A Limnology and Fisheries Investigation of Kanalku Lake

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Regional Information Report No. 5J96-18

Alaska Department of Fish and Game
Commercial Fisheries Management and Development Division
Juneau, Alaska

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ACKNOWLEDGMENTS

Without the cooperative funding provided by the U.S. Forest Service, Admiralty National Monument, this project would not have occurred. The authors also thank Mark Laker both for his support in the field and for his work on the administrative aspects of this project.

PROJECT SPONSORSHIP

Project funding was partially financed by the U.S. Forest Service, Admiralty National Monument, through a Challenge Cost-Share Agreement: ADF&G Coop-95-023; FS No. 94-03-04-39.

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ABSTRACT

A limnological study of Kanalku Lake was conducted for a 1-year period to assess the existing trophic status of this lake and to attempt to identify the potential and existing in-lake sockeye salmon *Oncorhynchus nerka* production using habitat-based models. This lake is an important nursery area for sockeye salmon on Admiralty Island and an important food source for subsistence fishermen from the community of Angoon.

The development of the euphotic volume (EV) model by Koenings and Burkett (1987) and the smolt biomass model by Koenings and Kyle (*in press*) have provided fisheries managers with a habitat-based tool for identifying potential sockeye production from Alaskan coastal lakes. The results of this study indicate that, although current zooplankton production is relatively high, Kanalku Lake is currently below its potential in-lake carrying capacity for sockeye salmon juveniles.

Calculated sockeye smolt production (based on fall acoustic surveys) from Kanalku Lake indicates this lake is currently producing ~0.083 x 10^6 smolts·year^{-1}. The EV and smolt biomass models predict this production should range from 0.380 to 0.306 x 10^6 smolts·year^{-1}. When compared to other sockeye salmon nursery lakes in Southeast Alaska, Kanalku Lake ranks relatively high in macrozooplankton abundance (102,427 organisms·m^{-2}) and biomass (372 mg·m^{-2}). Results indicate this lake could potentially increase its current level of sockeye production if additional fry were available to utilize the existing zooplankton food-forage resource.

INTRODUCTION

Kanalku Lake is the primary producer of sockeye salmon *Oncorhynchus nerka* in the Mitchell Bay area of Admiralty Island in Southeast Alaska. The sockeye salmon produced from this area are an extremely important food source to the subsistence fishermen from the community of Angoon. During the 1981–1986 period it was reported by George and Bosworth (1988) that this lake contributed 56% of the sockeye salmon subsistence harvest reported by residents of Angoon. An average of 435 sockeye·$year^{-1}$ (range 90–701) were harvested during this 6-year period.

Due to the small magnitude of the run size from Kanalku Lake, no commercial fishery is targeted on this stock. Based on aerial-survey methods, observed sockeye escapements to this lake averaged <300 fish·$year^{-1}$ during the 1960–1993 period. Any incidental commercial harvest would occur as bycatch in the Chatham Strait purse seine fisheries conducted along the shores of Admiralty and Chichagof Islands.

The purpose of this investigation was to evaluate rearing conditions for juvenile sockeye salmon relative to juvenile sockeye densities and to document the in-lake productivity of Kanalku Lake. Results will be used to determine the lake's rearing capacity for juvenile sockeye salmon and resulting adult production relative to the empirical sockeye production models developed by Koenings and Burkett (1987). The evaluation of the in-lake rearing potential will be used to identify potential management and/or enhancement strategies to optimize sockeye production.

This report summarizes a 1-year study conducted during 1995. It was a cooperative effort involving the Commercial Fisheries Management and Development (CFMD) Division of the Alaska Department of Fish and Game (ADF&G) and the U. S. Forest Service, Admiralty National Monument.

STUDY SITE

Kanalku Lake is located on the west side of Admiralty Island within the Alexander Archipelago of Southeast Alaska (Figure 1). Of the 5 species of Pacific salmon, 4 species rear in the lake's outlet stream. The harvest and utilization of fishery resources by subsistence, commercial, and sport fishermen make up the principal economy for the inhabitants of the area.

Kanalku Lake (57°29'14"N, 134°21'0"W) is a relatively small, stained lake with a mean depth of 15.0 m and a volume of 17.5 x 10^6 m^3 (Table 1, Figure 2). The outlet of this lake is located ~10 mi southeast of the community of Angoon and flows directly into Kanalku Bay. The lake drains into Kootznahoo Inlet via Kanalku and Mitchell Bays. The study site is located within the northern temperate old-growth rainforest that dominates the Pacific northwest coast of North America. The climate of this area is characterized by cold winters and cool, wet summers. Average precipitation for the study area is ~280 cm·$year^{-1}$ (Anonymous 1979). The forested watershed is dominated by Sitka spruce, western hemlock, and Sitka alder. Wild currants, devils club, and berries form a dense undergrowth thicket. Muskegs and clearings interrupt this dense forest canopy to admit light. Lake-resident fish include sockeye and coho salmon *O. kisutch*, Dolly Varden char *Salvelinus malma*, and sculpin *Cottus* sp. (Anonymous 1987).

MATERIALS AND METHODS

Field Surveys and Sampling

A bathymetric map was prepared for the project site using a Lowrance[1] model X-16 sonar unit with a strip chart recorder. A variable number of transects were run orthogonally across the lake to achieve representative sampling of the lake bottom.

Lake surface area (A_L) and drainage area (A_D) were computed from topographic maps using a polar planimeter. Using the bathymetric map, the area of component depth strata was determined with a polar planimeter, and total lake volume (V) was computed through summation of successive strata after Hutchinson (1957):

$$\text{Lake Strata Volume } (\upsilon_i) = \frac{h_i}{3}\left(A_i + L_i + \sqrt{A_i L_i}\right),$$

where

υ_i	=	volume of strata i,
A_i	=	area (m^2) of upper depth strata,
L_i	=	area (m^2) of lower depth strata, and
h_i	=	depth (m) difference of $L_i - A_i$;

and

$$\text{Total Lake Volume } (V) = \sum_{i=1}^{n} \upsilon,$$

where

n	=	number of depth strata.

Lake mean depth (Z) was calculated as:

$$Z = V/A_L,$$

where

Z	=	lake mean depth (m),
V	=	lake volume ($10^6\ m^3$), and
A_L	=	lake area ($10^6\ m^2$).

The theoretical water residence time (T_w) was then calculated as:

$$T_w(\text{year}) = V/\text{TLO},$$

[1] Mention of trade names is included for scientific completeness and does not imply endorsement by the author or the Alaska Department of Fish and Game.

where

V = total lake volume (10^6 m^3), and
TLO = total lake outflow (10^6 m^3).

The total lake outflow (TLO) was calculated as:

$$Q(\text{cfs}) = 0.0312\, P^{1.13} A_D^{1.03},$$

where

Q = mean annual stream flow (cfs),
P = mean precipitation (in), and
A_D = watershed area (mi^2).

Limnological data from each study site were collected and analyzed by the ADF&G, CFMD limnology section according to Koenings et al. (1987). Physical, chemical, and biological production data were collected at 2 permanent sampling sites within Kanalku Lake. Sampling occurred once each month during the ice-free (May–October) portion of 1995.

The collection of physical data included the measurement of lake temperatures, dissolved oxygen levels, conductivity, and light penetration at a permanent station located in the major lake basin. Lake temperature and dissolved oxygen profiles were measured using a Yellow Springs Instrument (YSI) model 57 meter. These recordings were taken at 1-m increments from the surface to the bottom. The algal light compensation point is defined as the depth at which 1% of the subsurface light (photosynthetically available radiation, 400–700 nm) penetrates (Schindler 1971): this point was measured using a Protomatic submersible photometer. Recordings were taken at several depths between the surface and the compensation depth. In addition, water transparency was estimated using a 20-cm Secchi disk.

Bulk (~5 L) water samples (for water quality and nutrient chemistries) were collected from 1 and 17 m to characterize the epilimnion and hypolimnion of the lake.

Primary production (algal standing crop) samples were collected from the permanent sampling site on the same interval as the water samples were collected for nutrient analysis. Samples were collected at 1 m, mid-euphotic zone, and at the compensation depth defined as the depth penetrated by 1% of subsurface sunlight.

Vertical zooplankton tows were collected from a standard depth of 50 m (if the lake depth was >50 m) or from a depth of 1 m less than the sampling-site depth from 2 sites within the lake. These tows were collected using a 0.5-m-diameter, 153-μ-mesh, 1:3 conical zooplankton net. The net was retrieved at a constant rate of ~1–1.5 m·sec^{-1}, rinsed with lake water to remove all organisms collected, and preserved in a solution of 10% neutralized formalin.

Juvenile sockeye salmon distribution and abundance within Kanalku Lake was estimated once in the fall during the study period using a BioSonics model 105 (420-kHz dual-beam transducer) hydroacoustic system. The sampling survey was conducted to coincide with the prewinter period (October). Data collection was accomplished using a downlooking transducer mounted in a towed body, ~1 m below the lake surface and suspended from the side of the boat. Signals were recorded on digital audiotape (DAT; BioSonics) format for analysis.

The monitoring and recording of calibration tones and fish signal targets was accomplished using a Leader (model LCD-100) oscilloscope, the audio DAT recording format, and a strip chart recorder calibrated to the sounding unit. Overall system gain of the echo sounder of the recorder was adjusted in the field to obtain optimal recording levels for the specific recording equipment. System gain and stability (calibration signals) were measured and recorded in the field immediately prior to and following each survey.

Sampling design for each survey was based on recording fish signals along a series of orthogonal transects across the lake. The location of sampling transects was based on a stratified random-sampling design. The lake was divided into sampling areas based on its size and basin configuration, and 1 transect within each area was then randomly selected. Transect sampling was conducted during the hours of complete darkness. A boat speed of ~1.5 m·sec^{-1} was used for sampling all transects.

Midwater townet (2 m x 2 m) sampling was used to verify hydroacoustic target signals and to determine fish species composition. Sampling occurred at the same time on the day immediately following the hydroacoustic survey. Townet sampling occurred in the pelagic areas along the longitudinal axis of the lake. Sampling depths were determined by using the target-signal densities observed during the hydroacoustic survey. Number and duration of townet samples were determined by relative fish densities and depth distributions. For this survey, replicate tows occurred at 5-, 10-, and 15-m depths.

Laboratory Analysis

Euphotic zone depth (EZD) is defined as the depth at which 1% of the subsurface light (photosynthetically available radiation 400–700 nm) penetrates (Schindler 1971). This value is equivalent to the Y-intercept determined by regressing depth against the natural logarithm of the percent subsurface light. The vertical extinction coefficient (K_d) was calculated as the reciprocal value of the regression slope.

Conductivities (temperature compensated to 25°C) were measured using a YSI model 32 conductance meter. Turbidities (NTU) were determined using a model DRT-100 laboratory turbidimeter. Water color was determined on filtered lake water by measuring the spectrophotometric absorbance at 400 nm and converting to platinum cobalt (Pt) units using a standard calibration curve (Koenings et al. 1987).

Calcium and magnesium concentrations were determined from separate EDTA (0.01 N) titrations after Golterman (1970). Total iron was analyzed by reduction of ferric iron with hydroxylamine after hydrochloric acid digestion using the Strickland and Parsons (1972) method.

Filterable reactive phosphorus (FRP) was determined using the molybdenum-blue method as modified by Eisenreich et al. (1975). Total phosphorus (TP) and total filterable phosphorus (TFP) utilized the same procedure following acid-persulfate digestion. Nitrate (NO_3) + nitrite (NO_2) was determined as nitrite following cadmium reduction of nitrate, and total ammonia was determined using the phenolhypochlorite procedure described by Stainton et al. (1977). Total Kjeldahl nitrogen (TKN) was determined as total ammonia following sulfuric acid block digestion (Crowther et al. 1980). Total nitrogen was reported as the sum of the TKN and NO_3 + NO_2 fraction. Reactive silicon was determined using ascorbic acid reduction to molybdenum-blue (Stainton et al. 1977), and alkalinities were determined by a sulfuric acid (0.02 N) titration to pH 4.5.

Estimates of yearly phosphorus loading were calculated after Vollenweider (1976):

Surface specific loading: $L_p(\text{mg P}\cdot\text{m}^{-2}\cdot\text{year}) = [\text{P}]_c^{sp}\cdot Q_s(1+z/Q_s)$

Surface critical loading: $L_c(\text{mg P}\cdot\text{m}^{-2}\cdot\text{year}) = 10\cdot Q_s(1+z/Q_s)$,

where

$[\text{P}]_c^{sp}$ = spring overturn period total P ($\text{mg}\cdot\text{m}^{-3}$),
Q_s = Z/T_w,
T_w = water residence time (years), and
Z = mean depth (m).

Chlorophyll *a* samples were prepared by filtering a known quantity of lake water through a Whatman 47-mm GF/F glass fiber filter using a vacuum pressure of <15 mm of mercury. Prior to the completion of the filtration; ~2 ml of 1 N magnesium carbonate was added to the filter. Filters were stored frozen in plexiglass petrislides until processed. Chlorophyll *a*, corrected for inactive phaeophytin *a*, was determined by the direct fluorometric method of Strickland and Parsons (1972) with a dilute acid-addition method developed by Reimann (1978).

Bosmina and *Daphnia* were identified from Brooks (1957) and Pennak (1978). Copepod zooplankters were identified from Wilson (1959) and Yeatman (1959). Zooplankters were enumerated from three 1-ml subsamples collected with a Hensen-Semple pipet and placed in a 1-ml Sedgewick-Rafter counting chamber. Average zooplankton body sizes were determined from measurements of 30 organisms of each species measured to the nearest 0.01 mm along a transect in each of the 1-ml subsamples using a calibrated ocular micrometer (Koenings et al. 1987). Biomass was determined from live-length-to-dry-weight regressions for individual macrozooplankters. The seasonal mean density and body size (numbers weighted length) was used to calculate the mean seasonal biomass for each species, which were then summed.

Fish collected from the townet samples were used to determine species, size, and age. Hydroacoustic survey tape analyses were performed by Dr. Richard Thorne of BioSonics, Inc. The analysis methods employed were duration-in-beam (Thorne 1988) or echo-integration counting techniques.

RESULTS AND DISCUSSION

Light Regimes and Heating and Cooling Cycles

The average euphotic zone depth (EZD) for Kanalku Lake was calculated to range from 10.8 m in the spring and fall to a 20.3-m maximum in mid summer (Table 3). The mean of 14.6 m for the year indicates that the majority of this lake is well within the euphotic zone. The shallower depths observed during the spring and fall were most likely caused by lake overturn periods and resulting phytoplankton blooms. Causes could also be related to turbidity brought on by normal storm events and resultant runoff.

The lake is probably ice-free by mid April or early May in most years. During 1995 the lake surface warmed rather quickly after ice-out (Figure 3). Lake surface temperatures were already at 11.1°C during the first sampling survey in early May. The water temperature cooled quickly with depth and reached a temperature of 7.8°C at a depth of 5 m. The May temperatures decreased gradually to a depth of 15 m where it remained constant at 4.0°C to the bottom of the lake. Lake temperatures were observed to increase gradually to form a stable thermocline during early July and August at a depth of ~5 to 7 m. A maximum surface temperature of 16°C was recorded during mid July. Surface temperatures remained relatively constant through August (14.5°C) and into mid September (14.4°C). However the thermocline had destabilized to a depth of 12 m by September. The observed temperatures in October indicated the lake cooled quickly, becoming isothermal at ~8.0°C.

A stable thermocline formed at a depth of ~5 to 7 m during the summer. The average light-compensation depth (14.6 m) indicated that autotrophic production was not limited to the epilimnion of the lake; it also occurred in the hypolimnion.

General Water Quality

Water-quality indicators were intermediate in relative magnitude compared to coastal Alaskan lakes, and levels were consistent throughout the sampling period. In addition, the observed levels indicated little variation relative to sampling periods or depths at each sampling site (Appendix A). Mean conductivity levels ranged from 120 to 128 μmohs·cm^{-1} (n = 6) within the epilimnion and from 119 to 121 μmohs·cm^{-1} (n = 6) within the hypolimnion during the sampling period. Similarly, alkalinity levels were high relative to coastal Alaskan lakes, as mean levels calculated to 58 ppm in the epilimnion compared to 54 ppm within the hypolimnion for the sampling year. Mean calcium and magnesium concentrations remained relatively constant over the study year, ranging from 20.2 to 18.9 ppm in the epilimnion and from 2.2 to 2.0 ppm in the hypolimnion. Iron (21 to 183 ppb), turbidity (<1.8 NTU units), and color (8 to 14 Pt units) were all within the range regarded as normal for oligotrophic, stained-water coastal lakes in Alaska. The pH levels were slightly acidic, ranging from 7.6 in the epilimnion to 7.1 in the hypolimnion.

Nutrient Concentrations and Atom Ratios

Seasonal nutrient concentrations (Appendix A) and cycles are of primary interest because they are responsible for powering the primary productivity of the lake system: they directly affect the conversion of available energy within the lake to rearing fish biomass. Alaskan sockeye nursery lakes are predominately oligotrophic (total phosphorus concentrations are generally 10–20 μg·L^{-1}) and can receive significant nutrient input from the decay of anadromous adult carcasses after spawning. Of primary importance to the lake are the concentrations of inorganic nitrogen (ammonium and NO_3 + NO_2), reactive silicon, reactive and total phosphorus, and the nitrogen:phosphorus ratio.

The mean values for inorganic nitrogen levels ranged from 129 ppb in the epilimnion to 184 ppb in the hypolimnion. The seasonal cycle suggests there is an adequate amount of inorganic nitrogen for algal photosynthesis, as the lake appears to recharge epilimnetic nitrogen at a rate sufficient to prevent a summer nitrogen depression. The mean reactive silicon (Si) levels are within the median range for coastal Alaskan lakes. The levels within the epilimnion (1,756–2,062 ppb) were slightly lower than levels observed within the hypolimnion (1,922–2,329), but were relatively constant. Average concentrations of filterable reactive phosphorus (FRP) were low at 0.9 ppb for the epilimnion to 2.9 ppb for the hypolimnion. Mean total phosphorus levels ranging between 1.9 (May) to 5.4 (August) ppb in the epilimnion and between 1.0 (July) to 4.6 (October) ppb within the hypolimnion are in the low range observed in Alaskan sockeye nursery lakes.

Algal Biomass (Chlorophyll a)

Changes in algal biomass in the lake was reflected by changes in the concentration of algal pigment chlorophyll *a* and phytoplankton population densities (Appendix A). The average chlorophyll *a* concentrations for Kanalku Lake ranged from 0.29 to 1.36 ppb at 1 m, 0.39 to 1.36 ppb within the mid-euphotic zone, and 0.50 to 1.20 at the 1% depth. Chlorophyll *a* levels were within levels expected for stained-water systems within Alaska.

Phytoplankton samples were collected at a depth of 1 m during the spring (May), summer (August), and fall (October) to characterize the seasonal species composition and relative densities. These results indicated the phytoplankton community is dominated by chrysophyceae and the general grouping of micro-algae.

Zooplankton Density, Body Size, and Biomass

The zooplankton community within Kanalku Lake was composed of 6 principal species of macro-zooplankton (Appendix C). The macrozooplankton were represented by 3 species of cladocerans, *Bosmina* sp., *Daphnia rosea, and Holopedium* sp., and 3 species of copepods, *Cyclops* sp., *Diaptomus* sp., *and Epischura* sp.

The macrozooplankton community abundance was dominated by the cladocerans throughout the sampling period. *Bosmina* sp. constituted 68% of the total community. The cladoceran portion of the community was 78.6% *Bosmina,* 16.7% *Daphnia,* and 4.7% *Holopedium.* The copepod portion of the community was 71.6% *Cyclops*, 13.7% *Diaptomus,* and 14.7% *Epischura.* Highest abundances for cladocerans were observed in July through September and during May through July for the copepods.

Due to the size of the individual organisms, the observed biomass of the community was highest for the copepods. Average size of the cladocerans ranged from 0.52 mm for *Bosmina* to 0.83 mm for *Daphnia* and 0.88 mm for *Holopedium.* The average size of the copepods ranged from 0.88 mm for *Cyclops* to 1.18 mm for *Diaptomus* and 1.41 mm for *Epischura.* The total seasonal macrozooplankton biomass average for 1995 was 372 $mg{\cdot}m^{-2}$.

Rearing Fish Densities, Sizes, and Species Composition

The total number of fish enumerated in the September hydroacoustic survey was 127,377 fish (Appendix C). Sockeye salmon fry composed the majority (93.3%) of the rearing fish population during the fall survey period. In addition, a small percentage of sculpin (6.7%) were sampled during the survey. Only sockeye salmon fry and sculpin were collected during the 1995 townet sampling.

Townet sampling collected a total of 42 sockeye fry and 3 sculpins. The majority of the sockeye fry were collected from the 10- and 15-m sample depths. This sampling coincided with the depth of largest concentration of fish observed during the acoustic survey. Therefore, these fry compose >93% of the total rearing fish population within the lake.

Nutrient Loading Characteristics

The productive capacity of lakes is determined by edaphic, morphometric, and climatic factors linked to the cycling of carbon, nitrogen, phosphorus, and silica within the lake environment. In 1979 ADF&G established guidelines for initiating lake enrichment projects to rehabilitate depressed indigenous populations of sockeye salmon throughout the lake. This enhancement/rehabilitation technique was designed to supply the lake with an artificial source of nutrients necessary to the lake at critical periods to increase the production of rearing fish food organisms. This program resulted in the development of 17 lake enrichment projects statewide. Of these, 7 projects were developed in Southeast.

These guidelines established selection criteria that would be used to evaluate the potential benefits that would be derived to fish (sockeye salmon) production from any artificial application of nutrients to the lake. Based on the morphometric features, current zooplankton production, and nutrient loading rates, this lake would not be a good candidate for nutrient additions. The existing nutrient concentrations and calculated phosphorus loading rates for Kanalku Lake (Appendix A, Table 4) are extremely low, but zooplankton production (Table 6) ranks high relative to other sockeye nursery lakes in Southeast Alaska. In comparison to other lakes in Southeast (table 4), Kanalku Lake ranks at the bottom of the list relative to its observed phosphorus loading characteristics. This is due primarily to low phosphorus concentrations, shallow mean lake depth, and rapid lake flushing rate.

The mean depth (15.0 m) of this lake is approximately equal to the average euphotic depth (14.6 m). Although light would not be a limiting factor in this lake, it could cause stimulation of rooted aquatic vegetation and periphyton with any increase in available nutrients. The morphometry of this lake basin (Table 2) indicates that 62% of the lake bottom is presently within the euphotic zone and approximately equal to the mean depth of the lake.

Adult Sockeye Escapements, Harvest Rates, and Production Estimates

Adult sockeye salmon escapement data for Kanalku Lake is limited to aerial surveys conducted by ADF&G commercial fisheries management staff (1960–present). Harvest data is limited to the reported subsistence fishery data for the community of Angoon (Table 5).

Aerial-escapement surveys indicate the average observed escapement to Kanalku Lake for the 1960–1993 period was <300 fish (ADF&G, CFMD personal communication). The subsistence harvest data also indicate that ~450 fish·year^{-1} (George and Bosworth 1988) were harvested by local residents. Therefore, since the aerial-survey method is generally assumed to underestimate escapements for sockeye salmon in lake systems, total sockeye production from this lake can safely be assumed to be at least twice the number observed (escapement + harvest), or ~1,500 fish·year^{-1}.

Aerial surveys are generally a reliable method for estimating run timing and spawning activity. For Kanalku Lake, aerial-survey data indicate that adults begin entering the lake outlet stream in June. Sockeye salmon in Kanalku Lake are consistently observed spawning near the beaches and in the lake inlet stream during the months of August through September.

The purpose of this study was to examine and document Kanalku Lake's existing physical, chemical, and biological production characteristics leading to the production of sockeye salmon. Once the cycles are coupled, the information can be used to determine if the observed levels of sockeye fry and smolt production are equal to the lake's carrying capacity as modeled by Koenings and Burkett (1987). This model is based on the linkage between the differential fertility of oligotrophic sockeye nursery lakes within Alaska and the production of sockeye smolts and adults. The production of fry, smolts, and adults are highly correlated to units of euphotic volume (EV), an index of areal primary production potential within the trophogenic zone.

The seasonal mean euphotic zone depth (EZD) is 14.6 m for Kanalku Lake (Table 3). This average depth translates into a euphotic volume (EV) of 16.5 million m^3 (EV units). Based on these data, it is possible to calculate potential fall fry, smolt, and adult production capacities for the lake when the rearing environment is limiting production; that is, when sufficient numbers of spring fry are available to fully utilize the rearing environment (Table 5). Comparing these data to the expected capacities calculated by the model, the existing production of sockeye salmon at each life stage was evaluated.

Evaluation of the Sockeye Rearing Capacity of Kanalku Lake

The early fall hydroacoustic survey at Kanalku Lake resulted in an estimate of the rearing juvenile sockeye population (Table 5, Appendix C). This population estimate, combined with overwinter survival rates (fall fry to smolt) observed by Kyle (1990), can be used to calculate an existing smolt production estimate for this lake. These observations, coupled with threshold smolt size ranges and smolt-to-adult survival rates that are based on smolt size (Koenings and Burkett 1987), allowed an adult sockeye production estimate to be calculated. When the observed adult production levels are compared to the adult production calculated from hydroacoustically enumerated fall fry, the actual production for Kanalku Lake appears to be dramatically lower than the calculated value (Table 5). In addition, the calculated production value is also dramatically lower than the production potentials based on EV units.

Recent research (Koenings and Kyle *in press*) has indicated that an estimate of the biomass (kg) of zooplankton on a seasonal basis allows comparison to the biomass (kg) of sockeye salmon produced on an annual or seasonal basis. This approach is similar to the method developed to estimate smolt production numbers based on EV units. That is, the production potential of the entire lake is estimated and then linked to the production of sockeye smolts when the lake is at or approaching rearing capacity. Using zooplankton biomass, the concept is that the standing crop of zooplankton estimated from the seasonal sampling represents the amount of zooplankton biomass remaining after cropping by sockeye juveniles. Cropping by foraging sockeye salmon removes a portion (not measured) of the annual zooplankton production, which is assumed to be proportional to the measured standing crop. Thus, nursery lakes producing sockeye smolts of threshold size (63 mm, 2.0 g) support the growth of juvenile sockeye salmon from the annual production (renewal) of the zooplankton community. This zooplankton standing crop represents a dynamic equilibrium between lake productivity (supply) and magnitude of predation (demand) by rearing juveniles.

A comparison of the observed seasonal (May–October) mean zooplankton biomass values for a group of Alaskan lakes (Table 6) indicates the relative production level for Kanalku Lake (372 $mg \cdot m^{-2}$) as it relates to sockeye salmon nursery lakes throughout Southeast Alaska. Comparing smolt production estimates by the 3 previously described methods (Table 5) allows us to predict the sockeye production potential for Kanalku Lake. Based on the current productivity of this lake, the general conclusion is that the rearing area for juvenile sockeye salmon is being underutilized. The smolt production capacity of Kanalku Lake, based on both the measured zooplankton biomass and EV is far greater than that calculated from the enumerated fall fry population. Thus, the existing carrying capacity of the lake is being vastly underutilized by juvenile sockeye salmon.

RECOMMENDATIONS

Based on the observed zooplankton abundance and biomass of Kanalku Lake, sockeye production is likely limited by a small adult escapement. The relatively high concentration of zooplankton and low rearing juvenile sockeye population indicates the lake rearing area is currently underutilized due to low fry recruitment. Based on this, we recommend the following:

1. By using adult sockeye salmon within the lake as a brood source for eggs, initiate a sockeye fry-stocking project of sufficient magnitude to utilize the abundant zooplankton food source and rearing area.

2. Prior to any fry-stocking activities, a project should be initiated to collect accurate smolt production and adult escapement information.

3. Any fry-stocking enhancement project should be designed to effectively monitor any in-lake effects of fry additions on zooplankton productivity and smolt production.

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Table 1. Physical characteristics of Kanalku Lake.

Lake Area: 113.1 ha	Watershed Area: 3,165 ha
Maximum Depth: 22.0 m	Mean Depth: 15.0 m
Lake Volume: 17.5 x 10^6 m^3	Volume Development: 2.05
Shoreline Length: 5,786.0 m	Shoreline Development: 1.43
Lake Elevation: 27.5 m	

Table 2. Morphometry of Kanalku Lake.

Area by Depth Zone:

Depth Zone (m)	Area (m^2)	Percent of Surface Area
0	1,131,000	100.0
5	1,105,902	97.8
10	961,475	85.0
15	704,507	62.3
20	288,280	25.5

Lake Surface Area: 113.1 ha

Volume by Depth Zone:

Depth Zone (m)	Volume (m^3)	Percent of Total Volume
0–5	5,592,139	32.0
5–10	5,164,235	29.5
10–15	4,148,340	23.7
15–20	2,405,745	13.7
20–22	192,187	1.1

Lake Volume: 17.5 x 10^6 m^3

Table 3. Light-penetration data obtained from Kanalku Lake at sampling site #1, indicating the euphotic zone depth, vertical extinction coefficient (K_d), and Secchi disk depth by sample date, 1995.

Date	Euphotic Zone Depth (m)	Vertical Extinction Coefficient ($\cdot m^{-1}$)	Secchi Disk Depth (m)
5/10	10.8	0.42	6.8
6/15	15.9	0.29	9.8
7/14	20.3	0.23	10.0
8/15	16.3	0.28	8.5
9/15	13.3	0.34	7.8
10/20	10.8	0.42	4.4
Mean	14.6		7.9

Table 4. Comparison of spring phosphorus loading characteristics for Kanalku Lake to clear, stained (*), and glacial (**) sockeye salmon nursery lakes throughout Southeast Alaska.

Lake	Sampling Year(s)	Mean Depth (Z) (m)	Water Residence Time (T_w) (years)	Spring Total Phosphorus (TP_{sp}) ($\mu g \cdot L^{-1}$)	Surface Specific Loading (L_p) ($mg\ P \cdot m^{-2} \cdot year^{-1}$)	Surface Critical Loading (L_c) ($mg\ P \cdot m^{-2} \cdot year^{-1}$)	Spring Phosphorus Loading (L_p/L_c) (%)
Auke *	86, 90, 92	19.0	3.52	9.3	145	156	93
Tumakof	80	51.0	1.32	7.4	574	772	74
Speel *	90, 92	3.0	0.07	7.2	382	531	72
Chilkoot **	87–91	54.5	0.57	7.1	1,189	1,670	71
Chilkat	87–91	32.5	4.55	6.2	140	224	62
Hugh Smith *	80, 85	60.7	0.93	4.8	611	1,278	48
Sitkoh *	92	19.9	0.64	4.4	244	561	44
Hetta	79	48.0	1.38	4.3	326	757	43
Falls *	80	31.9	0.49	4.0	446	1,116	40
Situk *	88	14.0	0.74	4.0	140	353	40
Benzemen	81	89.0	1.64	3.4	423	1,233	34
Kook *	92, 94, 95	30.0	0.70	3.4	277	787	34
Crescent	80	30.5	0.18	3.2	767	2,396	32
McDonald *	81	45.6	0.84	2.9	299	1,038	29
Redoubt [a] *	80, 82, 83	94.9	3.28	2.5	203	814	25
Politofski	80	23.2	0.22	2.5	389	1,558	25
Mountain	88	23.0	0.48	1.8	145	805	18
Kanalku *	95	15.0	0.24	1.8	166	947	18

[a] Mean depth (Z) and water residence time (T_w) values reflect only the mixolimnion portion of this lake.

Table 5. Comparison of observed fish production and potential production based on the euphotic volume (EV) and zooplankton biomass models as applied to Kanalku Lake.

		Potential Production	
Life Stage	Observed	EV Model	Zooplankton Biomass Model
Spring Fry	—	1.82×10^6	—
Fall Fry	118,843	544,500	—
Smolts	(83,190) [a]	379,790	305,987
Adults	721 [b] (9,733) [c]	41,282	—

[a] Calculated value based on the observed fall fry estimate and fry-smolt survival study by Kyle (1989).

[b] Average escapements based on aerial surveys of the lake outlet stream, 1960–1993 (286 sockeye·year^{-1}) and the reported subsistence harvest, 1981–1986 (435 sockeye·year^{-1}).

[c] Calculated value based on threshold-size smolt-adult survival (11.7%) from the study by Koenings and Burkett (1987).

Table 6. Comparison of seasonal mean (April–November) macrozooplankton density and biomass for Kanalku Lake to clear, stained (*), and glacial (**) sockeye salmon nursery lakes throughout Southeast Alaska. Bold type indicates years of fertilizer application.

		Macrozooplankton (number-weighted seasonal means)	
Lake	Years Sampled	Density ($No \cdot m^{-2}$)	Biomass ($mg \cdot m^{-2}$)
Tumakof *	80	614,559	1,519
Chilkat	87–91, 94	567,899	1,333
Hugh Smith *	85–87, 93, 94	291,029	573
Hugh Smith *	**80–84**	**316,363**	**530**
Auke *	86, 89–94	146,849	424
Kanalku *	95	102,427	372
Virginia	89–90	38,102	79
Virginia	**91–92**	**161,498**	**322**
McDonald *	80–81	79,345	219
McDonald *	**82–94**	**95,776**	**323**
Sitkoh *	92	108,877	291
Kook *	92, 94, 95	76,218	246
Redoubt *	80–83	74,363	90
Redoubt *	**84–87, 90–94**	**105,867**	**130**
Chilkoot **	87–91	72,704	126
Mountain	87, 88	111,711	115
Situk *	87–89	104,732	95
Crescent	80–81, 87–92	46,598	74
Benzemen	81	50,067	71
Falls *	81–82	21,587	54
Falls *	**83–85**	**25,847**	**59**
Speel *	89–92	64,380	58
Politofski	80	17,967	39

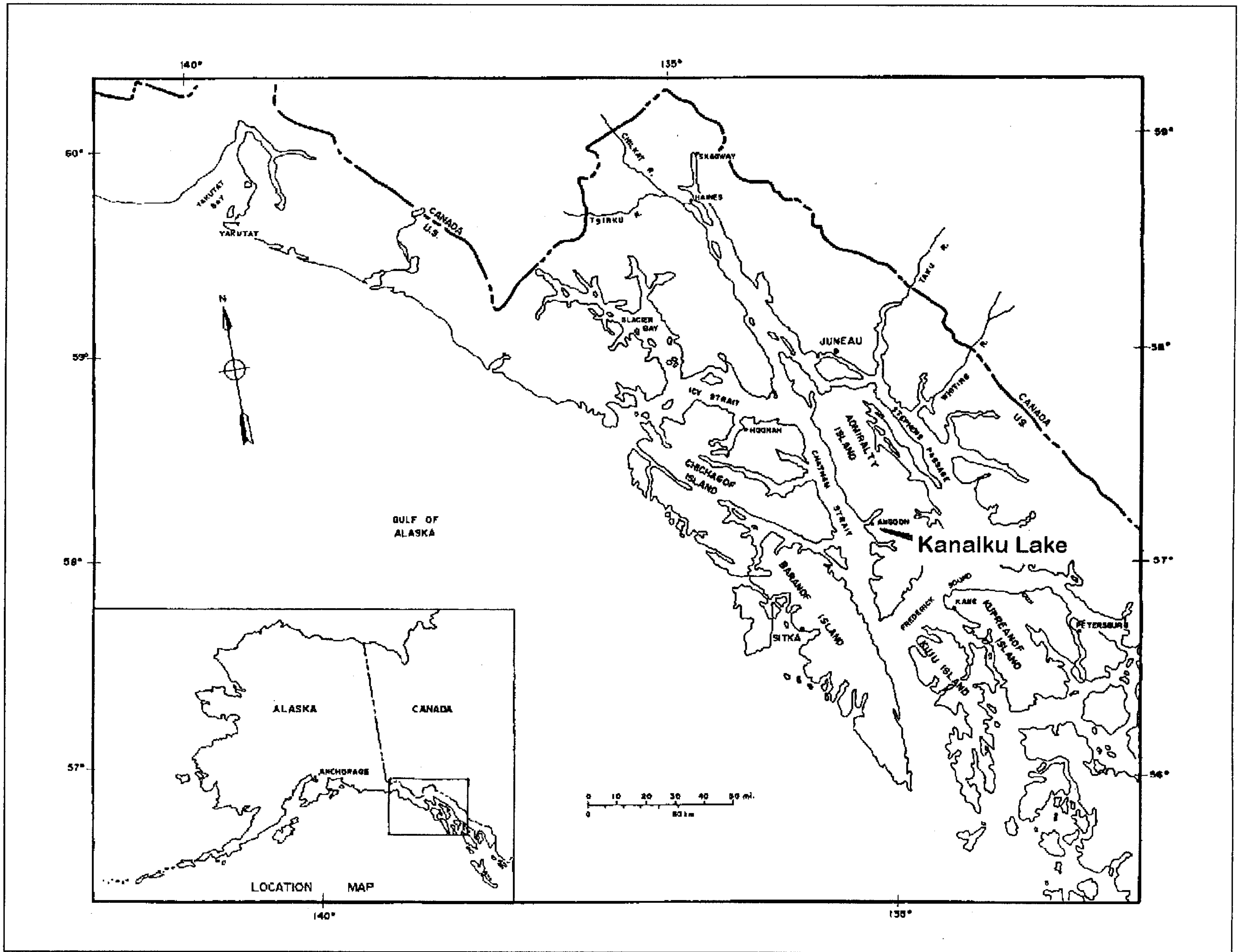


Figure 1. The geographic location of Kanalku Lake within the state of Alaska and relative to the Southeast communities of Angoon and Juneau.

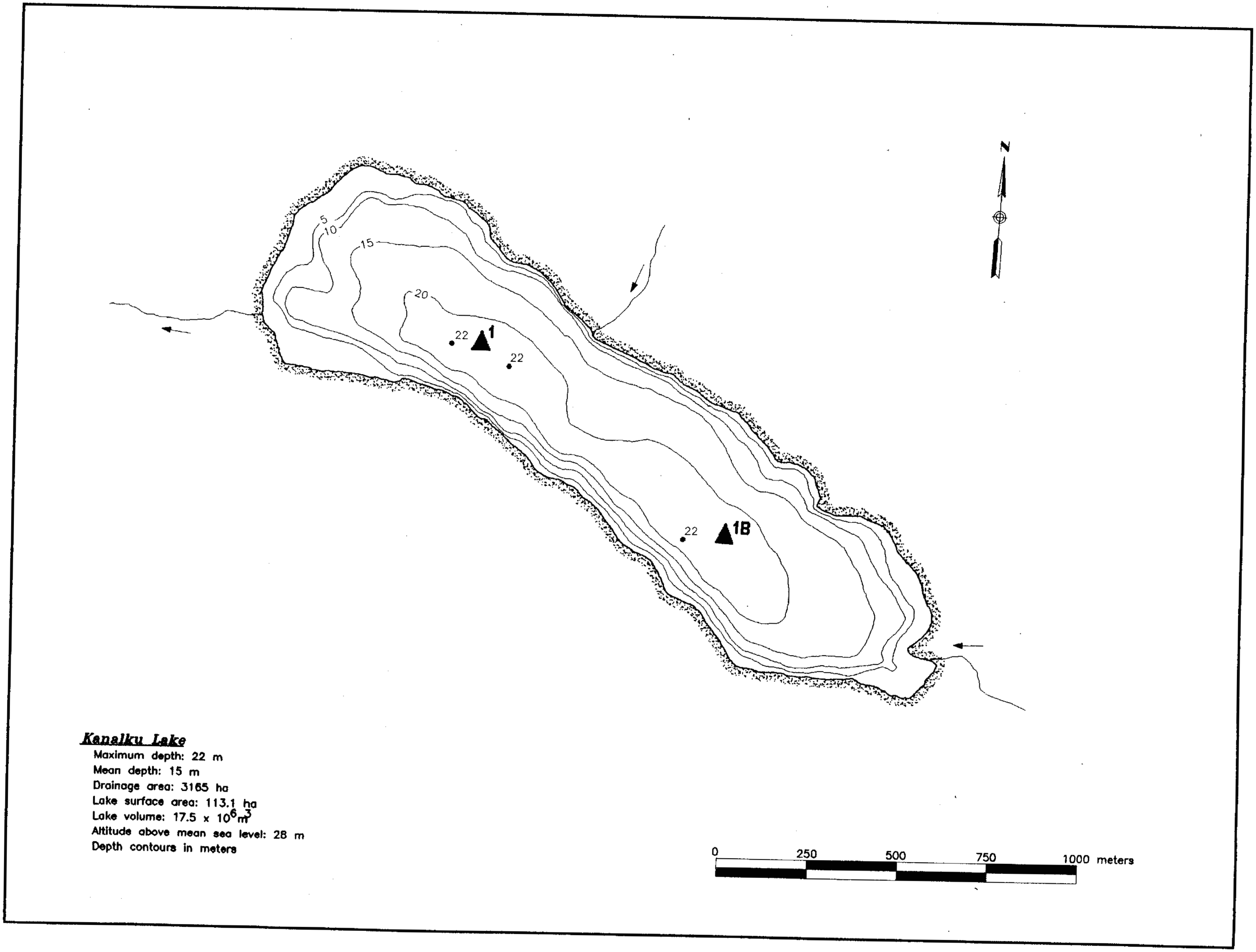


Figure 2. Morphometric map of Kanalku Lake indicating the locations of the limnological sampling sites.

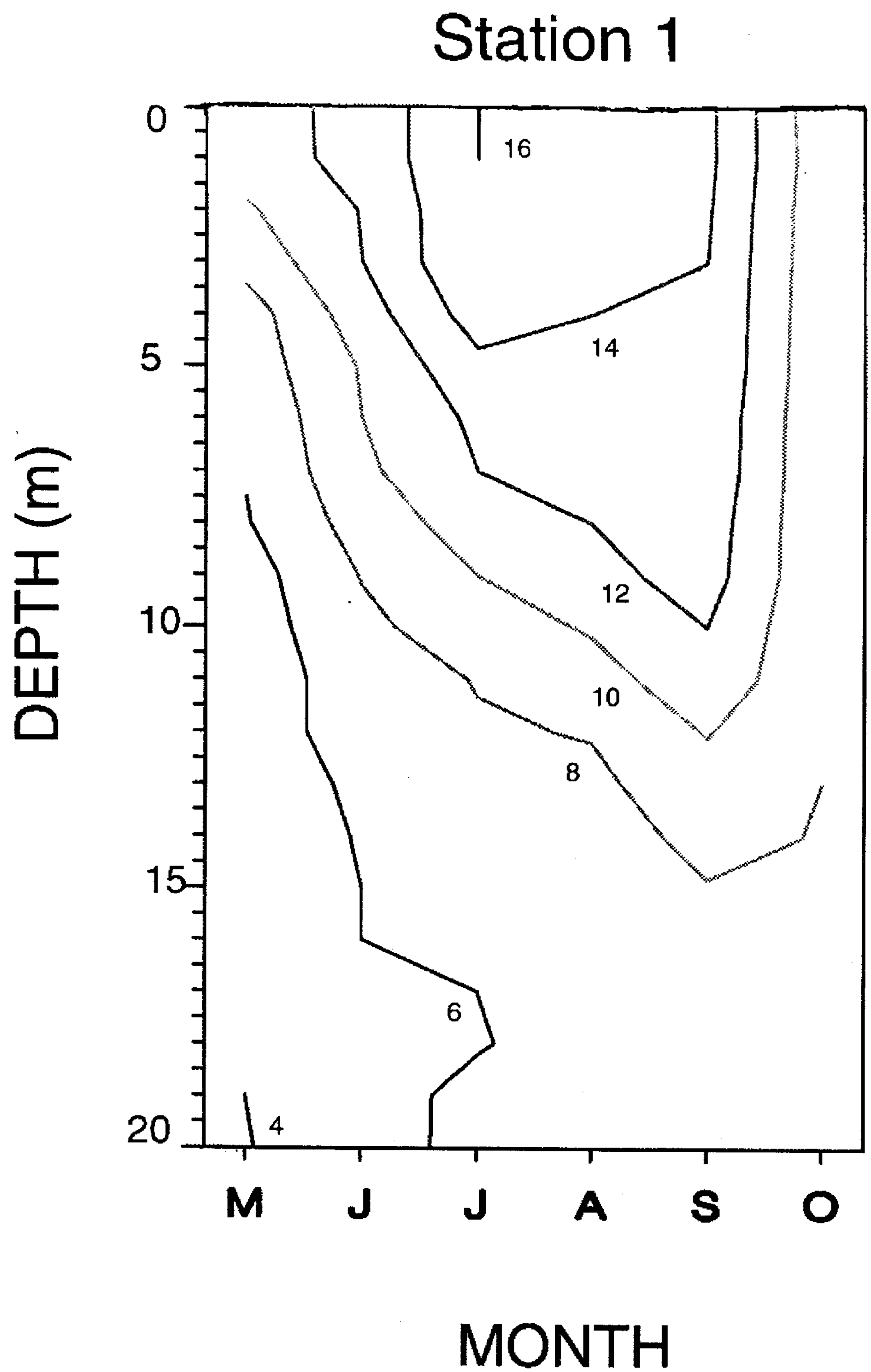


Figure 3. Temperature isopleths (°C) for sampling site #1 at Kanalku Lake during 1995. For the month abbreviations, M = May, A = April or August, J = June/July, O = October, and N = November.

APPENDIX

Appendix A

Water Chemistry and Algal Pigment Analysis Data, Kanalku Lake, 1995

Appendix A.1. Seasonal mean (May–October) values (n = 6) for general water-quality parameters, metal concentrations, nutrient concentrations, atom ratios, and algal pigment (chlorophyll *a* and phaeophytin *a*) concentrations obtained from the epilimnion (1 m) and hypolimnion (17 m) at sampling site #1, Kanalku Lake, 1995.

	Depth		
	1 m	17 m	
Conductivity (μmohs·cm^{-1})	124	120	
pH (units)	7.6	7.1	
Alkalinity (mg·L^{-1} as $CaCO_3$)	58.1	53.5	
Turbidity (NTU)	0.6	0.9	
Color (PT units)	10.2	11.5	
Calcium (mg·L^{-1})	20.2	18.9	
Magnesium (mg·L^{-1})	2.2	2.0	
Iron (μg·L^{-1})	54	73	
Total Phosphorus (μg·L^{-1} as P)	2.8	2.5	
Total Filterable Phosphorus (μg·L^{-1} as P)	1.5	1.1	
Filterable Reactive Phosphorus (μg·L^{-1} as P)	0.9	1.0	
Total Kjeldahl Nitrogen (μg·L^{-1} as N)	52.0	49.4	
Ammonia (μg·L^{-1} as N)	7.0	8.9	
Nitrate + Nitrite (μg·L^{-1} as N)	121.9	175.5	
Reactive Silicon (μg·L^{-1} as Si)	1,889	2,164	
Particulate Carbon (μg·L^{-1} as C)	NA	NA	
Total Particulate Phosphorus (μg·L^{-1} as P)	NA	NA	
Total Particulate Nitrogen (μg·L^{-1} as N)	NA	NA	
N:P (atom ratio)	148:1	215:1	
Chlorophyll *a* (μg·L^{-1})	0.59	0.86 [a]	0.93 [b]
Phaeophytin *a* (μg·L^{-1})	0.18	0.28 [a]	0.42 [b]

[a] Average values for the mid-euphotic zone.

[b] Average values for the 1% euphotic depth.

NA — not analyzed

Appendix A.2. Summary of water-quality analysis results within the epilimnion and hypolimnion of Kanalku Lake during 1995 at sampling site #1.

Sampling Date	5/10		6/15		7/14	
Depth	1 m	17 m	1 m	17 m	1 m	17 m
Conductivity (μ mohs·cm^{-1})	120	121	123	120	128	NA
pH (units)	7.5	7.3	7.7	7.3	7.6	NA
Alkalinity (mg·L^{-1} as $CaCO_3$)	53.5	52.4	57.1	54.3	59.9	NA
Turbidity (NTU)	0.7	1.5	0.8	0.8	0.4	NA
Color (PT units)	9	12	12	11	10	8
Calcium (mg·L^{-1})	18.6	18.6	19.1	19.1	20.7	NA
Magnesium (mg·L^{-1})	2.7	2.0	2.7	2.0	2.5	NA
Iron (μ g·L^{-1})	42	54	21	43	61	NA
Total Phosphorus (μ g·L^{-1} as P)	1.9	1.6	2.2	2.5	1.4	1.0
Total Filterable Phosphorus (μ g·L^{-1} as P)	1.1	0.9	1.0	1.0	1.2	0.6
Filterable Reactive Phosphorus (μ g·L^{-1} as P)	1.1	0.9	0.8	0.9	1.0	0.9
Total Kjeldahl Nitrogen (μ g·L^{-1} as N)	42.0	41.2	42.0	44.4	40.4	46.0
Ammonia (μ g·L^{-1} as N)	4.7	8.6	6.9	7.5	9.6	10.1
Nitrate + Nitrite (μ g·L^{-1} as N)	194.0	196.5	122.8	186.0	100.9	179.5
Reactive Silicon (μ g·L^{-1} as Si)	2,062	2,222	1,866	2,163	1,756	NA
Particulate Carbon (μ g·L^{-1} as C)	NA	NA	NA	NA	NA	NA
Total Particulate Phosphorus (μ g·L^{-1} as P)	NA	NA	NA	NA	NA	NA
Total Particulate Nitrogen (μ g·L^{-1} as N)	NA	NA	NA	NA	NA	NA
N:P (atom ratio)	296:1	354:1	179:1	220:1	241:1	537:1

NA — not analyzed

Appendix A.2. (Page 2 of 2)

Sampling Date	8/15		9/15		10/20	
Depth	1 m	17 m	1 m	17 m	1 m	17 m
Conductivity (μ mohs·cm^{-1})	124	120	126	120	125	119
pH (units)	7.8	7.2	7.5	7.0	7.4	7.1
Alkalinity (mg·L^{-1} as $CaCO_3$)	59.3	53.5	60.9	54.5	57.6	53.2
Turbidity (NTU)	0.6	0.5	0.4	0.5	0.9	1.7
Color (PT units)	11	12	9	12	10	14
Calcium (mg·L^{-1})	20.5	18.6	21.6	19.7	20.4	18.6
Magnesium (mg·L^{-1})	2.2	2.2	1.9	1.9	1.4	1.4
Iron (μ g·L^{-1})	64	37	49	54	84	193
Total Phosphorus (μ g·L^{-1} as P)	5.1	1.7	1.8	1.4	4.2	4.6
Total Filterable Phosphorus (μ g·L^{-1} as P)	2.8	0.7	0.8	1.1	2.1	2.2
Filterable Reactive Phosphorus (μ g·L^{-1} as P)	0.9	0.8	0.9	1.1	0.8	1.4
Total Kjeldahl Nitrogen (μ g·L^{-1} as N)	54.8	42.8	51.6	46.0	80.9	76.1
Ammonia (μ g·L^{-1} as N)	8.0	10.1	8.0	10.6	5.0	6.7
Nitrate + Nitrite (μ g·L^{-1} as N)	89.6	173.0	93.6	167.3	130.7	150.7
Reactive Silicon (μ g·L^{-1} as Si)	1,884	2,329	1,943	2,213	1,816	1,922
Particulate Carbon (μ g·L^{-1} as C)	NA	NA	NA	NA	NA	NA
Total Particulate Phosphorus (μ g·L^{-1} as P)	NA	NA	NA	NA	NA	NA
Total Particulate Nitrogen (μ g·L^{-1} as N)	NA	NA	NA	NA	NA	NA
N:P (atom ratio)	68:1	303:1	192:1	363:1	120:1	117:1

NA — not analyzed

Appendix A.3. Summary of algal pigment analysis results within Kanalku Lake during 1995 at sampling site #1.

Sampling Date	5/10			6/15			7/14		
Depth	1 m	5 m	9 m	1 m	7 m	13 m	1 m	9 m	17 m
Chlorophyll *a* ($\mu g \cdot L^{-1}$)	0.29	0.72	1.20	0.36	0.71	1.14	0.28	0.39	0.50
Phaeophytin *a* ($\mu g \cdot L^{-1}$)	0.12	0.26	0.40	0.12	0.35	0.62	0.11	0.19	0.37

Sampling Date	8/15			9/15			10/20		
Depth	1 m	8 m	15 m	1 m	6 m	11 m	1 m	5 m	9 m
Chlorophyll *a* ($\mu g \cdot L^{-1}$)	0.68	0.85	0.61	0.57	1.36	1.02	1.36	1.14	1.11
Phaeophytin *a* ($\mu g \cdot L^{-1}$)	0.22	0.26	0.32	0.19	0.32	0.43	0.31	0.32	0.39

Appendix A.4. Summary of phytoplankton densities (number of cells·m^{-3}) at sampling site #1 with corresponding particulate carbon concentration (μg C·m^{-3}) at 1-m depth, by taxa and sampling date, Kanalku Lake, 1995.

Species	Sampling Date 5/10	7/14	10/20
Bacillariophyceae			
Achnanthes minutissima	12,749,971 (107.57)	—	—
Achnanthes sp.		16,227,236 (201.66)	48,681,708 (604.99)
Cyclotella stelligera	25,499,942 (187.36)	—	—
Cyclotella stelligera	—	146,045,120 (1,073.08)	81,136,176 (596.16)
Cymbella sp.	—	16,227,236 (683.26)	—
Navicula sp.	—	—	16,227,236 (683.26)
Subtotal	**38,249,913 (294.93)**	**178,499,592 (1,958.00)**	**146,045,120 (1,884.41)**
Chrysophyceae			
Chromulina sp.	114,749,736 (581.74)	356,999,200 (1,809.86)	178,499,600 (904.93)
Chryptomonas sp.	—	16,227,236 (1,789.48)	48,681,708 (5,368.43)
Chrysochromulina sp.	152,999,648 (2,437.28)	210,954,064 (3,360.50)	64,908,944 (1,034.00)
Dinobryon lorica	203,999,536 (4,169.36)	—	—
Dinobryon sp.	216,749,504 (5,187.84)	—	—
Kephyrion sp.	63,749,856 (589.14)	178,499,600 (1,649.58)	178,499,600 (1,649.58)
Subtotal	**752,248,280 (12,965.36)**	**762,680,100 (8,609.42)**	**470,589,852 (8,956.94)**
Cyanophyceae			
Synechococcus sp.	—	1,541,587,456 (2,351.96)	2,920,902,400 (4,456.35)
Subtotal	—	**1,541,587,456 (2,351.96)**	**2,920,902,400 (4,456.35)**
Chlorophyceae			
Scenedesmus sp.	—	—	16,227,236 (213.07)
Subtotal	—	—	**16,227,236 (213.07)**

– continued –

(var) — indicates a variant of the species

Appendix A.4. (Page 2 of 2)

Species	Sampling Date 5/10	7/14	10/20
Dinophyceae			
Gymnodinium sp.	—	16,227,236 (2,437.28)	—
Peridinium sp.	127,499,712 (7,713.16)	48,681,708 (2,945.02)	16,227,236 (981.67)
Subtotal	**127,499,712 (7,713.16)**	**64,908,944 (5,382.30)**	**16,227,236 (981.67)**
Cryptochrysidaceae			
Chroomonas acuta	—	48,681,708 (1,813.70)	64,908,944 (2,418.26)
Subtotal	—	**48,681,708 (1,813.70)**	**64,908,944 (2,418.26)**
Cryptomonadineae			
Rhodomonos sp.	50,999,884 (669.64)	32,454,472 (663.31)	32,454,472 (663.31)
Subtotal	**50,999,884 (669.64)**	**32,454,472 (663.31)**	**32,454,472 (663.31)**
Micro-Algae			
Microflagellate	229,499,472 (638.27)	486,817,088 (1,353.90)	811,361,792 (2,256.50)
Picoplankton	114,749,736 (175.07)	—	—
Subtotal	**344,249,208 (813.34)**	**486,817,088 (1,353.90)**	**811,361,792 (2,256.50)**

(var) — indicates a variant of the species

Appendix B

Zooplankton Analysis Data from Kanalku Lake, 1995

Appendix B.1. Summary of seasonal changes in zooplankton densities (organisms·m^{-2}) with corresponding mean body sizes (mm) by taxa, sampling date, and site within Kanalku Lake, 1995.

	Site #1						
Species/Sampling Date	5/10	6/15	7/14	8/15	9/15	10/20	Seasonal Mean
Cladocera							
Bosmina sp.	12,990	41,773	77,475	122,941	76,074	36,169	61,237
	(0.53)	(0.48)	(0.55)	(0.49)	(0.54)	(0.55)	(0.52)
Daphnia longiremis	3,142	6,113	22,924	7,811	20,716	11,818	12,087
	(0.82)	(0.92)	(0.97)	(0.93)	(0.83)	(0.85)	(0.89)
Holòpedium sp.	849	7,811	11,674	679	0	0	3,502
	(0.56)	(0.76)	(1.05)	(1.17)			(0.89)
Subtotal	16,981	55,697	112,073	131,431	96,790	47,987	76,827
Copepod							
Cyclops sp.	37,697	20,376	12,311	1,359	11,717	16,505	16,661
	(0.89)	(1.07)	(1.16)	(1.14)	(0.53)	(0.61)	(0.90)
Diaptomus sp.	0	10,019	15,495	170	1,188	102	4,496
		(1.08)	(1.24)	(1.20)	(1.20)	NA	(1.18)
Epischura sp.	2,785	2,140	7,302	5,604	6,164	3,872	4,645
	(0.69)	(1.61)	(1.63)	(1.54)	(1.44)	(1.54)	(1.41)
Subtotal	40,482	32,535	35,108	7,133	19,069	20,479	25,801
Total Macrozooplankton	57,463	88,232	147,181	138,564	115,859	68,466	102,628

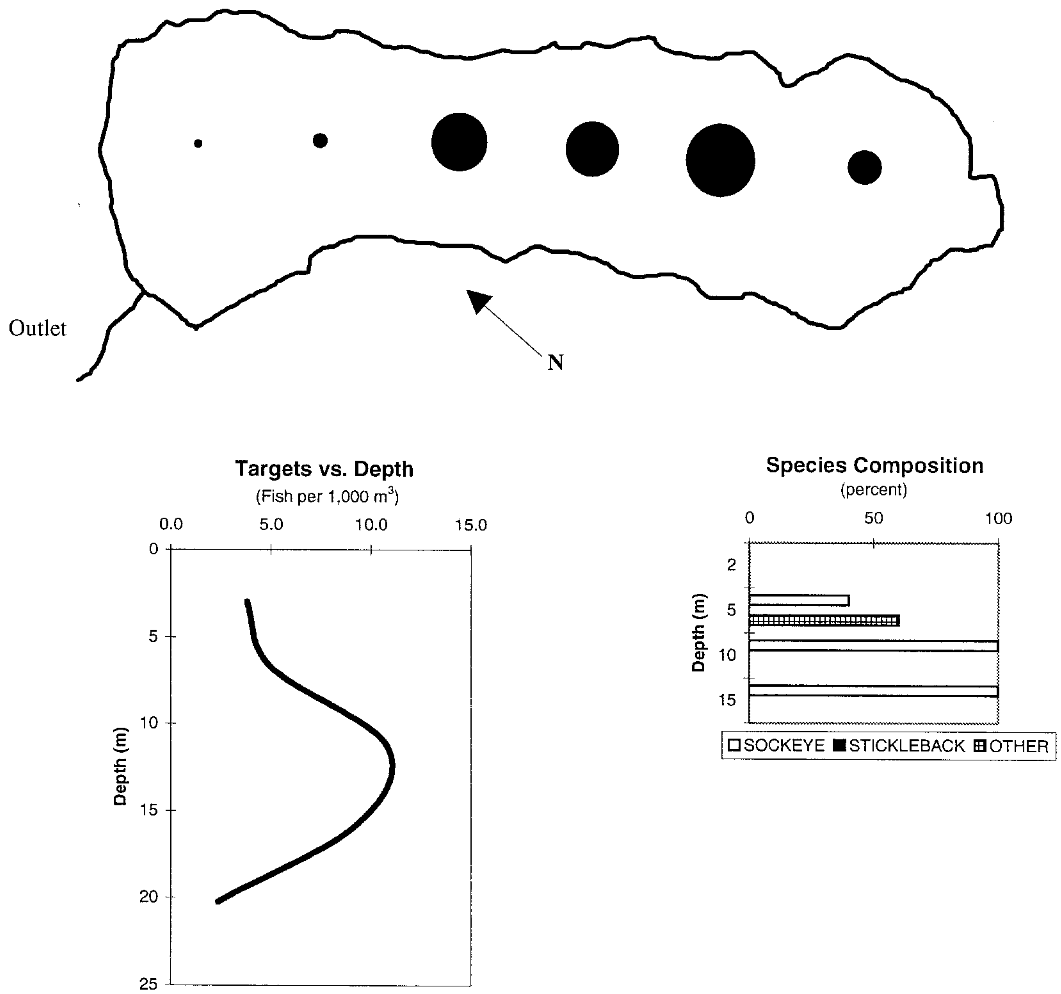
	Site #1B						
Species/Sampling Date	5/10	6/15	7/14	8/15	9/15	10/20	Seasonal Mean
Cladocera							
Bosmina sp.	5,298	20,173	109,526	62,455	16,455	82,782	49,448
	(0.53)	(0.51)	(0.57)	(0.59)	(0.51)	(0.63)	(0.56)
Daphnia longiremis	951	2,140	11,207	21,804	10,239	22,160	11,417
	(0.83)	(1.09)	(1.18)	(1.09)	(0.76)	(0.90)	(0.97)
Holopedium sp.	272	4,585	12,736	1,019	0	0	3,102
	(0.54)	(0.74)	(1.02)	(1.12)			(0.86)
Subtotal	6,521	26,898	133,469	85,278	26,694	104,942	63,967
Copepod							
Cyclops sp.	19,766	16,404	12,057	1,529	13,194	113,856	29,468
	(0.84)	(1.06)	(1.13)	(1.11)	(0.47)	(0.56)	(0.86)
Diaptomus sp.	0	8,355	15,452	1,528	459	0	4,299
		(1.10)	(1.20)	(1.17)	(1.22)		(1.17)
Epischura sp.	2,785	2,140	7,302	5,604	6,164	5,094	4,848
	(0.69)	(1.61)	(1.63)	(1.54)	(1.44)	(1.54)	(1.41)
Subtotal	22,551	26,899	34,811	8,661	19,817	118,950	38,615
Total Macrozooplankton	29,072	53,797	168,280	93,939	46,511	223,892	102,582

Appendix C

Acoustic Survey Results at Kanalku Lake, 1995

Total Population = 127,377

Relative Fish Density by Transect



Appendix C.1. Horizontal and vertical distribution of rearing fish and species composition by sampling depth within Kanalku Lake, 1995.

Appendix C.2. Age, length, and weight of fish captured during townet sampling at Kanalku Lake, 1995.

Survey Date	Species	Number of Fish Captured	Age	Mean Length (mm)	Mean Weight (g)
9/21	Sockeye	36	0	54.2	2.30
	juveniles	6	1	66.7	3.60
	Sculpin	3	NS	21.0	0.16

NS — not sampled