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Tumakof Lake (Redfish Bay) Sockeye Salmon Stock Assessment 2003 Annual Report

by

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February 2008

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

FISHERY DATA REPORT NO. 08-01

TUMAKOF LAKE (REDFISH BAY) SOCKEYE SALMON STOCK ASSESSMENT 2003 ANNUAL REPORT

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The Division of Sport Fish Fishery Data Series was established in 1987 for the publication of technically oriented results for a single project or group of closely related projects. Since 2004, the Division of Commercial Fisheries has also used the Fishery Data Series. Fishery Data Series reports are intended for fishery and other technical professionals. Fishery Data Series reports are available through the Alaska State Library and on the Internet: http://www.sf.adfg.state.ak.us/statewide/divreports/html/intersearch.cfm This publication has undergone editorial and peer review.

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ABSTRACT

In 2003, we estimated the sockeye escapement into Tumakof Lake and the number of sockeye salmon (*Oncorhynchus nerka*) harvested in the subsistence and sport fisheries at the head of Redfish Bay, and collected baseline information on the freshwater habitat of sockeye juveniles. We counted salmon through a weir and used mark-recapture methods to verify the sockeye weir count. The weir count (42,200 fish) was about 25% lower than the mark-recapture estimate (58,000 sockeye salmon). The 2003 weir count most likely under-represented the true escapement due to fish moving into the system during high water events and after removing the weir in mid-September. Therefore, the mark-recapture estimate is the official sockeye escapement estimate for Tumakof Lake in 2003. This estimate, however, could also be biased because the assumption of a closed population was most likely violated. The subsistence and sport fishers only harvested 2% of the sockeye adults returning to the marine terminal area of Redfish Bay. In 2003, we observed very low levels of *Daphnia longiremis*, the preferred zooplankton prey of sockeye fry, which suggests that the predation pressure was high. The highly variable percent of the number of sockeye smolt that left the lake after one year, 1% in 2002 and 44% in 2003, is difficult to evaluate without information about the sockeye spawning population in 2001 and several more years of information to account for environmental variability. In summary, the current subsistence and sport harvest in Redfish Bay does not appear to be appreciably limiting future sockeye recruitment in Tumakof Lake. Furthermore, the estimates of *D. longiremis* abundance and biomass suggest that this system could be approaching carrying capacity, especially in years when the environmental conditions are less than optimal for zooplankton production.

Key words: sockeye salmon, *Oncorhynchus nerka*, Redfish Bay, Baranof Island, stock assessment, limnology, zooplankton, harvest, subsistence, escapement

INTRODUCTION

Historically, the indigenous people on the west coast of Baranof Island relied heavily on the sockeye salmon (*Oncorhynchus nerka*) resource in the Tumakof Lake system (Goldschmidt and Haas 1998). The Tlingit Kiks.ádi clan was the traditional caretaker of Shee Lunaaxk Gatheeni, or Redfish Bay. Evidence of the Tlingit use and occupation of this area was demonstrated with the discovery of a shard of a 5,000 year old hemlock basket (R. Craig, Sitka Tribe of Alaska, personal communication) and weir stakes still visible at low tide on the beach. The outlet stream of Tumakof Lake empties into Redfish Bay, which has the fourth largest reported subsistence catch in the Sitka area (ADF&G Div. of Commercial Fisheries database; Appendix A1). Fishing pressure on Tumakof Lake sockeye population may intensify if sockeye populations within and near Sitka Sound experience poor returns.

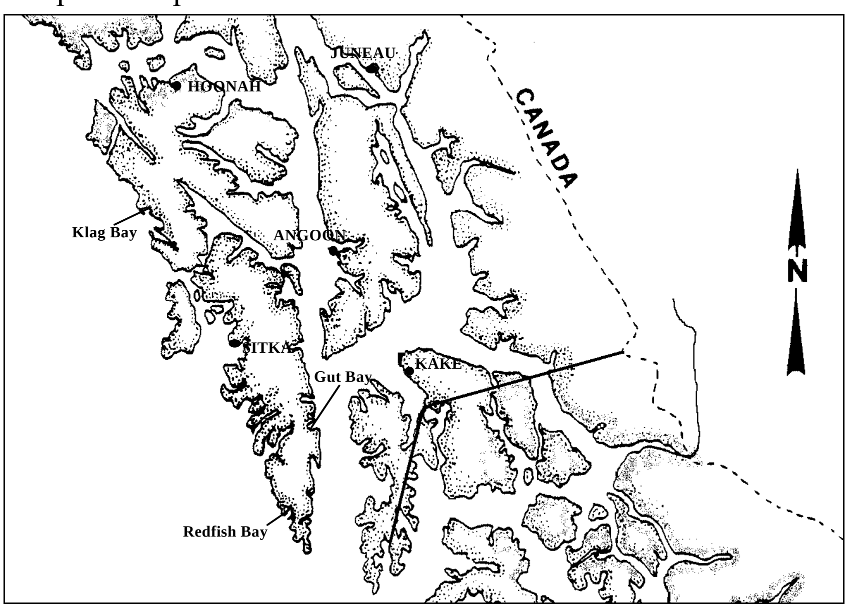

Figure 1.–The location of Redfish Bay in relation to Sitka on Baranof Island, Alaska.

Commercial sockeye harvest and sporadic escapement data indicate that sockeye returns to Tumakof Lake have been variable. Although historical records most likely included sockeye salmon from nearby systems, commercial harvests from Redfish Bay ranged from 103,000 in 1896 to 64,000 in 1897 (Moser 1899). Total escapements of 14,000 sockeye salmon in 1955 and 66,000 sockeye salmon in 1966 were counted through a weir (Hilsinger 1955; Lorrigan et al. 2003). During the first year of this study in 2002, sockeye escapement was estimated at 34,000 fish (Lorrigan et al. 2003).

A major impetus for this study was to assess the potential impact of an illegal harvest of approximately 8,000 sockeye in 2000 by a commercial seine vessel (Dave Gordon, ADF&G fishery biologist, personal communication). This illegal harvest was approximately 44% of the total commercial harvest (18,000 fish) in 2000. It is unknown whether this illegal harvest was a significant portion of the total sockeye return to Tumakof Lake, and if it will affect future returns.

The primary objectives of this project were to estimate sockeye escapement, including age, sex, and length composition, into Tumakof Lake, and to estimate subsistence and sport harvests in Redfish Bay. The study design included a weir to count escapement and sample for age, sex, and length data, a mark-recapture study to estimate escapement in the event of a weir failure, and an on-site survey to estimate subsistence and sport harvest. We also collected information on the rearing capacity of Tumakof Lake including estimates of zooplankton biomass and limnological measurements. This project is a cooperative study between Sitka Tribe of Alaska (STA), and Alaska Department of Fish and Game, Division of Commercial Fisheries (ADF&G). In this report, we summarize data collected during 2003, the second year of our study.

OBJECTIVES

1. Count the number of sockeye salmon entering Tumakof Lake through a weir.
2. Estimate sockeye escapement with a mark-recapture study on the spawning grounds so that the coefficient of variation is less than 15%.
3. Estimate the subsistence and sport harvest of sockeye salmon at the head of Redfish Bay so that the coefficient of variation is less than 15%.
4. Estimate the age and size composition of the sockeye escapement by sex so that the coefficient of variation is 5% or less for each estimate.
5. Collect baseline data on productivity of Tumakof Lake using established ADF&G limnology sampling procedures.

METHODS

STUDY SITE

Tumakof Lake (ADF&G stream no. 113-13-003; lat 56°22.387'N, long 134°51.409'W) is the southern most sockeye lake on Baranof Island (Figure 1), approximately 120 km from the community of Sitka. Redfish Bay, the location of the subsistence and sport fisheries, is approximately 500 m from the outlet of Tumakof Lake. The total watershed area is approximately 1,062 ha. Tumakof is a dimictic lake at an elevation of about 9 m, with a maximum depth of 99 m and an average depth of 51 m (Figure 2). Although Tumakof Lake is steep-sided with numerous cascades falling from the hillside, it has no well-defined inlet streams. Spawning sockeye salmon congregate in beach areas associated with the cascades at the northern end of the lake. Sockeye spawning habitat consists of large cobbles and boulders. In addition to sockeye salmon, this drainage supports small runs of coho salmon (*O. kisutch*), pink salmon (*O. gorbushca)*, chum salmon (*O. keta*), and Dolly Varden (*Salvelinus malma*). Sockeye and coho salmon have little difficulty negotiating the short outlet stream and cascades, but pink and chum spawners were only observed in the lower reaches of the outlet stream.

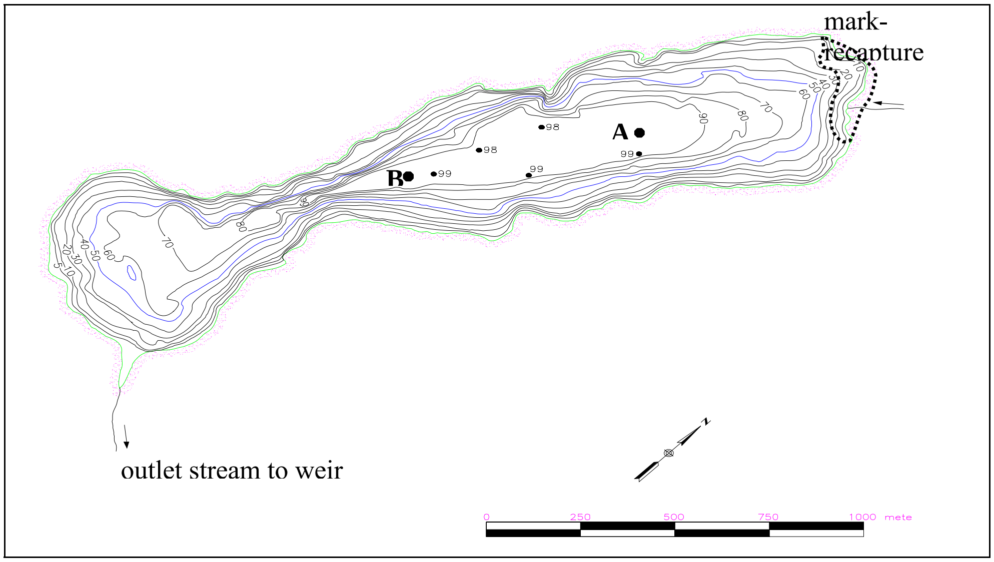

Figure 2.–Tumakof Lake bathymetric map with locations of the limnological sampling stations (A and B) and the beach spawning area sampled during the recovery phase of the mark-recapture study.

SOCKEYE ESCAPEMENT ESTIMATE

Weir Count

We counted salmon by species daily through an aluminum picket weir on the outlet stream of Tumakof Lake, which operated from 24 June to 17 September in 2003. The location and dimensions of the weir were described by Lorrigan et al. (2003).

Mark Recapture Estimate

To test the integrity of the weir and provide an independent estimate of sockeye escapement into Tumakof Lake, we also estimated escapement using a closed, stratified mark-recapture model. The crew consistently marked 15% of the fish that passed through the weir daily with two marks, a primary mark (adipose fin clip) plus a secondary mark used to stratify the run into roughly three segments. The secondary marks were: left ventral fin clip (1 July–6 August), right ventral fin clip (7 August–20 August), and partial dorsal fin clip (21 August–17 September). Marked fish were handled quickly to minimize stress and were released above the weir.

Fish were captured on the spawning grounds to estimate the proportion of marked fish during the recapture phase of the mark-recapture study. In Tumakof Lake, only the beach spawning area at the northern end of the lake was suitable for sampling fish using seine gear (Figure 2). Because this also appeared to be the primary spawning area of the lake, we conducted the entire recapture phase of the study in this beach-spawning area, and we stratified sampling by time.

Prior to each recapture-sampling event, the crew surveyed the perimeter of Tumakof Lake from a boat and counted the number of sockeye spawners in order to identify the highest concentrations that could be captured by seine nets. The crew made as many seine sets as possible in a day in these spawning areas. All captured fish during the recapture sampling events were examined for marks and marked with an opercular punch to prevent duplicate sampling (sampling without replacement) in future trips.

Data Analysis

The two-sample Petersen method is a simplistic model for estimating total escapement based on the total number of fish marked at the weir (first sample), the total number of fish subsequently sampled for marks on the spawning grounds (second sample), and the number of marks recovered in the second sample (Seber 1982, p. 59; Pollock et al. 1990). Stratified mark-recapture models extend the two-sample Petersen method over two or more sampling occasions or events in both the marking (first) and mark-recovery (second) samples. Stratified models are also widely used for estimating escapement of salmonids as they migrate into their spawning systems (Arnason et al. 1996). Spawning migrations may last for a month or more, during which there can be substantial variation in biological parameters such as daily immigration or mortality rates. A fundamental assumption of the Petersen and related mark-recapture models is that capture probabilities for individual animals are equal (Pollock et al. 1990). The natural variation typical of salmon escapements presents many possibilities for individual capture probabilities to vary, but if certain conditions are met, assumptions of equal capture probability can be used to simplify the model. Briefly stated, the three assumptions of equal probability of capture required by the Petersen model are: 1) all fish have an equal probability of capture in the first sample (marking), 2) all fish have an equal probability of capture in the second sample (mark-recovery), and 3) fish mix completely between the first and second sample. Generally, if one or more of these assumptions is met, data from all marking and all mark-recovery samples can be pooled, thereby providing the most precise estimate. However, if none of the assumptions are met, the pooled estimate can be badly biased (Arnason et al. 1996).

We used the Stratified Population Analysis System (SPAS)[1] software to aid in analyzing and interpreting mark-recapture results (Arnason et al. 1996; for details, refer to http://www.cs.umanitoba.ca/~popan/). SPAS calculates Darroch and "pooled Petersen" estimates, and provides two goodness-of-fit tests to compare observed and expected capture probabilities in the marking (first) and mark-recovery (second) samples (Arnason et al. 1996). The test of the assumption of complete mixing is incorporated into the test for equal probability of capture in the second sample. A test statistic with p-value ≤ 0.05 was considered significant, and prompted us to further examine the data and alternate stratification schemes. We looked at sample sizes and capture probabilities in each marking and mark-recovery stratum, and considered any problems with or failures to follow the sampling design. We then checked the Darroch estimate for possible problems, such as a failure of the SPAS program to converge on a solution, or an estimate much larger or smaller than the pooled Petersen estimate. Depending on the nature of the problems, we searched for a partial pooling scheme that more closely fit actual

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

sampling conditions, and we followed the guidelines and suggestions in Arnason et al. (1996) to help decide between the pooled Petersen or Darroch estimate.

If we accepted the pooled Petersen estimate, we used the following alternative method to estimate the 95% confidence interval for the number of fish in the escapement, *N*. We let *K* denote the number of fish marked in a random sample of a population of size *N*. We let *C* denote the number of fish examined for marks in the second sample (recovery phase), and let *R* denote the number of fish in the second sample with a mark. Then the pooled Petersen estimate of the number of fish in the entire population, $\hat{N}$, is given by

$$\hat{N} = \frac{(K+1)(C+1)}{(R+1)} - 1. \tag{1}$$

In this equation, *R* is the random variable, and *C* and *K* are assumed to be constants. In mark-recapture sampling, *R* follows a hypergeometric distribution by definition, which can be approximated with the Poisson distribution (Thompson 1992). Simplifying the Petersen mark-recapture equation, we have

$$\frac{1}{\hat{N}} \approx \frac{R}{C\,K} . \tag{2}$$

In the Poisson approximation for *R*, the mean and variance are the same, so

$$\text{var}(\frac{1}{\hat{N}}) \approx \frac{R}{(C\,K)^2}, \text{ and } \text{SE}(\frac{1}{\hat{N}}) = \frac{\sqrt{R}}{C\,K}. \tag{3}$$

With moderate or large numbers of mark-recoveries, which will generally be the case if the pooled Petersen estimate meets the criteria outlined above, the distribution for *R* could be approximated with the normal distribution. Therefore we could assume $\frac{1}{\hat{N}}$ is approximately normally distributed, and we generated 95% confidence intervals for $\frac{1}{N}$ as,

$$\frac{1}{\hat{N}} \pm 1.96 \cdot \text{SE}(\frac{1}{\hat{N}}) . \tag{4}$$

Finally, 95% confidence intervals for *N* were generated by inverting the confidence intervals for $\frac{1}{N}$.

SOCKEYE ESCAPEMENT AGE, SEX, AND LENGTH DISTRIBUTION

We sampled 600 sockeye salmon for scales, length, and sex at the Tumakof Lake weir to describe the age and size structure of the population, by sex. In the field, we measured the length of each fish from mid eye to tail fork to the nearest millimeter (mm). Three scales were taken from the preferred area of each fish (INPFC 1963) and prepared for analysis (Clutter and Whitesel 1956). Scale and length data were paired for each sample. Because of large pulses of sockeye salmon that passed through the weir on several days (Figure 3) and the priority given to marking the fish at a constant rate, the crew was unable to systematically sample fish proportional to the run. Consequently post-season, we weighted the average proportion in each age class by weekly escapement. To determine if different age classes of sockeye salmon returned to the lake at different times throughout the season, we examined weekly percentages in each age class.

Ages were determined by technicians at the ADF&G Age Laboratory in Douglas, Alaska. Age classes were designated by the European aging system where freshwater and saltwater years are separated by a period. For example, a fish designated as age 2.3 means the fish spent two years in freshwater after hatching and 3 years in saltwater, with a total age of 6 years (Koo 1962). The proportion of each age-sex group was estimated along with its associated standard error, using standard statistical techniques and assuming a binominal distribution (Thompson 1992).

SUBSISTENCE AND SPORT HARVEST CENSUS

Because the crew was confident that they interviewed all subsistence and sport fishers in Redfish Bay, the number of sockeye salmon harvested was simply a census in 2003. The sampling unit for subsistence fishing was a boat-party, that is, any number of people fishing from a single boat, and all participating boat-parties could be accurately counted. All boat-parties were interviewed after they completed fishing. The sampling unit for sport fishing was an individual fisher with a fishing rod, and again, all fishers could be accurately counted and were interviewed at the conclusion of fishing. We conducted interviews during daylight hours and to determine gear type used, effort (net or rod hours), and harvest by species. We summed the sockeye harvest across all gear types and days for each type of fishery to obtain the total number of sockeye salmon harvested in Redfish Bay by fishery. The total subsistence sockeye harvest was compared to the reported subsistence harvest on the 2003 ADF&G subsistence permits. Estimates of sport harvest were compared to estimates generated from statewide postal surveys.

LIMNOLOGY

The crew conducted limnology sampling at two stations (A and B) in Tumakof Lake (Figure 2) on 29 June, 6 August, and 29 October to measure euphotic zone depth (EZD), temperature, and dissolved oxygen (DO), and to collect zooplankton samples. Physical measurements were only collected at Station A, the deeper of the two stations, and one zooplankton sample was collected at each station on each sampling trip.

Light, Temperature and Dissolved Oxygen Profiles

We recorded underwater light intensity at 0.5 m intervals to the depth where measured intensity was one percent of the value just below the surface, using an electronic light sensor and meter (Protomatic). The vertical light extension coefficients (K_d) were estimated as the slope of the light intensity (natural log of percent subsurface light) versus depth. The EZD, the zone with sufficient light for photosynthesis, was defined as the lake surface to the depth in which the light [photosynthetically available radiation (400–700nm)] attenuated to 1% of the level just below the lake surface (Schindler 1971). The EZD was calculated from the equation: EZD=4.6205/ K_d (Kirk 1994).

Temperature and DO profiles were measured with a Yellow Springs Instrument (YSI) Model 58 DO meter. We measured temperature in Celsius (C) and DO in absolute (mg L^{-1}) and relative (%) values. Measurements were made at one-meter intervals to the first 10 m or the lower boundary of the thermocline (defined as the depth at which the change in temperature decreased to less than 1 ^{o}C per meter), and thereafter at five-meter intervals to within two meters of the bottom (or 50 m). The dissolved oxygen meter reading at one meter was calibrated prior to measurements using the values from a 60 ml Winkler field titration (Koenings et al. 1987).

Secondary Production

Zooplankton are the primary food for sockeye salmon and cladocerans are their preferred food within the zooplankton community—especially *Daphnia* spp. We collected zooplankton samples at stations A and B on each sampling date, using a 0.5 m diameter, 153 um mesh, 1:3 conical net. Vertical zooplankton tows were pulled from a maximum depth of 50 m, or 2 m from the bottom of the lake if shallower than 50 m, at a constant speed of 0.5 m sec^{-1}. We rinsed the net prior to removing the organisms, and all specimens were preserved in neutralized 10% formalin (Koenings et al. 1987).

Laboratory technicians at the ADF&G Commercial Fisheries Limnology Laboratory in Soldotna, counted and measured specimens from a sub-sample from each vertical tow, by zooplankton genus or, if possible, by species. The seasonal mean density (number per m^2), body length weighted by number present at each sampling date, and biomass (weight per m^2) estimated from the density and a standard length-weight conversion for each taxon, were estimated (Koenings et al. 1987). The total zooplankton density or biomass per unit of lake surface area was simply the sum of density or biomass over all taxa.

RESULTS

SOCKEYE ESCAPEMENT ESTIMATE

Weir count and Mark-Recapture Estimate

The escapement of sockeye salmon counted through the Tumakof weir between 24 June and 17 September 2003 totaled 42,241 fish. In addition, 1,544 coho, 5,741 pink, and 22 chum salmon were counted during this period. Peak sockeye counts occurred on 15 August and 2 September and coincided with dramatic increases in water levels of the outlet stream to Tumakof Lake (Figure 3; Appendix A2). The water level generally remained high from mid-August to the end of the weir operations (Figure 3). The crew observed the water level in the creek to be higher than the stream banks and water flowing around both ends of the weir on at least one occasion in mid-August. Immediately before removing the weir, the crew counted 300–500 sockeye salmon in the outlet stream below the weir.

The crew performed a single shoreline survey of Tumakof Lake on 14 October 2003. Ninety percent of sockeye spawners were observed around the northernmost beaches where upwelling is most prevalent (Figure 2). The recovery phase of the mark-recapture study occurred on 14–15 and 25–26 October in this area. Although the crew marked sockeye salmon throughout the run at a consistent rate of 15% of all sockeye salmon counted through the weir, marked fish comprised only 11% of fish sampled on the spawning grounds (Table 1). The proportion of secondary marks recaptured on the spawning grounds declined from 10% of first stratum marks to 4% of second and only 1% of third stratum marks (Table 1).

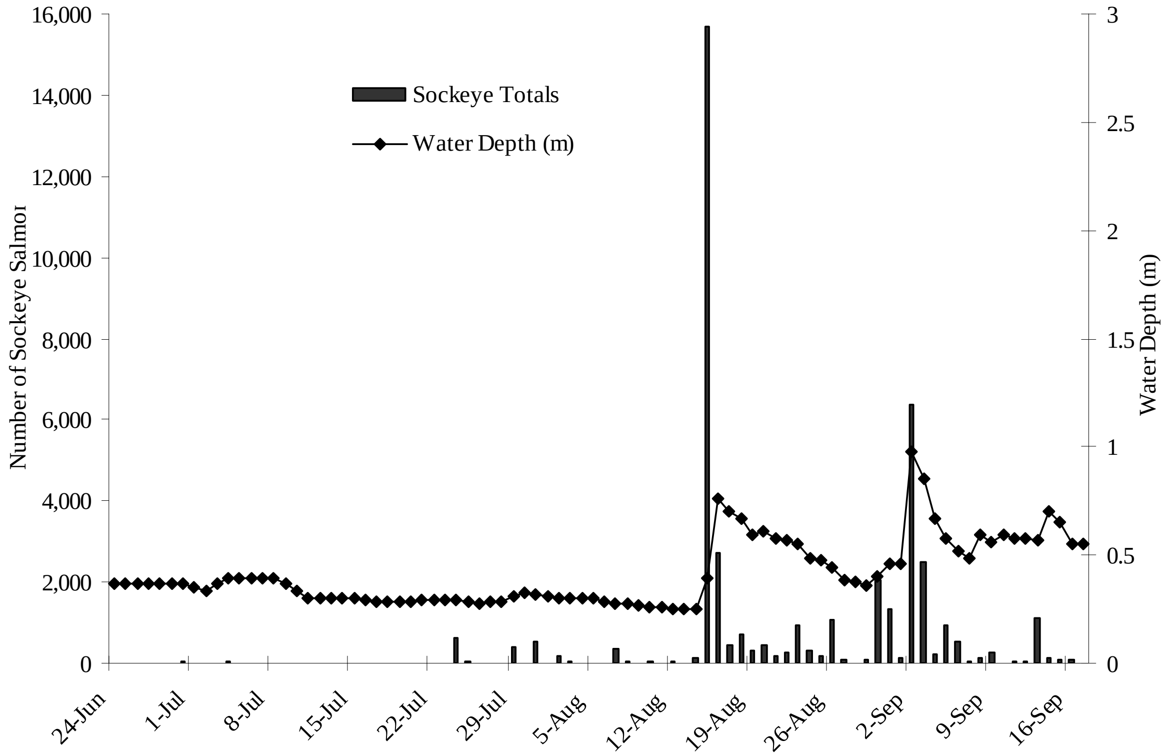

Figure 3–Daily weir counts of sockeye salmon and comparison with water depth in Tumakof Lake's outlet stream in 2003.

Table 1.–Number of sockeye salmon marked at the weir for each marking period, and number of recoveries of marked fish by recapture event and marking stratum in Tumakof Lake 2003. The number of fish passed through the weir during each marking period is included for comparison. Recapture sampling occurred on 14–15 (recapture event 1) and 25–26 (recapture event 2) October.

		Marking at weir				**Marks recaptured on spawning grounds**			
Marking stratum	**Marking dates**	**Secondary mark**	**Total sockeye count (weir)**	**Number marked**	**Percent marked**	**Recapture event 1**	**Recapture event 2**	**Total recaptures**	**Percent of marks recovered**
1	1 July–6 Aug	Left ventral	2,103	328	16%	18	16	34	10%
2	7–20 Aug	Right ventral	20,973	3,139	15%	73	48	121	4%
3	21 Aug–17 Sep	Dorsal	19,165	2,956	15%	11	17	28	1%
Total marked and recaptured			42,241	6,423	15%	102	81	183	3%
					Total sampled	907	748	1,655	
Percent of fish in recapture samples with marks						11%	11%	11%	

We accepted the pooled Petersen estimate of 58,000 sockeye salmon (CV=7%), with a 95 % confidence interval of 51,000–67,000 fish. Consistency chi-square tests, performed to determine appropriateness of pooling strata, resulted in no indication of violation of the assumption of equal probability of capture in the first event (i.e. fish marked in a given stratum had an equal probability of recovery in either recapture event; X^2=0.86, *df*=1; *p*=0.77). However, a violation for the assumptions of complete mixing or equal probability of capture in the second event was indicated (i.e. recapture probabilities were different for fish marked in different strata; X^2=119.91, *df*=2; $p \leq 0.001$). We accepted the pooled Petersen estimate because one of the consistency tests passed (i.e. $p > 0.05$).

ESCAPEMENT AGE, SEX, AND LENGTH COMPOSITION

The largest sockeye age class in the 2003 Tumakof Lake escapement was age-2.3, comprising 32% of the samples aged (Table 2). The second largest age class was age-1.2, representing about 25% of the fish. Combining age classes by brood year, we found 27% 4-year olds, 37% 5-year olds, and 32% 6-year olds. About 44% of the returning sockeye salmon showed one year of freshwater growth. The majority of this sockeye escapement (53%) had two years of freshwater growth, and a small proportion (3%) had three freshwater years (Table 2). Weighting the percentage of fish in each age class by weekly escapement adjusted the average percentages in the age 1.2 and 1.3 classes substantially higher, and those in the age 2.2 and 2.3 classes substantially lower (Table 2). The mean fork length was 589 mm (SE=1.6 mm, *n*=183) for age-2.3 fish and 524 mm (SE=2.0 mm, *n*=146) for age-1.2 fish (Table 3). Only 20 jacks (3%) were sampled of age class 1.1 (mean length=390 mm) and of age class 2.1 (mean length=385 mm). Examining weekly percentages by age class showed that sockeye salmon with one freshwater year (age 1.2 and 1.3 fish) made up a larger percentage of escapement in the latter part of the run (Table 4). Conversely, fish with two years of freshwater growth made up a larger percentage of the early escapement. The small numbers of jacks and also fish with three freshwater years were evenly represented in the weekly escapement throughout the season.

Table 2.–Age-sex composition of sockeye salmon in Tumakof Lake escapement, by brood year, estimated from fish sampled between 24 June and 17 September 2003. Std. error represents the standard error of the percent measure in each age class.

Brood Year	2000	1999	1998	1999	1998	1997	1997	1996	
Age	**1.1**	**1.2**	**1.3**	**2.1**	**2.2**	**2.3**	**3.2**	**3.3**	**Total**
Male									
Sample size	7	90	46	13	87	94	4	4	345
Percent	1.2%	15.5%	7.9%	2.2%	15.0%	16.2%	0.7%	0.7%	59.4%
Std. error	0.5%	1.5%	1.1%	0.6%	1.5%	1.5%	0.3%	0.3%	2.0%
Female									
Sample size		56	57		25	89	1	8	236
Percent	0.0%	9.6%	9.8%	0.0%	4.3%	15.3%	0.2%	1.4%	40.6%
Std. error	0.0%	1.2%	1.2%	0.0%	0.8%	1.5%	0.2%	0.5%	2.0%
All Fish									
Sample size	7	146	103	13	112	183	5	12	581
Unweighted percent	1.2%	25.1%	17.7%	2.2%	19.3%	31.5%	0.9%	2.1%	100%
Std. error	0.5%	1.8%	1.6%	0.6%	1.6%	1.9%	0.4%	0.6%	
Weighted percent	1.5%	31.7%	21.5%	2.0%	13.2%	26.7%	1.1%	2.2%	100%
Estimated escapement by age class	892	18,413	12,497	1,176	7,649	15,475	634	1,264	58,000

Table 3.–Mean fork length (mm) of sockeye salmon in Tumakof Lake escapement by brood year, sex, and age class, estimated from fish sampled between 24 June and 17 September 2003. Std. error represents the standard error of the length measurements in each age class.

Brood year	2000	1999	1998	1999	1998	1997	1997	1996
Age	**1.1**	**1.2**	**1.3**	**2.1**	**2.2**	**2.3**	**3.2**	**3.3**
Male								
Mean length (mm)	390	525	586	385	532	593	558	593
Std. error	6.5	2.8	4.2	6.6	3.0	2.2	9.2	8.8
Sample size	6	90	46	13	87	94	4	4
Female								
Mean length (mm)		523	585	0.0	524	584	525	579
Std. error		2.7	2.6	0.0	7.0	2.3		8.4
Sample size		56	57	0.0	25	89	1	8
All Fish								
Mean length (mm)	390	524	586	385	530	589	551	583
Std. error	6.5	2.0	2.3	6.6	2.8	1.6	9.7	6.4
Sample size	6	146	103	13	112	183	5	12

Table 4.–Percentage of sockeye salmon in the Tumakof Lake escapement by age class and week from 1 July to 13 September 2003. The weighted percent is based on the week weir count. Although fish were passed through the weir before 1 July and in the week beginning 8 July and 5 August, scale samples were not taken. Therefore, estimates apply only to sockeye salmon counted through the weir on weeks that were sampled, a total of 23,144 fish.

Week beginning	1.1	1.2	1.3	2.1	2.2	2.3	3.2	3.3	Weekly weir totals
1-Jul	0%	4%	4%	4%	37%	53%	0%	0%	117
8-Jul									
15-Jul	5%	5%	0%	5%	40%	45%	0%	0%	701
22-Jul	0%	17%	7%	0%	21%	48%	3%	3%	1,192
29-Jul	1%	11%	6%	3%	41%	35%	0%	3%	498
5-Aug	-	-	-	-	-	-	-	-	-
12-Aug	0%	17%	17%	3%	21%	38%	1%	4%	3,146
19-Aug	1%	34%	24%	1%	13%	22%	1%	4%	4,802
26-Aug	2%	39%	25%	2%	8%	21%	1%	1%	10,765
2-Sep	1%	33%	27%	3%	10%	24%	0%	1%	1,738
9-Sep	2%	42%	27%	2%	2%	23%	2%	0%	185

SUBSISTENCE AND SPORT HARVEST CENSUS

In 2003, about two-thirds of the Redfish Bay sockeye harvest was subsistence and about one-third was sport (Table 5). Subsistence fishing took place on only three days of the season (21 July, 22 July, and 7 August), while sport users fished for 16 days in Redfish Bay between 7 July and 14 August. Subsistence fishers used gill nets and beach seines and sport fishers used rod and reel gear only. Beach seines were the most efficient method of harvest, with a total harvest of 390 sockeye salmon in four hours, while 207 sockeye salmon were harvested in eight hours' fishing with gill nets. In the sport fishery, a total harvest of 330 sockeye salmon was taken with a total of 69 rods fished for 238 hours. All boat-parties observed on the fishing grounds were interviewed. Harvest of other salmon species was negligible.

Table 5.–Number of sockeye salmon harvested in the subsistence and sport fisheries at Redfish Bay in 2003, determined from on-site surveys.

Fishery type	Boats counted	Boats sampled	Total sockeye harvest
Subsistence	4	4	597
Sport	22	22	330
Total	26	26	927

The on-site harvest census of sockeye salmon was less than the harvest reported on the subsistence permits but higher, for sport fish, than the postal survey estimates. A total harvest of 784 sockeye salmon was reported in Redfish Bay on ADF&G subsistence permits by 19 permit holders (ADF&G database; 113-13-01). ADF&G Division of Sport Fish estimated 245 sockeye salmon were harvested in Redfish Bay in 2003; this estimate was extrapolated from the number of sockeye salmon reported by a subsample of license holders on a statewide harvest postal survey (R. Chadwick, ADF&G fishery biologist, personal communication).

LIMNOLOGY

Limnology sampling was conducted on Tumakof Lake on 29 June, 6 August, and 29 October in 2003. The crew collected physical data (light, temperature, and dissolved oxygen) at the main station (A), and a zooplankton sample at both stations (A and B) on each date. The euphotic zone depth information was only collected on 29 June and 6 August in 2003.

Light, Temperature, and Dissolved Oxygen Profiles

The physical characteristics of Tumakof Lake were typical of most sockeye lakes in Southeast Alaska, with thermal stratification in mid-summer and near isothermic conditions by the end of October (Table 6; Appendix A3). The estimated euphotic zone depth was approximately 11 m on 29 June and approximately 8 m on 6 August 2003 (Appendix A4). The percentage saturation of dissolved oxygen between 0 and 17 m ranged from 78 to 95%; the inconsistent and lower than expected values probably reflect measurement error rather than actual conditions in the lake (Appendix A5).

Table 6.–The 2003 upper and lower depth and range of the thermocline in Tumakof Lake by sample date.

Date	Upper (m)	Lower (m)	Range (m)
29–June	6	7	1
6–August	4	7	3
29–October	No thermocline		

Secondary Production

The estimated seasonal mean density of zooplankton in Tumakof Lake in 2003 was 300,530 individuals per m^{-2} of lake surface area, with an estimated seasonal mean biomass of 493 mg per m^{-2} of lake surface area (Table 7). The *Cyclops* species, in the copepod group of zooplankton, dominated the assemblage at 82% by seasonal mean density, and 80% by seasonal mean biomass (Table 7; Appendices A6 and A7). *Daphnia longiremis*, the only *Daphnia* species present in the sample, was marginally represented with less than 0.01% by density and biomass.

Table 7.– Zooplankton seasonal mean densities, body lengths, and biomass, from Tumakof Lake in 2003.

	Seasonal mean density		Mean weighted length	Seasonal mean biomass	
Taxon	**(number·m^{-2})**	**Percent (%)**	**(mm)**	**(mg·m^{-2})**	**Percent (%)**
Bosmina sp.	46,400	15%	0.43	81	20%
Ovig. *Bosmina*	900	0%	0.47	1	0.0%
Daphnia longiremis	30	0%	0.66	0	0.0%
Cyclops sp.	246,600	82%	0.7	409	80%
Ovig. *Cyclops*	700	0%	1.07	3	0.0%
Copepod nauplii	5,900	2%			
Totals	300,530			493	

DISCUSSION

The 2003 estimated sockeye escapement (58,000 fish) was at the upper end of the range of historic estimates (14,000–66,000 fish). The 2003 estimate was about one-third higher than estimated escapement of 34,000 fish in 2002 (Lorrigan et al. 2003), three and a half times higher than the 1955 weir count of 14,000 fish (Hilsinger 1955), and only slightly lower than the 1966 count of 66,000 fish (Lorrigan et al. 2003). Evidently, the escapement varies widely from year to year in this system. It should be noted that the older escapement estimates are based solely on weir counts and may under-represent true escapement, especially in this system which is susceptible to high water events.

Clearly, the 2003 sockeye weir count (42,200 fish) underestimated the true sockeye escapement because water was observed going around the weir in high water and fish moved into the system after the weir was removed. The percent of marked fish on the spawning grounds was less than the percent marked at the weir—documenting that fish escaped through the weir undetected. Flooding occurred on at least one occasion in mid-August. The crew observed water rising above the stream banks and flowing around both ends of the weir—allowing an unknown number of fish to pass around the weir undetected. Flooding occurred again in early September, and in general, the water level remained high for the rest of the season—making it difficult to maintain a fish-tight weir. On 13 September, over 1,000 fish were passed through the weir, one of the highest daily escapements of the season. When the crew removed the weir just four days later, on 17 September, they estimated that 300–500 sockeye salmon remained in the lower stream and marine estuary below the weir site. It is possible even more fish were in marine waters. In the past, sockeye salmon have been observed remaining below the weir site into October (Lorrigan et al. 2003; Hilsinger 1955). The discrepancy in recapture probabilities of fish marked in different strata, in part, provides further evidence that not all fish were counted at the weir. Even though a consistent 15–16% of fish counted at the weir were marked in all three strata, a much higher proportion of the fish marked in the earliest stratum were recaptured (10%) compared to the second (4%) and third (1%) strata (Table 1). The declines in recapture rates from the later marking strata probably correspond with flooding events at the weir; fish that passed through the weir undetected, diluted the proportion of fish marked. In addition, the actual proportion marked in the third stratum may have been even lower because of unmarked fish entering the lake after the weir was removed and marking had ended.

Although it is almost certain that the actual sockeye escapement into Tumakof Lake was higher than the weir count in 2003, it is also possible the pooled Petersen estimate (58,000 fish) could be biased. We think the escapement estimate was biased high because both conditions of a closed population were violated: 1) fish spawned and died on the spawning grounds before sampling began and between sampling events and 2) fish immigrated into the system during flooding and after the weir removal (p. 26; Arnason et al. 1996). No sampling occurred for nearly a month after weir removal on 17 September, and only two sampling events, spanning a period of less than two weeks, were conducted on the spawning grounds.

Complete mixing of sockeye salmon between marking and recapture sampling events did not occur, which is suggested by the decreasing proportion of secondary marks recovered and the failure of the chi-square test. One explanation for the unequal mixing of fish between sampling events is that some marked fish may have not yet moved to the spawning grounds and were not available for sampling.

So if the weir count is biased low and the pooled Petersen mark-recapture estimate may be biased high, then could a stratified estimate that combines two strata improve the estimate by minimizing the potential for violating the closed assumption? Unfortunately, the number of secondary marks applied in the first stratum was very small compared to the second stratum, so combining it with the second stratum did not improve the stratified estimate. The second and third strata included most of the fish marked, so combining them resulted in an estimate close to the pooled Petersen. Consequently, the pooled Petersen estimate is the best estimate of the sockeye escapement in Tumakof Lake in 2003. The fact that one of the goodness-of-fit tests passed, supports this decision to use the pooled Petersen estimate of sockeye escapement in this system (Arnason et al. 1996).

Exploitation by subsistence, sport, and commercial fishers in Redfish Bay was extremely low in 2003; sport and subsistence sockeye harvest estimates were only a small portion, about 2%, of the total sockeye return in 2003. Subsistence harvests at this low level pose little risk to the sustainability of the Tumakof Lake sockeye population at the current sockeye run size. However, an increase in participation in the subsistence fishery by only a few individuals may have a large effect, because fishers often use large boats and are capable of catching large numbers of fish in a short period of time.

Subsistence harvest of sockeye estimated on the grounds (600 fish) was less than total harvest reported on ADF&G subsistence permits for Redfish Bay (800 fish) in 2003. A similar discrepancy between the on-grounds survey estimate and total of harvests reported on subsistence permits was observed for the Klag Bay subsistence fishery in 2002 (Lorrigan et al. 2004). This discrepancy could be caused by crew failing to observe all boats fishing in Redfish Bay or by fishers under-estimating their catch during the fishery but accurately reporting it on their permits after cleaning and counting every fish. Either way, it appears that Sitka subsistence fishers are accurately reporting their harvests, and on-grounds harvest surveys may not be necessary in the Sitka permit areas.

It is difficult to draw conclusions about factors that may be limiting sockeye production in Tumakof Lake, with only two years of zooplankton and lake habitat information. We only have one set of paired data, the 2002 sockeye escapement estimate and the zooplankton biomass and densities in 2003. This lake may be spawning-area limited because of the morphology of the watershed and restriction of spawners to a small beach area. An accurate estimate of the number of sockeye fry produced per spawner, over several years to account for variation in over-wintering conditions, would provide some indication as to whether sockeye production in the lake is, in fact, limited by spawning area. The large numbers of floating and submerged logs in the lake, however, make fry sampling using hydroacoustic and trawl gear nearly impossible.

A comparison of zooplankton biomass, by species, over several years in Tumakof Lake and other lakes in Southeast Alaska shows a glimpse into the ability of this lake to support sockeye fry (Mills and Schiavone 1982). Zooplankton biomass estimates in Tumakof Lake were high in 2002 and 2003 compared to other Southeast Alaska lakes, but *Daphnia* sp. biomass and mean size were among the lowest, suggesting a large sockeye fry population that consumed most of the preferred prey base (Table 8; Koenings and Burkett 1987; Mazumder and Edmundson 2002). This assessment is further supported by the proportion of returning adults with more than one year of freshwater growth. Researchers have theorized that if sockeye fry are able to increase their weight to the minimum threshold size of 2.0 g by spring, then they will smolt, otherwise they will remain in the lake for at least another year (Koenings and Burkett 1987). In most Southeast Alaskan sockeye lakes, the majority of sockeye salmon achieve sufficient growth to leave freshwater after only one year, but sockeye spawners returning to Tumakof Lake in 2003 did not appear to fit this pattern. Furthermore, in 2002, only one percent of returning spawners had only one freshwater year, while 89% had two freshwater years and 9% had three freshwater years, a rare occurrence in Southeast Alaska (Lorrigan et al. 2003).

Table 8.–Zooplankton biomass and *Daphnia longiremis.* biomass and average size in 2002 and 2003 for 13 small lakes in Southeast Alaska.

2002				2003			
Lake	**Zooplankton biomass ($mg \cdot m^{-2}$)**	***Daphnia* biomass ($mg \cdot m^{-2}$)**	***Daphnia* avg. length (mm)**	**Lake**	**Zooplankton biomass ($mg \cdot m^{-2}$)**	***Daphnia* biomass ($mg \cdot m^{-2}$)**	***Daphnia* avg. length (mm)**
Klawock	499	16	0.9	Kutlaku	618	84	0.51
Tumakof	496	2	0.65	Tumakof	500	0	0.66
Luck	316	18	0.77	Klawock	431	37	0.97
Klag	222	5	0.97	Salmon Bay	351	32	0.93
Salmon Bay	205	19	0.75	Klag	316	7	0.68
Kutlaku	131	35	0.51	Luck	201	6	0.73
Thoms	119	7	0.57	Thoms	163	7	0.55
Hetta	49	7	0.67	Hetta	45	2	0.68
Falls	41	1	0.69	Falls	29	1	0.66
Average	231	12	1	Average	295	20	1
Median	214	10	1	Median	305	7	1

We achieved our primary objectives of estimating escapement and subsistence and sport harvests. Our assessment is that Tumakof Lake sustains a lightly exploited population estimated at approximately 14,000–70,000 sockeye salmon. Our 2003 measurements do not provide any direct assessment of the year 2000 illegal harvest of concern (8,000); however, that harvest should not severely impact future returns at these run sizes.

Clearly, sockeye salmon enter the lake well past the middle of September at a time when high water makes it difficult to maintain the integrity of the weir. It is not practical to expect the weir count to be accurate unless we have an unusually dry fall and the weir can be left in until the end of the sockeye run. Consequently, more effort needs to be focused on mark-recapture sampling on the spawning grounds. Late arrival of spawners on the spawning grounds means the mark-recapture recovery phase must extend into November, but in late fall, access to the site can be difficult and dangerous, and seasonal crew are difficult to retain on a part-time basis. Despite these difficulties, we recommend that sampling span the entire spawning period, with at least 4–5 sampling events throughout the fall, starting at the beginning of September and continuing into November, weather permitting. We also recommend that individual numbered tags be placed on sockeye salmon at the weir to be able to group marked fish into equal numbers in each secondary mark stratum after the season has ended. Numbered tags would also allow us to document the timing of the sockeye spawners between the weir and the spawning grounds.

Because the reported subsistence sockeye harvest was greater than the on-grounds harvest estimate, we recommend that a crew member be stationed to observe boats in Redfish Bay, rather than remaining in camp until a boat motor can be heard in the bay. If this is not practical, relying on the reported sockeye harvest may be adequate since it was very similar to the on-site survey results in both 2002 and 2003.

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APPENDIX A

Appendix A1.– Sockeye salmon harvest at the head of Redfish Bay (113-13-001) 1985–2003 by reported totals on returned subsistence permits (ADF&G Div. of Commercial Fisheries database 2004).

Year	Permits	Sockeye	Sockeye per permit
1985	7	128	18
1986	4	100	25
1987	5	222	44
1988	4	186	47
1989	7	260	37
1990	10	515	52
1991	5	250	50
1992	11	532	48
1993	10	397	40
1994	22	1111	51
1995	13	483	37
1996	13	618	48
1997	26	1016	39
1998	25	915	37
1999	26	659	25
2000	13	281	22
2001	22	478	22
2002	21	1101	52
2003	19	784	41

Appendix A2.–Tumakof Lake weir data for 2003, showing water temperature and depth at the weir site, sockeye marking and sampling schedule, and daily salmon counts by species.

						Sockeye counts		Cumulative marking		Other salmon daily counts		
Date	Water depth (m)	Water temp. (^{o}C)	Mark given	Number marked	Number ASL samples	Daily	Percent	Number	Percent	Coho	Pink	Chum
24-Jun	0.37	12		0	0	2	2	0	0	0	0	0
25-Jun	0.37	12		0	0	3	5	0	0	0	0	0
26-Jun	0.37	12		0	0	2	7	0	0	0	0	0
27-Jun	0.37	12		0	0	4	11	0	0	0	0	0
28-Jun	0.37	12		0	0	0	11	0	0	0	0	0
29-Jun	0.37	12		0	0	0	11	0	0	0	0	0
30-Jun	0.37	13		0	0	26	37	0	0	0	0	0
1-Jul	0.35	15	AD LV	10	10	11	48	10	21	0	0	0
2-Jul	0.34	15	AD LV	3	0	3	51	13	25	0	0	0
3-Jul	0.37	15	AD LV	0	0	8	59	13	22	0	0	0
4-Jul	0.40	13	AD LV	34	30	39	98	47	48	0	0	0
5-Jul	0.40	14	AD LV	18	10	18	116	65	56	0	0	0
6-Jul	0.40	15	AD LV	0	0	20	136	65	48	0	0	0
7-Jul	0.40	16	AD LV	18	10	18	154	83	54	0	0	0
8-Jul	0.40	16	AD LV	0	0	2	156	83	53	0	0	0
9-Jul	0.37	14	AD LV	0	0	8	164	83	51	0	0	0
10-Jul	0.34	15	AD LV	0	0	0	164	83	51	0	0	0
11-Jul	0.30	15	AD LV	0	0	2	166	83	50	0	0	0
12-Jul	0.30	15	AD LV	0	0	3	169	83	49	0	0	0
13-Jul	0.30	16	AD LV	0	0	3	172	83	48	0	0	0
14-Jul	0.30	16	AD LV	0	0	0	172	83	48	0	0	0
15-Jul	0.30	17	AD LV	0	0	0	172	83	48	0	0	0
16-Jul	0.29	17	AD LV	0	0	0	172	83	48	0	0	0
17-Jul	0.29	16	AD LV	20	20	22	194	103	53	0	0	0
18-Jul	0.29	16	AD LV	0	0	0	194	103	53	0	0	0
19-Jul	0.29	17	AD LV	0	0	0	194	103	53	0	0	0
20-Jul	0.29	17	AD LV	0	0	0	194	103	53	0	0	0
21-Jul	0.29	16	AD LV	0	0	0	194	103	53	0	0	0

(continued)

Appendix A2.–(Page 2 of 3)

Date	Water depth (m)	Water temp. (°C)	Mark given	Number marked	Number ASL samples	Sockeye counts		Cumulative marking		Other salmon daily counts		
						Daily	Percent	Number	Percent	Coho	Pink	Chum
22-Jul	0.30	16	AD LV	0	0	0	194	103	53	0	0	0
23-Jul	0.30	15	AD LV	0	0	0	194	103	53	0	0	0
24-Jul	0.29	16	AD LV	30	30	637	831	133	16	0	0	0
25-Jul	0.28	16	AD LV	0	0	56	887	133	15	0	0	0
26-Jul	0.27	16	AD LV	1	0	4	891	134	15	0	0	0
27-Jul	0.28	16	AD LV	0	0	4	895	134	15	0	0	0
28-Jul	0.28	16	AD LV	5	0	13	908	139	15	0	0	0
29-Jul	0.31	16	AD LV	126	0	390	1,298	265	20	0	0	0
30-Jul	0.32	16	AD LV	0	0	20	1,318	265	20	0	0	0
31-Jul	0.32	16	AD LV	40	40	517	1,835	305	17	0	2	0
1-Aug	0.31	16	AD LV	0	0	20	1,855	305	16	0	0	0
2-Aug	0.30	16	AD LV	0	0	158	2,013	305	15	0	1	0
3-Aug	0.30	16	AD LV	23	10	59	2,072	328	16	0	0	0
4-Aug	0.30	16	AD LV	0	0	15	2,087	328	16	0	0	0
5-Aug	0.30	16	AD LV	0	0	11	2,098	328	16	0	0	0
6-Aug	0.29	16	AD LV	0	0	5	2,103	328	16	0	0	0
7-Aug	0.27	16	AD RV	37	30	351	2,454	365	15	0	0	0
8-Aug	0.27	17	AD RV	0	0	49	2,503	365	15	0	0	0
9-Aug	0.27	17	AD RV	0	0	9	2,512	365	15	0	0	0
10-Aug	0.26	16	AD RV	30	0	58	2,570	395	15	0	0	0
11-Aug	0.26	16	AD RV	0	0	15	2,585	395	15	0	0	0
12-Aug	0.25	17	AD RV	0	0	38	2,623	395	15	0	0	0
13-Aug	0.25	17	AD RV	0	0	1	2,624	395	15	0	0	0
14-Aug	0.25	17	AD RV	13	10	134	2,758	408	15	0	10	0
15-Aug	0.40	16	AD RV	783	10	15,687	18,445	1,191	6	8	151	0
16-Aug	0.76	15	AD RV	526	20	2,703	21,148	1,717	8	7	146	0
17-Aug	0.70	15	AD RV	449	20	457	21,605	2,166	10	13	78	1
18-Aug	0.67	15	AD RV	663	10	704	22,309	2,829	13	31	79	2
19-Aug	0.59	15	AD RV	208	20	307	22,616	3,037	13	5	52	1

(continued)

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Date	Water depth (m)	Water temp. (°C)	Mark given	Number marked	Number ASL samples	Sockeye counts Daily	Sockeye counts Percent	Cumulative marking Number	Cumulative marking Percent	Other salmon daily counts Coho	Pink	Chum
20-Aug	0.61	15	AD RV	430	20	460	23,076	3,467	15	17	41	1
21-Aug	0.58	15	AD D	144	20	182	23,258	3,611	16	0	0	0
22-Aug	0.57	14	AD D	162	20	263	23,521	3,773	16	12	43	0
23-Aug	0.55	14	AD D	0	0	923	24,444	3,773	15	12	119	0
24-Aug	0.49	14	AD D	0	0	307	24,751	3,773	15	1	26	1
25-Aug	0.48	14	AD D	28	10	172	24,923	3,801	15	2	34	2
26-Aug	0.45	14	AD D	20	0	1,056	25,979	3,821	15	14	99	0
27-Aug	0.38	15	AD D	67	10	83	26,062	3,888	15	0	31	0
28-Aug	0.38	15	AD D	0	0	12	26,074	3,888	15	2	2	0
29-Aug	0.36	15	AD D	10	10	91	26,165	3,898	15	3	74	0
30-Aug	0.40	14	AD D	348	20	2,044	28,209	4,246	15	31	544	1
31-Aug	0.46	14	AD D	187	30	1,344	29,553	4,433	15	32	758	1
1-Sep	0.46	14	AD D	80	20	123	29,676	4,513	15	23	250	0
2-Sep	0.98	13	AD D	828	30	6,364	36,040	5,341	15	283	1,085	0
3-Sep	0.85	12	AD D	467	30	2,492	38,532	5,808	15	165	441	0
4-Sep	0.67	12	AD D	233	20	239	38,771	6,041	16	21	102	0
5-Sep	0.58	12	AD D	58	20	955	39,726	6,099	15	46	115	1
6-Sep	0.52	13	AD D	55	0	549	40,275	6,154	15	26	74	1
7-Sep	0.49	13	AD D	15	10	43	40,318	6,169	15	23	121	3
8-Sep	0.59	12	AD D	0	0	140	40,458	6,169	15	99	228	1
9-Sep	0.56	12	AD D	55	20	270	40,728	6,224	15	32	127	0
10-Sep	0.59	12	AD D	5	0	6	40,734	6,229	15	1	38	1
11-Sep	0.58	12	AD D	23	20	57	40,791	6,252	15	36	127	0
12-Sep	0.58	12	AD D	0	0	41	40,832	6,252	15	25	38	3
13-Sep	0.57	12	AD D	66	10	1,103	41,935	6,318	15	467	380	0
14-Sep	0.70	10	AD D	105	0	121	42,056	6,423	15	46	76	0
15-Sep	0.66	11	AD D	0	0	111	42,167	6,423	15	27	121	0
16-Sep	0.55	11	AD D	0	0	67	42,234	6,423	15	24	111	2
17-Sep	0.55	11	AD D	0	0	7	42,241	6,423	15	10	17	0

Appendix A3.–Tumakof Lake temperature profiles (ºC) by sample date and depth (m) in 2003. The shaded temperature values represent the upper and lower thermocline depth for each sample date. No temperature measurements were taken below 16 m on 29 October (denoted by *).

Depth (m)	29–June	6–August	29–October
1	12.9	17.8	9.5
2	12.7	17.5	9.5
3	12.7	16.8	9.5
4	12.6	15.1	9.5
5	12.2	12.7	9.5
6	10.9	12.1	9.5
7	9.5	9.8	9.5
8	8.9	8.3	9.5
9	8.1	7.6	9.4
10	7.4	6.7	9.4
11	6.8	6	9.4
12	6.2	5.7	9.4
13	5.7	5.3	9.4
14	5.4	4.9	9.4
15	5	4.8	6.7
16	4.7	4.7	*
17	4.5	4.6	*

Appendix A4.–Light intensity profiles ($mE{\cdot}m^{-2}{\cdot}s^{-1}$) in Tumakof Lake in 2003 by sample date and depth (m). No light measurements were taken below 13 m on 6 August (denoted by *).

Depth (m)	29–Jun	6–Aug
1	478.4	560
2	144.6	478
3	122.3	256.1
4	108.2	180.3
5	68.2	109.9
6	59.4	65.8
7	58.3	27.2
8	36.8	13.2
9	31.4	6.67
10	22.3	3.6
11	16.2	2.8
12	11.1	2
13	4.3	1.5
14	2.9	*
15	2.5	*

Appendix A5.–Dissolved oxygen measurements for Tumakof Lake in 2003, in percent saturation.

Depth (m)	29-Jun	6-Aug	29-Oct
1	87	91	83
2	90	89	82
3	89	90	83
4	84	93	82
5	82	95	83
6	84	93	83
7	92	91	83
8	93	88	83
9	92	88	83
10	87	85	83
11	88	84	83
12	90	83	82
13	84	81	82
14	81	81	82
15	80	80	78
16	81	80	
17	79	80	

Appendix A6.–Zooplankton densities (number · m^{-2}) by species, sample date, and station in Tumakof Lake in 2003.

Taxon	29 June	6 August	15 October	Seasonal Mean
Station A				
Bosmina sp.	61,131	73,357	6,775	47,088
Ovig. *Bosmina*	1,274	0	0	425
Daphnia longiremis	0	0	0	0
Cyclops sp.	304,806	542,028	1,172	282,668
Ovig. *Cyclops*	0	2,038	0	679
Copepod nauplii	6,368	8,151	1,783	5,434
Total				**336,294**
Station B				
Bosmina sp.	68,348	64,527	4,007	45,627
Ovig. *Bosmina*	0	3,821	34	1,285
Daphnia longiremis	0	0	170	57
Cyclops sp.	377,823	253,014	815	210,551
Ovig. *Cyclops*	0	2,123	0	708
Copepod nauplii	12,311	5,094	1,800	6,402
Total				**264,629**

Appendix A7.–Weighted mean body length (mm) and biomass (mg·m^{-2}) of zooplankton in Tumakof Lake in 2003 by species, sample date, and station. Mean lengths were weighted by numbers (density) at each sampling date. Biomass estimates were based on standard length to weight conversions for each taxon (Koenings et al. 1987).

Station A	**Average length (mm)**			**Seasonal means**	
Zooplankton Species	**29 June**	**6 August**	**15 October**	**Length (mm)**	**Biomass (mg·m^{-2})**
Bosmina sp.	0.38	0.48	0.41	0.43	82.8
Ovig. *Bosmina*	0.60	-	-	0.60	1.5
Daphnia longiremis	-	-	-	-	0
Cyclops sp.	0.70	0.67	0.75	0.68	445.8
Ovig. *Cyclops*	-	1.07	-	1.07	2.4
Total					**532.5**
Station B					
Bosmina sp.	0.43	0.44	0.38	0.43	79.3
Ovig. *Bosmina*	-	0.34	0.46	0.34	1.4
Daphnia longiremis	-	-	0.66	0.66	0.1
Cyclops sp.	0.69	0.76	0.64	0.72	372.6
Ovig. *Cyclops*	-	1.06	-	1.06	2.9
Total					**453.3**