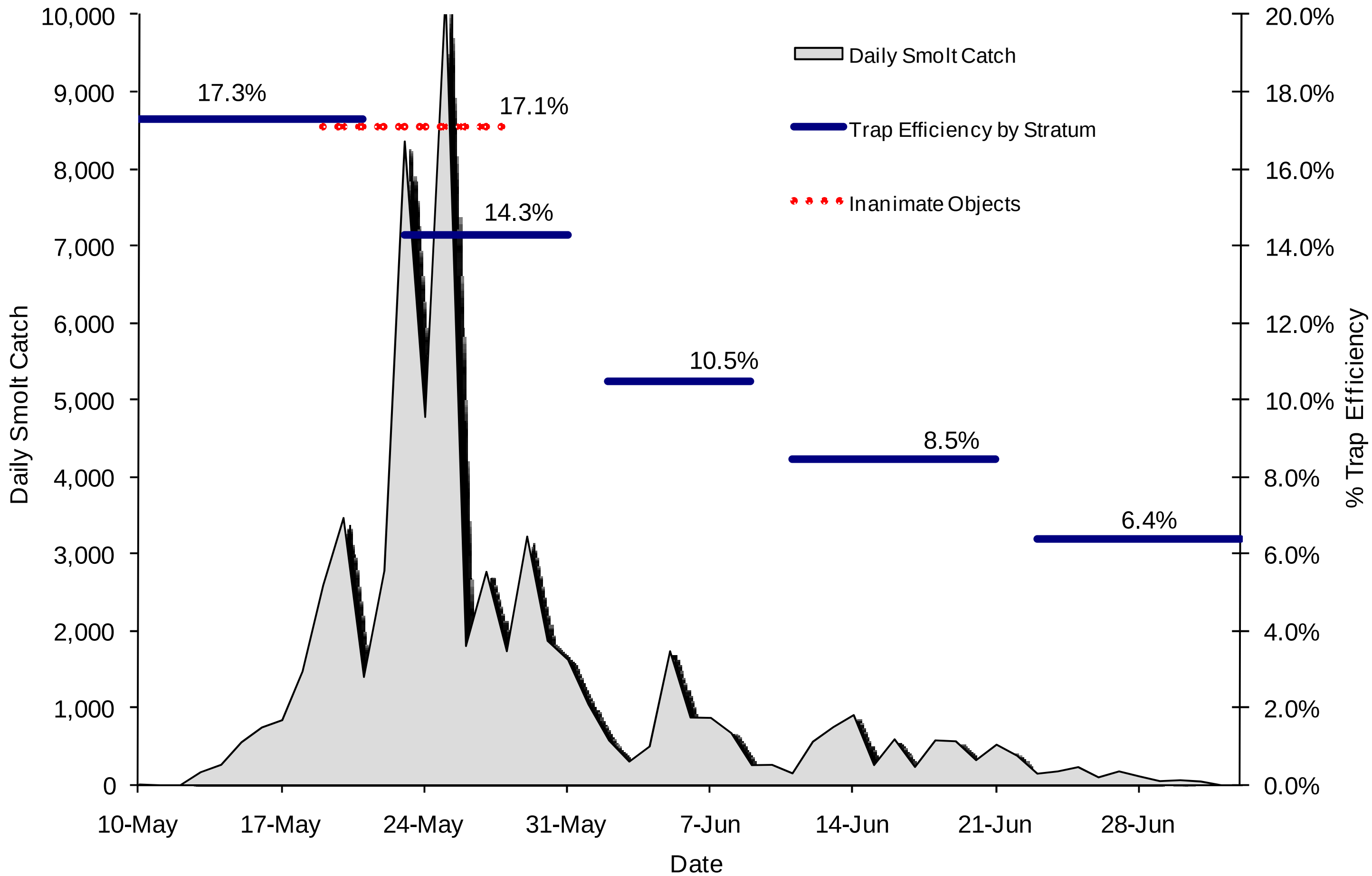

Figure 7.–Daily sockeye salmon smolt trap catch and trap efficiency estimates by strata from 10 May to 3 July in the Afognak River, 2009.

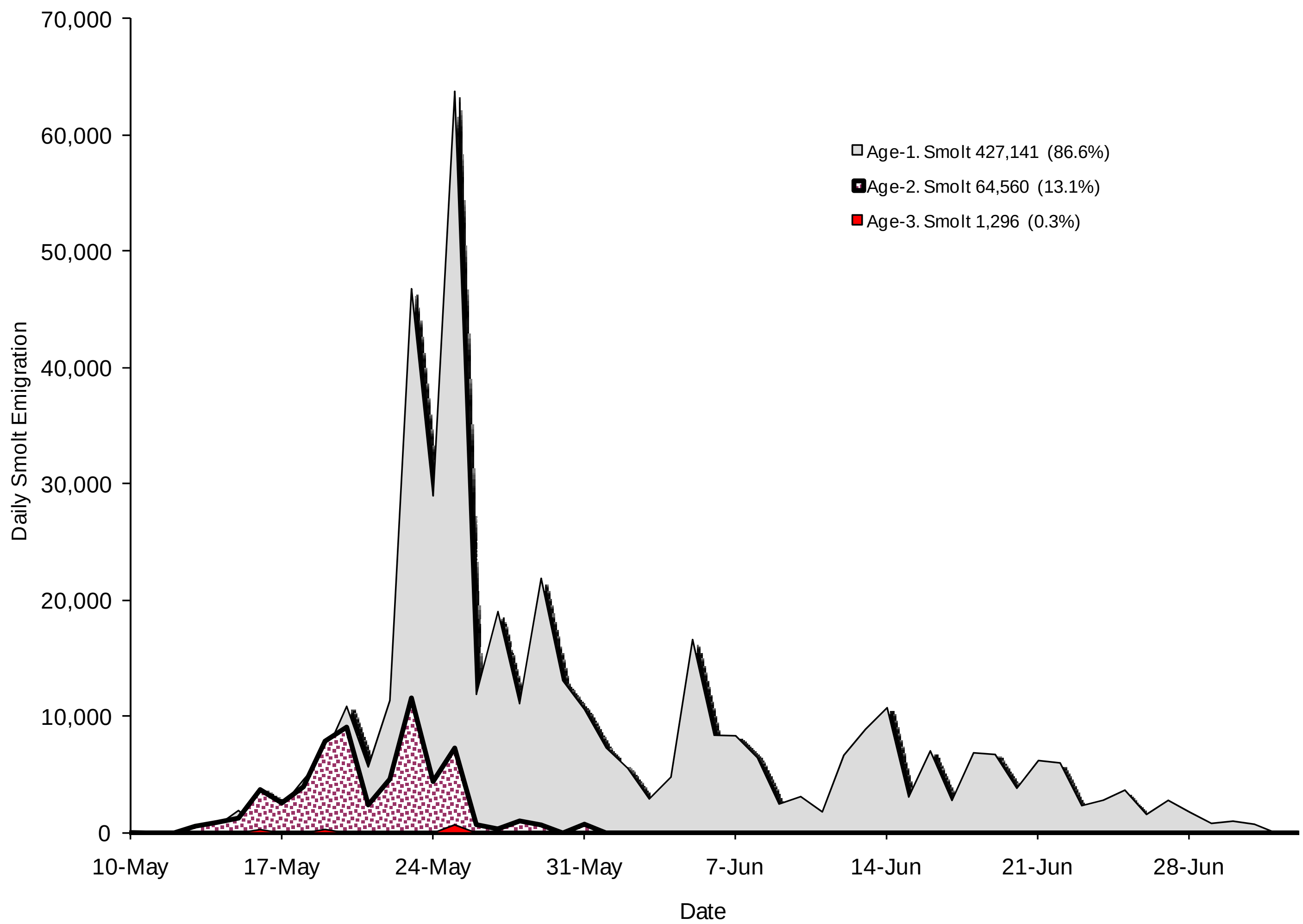

Figure 8.–Afognak Lake sockeye salmon smolt daily emigration estimates by age class, 2009.

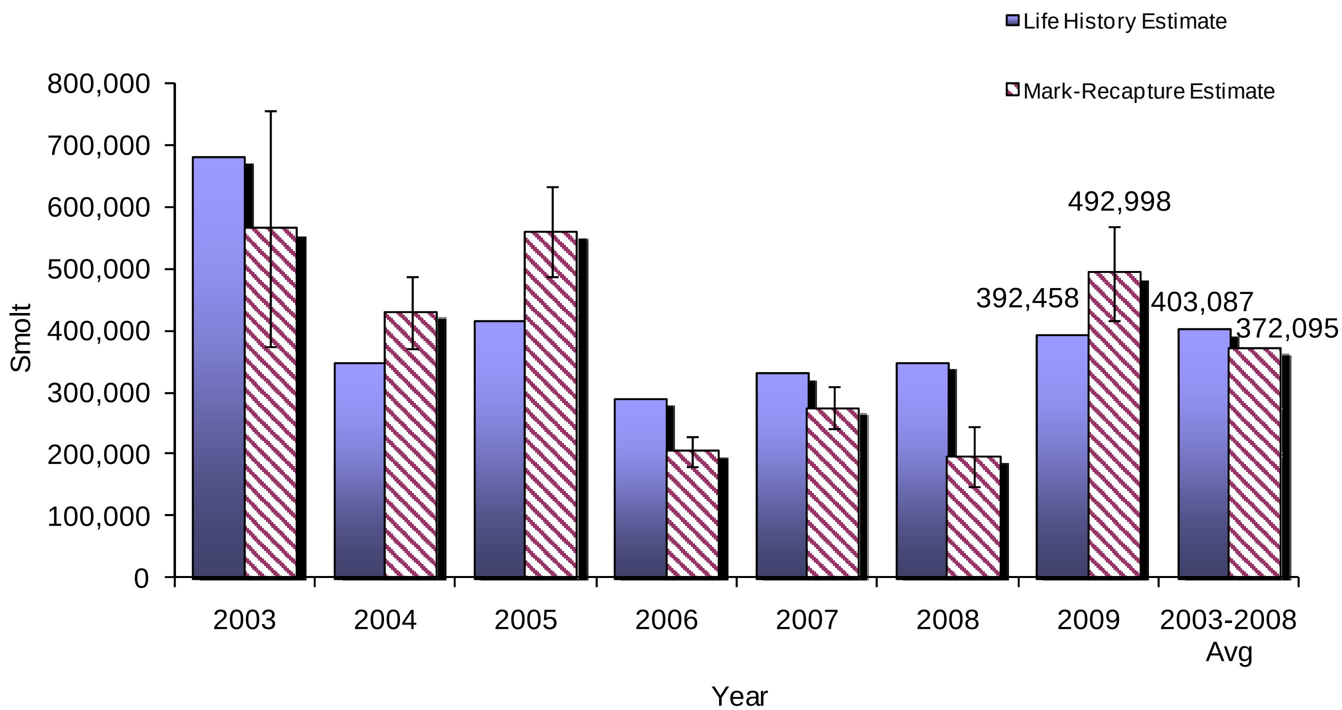

Figure 9.–Comparison of sockeye salmon smolt abundance estimates from life history and mark-recapture models (95% CI), 2003-2009.

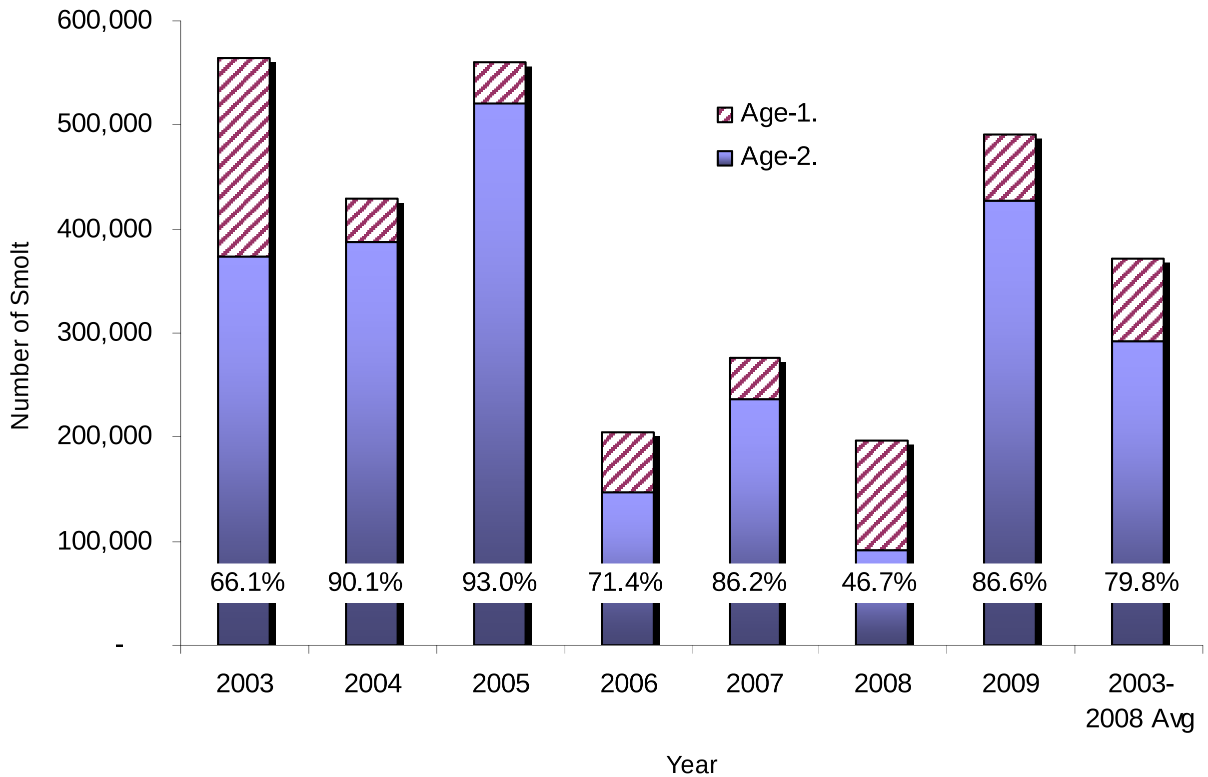

Figure 10.–Age proportion of sockeye salmon smolts emigrating from Afognak Lake, 2003-2009.

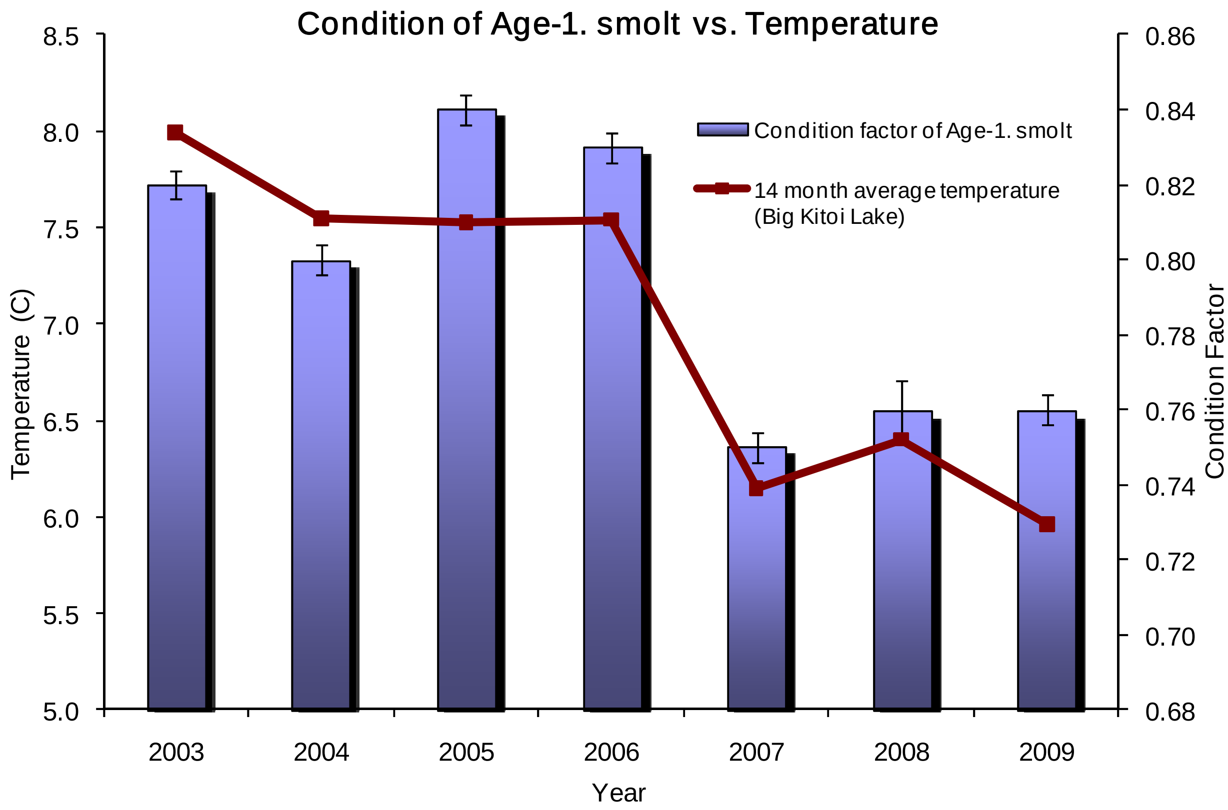

Figure 11.–Age-1. sockeye salmon smolt body condition (95% CI) and estimated 14 month average water temperature of Afognak Lake, 2003-2009.

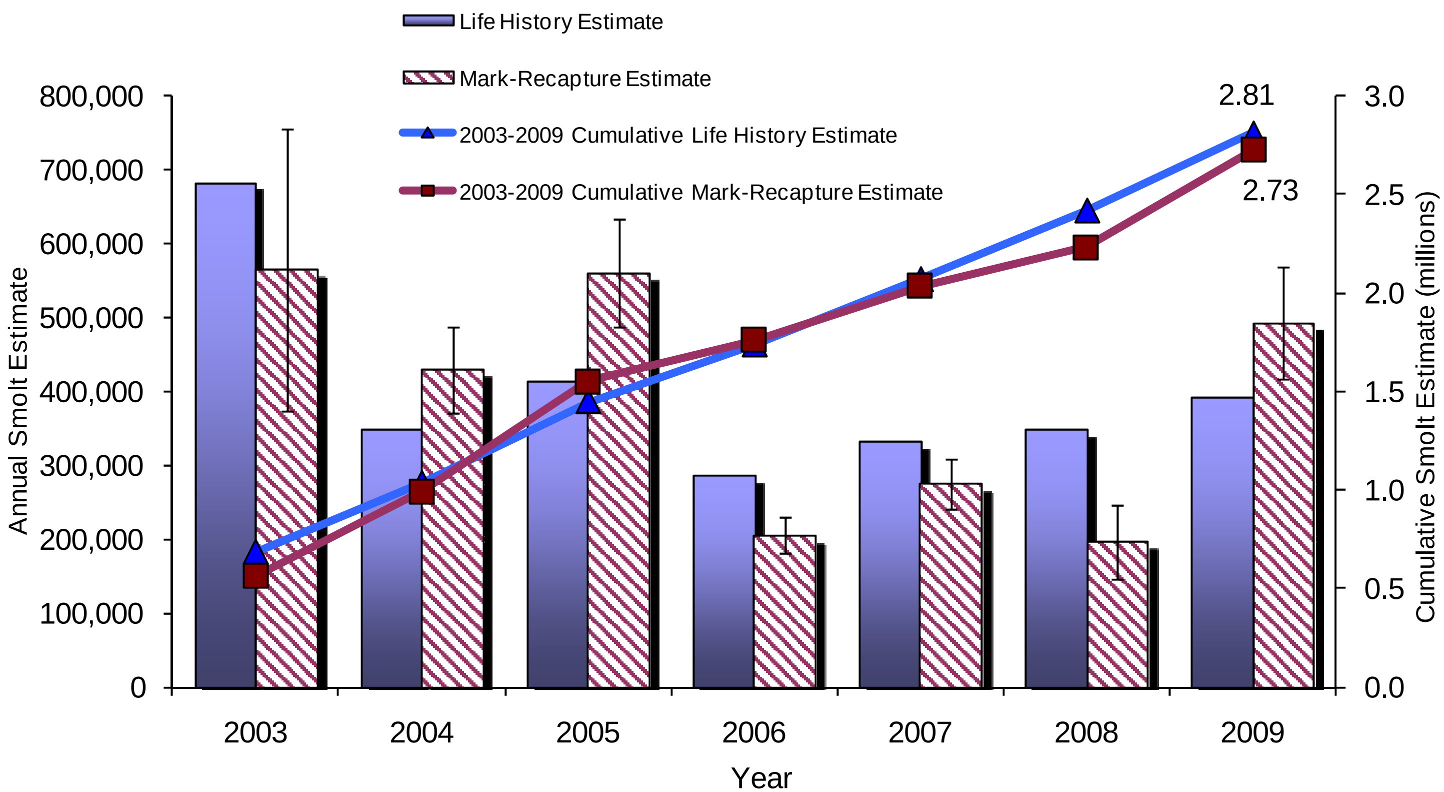

Figure 12.–Afognak Lake annual and cumulative smolt abundance estimates from life history and mark-recapture models (95% CI), 2003-2009.

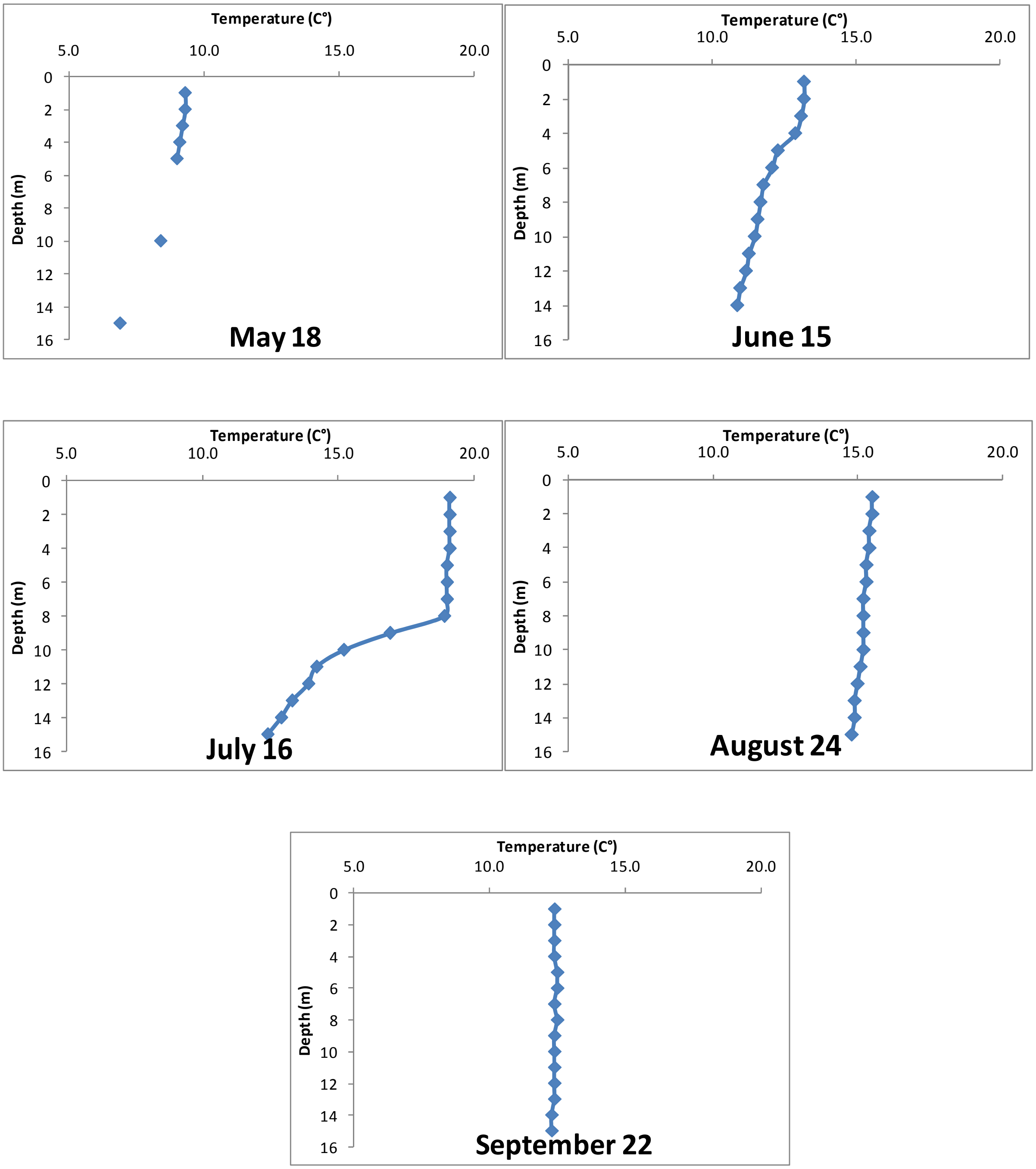

Figure 13.–Temperature profiles by sampling date from Afognak Lake, 2009.

APPENDIX: SUPPORTING HISTORICAL INFORMATION

Appendix 1.–Population estimates of the sockeye salmon emigrations from Afognak Lake 2003-2009.

Stratum (h)	Starting date	Ending date	Catch (u_h)	Released (M_h)	Recaptured (m_h)	Avg.trap efficency (%)	Estimate (U_h)	Variance (U_h)	95% Confidence Interval lower	95% Confidence Interval upper
					2003					
1	5/12	5/19	1,387	239	5	2.1%	55,480	4.31E+08	14,809	96,151
2	5/20	5/25	2,912	239	5	2.1%	116,480	1.89E+09	31,188	201,772
3	5/26	5/31	11,966	706	161	22.8%	52,222	1.31E+07	45,136	59,308
4	6/1	6/7	31,358	638	133	20.8%	149,536	1.31E+08	127,063	172,008
5	6/8	6/10	11,153	686	257	37.5%	29,698	2.18E+06	26,807	32,589
6	6/11	6/18	18,696	679	103	15.2%	122,243	1.21E+08	100,663	143,823
7	6/19	6/26	4,762	506	79	15.6%	30,179	9.63E+06	24,097	36,261
8	6/27	7/3	736	218	17	7.8%	8,955	3.97E+06	5,050	12,859
Total			82,970	3,911	760	19.9%	564,793	2.61E+09	374,814	754,772
							SE=	51,047		
					2004					
1	5/11	5/26	24,278	525	56	10.7%	224,039	7.73E+08	169,530	278,548
2	5/27	6/3	17,727	547	96	17.6%	100,148	8.47E+07	82,111	118,186
3	6/4	6/11	16,658	700	211	30.1%	55,081	1.01E+07	48,864	61,299
4	6/12	6/19	5,086	613	119	19.4%	26,023	4.61E+06	21,815	30,231
5	6/20	7/3	3,779	581	88	15.1%	24,712	5.88E+06	19,958	29,466
Total			67,528	2,966	570	18.6%	430,004	8.79E+08	371,905	488,104
							SE=	2.96E+04		

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Appendix 1.–Page 2 of 3.

Stratum (h)	Starting date	Ending date	Catch (u_h)	Released (M_h)	Recaptured (m_h)	Avg. trap efficency (%)	Estimate (U_h)	Variance (U_h)	95% Confidence Interval lower	95% Confidence Interval upper
2005										
1	5/10	5/21	27,226	489	70	14.3%	184,879	4.05E+08	145,443	224,314
2	5/22	5/26	13,627	518	43	8.3%	155,259	4.89E+08	111,932	198,587
3	5/27	6/5	15,210	482	44	9.1%	158,499	4.94E+08	114,948	202,050
4	6/6	6/27	17,634	368	103	28.0%	61,593	2.58E+07	51,640	71,546
Total			73,697	1,857	260	14.9%	560,230	1.41E+09	486,554	633,906
							SE=	3.76E+04		
2006										
1	5/16	6/1	25,983	312	73	23.6%	110,017	1.24E+08	88,224	131,809
2	6/2	6/6	8,199	515	98	19.2%	42,726	1.49E+07	35,153	50,299
3	6/7	6/16	7,108	485	95	19.8%	35,975	1.09E+07	29,519	42,432
4	6/17	6/29	2,534	492	75	15.4%	16,435	3.06E+06	13,009	19,861
Total			43,824	1,804	341	19.5%	205,153	1.52E+08	180,952	229,353
							SE=	1.23E+04		
2007										
1	5/10	6/5	14,450	415	51	12.5%	115,690	2.22E+08	86,501	144,879
2	6/6	6/12	19,469	202	124	61.5%	31,680	3.09E+06	28,235	35,125
3	6/13	6/20	15,281	510	82	16.2%	94,135	8.88E+07	75,660	112,609
4	6/21	6/27	5,216	541	108	20.1%	25,914	4.98E+06	21,541	30,288
5	6/28	7/4	899	401	44	11.2%	8,031	1.31E+06	5,790	10,272
Total			55,315	2,070	409	19.9%	275,450	3.20E+08	240,388	310,512
							SE=	1.79E+04		

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Appendix 1.–Page 3 of 3.

Stratum (h)	Starting date	Ending date	Catch (u_h)	Released (M_h)	Recaptured (m_h)	Avg. trap efficency (%)	Estimate (U_h)	Variance (U_h)	95% Confidence Interval lower	95% Confidence Interval upper
					2008					
1	5/16	5/31	6,516	202	44	21.8%	29,434	1.48E+07	21,903	36,966
2	6/1	6/11	12,500	394	32	8.1%	149,621	6.05E+08	101,411	197,831
3	6/12	6/19	2,559	244	53	21.7%	11,989	2.08E+06	9,162	14,815
4	6/20	7/3	1,290	306	62	20.3%	5,896	4.54E+05	4,575	7,217
Total			22,865	1,147	191	18.0%	196,941	6.22E+08	148,046	245,835
							SE=	2.49E+04		
					2009					
1	5/10	5/22	14,338	381	65	17.1%	82,891	8.52E+07	64,799	100,983
2	5/23	6/1	37,537	356	50	14.1%	262,568	1.14E+09	196,454	328,681
3	6/2	6/9	5,829	420	43	10.2%	55,727	6.23E+07	40,261	71,192
4	6/10	6/21	5,753	425	35	8.2%	68,080	1.15E+08	47,025	89,136
5	6/22	7/3	1,510	93	5	5.4%	23,732	7.56E+07	6,686	40,778
Total			64,967	1,674	198	11.0%	492,998	1.48E+09	417,689	568,306
							SE=	3.84E+04		

Appendix 2.–Mean weight, length, and condition factor by age for sockeye salmon smolts sampled at Afognak Lake, 1987-2001, and 2003-2009.

		Age-1				Age-2			
Year	Sampling Period	n	Weight (g)	Length (mm)	Condition (K)	n	Weight (g)	Length (mm)	Condition (K)
1987	8-Jun	36	3.6	74.9	0.85	186	3.6	79.3	0.86
1988	15-Jun	202	4.1	77.9	0.90	0			
1989	15-Jun	208	4.1	76.8	0.91	2	5.2	78.0	1.10
1990	May 23-June 24	544	2.5	68.8	0.76	21	3.4	77.3	0.73
1991	May 13-June 26	1,895	3.1	72.9	0.78	176	3.9	78.3	0.81
1992	June 7-20	268	3.8	77.0	0.82	37	3.8	76.9	0.83
1993	May 24-30	274	3.0	72.7	0.78	21	3.3	74.8	0.79
1994	May 17-23	138	3.0	72.0	0.81	142	4.7	84.3	0.79
1995	May 31-June 13	394	2.8	69.4	0.84	5	3.6	78.8	0.74
1996	June 5-11	54	4.6	80.9	0.87	339	4.8	81.6	0.88
1997	May 24-30	76	4.3	81.7	0.78	122	4.4	82.1	0.79
1998	May 24-30	116	2.6	66.4	0.82	46	6.6	88.0	0.90
1999	May 31-June 6	96	2.8	74.6	0.66	98	2.1	66.6	0.69
2000	May 31-June 13	84	4.9	81.5	0.89	100	5.6	85.3	0.89
2001	June 11-13	44	7.0	90.1	0.93	17	5.8	85.6	0.92
2003	May 12-July 3	1,031	4.2	79.1	0.82	383	4.2	81.4	0.77
2004	May 11-July 3	1,370	3.6	75.7	0.80	81	3.6	78.7	0.74
2005	May 10-June 27	1,248	3.9	76.8	0.84	65	4.2	81.3	0.77
2006	May 16-June 29	765	3.0	70.8	0.83	202	3.8	79.6	0.75
2007	May 21 - July 2	960	2.6	70.4	0.75	129	3.4	76.5	0.74
2008	May 26 - June 28	169	3.4	75.9	0.76	164	4.0	81.7	0.73
2009	May 13 - June 29	1,053	3.5	76.7	0.76	205	5.3	88.8	0.75
2003-2008		5,543	3.5	74.8	0.80	1,024	3.9	79.9	0.75
2003-2009		6,596	3.5	75.1	0.79	1,229	4.1	81.1	0.75

Appendix 3.–Temperatures (°C) measured at the 1-meter and near bottom strata in the Spring (May-June), summer (July-August), and fall (September-October) for Afognak Lake 1989-2009.

	Spring		Summer		Fall	
Year	Surface	Bottom	Surface	Bottom	Surface	Bottom
1989	7.8	7.0	16.3	12.8	15.3	13.6
1990	9.4	8.3	14.8	13.6	11.9	11.4
1991	6.2	5.7	15.1	12.5	12.4	12.1
1992	10.0	8.9	15.5	13.9	11.1	11.0
1993	11.9	10.4	17.6	14.5	13.5	12.6
1994	10.8	8.8	15.5	13.5	10.2	9.7
1995	8.8	7.3	15.2	12.8	12.5	11.9
1996	11.5	9.7	15.2	13.9	11.1	10.5
1997	10.3	7.5	17.6	10.6	14.1	12.4
1998	7.9	7.7	14.3	13.0	11.8	11.6
1999	7.0	6.2	15.1	11.4	10.4	10.1
2000	9.7	8.7	15.0	13.1	10.1	10.0
2001	9.1	7.0	17.1	10.2	12.9	12.5
2002	10.0	7.8	16.0	10.8	9.3	9.2
2003	9.7	5.5	18.3	12.9	11.5	11.3
2004	9.2	8.2	15.1	11.7	13.1	12.9
2005	11.8	9.5	18.1	13.5	13.6	13.5
2006	9.2	8.0	15.8	12.5	12.6	12.5
2007	9.2	6.7	15.4	9.5	12.4	12.3
2008	8.6	6.9	14.7	13.3	11.9	11.4
2009	11.1	8.4	17.4	13.9	12.4	12.2
Avg 1989-2008	9.4	7.8	15.9	12.5	12.1	11.6
Avg 1989-2009	9.5	7.8	16.0	12.6	12.1	11.6

Appendix 4.–Dissolved oxygen concentrations (mg L-1) measured at the 1-meter and near bottom strata in the Spring (May-June), summer (July-August), and fall (September-October) for Afognak Lake 1989-2009.

	Spring		Summer		Fall	
Year	Surface	Bottom	Surface	Bottom	Surface	Bottom
1989	11.7	11.2	10.3	9.2	13.1	10.3
1990	14.0	11.8	9.5	8.6	9.6	8.9
1991	12.6	11.1	10.9	8.2	10.5	9.4
1992	11.5	10.8	10.1	8.7	10.8	10.8
1993	10.9	9.8	9.5	7.5	10.5	10.1
1994	11.0	9.8	10.0	8.1	11.3	10.9
1995	11.4	11.3	10.0	8.4	10.5	9.8
1996	10.9	10.5	10.0	7.7	11.2	11.1
1997	10.5	10.7	9.0	4.6	10.2	7.6
1998	11.8	11.7	10.2	6.1	10.2	10.0
1999	11.9	11.5	9.6	6.2	10.9	10.4
2000	11.0	9.1	9.7	6.8	10.5	10.1
2001	9.7	9.6	9.3	4.7	9.0	8.1
2002	10.8	9.3	9.8	0.1	10.5	10.1
2003	12.0	11.1	9.2	5.5	18.0	10.3
2004	12.9	11.2	11.5	8.1	10.5	6.4
2005	10.8	10.2	9.5	5.1	9.5	8.7
2006	10.9	10.0	9.8	8.3	10.5	10.0
2007	11.4	10.8	9.2	6.6	10.6	9.9
2008	12.5	10.7	9.5	8.9	9.5	9.9
2009	10.9	10.3	9.0	7.9	8.9	8.6
Avg 1989-2008	11.5	10.6	9.8	6.9	10.9	9.6
Avg 1989-2009	11.5	10.6	9.8	6.9	10.8	9.6

Appendix 5.–Average euphotic zone depth (EZD), light extinction coefficient (K_d), Secchi disk (SD) transparency, and euphotic volume (EV) for Afognak Lake, 1990-2009.

Year	EZD (m)	SD	K_d (m^{-1})	SD	Secchi (m)	SD	EV ($10^6 m^3$)	SD
1990	7.47	2.46	-2.01	0.53	3.6	0.6	39.60	13.02
1991	8.36	2.40	-2.25	0.68	2.7	0.5	44.32	12.75
1992	9.39	2.79	-2.28	0.35	2.8	0.9	49.77	14.77
1993	9.27	2.23	-2.09	0.52	3.5	0.5	49.14	11.81
1994	7.73	1.45	-1.86	0.33	3.4	0.4	40.97	7.67
1995	7.56	1.18	-1.79	0.27	2.5	0.6	40.08	6.23
1996	8.19	1.53	-1.92	0.37	3.5	0.4	43.41	8.13
1997	6.15	1.75	-1.68	0.59	3.2	0.7	32.61	9.27
1998	7.64	0.82	-1.76	0.25	3.8	1.2	40.50	4.36
1999	9.12	2.67	-1.82	0.35	2.9	0.6	48.36	14.14
2000	9.93	1.65	-2.28	0.39	3.4	0.6	52.62	8.76
2001	10.87	3.24	-2.24	0.40	4.0	1.1	57.61	17.17
2002	10.15	0.69	-2.43	0.17	4.3	0.5	53.80	3.66
2003	9.91	1.11	-2.36	0.25	4.5	0.2	52.51	5.87
2004	10.27	2.57	-2.32	0.31	4.0	0.3	54.42	13.60
2005	9.77	0.64	-2.28	0.20	4.7	0.6	51.77	3.37
2006	9.18	1.05	-2.16	0.36	4.0	0.7	48.67	5.54
2007	9.36	1.27	-2.05	0.36	4.1	0.7	49.61	6.73
2008	9.10	1.40	-2.03	0.27	4.4	0.4	48.23	7.42
2009	9.10	0.57	-2.08	0.15	4.4	0.7	48.21	3.01
Avg 1990-2008	8.92	1.73	-2.08	0.37	3.65	0.62	47.26	9.17
Avg 1990-2009	8.93	1.67	-2.08	0.36	3.68	0.62	47.31	8.86

Appendix 6.–Summary of seasonal mean water chemistry parameters by station and depth for Afognak Lake, 1987-2009.

	Station	Depth	Sp. Conductivity		pH		Alkalinity		Turbidity		Color		Calcium		Magnesium		Iron	
Year		(m)	(umhos cm^{-1})	SD	(Units)	SD	(mg L^{-1})	SD	(NTU)	SD	(Pt units)	SD	(mg L^{-1})	SD	(mg L^{-1})	SD	(ug L^{-1})	SD
1987	1	1	47	2.6	6.7	0.2	10.0	0.8	0.8	0.3	8	1.7	3.6	0	0.6	0	76	34.9
	1	17	46	2.8	6.7	0.4	9.5	1.0	0.7	0.4	8	2.6	4	0	1	0	58	17.3
1988	1	1	51	5.9	6.7	0.5	10.8	1.3	1.4	1.0	12	2.4	4.7	ND	1.6	ND	50	13.6
	1	15	50	0.5	6.9	0.2	11.3	1.0	1.1	0.8	10	1.3	ND	ND	ND	ND	81	77.7
	2	1	51	3.7	6.9	0.1	10.5	1.7	1.4	1.1	12	3.2	ND	ND	ND	ND	63	22.3
	2	10	50	2.3	6.8	0.1	10.3	0.6	1.5	1.2	9	2.9	ND	ND	ND	ND	96	52.7
1989	1	1	64	1.9	7.0	0.5	10.6	1.5	2.4	3.5	8	4.4	4.0	0.6	1.1	0.9	44	10.5
	1	15	63	1.0	6.9	0.2	10.2	1.6	0.7	0.1	10	0.7	4.3	0.2	1.2	0.8	51	19.3
	2	1	63	0.8	7.0	0.3	10.4	1.3	0.8	0.2	10	1.1	3.8	0.4	1.5	0.6	53	9.1
	2	12	65	3.3	6.9	0.4	10.6	2.2	0.8	0.2	10	1.4	4.4	0.1	1.4	0.3	91	39.1
1990	1	1	41	1.7	6.8	0.1	6.3	0.5	0.8	0.4	14	3.4	2.9	1.4	0.4	0.3	121	24.3
	1	16	41	1.0	6.7	0.2	6.1	0.6	0.7	0.4	11	2.2	3.2	1.8	0.4	0.3	128	38.7
1991	1	1	38	0.8	6.7	0.1	10.4	7.8	0.9	0.3	13	0.8	2.1	0.3	0.8	0.5	210	31.1
	1	14	38	1.0	6.6	0.2	6.9	0.3	0.9	0.2	16	3.9	1.9	0.1	0.8	0.5	190	45.0
1992	1	1	35	1.2	6.6	0.2	5.8	1.0	0.9	0.5	12	3.4	2.5	0.9	0.6	0.3	157	9.3
	1	24	35	0.5	6.3	0.1	4.9	1.0	0.8	0.6	11	1.5	2.5	1.2	0.6	0.3	162	56.9
1993	1	1	37	1.0	6.6	0.1	7.5	2.7	0.5	0.1	7	7.5	2.2	0.4	1.3	1.1	104	34.9
	1	25	39	4.0	6.4	0.4	7.8	2.1	0.5	0.2	10	10.7	2.6	0.9	0.8	0.1	134	52.0
1994	1	1	39	6.5	6.6	0.2	6.2	2.0	1.1	0.8	5	3.2	2.2	0.9	0.6	0.2	141	44.0
	1	2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	1	26	36	0.9	6.3	0.3	6.5	2.5	0.7	0.3	6	4.7	2.2	0.5	0.6	0.2	197	87.7
1995	1	1	60	5.6	6.6	0.2	9.8	1.0	2.0	0.8	11	2.6	3.7	1.4	1.3	0.4	85	45.6
	1	17	60	5.4	6.5	0.2	10.0	1.3	2.3	1.2	9	2.0	3.4	0.5	1.6	0.5	101	33.0
	2	1	58	4.9	6.6	0.2	9.7	1.1	1.9	0.9	11	4.3	3.2	0.3	1.1	0.3	87	55.9
	2	11	58	4.3	6.5	0.2	9.6	1.1	2.0	0.8	10	5.5	3.5	0.4	1.3	0.3	101	53.9
1996	1	1	56	1.5	6.7	0.2	10.5	0.7	1.4	1.0	10	2.5	3.2	0.5	1.3	0.2	54	25.9
	1	18	57	2.7	6.6	0.1	11.2	1.9	1.5	0.7	9	0.5	3.1	0.5	1.1	0.3	72	33.2
	2	1	56	1.4	6.7	0.1	10.7	1.0	1.2	0.6	9	1.3	3.1	0.5	1.1	0.3	54	25.7
	2	11	57	1.1	6.7	0.1	10.7	1.0	1.5	0.6	11	2.6	2.9	0.5	1.5	0.3	89	43.4

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	Station	Depth	Sp. Conductivity		pH		Alkalinity		Turbidity		Color		Calcium		Magnesium		Iron	
Year		(m)	(umhos cm^{-1})	SD	(Units)	SD	(mg L^{-1})	SD	(NTU)	SD	(Pt units)	SD	(mg L^{-1})	SD	(mg L^{-1})	SD	(ug L^{-1})	SD
1997	1	1	53	0.6	7.1	0.2	12.1	1.6	1.1	0.1	9	1.9	3.1	0.4	1.1	0.3	28	16.6
	1	18	58	6.7	6.8	0.2	13.9	3.5	1.7	0.4	10	0.8	2.9	0.5	1.7	1.1	68	37.7
	2	1	53	0.8	7.1	0.1	11.7	0.5	1.0	0.2	11	3.8	3.0	0.3	1.0	0.3	34	17.3
	2	13	53	0.5	7.0	0.1	11.9	0.3	1.3	0.5	10	3.0	2.9	0.3	1.0	0.3	44	25.8
1998	1	1	49	0.6	7.0	0.1	12.6	1.3	1.7	1.2	18	10.7	3.2	0.5	0.8	0.2	26	15.0
	1	18	48	ND	7.0	ND	11.8	ND	2.0	ND	11	ND	3.3	ND	1.0	ND	48	ND
1999	1	1	58	0.0	6.8	0.2	11.1	0.6	1.6	1.0	11	1.7	3.3	0.3	1.4	0.1	82	43.8
2000	1	1	ND	ND	7.1	0.2	8.7	2.4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2001	1	1	ND	ND	7.2	0.4	10.1	2.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2002	1	1	ND	ND	7.2	0.5	10.1	0.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2003	1	1	ND	ND	6.9	0.1	9.8	0.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2004	1	1	ND	ND	6.9	0.1	11.4	0.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	1	18	ND	ND	6.8	0.1	10.9	0.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2005	1	1	ND	ND	6.8	0.1	10.9	1.1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2006	1	1	ND	ND	6.8	0.1	11.3	0.9	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2007	1	1	ND	ND	6.8	0.1	10.9	1.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2008	1	1	ND	ND	6.7	0.2	11.4	1.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2009	1	1	ND	ND	7.0	0.4	11.7	0.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Pre-fertilization yrs.																		
1987-1989 Avg			55	3.0	6.8	0.3	10.5	1.3	1.3	1.2	10	2.6	4.0	0.3	1.2	0.5	57	18.1
Fertilization yrs.																		
1990-2000 Avg	1		49	2.1	6.8	0.2	9.5	1.7	1.2	0.6	11	3.6	2.9	0.6	1.0	0.3	91	30.0
All yrs.																		
1987-2008 Avg	1		50	2.3	6.8	0.2	10.0	1.5	1.3	0.8	10	3.3	3.2	0.6	1.0	0.4	81	26.7
1987-2009 Avg	1		50	2.3	6.8	0.2	10.1	1.5	1.3	0.8	10	3.3	3.2	0.6	1.0	0.4	81	26.7
Post-fertilization yrs.																		
2001-2008 Avg	1		ND	ND	6.9	0.2	10.5	1.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2001-2009 Avg	1		ND	ND	6.9	0.2	10.8	1.1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Appendix 7.–Summary of seasonal mean nutrient and algal pigment concentrations by station and depth for Afognak Lake, 1990-2009.

Year	Station	Depth (m)	Total Phosphorus ($ug\ L^{-1}$)	SD	Total filterable-P ($ug\ L^{-1}$)	SD	Filterable reactive-P ($ug\ L^{-1}$)	SD	Total Kjeldahl Nitrogen ($ug\ L^{-1}$)	SD	Ammonia ($ug\ L^{-1}$)	SD	Nitrate +Nitrite ($ug\ L^{-1}$)	SD	Reactive Silicon ($ug\ L^{-1}$)	SD	Organic Carbon ($ug\ L^{-1}$)	SD	Chlorophyll *a* ($ug\ L^{-1}$)	SD	Phaeophytin *a* ($ug\ L^{-1}$)	SD
1990	1	1	4.5	1.5	2.9	4.2	3.7	1.7	128	16.5	8	3.0	40	29.1	3250	247.5	145	13.0	0.34	0.19	0.17	0.03
	1	16	5.1	2.3	1.3	1.3	2.8	1.1	118	22.7	10	4.2	65	29.1	3390	154.5	144	30.6	0.21	0.03	0.28	0.07
1991	1	1	5.0	2.8	3.2	0.6	2.3	0.4	151	22.6	11	1.8	57	21.3	2865	108.6	ND	ND	0.31	0.21	0.27	0.07
	1	14	4.6	1.5	6.0	3.5	4.5	3.2	138	12.3	14	5.0	70	23.2	2966	156.3	ND	ND	0.22	0.14	0.22	0.08
1992	1	1	3.8	0.5	4.1	2.5	3.1	2.4	135	13.9	3	1.7	62	26.1	3163	158.9	199	64.1	0.44	0.29	0.28	0.13
	1	24	3.9	1.7	4.0	3.2	2.6	1.7	127	12.8	10	4.1	93	23.1	3182	198.0	163	52.9	0.31	0.25	0.28	0.12
1993	1	1	4.5	0.8	3.7	1.3	2.8	0.5	148	18.5	5	2.2	49	30.4	3132	220.6	147	53.3	1.01	0.31	0.36	0.03
	1	25	4.9	1.3	8.5	11.7	6.8	9.9	136	17.3	19	10.1	98	31.7	3380	244.0	121	47.5	0.52	0.21	0.45	0.14
1994	1	1	5.7	0.7	4.5	3.3	3.6	2.3	160	23.8	3	1.7	40	21.4	2843	122.4	114	33.0	0.56	0.26	0.28	0.08
	1	2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.56	0.34	0.34	0.10
	1	26	5.3	1.1	4.8	3.9	4.2	3.2	160	17.7	15	9.7	74	23.8	3177	285.5	128	52.1	0.36	0.21	0.27	0.09
1995	1	1	8.7	2.7	3.0	1.5	2.0	1.1	168	21.6	9	14.1	66	22.1	1873	735.0	ND	ND	3.92	2.44	1.13	0.62
	1	17	8.1	2.0	1.9	1.1	1.1	0.4	187	47.1	35	44.3	45	35.0	2046	618.4	ND	ND	3.13	1.75	1.10	0.54
	2	1	7.4	2.1	2.1	1.2	1.7	1.0	169	31.0	9	14.0	54	33.2	1942	753.9	ND	ND	4.20	2.90	1.05	0.65
	2	11	7.2	1.7	2.2	2.0	1.6	1.1	157	26.0	16	17.4	52	34.1	2143	805.6	ND	ND	3.27	2.18	1.05	0.62
1996	1	1	9.2	2.6	3.4	0.7	2.8	0.3	161	34.0	18	13.9	40	29.2	2465	297.2	225	80.3	2.39	1.16	0.82	0.38
	1	18	8.2	2.7	2.4	0.7	2.2	0.3	161	56.5	36	37.6	51	27.8	2663	176.1	190	73.1	1.40	0.56	0.81	0.37
	2	1	8.8	2.6	2.7	0.8	2.2	0.4	160	37.3	8	14.6	41	25.9	2466	275.0	226	52.5	1.77	0.50	0.85	0.36
	2	11	8.4	2.8	3.4	1.6	2.9	1.3	147	41.3	29	24.5	50	25.9	2630	220.7	169	55.7	1.07	0.29	0.77	0.31
1997	1	1	7.3	1.9	2.7	1.0	2.6	0.9	155	33.9	14	14.2	22	23.9	2347	354.4	273	63.8	2.56	1.42	1.51	0.66
	1	18	7.2	1.5	2.6	0.5	2.3	0.4	194	68.6	64	53.3	55	14.5	2995	503.5	197	28.8	1.12	0.50	1.08	0.38
	2	1	6.9	1.7	3.6	1.8	3.1	1.5	156	37.8	13	15.8	17	21.8	2435	351.3	252	62.8	1.68	1.25	1.19	0.83
	2	13	6.5	1.4	2.8	1.9	2.3	0.8	148	38.7	21	12.4	30	20.1	2584	433.5	156	50.6	1.33	1.17	1.06	0.76

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	Station	Depth	Total Phosphorus		Total filterable-P		Filterable reactive-P		Total Kjeldahl Nitrogen		Ammonia		Nitrate +Nitrite		Reactive Silicon		Organic Carbon		Chlorophyll *a*		Phaeophytin *a*	
Year		(m)	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD	(ug L^{-1})	SD
1998	1	1	9.0	1.7	3.3	0.8	1.9	0.0	193	7.7	21	13.9	38	15.9	2387	73.0	152	118.8	0.10	0.04	0.04	0.02
	1	18	7.5	ND	3.7	ND	1.9	ND	182	ND	25	ND	63	ND	2311	ND	36	ND	0.09	ND	0.03	ND
1999	1	1	17.7	18.3	8.6	10.2	6.8	10.0	247	147.2	36	42.6	124	35.2	2390	431.5	261	122.2	2.94	3.19	0.56	0.35
2000	1	1	9.5	4.3	3.1	1.6	1.8	1.6	57	36.6	19	12.5	72	36.1	ND	ND	ND	ND	2.43	1.46	1.10	0.80
2001	1	1	7.8	5.1	6.4	5.2	8.2	6.7	115	22.2	5	3.6	38	32.5	ND	ND	ND	ND	2.37	0.53	0.30	0.20
2002	1	1	6.4	2.3	4.5	3.1	1.5	0.9	131	15.4	5	2.5	27	18.8	ND	ND	ND	ND	1.36	0.14	0.30	0.20
2003	1	1	6.5	3.0	2.2	0.8	2.1	0.8	ND	ND	6	1.8	54	26.9	ND	ND	ND	ND	1.20	0.20	0.50	0.40
2004	1	1	6.2	3.5	4.3	3.2	2.0	0.7	169	103.8	9	2.8	61	31.5	2764	342.8	ND	ND	1.15	0.18	0.28	0.08
	1	18	5.9	2.3	6.2	8.3	3.5	3.5	ND	ND	19	13.2	80	28.4	2914	277.1	ND	ND	0.70	0.35	0.19	0.11
2005	1	1	11.4	4.4	7.6	3.6	3.6	3.1	161	45.6	4	2.0	41	34.8	2701	243.7	ND	ND	1.60	0.68	0.24	0.11
2006	1	1	7.2	4.3	2.2	1.6	2.3	1.1	97	59.6	7	1.7	28	30.8	ND	ND	ND	ND	1.92	0.32	0.50	0.09
2007	1	1	3.6	0.4	1.1	0.3	1.1	0.6	115	32.4	6	0.7	56	39.5	ND	ND	ND	ND	1.47	0.43	0.21	0.08
2008	1	1	3.8	1.1	2.3	1.5	1.6	0.9	113	28.6	6	0.6	65	42.3	ND	ND	ND	ND	1.22	0.66	0.58	0.37
2009	1	1	4.8	1.1	1.3	0.3	1.8	1.0	131	29.7	4	0.8	39	40.0	ND	ND	ND	ND	1.92	0.64	0.63	0.33
Pre-fertilization yrs.																						
1987-1989 Avg		1	8.0	2.6	4.4	1.8	2.5	0.5	133	14.0	3.6	2.8	79	43.5	2766	321.2	191	42.2	1.10	0.61	0.59	0.21
Fertilization yrs.																						
1990-2000 Avg		1	7.7	3.1	3.6	2.2	2.9	1.7	156	34.5	12.8	11.8	51	26.5	2581	317.6	199	66.4	1.76	1.12	0.69	0.36
All yrs.																						
1987-2008 Avg		1	7.4	3.0	3.8	2.2	2.8	1.5	144	33.1	9.0	7.2	55	31.3	2643	316.1	197	60.8	1.57	0.81	0.57	0.28
1987-2009 Avg		1	7.3	2.9	3.7	2.2	2.8	1.5	144	33.0	8.9	7.0	54	31.7	2643	316.1	197	60.8	1.58	0.80	0.57	0.28
Post-fertilization yrs.																						
2001-2008 Avg		1	6.6	3.0	3.8	2.4	2.8	1.9	129	43.9	5.8	2.0	46	32.1	2732	293.3	ND	ND	1.54	0.39	0.36	0.19
2001-2009 Avg		1	6.4	2.8	3.5	2.2	2.7	1.8	129	42.2	5.7	1.8	45	33.0	2732	293.3	ND	ND	1.58	0.42	0.39	0.21

Appendix 8.–Weighted mean zooplankton density, biomass, size by species for station 1 (1987-2009) and station 2 (1988-2009), Afognak Lake.

Station		*Epischura*			*Diaptomus*			*Cyclops*			*Bosmina*			*Daphnia*			*Holopedium*			TOTALS	
1	No.	Density	Biomass	Size	Density	Biomass	Size	Density	Biomass	Size	Density	Biomass	Size	Density	Biomass	Size	Density	Biomass	Size	Density	Biomass
Year	Samples	(no/m^2)	(mg/m^2)	(mm)	(no/m^2)	(mg/m^2)	(mm)	(no/m^2)	(mg/m^2)	(mm)	(no/m^2)	(mg/m^2)	(mm)	(no/m^2)	(mg/m^2)	(mm)	(no/m^2)	(mg/m^2)	(mm)	(no/m^2)	(mg/m^2)
1987	4	28,835	100	0.91	173	1	1.01	4,127	6	0.65	138,370	134	0.33	3,218	4	0.54	2,574	6	0.52	177,297	251
1988	4	22,360	77	0.91	0	0	-	3,185	5	0.69	106,462	104	0.33	962	2	0.71	1,228	3	0.53	134,197	191
1989	5	16,322	71	0.99	0	0	-	3,663	5	0.66	69,638	59	0.31	1,778	3	0.64	1,347	3	0.48	92,748	141
1990	7	15,378	60	0.95	7	0	0.90	9,987	16	0.68	155,051	134	0.31	3,392	5	0.61	4,944	9	0.47	188,759	224
1991	6	21,278	102	1.02	265	1	0.79	6,606	12	0.74	208,574	193	0.32	4,089	9	0.72	4,025	8	0.50	244,837	325
1992	7	23,468	104	0.99	485	1	0.88	4,807	8	0.68	106,832	108	0.33	5,513	13	0.74	3,306	6	0.45	144,411	240
1993	7	33,893	127	0.94	76	0	0.83	5,960	11	0.72	240,817	247	0.34	7,689	14	0.66	3,715	8	0.50	292,150	407
1994	8	23,713	66	0.85	1,844	7	0.98	10,231	17	0.69	257,749	256	0.33	9,621	18	0.66	7,271	13	0.48	310,429	377
1995	7	16,758	84	1.04	5,596	16	0.87	24,932	39	0.68	212,768	197	0.32	13,740	22	0.62	1,410	2	0.46	275,204	360
1996	5	42,112	223	1.06	191	0	0.49	11,614	19	0.69	350,806	378	0.34	16,072	44	0.78	2,909	5	0.47	423,704	670
1997	6	14,367	69	1.02	5,520	11	0.75	24,567	41	0.69	81,591	66	0.30	11,720	17	0.58	915	1	0.43	138,679	205
1998	4	15,672	62	0.96	1,088	5	1.05	2,070	3	0.67	169,971	144	0.31	10,881	14	0.56	5,441	8	0.42	205,123	236
1999	4	18,737	78	0.97	5,945	24	0.97	6,688	12	0.71	133,175	130	0.33	9,449	20	0.68	2,495	5	0.46	176,489	269
2000	5	57,643	180	0.88	8,121	44	1.09	10,743	16	0.66	114,297	126	0.35	5,042	9	0.64	1,408	2	0.46	116,722	188
2001	5	30,122	66	0.77	2,548	6	0.79	8,121	10	0.61	40,764	33	0.30	1,253	1	0.49	2,638	4	0.43	85,446	120
2002	4	8,174	21	0.82	1,009	3	0.92	6,380	7	0.56	38,256	36	0.32	2,935	3	0.51	557	1	0.41	57,311	71
2003	4	39,743	73	0.73	3,782	7	0.74	3,185	4	0.62	102,110	85	0.30	1,393	2	0.60	1,194	2	0.48	151,407	173
2004	5	23,206	37	0.69	510	1	0.86	6,374	8	0.62	58,598	52	0.31	11,472	16	0.58	2,771	5	0.48	102,931	119
2005	5	21,369	59	0.84	1,592	4	0.83	8,238	10	0.60	82,409	65	0.30	4,979	7	0.57	2,027	3	0.43	120,614	148
2006	5	29,565	92	0.88	3,450	10	0.85	9,915	20	0.76	76,518	61	0.30	8,408	11	0.56	6,348	11	0.46	134,204	205
2007	5	10,913	24	0.78	2,930	9	0.88	7,718	13	0.70	74,257	66	0.31	3,386	5	0.58	1,730	3	0.47	100,934	120
2008	5	16,561	45	0.84	823	2	0.83	2,670	3	0.61	66,762	55	0.30	4,231	7	0.62	3,079	6	0.49	94,126	119
2009	5	13,402	42	0.88	0	0		1,409	2	0.60	31,539	24	0.29	2,866	4	0.54	1,208	2	0.45	50,424	73
Pre-fertilization yrs.																					
1987-1989 Avg		22,506	83	0.94	58	0	1.01	3,658	5	0.67	104,823	99	0.32	1,986	3	0.63	1,716	4	0.51	134,747	194
Fertilization yrs.																					
1990-2000 Avg		25,729	105	0.97	2,649	10	0.87	10,746	18	0.69	184,694	180	0.33	8,837	17	0.66	3,440	6	0.46	228,773	318
All yrs.																					
1987-2008 Avg		24,100	83	0.90	2,089	7	0.87	8,263	13	0.67	131,172	124	0.32	6,419	11	0.62	2,879	5	0.47	171,260	234
1987-2008 Avg		23,634	81	0.90	1,998	7	0.87	7,965	12	0.67	126,840	120	0.32	6,265	11	0.62	2,806	5	0.47	166,006	227
Post-fertilization yrs.																					
2001-2008 Avg		22,457	52	0.79	2,081	5	0.84	6,575	9	0.64	67,459	57	0.31	4,757	6	0.56	2,543	4	0.46	105,872	134
2001-2009 Avg		21,451	51	0.80	1,849	5	0.84	6,001	9	0.63	63,468	53	0.30	4,547	6	0.56	2,395	4	0.46	99,711	128

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Station 2 Year	No. Samples	*Epischura* Density (no/m^2)	*Epischura* Biomass (mg/m^2)	*Epischura* Size (mm)	*Diaptomus* Density (no/m^2)	*Diaptomus* Biomass (mg/m^2)	*Diaptomus* Size (mm)	*Cyclops* Density (no/m^2)	*Cyclops* Biomass (mg/m^2)	*Cyclops* Size (mm)	*Bosmina* Density (no/m^2)	*Bosmina* Biomass (mg/m^2)	*Bosmina* Size (mm)	*Daphnia* Density (no/m^2)	*Daphnia* Biomass (mg/m^2)	*Daphnia* Size (mm)	*Holopedium* Density (no/m^2)	*Holopedium* Biomass (mg/m^2)	*Holopedium* Size (mm)	TOTALS Density (no/m^2)	TOTALS Biomass (mg/m^2)
1988	4	10,656	45	0.98	40	0	1.44	809	1	0.70	108,838	110	0.33	1,405	3	0.65	942	3	0.55	122,690	162
1989	5	10,306	35	0.90	0	0	-	1,261	2	0.66	48,235	40	0.30	420	1	0.63	553	1	0.46	60,775	79
1990	7	12,610	48	0.94	0	0	-	3,460	5	0.66	128,277	108	0.31	2,350	4	0.64	4,026	7	0.47	150,723	172
1991	6	19,285	80	0.97	1,274	4	0.89	4,277	8	0.74	154,341	132	0.31	3,347	6	0.65	5,083	10	0.49	187,607	240
1992	7	8,948	34	0.94	144	1	1.00	1,436	2	0.67	82,879	84	0.33	2,521	5	0.70	1,579	3	0.45	97,507	129
1993	7	19,033	70	0.93	773	1	0.69	3,882	5	0.62	175,106	157	0.32	2,570	5	0.67	3,988	7	0.47	205,352	245
1994	8	11,006	40	0.93	783	3	0.91	2,736	4	0.65	125,352	116	0.32	4,321	7	0.64	2,468	4	0.46	146,666	174
1995	7	12,193	44	0.92	1,168	4	0.94	9,054	11	0.61	111,525	98	0.31	8,902	12	0.58	1,152	1	0.4	143,994	170
1996	5	20,892	99	1.02	255	2	1.17	2,930	6	0.77	219,747	239	0.35	4,331	11	0.76	1,571	2	0.46	249,726	359
1997	6	13,677	57	0.97	3,468	7	0.75	3,822	5	0.64	86,060	63	0.29	9,652	13	0.56	924	1	0.41	117,601	146
2004	5	27,192	44	0.70	32	0	0.95	5,125	8	0.66	34,843	27	0.29	2,187	4	0.62	1,624	3	0.44	71,003	84
2005	5	22,282	60	0.83	0	0	-	2,850	4	0.63	49,992	37	0.29	815	2	0.73	900	1	0.38	76,839	104
2006	5	9,408	14	0.68	510	1	0.78	3,083	5	0.70	44,282	31	0.28	3,571	5	0.59	1,274	2	0.43	62,128	59
2007	5	16,269	63	0.95	1,141	4	0.93	6,693	12	0.71	57,065	49	0.31	934	1	0.55	2,049	4	0.50	84,151	133
2008	5	20,786	51	0.81	1,592	8	1.04	2,484	3	0.59	49,260	38	0.29	786	2	0.67	1,314	2	0.44	76,222	103
2009	5	5,149	11	0.77	106	0	0.70	1,645	2	0.64	16,189	10	0.27	1,380	2	0.51	902	2	0.46	25,371	27
Pre-fertilization yrs.																					
1988-1989 Avg		10,481	40	0.94	20	0	1.44	1,035	2	0.68	78,537	75	0.32	913	2	0.64	748	2	0.51	91,733	121
Fertilization yrs.																					
1990-1997 Avg		14,705	59	0.95	983	3	0.91	3,950	6	0.67	135,411	125	0.32	4,749	8	0.65	2,599	4	0.45	162,397	204
All yrs.																					
1988-2008 Avg		15,636	52	0.90	745	2	0.96	3,593	5	0.67	98,387	89	0.31	3,207	5	0.64	1,963	3	0.45	123,532	157
1988-2009 Avg		14,981	50	0.89	705	2	0.94	3,472	5	0.67	93,249	84	0.31	3,093	5	0.63	1,897	3	0.45	117,397	149
Post-fertilization yrs.																					
2004-2008 Avg		19,187	46	0.79	655	3	0.93	4,047	6	0.66	47,088	36	0.29	1,659	3	0.63	1,432	2	0.44	74,069	97
2004-2009 Avg		16,848	41	0.79	564	2	0.88	3,647	6	0.66	41,939	32	0.29	1,612	3	0.61	1,344	2	0.44	65,952	85