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A Review of Historical Bear Lake (Alaska Peninsula) Limnology and Sockeye Salmon Smolt Data, 1992-2007

by

Heather Finkle

December 2008

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

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Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

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

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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A REVIEW OF HISTORICAL BEAR LAKE (ALASKA PENINSULA) LIMNOLOGY AND SOCKEYE SALMON SMOLT DATA, 1992-2007

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ABSTRACT

It is necessary to establish benchmarks of water quality, primary production, and secondary production in order to define and understand how potential changes to ecological components affect resident fish populations. This report seeks to present how limnological conditions in Bear Lake, located on the north side of the Alaska Peninsula, may affect rearing juvenile sockeye salmon (*Oncorhynchus nerka*). Water quality and zooplankton data from 2000 to 2007 and age, weight, and length data from 1992 to 2007 were seasonally collected from May through August. Bear Lake, a large, deep lake, possessed sufficient nutrients to supply rearing juvenile sockeye salmon with a healthy zooplankton population (average biomass > 1,000 mg/m^2). Sockeye salmon smolts generally outmigrated from Bear Lake as age-2. fish. However, from 2002 to 2005, age-1. fish were the predominant age class. This shift in age composition coincided with average seasonal zooplankton biomasses below 1,000 mg/m^2 and warmer than average (10.2 °C) summer water temperatures. Top-down grazing pressure does not appear to noticeably affect the zooplankton population as mean lengths of *Bosmina* were above the threshold feeding size of 0.40 mm for juvenile sockeye salmon. These data suggest that Bear Lake production continues to be limited by its spawning area and underutilized in its rearing habitat.

Key words: Bear Lake, Alaska Peninsula, euphotic volume, limnology, juvenile sockeye salmon, zooplankton.

INTRODUCTION

Ecological assessment data have been used to describe sockeye salmon *Oncorhynchus nerka* production trends and life history strategies relative to their rearing environments (Bouwens and Finkle 2003; Finkle 2004). This report serves to summarize the Bear Lake sockeye salmon smolt data collected from 1992 to 2007 and limnology data collected from 2000 to 2007 and seeks to identify and establish relationships between Bear Lake and its resident fauna.

Bear Lake, a deep (mean depth 35 m, maximum depth 104 m) lake located on the north side of the Alaska Peninsula (Figure 1), supports two distinct runs of sockeye salmon; the early run enters Bear Lake through July 31 and the late run returns after July 31 (Ramstad 1998). Each run has its own escapement goal for sockeye salmon [early run Sustainable Escapement Goal (SEG) of 176,000 to 293,000 fish; late run SEG of 117,000 to 195,000 fish; Honnold et al. 2007]. Counting towers were initially used to enumerate total escapement at the mouth of Bear Lake in 1964. A full weir was implemented in 1986 and continues to be the primary means for counting total escapement into the lake and its tributaries.

Limnology data were initially collected from Bear Lake from 1993 to 1995. This study indicated that Bear Lake was underutilized by its population of rearing juvenile sockeye salmon as it generally had an abundant forage base of zooplankton despite relatively low concentrations of primary nutrients such as nitrogen and phosphorous (Honnold et al. 1996). Limnology data collection resumed in 2000, with a preliminary review of these data suggesting that lake conditions were similar to those from 1993 to 1995 (Bouwens 2003). Sockeye salmon smolt age, length, and weight data have been collected intermittently from 1967 to the present. Smolt sampling was performed on a weekly basis during the summer by the Bear River weir crew. These data showed that Bear Lake sockeye salmon smolts typically outmigrate as age-2. fish and are in excellent condition, which also suggests that rearing habitat has been underutilized and that the lake is limited by spawning area (Honnold et al. 1996).

It is necessary to establish benchmarks of water quality, primary production, and secondary production in order to define and understand how potential changes to those ecological components can affect resident salmon populations. Examination of the past and current Bear Lake limnology and sockeye salmon smolt data will provide valuable insight into the mechanisms that drive the life history strategies of the lake's fauna and provide a touchstone for

assessing any potential events that may affect the watershed. These data will also enable the construction of a platform from which to reassess the current carrying capacity and thus escapement goals for the Bear watershed relative to the present ecological conditions and fishery production levels.

METHODS

LIMNOLOGY

Limnology data were collected from Bear Lake from 2000 to the present. Four pre-established stations were sampled from 2000 to 2003 and two of those four stations (stations two and four) were sampled from 2004 to the present (Figure 1). Each station's location was logged with a global positioning system (GPS) and marked with a buoy. Sampling was conducted following protocols established by Finkle and Bouwens (2001). The reduction in sampling effort occurred because the data indicated that conditions were fairly homogenous across the lake and that greater sampling efficiency could be achieved without compromising the quality of the data.

Sampling events occurred roughly once per month beginning in May and ending in August. Sampling occurred only in June and July in 2006 and 2007 because the manpower was not available to collect and initially process August water samples. May samples were often difficult to collect because of logistical limitations: the only May sampling event was conducted in 2001. Samples were initially processed at the Alaska Department of Fish & Game (ADF&G) Chignik Weir research laboratory and shipped to the Kodiak Near Island Laboratory for further analyses.

Dissolved Oxygen, Light, and Temperature

Water temperature (°C) and dissolved oxygen (mg/L) levels were measured with a YSI Y-52 meter. Readings were recorded at half-meter intervals to a depth of 5 m, then the intervals increased to one meter. Upon reaching a depth of 20 m, the intervals increased to every five meters. A mercury thermometer was used to ensure the meter's calibration. Measurements of photosynthetically active wavelengths (kLux) were taken with an International Light IL1400A photometer. Readings began above the surface, at the surface, and proceeded at half-meter intervals until reaching a depth of 5 m. Readings were then recorded at one-meter intervals until the lake bottom or 0 kLux light penetration was reached. The mean euphotic zone depth (EZD) was determined (Koenings et al. 1987) and incorporated into a model for estimating sockeye salmon fry production (Koenings and Kyle 1997). One-meter temperature and dissolved oxygen measurements were compared to assess the physical conditions in the euphotic zones of the lake. Secchi disc readings were collected from each station to measure water transparency. The depths at which the disc disappeared when lowered into the water column and reappeared when raised in the water column were recorded and averaged.

Water Sampling

Seven to eight liters of water were collected with a Van Dorn bottle from the epilimnion (depth of 1 m) and from the hypolimnion (depth of 29 m) of Bear Lake stations 2 and 4. Water samples were stored in polyethylene (poly) carboys and refrigerated until processed.

One-liter samples were passed through 4.25-cm diameter 0.7-µm Whatman™ GF/F filters under 15 to 20-psi vacuum pressure for particulate N, P, and C analyses. For chlorophyll-*a* analysis, one liter of lake water from each depth sampled was filtered through a 4.25-cm diameter 0.7-µm Whatman™ GF/F filter, adding approximately 5 ml of $MgCO_3$ solution to the last 50 ml of the

sample water during the filtration process. Upon completion of filtration, all filters were placed in individual petri dishes, labeled and frozen. For each sampled depth, 120 ml of sample water and 2 ml of Lugol's acetate were placed in a 125-ml poly bottle for phytoplankton analysis and stored at room temperature until processing.

The water chemistry parameters of pH and alkalinity were assessed with a Eutech Instruments Oakton® pH meter. One hundred milliliters of refrigerated lake water were warmed to 25 °C. The pH of the water was measured and then the water sample was titrated with 0.02-N sulfuric acid to measure alkalinity following the methods of Thomsen (2008).

All filtered and unfiltered water samples were stored and frozen in clean poly bottles. Water analyses were performed at the ADF&G Kodiak Near Island laboratory for total phosphorous (TP), total filterable phosphorous (TFP), filterable reactive phosphorous (FRP), total ammonia (TA), nitrate + nitrite, chlorophyll *a* and phaeophytin *a*. All laboratory analyses adhered to the methods of Koenings et al. (1987) and Thomsen (2008). Total Kjeldahl nitrogen (TKN) was processed for one-meter samples by the Olsen Biochemistry Lab at South Dakota State University. No TKN samples were processed for 2000 because of logistic constraints.

ZOOPLANKTON

One vertical zooplankton tow was made at each limnology station with a 0.2-m diameter, 153-micron net from one meter above the lake bottom to the surface, or until the end of the sample rope (60 m) if bottom depth exceeded the sample rope length. Each sample was placed in a 125-ml poly bottle containing 12.5 ml of concentrated formalin to yield a 10% buffered formalin solution. Samples were stored for analysis at the ADF&G Kodiak Near Island laboratory. Subsamples of zooplankton were keyed to family or genus and counted on a Sedgewick-Rafter counting slide. This process was replicated three times per sample then counts were averaged and extrapolated over the entire sample. For each plankton tow, mean length (±0.01 mm) was measured for each family or genus with a sample size derived from a student's t-test to achieve a confidence level of 95% (Edmundson et al. 1994). Biomass was calculated via species-specific linear regression equations between weight and unweighted and weighted length measurements (Koenings et al. 1987).

JUVENILE SOCKEYE SALMON SAMPLING

Historical juvenile sockeye salmon data are available from 1967 to 1975, 1978 to 1980, 1986 to 1989, and from 1992 to the present. For the purposes of this report, data from 1992 to 2007 will be presented as they are a consistent time series and the methods of data collection were better documented than those of prior years. Data collected prior to 1996 were often tabulated without citations or references to the procedures used and were assumed to follow the same methods employed during 1996 (Honnold et al. 1996). From 1996 to the present, a fyke net was deployed at the mouth of Bear Lake, directly behind the weir. The net was fished generally during the working hours of the weir crew. The net was fished during the night when the outmigration was slow enough not to overcrowd the fyke net's live box or weather conditions would not affect the ability of the net to capture fish. From 2000 to 2002, a smolt enumeration project utilized fyke nets, a rotary screw trap, and an incline plane trap to capture outmigrating sockeye salmon smolts from the Bear River with varying degrees of success. The annual protocols and results of this project are documented by Bouwens (2001, 2002, and 2003). The first 200 sockeye salmon smolts collected during a statistical week were sampled for age, weight, and length (AWL) data.

Juvenile sockeye salmon collection seasonally spanned from the time the weir was deployed in May until it approximately the second week in August.

Scales were taken from the preferred area (INPFC 1963) of each fish sampled for AWL data and placed on a labeled glass slide. Weight was measured to the nearest 0.1 g, and fork length (FL) was measured to the nearest 1 mm. All juvenile sockeye salmon scales were aged on a microfiche reader (Eyecom 3000) under 36X or 60X magnification and recorded in European notation (Koo 1962). AWL data were compiled in a database for comparison. Relative condition factor was determined for fish in each rearing area following the methods outlined by Quinn and Deriso (1999).

RESULTS

LIMNOLOGY DATA

Physical Data

Temperature-depth profiles indicated that Bear Lake was weakly stratified from the lake's surface to a depth of 50 m, which was the maximum depth the equipment could measure (Figure 2). The average 1-m temperatures increased over the sampling season; they were 8.6°C for June, 11.0 °C for July, and 13.6 °C for August (Figure 2). The warmest average 1-m temperature was recorded in 2003 (13.9°C) and the coldest average 1-m temperature was in 2007 (5.2°C), however, it should be noted that no temperature data were collected in August of 2006 and 2007 (Table 1). Additionally, no temperature data were collected in June of 2003 because of a malfunctioning meter.

Dissolved oxygen-depth profiles corroborated that Bear Lake was weakly stratified from the lake's surface to a depth of 50 m (Figure 3). The average 1-m dissolved oxygen concentrations increased over the sampling season; they were 11.0 mg/L for June, 11.3 mg/L for July, and 14.4 mg/L for August (Figure 3). The highest average 1-m dissolved oxygen measurement was recorded in 2007 (13.5 mg/L) and the lowest average 1-m dissolved oxygen measurement was in 2003 (9.6 mg/L), however it should be noted that no dissolved oxygen data were collected in August of 2006 and 2007 (Table 1). Additionally, no dissolved oxygen data were collected in June of 2003 because of a malfunctioning meter.

Solar illuminance data indicated that light increasingly penetrated the water column from June to August (Figure 4). Additionally, Bear Lake had an annual average euphotic zone depth (EZD) of 24.9 m (Table 1). The EZD was deepest in 2007 (27.2 m) and shallowest in 2004 (18.4 m). Secchi disc readings were deepest in 2007 (7.6 m) and shallowest in 2004 (4.9 m; Table 1). No solar illuminance measurements were taken in August of 2006 and 2007.

Nutrient Data

The following seasonal averages of nutrient data have been summarized in Table 2. The average pH of Bear Lake was 7.3, ranging from 7.2 to 7.7 between 2000 and 2007. Measurements of pH were generally similar between sample depths of 1 and 29 meters. Alkalinity from 2000 to 2007 averaged 14.6 mg/L at a depth of one meter and 12.1 mg/L at a depth of 29 meters. Total phosphorous (TP) was at its greatest seasonal average concentration in 2001 (12.4 µg/L P) and its lowest in 2006 (3.7 µg/L P). Nitrate + nitrite had an eight-year mean of 64.9 µg/L N. Total Kjeldahl nitrogen (TKN), which was only determined from a depth of one meter, had a seven-year mean of 98.8 µg/L N. The seasonal average ammonia concentration ranged from 3.3 to

8.9 µg/L N with an eight-year average of 6.2 µg/L N. The seasonal mean concentration of chlorophyll *a* at a depth of 1 meter was 1.0 µg/L, ranging from 0.7 µg/L in 2005 to 1.3 µg/L in 2001. Chlorophyll-*a* concentrations from a depth of 29 meters were similar to the one meter concentrations. Phaeophytin-a concentrations seasonally averaged 0.4 µg/L.

Monthly averages of nutrient data have been summarized in Table 3. Values of pH, Nitrate+nitrite, TKN, and ammonia increased from May to June and then declined from June to August for 1-m samples. Alkalinity and TP coincidentally fluctuated over the summer sampling season. For samples collected from a 29-m depth, data are only available from June through August. For these samples, alkalinity varied over time, phaeophytin-*a* and ammonia concentrations increased and all other nutrient concentrations and pH decreased. Chlorophyll-*a* levels of water collected at a depth of 1 meter declined over the summer sampling seasons. Phaeophytin-*a* levels of water collected at a depth of 1 meter increased over the summer sampling seasons.

ZOOPLANKTON DATA

Seasonally, copepods were more abundant than cladocerans in Bear Lake from 2000 to 2007 (Table 4). Zooplankton samples were not collected from Bear Lake in August of 2006 and 2007. The greatest seasonal abundance of copepods was in 2006 (708,598/m^2). The seasonal copepod abundance was predominantly composed of *Cyclops*, ranging between 250,973 to 625,365/m^2 (Table 4). The seasonal cladoceran abundance was predominantly composed of *Bosmina*, with abundances ranging between 10,382 to 284,501/m^2.

Copepods were greater in biomass than cladocerans based on annual seasonal values (Table 5; Figure 5). The greatest copepod biomass (1,513.91 mg/m^2) occurred in 2006 and the lowest copepod biomass (432.71 mg/m^2) occurred in 2004 (Table 5). The cladoceran biomass was greatest (816.59 mg/m^2) in 2000 and at its lowest (38.33 mg/m^2) in 2007 (Table 5). Seasonal *Cyclops* biomass estimates were consistently greater than any other genera of zooplankton. Seasonal averages of cladoceran biomass were predominantly composed of *Bosmina*. The majority of the total seasonal average zooplankton biomasses were greater than 1,000 mg/m^2 (Table 5; Figure 5). Monthly averages of zooplankton showed increases in the cladoceran biomass from May to August where as the copepod biomass increased from May to June, followed by a decline from June to August (Figure 6).

Average seasonal lengths of the major zooplankton genera in Bear Lake from 2000 to 2007 were 0.83 mm for *Epischura*, 0.93 mm for *Diaptomus*, 0.76 mm for *Cyclops*, 0.60 mm for ovigerous *Bosmina*, 0.57 mm for *Daphnia*, and 0.46 mm for non-ovigerous *Bosmina* (Table 6; Figure 7). All *Bosmina* were on average longer than the juvenile sockeye salmon feeding threshold size of 0.40 mm (Kyle 1992; Figure 7).

SOCKEYE SALMON SMOLT DATA

Of the 27,140 sockeye salmon smolt sampled for AWL data in the Bear River between 1992 and 2007, 37.9% were age-1. fish, 61.2% were age-2. fish, 0.7% were age-3. fish, and 0.1% were age-0. fish. Age-2. fish generally composed the largest proportion of the sample population, with the exceptions of 1998 and from 2002 to 2005 when age-1. fish were more abundant in the samples (Figure 8). Age-0. sockeye salmon had a mean weight of 4.4 g and a mean length of 78 mm (Table 7). Age-1. sockeye salmon had a mean weight of 10.9 g and a mean length of 103 mm (Table 7). Age-2. sockeye salmon had a mean weight of 13.6 g and a mean length of 112

mm (Table 7). Age-3. sockeye salmon had a mean weight of 20.3 g and a mean length of 127 mm (Table 7). For age-1. fish the mean seasonal weights ranged from 7.1 g in 1992 to 16.3 g in 2001 and the mean seasonal lengths ranged from 90 mm in 1993 to 117 mm in 2001 (Table 7; Figure 9). For age-2. fish, the mean seasonal weights ranged from 8.7 g in 1992 to 18.6 g in 2004 and the mean seasonal lengths ranged from 98 mm in 1992 to 125 mm in 2004 (Table 7; Figure 9).

DISCUSSION

Oligotrophic lakes are preferred habitat for rearing sockeye salmon (Carlson 1977; Carlson and Simpson 1996). Limnology data indicated that Bear Lake could be classified as having oligotrophic (low) production levels as defined by several trophic state indices (Carlson 1977; Carlson and Simpson 1996; Forsberg and Ryding 1980).

Nutrient data may be used to indicate limitations in aquatic environments. Nitrogen-phosphorous ratios of less than 10:1 indicate nitrogen limitations (USEPA 2000). In Bear Lake, the average ratios of total nitrogen to total phosphorous were greater than a ratio of 10:1 (range of 15.4:1 to 27.3:1 from 2000 to 2007) which suggested that nitrogen was not a limiting nutrient to photosynthesis (USEPA 2000). A comparison of the photosynthetic pigment, chlorophyll *a,* to its by-product, phaeophytin *a,* showed that chlorophyll-*a* concentrations were generally proportionally high (annual seasonal means ranging from 1.3 to 5.9 chlorophyll *a* to 1 phaeophytin *a*). This indicated that algae levels in Bear Lake were adequate for supporting primary consumption because the potential for algal (phytoplankton) growth existed as chlorophyll *a* was available for photosynthesis (COLAP 2001). Conversely, when primary production is taxed, phaeophytin-*a* levels tend to exceed chlorophyll-*a* levels (COLAP 2001). Historically phaeophytin-*a* levels have not exceed chlorophyll-*a* levels in Bear Lake. Therefore primary nutrients have not appeared to be a limiting factor in Bear Lake for its level of productivity.

Review of the Bear Lake pH and alkalinity data suggested that primary production was not limited. Photosynthesis uses dissolved carbon dioxide (CO_2), which acts like carbonic acid (H_2CO_3) in water. The removal of carbon dioxide through photosynthesis, in effect, reduces the acidity of the water and therefore pH increases (Wetzel 1983). The monthly average Bear Lake pH levels increased from 7.3 (May) to 7.4 (June) during the peak of the summer growing season when daylight hours, and therefore photosynthetic rates, were greatest. This suggested that sufficient nutrients were available for primary production as evidenced by a measurable seasonal increase in pH. During July and August, average pH levels decreased, which may be the result of increased zooplankton respiration releasing CO_2 into the water. This can be expected because the total zooplankton abundance generally increased over the summer with increased temperatures and forage (phytoplankton) availability and decreased grazing pressure from juvenile salmon as rearing fish leave the lake during the spring smolt outmigration. Additionally, as zooplankton abundance increases, so does their grazing pressure upon phytoplankton. The increased grazing upon phytoplankton may also contribute to reducing the removal of CO_2 from the water, and therefore the pH-reducing effect of photosynthesis. Analysis of alkalinity data indicated that Bear Lake became less resistant to changes in pH (decreased alkalinity) and the total phosphorous concentration generally declined as the summer progressed, which corresponds to how measures of ionic concentration, such as alkalinity, are positively correlated to phosphorous concentrations (Cardoso et al. 2007). This may be explained by the removal of phosphorous from

the water column via photosynthesis and sedimentation of those nutrients following a spring turn-over of the lake (Cardoso et al. 2007; Wetzel 1983).

Physical data also suggested that zooplankton were not limited by phytoplankton production. Changes in phytoplankton species composition mediated by physical factors such as water clarity can negatively affect zooplankton consumption and assimilation rates (Kerfoot 1987; Kyle 1996; Wetzel 1983). Cladocerans, which are selective feeders, can have periods of reduced growth or reproduction in the absence of preferred forage (Dodson and Frey 2001). Similarly, Kirk and Gilbert (1990) noted that suspended particles dilute food concentrations in the water column reducing cladoceran population growth rates. For Bear Lake zooplankton, water clarity normally has not been an issue as evidenced by an average summer euphotic zone depth (EZD) of 24.9 m and average summer Secchi disc readings ranging from 4.9 to 7.6 m between 2000 and 2007. It should be noted however, that comparisons of Bear Lake Secchi disc readings to chlorophyll-*a* concentrations do not reveal a hyperbolic relationship that is often seen in other lakes (Figure 10; COLAP 2001). Typically, as chlorophyll-*a* concentrations increase, Secchi discs become less visible because of increased phytoplankton in the water column and vice versa. The lack of this relationship may be due to two factors: 1) other particulates, such as sediments may be present in the water column affecting visibility and 2) we do not have the contrast in the data to reveal a hyperbolic trend. Despite any potential limitations of the data, the lack of the hyperbolic relationship suggests that the glacial tributaries of Bear Lake cause some sediment-based turbidity, yet because the zooplankton biomass is relatively high (Mazumder and Edmundson 2002) nutrient availability would appear to have a greater influence over primary production (and therefore primary consumers such as zooplankton) than water clarity or turbidity.

Planktivorous fishes, such as sockeye salmon, can exert top-down pressures on zooplankton communities (Kyle 1996; Stockner and MacIsaac 1996). This type of predation can result in changes to the zooplankton species composition (Donald et al. 2001; Helminen and Sarvala 1997; Thorpe and Covich 2001). Specifically, copepods can enter a state of diapause as an egg or copepdid in response to overcrowding, photoperiod, or predation (Thorpe and Covich 2001). Average monthly density estimates for copepods in Bear Lake increased from May to June, yet declined from June to August, which could indicate a response to predation. However, the decline in copepod biomass followed a seasonal high of over 1,000 mg/m^2 in June, which is considered a satiation level for rearing salmonids (Mazumder and Edmundson 2002) and coincided with temperature and cladoceran biomass increases in each month. Therefore, it is possible that the high June density of copepods coupled with increasing seasonal temperatures and *Bosmina* biomass caused the copepods to go into a state of diapause in July and August, essentially removing them from the population and causing the decline in their biomass rather than predation. The average length of *Bosmina* supports this hypothesis. Evidence of overgrazed zooplankton populations can be reflected by a reduction in cladoceran body length (Kyle 1992; Schindler 1992). In Bear Lake, *Bosmina* on average were longer than the minimum elective feeding threshold of 0.40 mm for juvenile sockeye salmon (Kyle 1992). This suggests that top-down grazing pressures were not severely stressing or substantially removing the larger *Bosmina* from the zooplankton population, and perhaps not as influential upon the zooplankton community as interspecific competition and physical conditions in Bear Lake.

Comparisons of juvenile sockeye salmon age class compositions may offer evidence of rearing limitations in Bear Lake. Age composition data of Bear Lake sockeye salmon smolts indicated that historically age-2. fish composed the majority of the outmigrating smolt population. Only in

1998 and from 2002 to 2005, were age-1. fish the predominant age group. Although limnology data are unavailable for 1998, limnology data from 2003 to 2005 suggested that summer rearing conditions were warmer than average. It should also be noted that the total zooplankton biomass fell below the satiation level threshold for rearing salmonids (Mazumder and Edmundson 2002) and adult sockeye salmon escapements were relatively low during those same years. Thus, temperature, zooplankton abundance, and escapement levels may have influenced the outmigration of more age-1. fish than age-2. fish from Bear Lake. Because condition factor data indicated that both age classes can be considered in good condition, this would suggest that physical conditions may have a greater effect upon the rearing and outmigration of Bear Lake smolt than any density dependent effects via competition for zooplankton. Because Bear Lake sockeye salmon smolts are of large size and good condition and zooplankton forage generally appears abundant, these data corroborate that the rearing habitat has been underutilized and sockeye salmon production may be influenced more by factors such as spawning area as indicated by Honnold et al. (1996). Furthermore, because fully-recruited adult age composition data showed that age-2. fish composed the majority of the adult returns, this would also suggest that factors other than competition in Bear Lake are influencing Bear Lake sockeye salmon survival.

Changes in nutrients and forage bases can significantly impact higher trophic levels such as secondary or tertiary consumers (Kyle et al. 1988; Milovskaya et al. 1998). In some lake systems, these negative changes can cause migratory behavior or decreased juvenile sockeye salmon freshwater survival (Bouwens and Finkle 2003; Parr 1972; Ruggerone 1994). Factors that influence the growth or migration, and therefore survival of juvenile fish can affect increases or decreases of adult returns, which sustain subsistence and commercial fishers. Thus, it is important to know and understand patterns of resource abundance and habitat usage in Bear Lake to enhance management of the system and conserve its resources. In light of these data, it is apparent that Bear Lake produces a healthy population of sockeye salmon smolt for its level of lake productivity. These data have elucidated patterns of ecological processes that suggest the lake is not rearing limited. Continued observation of Bear Lake limnology and smolts following these effects may indicate if the rearing environments are at sustainable production levels or if changing climatic conditions are impacting smolt survival.

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TABLES AND FIGURES

Table 1.–Seasonal average 1-m temperature, 1-m dissolved oxygen, euphotic zone depth (EZD), and Secchi disc measurements from Bear Lake, 2000 to 2007.

	Year								
	2000	2001[a]	2002	2003[b]	2004	2005	2006[c]	2007[c]	Average
1-m Temperature (°C)	10.0	9.5	9.5	13.9	11.8	12.2	9.6	5.2	10.2
1-m Dissolved oxygen (mg/L)	11.0	11.6	12.8	9.6	11.3	11.8	13.5	13.5	11.9
EZD (m)	24.3	24.5	24.8	24.7	18.4	25.0	22.9	27.2	24.9
Secchi depth (m)	5.7	7.0	7.4	7.4	4.9	5.3	6.4	7.6	6.5

[a] The only May sample was collected in 2001.

[b] No June temperature or dissolved oxygen samples collected.

[c] No August samples collected

Table 2.–Seasonal water quality properties, nutrient and photosynthetic pigment concentrations in Bear Lake from 2000 to 2007.

Water Sample Depth (m)		Year								
		2000	2001[a]	2002	2003[b]	2004	2005	2006[c]	2007[c]	Average
1	pH	7.9	7.2	7.2	7.2	7.3	7.2	7.5	7.4	7.3
	Alkalinity(mg/L)	15.9	17.5	15.7	13.4	13.5	15.3	12.3	9.5	14.6
	Total P (ug/L P)	9.0	12.4	8.6	5.9	5.8	9.6	3.7	6.3	8.09
	Nitrate + Nitrite (ug/L N)	40.9	52.4	52.1	75.5	53.1	56.7	86.1	105.0	62.0
	TKN (ug/L N)	ND	81.8	92.4	85.0	94.3	108.0	144.0	85.0	98.8
	Ammonia (ug/L N)	2.9	3.3	5.2	7.8	6.4	3.6	8.1	6.0	5.2
	Chlorophyll *a* (ug/L)	0.9	1.3	0.5	1.1	1.0	0.7	1.2	1.0	1.0
	Phaeophytin *a* (ug/L)	0.4	0.2	1.9	0.1	0.2	0.3	0.2	0.3	0.5
29	pH	7.4	ND	ND	7.2	7.3	7.2	7.4	7.3	7.3
	Alkalinity(mg/L)	9.0	ND	ND	13.5	12.3	14.9	12.3	10.0	12.1
	Total P (ug/L P)	8.8	ND	ND	5.5	6.2	8.1	3.7	7.3	6.7
	Nitrate + Nitrite (ug/L N)	46.1	ND	ND	75.0	58.4	56.0	95.3	103.3	69.0
	TKN (ug/L N)	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Ammonia (ug/L N)	5.0	ND	ND	9.5	11.5	4.9	9.7	5.3	7.6
	Chlorophyll *a* (ug/L)	0.8	ND	ND	1.2	1.1	1.0	1.2	1.3	1.1
	Phaeophytin *a* (ug/L)	0.6	ND	ND	0.2	0.4	0.3	0.3	0.3	0.3
Average	pH	7.7	7.2	7.2	7.2	7.3	7.2	7.4	7.4	7.3
	Alkalinity(mg/L)	12.5	17.5	15.7	13.4	12.9	15.1	12.3	9.8	13.6
	Total P (ug/L P)	8.9	12.4	8.6	5.7	6.0	8.9	3.7	6.8	7.52
	Nitrate + Nitrite (ug/L N)	43.5	52.4	52.1	75.3	55.7	56.4	90.7	104.1	64.9
	TKN (ug/L N)	ND	81.8	92.4	85.0	94.3	108.0	144.0	85.0	98.8
	Ammonia (ug/L N)	3.9	3.3	5.2	8.6	8.9	4.2	8.9	5.6	6.2
	Chlorophyll *a* (ug/L)	0.8	1.3	0.5	1.2	1.0	0.8	1.2	1.1	1.0
	Phaeophytin *a* (ug/L)	0.5	0.2	1.9	0.2	0.3	0.3	0.2	0.3	0.4

[a] The only May sample was collected in 2001.

[b] No June temperature or dissolved oxygen samples collected.

[c] No August samples collected

Table 3.–Average monthly water quality properties, nutrient and photosynthetic pigment concentrations in Bear Lake from 2000 to 2007.

Water Sample Depth (m)		Month				
		May[a]	June	July	August[b]	Average
1	pH	7.3	7.5	7.3	7.2	7.3
	Alkalinity(mg/L)	15.5	17.0	12.6	13.8	14.6
	Total P (ug/L P)	15.7	7.1	8.1	8.1	8.09
	Nitrate + Nitrite (ug/L N)	57.6	83.1	57.9	40.1	62.0
	TKN (ug/L N)	81.8	106.8	97.8	92.4	98.8
	Ammonia (ug/L N)	2.9	5.8	5.1	4.7	5.2
	Chlorophyll *a* (ug/L)	2.1	1.1	0.9	0.7	1.0
	Phaeophytin *a* (ug/L)	0.0	0.3	0.3	1.0	0.5
29	pH	ND	7.4	7.3	7.2	7.3
	Alkalinity(mg/L)	ND	12.6	11.9	11.7	12.1
	Total P (ug/L P)	ND	5.3	7.6	7.5	6.7
	Nitrate + Nitrite (ug/L N)	ND	78.9	67.9	55.7	69.0
	TKN (ug/L N)	ND	ND	ND	ND	ND
	Ammonia (ug/L N)	ND	5.0	7.5	11.9	7.6
	Chlorophyll *a* (ug/L)	ND	1.2	1.1	0.8	1.1
	Phaeophytin *a* (ug/L)	ND	0.3	0.3	0.4	0.3
Average	pH	7.3	7.4	7.3	7.2	7.3
	Alkalinity(mg/L)	15.5	15.1	12.3	12.9	13.6
	Total P (ug/L P)	15.7	6.3	7.9	7.9	7.52
	Nitrate + Nitrite (ug/L N)	57.6	81.3	62.2	46.4	64.9
	TKN (ug/L N)	81.8	106.8	97.8	92.4	98.8
	Ammonia (ug/L N)	2.9	5.5	6.1	7.6	6.2
	Chlorophyll *a* (ug/L)	2.1	1.1	1.0	0.8	1.0
	Phaeophytin *a* (ug/L)	0.0	0.3	0.3	0.8	0.4

[a] The only May sample was collected in 2001.

[b] No August samples collected in 2006 and 2007.

Table 4.–The 2000 to 2007 seasonal average number of zooplankton per m^2 from Bear Lake.

Taxon	2000	2001[a]	2002	2003	2004	2005	2006[b]	2007[b]
Copepods:								
Epischura	398	1,592	265	531	531	354	-	-
Ovig. *Epischura*	-	-	-	-	-	-	-	-
Diaptomus	-	-	1,216	531	-	-	-	-
Ovig. *Diaptomus*	-	-	-	-	-	-	-	-
Cyclops	371,716	330,729	396,553	250,973	281,759	295,294	625,365	425,053
Ovig. *Cyclops*	22,426	7,409	13,184	19,374	8,625	22,957	19,108	4,379
Harpaticus	-	-	1,239	531	-	-	-	-
Napulii	19,108	23,653	69,961	48,390	42,198	108,369	64,126	84,347
Total copepods	413,647	363,383	482,418	320,329	333,112	426,973	708,598	513,779
Cladocerans:								
Bosmina	284,501	62,981	27,880	185,864	69,268	90,145	36,491	10,382
Ovig. *Bosmina*	13,767	4,810	7,647	26,982	15,747	18,843	6,204	4,703
Daphnia l.	1,327	-	1,209	-	531	1,416	-	-
Ovig. *Daphnia l.*	-	-	-	-	-	-	-	-
Chydorinae	-	2,654	-	531	-	-	-	3,185
Total cladocerans	299,595	70,445	36,735	213,376	85,545	110,404	42,695	18,269
Total abundance	713,242	433,829	519,153	533,705	418,657	537,376	751,293	532,049

[a] The only May sample was collected in 2001.

[b] No August samples collected in 2006 and 2007.

Table 5.–The 2000 to 2007 seasonal weighted biomass (mg dry weight/m^2) estimates of the major Bear Lake zooplankton taxa.

Taxon	2000	2001[a]	2002	2003	2004	2005	2006[b]	2007[b]
Copepods								
Epischura	1.59	4.73	1.72	1.48	0.56	-	-	-
Ovigerous *Epischura*	-	-	-	-	-	-	-	-
Diaptomus	-	-	7.29	1.40	-	-	-	-
Ovigerous *Diaptomus*	-	-	-	-	-	-	-	-
Cyclops	1,051.65	828.17	593.31	432.71	421.65	673.08	1,431.48	1,027.14
Ovigerous *Cyclops*	124.70	33.63	40.96	59.60	28.37	114.00	82.43	27.18
Harpaticus	-	-	2.21	0.43	-	-	-	-
Total copepods	1,177.94	866.54	645.48	495.62	450.58	787.08	1,513.91	1,054.32
Cladocerans								
Bosmina	755.20	143.03	47.86	318.67	97.76	153.39	65.34	22.83
Ovigerous *Bosmina*	61.39	14.44	20.60	92.79	53.52	54.70	23.65	14.56
Daphnia longiremis	-	-	3.69	-	0.11	5.64	-	-
Ovigerous *Daphnia longiremis*	-	-	-	-	-	-	-	-
Chydorinae	-	-	-	-	-	-	-	0.94
Total cladocerans	816.59	157.46	72.15	411.46	151.39	213.74	88.99	38.33
Total Biomass	1,994.53	1,024.00	717.64	907.09	601.97	1,000.81	1,602.90	1,092.64

[a] The only May sample was collected in 2001.

[b] No August samples collected in 2006 and 2007.

Table 6.–Seasonal average lengths (mm) of Bear Lake zooplankton from 2000 to 2007.

Taxon	2000	2001[a]	2002	2003	2004	2005	2006[b]	2007[b]	Average
Copepods									
Epischura	0.96	0.87	0.89	0.82	0.60	-	-	-	0.83
Diaptomus	-	-	1.01	0.84	-	-	-	-	0.93
Ovigerous *Diaptomus*	-	-	-	-	-	-	-	-	-
Cyclops	0.79	0.86	0.66	0.72	0.65	0.81	0.80	0.83	0.76
Ovigerous *Cyclops*	1.07	1.22	1.00	0.96	0.97	1.15	1.14	1.18	1.08
Harpaticus			0.61	0.50	-			-	0.56
Napulii	-	-	-	-	-	-	-	-	-
Cladocerans									
Bosmina	0.48	0.47	0.54	0.44	0.43	0.43	0.45	0.47	0.46
Ovigerous *Bosmina*	0.59	0.56	0.69	0.60	0.60	0.56	0.61	0.63	0.60
Daphnia l.	-	-	0.78	-	0.24	0.68	-	-	0.57
Ovigerous *Daphnia l.*	-	-	-	-	-	-	-	-	-
Chydorinae	-	0.20	-	0.25	-	-	-	0.19	0.21

[a] The only May sample was collected in 2001.

[b] No August samples collected in 2006 and 2007.

Table 7.–Seasonal average length, weight, and condition factor of Bear Lake sockeye salmon smolt by age from 1992 to 2007.

		Age											
	Sample	0			1			2			3		
Year	Size	Length (mm)	Weight (g)	K	Length (mm)	Weight (g)	K	Length (mm)	Weight (g)	K	Length (mm)	Weight (g)	K
1992	1,337	-	-	-	92	7.1	0.92	98	8.7	0.92	148	31.5	0.98
1993	1,587	-	-	-	90	7.2	0.98	98	9.1	0.96	118	14.1	0.86
1994	1,283	-	-	-	99	9.5	0.99	108	12.0	0.97	113	13.8	0.95
1995	1,021	83	3.9	0.68	105	11.5	0.99	112	13.7	0.97	135	21.3	0.87
1996	603	75	3.2	0.76	102	10.0	0.96	113	13.6	0.94	115	14.8	0.97
1997	1,240	96	8.2	0.93	106	12.0	1.02	115	14.3	0.95	125	18.0	0.92
1998	1,424	-	-	-	105	10.8	0.93	114	13.6	0.93	130	18.0	0.82
1999	2,057	67	2.4	0.80	94	7.2	0.88	103	9.4	0.87	139	24.7	0.91
2000	2,135	71	3.6	0.99	106	12.7	1.06	110	13.9	1.03	133	23.3	1.00
2001	1,917	73	3.8	0.97	117	16.3	1.01	121	17.5	0.99	131	22.1	0.98
2002	2,931	90	6.4	0.88	113	14.2	0.98	121	17.0	0.95	152	33.4	0.96
2003	1,788	-	-	-	115	15.3	1.01	116	14.7	0.95	145	29.8	0.98
2004	1,786	-	-	-	103	10.2	0.92	125	18.6	0.94	122	17.6	0.97
2005	2,197	84	4.9	0.82	100	9.7	0.97	120	15.5	0.90	90	7.6	1.04
2006	1,646	-	-	-	99	9.4	0.97	108	11.6	0.93	-	0.0	-
2007	2,188	62	3.2	1.32	104	11.6	1.03	113	14.3	0.99	115	15.0	0.99
Average		78	4.4	0.93	103	10.9	1.00	112	13.6	0.96	127	20.3	0.98

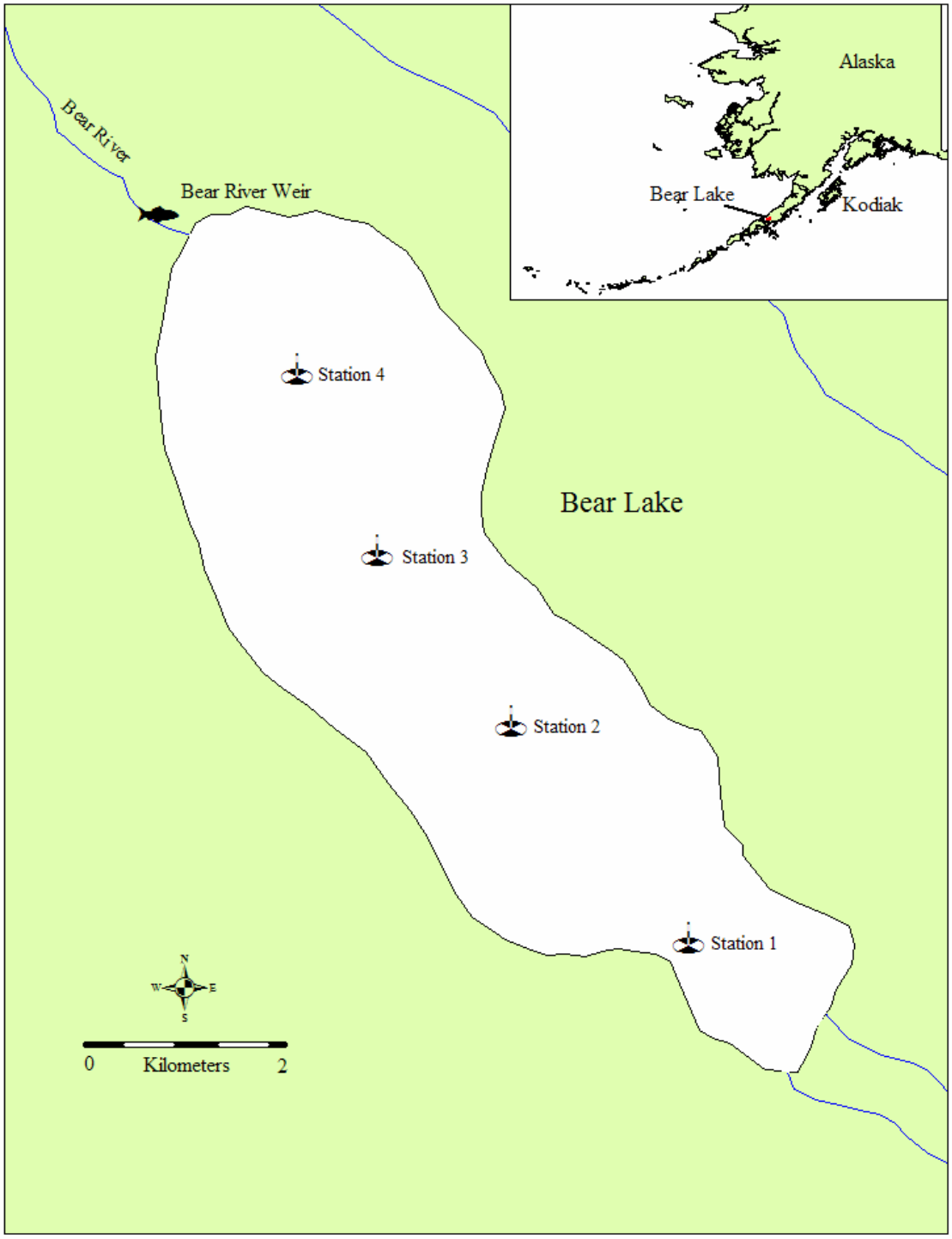

Figure 1.–Bear Lake sampling sites.

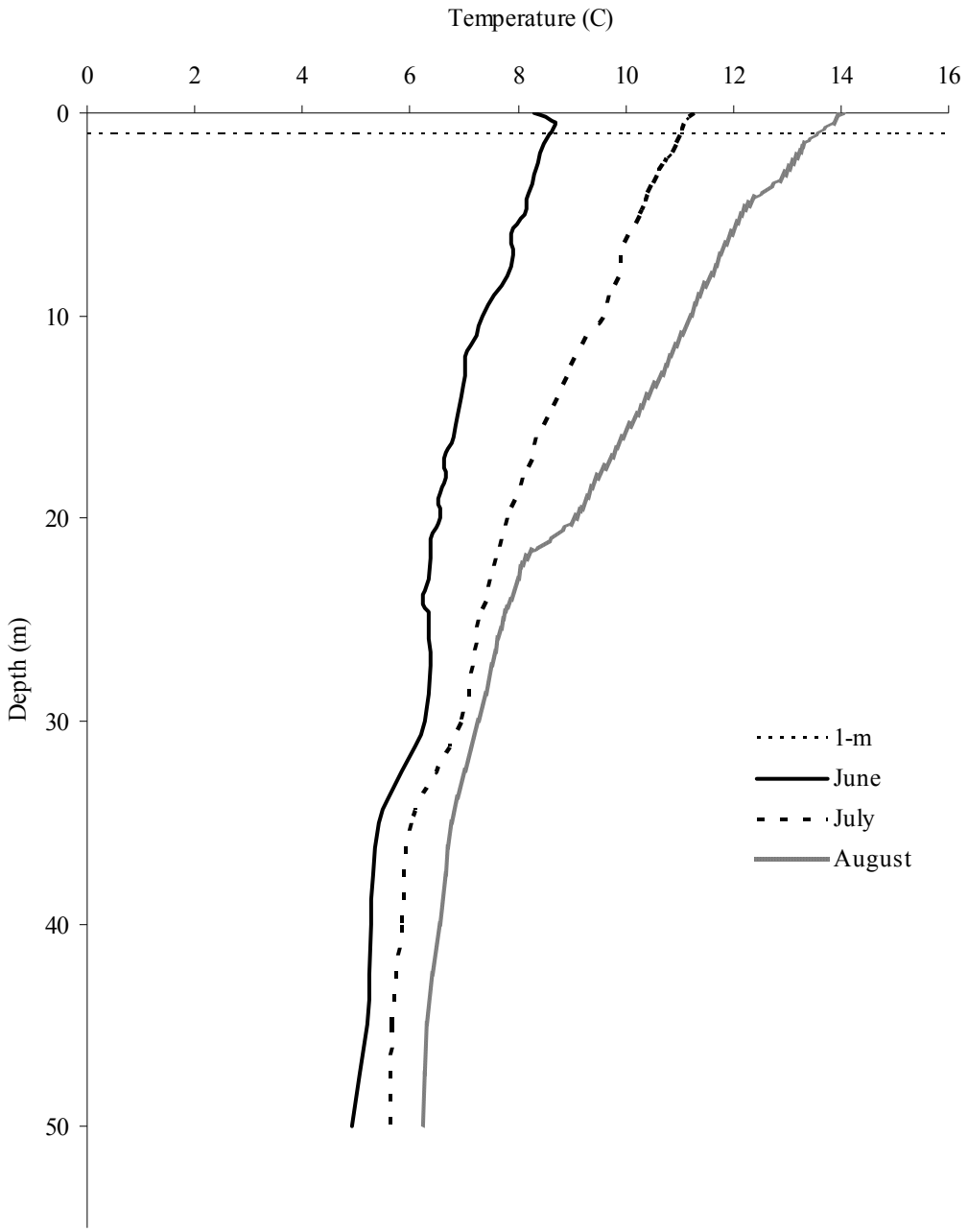

Figure 2.–Average monthly temperature profiles for Bear Lake from 2000 to 2007.

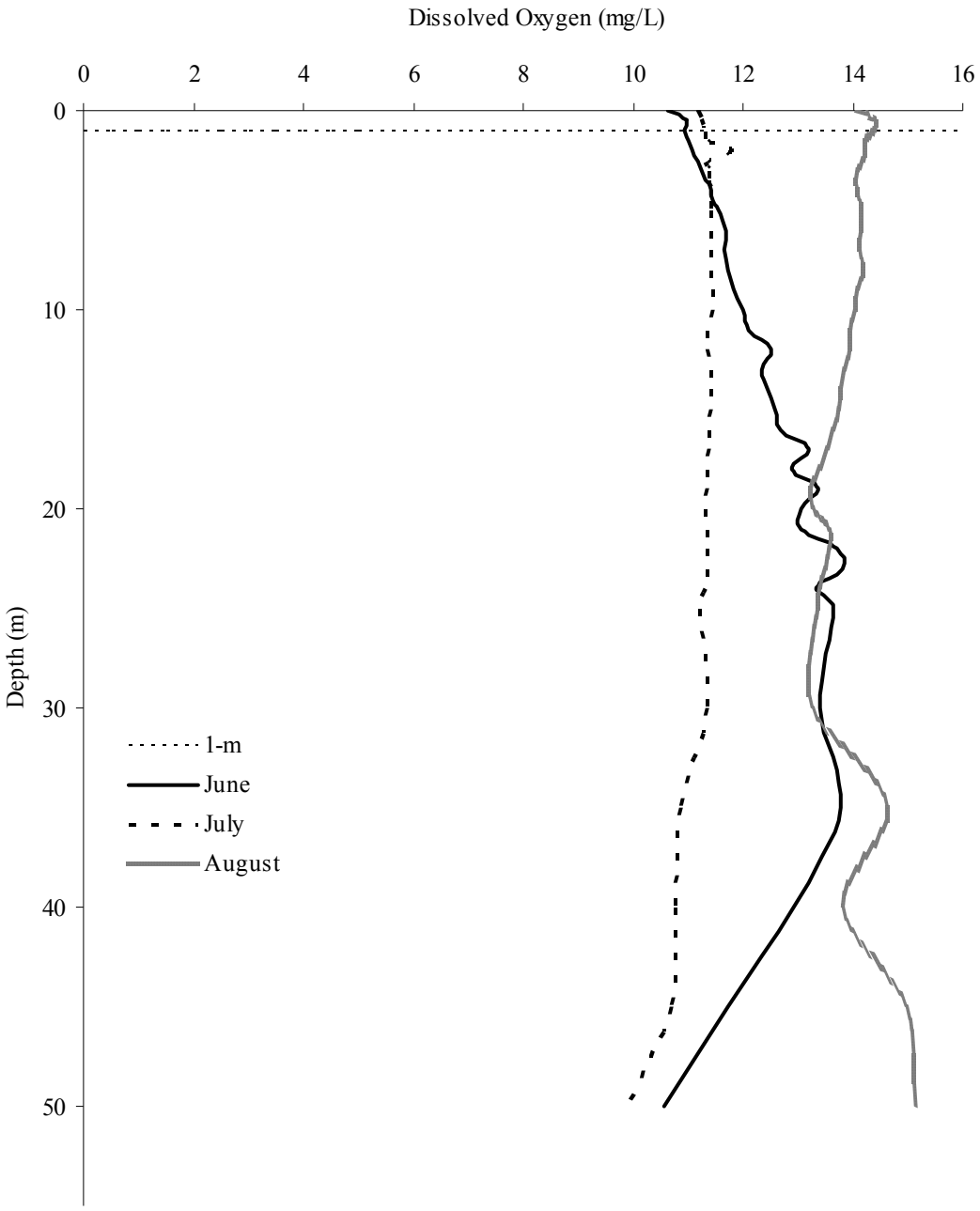

Figure 3.–Average monthly dissolved oxygen profiles for Bear Lake from 2000 to 2007.

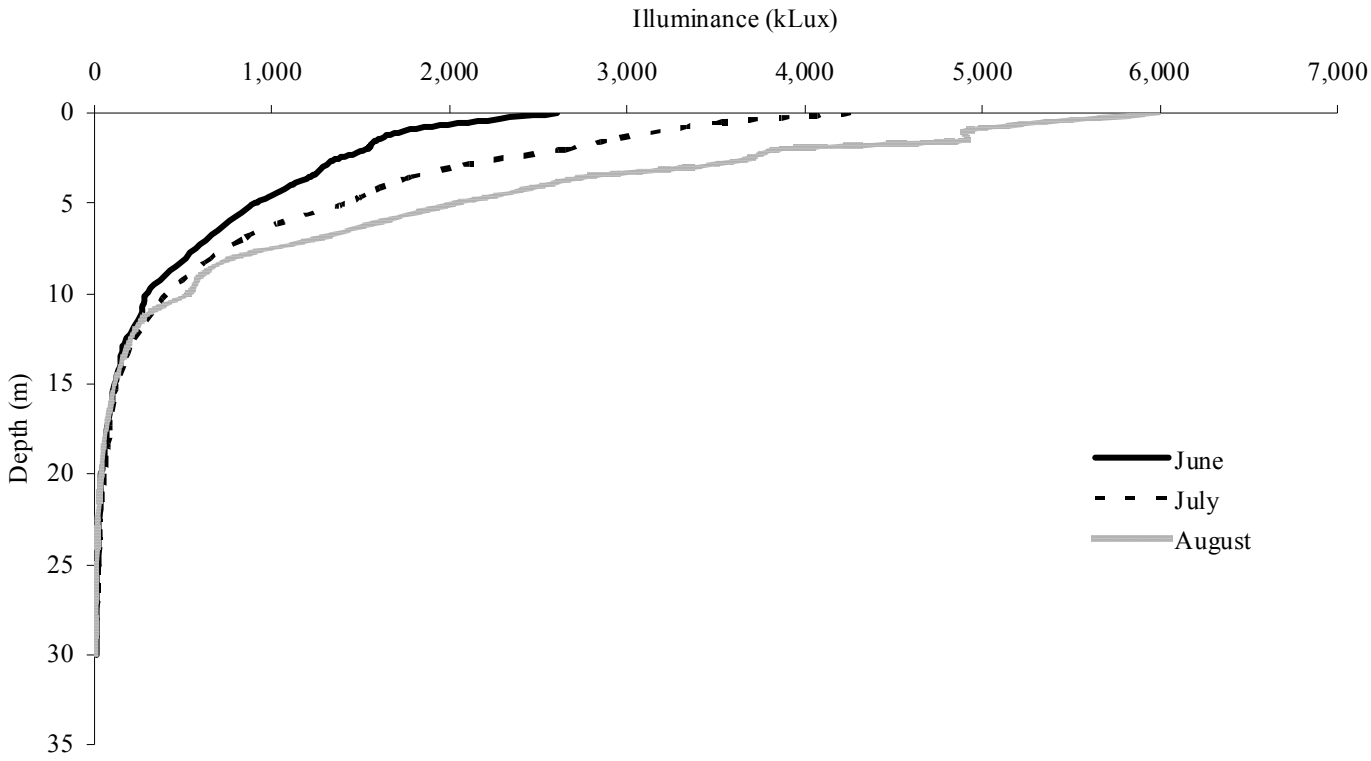

Figure 4.–Average monthly solar illuminance profiles for Bear Lake from 2000 to 2007.

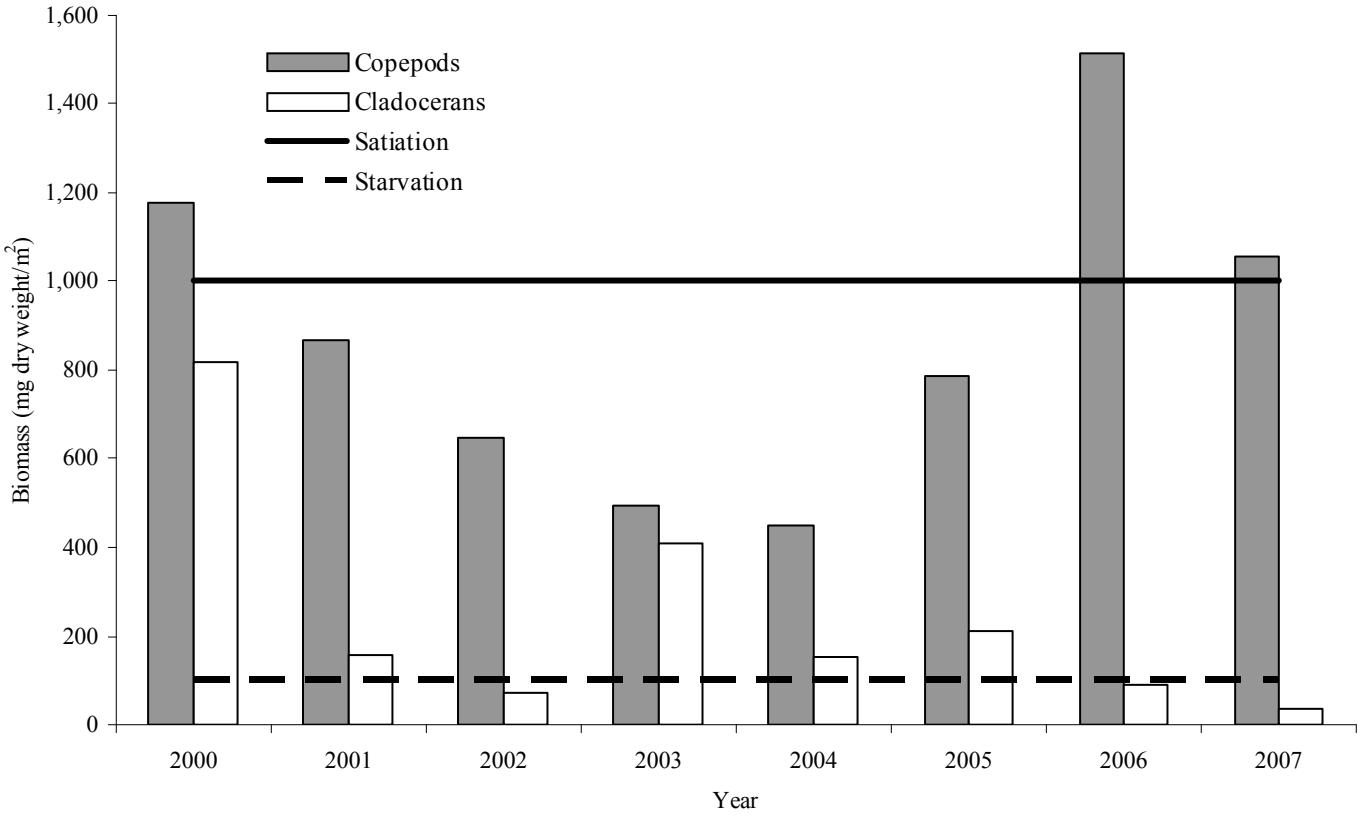

Figure 5.–Average seasonal weighted biomass (mg dry weight/m^2) estimates, by class, of Bear Lake zooplankton from 2000 to 2007 relative to sockeye salmon feeding threshold levels.

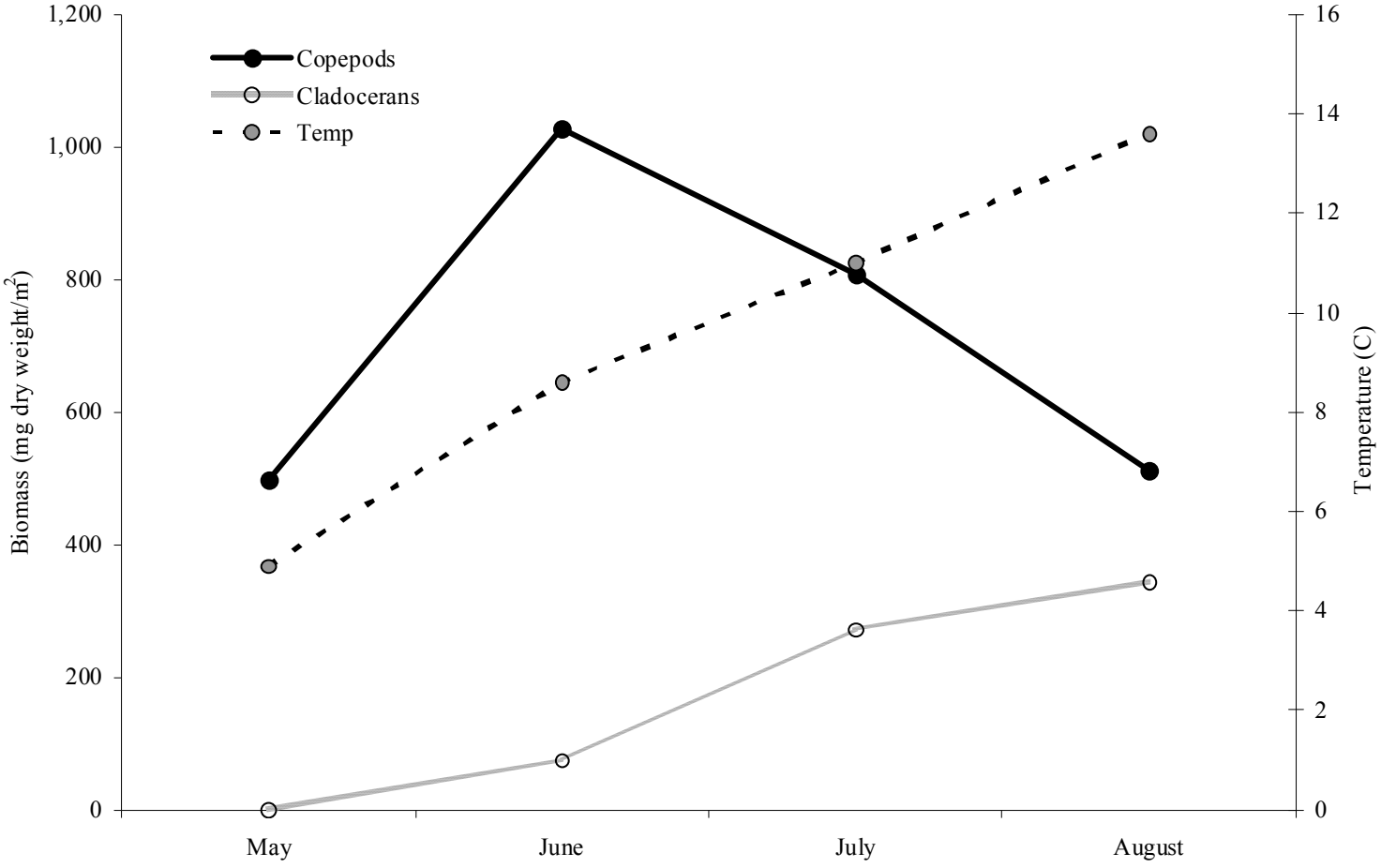

Figure 6.–Average 2000 to 2007 monthly weighted biomass (mg dry weight/m^2) estimates, by class, of Bear Lake zooplankton.

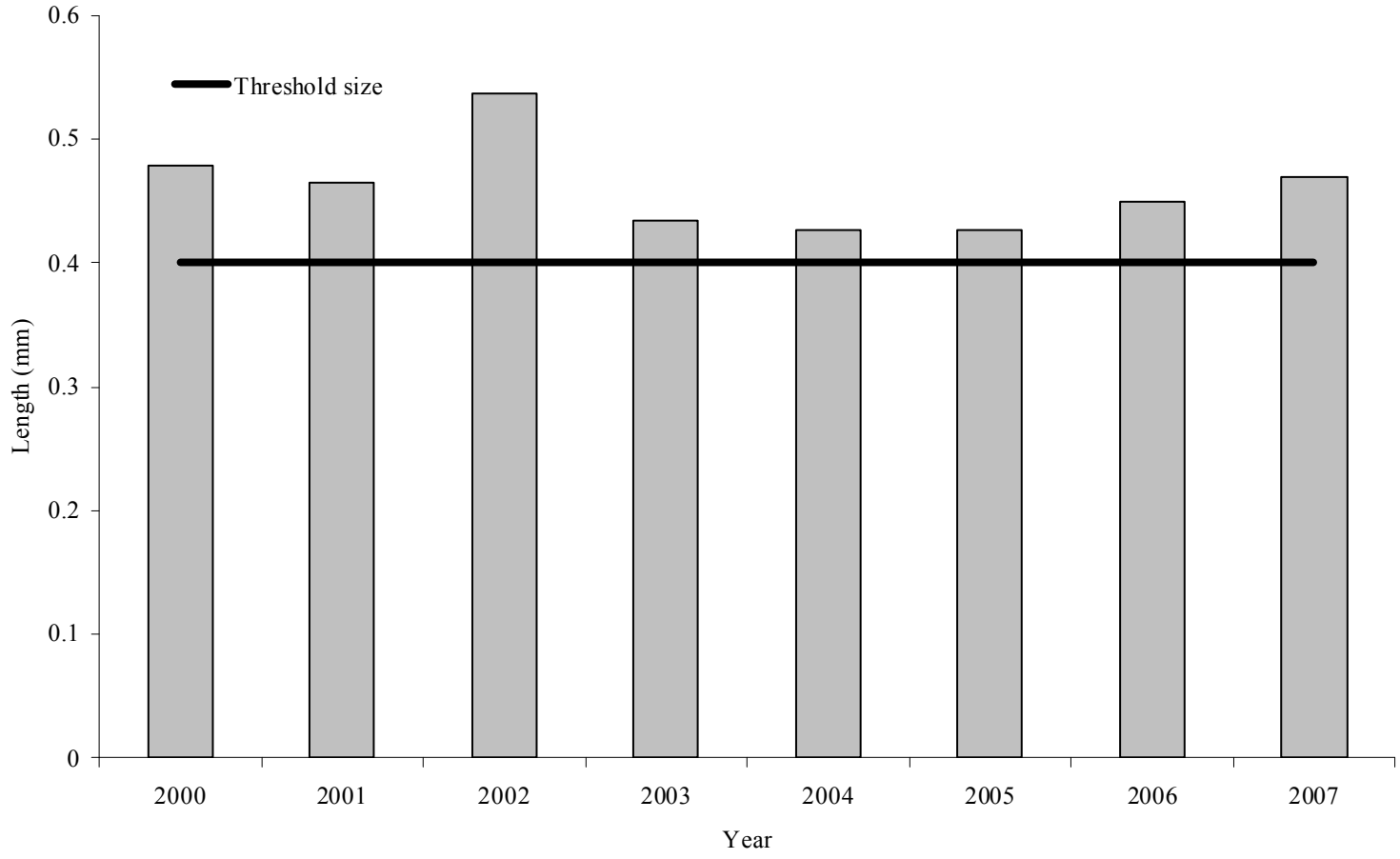

Figure 7.–Seasonal average lengths (mm) of *Bosmina* from Bear Lake from 2000 to 2007 relative to the sockeye salmon feeding threshold size.

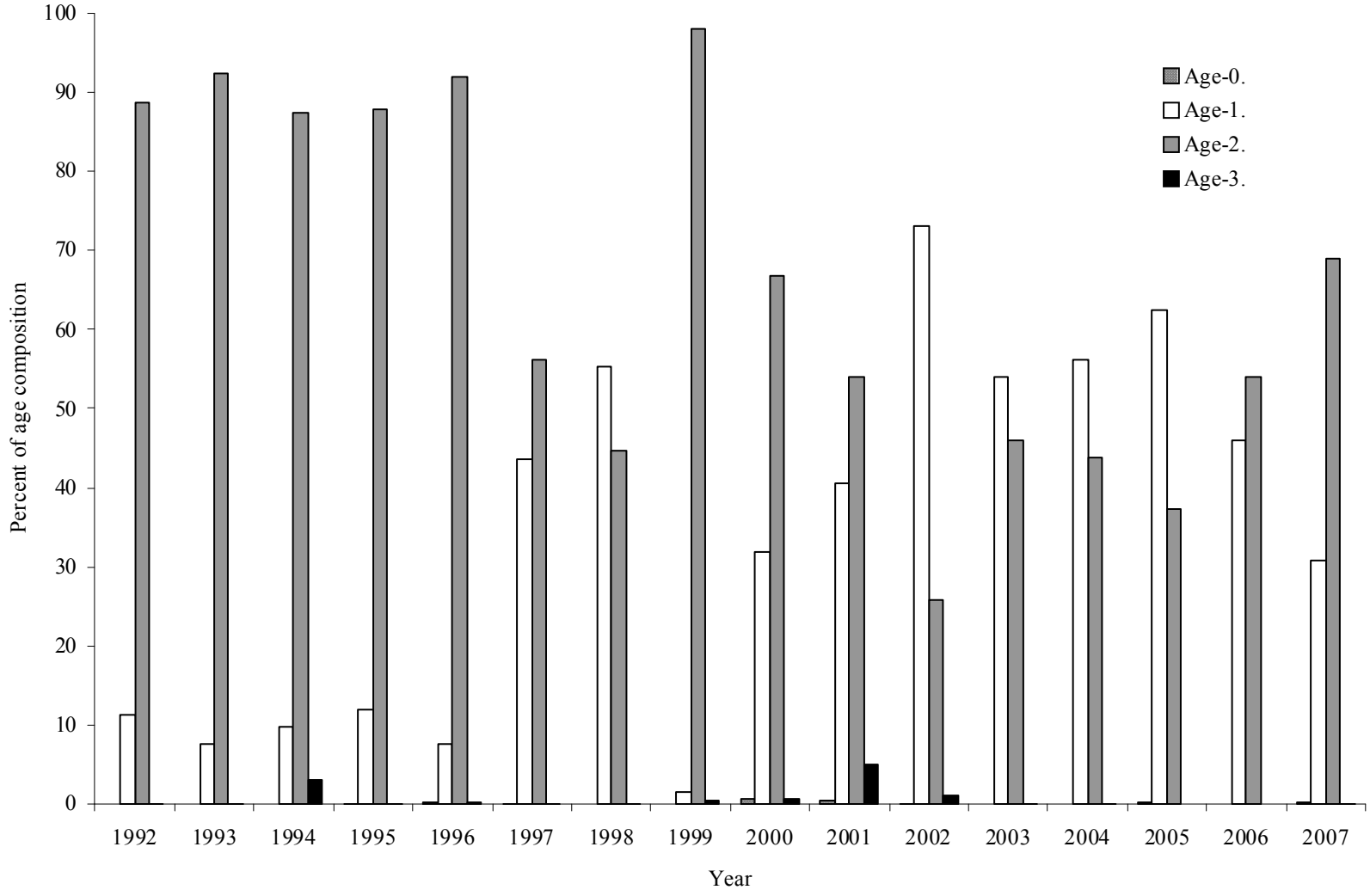

Figure 8.–Seasonal age class compositions of Bear Lake sockeye salmon smolt from 1992 to 2007.

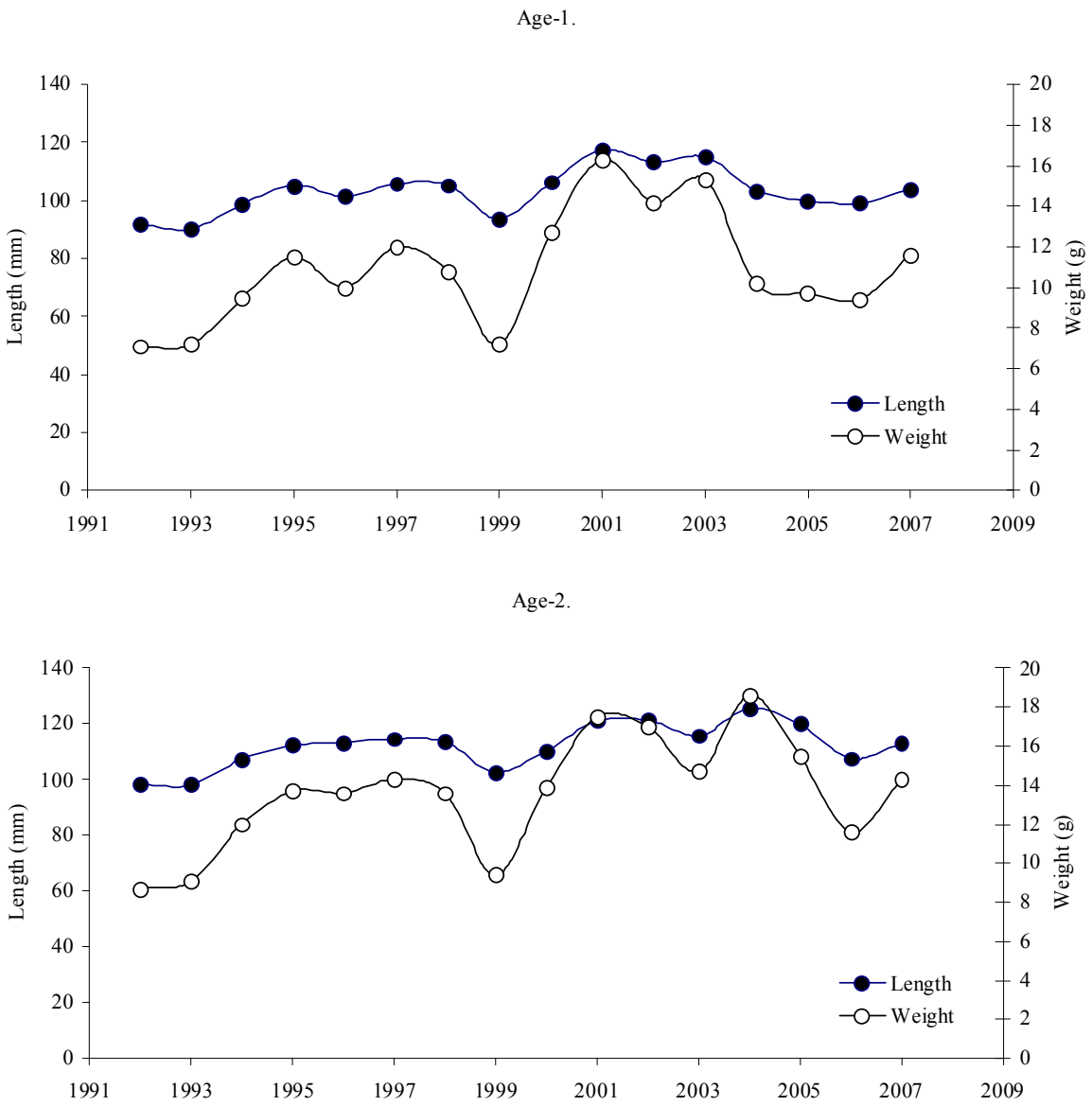

Figure 9.–Average length and weight of age-1. and -2. Bear Lake sockeye salmon smolts from 1992 to 2007.

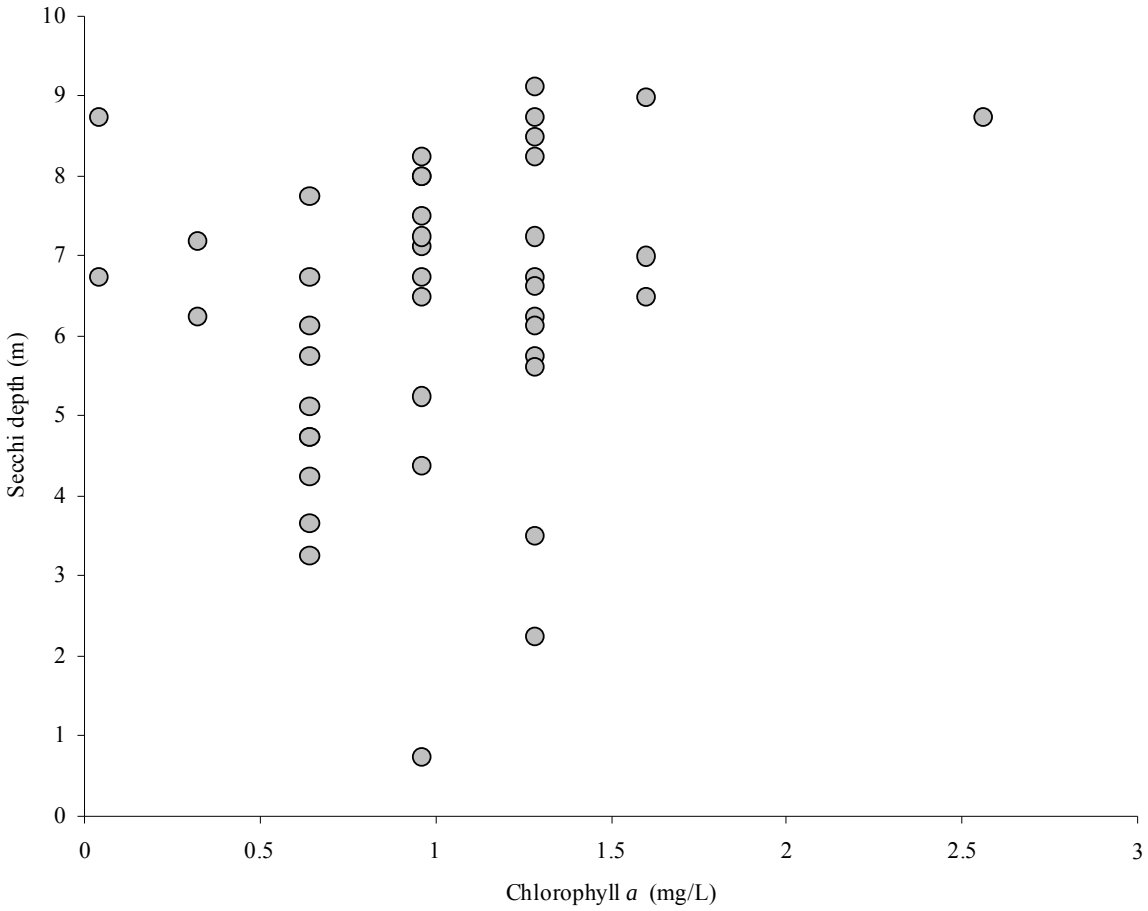

Figure 10.–The relationship between Secchi depth and chlorophyll *a* for Bear Lake.