LIMNOLOGICAL AND SOCKEYE SALMON PRODUCTIVITY INVESTIGATIONS IN SALMON AND GLACIAL LAKES: PROJECT COMPLETION REPORT

by

G. L. Todd
G. B. Kyle

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Alaska Department of Fish and Game
Division of Commercial Fisheries
Management and Development
P. O. Box 25526
Juneau, Alaska 99802-5526

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AUTHORS

Gary L. Todd is the project biologist for the Nome area lake investigations for the Alaska Department of Fish and Game (ADF&G), Limnology Unit, Division of Commercial Fisheries Management and Development, 34828 Kalifornsky Beach Road, Suite B, Soldotna Ak 99669.

Gary B. Kyle is the south-central Regional Limnologist for the Alaska Department of Fish and Game (ADF&G), Limnology Unit, Division of Commercial Fisheries Management and Development, 34828 Kalifornsky Beach Road, Suite B, Soldotna Ak 99669.

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ABSTRACT

Limnological and fisheries investigations were conducted on Salmon and Glacial lakes from 1994 through 1996 to assess sockeye salmon *Oncorhynchus nerka* rearing capacity, lake productivity, and potential strategies to increase the run size of these stocks. Both lake systems were sampled for emigrating smolts; in Salmon Lake site problems and trap avoidance by the smolts precluded obtaining a population estimate. In 1996 a total of 48,256 sockeye salmon smolts were enumerated at Glacial Lake, which was 3.6 times the 1995 emigration of 13,485. The size of smolts in Glacial Lake are robust (age-1 averaged over 5 g and age-2 over 7 g); indicating that for the number of juveniles rearing in this lake there appears to be an ample food source. In Salmon Lake, the majority of smolts in 1995 and 1996 were age-1, but both age-1 and age-2 smolts were smaller (age-1 averaged 3.5 g and age-2 averaged 5.6 g) than in Glacial Lake, indicating that the forage base (zooplankton) may be limiting growth. An adult weir was installed in Pilgrim River at the outlet of Salmon Lake in 1996 and resulted in an escapement count of 10,845 sockeye salmon, of which 9,956 (92 %) were age 2.3. Historical aerial survey counts of sockeye salmon have averaged 1,960 in Salmon Lake and 760 in Glacial Lake. In 1996, the aerial survey counts were 6,610 and 1,852 (3.4 times and 2.4 times the mean historic surveys) for Salmon and Glacial lakes, respectively. In the last ten years, aerial salmon counts in Salmon Lake have doubled. Both lakes are ultra-oligotrophic as nutrient and chlorophyll *a* concentrations were low compared to other lakes supporting sockeye salmon. In 1996, macrozooplankton biomass in Salmon Lake was 443 mg/m^2, which was almost two times the 1994-1995 mean of 231 mg/m^2. A smaller increase in mean macrozooplankton biomass was found in Glacial Lake during 1996 than during 1994-1995 (193 mg/m^2 compared to 167 mg/m^2). Based on macrozooplankton biomass and sockeye abundance in other Alaskan nursery lakes, these two lakes appear to currently have a deficient number of sockeye salmon. The current zooplankton forage base indicates that both lakes could support additional numbers of rearing fry. Although both lakes would benefit from increasing lake fertility through a nutrient enrichment project, the current low density of sockeye fry in Glacial Lake and the existing large smolt sizes is evidence that the zooplankton forage base is not being challenged. Thus, a nutrient enrichment project would increase fertility of Glacial Lake, but the benefit would be minimal due to the currently low fry recruitment. Until such time that the rearing fry density increases (either through larger escapements or supplemental fry stocking), Glacial Lake is not recommended for nutrient enrichment. However, Salmon Lake is a more suited candidate for nutrient enrichment because it has substantially smaller smolts (suggesting food limitation), a much higher potential for increasing smolt production, and a higher density of rearing fry.

INTRODUCTION

Historically, Salmon and Glacial lakes supported large(r) populations of sockeye salmon *Oncorhynchus nerka*; several written accounts from news articles mention large returns of spawning salmon available for dog food. Verbal accounts from local residents living in the area reveal that many years ago gill netting for sockeye salmon was done in Salmon Lake, and they had numerous fish drying racks along the lake shore. The Salmon Lake/Pilgrim River sockeye salmon stock was a traditional source of subsistence salmon for people living in Teller, Brevig Mission, Mary's Igloo, and Nome. The salmon were used for both human consumption and dog food. At Glacial Lake, there are verbal accounts of fish camps along the shore and salmon bones littering the beaches; suggesting Glacial Lake had larger runs of sockeye salmon than exists today.

Since the early 1960s, the Alaska Department of Fish and Game (ADF&G) has been concerned about the strength of the sockeye salmon populations in Salmon and Glacial lakes, particularly for the Salmon Lake/Pilgrim River system, and began monitoring the Port Clarence District subsistence sockeye salmon harvest. In 1964 a permit was required for subsistence fishing, and subsistence fishing was prohibited in the Grand Central River, which is the main spawning tributary of Salmon Lake. Additional restrictions were placed upon the Pilgrim River fishery prior to 1966, and the catch declined considerably; subsistence sockeye salmon harvests were 3,586 in 1963, 1,475 in 1964, 1,267 in 1965, and 130 in 1966 (Regnart et al. 1966). Aerial surveys of Salmon Lake and the Grand Central River have been conducted since 1963, and the sockeye salmon subsistence harvest has also been monitored since 1963. A small commercial chum salmon (*O. keta*) fishery was conducted in the Port Clarence District in 1966. The commercial catch for all subdistricts in Norton Sound averaged 309 sockeye salmon for 1983-1993 (Lean et al. 1995). Preliminary harvest data for the 1996 commercial salmon harvest for all the Norton Sound area included only one sockeye salmon harvested (Bue 1996). Sport fishing effort has increased steadily on the Seward Peninsula since 1982. The sockeye salmon sport harvest in 1991 and 1992 for the Seward Peninsula was 237 and 131, respectively (Arvey et al. 1995). In 1991, 124 sockeye salmon were harvested in the Pilgrim River (Arvey 1993). Aerial surveys of Glacial Lake have been conducted since 1977.

In 1994, the ADF&G Division of Sport Fish conducted a fisheries survey on Salmon Lake to determine fish species composition and estimate mean gill net catch-per-unit effort by species. A total of 309 fish were captured with variable mesh (five different mesh panels) gill nets, baited minnow traps, and hoop traps. The catch consisted of the following species (in order of magnitude of catch): ninespine stickleback *Pungitius pungitius*, round whitefish *Prosopium cylindraceum*, least cisco *Coregonus sardinella*, slimy sculpin *Cottus cognatus*, Arctic grayling *Thymallus arcticus*, Dolly Varden *Salvelinus malma*, sockeye salmon adults, coho salmon *O. kisutch* fry, and burbot *Lota lota* (DeCicco 1995). Another fish specie previously documented in Salmon Lake is Arctic char *Salvelinus alpinus*, and anecdotal evidence suggests that the following species may have or do occur: northern pike *Esox lucius*, humpback whitefish *Coregonus pidscian*, lake trout *Salvelinus namaycush*, and Alaska blackfish *Dallia pectoralis* (DeCicco 1995). Some of these fish may compete with rearing juvenile sockeye salmon as the following species are known to graze on zooplankton (some only during their early juvenile life stage): ninespine stickleback, least cisco, coho salmon fry, northern pike, humpback whitefish, lake trout, and Alaska blackfish. Also pisciverous fish species preying on sockeye salmon alevins and juveniles are: Dolly Varden, Arctic char, lake trout, burbot, coho salmon fry, and northern pike (Morrow 1980). In 1990, an estimated 1,194 northern pike were harvested in the

Pilgrim River, and this harvest was the second largest in Alaska during 1990 (Mills 1991). Burkholder (1994) using hoop traps with wings, estimated the abundance of northern pike (greater than 300 mm fork length) near the confluence of the Pilgrim and Kuzitrin Rivers at 10,828. He also found that northern pike immigration between the two rivers exceeded 5%.

Sockeye salmon investigations in Salmon and Glacial lakes were initiated in 1994 to determine the status of these two stocks relative to the potential for increasing production. The project was designed to collect information on sockeye salmon smolt and adult populations, and to integrate these data with limnological parameters to assess rearing capacities and restoration options. In 1995, the studies continued (Todd and Kyle 1996), and several agencies became involved; including the ADF&G, the U. S. Bureau of Land Management (BLM), the Bering Sea Fishermen's Association (BSFA) and KAWERAK Inc. Native Association. In 1996, ADF&G, BLM, and the Norton Sound Economic Development Corporation (NSEDC) continued these studies. This report presents results of the 1996 field season and selected data from other years, discusses the limnology of these lakes relative to sockeye production, and makes recommendations regarding restoration options to increase run size.

Study Site Description

Both Salmon and Glacial lakes are located on the Seward Peninsula, near Nome, Alaska (Figure 1). Salmon Lake (64° 54' N, 165° 00' W) is approximately 55 km northeast of Nome and is accessible via the Nome-Taylor road. The Salmon Lake morphometric map was revised in 1996; this lake has a volume of 111.5 x 10^6 m^3, a surface area of 7.49 km^2 (1,851 acres), a mean depth of 14.9 m, and a maximum depth of 40 m (Figure 2). Salmon Lake drains a watershed area of 209 km^2 and is the headwater of the Pilgrim River, which drains into Imuruk Basin. The water residence time for Salmon Lake is estimated at 1.6 years. The mean summer discharge for the Pilgrim River for 1995 and 1996 was 14.3 m^3/sec; the 1995 mean summer discharge of 18.6 m^3/sec was almost twice that in 1996 (10.1 m^3/sec). There are several tributary creeks draining into Salmon Lake, and the Grand Central River is the largest tributary. The land at the smolt sampling and adult weir sites are currently under the jurisdiction and management of the BLM, as is the majority of the watershed. The land near the lake outlet has been selected for conveyance by the Bering Straits Native Corporation. Land immediately bordering Salmon Lake is owned by either the State of Alaska or private individuals.

Glacial Lake (64° 52' N, 165° 42' W) is approximately 40 km northwest of Nome and is accessible by air or off-road vehicle. Glacial Lake has a volume of 23 x 10^6 m^3, a surface area of 3.99 km^2 (986 acres), a mean depth of 5.8 m, and a maximum depth of 22 m (Figure 3). Glacial Lake drains a watershed area of 49 km^2 and drains into the Sinuk River, which drains into the Bering Sea. The water residence time for Glacial Lake is an estimated 1.5 years. The summer discharge for the outlet was similar in 1995 and 1996 and averaged 4.4 m^3/sec for both years. The land around Glacial Lake and the outlet are under the jurisdiction and management of the BLM. However, the land surrounding Glacial Lake has been selected for conveyance by the Bering Straits Native Corporation.

MATERIALS AND METHODS

Smolt Enumeration and Sampling

At Glacial Lake, smolts were captured with the use of a fyke net and leads that fished the total outlet width. The fyke net was installed on 14 June and was operational through 9 July 1996. The leads extended from the west bank to the east bank, and a small holding area was made along the east bank to allow upstream enumeration and passage of adult fish. On 25 June the net was loosened and allowed to lay on the creek bottom because of storm waves, and it remained down until 1000 on 28 June. All fish captured were individually enumerated by species and released. Stratified random sampling methods (Cochran 1977) were used to estimate age-class population estimates and mean weight and length of migrating smolts. The strata were defined as contiguous three-day sampling periods beginning on 14 June and ending on 9 July.

Sockeye smolts emigrating Salmon Lake were enumerated and sampled with the use of two inclined-plane traps (Todd 1994) placed in the Pilgrim River. In 1996, leads made of vexar (plastic netting) overlaid on adult weir sections were attached to the traps to increase smolt catch. The traps were installed on 13 June just below the outlet, and the traps with leads blocked approximately 80% of the river. The outer lead was pulled the evening of 13 June due to floating ice, and the traps were removed on 15 June due to ice break up in the lake. On 20 June, one trap was placed back in the river (at the adult weir site) upstream of the 13 June location, and an 8-m lead connected the trap to the south bank. On 21 June the second trap was placed adjoining trap one, and a 6-m lead was installed extending outward into the river. The Pilgrim River could not be totally blocked at this location because the velocity was too great to place vexar on the adult weir sections. The traps were then relocated to the approximate location used in 1995. Both traps were placed adjoining each other and vexar leads were connected to the south bank and on the outside of the traps continuing upstream 15 m. Approximately 50% of the width and 80% of the volume of the river were sampled by the traps and leads at this site. However, the catch was low at this site, so on 25 June both traps were moved upstream (approximately 200 m) to a shallower location. At this site approximately 40% of the river width and volume were sampled. The traps were fished continually at this site until 9 July; one smolt trap was installed while the adult weir was operated to determine if sockeye smolts continue to emigrate this system throughout the latter part of the summer. With the exception of the morning of 22 June when captured fish were estimated using a biomass technique, all fish captured were individually enumerated. On 27 June, smolts caught in the Pilgrim River were held for a mark-recapture test to estimate trapping efficiency (Rawson 1984). Smolts were enumerated and placed into a cooler containing a dye solution (2 g Bismarck Brown Y dye and 60 L of water). The smolts were aerated (G. Lox® bait aerator) for 30 minutes before being placed in a live-box at the release site located just below the lake outlet. These smolts were held for 6 hours to assess handling mortality prior to release. Dyed smolts recaptured in the traps were enumerated and released. The catch efficiency was estimated from the number of marked (dyed) to unmarked smolts captured in the traps. No estimate of the smolt population was made due to the low trap catches.

At both lakes, a random sample of up to 25 sockeye salmon smolts were sampled daily for size and age; on peak days 50 smolts were sampled. After the emigration peak, smolts were sampled twice weekly. The smolts were anesthetized in a solution of MS-222 (methanesulfonate) and measured for snout-to-fork length (nearest millimeter) and weight (nearest 0.1 g). A scale smear was taken from the primary scale growth area and placed on a labeled glass slide for later aging with a microfiche scale reader.

Adult Enumeration and Sampling

An adult salmon weir was installed in the Pilgrim River on 6 July and operated through 19 August 1996. The weir was a Rack Master metal weir consisting of: Nu-Rail fittings connecting the structural framework, "A" frames of structural (schedule 40) pipe, and aluminum angle stringers for the conduit pickets. Both ends of the weir (against the banks) were closed off with metal screen. The weir was placed approximately 15° perpendicular to the water flow, in order to lead fish into a counting area. The counting area was built into the upstream side of the weir with pickets and vexar. Fish were enumerated and passed upstream through the weir by removing several pickets from the back and front of the holding area. A minimum random sample of 20 sockeye salmon were sampled three times each week for length (mid-eye to fork length), sex, and age. Three scales were collected from the primary scale growth area, and placed on labeled gummed cards. The gummed cards were later pressed onto acetate cards with a scale press, and read with a microfiche scale reader.

Hydroacoustic-Tow Net Survey

A hydroacoustic survey was conducted at Salmon Lake on the night of 6 September 1996 to estimate the number and distribution of rearing sockeye salmon juveniles. Eight transects in the west basin and six transects in the east basin were used to record fish signals. The survey was done at night because juvenile sockeye salmon were more dispersed and not near the surface; making the fry were more susceptible to the hydroacoustic gear. A BioSonics model-105 echo-sounder system with a 6/15° dual-beam transducer was used for the survey. Fish signals were recorded electronically using a Sony model-TCD-D10 digital audio tape recording system, and on paper using a BioSonics model-115 chart recorder. Analysis of the recorded hydroacoustic tapes was conducted by Dr. Richard Thorne of BioSonics Inc. Tow netting (2 x 4 m net) was conducted on the night of 7 September 1996 to determine species of the acoustically-counted fish, and to determine sizes and ages of juvenile sockeye salmon. The townet was pulled at a speed of approximately 0.5-1.0 m/sec by two boats to reduce avoidance of the net (tow ropes were not present in the net opening while towing). Tows were conducted at the surface, 5 m, and 15 m depths intervals.

Limnological Surveys

In 1996, limnological surveys were conducted three times (3 July, 30 July, and 2 September) at Glacial Lake and four times (23 June, 12 July, 4 August, and 3 September) at Salmon Lake. Two permanent sampling stations (buoys attached to lines anchored on the lake bottom) that were placed in each lake in 1995 were also used in 1996 (Figures 2 and 3). Two additional stations were used at each lake to collect zooplankton. On 11 and 14 July of 1981 Nome High School students collected and analyzed zooplankton samples from Glacial Lake. Water and zooplankton samples were collected and analyzed according to procedures described by Koenings (et al. 1987). Temperature and dissolved oxygen profiles (taken at 1-m intervals from the surface to 5 m, then at 5-m intervals to the bottom) were recorded at each station using a Yellow Springs Incorporated meter. The 1% incident light level (euphotic zone depth) was measured using an International Light photometer. Water samples for nutrient and general water-quality analysis were taken at 1 m and 75% of the station depth. Water samples were preprocessed (filtered, preserved, and/or stored) at the Nome ADF&G laboratory for later analysis at the ADF&G limnological laboratory in Soldotna. Algal biomass (chlorophyll *a*) was determined on water samples using procedures described by Koenings et al. (1987). Finally, zooplankton were collected with a 0.5-m diameter zooplankton net (153 μm mesh). Vertical tows were taken from 1 m above the bottom to the surface at each station, and samples were preserved in a 10% buffered formalin solution for latter analysis. Species identification, enumeration and sizing, and computation of density and biomass followed procedures described by Koenings et al. (1987).

RESULTS

Smolt Abundance, Size, and Age

A total of 48,256 sockeye salmon smolts were enumerated at Glacial Lake during 14 June-9 July 1996 (Table 1). One large peak occurred during the emigration on 19 June, when over 50% (24,839) of the smolts migrated (Figure 4). The age-2 smolts comprised 99% of the 1996 migration compared to 49% in 1995 (Table 2). The weighted mean size of age-2 smolts was slightly larger in 1996; 102 mm and 7.7 g (Table 2) compared to 97 mm and 7.1 g for 1995 (Todd and Kyle 1996). Age-1 smolt comprised 1% of the 1996 emigration (compared to 44% in 1995) and averaged 94 mm and 6.5 g, which was also slightly larger than the 1995 age-1 smolt size of 89 mm and 5.9 g (Todd and Kyle 1996). No age-3 sockeye salmon smolts were collected in 1996; the 1995 emigration comprised 7% age-3 smolts.

A total of 16,324 sockeye salmon smolts were caught in the Pilgrim River traps during 13 June-8 July 1996 (Table 3). After moving the traps to three different locations due to low catches, a large enough number of smolts were caught at the fourth site to conduct a dye test. On 28 June a total of 800 sockeye salmon smolts were stained and released after holding to assess mortality. A total of 171 marked smolts were recaptured for a trap efficiency of 21%. Due to the low trap catches and insufficient trap efficiency data, no estimate of the smolt emigration was possible for Salmon Lake. The sizes of sockeye smolts in 1996 were similar to that found in 1995. In 1996, age-1 smolts averaged 77 mm and 3.4 g and age-2 smolts averaged 93 mm and 5.6 g (Table 4). In comparison, the age-1 smolts in 1995 averaged 76 mm and 3.5 g, and age-2 smolts averaged 92 mm and 5.6 g. The age composition in 1996 was 95% age-1 and 5% age-2. In 1995, the age-1 smolts comprised 77% of the population and age-2 smolts comprised 19%.

Adult Abundance, Size, and Age

The aerial survey of Glacial Lake in 1996 estimated a total of 1,852 sockeye salmon, which was 2.4 times the mean of 759 (Table 5). In 1977 and 1979 weir counts indicated an escapement of 545 sockeye salmon each year (Pearson 1977; Table 5). During the last ten years, the mean aerial survey count was 1,068 sockeye salmon. In 1996, an aerial survey of Salmon Lake and the Grand Central River estimated 5,910 and 700 sockeye salmon, respectively (Table 5). The 1996 weir count for Salmon Lake was 10,845 (Table 6); thus the aerial survey count was 60% of the weir count. The peak of the migration occurred on 19 July when 1,573 (14.5%) sockeye salmon passed through the weir (Figure 5). Since 1963, the mean sockeye survey count for Salmon Lake was 1,570 and for the Grand Central River was 418. For the past 10 years (1987-1996), the mean survey count for the Salmon Lake system was 4,009 sockeye salmon. The subsistence harvest of Salmon Lake sockeye salmon averaged 916 since 1963 (Table 5). The average annual commercial harvest of sockeye salmon in the Norton Sound district during the last ten years has averaged 338 (Bue 1996); however, in 1996 only one sockeye salmon was reported as commercially harvested.

In 1996, the Salmon Lake sockeye salmon escapement comprised 92% age-2.3 fish which had a mean length of 59 cm (Table 7). In 1995, age-2.3 fish comprised 67% of the run and had a mean length of 61 cm (Todd and Kyle 1996). Age-2.2 and age-3.3 fish each comprised 2% of the 1996 escapement. No recent adult sockeye salmon age or size data are available for Glacial Lake; however, in 1977 and 1979 sockeye salmon entering Glacial Lake were sampled by students of the Nome High School. For both years, the mean length of all fish sampled was 52 cm, and in 1977 age-2.3 comprised 76% of the fish sampled (Dan Levinson, Homer, Alaska, personal communication).

Salmon Lake Hydroacoustic Estimate of Rearing Fish

Based on the hydroacoustic survey conducted on 6 September 1996, an estimated 1.4 ± 0.35 million fish were rearing in Salmon Lake (Table 8). In 1995, a 26 September survey resulted in a total estimate of 2.26 million rearing fish (Todd and Kyle 1996). The majority of the rearing fish in 1996 were in the west (deeper) basin of the lake (Figure 6). Transect 8, which is located in the west basin, was included in the east basin for the population estimate because the bottom morphometry resembled the east basin; flat gradient near shore and shallow depth. The central area of transects 3, 4 and 5, which were located in the deepest area of the lake, had the highest fish densities; 573, 843, and 503 fish/1,000 m^2 respectively (Figure 6). The highest relative percent of rearing fish was observed between 18-27 m (Figure 7).

A total of six net tows were conducted from the surface to 15 m on the night of 7 September 1996 (Table 9). In the 170 minutes of towing, a total of 108 sockeye salmon fry, 4 least cisco and 3 nine-spine stickleback were captured. The majority of the sockeye salmon fry were captured in the surface and 5 m tows, while the least cisco and stickleback were all captured in the 15 m tows. Based on the tow net catches, an estimated 1.3 million of the total 1.4 million fish counted in the hydroacoustic survey were sockeye salmon fry (Table 10). Ninety percent of the sockeye fry caught were age-0, and the mean length and weight of these fish were 53 mm and 1.3 g, respectively (Table 10).

Limnological Conditions

Temperature, Oxygen, and Light

The seasonal mean water column temperature in Glacial Lake centered about 8.5° C except at Station 2 in 1995 when the mean temperature was 9.3° C (Table 11). In Salmon Lake, the mean temperature at Station 3 was similar (about 8.5° C), but at Station 1 the mean temperature was about a degree cooler (Table 12). The initiation of heating (when the lake temperature at 1 m was at or greater than 4° C) was about 11 days latter in Glacial Lake in 1996 than in 1995 (Table 11). The rearing duration (days when the lake was above 4° C) in Salmon Lake was slightly longer, presumably due to the larger size of Salmon Lake (Table 12). The rearing duration (days above 4° C at 1 m) in both lakes ranged from 117 to 130 in 1996, which was less than the 143-153 days in 1995. During both years, the rearing duration was relatively short compared to other sockeye nursery lakes (Jim Edmundson, ADF&G, Soldotna, personal communication). The dissolved oxygen (D.O.) concentrations in the surface water of both lakes was about 12 mg/L or

100% saturation in 1996. As in 1995, near the bottom of Salmon Lake in 1996 the D.O. was slightly lower at about 70% saturation. In 1996, the euphotic zone depth (depth in which photosynthesis occurred) extended to the bottom of Glacial Lake and to over half the maximum depth in Salmon Lake. As observed in 1995, there was little turbidity (<1 NTU) in these lakes in 1996, and color averaged about 5 Pt units; indicating that these systems are clear-water lakes (Tables 11 and 12).

General Water Quality

Summaries of measured limnological parameters during 1994-1996 in Glacial and Salmon lakes are presented in Tables 11 and 12, respectively. Conductivity, which is an indirect measure of dissolved materials and an index of lake fertility, was about half the concentration in Glacial Lake (~65 μmhos/cm) as that found in Salmon Lake. Alkalinity (the measurement of the ability of water to resist changes in pH which is important in chemical reactions such as photosynthesis) was also lower in Glacial Lake (~11 mg/L) compared to Salmon Lake (48 mg/L). Although conductivity and alkalinity in Glacial Lake were lower compared to Salmon Lake, the mean concentrations in Glacial Lake were within the range found in other sockeye-producing lakes in Alaska (Table 13). Calcium and magnesium, which are micro-nutrients needed for metabolism of higher plants, were lower in Glacial Lake than in Salmon Lake, but again was similar to many other lakes supporting sockeye. Iron is an essential element for phytoplankton production and in both lakes the concentrations ranged within those observed in other sockeye nursery lakes.

Nutrients

The mean total phosphorous (TP) concentration within the epilimnion (1 m) of Glacial Lake during all years sampled ranged from 2.4 to 4.0 μg/L (Table 11). In Salmon Lake, the mean TP in the epilimnion ranged slightly lower; from 1.7 to 3.9 μg/L (Table 12). The TP concentration in both lakes were lower than the mean of 6.8 μg/L for 57 other sockeye-producing lakes in Alaska (Table 13). The mean concentration of inorganic phosphorous (filterable reactive phosphorous [FRP]), the fraction that is immediately available for phytoplankton production was also quite low; averaging about 1.5 μg/L in Glacial Lake and 1.7 μg/L in Salmon Lake. Total Kjeldahl nitrogen (TKN) averaged 64 μg/L in Glacial Lake and 47 μg/L in Salmon Lake, and was also low compared to the average for other sockeye nursery lakes (Table 13). The inorganic fractions of nitrogen (mainly nitrate) were mostly below the detection limits, indicating that available inorganic nitrogen is quickly assimilated and in high demand by phytoplankton. The ammonia concentrations in both lakes were also quite low. Finally, reactive silicon (Si), which is assimilated in large quantities by diatoms in the synthesis of their cell walls (frustules), was present in both lakes at concentrations (1,600-2,200 μg/L) similar to other sockeye nursery lakes.

Phytoplankton

Algal biomass (as indicated by chlorophyll *a* levels) in the epilimnion of Glacial and Salmon lakes averaged 1.22 and 0.82 μg/L, respectively (Tables 11 and 12). The chlorophyll *a* concentration in 57 other sockeye-producing lakes averaged 1.23 μg/L (Table 13). Based on the 1994 samples (Todd and Kyle 1996), the edible phytoplankton (useable for food by zooplankton), particularly the chyrso-cryptophtyes and other miscellaneous taxa in both lakes were observed in higher densities than the non-edible forms. Overall, the samples analyzed in 1994 indicated few inedible taxa of phytoplankton, and many of the species were rated prime food for zooplankton.

Zooplankton

In Glacial Lake, the macrozooplankton community (by density) comprised mainly of *Bosmina*, *Cyclops*, and *Diaptomus*, and a smaller composition of *Daphnia* and *Holopedium* (Figure 8). In 1996, the mean macrozooplankton density and biomass for all taxa averaged 94,100 per m^2 and 193 mg/m^2, respectively (Figures 8 and 9). The zooplankton density in 1996 was about one-third higher than the 1981 and 1994-1995 means. The mean density and biomass for 1994-1996 were 78,365/m^2 and 160 mg/m^2, respectively (Appendix A).

In Salmon Lake, *Cyclops* and *Bosmina* were the most abundant zooplankton taxa, followed by *Daphnia* (Figure 10). In 1995 and especially in 1996, *Cyclops* were more abundant than *Bosmina*. The mean macrozooplankton density and biomass in 1996 were 214,700 per m^2 and 443 mg/m^2, respectively (Figures 10 and 11). The *Cyclops* mean density was 2.7 times higher in 1996 than the mean for 1994-1995, while *Daphnia* density was greater in 1994 (Figure 10). During 1994-1996, the macrozooplankton density and biomass in Salmon Lake averaged 153,500/m^2 and 240 mg/m^2, respectively (Appendix B).

DISCUSSION

For the two years of smolt sampling at Glacial Lake, the age 1 smolt composition varied from 44% in 1995 (Todd and Kyle 1996) to 1% in 1996 (Table 2). The size of smolts in Glacial Lake are quite robust (age-1 averaged over 5 g; age-2 over 7 g); indicating that for the number of juveniles rearing in this lake there appears to be an ample food source. In Salmon Lake, the majority of smolts in 1995 (Todd and Kyle 1996) and 1996 (Table 4) were age-1, but both age-1 and age-2 smolts were smaller (age-1 averaged 3.5 g; age-2 averaged 5.6 g) than in Glacial Lake, indicating that the forage base (zooplankton) may be limiting growth.

Aerial surveys of sockeye returning to Glacier Lake ranged from <100 to 2,400 during 1977-1996 (Table 5). Because of varying survey conditions, different survey observers and pilots, limited visibility, and deep spawning in lakes - sockeye escapements can be 2 to 3 times higher than aerial counts. If this is the case, at Glacial Lake the actual escapements during 1977-1996 could range from a low of several hundred to a high of over 5,000 sockeye. In the last ten years the annual escapement probably averaged 2,000 sockeye. Based on the Glacial Lake aerial surveys, no trend in the sockeye escapement abundance is evident. In Salmon Lake, the aerial surveys ranged from <200 to 6,600 during 1963-1996, but assuming a 2-fold undercounting error would result in an average escapement of ~4,000 since 1963, and 8,000 during the last 10 years (Table 5). Thus, in the last 10 years, a doubling of escapement or at least a doubling of the aerial counts has occurred; indicating an increasing number of rearing fry in the lake.

The limnetic population estimate of fish species in Salmon Lake based on the hydroacoustic-tow net survey in 1996 should be considered suspect (Table 9). The majority of the fish during the hydroacoustic survey were detected below 18 m (Figure 7), which was deeper than the effective sampling depth of the tow net. Thus, species apportionment based on the limitation of the tow net are most likely in error. In addition, only 115 fish were captured by tow net which is a relatively small sample size for the population of fish in Salmon Lake. Based on the total fish population estimates in Salmon Lake in September 1995 (Todd and Kyle 1996) and 1996 (Table 8), and the estimated production from recent sockeye escapements, there could be a high density of other fish than sockeye in the limnetic area of the lake. If these fish are mainly cisco and stickleback, there could be competition with rearing sockeye fry for food as these two species also rely on zooplankton as a major food item.

Nutrients such as nitrogen and phosphorous are major cellular components of all organisms and can regulate or limit the productivity of organisms in freshwater ecosystems. Concentrations of nitrogen and phosphorus are dynamic because they are constantly being utilized, stored, transformed, and excreted by various aquatic organisms. Other elements such as iron, silica, calcium, and magnesium are essential cellular constituents but are required in relatively low concentrations in relation to availability in fresh waters.

Nitrogen is necessary for aquatic and terrestrial life, and because nitrogen is more abundant it has been generally considered not as limiting to primary production as phosphorus. However, there is growing evidence to suggest that the nitrogen supply combined with lower phosphorus levels can significantly change biological responses (regulating photosynthesis and algal standing crop) in lakes (Smith 1982; Elser et al. 1990). There are various inorganic and organic fractions of nitrogen that are measured in water; however, both inorganic forms (ammonia and nitrate) are readily utilized by aquatic plants for production. Except under alkaline conditions ($pH>9.0$), most of the ammonia in fresh water exists in the ionic form known as ammonium (NH_4^+). Throughout the sampling period in Salmon and Glacial lakes, epilimnetic (1 m) ammonium concentrations were quite low and often below the detection limit (Tables 11 and 12). Epilimnetic nitrate concentrations were also quite low and were more often found below the detection limit. Total Kjeldahl nitrogen (TKN), which measures organic nitrogen and ammonium was above the detection limits, but relative to other clear-water sockeye lakes (Table 13) was low in both lakes.

Phosphorus (P) has been considered as the limiting factor of primary productivity in many lakes. In sockeye nursery lakes, nutrients from decomposing salmon carcasses (mainly phosphorus) has been strongly correlated to lake productivity (Gilbert and Rich 1927; Juday et al. 1932; Krohkin 1967; Donaldson 1967). In Glacial and Salmon lakes, total phosphorus (TP), which comprises both dissolved and particulate P, averaged 3.2 μg/L and 2.7 μg/L, respectively in the epilimnion. Total phosphorus in other clearwater sockeye nursery lakes in Alaska averaged about 7 μg/L (Table 13). The low concentration of TP is due to the relatively low density of sockeye in these lakes, and the low allochthonous (watershed) input of nutrients due to the lack of vegetation surrounding these lakes. Filterable reactive phosphorus (FRP) is the form most readily available for algal uptake. On average, FRP comprised 47% and 63% of TP in Glacial and Salmon lakes, but because TP values in these lakes are low the FRP concentrations are considered quite low. Thus, both lakes have TP, FRP, and inorganic N concentrations below the average for other Alaskan sockeye nursery lakes, which results in limited primary production (chlorophyll *a*).

For optimal algal production (without coupled nutrient limitation), the atomic ratio of total nitrogen (TKN and nitrate) to total phosphorus (TN:TP) approximates 20:1 (Schindler 1978; Rhee 1978; Smith 1982, 1983). Based on the 1994-1996 data, the TN:TP ratio for Glacial and Salmon lakes was 44:1 and 40:1, respectively. Thus, although the nutrient ratios do not indicate an extreme imbalance of nutrients in Glacial and Salmon lakes, it is important to note that coupled low nitrogen and phosphorus makes the ratio inadequate in representing nutrient limitation in these lakes.

The macrozooplankton biomass in Glacial Lake for the last three years averaged 160 mg/m^2 (Appendix A). If it is assumed that this is the long term average, an estimated 224,500 (6 g) smolts would be produced each year based on the zooplankton-smolt biomass model of Koenings and Kyle (1997). Thus, the smolt population estimates in 1995 (13,500) and 1996 (48,300) are considerably lower than the potential based on the current standing stock of zooplankton. In Salmon Lake, the macrozooplankton biomass averaged 240 mg/m^2 during 1994-1996 (Appendix B). The zooplankton-smolt biomass model estimates Salmon Lake is currently capable of producing about 950,000 (4 g) smolts. This compares with the estimated current smolt production of 180,000 based on the following assumptions: a mean of 4,000 spawning females, a fecundity of 3,000/female, an egg to fry survival of 10%, and a fry to smolt survival of 15%. Thus, Salmon Lake has a much higher potential for smolt production than Glacial Lake. However, because these lakes are at the most northern limit for sockeye salmon, are ultra-oligotrophic (very low nutrients), and have a short rearing season, extrapolation of smolt production from lakes used in the model of Koenings and Kyle (1997) may overestimate smolt production.

RECOMMENDATIONS

Among the fundamental factors limiting the productive (rearing area) capacity of salmon nursery lakes is the quantity of nutrients needed for plant growth. Other essential factors include light and heat; however, without nutrients primary production is limited, which in turn, regulates zooplankton production. Differences in the capacity of a lake to produce food (i.e. zooplankton) results in distinctive capacities of a lake to support planktivores such as juvenile sockeye salmon. In Alaska, investigations of trophic responses to nutrient additions, fry stocking, adult escapements, and environmental factors have been conducted in a variety of lakes (Koenings and Burkett 1987; Kyle et al. 1988; Edmundson et al. 1993; Kyle 1994ab; Koenings and Kyle 1997; Kyle et al. 1997). These investigations revealed a basic tenet of rearing efficiency in sockeye nursery lakes; that juvenile sockeye production is not an exclusive function of spawner density, and a high-quality rearing environment (which can be attained through nutrient enrichment) improves juvenile sockeye growth and survival.

Nutrient additions in three coastal oligotrophic lakes in south-central Alaska increased primary production (chlorophyll *a*) by as much as 500%, and resulted in a sustained higher level of zooplankton biomass than before treatment (Kyle 1994b). A 40 to 700% increase in zooplankton biomass occurred after nutrient treatment in the three lakes. For two of these lakes in which data were available, sockeye smolt biomass increased 50 to 250%, and in the third lake the mean weight of age-1 smolt increased by 35%. In these lakes, adult sockeye production increased as much as 2.5 times the pre-enrichment period. The sustained high production of zooplankton and the consistent production of larger or more abundant smolts indicated that the nutrient enrichment projects conducted in these lakes were advantageous to rearing sockeye salmon fry.

Based on the data collected to date it is evident that: 1) Glacial and Salmon lakes are quite oligotrophic, 2) the density of rearing sockeye fry in Glacial Lake is low relative to the zooplankton forage base, and 3) in the last 10 years the number of adult sockeye (and potentially the number of rearing fry) have doubled in Salmon Lake. Although both lakes would benefit in terms of increasing lake fertility through a nutrient enrichment project, the current low density of sockeye fry in Glacial Lake and the existing large smolt sizes is evidence that the zooplankton forage base is not being challenged. Thus, a nutrient enrichment project would increase fertility of Glacial Lake, but the current low numbers of rearing fish would not be significantly affected from such a project. Until such time that the rearing fry density increases (either through larger escapements or hatchery fry stocking) it is not recommended for nutrient enrichment. However, Salmon Lake is a more suited candidate for nutrient enrichment because it has substantially smaller smolts (suggesting food limitation), a much higher potential for increasing smolt production, and a higher density of rearing fry. In addition, since Salmon Lake is on the road system, logistical problems associated with conducting project activities would be diminished, and therefore the benefit-to-cost ratio would be larger compared to Glacial Lake. Also, if the Salmon Lake sockeye run was increased, more users would have access to potentially harvest sockeye than at Glacial Lake due to the Salmon Lake fish migrating through the Port Clarence fishing district close to Teller and Brevig Mission.

The goal of the lake enrichment program in Alaska is to increase zooplankton biomass without negatively altering the species composition or changing the lake's oligotrophic state (Kyle et al. 1997). This, in turn, should lead to a higher quality rearing habitat for planktivorous juvenile sockeye, and ultimately result in an increase in smolt and adult production. For Salmon Lake, a nutrient enrichment project would entail weekly applications of two types of liquid fertilizer. Approximately 40 tons of 20-5-0 and 2 tons of 32-0-0 would be added during the months of July and August. The blended fertilizer (20-5-0) is in a N:P ratio of about 20:1 (by atoms), which is desired for optimum phytoplankton growth and preventing nuisance algal blooms. This fertilizer is formulated from mixtures of pharmaceutical grade (white acid) phosphorus and nitrogen. The nitrogen fertilizer (32-0-0), which comprises 50% urea, 25% nitrate, and 25% ammonium would be added to elevate the currently very low mid-summer N concentrations. Typically, nutrient enrichment projects are conducted at least five years; one life span of sockeye.

In addition, to the recommendation of a nutrient enrichment project at Salmon Lake, investigations should continue in an effort to develop a method to provide supplemental fry to both Glacial and Salmon lakes. For both lakes, a stocking program (using brood stock from each lake) would expedite increasing the current low run of sockeye salmon. Due to the instability of the macrozooplankton community when faced with increased predation pressure, the stocking programs would be based on a conservative and gradual approach with close evaluation. In addition, experimenting with stocking strategies (varying stocking density, release date, and/or fry size) should be part of the stocking programs to ameliorate significant impacts to the macrozooplankton community.

Because of the interacting links between fish and lake ecology, salmon enhancement or restoration programs such as lake stocking and/or nutrient enrichment require a systematic evaluation program. Evaluation focuses on monitoring the responses in nutrient concentrations, algal biomass, zooplankton community structure and biomass, and age and size of salmon juveniles. Such evaluation is necessary before and during restoration projects to make annual adjustments (in fertilizer quantities and stocking densities) and to determine the efficacy of a restoration project.

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Table 1. Daily counts of sockeye salmon smolts emigrating Glacial Lake, 1996.

Date	Sockeye	Sockeye accum.	Coho	Coho accum.
6/15	96	96	0	0
6/16	1,213	1,309	10	10
6/17	1,483	2,792	2	12
6/18	4,167	6,959	37	49
6/19	24,839	31,798	271	320
6/20	4,910	36,708	17	337
6/21	2,029	38,737	29	366
6/22	3,422	42,159	31	397
6/23	5,156 [1]	47,315	52	449
6/24	204	47,519	18	467
6/25	340 [2]	47,859	0	467
6/26	0 [2]	47,859	0	467
6/27	0 [2]	47,859	0	467
6/28	37 [2]	47,896	0	467
6/29	6	47,902	1	468
6/30	1	47,903	2	470
7/1	0	47,903	0	470
7/2	5	47,908	0	470
7/3	2	47,910	0	470
7/4	44	47,954	0	470
7/5	146	48,100	4	474
7/6	67	48,167	2	476
7/7	23	48,190	0	476
7/8	11	48,201	0	476
7/9	55	48,256	0	476
Total		48,256		476

[1]Net blown down by wind from 0800-1800.

[2]On 25 June at 2000 the net was lowered because of wind and whitecaps, and remained down until 1000 on 28 June.

Table 2. Population, size, and age of Glacial Lake sockeye salmon smolts by sample period in 1996 compared to 1995.

Sample period	Age class	Pop. estimate	Sample size	Percent comp.	Mean length (mm)	S.D.	Mean weight (g)	S.D
15-17 Jun	1	0	0	0.0				
	2	2,792	125	100.0	103	4.8	8.10	1.2
18-20 Jun	1	546	2	1.6	94	2.8	6.6	0.6
	2	33,370	122	98.4	101	6.2	7.7	1.4
21-23 Jun	1	0	0	0.0				
	2	10,607	100	100.0	102	6.4	7.6	1.3
24 Jun-9 Jul	1	5	1	0.6	89		5.4	
	2	936	173	99.4	99	8.7	7.8	1.9
	1996			Weighted means				
	1	551	3	1.1	94	2.0	6.5	0.4
	95 % C.I.	769						
	2	47,705	520	98.9	102	0.4	7.7	0.1
	95 % C.I.	769						
	1995			Weighted means				
	1	5,973	391	44.3	89	0.3	5.7	0.1
	95 % C.I.	372						
	2	6,543	279	48.5	97	0.2	7.1	0.1
	95 % C.I.	445						
	3	969	44	7.2	108	0.8	10.0	0.3
	95 % C.I.	261						

Table 3. Daily counts of sockeye salmon smolts, trap configuration, and trap site characteristics in the Pilgrim River, 1996.

Site location	Dates	Sockeye catch	Traps and lead configuration	Trapping site characteristics: velocity	deepest depth (m)	% river fished: width	volume
1	13-Jun		2-traps w/vexar leads: both	slow	1.2	80%	90%
First pool			sides not connected to banks				
below outlet	13-Jun		1 lead pulled due to ice			40%	50%
	14-Jun	375					
	15-Jun	82	Traps pulled @ 1200 due to ice				
	Sub total	457					
2	20-Jun		1 trap w/3 weir sections for leads	very fast	0.7	20%	20%
Outlet	21-Jun	289	trap 2 w/2 weir sections for leads			35%	50%
	22-Jun	12,740	Traps pulled due to high velocity				
	Sub total	13,029					
3	22-Jun		2 traps w/vexar leads connected	moderate	1.2	50%	80%
upstream and	23-Jun	100	to south side				
opposite of	24-Jun	100	Outside trap moved further out		1.0	50%	60%
1995 site	25-Jun		and downstream of other trap				
	Sub total	383	Traps pulled and moved upstream				
4	26-Jun		2 traps staggered w/vexar	fast	0.5	40%	35%
0.5 km upstream	27-Jun	300	leads, connected south bank to				
of 1995 site	28-Jun	1,289	mid river				
	29-Jun	413					
	30-Jun	108					
	1-Jul	169					
	2-Jul	8					
	3-Jul	9					
	4-Jul	16					
	5-Jul	3					
	6-Jul	50					
	7-Jul	71					
	8-Jul	19					
	Sub total	2,455					
	Season Total	16,324					

Table 4. Size and age of Salmon Lake sockeye salmon smolts in 1996 compared to 1995.

Sample period	Sample size	Age class	Percent comp.	Mean length (mm)	S.D.	Mean weight (g)	S.D.
1996							
13 Jun - 8 Jul	242	1	95.3	77	3.1	3.4	0.5
	12	2	4.7	93	6.6	5.6	1.0
1995							
6 Jun - 26 Jul	4	0	4.3	52	1.2	1.2	0.1
	72	1	76.6	76	3.5	3.5	0.9
	18	2	19.1	92	5.6	5.6	1.1

Table 5. Summary of aerial salmon surveys for Salmon and Glacial lakes, and Port Clarence District sockeye salmon subsistence harvest.

Year	Salmon Lake system			Glacial Lake	Port Clarence sockeye harvest
	Salmon Lake	Grand Central River	Survey total		
1963	866	620	1,486	[1]	4,866
1964 [2]	76	590	666	[1]	1,475
1965	250	160	410	[1]	1,804
1966	1,120	370	1,490	[1]	1,000
1967	129	280	409	[1]	2,068
1968 [2]	830	645	1,475	[1]	688
1969	24	171	195	[1]	180
1970 [1]	--	--	--	[1]	588
1971	538	512	1,050	[1]	850
1972	680	300 [3]	980	[1]	68
1973 [2]	1,747	607	2,354	[1]	46
1974	820	0	820	[1]	28
1975	537	123	660	[1]	244
1976	132	22	154	[1]	291
1977	317	235	552	545 [5]	591 [4]
1978	822	280	1,102	25	392
1979	1,250	261	1,511	546 [5]	320
1980 [2]	512	175	687	837	3,195
1981 [1]	--	--	--	60	255
1982 [1]	--	--	--	[1]	405
1983	970	-- [1]	970	470	261 [6]
1984	445	30	475	147	-- [1]
1985	730	250	980	385	-- [1]
1986	2,125	160	2,285	726	-- [1]
1987	4,040	530	4,570	2,427	-- [1]
1988	1,195	6	1,201	263	-- [1]
1989	3,055	525	3,580	470 [2]	535 [7]
1990	2,834	926	3,760	639	-- [1]
1991	3,790	1,570	5,360	2,141	-- [1]
1992	1,500	--	1,500	510	-- [1]
1993	2,885	216	3,101	419	-- [1]
1994	3,740	1,230	4,970	1,230	-- [1]
1995 [8]	4,805	628	5,433	733	-- [1]
1996	5,910	700	6,610	1,852 [2]	-- [1]
Mean	1,570	418	1,961	759	916
10 yr mean	3,375	703	4,009	1,068	

[1] No aerial survey made, or subsistence survey conducted.

[2] Poor survey.

[3] Boat Survey.

[4] Species composition estimated; 10% sockeye.

[5] Weir count.

[6] Data collected from returned catch calendars; due to small numbers of returned calenders this harvest estimate is considered inaccurate.

[7] Survey conducted by Subsistence Division.

[8] Numbers corrected from those reported in Todd and Kyle (1996).

Table 6. Daily counts of adult salmon returning to Salmon Lake, 1996.

Date	Sockeye	Accum. sockeye	Pink	Accum. pink	Chum	Accum. chum
7/7	0	0	0	0	0	0
7/8	252	252	0	0	1	1
7/9	0	252	0	0	0	1
7/10	124	376	0	0	0	1
7/11	612	988	0	0	0	1
7/12	0	988	0	0	0	1
7/13	0	988	0	0	0	1
7/14	44	1,032	0	0	0	1
7/15	296	1,328	0	0	0	1
7/16	29	1,357	0	0	0	1
7/17	303	1,660	0	0	0	1
7/18	222	1,882	0	0	0	1
7/19	1,573	3,455	0	0	0	1
7/20	681	4,136	0	0	0	1
7/21	859	4,995	0	0	0	1
7/22	0	4,995	0	0	0	1
7/23	36	5,031	0	0	0	1
7/24	12	5,043	0	0	0	1
7/25	345	5,388	0	0	0	1
7/26	791	6,179	0	0	0	1
7/27	148	6,327	2	2	9	10
7/28	197	6,524	1	3	6	16
7/29	109	6,633	0	3	0	16
7/30	1	6,634	0	3	0	16
7/31	21	6,655	0	3	0	16
8/1	434	7,089	0	3	1	17
8/2	804	7,893	1	4	1	18
8/3	72	7,965	0	4	0	18
8/4	158	8,123	0	4	0	18
8/5	556	8,679	0	4	10	28
8/6	321	9,000	0	4	5	33
8/7	295	9,295	0	4	9	42
8/8	614	9,909	0	4	2	44
8/9	70	9,979	0	4	4	48
8/10	50	10,029	0	4	1	49
8/11	2	10,031	0	4	0	49
8/12	61	10,092	0	4	0	49
8/13	29	10,121	0	4	1	50
8/14	124	10,245	1	5	1	51
8/15	423	10,668	0	5	0	51
8/16	113	10,781	1	6	0	51
8/17	21	10,802	0	6	0	51
8/18	0	10,802	0	6	0	51
8/19	3	10,805	0	6	0	51
8/20	40 [1/]	10,845	0	6	1	52
	Total	10,845		6		52

[1/] The weir was removed on 20 August and approximately 40 sockeye salmon were observed swiming upstream.

Table 7. Mean length, sex, and age composition of adult sockeye salmon sampled at Salmon Lake, 1996.

Age class	Sample size	Mean length (cm)	S.D.	Age comp. (%)
1.2	3	50.5	1.04	0.7
1.3	7	56.6	2.94	1.7
1.4	1	58.5		0.2
2.2	9	51.1	3.00	2.2
2.3	379	59.3	2.52	91.8
3.2	5	51.4	2.04	1.2
3.3	9	56.7	2.20	2.2
Total	413			
Male	209			50.6
Female	204			49.4

Table 8. Densities and population estimates of juvenile fish rearing in Salmon Lake by transect based on the 6 September 1996 hydroacoustic survey.

Transect	Fish density (no./1000 m^2)	Area (X 10^3 m^2) transect	Area (X 10^3 m^2) total	Weighted mean fish density (no./1000 m^2)	Transect abundance	Basin abundance	Variance
				Basin A			
1-S	117.44	123					
1-C	220.38	123	369	139.39	476,981		
1-N	80.34	123					
2-N	178.59	171					
2-C	331.88	172	515	234.83	803,585		
2-S	193.69	172					
3-S	197.88	177					
3-C	573.46	177	531	418.24	1,431,217		
3-N	483.38	177					
4-N	394.80	187					
4-C	843.44	186	559	492.46	1,685,192		
4-S	239.66	186					
5-S	383.05	174					
5-C	503.27	173	520	395.49	1,353,365		
5-N	300.22	173					
6-N	252.16	162					
6-C	452.89	160	482	371.94	1,272,793		
6-S	412.28	160					
7-S	468.95	148					
7-C	419.96	149	446	360.10	1,232,250		
7-N	192.11	149					
		Total	3,422			1,179,341	2.37E+10
				Basin B			
8-N	65.81	120					
8-C	11.73	121	362	39.18	159,437		
8-S	40.23	121					
9-S	33.86	121					
9-C	134.22	120	361	78.61	319,847		
9-N	68.11	120					
10-N	102.17	211					
10-C	64.80	210	631	55.73	226,767		
10-S	0.00	210					
11-S	27.36	216					
11-C	127.64	217	650	83.57	340,059		
11-N	95.46	217					
12-N	94.02	256					
12-C	199.12	256	768	101.41	412,637		
12-S	11.09	256					
13-S	29.82	226					
13-C	67.20	226	678	32.34	131,591		
13-N	0.00	226					
14-N	0.00	207					
14-C	5.95	206	619	1.98	8,057		
14-S	0.00	206					
		Total	4,069			228,342	2.80E+09
Lake Total	8,418.42		7,491			1,407,683	2.65E+10
						S.E.:	162,795.6
				95% confidence interval (+/-)		354,701	
						TINV	2.1788

Table 9. Sumary of townetting in Salmon Lake on 7 September 1996, and resulting population estimates of encountered fish.

Tow number	Tow depth (m)	Tow time (min)	Species	No. caught	Population estimate
1 - W[1]	Surface	30	sockeye	13	
2 - W	Surface	30	sockeye	69	
3 - W	5	30	sockeye	13	
4 - W	10	30	sockeye	7	
5 - W	15	30	sockeye	2	
			least cisco	4	
6 - E	15	20	sockeye	4	
			stickleback	3	
	Total	170	sockeye	108	1,322,014
			least cisco	4	36,723
			stickleback	3	48,963
			Total	115	1,407,700

[1]W - west basin; E - east basin.

Table 10. Mean size, age composition, and population of age-0 and age-1 sockeye salmon fry based on townetting on 7 September, 1996 in Salmon Lake.

Age	Sample size	Age Comp.	Mean length (mm)	S.D.	Mean weight (g)	S.D.	Population estimate
0	97	89.8%	52.5	3.71	1.3	0.30	1,187,364
1	11	10.2%	79.7	5.02	4.8	0.99	134,650
						Total	1,322,014

Table 11. Summary of limnological parameters (seasonal means by year, station, and depth) for Glacial Lake, 1994-1996.

	Station 1						Station 2					
Year	1994	1995	1996	1994	1995	1996	1994	1995	1996	1994	1995	1996
Parameter / Depth (m)	1	1	1	12	12	12	1	1	1	15	15	15
Seasonal mean water column temp.(°C)		8.6	8.3					9.3	8.3			
Date of 1 m water at 4°C		6/10	6/23					6/9	6/20			
Date of heat max. (°C)		8/19	8/9					8/19	8/11			
Seasonal heat budget (g-cal/cm^2)		2,778	2,482					5,162	4,604			
Rearing duration (days above 4°C @ 1m)		143	117					145	118			
Euphotic zone depth (m)	20.0	36.2	19.5				24.4	39.2	20.1			
Conductivity (μmhos/cm)	67	67	68	67	67	68	65	66	68	64	64	66
pH (units)	6.7	6.5	7.0	6.5	6.5	7.0	6.6	6.6	7.1	6.5	6.5	7.0
Alkalinity (mg/L)	10.5	10.7	11.7	11.0	11.0	11.7	10.5	11.1	11.8	11.0	11.0	11.3
Turbidity (NTU)	0.6	0.9	0.8	0.6	0.8	1.1	0.7	0.7	0.9	0.5	0.7	0.6
Color (Pt units)	5	4	4	4	3	3	4	3	4	15	3	4
Calcium (mg/L)	7.9	7.5	7.4	8.1	7.1	7.1	7.9	7.5	7.4	8.1	7.2	7.1
Magnesium (mg/L)	1.4	1.7	1.4	1.5	1.7	1.4	1.4	1.3	1.4	1.5	1.3	1.2
Iron (μg/L)	13	34	19	18	38	20	18	28	19	19	31	16
TP (μg/L)	3.2	2.8	4.0	4.3	3.1	5.0	3.1	2.3	4.0	4.0	2.6	4.2
TFP (μg/L)	1.8	1.8	2.4	1.9	1.6	2.0	2.5	1.3	1.4	9.2	1.3	2.3
FRP (μg/L)	2.2	1.2	1.5	1.7	1.0	1.6	2.4	0.7	1.0	10.2	0.9	1.7
TKN (μg/L)	50	67	73	88	72	72	62	65	67	87	67	61
Ammonia (μg/L)	<DL	<DL	7.3	<DL	<DL	8.9	<DL	<DL	7.7	<DL	<DL	11.2
Nitrate (μg/L)	<DL	7.3	<DL	<DL	7.3	<DL	<DL	7.8	<DL	<DL	9.5	9.7
Silica (μg/L)	1,926	2,151	1,620	1,930	2,205	1,604	1,955	2,115	1,620	1,917	2,126	1,648
Chl *a* (μg/L)	1.05	1.54	1.12	0.85	2.04	1.49	1.16	1.34	1.12	0.53	1.71	1.12
Phaeo *a* (μg/L)	0.22	0.35	0.23	0.25	0.43	0.61	0.24	0.19	0.17	0.25	0.41	0.28

DL indicates detection limits.

Table 12. Summary of limnological parameters (seasonal means by year, station, and depth) for Salmon Lake, 1994-1996.

	Station 1						Station 3					
Year	1994	1995	1996	1994	1995	1996	1994	1995	1996	1994	1995	1996
Parameter / Depth (m)	1	1	1	27	31	27	1	1	1	15	15	15
Seasonal mean water column temp.(°C)		7.6	7.4					8.7	8.8			
Date of 1 m water at 4°C		6/13	6/13					6/11	6/15			
Date of heat max. (°C)		7/29	7/13					7/27	7/13			
Seasonal heat budget (g-cal/cm^2)		4,749	4,242					2,584	3,607			
Rearing duration (days above 4°C @ 1m)		153	130					150	122			
Euphotic zone depth (m)	33.1	28.4	19.5				31.4	20.2	17.0			
Conductivity (μmhos/cm)	136	124	132	135	133	134	138	126	129	136	124	131
pH (units)	7.4	7.4	7.4	7.4	7.1	7.3	7.2	7.5	7.5	7.4	7.5	7.4
Alkalinity (mg/L)	49.5	47.3	47.3	49.3	52.3	49.8	47.3	47.9	48.6	48.3	48.1	48.4
Turbidity (NTU)	0.8	0.6	0.5	0.5	0.6	0.6	0.7	0.8	0.7	0.5	0.7	0.6
Color (Pt units)	5	4	5	5	4	4	8	4	6	6	5	5
Calcium (mg/L)	19.7	17.6	17.6	19.7	18.6	18.0	19.2	17.6	17.1	19.2	17.4	17.8
Magnesium (mg/L)	3.2	4.2	3.2	3.5	4.5	3.2	3.0	4.0	3.2	3.5	3.8	3.2
Iron (μg/L)	20	26	14	11	28	13	20	39	17	12	48	16
TP (μg/L)	2.1	1.7	3.2	5.4	1.9	3.7	2.4	3.1	3.9	2.6	2.6	4.4
TFP (µg/L)	1.3	0.8	2.1	5.1	0.7	1.8	4.2	1.0	2.1	1.8	1.5	2.0
FRP (μg/L)	1.8	0.6	1.6	2.0	0.7	1.4	4.1	0.6	1.7	1.9	1.2	1.7
TKN (μg/L)	31	41	66	34	48	54	36	51	55	34	50	73
Ammonia (μg/L)	<DL	2.6	7.9	<DL	6.8	9.6	<DL	2.0	5.3	<DL	2.1	6.1
Nitrate (μg/L)	4.3	4.5	14.3	<DL	31.4	<DL	<DL	<DL	5.1	<DL	<DL	<DL
Silica (μg/L)	1,955	1,902	1,750	2,000	2,284	1,865	1,948	1,925	1,755	2,020	2,000	1,812
Chl *a* (μg/L)	0.63	0.89	0.93	1.35	1.26	0.96	0.58	0.95	0.96	0.79	1.64	1.39
Phaeo *a* (μg/L)	0.06	0.13	0.12	0.03	0.16	0.13	0.07	0.20	0.22	0.14	0.37	0.30

DL indicates detection limits.

Table 13. Seasonal (May-September) concentrations of key limnological parameters on 57 clear-water Alaskan lakes containing sockeye salmon.

Parameter	(n)	Minimum	Maximum	Mean
Conductivity (μmhos/cm)	657	6	173	68
pH (units)	657	5.4	8.9	7.2
Alkalinity (mg/L)	658	1.5	85.0	21.6
Turbidity (NTU)	653	0.2	5.2	0.9
Color (Pt units)	642	2	27	8
Calcium (mg/L)	655	0.7	33.2	7.9
Magnesium (mg/L)	602	0.2	11.6	1.4
Iron (μg/L)	628	3	457	44
TP (μg/L)	652	1.0	36.6	6.8
TFP (μg/L)	642	0.1	23.1	3.7
FRP (μg/L)	647	0.2	21.3	2.5
TKN (μg/L)	659	11	431	105
Ammonia (μg/L)	598	1.0	118.1	8.4
Nitrate (μg/L)	613	1.0	634	99.7
Silica (μg/L)	642	4	6,809	1,722
Chl *a* (μg/L)	612	0.02	18.72	1.23
Phaeo *a* (μg/L)	610	0.01	10.07	0.60

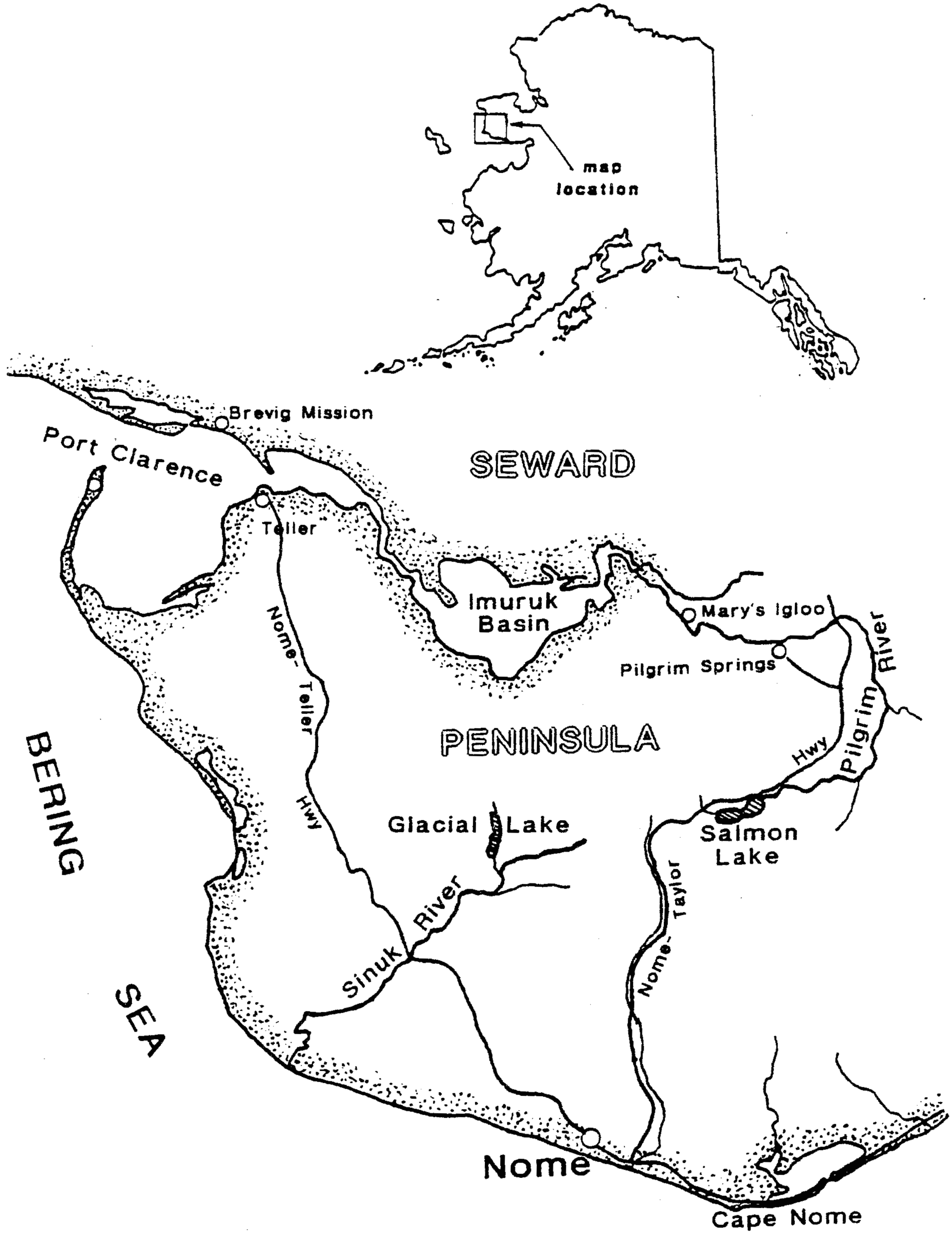

Figure 1. Map of the Nome area (Seward Peninsula) showing the location of Salmon and Glacial lakes, and the Pilgrim River.

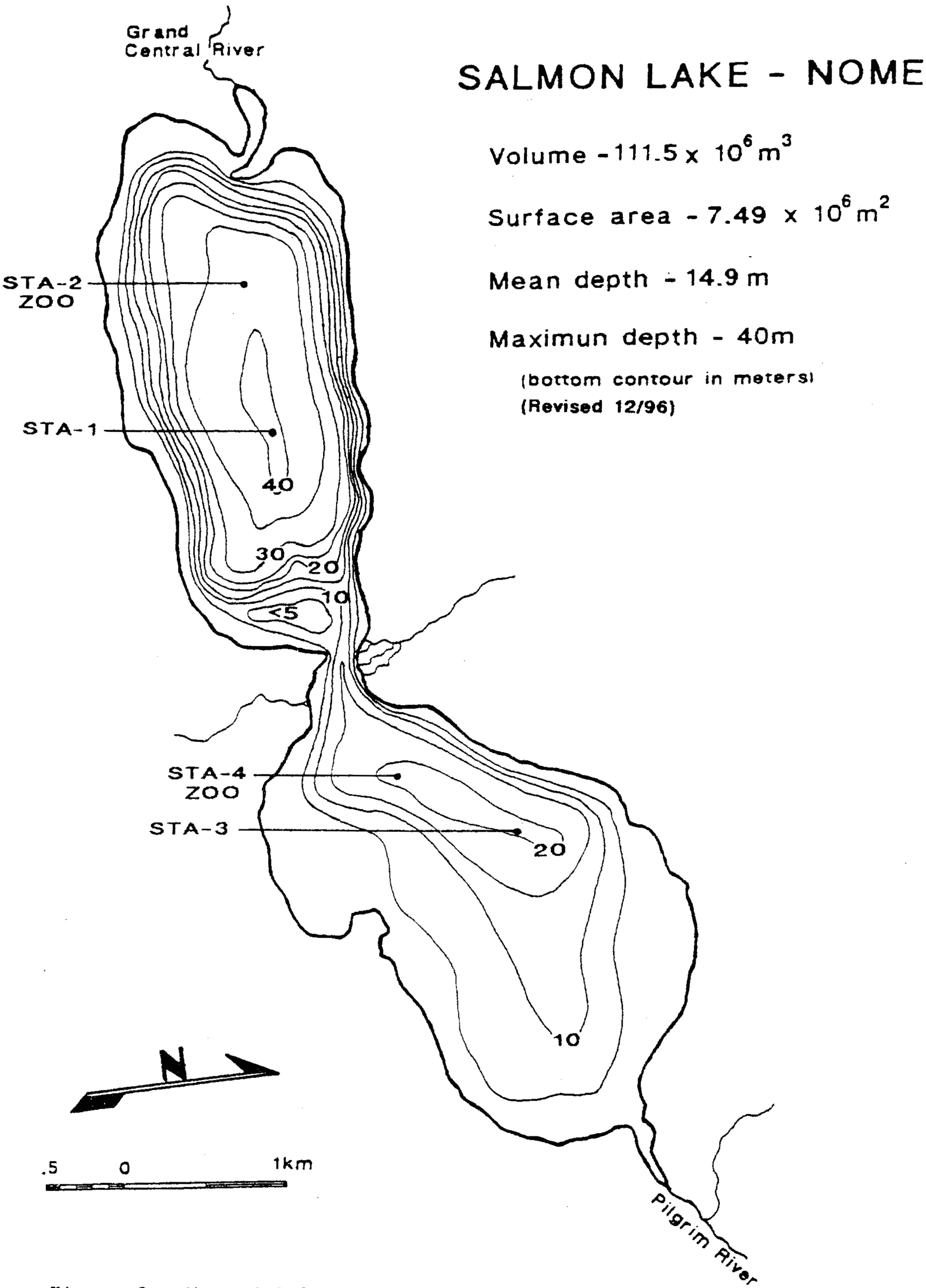

Figure 2. Map of Salmon Lake showing general morphmetric information, and the locations of the limnology survey stations.

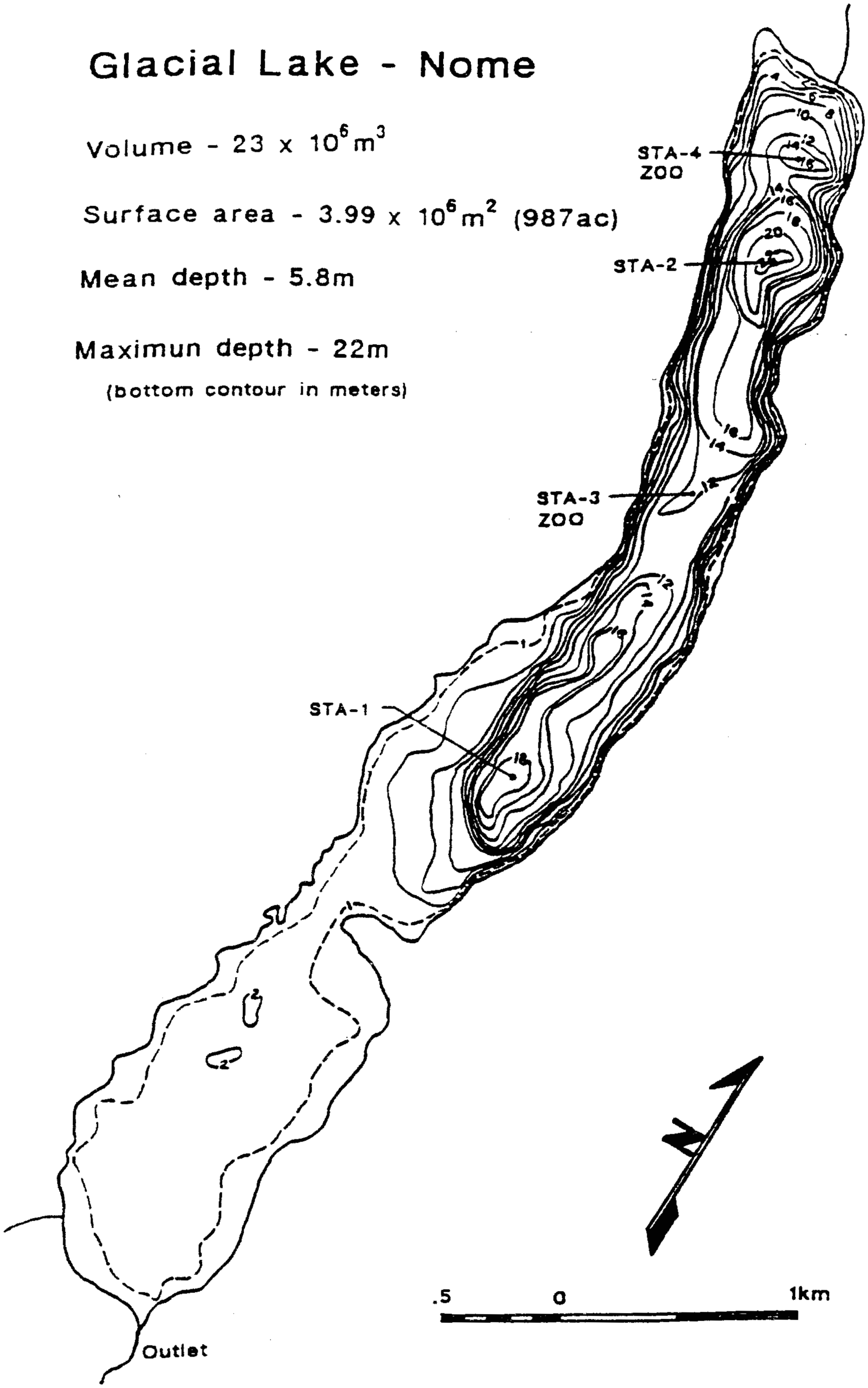

Figure 3. Map of Glacial Lake showing general morphometric information, and locations of the limnological survey stations.

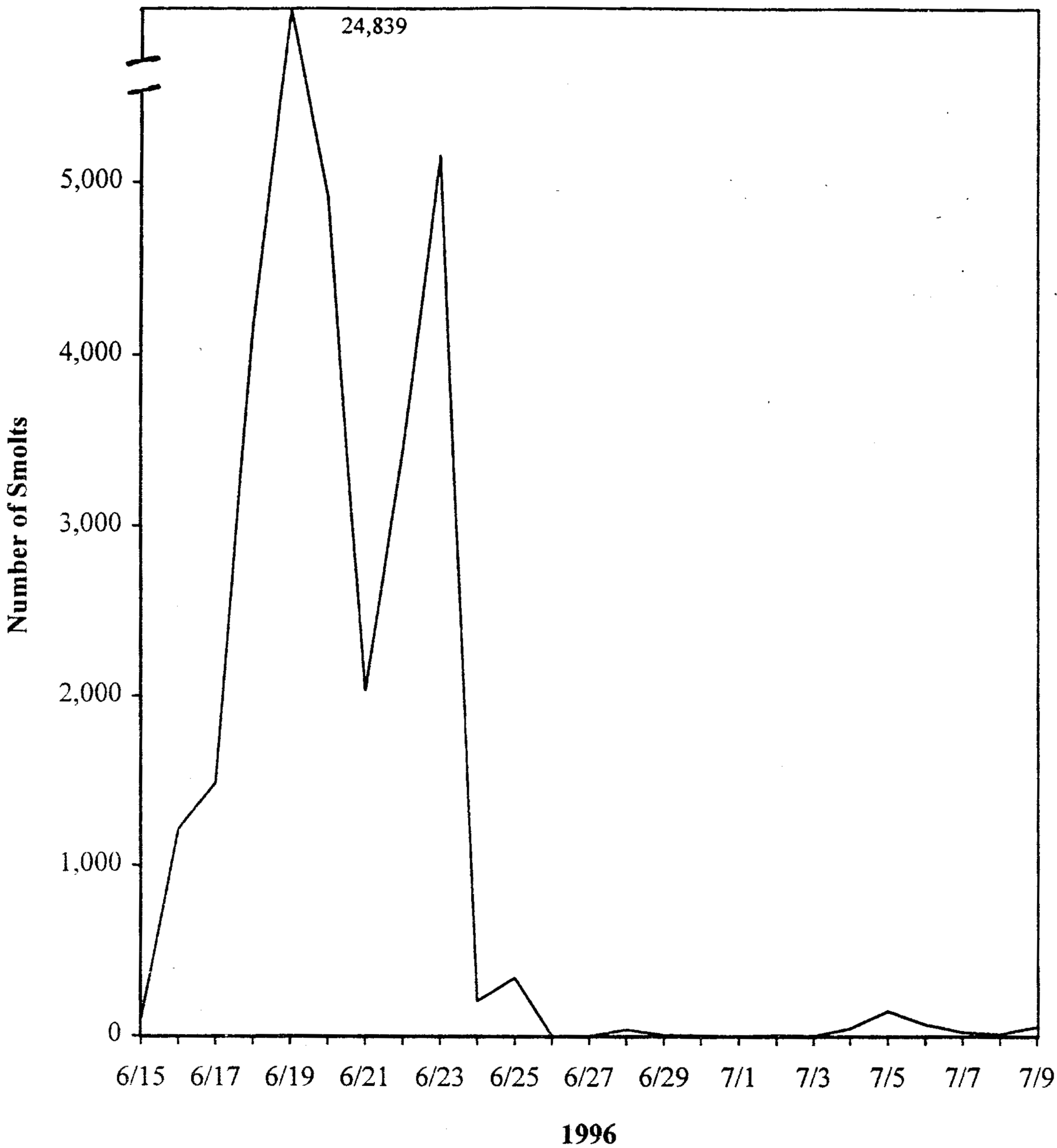

Figure 4. Migration timing for sockeye salmon smolts emigrating Glacial Lake, 1996.

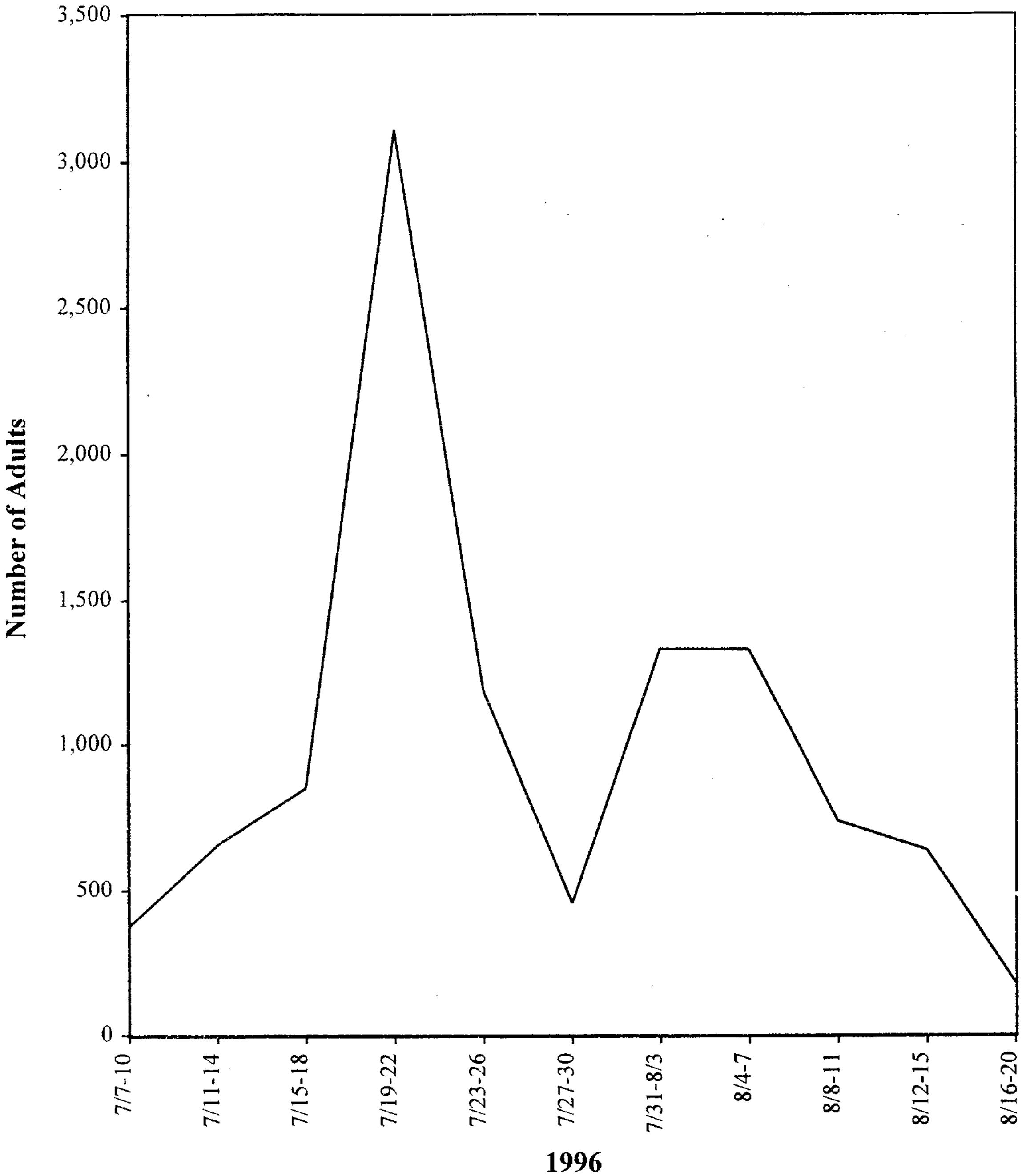

Figure 5. Migration timing for sockeye salmon adults entering Salmon Lake, 1996.

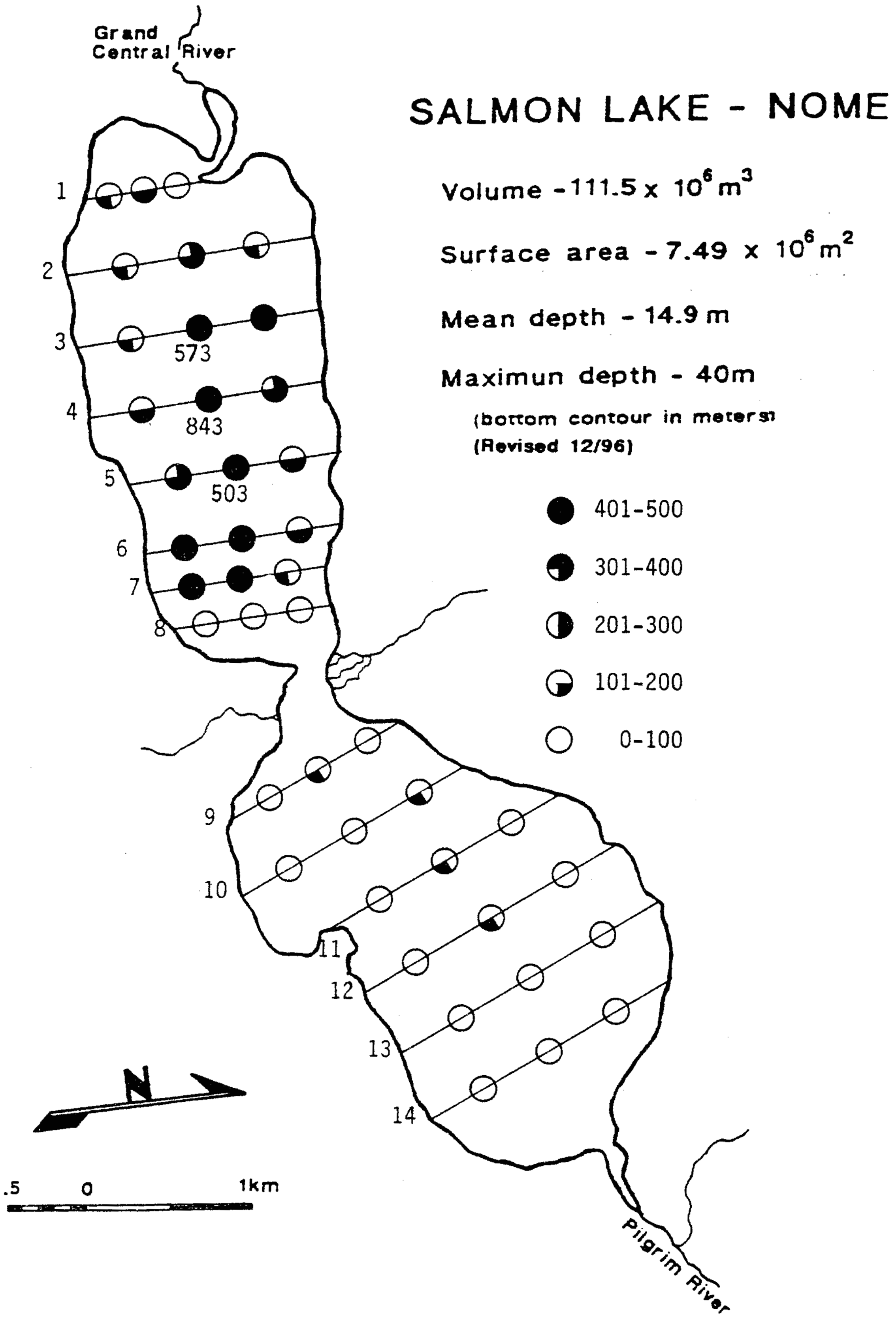

Figure 6. Map of Salmon Lake showing the distribution of rearing fish by density for the 6 September 1996 hydroacoustic survey.

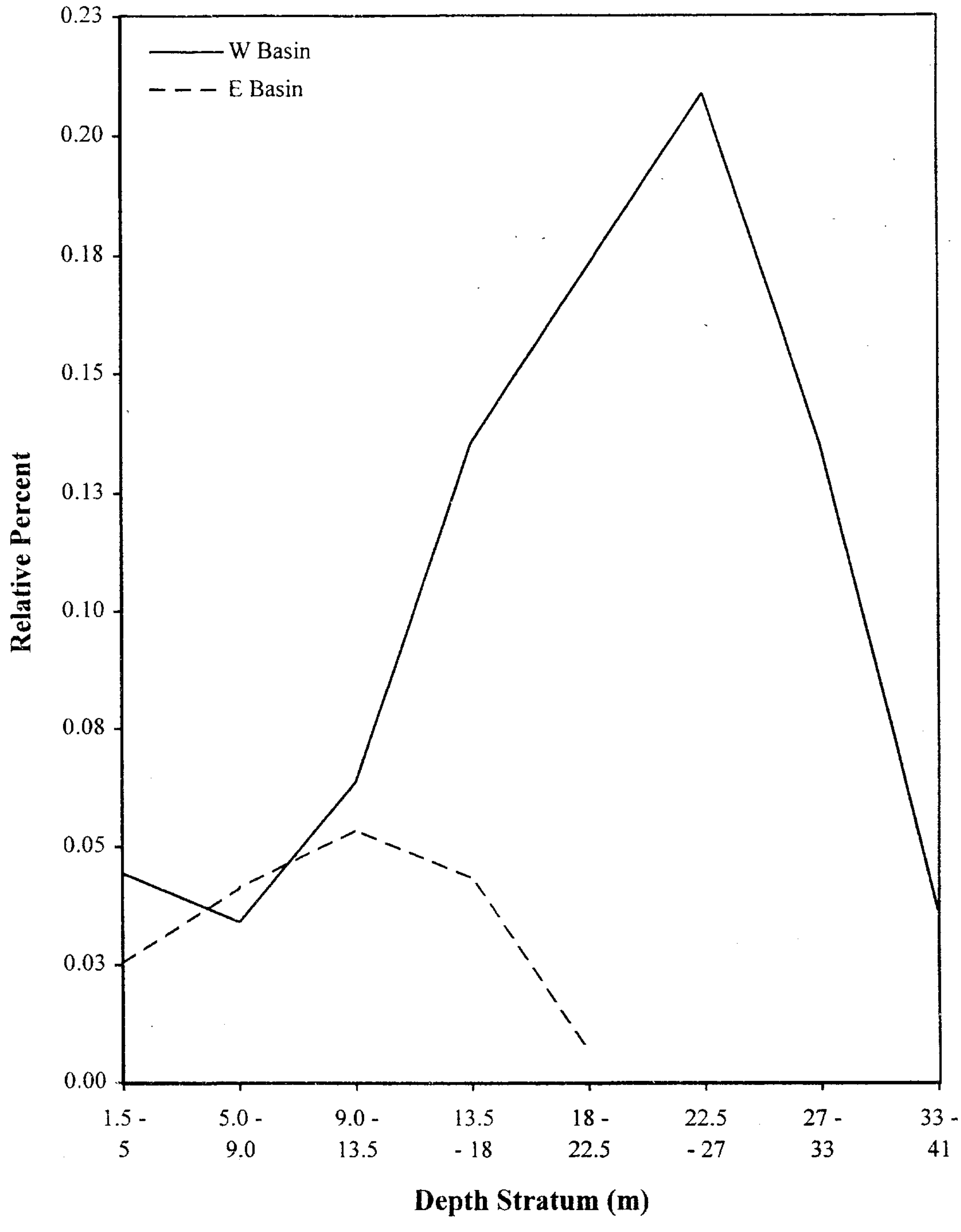

Figure 7. Relative percent of rearing fish by depth stratum in Salmon Lake based on the 6 September 1996 hydroacoustic survey.

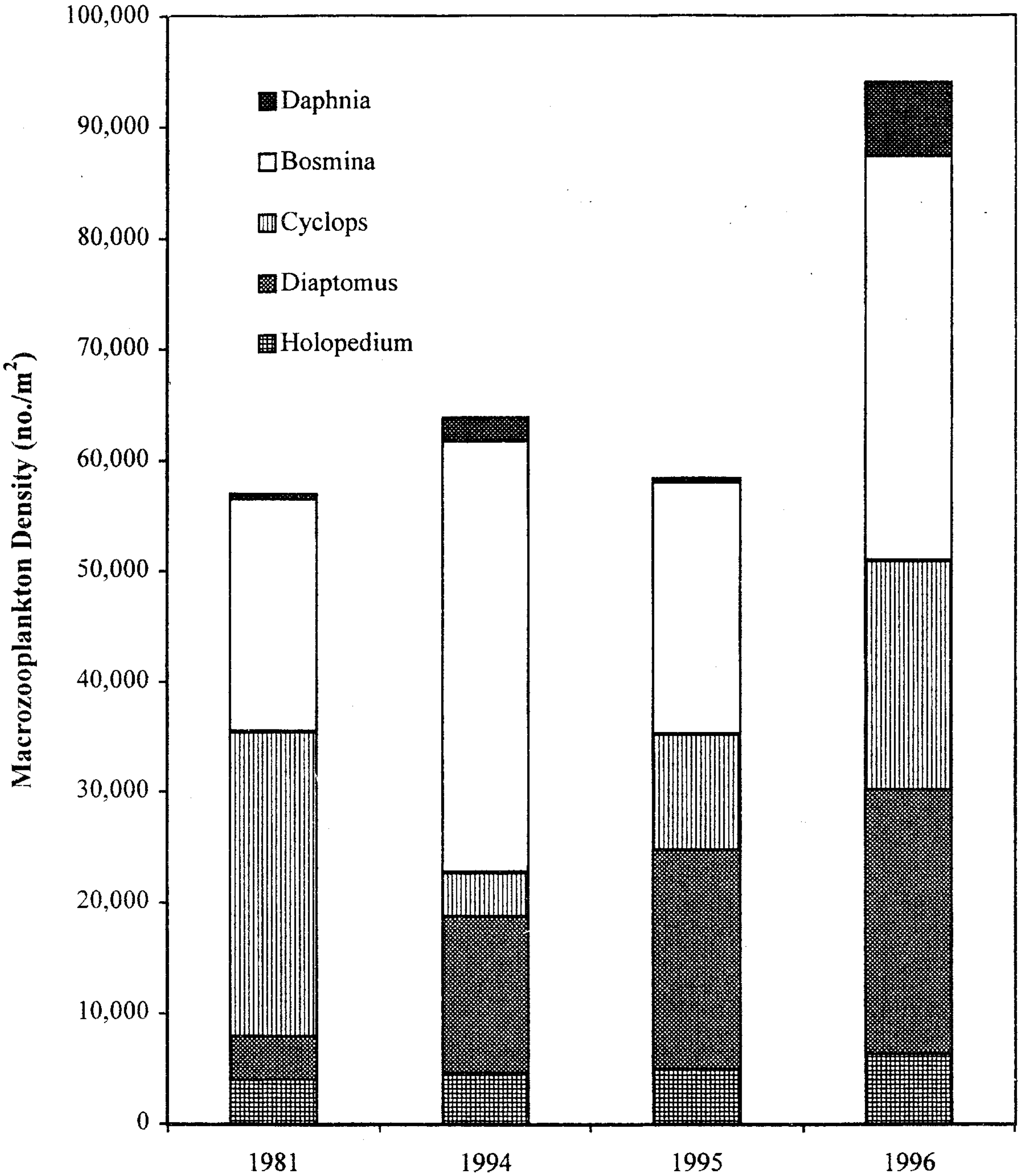

Figure 8. Macrozooplankton density in Glacial Lake by taxa for 1981, and 1994-1996.

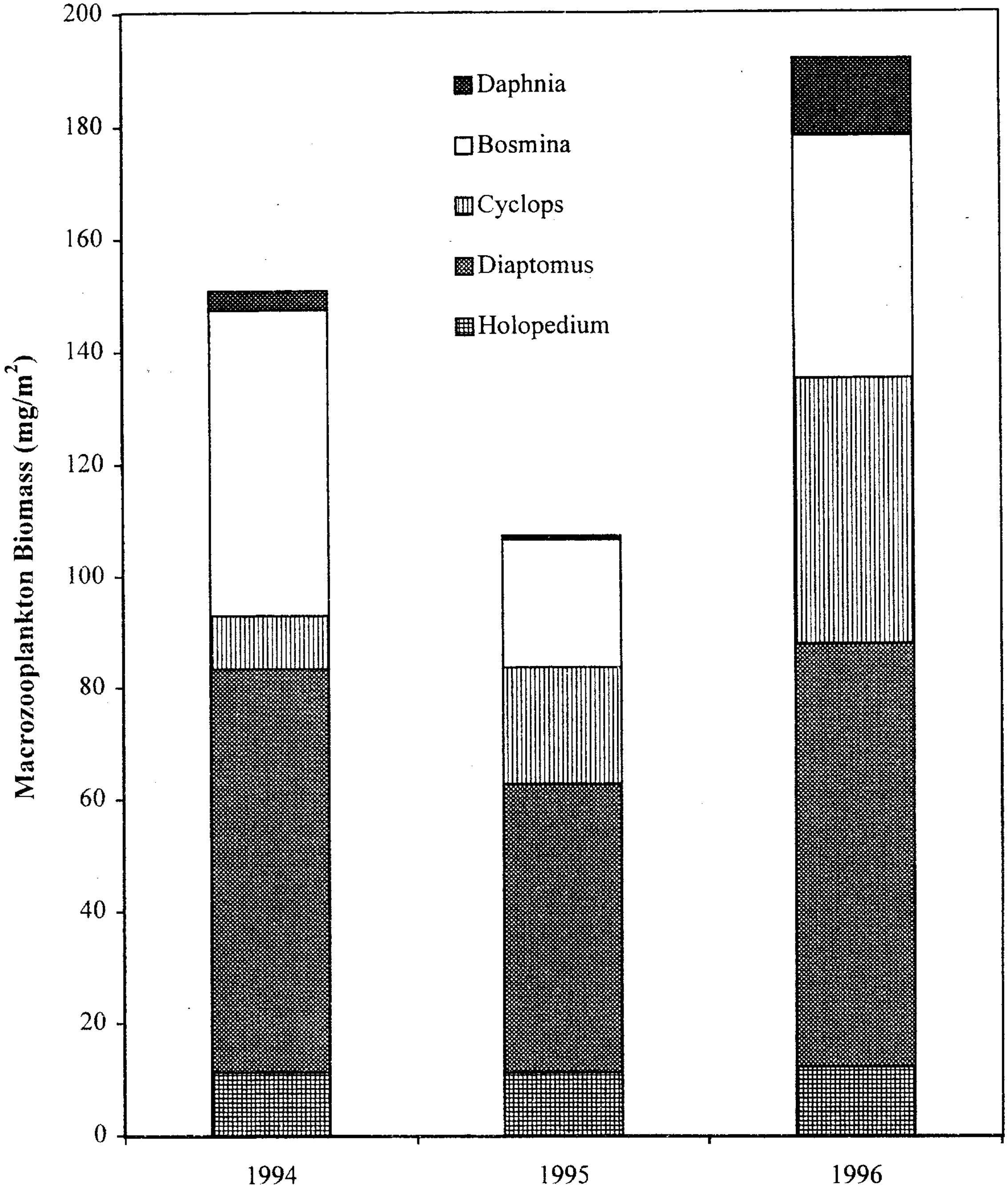

Figure 9. Macrozooplankton biomass in Glacial Lake by taxa, 1994-1996.

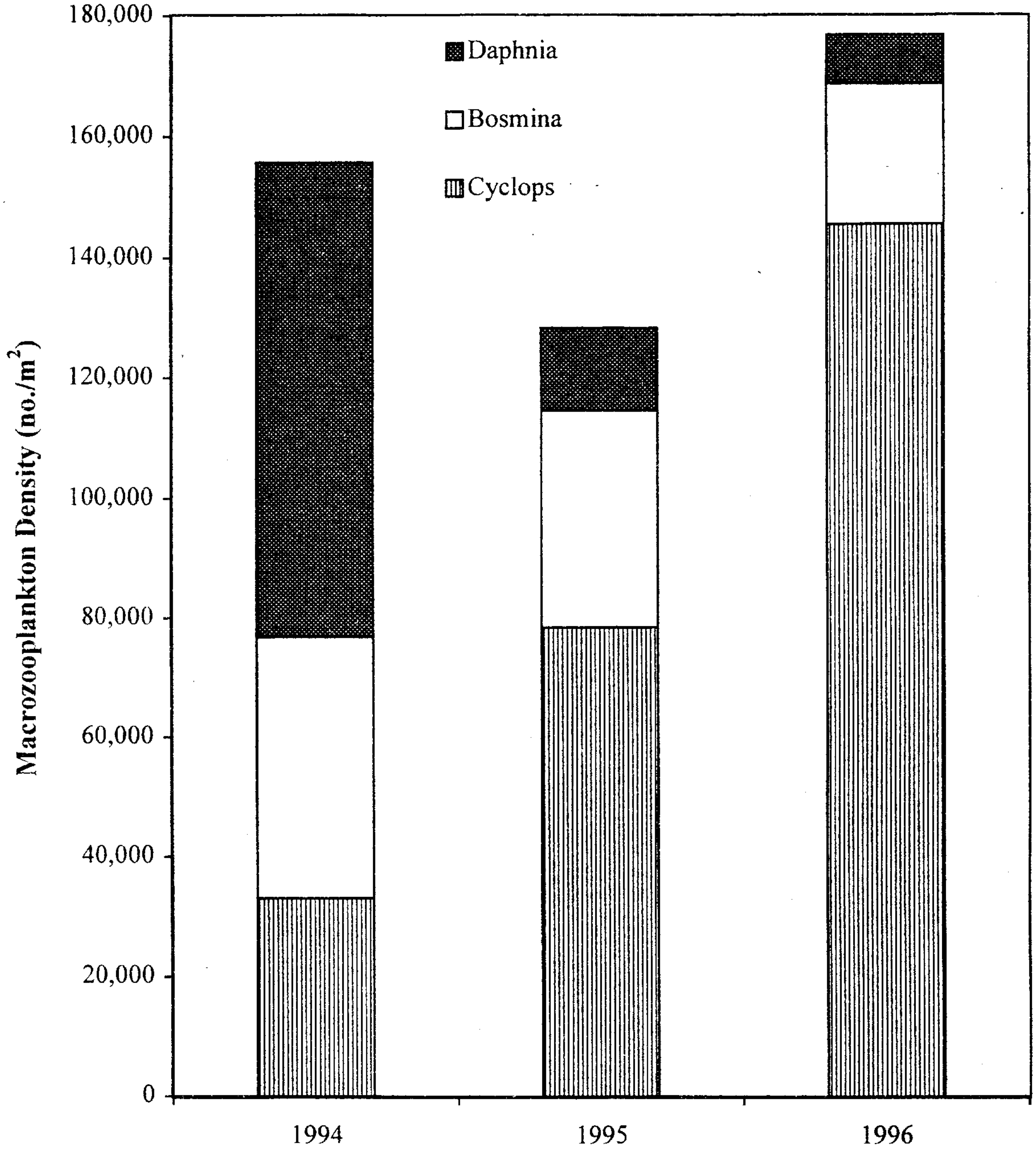

Figure 10. Macrozooplankton density in Salmon Lake by taxa, 1994-1996.

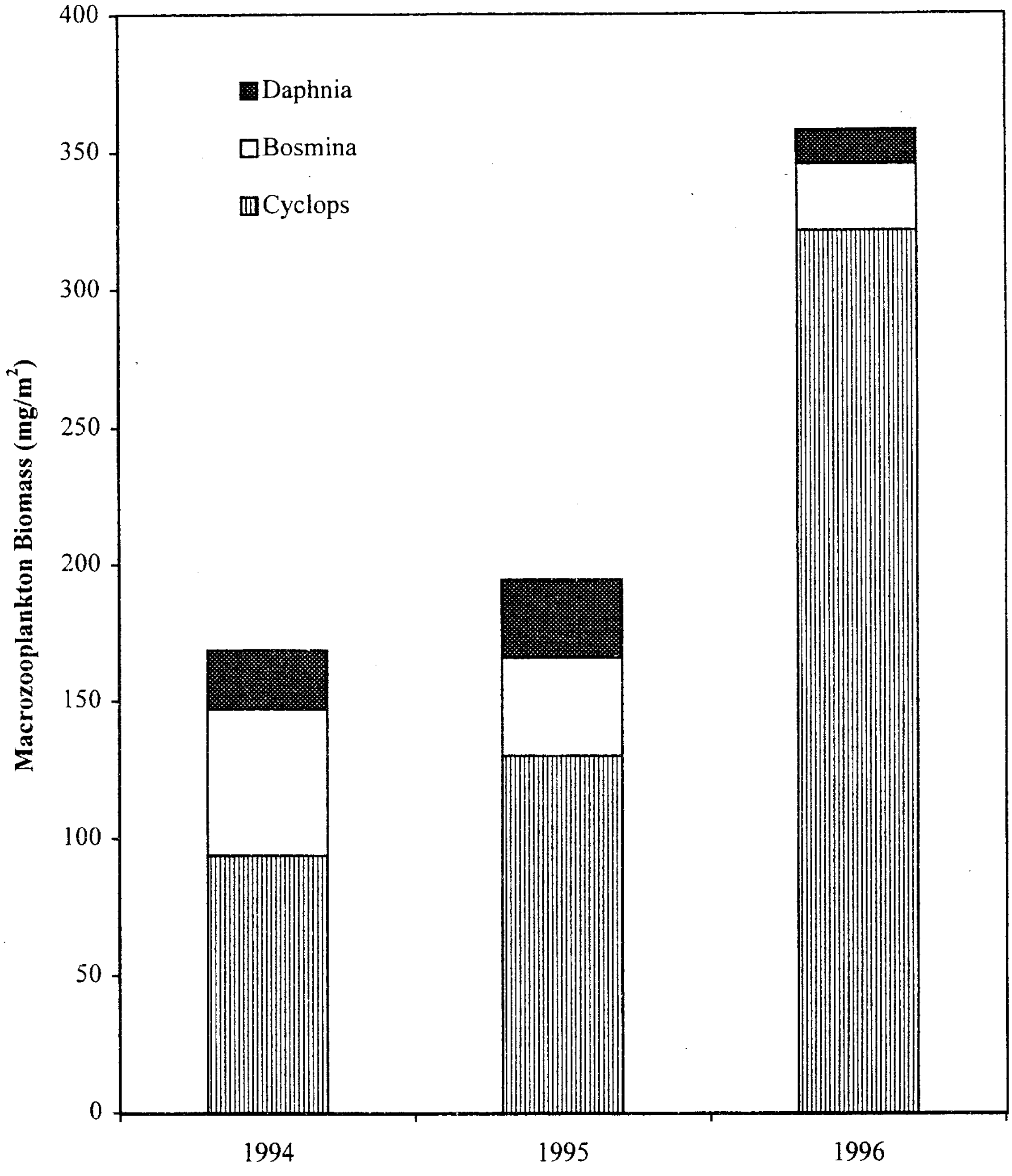

Figure 11. Macrozooplankton biomass in Salmon Lake by taxa, 1994-1996.

APPENDICES

Appendix A. Summary of seasonal mean zooplankton density, biomass, and size by taxa and year for Glacial Lake, 1994-1996.

		No. of	*Diaptomus*			*Cyclops*			*Bosmina*			*Daphnia*			*Holopedium*			Total	
Station	Year	sample dates	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)
1	1994	2	12,855	67	1.07	2,972	6	0.76	43,718	56	0.37	3,770	6	0.59	4,177	8.7	0.50	67,491	144
	1995	4	7,883	39	1.05	7,013	14	0.76	27,662	24	0.31	191	0.4	0.33	6,224	12	0.46	48,973	90
	1996	3	19,783	58	0.86	11,490	31	0.87	19,075	23	0.37	6,708	9	0.56	7,118	13	0.47	64,174	134
	Mean		13,507	55	0.99	7,159	17	0.80	30,151	35	0.35	3,556	5	0.49	5,840	11	0.47	60,213	123
2	1994	2	19,868	97	1.05	5,527	12	0.79	64,113	90	0.39	2,242	4	0.66	6,088	15	0.54	97,836	219
	1995	3	29,852	72	0.79	12,764	28	0.80	25,805	28.7	0.35	227	0	0.63	5,904	14	0.53	74,551	144
	1996	3	24,750	87	0.92	23,843	59	0.84	17,547	20	0.35	5,179	8	0.61	7,373	15	0.49	78,692	190
	Mean		49,720	169.7	1.84	9,146	20	0.79	44,959	59	0.37	1,234	2	0.64	5,996	15	0.53	86,194	181
3	1994	2	6,538	35	1.08	1,665	5	0.88	19,579	28	0.39	892	1.4	0.60	3,328	9	0.55	32,001	78
	1995	3	12,697	21	0.69	7,279	12	0.70	11,983	13	0.34	232	0.3	0.59	2,768	7	0.53	34,959	52
	1996	3	15,931	49	0.87	16,254	32	0.75	67,606	76	0.35	5,179	8	0.62	6,993	14	0.49	111,963	180
	Mean		19,235	55.8	1.77	4,472	8	0.79	15,781	20	0.37	562	1	0.60	3,048	8	0.54	33,480	65
4	1994	2	17,193	88	1.06	5,391	16	0.91	28,995	44	0.40	1,146	1.4	0.54	5,434	13	0.53	58,159	163
	1995	3	29,060	73	0.74	14,598	29	0.75	26,082	26	0.33	255	0.3	0.56	5,235	13	0.53	75,230	141
	1996	3	35,292	107	0.88	31,301	67	0.78	41,518	53	0.37	8,830	28	0.83	4,245	8	0.47	121,186	263
	Mean		46,253	161.7	1.81	9,994	22	0.83	27,538	35	0.37	700	1	0.55	5,335	13	0.53	66,694	152
All stations	1994	2	14,113	72	1.07	3,889	10	0.83	39,101	54	0.39	2,012	3.1	0.60	4,757	11	0.53	82,664	181
	1995	3	19,873	51	0.82	10,414	21	0.75	22,883	23	0.33	226	0.4	0.53	5,033	11	0.51	58,428	107
	1996	3	23,939	75	0.88	20,722	47	0.81	36,437	43	0.36	6,474	13	0.66	6,432	12	0.48	94,004	192
	Mean		19,308	66	0.92	11,675	26	0.80	32,807	40	0.36	2,904	6	0.59	5,407	12	0.51	78,365	160

Appendix B. Summary of seasonal mean zooplankton density, biomass, and size by taxa and year for Salmon Lake, 1994-1996.

		No. of	*Cyclops*			*Bosmina*			*Daphnia*			*Chydorinae*			Total	
Station	Year	sample dates	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)	Size (mm)	Density (no./m^2)	Biomass (mg/m^2)
1	1994	2	56,715	179	0.94	67,330	85	0.37	129,988	43	0.72				254,033	306
	1995	5	81,976	157	0.74	27,074	27	0.33	14,987	28	0.65				124,037	212
	1996	4	261,218	588	0.80	21,863	23	0.34	14,211	22	0.60				297,292	633
	Mean		133,303	308	0.82	38,755	45	0.35	53,062	31	0.65				225,120	384
2	1994	2	68,434	197	0.90	74,053	87	0.38	170,853	92	0.73				313,339	376
	1995	5	132,737	297	0.79	53,586	58	0.35	29,254	44	0.59				215,577	399
	1996	4	284,093	635	0.80	24,304	23	0.32	20,122	38	0.67				328,519	696
	Mean		161,754	376	0.83	50,647	56	0.35	73,410	58	0.66				285,811	490
3	1994	2	19,078	48	0.85	40,728	46	0.35	61,266	15	0.69				121,072	110
	1995	5	68,117	115	0.70	22,160	21	0.33	13,140	35	0.77				103,417	171
	1996	4	89,535	174	0.75	24,652	27	0.35	5,035	7	0.57	85	0.1	0.28	119,307	207
	Mean		58,910	112	0.76	29,180	31	0.34	26,480	19	0.68	85	0	0.28	114,599	163
4	1994	2	23,874	55	0.81	23,213	29	0.37	44,574	5	0.60				91,660	89
	1995	5	85,465	120	0.64	59,077	59	0.33	12,464	21	0.61				157,006	199
	1996	4	86,435	205	0.82	22,952	22	0.33	4,230	6	0.59	196	0.2	0.31	113,813	234
	Mean		65,258	127	0.76	35,080	37	0.34	20,423	11	0.60	196	0	0.31	120,826	174
All stations	1994	2	33,222	94	0.87	43,757	53	0.36	78,609	21	0.67				155,588	168
	1995	5	78,520	131	0.69	36,104	36	0.33	13,530	28	0.68				128,153	194
	1996	4	145,729	322	0.79	23,155	24	0.34	7,825	12	0.59	140	0	0.30	176,804	358
	Mean		85,824	182	0.78	34,339	38	0.34	33,322	20	0.64	140	0	0.30	153,515	240