LIMNOLOGICAL AND FISHERIES INVESTIGATIONS AT

VIRGINIA LAKE, SOUTHEAST ALASKA

1999

by
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and
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ABSTRACT

The Virginia Lake nutrient enrichment program was continued in 1999. Fertilizer was applied at 50% of the critical phosphorous load, using both 32-0-0 liquid fertilizer that was applied weekly from late May to mid-September, and an 8-24-8 solid controlled release fertilizer (CRF) that was placed experimentally into the lake in late May to mid-June. Limnological sampling showed the CRF fertilizer, including most of the phosphorous, dissolved and passed through the lake by late June. The phosphorous decline in July resulted in very low phytoplankton and zooplankton production. The fall rearing sockeye salmon fry population was estimated at 115,600 sockeye salmon fry on 29 November 1999. Based on the EV-ZBD model the lake was capable of producing 154,500 fall fry at optimum production. The 1999 rearing fry were not planted but were F_1 progeny of the adults that returned in 1997 and 1998 from the initial colonization program (1989 to 1996). Based on 12% marine survival, the predicted total adult return for 2000 is estimated at 32,328 (73% enhanced) sockeye salmon.

KEY WORDS: sockeye salmon, *Oncorhynchus nerka*, Virginia Lake, Mill Creek, Southeast Alaska, limnology, zooplankton, lake fertilization, nutrient enrichment, controlled release fertilizer, survival, rearing, hydroacoustics, mid-water trawl, fishpass

INTRODUCTION

Historically, Virginia Lake had a flow limiting natural barrier located just above tidewater that was size specific to the passage of fish, and allowed only a very small population of sockeye salmon to utilize the lake. (Zadina and Haddix 1993). A cooperative plan between the U.S. Forest Service (USFS), the Alaska Department of Fish and Game (ADF&G), Fisheries Rehabilitation, Enhancement, and Development Division (FRED), and the Southern Southeast Regional Aquaculture Association (SSRAA) was implemented in 1987 to colonize a natural run of sockeye salmon *Oncorhynchus nerka* into Virginia Lake. The USFS installed a fishpass in 1988, and ADF&G and SSRAA stocked the lake with sockeye salmon fry from 1989 to 1996 (Edmundson et al. 1991, Zadina and Haddix 1993).

Edmundson et al. (1991) discussed the importance of increasing the fertility of Virginia Lake. Phytoplankton (primary production) and zooplankton (secondary production) biomass were naturally low because Virginia Lake is a nutrient poor system with a rapid flushing rate. Increased planktivory, a result of stocking fry, further reduced the rearing capacity of the lake, particularly when fry were planted too early in the season (e.g. late April and early May in 1989). The introduced fry cropped the zooplankton population down to minimal levels prior to the annual seasonal population expansion that starts in mid-May. This resulted in poor survival rates of sockeye salmon fry from the first two years of fry planting (Edmundson et al. 1991, Zadina and Haddix 1993). Increasing nutrient levels through lake fertilization can potentially boost primary production and zooplankton biomass of some rearing-limited lakes, providing more food for rearing sockeye salmon fry, and, in turn, increasing fry survival and potential adult returns. (See Koenings and Burkett 1987 for an excellent discussion of this topic). A nutrient enrichment program was initiated at Virginia Lake and fertilizer was applied at 90% of the critical phosphorous load (after Vollenweider 1976) every year that sockeye salmon fry were planted in the lake, from 1991 to 1996 (Zadina 1997).

Sockeye salmon fry were not planted into Virginia Lake in 1997, and no nutrients were added to the lake. Evaluation of primary and secondary production showed that lake productivity had dropped dramatically compared to the levels found during nutrient enriched years (Zadina 1997). Despite this, the zooplankton biomass was sufficient to support the fall 1997 sockeye salmon fry population, based on currently used lake rearing models (ADF&G unpublished data). The nutrient enrichment program was reimplemented at Virginia Lake in 1998, with the critical phosphorous loading rate reduced from 90% to 50% (Zadina and Weller 1999). The primary goal was to increase all trophic levels in Virginia Lake, hopefully to the benefit of the resident cutthroat trout *Oncorhynchus clarki* population. Increasing the forage base for rearing sockeye salmon fry is now a secondary goal of lake fertilization, and in fact, zooplankton biomass in 1998 was sufficient to potentially support seven-times the estimated fry population enumerated in 1998 (Zadina and Weller 1999).

Here we report the results of continued limnological studies at Virginia Lake during the 1999 field season. These studies included: (1) an assessment of the primary and secondary production in the lake; (2) an assessment of the lake fertilization application program; (3) an estimate of the rearing sockeye salmon fry population through hydroacoustic sampling; and (4) a forecast of the total adult returns for the years 2000 and 2001. The escapement, age structure, and coded wire tag recoveries of adult sockeye salmon returning to Virginia Lake were evaluated by USFS personnel and are not included in this report.

Study Site

Virginia Lake (56°20' N, 132°10' W) is located 16 km east of Wrangell on mainland Southeast Alaska at an elevation of 32 m (Figure 1). The lake is organically stained with a surface area of 256.7 ha, mean depth of 27.5 m, maximum depth of 54 m, and volume of $70.7 \cdot 10^6$ m^3 (Figure 2). The lake empties into Eastern Passage via Mill Creek (<1 km). Mean annual precipitation is an estimated 280 cm, the lake watershed area encompasses approximately 83 km^2, and the hydraulic residence time or flushing rate is estimated at 4.2 months (Edmundson et al. 1991).

Project Sponsorship

Funding to evaluate the limnological and lake fertilization assessment program was provided by the United States Forest Service through the Alaska Department of Fish and Game. This is the final report fulfilling contract obligations for Sikes Act Contract 43-0109-9-1095.

METHODS

Limnological Assessment

Sampling to evaluate the lake fertilization program was conducted primarily at station A, with zooplankton samples also collected at Station B (Figure 2). Physical data, water quality, and biological samples were collected on 12 May, 14 June, 8 July, 5 August, 10 September, and 14 October, and analyzed at the ADF&G, Division of Commercial Fisheries, Limnology Laboratory in Soldotna, Alaska.

Physical Parameters

Measurements of underwater light penetration (footcandles) were recorded at 0.5 m intervals, from the surface to a depth equivalent to one percent of the subsurface light reading, using an International Light[2] IL1350 submarine photometer. Vertical light extinction coefficients (K_d) were calculated as the slope of the light intensity (ln of percent subsurface light) versus depth. The euphotic zone depth (EZD), the depth to which 1% of the subsurface light [photosynthetically available radiation (400-700nm)] penetrates the lake surface (Schindler 1971), was calculated from the equation: $EZD = 4.6205/ K_d$ (Kirk 1994). Euphotic volume (EV) is the product of the EZD and lake surface area and represents the volume of water capable of photosynthesis. Temperature and dissolved oxygen concentrations were recorded at 1 m depth intervals, from the lake surface to 50 m, using a Yellow Springs Instruments (YSI) model 58 meter.

Water Quality

A Van Dorn sampler was used to collect water quality samples from the epilimnion at the 1 m depth, and from the mid-hypolimnion. Eight liters of water were collected from each depth, stored in pre-cleaned polyethylene carboys, transported to Ketchikan, and then filtered or preserved for laboratory analysis. Separate subsamples from each carboy were: (1) refrigerated for general tests and metals; (2) frozen for nitrogen and phosphorus analysis; and (3) filtered through a 0.7 μm particle retention glass fiber filter

[2] Mention of trade names does not constitute endorsement by ADF&G but are included for scientific completeness.

and frozen for analysis of dissolved nutrients (Koenings et al. 1987). Samples were analyzed for general qualities, metals, nutrients, and primary production by methods detailed in the Alaska Department of Fish and Game limnology field and laboratory manual (Koenings et al. 1987), and summarized in Edmundson et al. (1991) and Zadina and Weller (1999).

Secondary Production

Zooplankton samples were collected at station A and station B, using a 0.5 m diameter, 153 μm mesh, 1:3 conical net. Vertical zooplankton tows were pulled from a depth of 50 m to the surface at a constant speed of 0.5 m · sec^{-1}. The net was rinsed prior to removing the organisms, and all specimens were preserved in neutralized 10% formalin (Koenings et al. 1987). Samples were analyzed by methods detailed in the Alaska Department of Fish and Game limnology field and laboratory manual (Koenings et al. 1987), and summarized in Edmundson et al. (1991) and Zadina and Weller (1999).

Lake Fertilization

Nutrient additions to Virginia Lake were based on estimates of yearly phosphorus loading (P in mg · m^{-2} · yr^{-1}) calculated after Vollenweider (1976):

surface specific loading:

$$L_p = (\mathrm{P})_c^{sp} Q_s \left(1 + \sqrt{\bar{z}/Q_s}\right); \text{ and}$$

surface critical loading:

$$L_c = \left(10 \text{ mg P/m}^3\right) Q_s \left(1 + \sqrt{\bar{z}/Q_s}\right);$$

where: $(\mathrm{P})_C^{SP}$ = spring overturn total P (mg · m^{-3}),
Q_s = $\bar{z}/T_w$,
T_w = water residence time (0.35 yr),
$\bar{z}$ = mean depth (27.5 m), and
10 mg P/m^3 = lower critical phosphorus level.

The addition of nutrients in 1999 was based on 50% of the critical load, and is equal to:

$$0.5L_c - L_p$$

The recommended quantity of fertilizer to be applied in 1999, based on a spring overturn total of 3.45 mg P · m^{-3}, was 3.1 tons of 8-24-8 solid, controlled release fertilizer (CRF), and 14.9 tons of 32-0-0 liquid fertilizer (Zadina and Weller 1999). During the 1999 field season 3 tons of CRF and 15.4 tons of liquid were applied. An average of 159 gallons of liquid fertilizer was applied once weekly from 21 May to 13 September (Appendix Table A.1), using the same methods described by Zadina and Weller (1999).

Three tons of Easy Gardener – Jobe's Fertilizer Spikes (special formula 8-24-8 for tomatoes) as a solid fertilizer (in 7 g briquettes with a paper binder) were to be released into Virginia Lake in experimental fashion during the 1999 field season. However, a high water event in late May flooded the fertilizer storage area and damaged much of the fertilizer before it could be deployed (Dennis Reed, USFS, personal communication). Different methods of application were tested with the undamaged portion, from late May to early June. Bags of fertilizer were suspended in the limnetic area of the upper half of the lake (both burlap and poly mesh bags were used) and bags of fertilizer were placed in two littoral areas in the upper half of the lake and also in the two inlet streams. Damaged fertilizer was placed in a perforated aluminum box and suspended in the limnetic area near the other littoral release sites, and simply spread loosely in shallow water at these same locations around the lake and in the inlet streams.

Juvenile Sockeye Salmon Assessment

Rearing Fry Population

The distribution and abundance of rearing sockeye salmon fry was estimated by hydroacoustic and mid-water trawl sampling conducted in the fall using the same methods described by Zadina and Weller (1999).

Lake Rearing Model

This report uses the ZB-EZD model (Zadina and Weller 1999) that utilizes zooplankton biomass and euphotic zone depth to estimate the potential sockeye salmon fry rearing capability of the lake.

$$SB = 1.95(ZB) + 15.5(EZD) - 183.0; \quad r^2 = 0.94$$

where: SB = total smolt biomass ($kg \cdot km^{-2}$),
ZB = zooplankton biomass ($mg \cdot m^{-2}$), and
EZD = euphotic zone depth (m).

The total potential smolt biomass is estimated by multiplying the calculated SB by the total lake area (km^2). Since sockeye salmon fry do not rear in water <5 m deep, it is logical to exclude the littoral zone from the total lake area when making this calculation. Virginia Lake has a surface area of 2.49 km^2 that covers depths >5m. Thus the total potential smolt biomass of Virginia Lake will be the SB multiplied by 2.49 km^2. Maximum smolt production assumes an individual fish size of 2.4 g. The potential maximum number of smolt that can be produced at Virginia Lake will be calculated by taking the estimated total smolt biomass and dividing by 2.4 g. Optimum smolt production assumes an individual fish size of 4.0 g. The potential optimum number of smolt that can be produced at Virginia Lake will be calculated by taking the estimated total smolt biomass and dividing by 4.0 g.

This model, based on current physical and biological information, allows a comparison of the potential to the actual sockeye salmon fry rearing population (estimated from hydroacoustic sampling). The survival rate from fall rearing fry to smolt is assumed to be 70%. Therefore the potential fall fry population (the number of fry the lake can support) can be estimated by taking the maximum or optimum smolt production and dividing by 70%.

Projected Returns and Marine Survival

Projected adult returns at Virginia Lake were calculated from the hydroacoustic population estimate of rearing fall fry that produced an estimated smolt population. Standard survival and age at adult return assumptions derived from previous data at Hugh Smith and McDonald Lakes (Zadina and Haddix 1989) are presented in Table 1. A matrix was constructed that used multiple brood years to estimate adult returns.

RESULTS

Limnological Assessment

Physical Parameters

The euphotic zone depth (EZD) ranged from 7.2 m (14 October) to 16.3 m (8 July), with an annual mean depth of 10.48 m. Euphotic volume (EV) was estimated at $26.91 \cdot 10^6$ m^3 or 26.91 EV units. This volume, capable of photosynthesis, represents 38.1% of the total lake volume. The thermocline depth was approximately 25.0 m in 1999. The lake was isothermic in May and October. Although dissolved oxygen levels were probably normal, we were unable to obtain an accurate measure of that parameter due to equipment malfunction.

General Water Quality and Nutrient Concentrations

General water quality parameters and metal concentrations continued to be within the range regarded as normal for stained oligotrophic coastal lakes (Table 2 and 3; see Edmundson et al. 1991). The slightly acidic pH (mean 6.5) and low conductivity and alkalinity indicated soft water; and the color (mean 14 Pt units) and iron concentrations (mean 123 $\mu g \cdot L^{-1}$) were characteristic of an organically stained lake.

Phosphorus is the primary element controlling lake productivity because it is the least abundant element of the nutrients required for algal growth in Virginia Lake. The concentration of total phosphorus was not stable through the season in 1999, but was highest in May and June (>8 $\mu g \cdot L^{-1}$), then dropped in July (2.4 $\mu g \cdot L^{-1}$), and rose slightly through the remainder of the year (Table 2). The concentrations of filterable reactive phosphorous (FRP, the most available form of phosphorous for algal uptake, Koenings et al. 1987), and total filterable phosphorous (TFP), were low, but within normal ranges for Virginia Lake, and fairly stable through the season (Table 2).

Total nitrogen levels were fairly stable through the entire season, and were higher in 1999 than in the previous two years (Tables 2 and 3). Ammonia, which contains both the ammonium ion and ammonia, is the preferred form of nitrogen for uptake by phytoplankton (Koenings et al. 1987). Ammonia levels were fairly low in August, though the overall mean seasonal concentration (10.2 $\mu g \cdot L^{-1}$) was the second highest since studies began at Virginia Lake. Total Kjeldahl nitrogen (TKN), and nitrate + nitrite levels were also at relatively high levels compared to other years. The concentrations of reactive silicon (required for the formation of frustrule cell structure by diatoms) were stable through the entire season, and were the highest since studies began (Tables 2 and 3). The concentrations of organic carbon, which estimates the amount and energy content of organic material in the lake (Koenings et al. 1987), were higher than in 1998 (Table 3).

Primary and Secondary Production

Primary and secondary productions were both low compared to recent years despite relatively good nutrient levels. In fact, production was comparable to years when no fertilization took place at all; from 1989-1990 (Edmundson et al. 1991) and in 1997 (Table 4). The mean epilimnion concentration of chl a in 1999 ranged from 0.16 to 0.54 $\mu g \cdot L^{-1}$ (seasonal mean 0.29 $\mu g \cdot L^{-1}$). Edmundson et al. (1991) considered the average chl a concentration of 0.22 $\mu g \cdot L^{-1}$ in 1989 and 1990 to be very low compared to other oligotrophic Alaska lakes.

The macrozooplankton community of Virginia Lake in 1999 comprised two species of Copepods (*Cyclops* sp. and *Diaptomus franciscanus*), the Cladocerans *Bosmina longirostris*, *Daphnia longiremus*, and unspecified Cladocerans of the subfamily Chydorinae (Table 5). Total zooplankton productivity at Virginia Lake was below the 13-year average (Figures 3 and 4). The proportion of the total zooplankton density and biomass that were Cladocerans were also well below average (Figures 5 and 6). Cladocerans are the preferred prey of sockeye salmon fry (Koenings and Burkett 1987).

Lake Fertilization

The results of the use of 8-24-8 solid CRF fertilizer were mixed at best (Dennis Reed, USFS, personal communication). It was difficult to monitor the rate that fertilizer was released into the lake or streams, but Reed reported that the fertilizer appeared to dissolve into solution at a rate much faster than was desired with 15 to 17% weight loss in the first month. That weight loss was equivalent to the fertilizer content. The use of burlap bags seemed to release the fertilizer very quickly as the bag itself broke down rapidly. Poly mesh bags remained intact but also released fertilizer more rapidly than desired. With both bag types there was extensive algal growth on the exterior that deterred the ability to accurately monitor weight loss. Reed estimated that most of the fertilizer had dissolved within three weeks. After two months the remaining content of the briquettes appeared to be binder.

Juvenile Sockeye Salmon Assessment

A total lake population of 115,600 sockeye salmon fry was estimated from the hydroacoustic survey conducted on 29 November 1999. No sockeye salmon fry were captured during one 45-minute mid-water trawl, due to the low densities of sockeye salmon fry (1 fry $\cdot$ 605 m^{-3}) in 1999. Two lamprey (Petromyzontidae) were the only fish captured, and equipment problems prevented another trawl sample to be taken. Therefore, it was assumed that all targets that fell within a target strength range of –50 dB to –68 dB during hydroacoustics were considered to be sockeye salmon fry. This population of fry is expected to produce approximately 80,900 smolt in spring 2000, based on 70% overwinter survival.

The ZB-EZD model predicted that the optimum fall fry rearing capabilities of Virginia Lake in 1999 was estimated at 154,500 sockeye salmon fry. Based on standard overwinter survival estimates of 70% Virginia Lake could produce an estimated 108,000 smolt at an average weight of 4.0 g. The model also predicts a maximum production capability of 257,000 fall fry, which would produce 180,000 smolt at an average weight of 2.4 g.

Adult Sockeye Salmon Assessment

The total adult return forecast for 2000 is estimated at 32,328 sockeye salmon (73% from stocked fry) and the preliminary total adult return forecast for 2001 is estimated at 14,175 sockeye salmon (36% from stocked fry) based on 12% marine survival (Table 6).

DISCUSSION

The addition of nutrients to Virginia Lake in 1999 was an experiment on two levels. First, nutrients were added at only 50% of the critical phosphorous load, whereas fertilization at sockeye salmon rearing lakes has generally been conducted at 90% of the critical phosphorous load (Koenings and Burkett 1987). The addition of fertilizer at 50% load to Virginia Lake in 1998 was shown to increase nutrient levels sufficiently to boost phytoplankton and zooplankton populations to a higher level than that found in years when no fertilizer was added (Zadina and Weller 1998). Second, the entire prescription of phosphorous to be added to the lake was contained in 8-24-8 CRF fertilizer, rather than in liquid fertilizer as has been used in past years.

The CRF fertilizer was to be deployed in experimental fashion, and monitored over time to determine the rate at which the fertilizer was released. However, the solid fertilizer was not added to the lake in the desired time frame or method, because it was damaged by high water before it could be deployed. When it was deployed from late May to mid-June, it was thought that all the fertilizer (and thus all of the phosphorous) had dissolved and been released within about 3 weeks – much faster than had been hoped for (Dennis Reed, USFS, personal communication). It turns out that this observation was correct. The rapid release of phosphorous can be seen in the monthly total phosphorous concentrations, which were highest in May and June (>8 $\mu g \cdot L^{-1}$), then dropped abruptly to very low levels in July (2.4 $\mu g \cdot L^{-1}$; Table 2). The result was a phosphorous deficit in July, when the atomic ratio of nitrogen to phosphorous was 90:1 (Figure 7).

Concentrations of chl a (Table 4) and zooplankton density (Figure 3) and biomass (Figure 4) were all well below the 1986-1999 average. In addition, the Cladoceran component of the zooplankton community, particularly the late blooming *Bosmina*, were at much lower levels than average (Figures 5 and 6). If we examine July and August more closely, we see that phosphorous and chl a concentrations, and zooplankton densities were all very low, and most comparable to 1997, a year when the lake was not fertilized at all (Table 7). Climate may play an important role in phytoplankton productivity (Wetzel 1975) and thus, zooplankton productivity. The mean temperature of the euphotic zone at Virginia Lake in July and August 1999 was also the lowest during the period 1992-1999 (Table 7). It may be that climactic conditions also contributed to the poor primary and secondary production at Virginia Lake in 1999, but to what extent is unknown.

While zooplankton production was below average in 1999, there appeared to be sufficient food for the number of sockeye salmon fry present. The estimated sockeye salmon fry population of 115,600, based on fall hydroacoustics, was about 75% of the optimum number of 154,500 sockeye salmon fry that the ZB-EZD model predicts the lake could support. The primary intention of the 1999 nutrient additions was not to increase the sockeye salmon fry forage base (although sockeye salmon fry would certainly benefit from this), but to increase all trophic levels in Virginia Lake to ultimately benefit the resident cutthroat trout population. How the cutthroat trout populations have been affected is not known.

RECOMMENDATIONS

Suggested fertilizer quantities for 2000 are dependent on desired loading rates (Table 8). These suggested amounts are based on Vollenweider's loading equations and assumes a 2000 spring overturn period total phosphorus level of 4.50 mg $\cdot$ m^{-3}. Distribution of the CRF solid fertilizer in 2000 is recommended via three methods: 1) suspending bags throughout the limnetic lake area, preferably in the upper half of the lake; 2) distributing 25% of the pellets in the upper portions of the two inlet streams; and 3) distributing 25% of the pellets throughout the littoral areas of Virginia Lake. The CRF fertilizer should be divided into four equal groups and added at three-week intervals so that phosphorous will be added to the lake over the course of the entire growing season, rather than all at once. Use of solid fertilizer in 2000 could provide a useful comparison to the 1999 season for future feasibility of using this type of product.

It is imperative that limnological evaluation continues if nutrient additions proceed at Virginia Lake. If CRF fertilizer is placed in the upper reaches of Porterfield and Glacier Creeks it is recommended that water samples be taken in Porterfield Creek to evaluate the P and N levels from the stream nutrient enhancement. Weekly samples taken near the stream mouth would begin two weeks prior to the first CRF placement for a sixteen week period. If possible grab samples should be taken at least once monthly, just above the fertilizer placement area, to monitor the natural watershed nutrient levels entering the system. This may demonstrate how large the nutrient uptake is occurring in the stream and/or how quickly the nutrients are moving into Virginia Lake from the inlet streams.

Evaluation of sockeye salmon juveniles, returning adult salmon, and resident salmonids should also continue to monitor the long-term effects of this program. This will provide information about the benefits that the Virginia Lake salmonid populations derive from nutrient additions.

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TABLES

Table 1. Age distribution assumptions of adult sockeye salmon returning to Virginia Lake by brood year and return year.

Brood Year	Smolt Years	Projected Adult Age Distribution	Adult age class	Return Year
1994	1996	10.5%	1.2	1998
	or	65.1%	1.3	1999
	1997	5.5%	2.2	1999
		18.0%	2.3	2000
1995	1997	10.5%	1.2	1999
	or	65.1%	1.3	2000
	1998	5.5%	2.2	2000
		18.0%	2.3	2001

Table 2. Summary of general water quality parameters, metal concentrations, and nutrient concentrations within the epilimnion (1 m) and mid-hypolimnion at Virginia Lake, Station A, 1999**.**

Date	12-May		14-Jun		8-Jul		5-Aug		10-Sep		14-Oct	
Depth	1 m	Hypo	1 m	Hypo	1 m	Hypo	1 m	Hypo	1 m	Hypo	1 m	Hypo
pH (units)	6.4	6.3	6.5	6.3	6.2	6.2	6.9	6.5	6.5	6.5	6.7	6.5
Conductivity (µmhos · cm^{-1})	28	29	23	28	20	28	21	28	21	28	24	29
Alkalinity (mg · L^{-1})	9.6	10.3	9.2	11.0	8.5	10.9	11.5	11.4	12.5	12.4	9.9	11.8
Turbidity (NTU)	0.3	0.4	0.5	0.9	0.6	0.6	1.9	1.1	0.8	1.7	1.3	0.8
Color (Pt units)	17	15	11	19	8	19	10	15	14	14	4	17
Calcium (mg · L^{-1})	4.2	4.4	4.0	4.7	3.3	4.1	3.5	4.4	3.8	4.3	3.7	4.5
Magnesium (mg · L^{-1})	0.5	0.4	0.3	0.3	0.4	0.6	0.3	0.4	0.2	0.4	0.3	0.5
Total Iron (µg · L^{-1})	140	154	63	168	46	152	63	144	109	150	133	154
Total P (µg · L^{-1})	8.8	3.4	8.5	6.3	2.4	7.7	4.7	3.9	5.2	4.0	4.7	4.3
TFP (µg · L^{-1})	3.0	2.3	2.9	6.3	2.1	4.9	2.1	3.8	2.8	3.2	1.9	3.2
FRP (µg · L^{-1})	1.6	2.9	2.7	5.9	2.2	3.7	2.2	3.8	2.7	3.1	1.7	3.5
TKN (µg · L^{-1})	85.3	76.2	71.6	77.3	57.9	88.8	96.6	71.6	86.2	97.9	91.0	39.6
Ammonia (µg · L^{-1})	12.2	8.2	2.3	8.8	7.3	12.8	1.3	4.0	17.0	11.4	16.4	20.2
Nitrate+Nitrite (µg · L^{-1})	96.1	86.3	59.1	84.5	39.9	88.4	38.3	91.3	43.9	91.7	52.3	104.7
Total N (µg · L^{-1})	181.4	162.5	130.7	161.8	97.8	177.2	134.9	162.9	130.1	189.6	143.3	144.3
Reactive Silicon (µg · L^{-1})	1,398	1,401	1,064	1,341	889	1,349	965	1,347	1,079	1,279	1,119	1,273
Carbon (µg · L^{-1})	142	145	196	145	142	103	109	112	136	97	112	112

Table 3. Comparison of the seasonal mean general water quality parameters, metal concentrations, and nutrient concentrations, at Virginia Lake, Station A, 1989-1990, and 1992-1999.

	1989[a]	1990[a]	1992[b]	1993[b]	1994[b]	1995[b]	1996[b]	1997[c]	1998[d]	1999[d]
pH (units)	6.5	6.6	6.4	6.5	6.3	6.4	6.3	6.8	6.8	6.5
Conductivity ($\mu mhos \cdot cm^{-1}$)	26	25	23	24	26	29	29	27	26	26
Alkalinity ($mg \cdot L^{-1}$)	7.5	9.0	6.8	9.0	8.6	10.9	10.0	11.7	11.1	10.8
Turbidity (NTU)	0.8	2.0	1.0	2.2	1.1	1.3	0.9	0.7	0.7	0.9
Color (Pt units)	15	NA	13	12	16	13	16	15	14	14
Calcium ($mg \cdot L^{-1}$)	4.3	4.1	3.9	4.0	4.1	4.4	4.1	4.0	3.9	4.1
Magnesium ($mg \cdot L^{-1}$)	<0.2	0.5	0.7	0.5	0.6	0.7	0.4	0.4	0.3	0.4
Total Iron ($\mu g \cdot L^{-1}$)	130	175	121	257	152	161	146	87	67	123
Total P ($\mu g \cdot L^{-1}$)	4.4	5.4	5.0	9.5	5.5	4.6	5.4	2.6	4.2	5.3
TFP ($\mu g \cdot L^{-1}$)	3.0	2.8	2.5	3.2	4.3	2.9	3.5	2.6	3.0	3.2
FRP ($\mu g \cdot L^{-1}$)	2.3	2.6	1.1	1.8	2.2	1.4	2.3	2.5	2.1	3.0
TKN ($\mu g \cdot L^{-1}$)	53.5	53.8	68.4	134.3	79.2	67.6	97.9	65.8	69.9	78.3
Ammonia ($\mu g \cdot L^{-1}$)	8.0	4.2	9.1	11.9	6.8	3.3	9.9	7.7	4.2	10.2
Nitrate+Nitrite ($\mu g \cdot L^{-1}$)	75.0	76.7	64.4	65.6	65.7	98.7	71.0	68.7	59.3	73.0
Total N ($\mu g \cdot L^{-1}$)	128.5	128.8	132.8	199.9	139.8	150.5	168.9	134.5	129.2	151.4
Reactive Silicon ($\mu g \cdot L^{-1}$)	1,124	843	883	1,029	976	1,073	834	1,159	1,082	1,209
Carbon ($\mu g \cdot L^{-1}$)	NA	NA	NA	NA	NA	NA	NA	NA	111	129

[a] In 1989-1990 Virginia Lake was not fertilized (data from Edmundson et al. 1991).
[b] From 1992 to 1996 Virginia Lake was fertilized at 90% of the critical phosphorous load.
[c] In 1997 Virginia Lake was not fertilized.
[d] In 1998 and 1999 Virginia Lake was fertilized at 50% of the critical phosphorous load.

Table 4. Summary of algal pigment concentrations ($\mu g \cdot L^{-1}$) at Virginia Lake, Station A, 1992-1999.

		1992		1993		1994		1995		1996		1997		1998		1999[a]	
Month	Depth	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a
May	1			0.17	0.12			0.31	0.12	0.28	0.17	0.45	0.26			0.16	0.02
	2							0.32	0.12	0.24	0.17	0.45	0.29			0.54	0.09
	MEU			0.19	0.09			0.34	0.12	0.27	0.17	0.45	0.26			0.36	0.15
	EZD			0.09	0.05			0.31	0.11	0.03	0.09	0.35	0.26			0.19	0.05
	Hypo			0.02	0.03			0.03	0.04	0.25	0.18	0.33	0.24			0.00	0.02
June	1	0.84	0.47	1.20	0.38	3.57	0.03	1.80	0.47	6.36	1.26	0.16	0.09	0.19	0.20	0.54	0.24
	2					2.58	0.15							0.38	0.33		
	MEU	1.01	0.46	0.76	0.43	2.56	0.54	0.96	0.46	6.91	1.44	0.41	0.20	0.88	0.71	0.57	0.15
	EZD	0.66	0.35	0.48	0.37	2.76	0.56	0.93	0.36	7.09	1.16	0.48	0.27	2.06	1.50	0.48	0.12
	Hypo	<0.01	0.08			0.03	0.06	0.03	0.05	0.09	0.07	0.23	0.15	0.04	0.08	0.02	0.04
July	1	1.06	0.52	6.24	1.73	0.47	0.64	1.63	0.35	2.80	0.95	0.26	0.17	1.81	0.60	0.19	0.12
	2							1.56	0.39			0.23	0.17	2.23	0.32	0.34	0.20
	MEU	1.24	0.85	0.99	0.61	0.47	0.50	1.97	0.88	1.99	0.83	0.29	0.25	3.14	0.05	0.23	0.09
	EZD	0.72	1.21	3.59	0.62	1.04	1.04	3.93	3.30	1.55	1.05	0.52	0.46	0.63	0.46	0.43	0.09
	Hypo	0.08	0.14	0.09	0.12	0.13	0.15	0.23	0.24	0.39	0.23	0.15	0.08	0.10	0.17	0.05	0.08
Aug.	1	1.13	0.99	1.14	0.87	2.15	0.73	1.83	0.44	3.59	0.70	0.38	0.27	0.29	0.19	0.12	0.11
	2					1.86	0.59	2.09	0.57	3.35	0.60			0.55	0.40	0.10	0.03
	MEU	1.25	1.11	0.76	0.69	1.82	0.51	1.90	0.70	2.87	0.63	0.52	0.39	0.25	0.23	0.35	0.09
	EZD	1.71	1.34	1.48	0.77	1.47	0.49	1.37	0.71	2.26	1.29	0.62	0.47	0.24	0.16	0.29	0.28
	Hypo	0.05	0.23	0.22	0.27	0.55	0.39	0.10	0.22	0.35	0.31	0.12	0.14	0.03	0.09	0.04	0.05
Sept.	1	0.50	0.19	0.37	0.21	0.82	0.34	6.30	1.33	9.82	0.01	0.34	0.29	0.55	0.32	0.49	0.10
	2					0.88	0.36			12.71	0.21	0.31	0.28	0.69	0.38	0.51	0.12
	MEU	0.63	0.31	0.34	0.19	1.06	0.20	7.20	0.42			0.43	0.31	0.43	0.31	0.68	0.16
	EZD	0.48	0.29	0.48	0.36	1.76	0.74	9.21	3.06	11.23	0.50	0.21	0.26	0.28	0.11	0.24	0.11
	Hypo	0.05	0.19	<0.01	0.40	0.16	0.19	0.42	0.46	0.17	0.12	0.05	0.07	0.04	0.09	0.02	0.03
Oct.	1	0.19	0.15	0.23	0.35	0.24	0.13	2.36	0.87	5.00	0.28					0.23	0.06
	2							2.15	0.77							0.19	0.12
	MEU	0.22	0.14			0.23	0.13	1.80	0.76	5.05	0.36					0.14	0.09
	EZD	0.19	0.13	0.18	0.31	0.16	0.14	1.69	0.62	0.24	0.10					0.18	0.10
	Hypo	0.03	0.12	0.08	0.24	0.04	0.07	0.17	0.15	5.22	0.01					0.02	0.04

[a] The 1999 sampling dates were 12 May, 14 June, 8 July, 5 August, 10 September, and 14 October.

Table 5. Seasonal mean macrozooplankton density and weighted mean biomass distribution at Virginia Lake, 1999.

Species		Date: 12 May	14 Jun	8 Jul	5 Aug	10 Sep	14 Oct	Mean Density $n \cdot m^{-2}$	Mean Density Percent	Weighted Mean Biomass $mg \cdot m^{-2}$	Weighted Mean Biomass Percent
Copepoda											
Diaptomus	Density (No. $\cdot m^{-2}$)	272	12,039	1,112	1,248	764	1,291	2,788	5.3%	29.0	29.1%
	Size (mm)	0.86	0.94	1.15	1.54	1.81	1.80				
Diaptomus – ovig.	Density (No. $\cdot m^{-2}$)					383	391	387	0.7%	3.3	3.3%
	Size (mm)					1.95	1.84				
Cyclops	Density (No. $\cdot m^{-2}$)	7,166	20,352	47,139	26,983	14,264	12,931	21,472	41.2%	32.2	32.3%
	Size (mm)	0.57	0.54	0.61	0.71	0.78	0.79				
Cyclops – ovig.	Density (No. $\cdot m^{-2}$)	102	51	51		85	153	88	0.2%	0.2	0.2%
	Size (mm)	1.10	1.24			1.14	1.18				
Cladocera											
Bosmina	Density (No. $\cdot m^{-2}$)	909	1,979	4,373	25,658	68,603	49,924	25,241	48.4%	32.3	32.5%
	Size (mm)	0.42	0.40	0.35	0.33	0.36	0.38				
Bosmina – ovig.	Density (No. $\cdot m^{-2}$)		85	111	985	6,538	594	1,662	3.2%	2.5	2.5%
	Size (mm)		0.42	0.48	0.42	0.43	0.45				
Daphnia	Density (No. $\cdot m^{-2}$)					0		0	0.0%	0.0	0.0%
	Size (mm)										
Daphnia – ovig	Density (No. $\cdot m^{-2}$)					85		85	0.2%	0.0	0.0%
	Size (mm)					0.64					
Chydorinae	Density (No. $\cdot m^{-2}$)	102				340	374	272	0.5%	0.1	0.1%
	Size (mm)	0.26				0.35	0.33				
Chydorinae – ovig.	Density (No. $\cdot m^{-2}$)					170		170	0.3%	0.0	0.0%
	Size (mm)					0.35					

Table 6. The forecasted total adult return of Virginia Lake sockeye salmon by age class and hatchery and wild components based on the projected smolt population, 2000 and 2001.

Return Year	Brood Year	Age Class	Stocked	%	Wild	%	Total Adult Return
2000	1994	2.3	3,567		1,067		4,634
2000	1995	1.3	18,362		5,968		24,330
2000	1995	2.2	1,699		552		2,251
2000	1996	1.2	0		1,113		1,113
Total			25,157	73%	9,289	27%	32,328
2001	1995	2.3	5,096		1,656		6,752
2001	1996	1.3	0		5,843		5,843
2001	1996	2.2	0		541		541
2001	1997	1.2	0		1,039		1,039
Total			5,096	36%	9,079	64%	14,175

Table 7. Mean temperature and concentration of chlorophyll a in the euphotic zone, mean concentration of total phosphorous in the epilimnion, and mean density of the Cladoceran *Bosmina*, and total macrozooplankton density, at Virginia Lake during the two months July-August, 1992-1999.

	1992[a]	1993[a]	1994[a]	1995[a]	1996[a]	1997[b]	1998[c]	1999[c]
Temperature (C)	12.3	13.8	11.5	11.8	11.3	11.4	12.4	10.2
Total P ($\mu g \cdot L^{-1}$)	13.6	12.6	5.2	5.3	9.8	2.1	5.1	3.6
Chl a ($\mu g \cdot L^{-1}$)	1.2	2.4	1.3	2.0	2.6	0.4	1.1	0.3
Bosmina (No. $\cdot m^{-2}$)	601,036	163,875	43,152	164,141	340,482	26,367	150,361	15,015
Zooplankton (No. $\cdot m^{-2}$)	625,064	187,490	91,356	214,765	389,324	46,432	185,447	53,817

[a] From 1992 to 1996 Virginia Lake was fertilized at 90% of the critical phosphorous load.
[b] In 1997 Virginia Lake was not fertilized.
[c] In 1998 and 1999 Virginia Lake was fertilized at 50% of the critical phosphorous load.

Table 8. Suggested fertilizer application amounts, based on various phosphorous loading rates, for the 2000 field season at Virginia Lake.

Percent of Critical Load	Tons of 8-24-8 needed	50lb bags of 8-24-8 needed	Amount for stream distribution	30-gal drums of 32-0-0 needed	Drums of 32-0-0 per week	**OR** 30-gal barrels of 20-5-0 needed to meet same rate
50%	1.0	40	10 bags	28	2	51
60%	3.0	120	30 bags	85	7	153
70%	5.0	200	50 bags	141	12	255
90%	9.0	360	90 bags	254	21	459

FIGURES

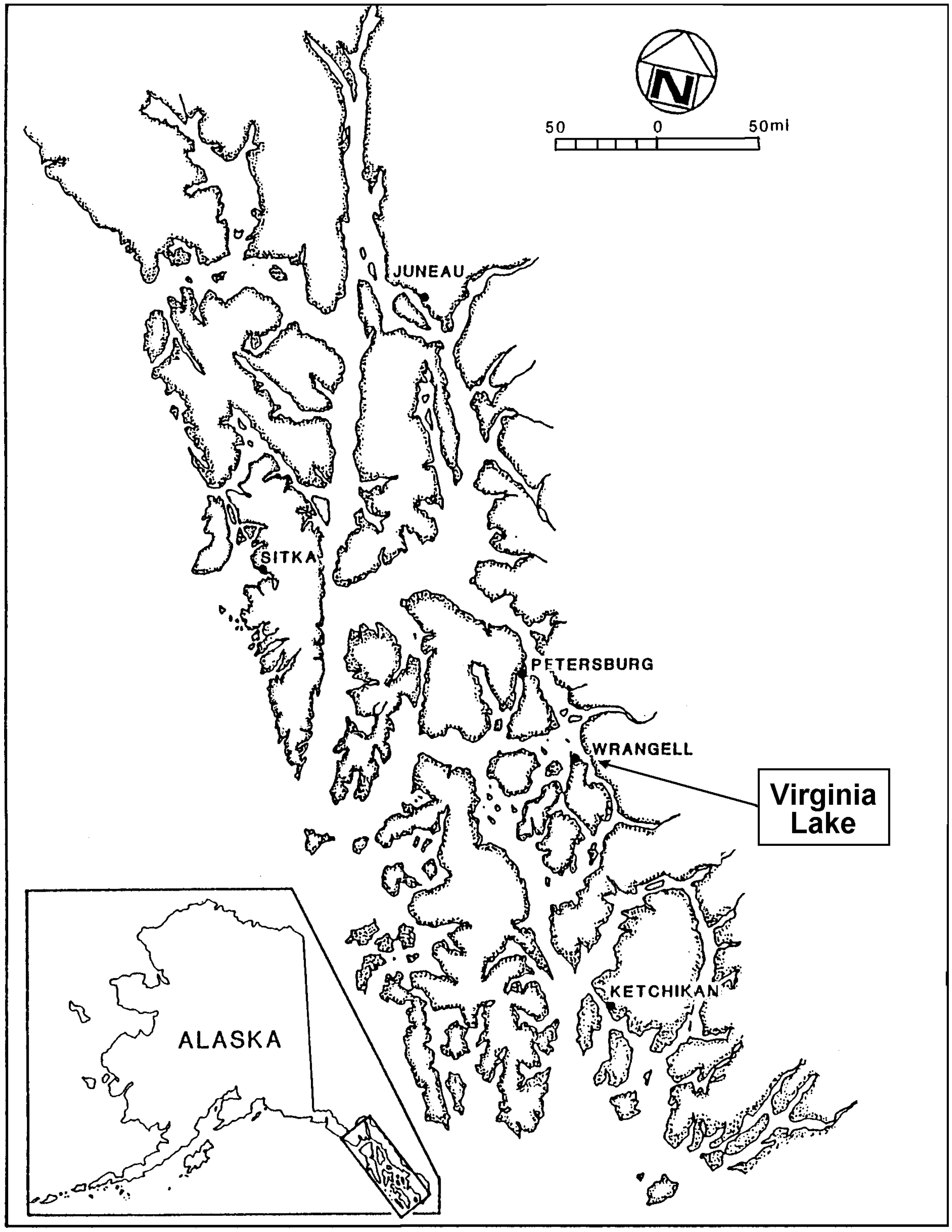

Figure 1. The geographic location of Virginia Lake, within the State of Alaska, and relative to cities within Southeast Alaska.

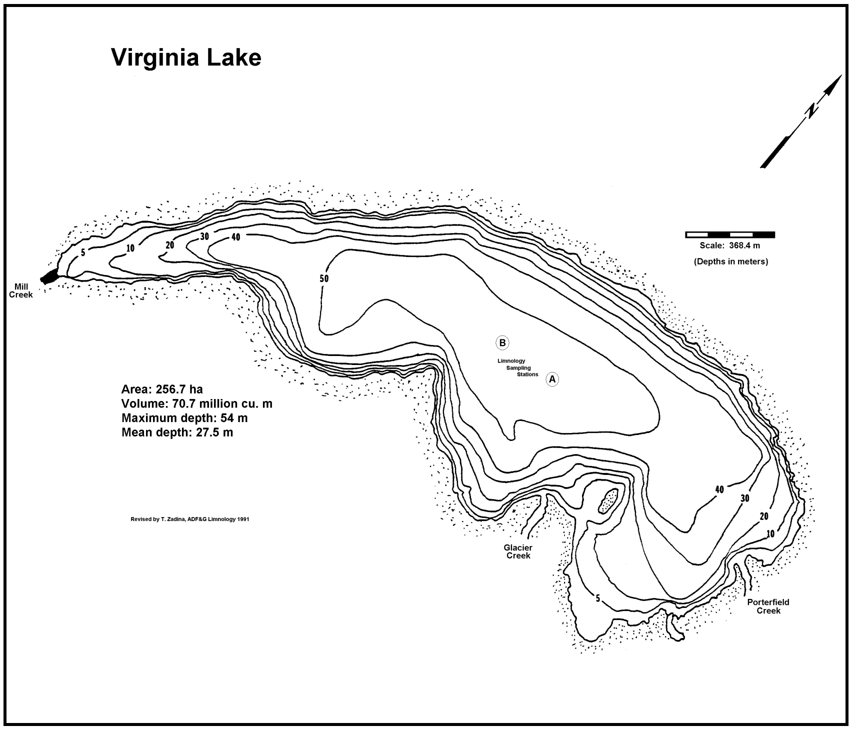

Figure 2. Bathymetric map of Virginia Lake, Southeast Alaska with limnology sampling stations.

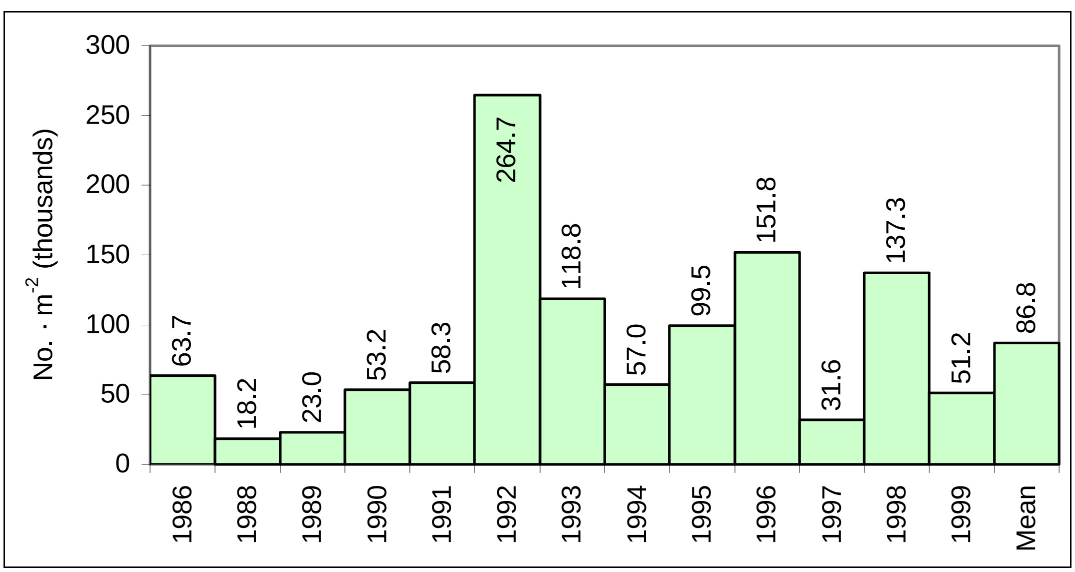

Figure 3. Mean seasonal macrozooplankton density at Virginia Lake, from 1986 to 1999, and for the 13-year mean.

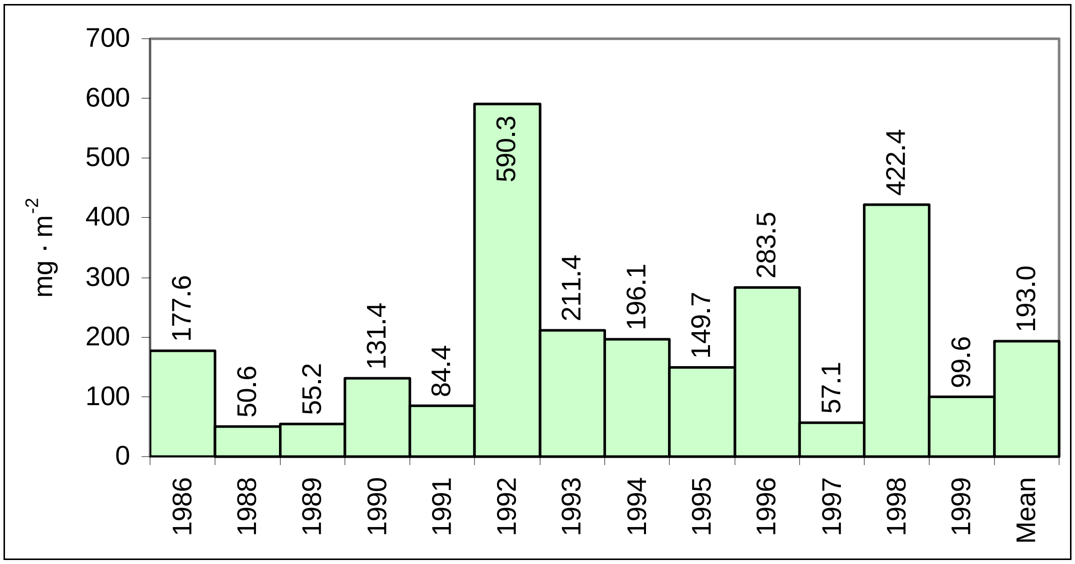

Figure 4. Mean seasonal macrozooplankton biomass at Virginia Lake from 1986 to 1999, and for the 13-year mean.

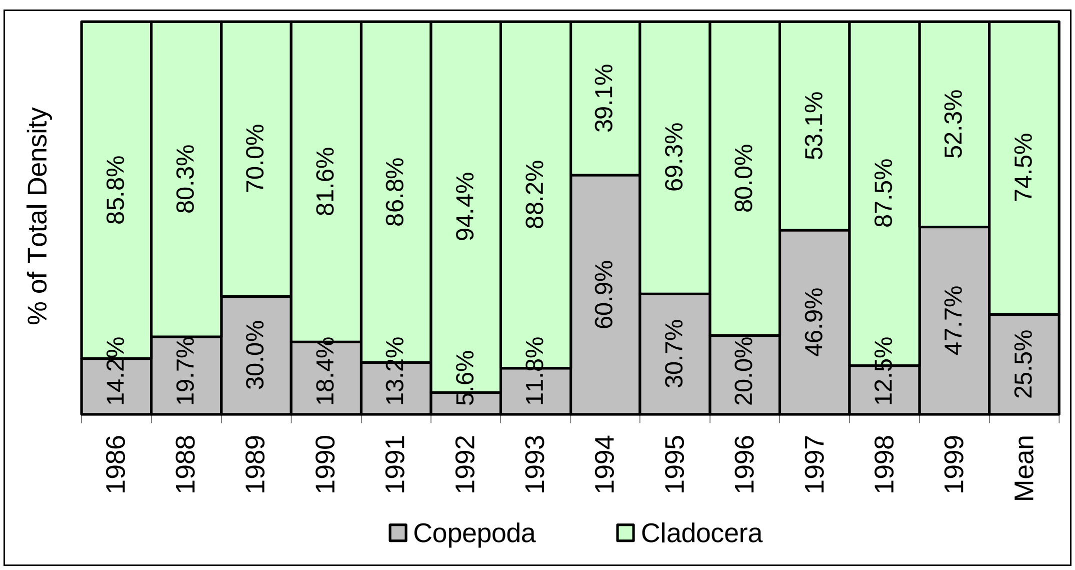

Figure 5. Mean seasonal macrozooplankton density distribution by plankter order at Virginia Lake, from 1986 to 1999, and for the 13-year mean.

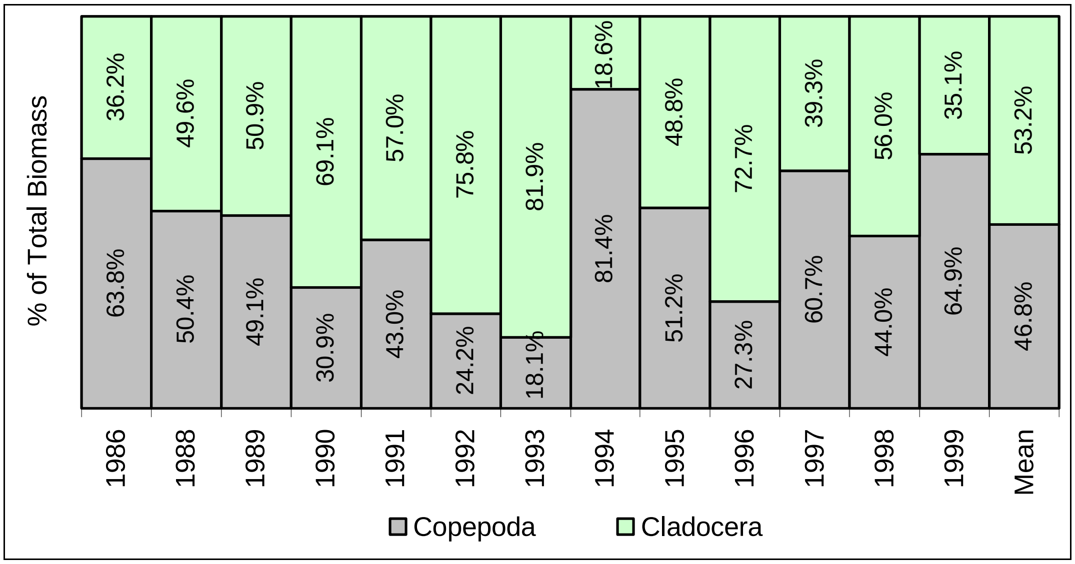

Figure 6. Mean seasonal macrozooplankton biomass distribution by plankter order at Virginia Lake, from 1986 to 1999, and for the 13-year mean.

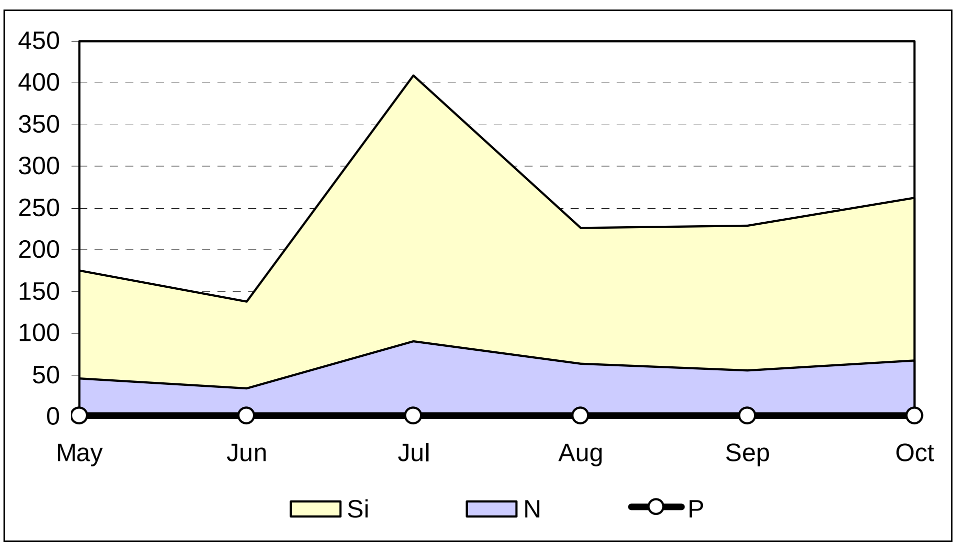

Figure 7. Monthly atomic concentration ratios of nitrogen (N), phosphorus (P; where P=1), and reactive silicon (Si) in the epilimnion at Virginia Lake, 1999.

APPENDIX

Appendix A.1. Weekly 32-0-0 fertilizer applications at Virginia Lake, 1999.

Application Date	Amount Applied (gal)	Time Applied Start	Time Applied Stop	Total Hours	Gallons Applied hr^{-1}	Water Level	Weather	Applicator
21-May	180	14:00	16:00	3.3	54.0	Normal	Rain	J. Robinson
3-Jun	180	15:00	17:00	3.3	54.0	High	Overcast	J. Robinson
12-Jun	150	13:00	15:00	3.3	45.0	Normal	Sunny	J. Robinson
19-Jun	180	16:00	18:00	3.3	54.0	Normal	Overcast	J. Robinson
26-Jun	150	15:00	17:00	3.3	45.0	Low	Rain	J. Robinson
3-Jul	180	12:00	14:00	3.3	54.0	Low	Sunny	J. Robinson
10-Jul	150	13:30	15:30	3.3	45.0	Normal	Overcast	J. Robinson
17-Jul	180	15:30	17:00	2.8	63.5	Normal	Overcast	J. Robinson
24-Jul	150	17:00	19:00	3.3	45.0	Normal	Overcast	J. Robinson
25-Jul	150	13:00	14:50	2.5	60.0	Normal	Overcast	J. Robinson
7-Aug	150	11:00	13:50	4.2	36.0	Normal	Sunny	J. Robinson
8-Aug	150	08:00	10:30	3.8	39.1	Normal	Sunny	J. Robinson
19-Aug	150	14:00	15:30	2.2	69.2	High	Overcast	J. Robinson
28-Aug	150	15:00	17:00	3.3	45.0	Normal	Overcast	T. Robinson
2-Sep	150	17:00	19:00	3.3	45.0	Low	Overcast	T. Robinson
9-Sep	150	16:00	18:00	3.3	45.0	Low	Overcast	T. Robinson
13-Sep	150	13:30	15:50	3.7	40.9	Low	Sunny	T. Robinson
Total	2,700							