LIMNOLOGICAL AND FISHERIES INVESTIGATIONS AT

VIRGINIA LAKE, SOUTHEAST ALASKA

2001

by

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and
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ABSTRACT

The Virginia Lake nutrient enrichment program was continued in 2001. Fertilizer was applied at 50% of the critical phosphorus load, using 20-5-0 liquid fertilizer that was applied weekly from mid-May to early September. Solid, controlled release fertilizer (CRF) was not added to the lake in 2001 as it had been in the two previous years. Limnological sampling showed that total phosphorus, chlorophyll a concentrations, and zooplankton density and biomass continued to be at low levels throughout the 2001 growing season. The fall rearing sockeye salmon *Oncorhynchus nerka* fry population was estimated at 56,000 fish on 1 October 2001. The ZB-EZD model predicted the lake could support an estimated 98,000 – 158,000 fall fry dependent on either optimum or maximum production values. The 2001 rearing fry were not planted but were progeny of the adults that returned naturally in 1999 and 2000 from the initial colonization program (1989 to 1996). Based on 12% marine survival, the predicted total return for 2002 is estimated at 8,754 adult sockeye.

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

INTRODUCTION

Over the past thirteen years a great deal of fisheries work has been conducted at Virginia Lake. 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 limited population of sockeye salmon *Oncorhynchus nerka* to utilize the lake (Zadina and Haddix 1993). In a cooperative effort, the U.S. Forest Service installed a fishpass in 1988, and the Alaska Department of Fish and Game and Southern Southeast Regional Aquaculture Association stocked the lake with sockeye salmon fry from 1989 to 1996 (Edmundson et al. 1991; Zadina and Haddix 1993; Zadina 1997). A nutrient enrichment program was initiated at Virginia Lake and fertilizer was applied at 90% of the critical phosphorus load (after Vollenweider 1976) while sockeye salmon fry were planted in the lake, from 1991 to 1996. The nutrient enrichment program was added in 1993, two years after problems occurred stocking emergent sockeye salmon fry in April, prior to when the lake's food supply was ready for this introduction (Edmundson et al. 1991). After a hiatus in 1997, the nutrient enrichment program was reimplemented in 1998, with the total phosphorus additions reduced to 50% of the critical loading rate (Zadina and Weller 1999). The intent of the lower loading rate was to increase lower trophic level production in Virginia Lake, primarily to the benefit of the resident cutthroat trout *Oncorhynchus clarki spp.* population. Increasing the forage base for rearing sockeye salmon fry was a secondary goal of the lake fertilization program.

In 1999, Virginia Lake was fertilized at 50% of the critical phosphorus load, only this time all of the phosphorus added to the lake was contained in solid controlled release fertilizer (CRF) that was primarily distributed in the littoral zone of the upper half of the lake (Zadina and Heinl 2000). The initial results were both promising and problematic as difficulties with the fertilizer application made it almost impossible to determine if solid fertilizer could be successfully used to increase the nutrient levels in the lake. In 2000, the lake was again fertilized with a combination of liquid and solid CRF; this time at 60% of the critical phosphorus load, with 25% of the solid fertilizer distributed in upper Porterfield Creek, approximately 6.4 km above the confluence with Virginia Lake. In 2001, the nutrient enrichment program returned solely to liquid fertilizer and the application amount was again lowered to 50% of the estimated critical loading rate.

Here, we report the results of continued limnological studies at Virginia Lake during the 2001 field season. These studies included: (1) an assessment of the primary and secondary production in the lake; (2) an assessment of the nutrient enrichment program; (3) an estimate of the rearing sockeye fry population through hydroacoustic and mid-water trawl sampling; and (4) a forecast of the total adult return for 2002. The escapement, age structure, and coded wire tag recoveries of adult sockeye salmon returning to Virginia Lake were evaluated by U.S. Forest Service 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). There are two inlet streams: Porterfield Creek (ADF&G stream number 10740-10070-0010-2010) flows southwest 11 km to the east end of Virginia Lake, and Glacier Creek (ADF&G stream number 10740-10070-0010-2006) flows west 13 km to the south side of Virginia Lake (Orth 1967). 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

The United States Forest Service through the Alaska Department of Fish and Game provided funding to evaluate the limnological and nutrient enrichment assessment program in 2001. This is the final report fulfilling contract obligations for Sikes Act Contract 43-0109-1-0128.

METHODS

Limnological Assessment

Sampling to evaluate the nutrient enrichment program was conducted on the lake at station A, with a replicate zooplankton sample collected at Station B (Figure 2). Physical data, water quality, and biological samples were collected on 4 May, 8 June, 10 July, 6 August, 18 September, and 16 October, 2001. All samples were analyzed at the ADF&G, Division of Commercial Fisheries, limnology laboratory in Soldotna, Alaska.

Physical Parameters

Measurements of underwater light penetration (foot candles) 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 [400-700 nm]) penetrates the

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

lake surface (Schindler 1971), was calculated from the equation: EZD = 4.6205 · K_d^{-1} (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, calibrated each sampling trip with a 60 ml Winkler field titration (Koenings et al. 1987).

Water Quality

A 4 L Van Dorn sampler was used to collect water quality samples from the epilimnion at the 1 m depth, and from the mid-hypolimnion. Ten 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 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).

Secondary Production

Zooplankton samples were collected 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).

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:

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

surface critical loading:

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

where: $(P)_C^{SP}$ = 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 2001 was based on 50% of the critical load, and is equal to:

$$0.5L_c - L_p$$

Thus, the recommended quantity of fertilizer to be applied in 2001, based on a spring overturn total of 4.5 mg P · m^{-3}, was 3,430 gallons of 20-5-0 (Zadina and Heinl 2001).

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 using the same methods described by Zadina and Weller (1999). Virginia Lake was divided into ten sampling areas based on surface area. Sample design consisted of a series of ten stratified, randomly chosen orthogonal transects across the lake, one from each sampling area. Transect sampling was conducted during post-sunset darkness in one night. A constant boat speed of about 2.0 m sec^{-1} was attempted for all transects. A Biosonics DT-4000™ scientific echosounder (420 kHz, 6° single beam transducer) with Biosonics Visual Acquisition © version 4.0.2 software was used to collect data. Ping rate was set at 5 pings · sec^{-1} and pulse width at 0.4 ms. Data were analyzed using Biosonics Visual Analyzer © version 4.0.2 software after returning to the office. A 2 m × 2 m elongated trawl net was used for pelagic fish sampling. Trawl depths and duration were determined by fish densities and distributions throughout the lake based on observations during the hydroacoustic survey.

Lake Rearing Model

This report uses the ZB-EZD model (Stan Carlson, ADF&G Commercial Fisheries, Soldotna, personal communication, 1998) that utilizes zooplankton biomass and euphotic zone depth to estimate the potential sockeye fry rearing capability of the lake.

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

where: SB = total smolt biomass (kg · km^{-2}),

ZB = weighted seasonal mean zooplankton biomass (mg · m^{-2}), and

EZD = seasonal mean euphotic zone depth (m).

The total potential smolt biomass is estimated by multiplying the calculated smolt biomass (SB) by the total lake area (km^2). Since sockeye salmon fry do not normally rear in water less than 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 greater than 5 m. 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 and optimum smolt production assumes an individual fish size of 4.0 g. Taking the estimated total smolt biomass and dividing by either 2.4 or 4.0 g, respectively, will calculate the potential number of smolt that can be produced at Virginia Lake.

This model, based on current physical and biological information, allows a comparison of the estimated potential to the actual sockeye salmon fry rearing population (estimated from hydroacoustic sampling). This basic examination allows us to see if the lake rearing environment would produce any significant mortality to the existing population. The survival rate from fall rearing fry to smolt is assumed to be 70% (Geiger and Koenings 1991). 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 estimate of the rearing fall fry population and based on standard fall fry-to-smolt and marine survival assumptions for sockeye salmon (Koenings et al. 1989; Geiger and Koenings 1991). The age at adult return assumptions derived from previous sockeye salmon work at Hugh Smith and McDonald Lakes (Zadina and Haddix 1989) are presented in Table 1. A matrix was constructed using multiple brood years to estimate adult returns by year.

RESULTS

Limnological Assessment

Physical Parameters

The euphotic zone depth (EZD) ranged from 6.34 m (16 October) to 14.87 m (6 August); with a seasonal mean depth of 9.66 m. Euphotic volume (EV) was estimated at $24.05 \cdot 10^6$ m^3 or 24.05 EV units. This volume, capable of photosynthesis, represents 34.0% of the total lake volume. The thermocline depth ranged from 20 to 30 m. The lake was isothermic in May, and was approaching isothermic mixing during the last sampling effort in October. Dissolved oxygen levels were normal and consistent with other years (Figure 3).

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 Alaska lakes (Tables 2 and 3; see Edmundson et al. 1991; Zadina et al. 1992). The slightly acidic pH (mean 6.4), low conductivity, and low alkalinity indicated soft water; and the color (mean 15.6 Pt units) and iron concentrations (mean 109.9 µg · L^{-1}) were characteristic of an organically stained lake.

Phosphorus is the primary element controlling lake productivity. It was the least abundant element of the nutrients required for algal growth in Virginia Lake. The concentration of total phosphorus varied from lows in May and October of 3.5 and 3.1 µg · L^{-1} to a high of 6.8 µg · L^{-1} in early August (Table 2). The concentrations of filterable reactive phosphorus (FRP), the most available form of phosphorus for algal uptake (Koenings et al. 1987), and total filterable phosphorus (TFP) were within normal ranges found previously in Virginia Lake, and fairly stable through the season (Table 2).

Total nitrogen levels were highest in May and June (>200 µg · L^{-1}), decreased to a low in August, and then increased again in October (Table 2). Despite the drop in total nitrogen in August, the atomic ratio of nitrogen to phosphorus (55:1; Figure 4) was still within the desired range for promotion of growth by the appropriate phytoplankton. This mid-summer nitrogen deficit has occurred regularly in McDonald and Virginia lakes, where nutrient sampling has been done. The mean seasonal total nitrogen concentration was within the normal range of values for Virginia Lake (Table 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 fluctuated moderately throughout the summer, though the overall mean seasonal concentration (7.5 µg · L^{-1}) was within the range of measured seasonal values for this lake. The mean annual nitrate + nitrite concentration was the highest annual value for Virginia Lake since 1992 (Table 3). The total Kjeldahl nitrogen (TKN) concentration was within the normal range of values previously observed at this lake.

Concentrations of reactive silicon (required for the formation of frustrule cell structure by diatoms) were highest in May, decreasing through early August and then showing significant increase in both the September and October samples (Tables 2 and 3). The concentration of organic carbon, which estimates the amount and energy content of organic material in the lake (Koenings et al. 1987), was similar to other years (Table 3).

Primary and Secondary Production

The mean epilimnion concentration of chlorophyll a in 2001 was relatively low when compared to levels documented during years when fertilization was conducted at 90% of critical load levels (Table 5). This year concentrations ranged from 0.13 to 0.93 µg · L^{-1} with a seasonal mean 0.42 µg · L^{-1} (Table 5). The macrozooplankton community of Virginia Lake in 2001 was comprised of two species of Copepods (*Cyclops* sp. and *Diaptomus franciscanus*), the Cladoceran *Bosmina longirostris*, and unspecified Cladocerans of the subfamily Chydorinae (Table 6). Total zooplankton productivity by both density and biomass at Virginia Lake was less than half of the 15-year average (Figures 5 and 6). The proportion of the total zooplankton density and biomass that were Cladocerans were also below average (Figures 7 and 8). Cladocerans are the preferred prey of sockeye salmon fry (Koenings and Burkett 1987).

Lake Fertilization

During the 2001 field season a total of 19.0 tons (3,360 gallons) of 20-5-0 liquid fertilizer was applied to the lake at a rate of 210 gallons per week from 19 May – 4 September (Appendix Table A.1), using the methods described by Zadina and Weller (1999). The proportion of liquid fertilizer used this year was increased significantly from last year in order to compensate for not incorporating any solid, CRF fertilizer in the application schedule.

Juvenile Sockeye Salmon Assessment

The fall rearing sockeye salmon fry population was estimated at 56,000 from the hydroacoustic survey conducted on 1 October 2001 (Table 7). No sockeye fry were captured during one 30-minute mid-water trawl at 8 m, but three sockeye salmon fry were caught in a second, 35-minute trawl at 10 m depth. The small sample size was due primarily to the low densities of sockeye salmon fry (1 fry · 1,263 m^{-3}) in the lake. Since no other species of fish were sampled in our trawls, we assumed that all targets that fell within the target strength range of –50 dB to –68 dB during hydroacoustic sampling were sockeye salmon fry. This population of fry is expected to produce approximately 39,200 smolt in spring 2002, based on an average 70% over-winter survival.

Using the ZB-EZD model, we estimate that Virginia Lake could potentially support an optimum to maximum fall fry range of 98,000 – 158,000 fish, capable of producing between 69,000 and 111,000 smolt, based on standard survival assumptions, at an average weight of 4.0 and 2.4 g, respectively.

Adult Sockeye Salmon Assessment

The total adult return forecast for 2002 is estimated at 8,745 sockeye salmon based on 12% marine survival (Table 8). All of these fish are the progeny of naturally produced adults, as this lake was not stocked after 1996.

DISCUSSION

The primary intention of nutrient additions to Virginia Lake in 2001, was once again 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.

Nutrient additions most likely boosted trophic levels to some (unmeasured) degree, but how the sockeye salmon and cutthroat trout populations have been affected by nutrient enhancement is not known.

Samples from the pelagic portion of Virginia Lake throughout the 2001 season showed that concentrations of total phosphorus (Table 2) and chlorophyll a (Table 5), and both zooplankton density (Figure 5) and biomass (Figure 6) were relatively low. In fact, it appears that conditions were most similar to years when the lake was not fertilized at all (1989, 1990, and 1997). Similar results were also obtained in 1998 and 1999 when the lake was fertilized at 50% of the critical phosphorus load and 2000 at 60% of critical load with a mixture of liquid and solid fertilizer (Zadina and Heinl 2000). Thus it appears that the lower (50–60%) fertilizer loading rate, which in previous years included the use of solid fertilizer placed in the littoral zone, inlet streams, and the pelagic zone has not clearly elevated the lake's limnetic phytoplankton and zooplankton productivity (Table 5).

While zooplankton production was below average (for fertilized years) in 2001, there appeared to be sufficient food for the number of sockeye salmon fry present. The estimated sockeye salmon fry population of 56,000, based on fall hydroacoustics, fell below the range of maximum (153,000) and optimum (91,800) numbers of fry that we estimate the lake could support based on analysis of the 2001 light penetration and zooplankton biomass data (ZB-EZD model).

The original sockeye salmon production potential of Virginia Lake was estimated at 26,000–37,000 adult sockeye salmon (Edmundson et al. 1991). This estimate was based solely on the two original models. The EV model (Koenings and Burkett 1987), that only used physical characteristics of sockeye salmon nursery lakes and did not take into account the biological productivity of the study lake, and the ZB model (Koenings and Kyle 1997) that utilized the standing crop of zooplankton in sockeye salmon nursery lakes. The ZB model was driven by a few very productive lakes in Southcentral Alaska and Idaho (Stan Carlson, biometrician, ADF&G, Soldotna, personal communication 1997). Thus, the two models predict an unrealistic productivity index for most coastal oligotrophic lakes in Southeast Alaska. However, these were the only models available when studies to estimate production at Virginia Lake were initiated. Analysis using the ZB-EZD model with zooplankton productivity data for the original pre-stocking (1987–1988), post-fertilizer (1997) and low loading rate fertilizer (1998–2001) years suggests the estimated adult sockeye salmon production potential of Virginia Lake may only reach a maximum annual return of 10,000 – 17,000 fish. Virginia Lake is a naturally nutrient poor system, with a rapid flushing rate (Edmundson et al. 1991). It is our opinion that the lake may never be as productive in its natural state as the original models predicted. There is a possibility that future runs could be higher than this level if either: a) the system receives increased salmon escapement leading to the increased marine derived nutrients required for good lake productivity; or b) with proper nutrient additions and further enhancement with sockeye salmon fry or pre-smolt.

RECOMMENDATIONS

Suggested fertilizer quantities for 2002 are dependent on desired loading rates (Table 9). These suggested amounts are based on Vollenweider's (1976) loading equations and assume a 2002 spring overturn period total phosphorus level of $3.25\ mg \cdot m^{-3}$. This phosphorus level is estimated from water samples taken on 16 October 2001 (Table 2). We use the fall water sample because the collection of water samples and analysis of phosphorus concentrations in the spring cannot be accomplished in time to purchase and transport the fertilizer prior to the growing season. Should the goal of future nutrient additions to Virginia Lake be a clear and discrete boosting of limnetic zooplankton populations as forage for sockeye salmon fry and cutthroat trout, then we recommend considering an increase in the fertilization level above the current 50% of critical loading level. Specifically, liquid 20-5-0 fertilizer should be applied again weekly in the pelagic zone and the use of solid CRF applied to the littoral and feeder streams should be considered again as a method to maintain a stable elevated background level of nitrogen between liquid applications. If the decision to use CRF solid fertilizer is made then we suggest using the new Lesco[3] Nutri-stone Aquatic Restoration Fertilizer Briquette 16-30-0. This product is still in development, regarding its relative nutrient release timing, and is designed for single application at the beginning of the season. Since the current, primary intent of nutrient additions is benefiting resident salmonids, and the 2001 sockeye salmon escapement was low, we suggest placing 50% of the CRF product in the inlet stream with the remaining 50% distributed equally between the lake littoral area and the identified floating distribution areas. The additional 32-0-0 liquid fertilizer needed for supplementation should be added over 12 weeks, from early June to late August to address the mid-summer nitrogen deficit that has previously occurred. Until sockeye salmon production increases it is highly unlikely that the rearing fry will utilize the existing trophic structure to capacity. Monitoring and evaluation of the CRF should follow the same recommendations as the 1999 season (Zadina and Heinl 2000).

Limnological evaluation should continue if nutrient additions proceed at Virginia Lake. Evaluation of sockeye salmon juveniles, returning adult salmon, and resident salmonids should also continue.

[3] Lesco Inc., 15885 Sprague Rd, Strongsville, OH 44136-1799

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TABLES

Table 1. Age distribution assumptions of adult sockeye salmon returning to Virginia Lake by brood year returning in 2002.

Brood Year	Smolt Years	Projected Adult Age Distribution	Adult Age Class	Return Year
1996	1998 or 1999	10.50%	1.2	2000
		65.10%	1.3	2001
		5.50%	2.2	2001
		18.00%	**2.3**	**2002**
1997	1999 or 2000	10.50%	1.2	2001
		65.10%	**1.3**	**2002**
		5.50%	**2.2**	**2002**
		18.00%	2.3	2003
1998	2000 or 2001	**10.50%**	**1.2**	**2002**
		65.10%	1.3	2003
		5.50%	2.2	2003
		18.00%	2.3	2004

Table 2. Summary of general water quality parameters, metal concentrations, and nutrient concentrations within the epilimnion (Epi = 1 m) and mid-hypolimnion (Hypo) at Virginia Lake, Station A, 2001.

	4 May		8 June		10 July		6 August		18 September		16 October	
Depth strata	Epi	Hypo	Epi	Hypo	Epi	Hypo	Epi	Hypo	Epi	Hypo	Epi	Hypo
pH	6.4	6.4	6.4	6.2	6.2	6.4	6.7	6.3	6.6	6.6	6.4	6.3
Conductivity, (µmhos · cm^{-1})	25	27	24	27	18	27	23	29	22	27	21	22
Alkalinity, (mg· L^{-1})	9.6	10.2	9.1	10.2	6.2	9.8	8.8	10.4	8.8	10.9	8.2	9
Turbidity, (NTU)	0.4	0.4	1.2	0.9	0.8	0.6	0.6	0.5	0.5	0.6	1.1	1.8
Color, (Pt units)	17	17	13	15	14	19	8	15	17	13	21	18
Calcium, (mg · L^{-1})	4	4.1	3.7	4.3	2.8	3.7	3.5	4	3.6	4.2	3.1	3.5
Magnesium, (mg · L^{-1})	0.5	0.6	0.2	0.2	0.5	0.7	0.4	0.7	0.5	0.7	0.7	0.6
Total Iron, (µg · L^{-1})	122	144	83	130	85	147	64	176	74	114	88	92
Total P, (µg · L^{-1} P)	3.5	3.5	5.2	3.1	4.7	3.4	6.8	5	4.6	4.4	3.1	3.4
TFP, (µg · L^{-1} P)	2.8	2.6	2.8	2.1	2.6	3.8	3.1	2.4	3	2.1	12.3	5.4
FRP, (µg · L^{-1} P)	2	1.5	1.6	1.6	1.7	3.6	1.6	1.6	2.2	1.4	4.2	2.2
TKN, (µg · L^{-1} N)	62.2	45.9	70.3	49	56	51	83.5	59.1	64.2	54	55	49
Ammonia, (µg · L^{-1} N)	4.4	13.6	3.9	5.4	8.2	11.8	2	9.5	6.3	11.7	11.3	1.7
Nitrate+nitrite, (µg · L^{-1} N)	107.6	97.7	121	153	55	138	39.3	136	61	129	88	120
Total N, (µg · L^{-1} N)	169.8	143.6	191.3	202	111	189	122.8	195.1	125.2	183	143	169
Reactive Silicon, (µg · L^{-1} Si)	1,336	1,289	1,082	1,308	910	1,327	722	1,289	1,048	1,318	1,012	1,083
Carbon, (µg · L^{-1} C)	141	84	176	87	127	115	161	58	121	81	81	87

Table 3. Comparison of the seasonal mean general water quality parameters, metal concentrations, and nutrient concentrations, at Virginia Lake, Station A, all depths, 1989–2001.

Year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
pH	6.6	6.6	6.6	6.4	6.5	6.3	6.4	6.3	6.8	6.8	6.5	6.4	6.4
Conductivity, (μmhos · cm^{-1})	26	25	25	23	24	26	29	29	27	26	26	26	24
Alkalinity, (mg· L^{-1})	9.2	9.0	9.6	6.8	9.0	8.6	10.9	10.0	11.7	11.1	10.8	9.9	9.3
Turbidity, (NTU)	0.8	1.1	1.0	1.0	2.2	1.1	1.3	0.9	0.7	0.7	0.9	0.9	0.8
Color, (Pt units)	15	17	19	13	12	16	13	16	15	14	14	15	16
Calcium, (mg · L^{-1})	4.3	4.1	4.1	3.9	4.0	4.1	4.4	4.1	4.0	3.9	4.1	4.0	3.7
Magnesium, (mg · L^{-1})	0.2	0.4	0.3	0.7	0.5	0.6	0.7	0.4	0.4	0.3	0.4	0.4	0.5
Total Iron, (μg · L^{-1})	130	175	146	121	257	152	161	146	87	67	123	101	110
Total P, (μg · L^{-1} P)	4.4	5.1	4.1	5.0	9.5	5.5	4.6	5.4	2.6	4.2	5.3	3.5	4.2
TFP, (μg · L^{-1} P)	3.1	3.3	2.8	2.5	3.2	4.3	2.9	3.5	2.6	3.0	3.2	2.7	3.8
FRP, (μg · L^{-1} P)	2.5	2.6	2.6	1.1	1.8	2.2	1.4	2.3	2.5	2.1	3.0	1.6	2.1
TKN, (μg · L^{-1} N)	53.3	54.5	67.4	68.4	134.3	79.2	67.6	97.9	65.8	69.9	78.3	106.0	58.3
Ammonia, (μg · L^{-1} N)	6.6	4.2	4.8	9.1	11.9	6.8	3.3	9.9	7.7	4.2	10.2	12.5	7.5
Nitrate+nitrite, (μg · L^{-1} N)	75.0	76.7	78.8	64.4	65.6	60.6	82.9	71.0	68.7	59.3	73.0	101.2	103.8
Total N, (μg · L^{-1} N)	128.2	131.3	127.0	132.8	199.9	139.8	150.5	168.9	134.5	129.2	151.4	207.2	162.1
Reactive Silicon, (μg · L^{-1} Si)	1,124	843	1,073	883	1,029	976	1,073	834	1,159	1,082	1,209	1,188	1,144
Carbon, (μg · L^{-1} C)	N/A	136	120	151	N/A	N/A	N/A	N/A	N/A	111.0	129.3	101.4	109.9

Table 4. Summary of algal pigment concentrations (μg · L^{-1}) of chlorophyll a (Chl a) and phaeophytin a (Phaeo a) at Virginia Lake, Station A, 1992–2001.

		1992		1993		1994		1995		1996		1997		1998		1999		2000		2001	
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	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	0.32	0.21	0.13	0.02
	2							0.32	0.12	0.24	0.17	0.45	0.29			0.54	0.09	0.33	0.22		
	MEU			0.19	0.09			0.34	0.12	0.27	0.17	0.45	0.26			0.36	0.15	0.27	0.14	0.19	0.07
	EZD			0.09	0.05			0.31	0.11	0.03	0.09	0.35	0.26			0.19	0.05	0.11	0.09	0.14	0.08
	HYP			0.02	0.03			0.03	0.04	0.25	0.18	0.33	0.24			0.00	0.02	0.02	0.05	0.01	0.09
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	0.38	0.12	0.93	0.11
	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	0.56	0.11	0.81	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	0.27	0.15	0.28	0.07
	HYP	<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	0.02	0.06	0.10	0.47
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	0.59	0.17	0.64	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	0.79	0.13	0.43	0.12
	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	1.53	0.36	0.25	0.14
	HYP	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	0.03	0.07	0.02	0.07
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	0.76	0.16	0.03	0.09
	2					1.86	0.59	2.09	0.57	3.35	0.60			0.55	0.40	0.10	0.03	0.69	0.12	0.56	0.14
	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	0.63	0.14	0.41	0.18
	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	0.48	0.16	0.33	0.19
	HYP	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	0.14	0.32	0.70	0.17
Sept.	1	0.5	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	0.13	0.09	0.62	0.17
	2					0.88	0.36			12.71	0.21	0.31	0.28	0.69	0.38	0.51	0.12			0.76	0.16
	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	0.51	0.10	1.04	0.25
	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	0.39	0.26	0.40	0.20
	HYP	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	0.01	0.03	0.03	0.10
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	0.56	0.13	0.18	0.09
	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	0.31	0.13	0.22	0.08
	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	0.16	0.11	0.19	0.09
	HYP	0.03	0.12	0.08	0.24	0.04	0.07	0.17	0.15	5.22	0.01					0.02	0.04	0.03	0.06	0.07	0.10

Table 5. Seasonal mean macrozooplankton density and weighted mean biomass distribution at Virginia Lake, 2001.

Species		4 May	9 June	10 July	6 August	18 September	16 October	Mean Density		Weighted Mean Biomass	
								(No. · m^{-2})	Percent	(mg · m^{-2})	Percent
Copepoda											
Diaptomus	Density (No. · m^{-2})	17,074	2,157	646	442	688	815	3,637	9.4%	53.2	49.43%
	Size (mm)	1.01	1.27	1.60	1.67	1.87	1.86				
ovigerous *Diaptomus*	Density (No. · m^{-2})	0	0	0	272	238	238	125	0.3%	0.5	0.46%
	Size (mm)	0.00	0.00	0.00	1.98	1.95	1.93				
Cyclops	Density (No. · m^{-2})	7,107	11,360	16,871	6,385	5,366	7,964	9,175	23.6%	19.1	17.80%
	Size (mm)	0.68	0.61	0.69	0.79	0.95	0.95				
ovigerous *Cyclops*	Density (No. · m^{-2})	0	0	43	0	264	306	102	0.3%	0.0	0.04%
	Size (mm)	0.00	0.00	0.47	0.00	1.15	0.58				
Cladocera											
Bosmina	Density (No. · m^{-2})	7,795	5,978	8,898	84,021	44,218	238	25,191	64.9%	34.1	31.73%
	Size (mm)	0.42	0.41	0.37	0.35	0.36	0.40				
ovigerous *Bosmina*	Density (No. · m^{-2})	459	136	153	1,257	0	0	334	0.9%	0.4	0.34%
	Size (mm)	0.54	0.57	0.52	0.46	0.00	0.00				
Daphnia l.	Density (No. · m^{-2})	196	0	102	0	0	0	50	0.1%	0.0	0.02%
	Size (mm)	0.65	0.00	0.37	0.00	0.00	0.32				
ovigerous D*aphnia l.*	Density (No. · m^{-2})	43	0	0	0	0	0	7	0.0%	0	0.00%
	Size (mm)	0.39	0.00	0.00	0.00	0.00	0.00				
Chydorinae	Density (No. · m^{-2})	119	221	51	306	383	119	200	0.5%	0.2	0.18%
	Size (mm)	0.39	0.37	0.18	0.36	0.35	0.32				

Table 6. Fall sockeye salmon fry population estimates at Virginia Lake, 1989–2001.

Year	Total Limnetic Fish Population	Fry Population[a]	Fry · m^{-2}
1989[b]	282,000	270,000	0.115
1990[b]	139,000	139,000	0.059
1991[b]	121,000	121,000	0.051
1992[b]	150,000	128,000	0.054
1993[b]	no fall survey		
1994[b]	no fall survey		
1995[b]	313,000	313,000	0.133
1996[b]	no fall survey		
1997	110,000	110,000	0.047
1998	102,000	102,000	0.043
1999	116,000	116,000	0.049
2000	169,000	169,000	0.072
2001	56,000	56,000	0.024

[a] Population of fish based on trawl samples - some stickleback captured in 1989 and 1992.
[b] Fry stocked in lake.

Table 7. The 2002 forecasted adult return of Virginia Lake sockeye salmon by age class and hatchery and wild components based on the projected smolt population.

Brood Year	Age Class	Stocked	%	Wild	%	Total Adult Return
1997	2.3	0	0%	1,622	18.5	1,622
1998	1.3	0	0%	5,453	62.4	5,453
1998	2.2	0	0%	504	5.8	504
1999	1.2	0	0%	1,174	13.3	1,174
	Total	0	0%	8,745	100%	8,754

Table 8. Suggested fertilizer application amounts, based on two phosphorus loading rates, for the 2002 field season at Virginia Lake.

Percent of Critical P Load	Tons of 16-30-0 needed	13 kg buckets of 16-30-0 needed	Buckets for stream distribution (25%)	Buckets for stream distribution (50%)	30 gal drums of 32-0-0 needed	Drums 32-0-0 per week (12 wks)	OR 30-gal barrels of 20-5-0 liquid needed to meet same rate as solid and 32-0-0	Drums 20-5-0 per week (16 wks)
50%	4.72	330	83	165	90	8	179	11
60%	7.42	518	130	259	141	12	281	18

FIGURES

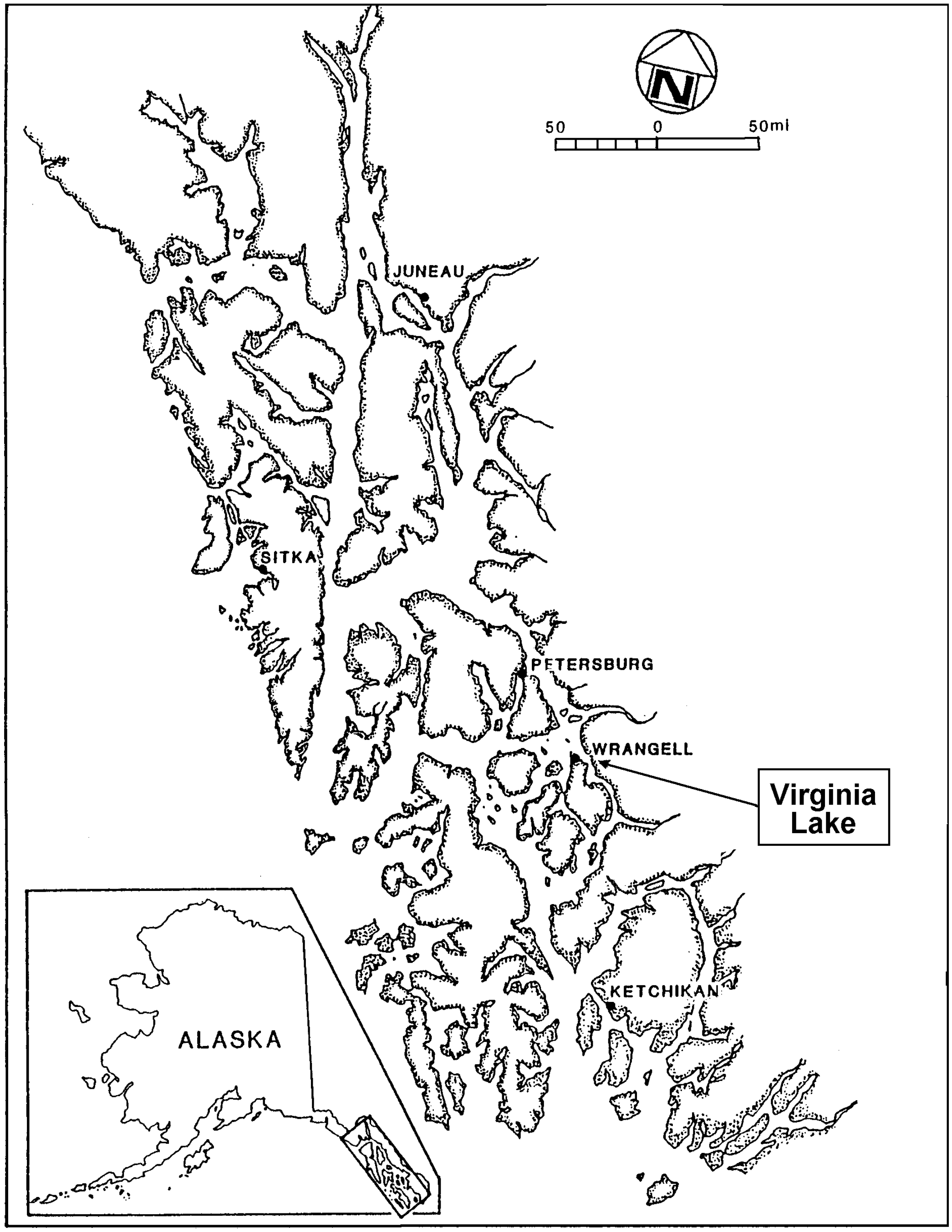

Figure 1. The geographic location of Virginia Lake, within the State of Alaska, and relative to cities within Southeast Alaska.

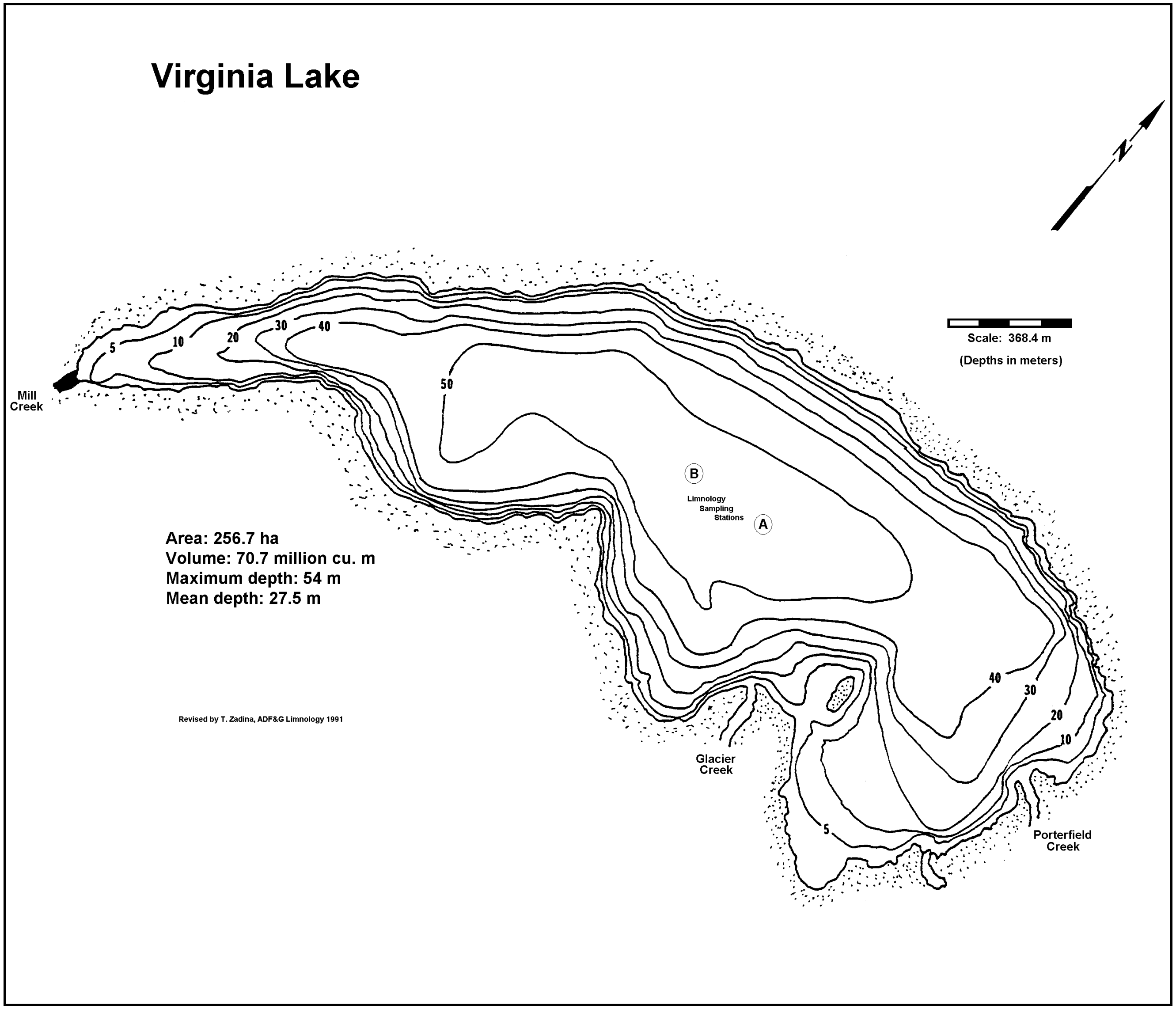

Figure 2. Bathymetric map of Virginia Lake, Southeast Alaska with limnology sampling stations.

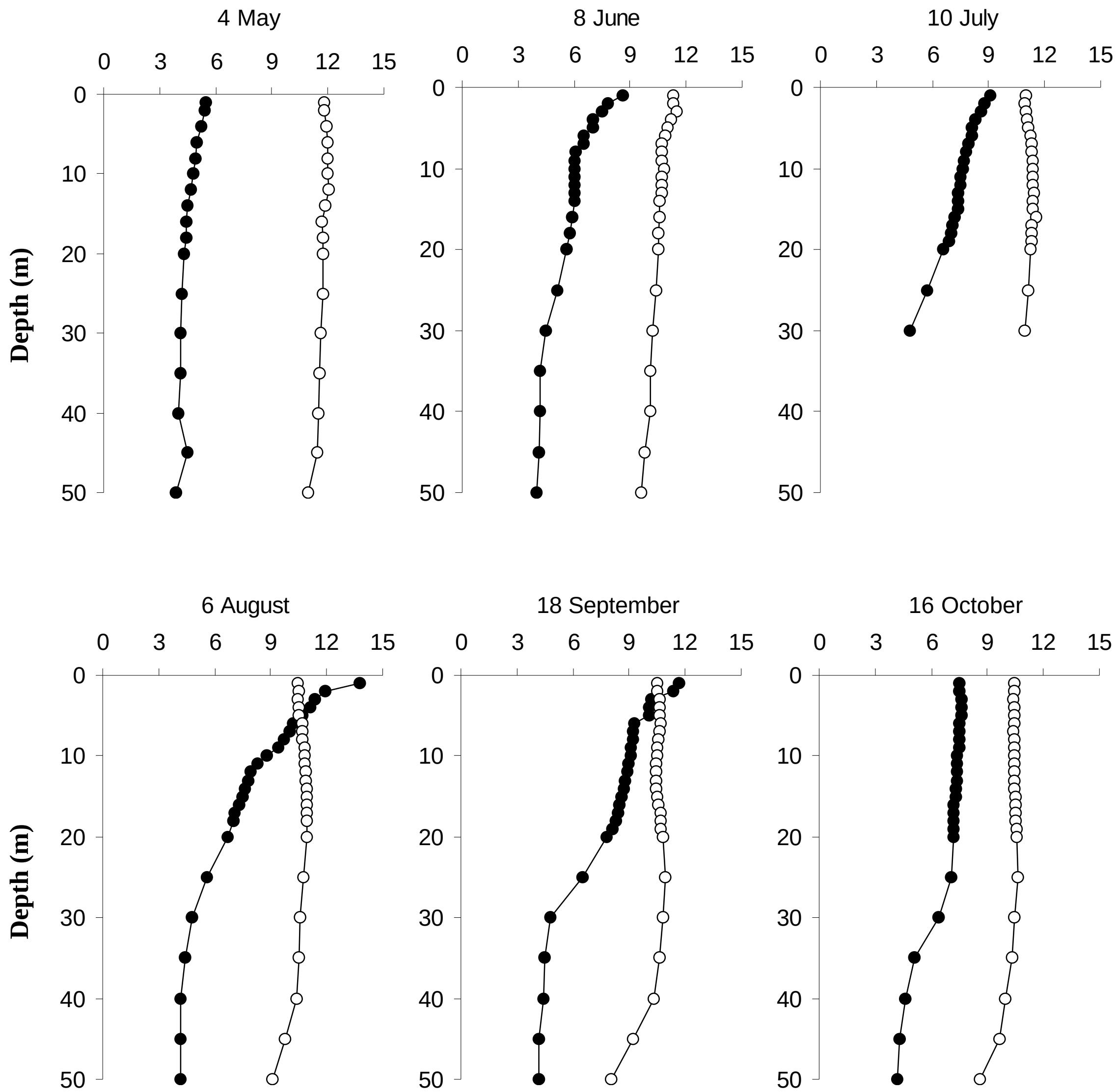

Figure 3. Seasonal temperature (^{o}C; closed circles) and dissolved oxygen ($mg \cdot L^{-1}$; open circles) profiles in Virginia Lake, 2001.

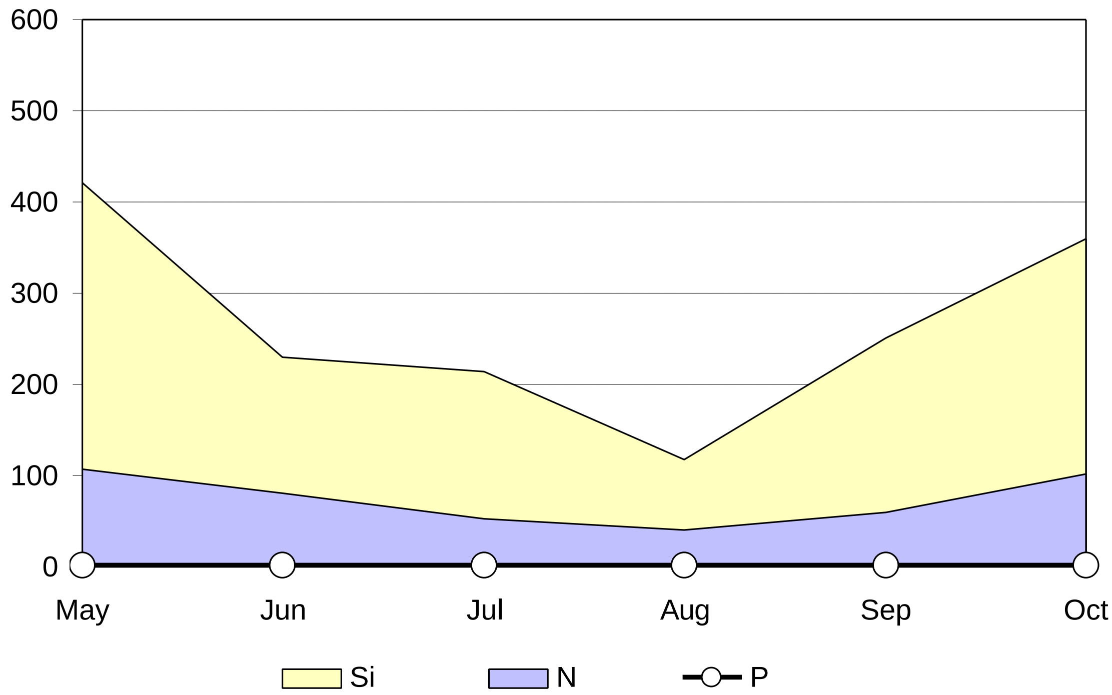

Figure 4. Monthly atomic concentration ratios of nitrogen (N), phosphorus (P; where the level of P is scaled to the value of 1), and reactive silicon (Si) in the epilimnion at Virginia Lake, 2001.

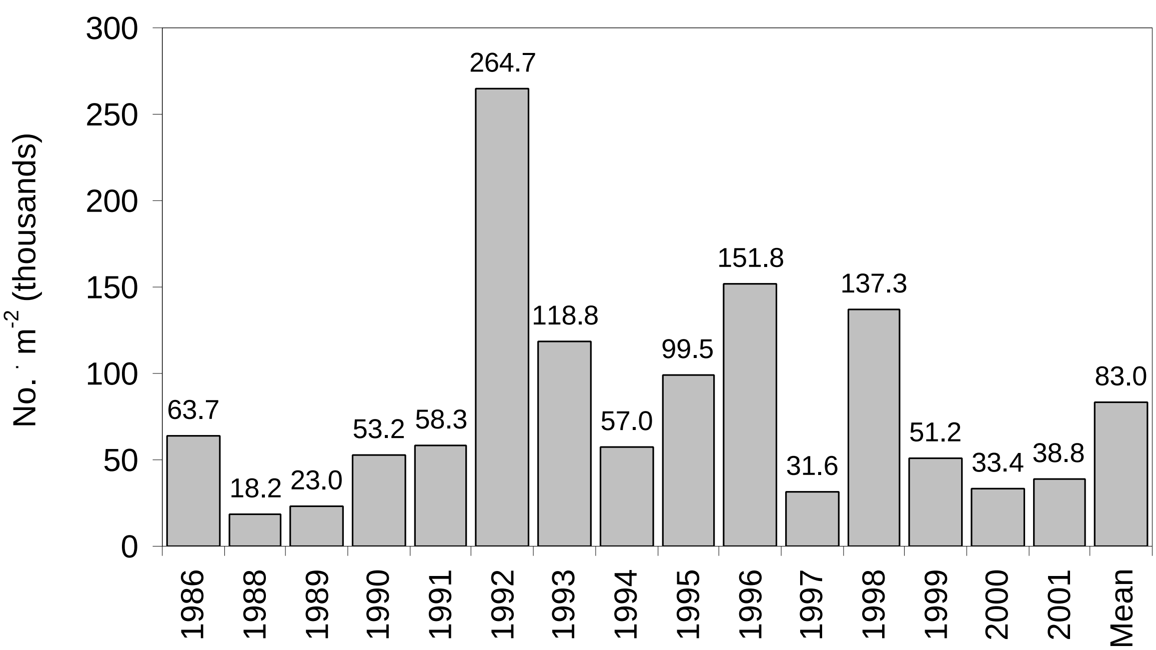

Figure 5. Mean seasonal macrozooplankton density at Virginia Lake, from 1986 to 2001, and for the 15-year mean.

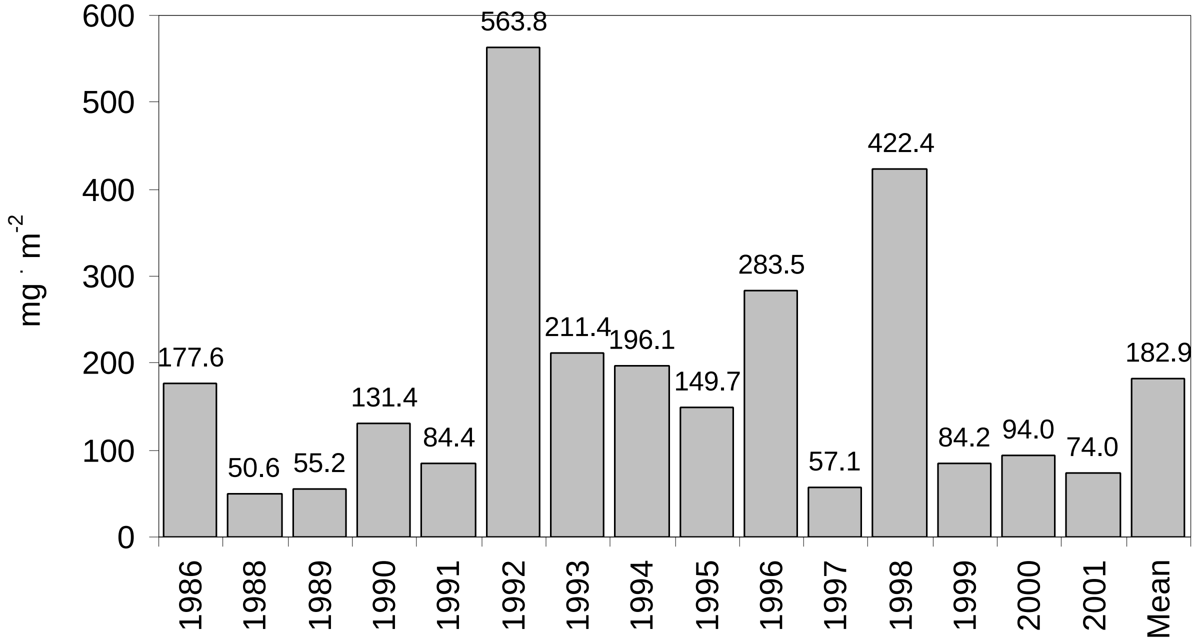

Figure 6. Mean seasonal macrozooplankton biomass at Virginia Lake from 1986 to 2001, and for the 15-year mean.

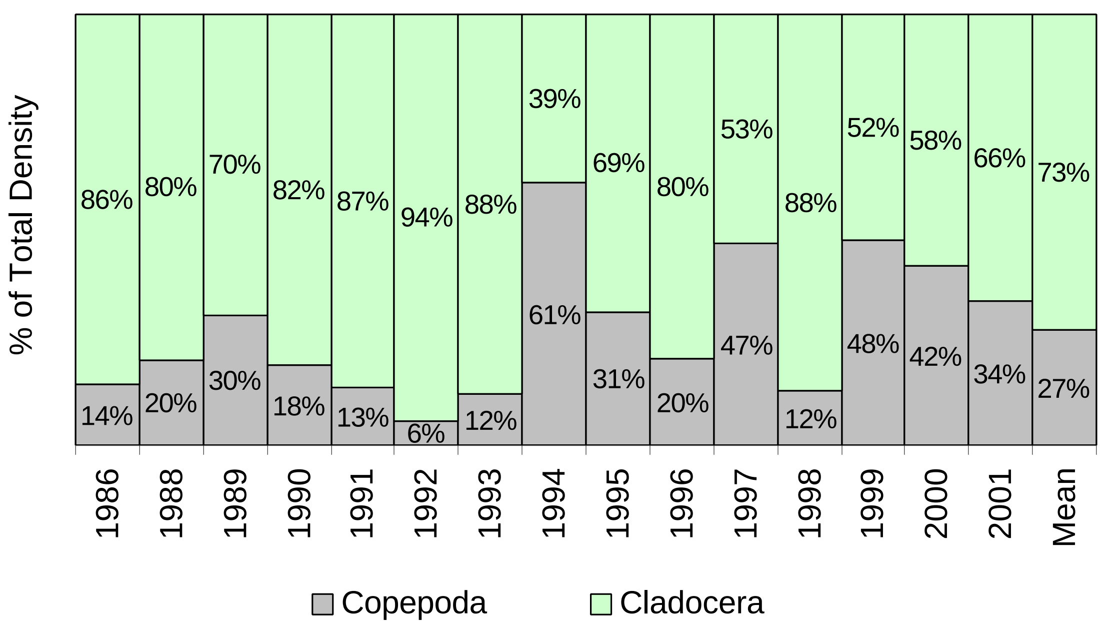

Figure 7. Mean seasonal macrozooplankton density distribution by plankter order at Virginia Lake, from 1986 to 2001, and for the 15-year mean.

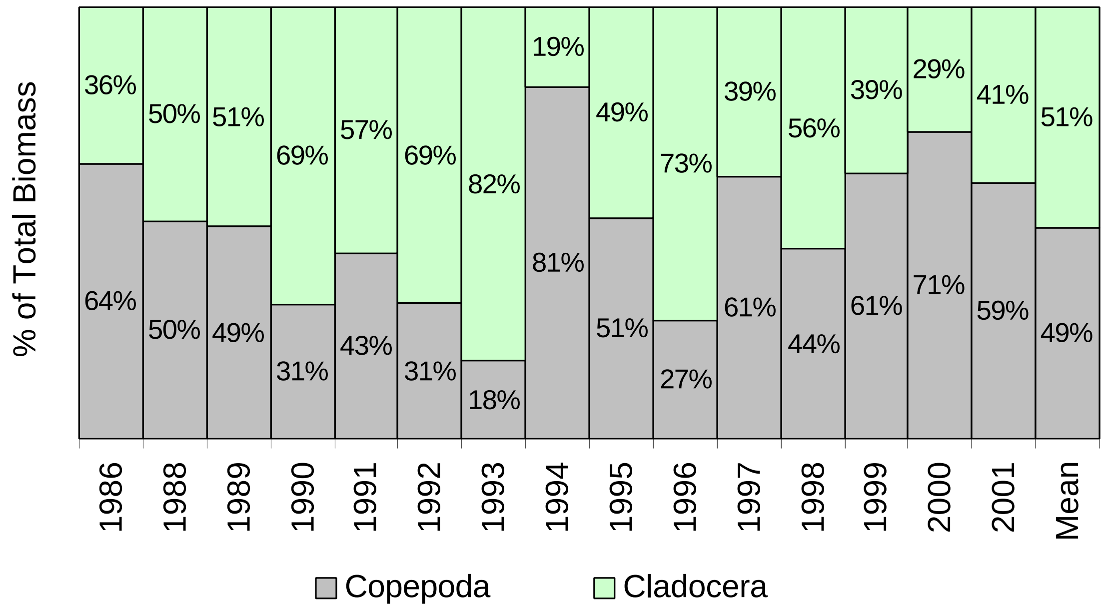

Figure 8. Mean seasonal macrozooplankton biomass distribution by plankter order at Virginia Lake, from 1986 to 2001, and for the 15-year mean.

APPENDIX

Appendix Table A.1. Weekly fertilizer applications at Virginia Lake, 2001.

Scheduled date	Application Date	Application amount	Time start applied	Time Elapsed (hours)	Gallons applied per hour	water level	Weather	Applicator
13-19 May	19 May	210	1300	4.2	50.4	low	overcast	J. Robinson
20-26 May	26 May	210	1400	5.5	38.2	low	overcast	J. Robinson
27 May - 2 June	30 May	210	1200	4.1	51.4	high	overcast	J. Robinson
3-9 June	3 June	210	1300	5.0	42.0	high	overcast	J. Robinson
10-16 June	13 June	210	1200	3.8	54.8	high	overcast	J. Robinson
17-23 June	20 June	210	1200	5.5	38.2	normal	overcast	J. Robinson
24-30 June	28 June	210	1200	5.0	42.0	normal	sunny	J. Robinson
1-7 July	5 July	210	1500	3.8	54.8	high	overcast	J. Robinson
8-14 July	12 July	210	1300	5.0	42.0	high	overcast	J. Robinson
15-21 July	15 July	210	1200	3.8	54.8	normal	overcast	J. Robinson
22-28 July	28 July	210	1200	5.0	42.0	normal	partly cloudy	J. Robinson
29 July - 4 Aug	3 August	210	1500	3.8	54.8	normal	sunny	J. Robinson
5-11 Aug	11 August	210	1300	3.8	54.8	normal	partly cloudy	J. Robinson
12-18 Aug	14 August	210	1000	5.0	42.0	low	sunny	J. Robinson
19-25 Aug	25 August	210	1430	4.5	46.7	normal	sunny	T. Robinson
26 Aug - 1 Sept	4 September	210	1500	5.5	38.2	flood	rain	T. Robinson
Yearly Totals		3,360		73.4				
Yearly Averages		210		4.6	46.7			