ASSESSMENT OF SOCKEYE SALMON PRODUCTION IN AKALURA LAKE

by

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ABSTRACT

Sockeye salmon *Oncorhynchus nerka* returning to Akalura Lake contribute to the Alitak Bay District fishery on the south end of Kodiak Island. Over the past 70 years, total runs (escapement plus harvest) ranged from <3,000 (1956) to nearly 700,000 (1937). Recent (1986-1993) runs (mean 110,000) approximate the historical average (91,000). In 1989, commercial fishing was closed due to contamination from the *Exxon Valdez* oil spill in Prince William Sound. As a result, the 1989 escapement (116,000) was nearly twice the desired escapement level (60,000). Since 1990, smolt production has steadily declined from 475,000 to 89,000. In addition, age-1 and age-2 smolt length and weight have decreased by 13 and 30%, respectively, compared to 1969-1977, indicating a reduced rearing capacity. Limnological studies revealed little change in the amount and composition of forage (zooplankton biomass) in the year after the 1989 overescapement. However, the seasonal mean zooplankton biomass decreased by 70% over the next 2 years. Akalura Lake is relatively productive, as evidenced by concentrations of total phosphorus (mean 13 $\mu g\ L^{-1}$) and chlorophyll *a* (mean 4.3 $\mu g\ L^{-1}$). Consequently, lower escapements (~40,000) and reduced grazing pressure allowed the macrozooplankton community to recover. In 1993, the seasonal mean macrozooplankton biomass was at a similar level as it was before the overescapement event. In addition, Akalura Lake supports a very large stickleback *Gasterosteus sp.* population within the pelagic zone. As both stickleback and sockeye salmon fry consume similar food resources, interspecific competition through interference or via direct removal of prey items may also be an important factor influencing smolt production in Akalura Lake.

Keywords: Sockeye production, limnology, stickleback, rearing capacity

INTRODUCTION

In 1989, the *Exxon Valdez* oil spill in Prince William Sound contaminated much of the Kodiak Management Area (KMA) salmon fishing grounds (Barrett and Monkiewiez 1989) and caused closures of the commercial fishery. As a result, several sockeye salmon systems experienced escapements in excess of the escapement goals. Within the Alitak-Olga Bay District fishery, the 1989 sockeye salmon escapement (116,000) in Akalura Lake was nearly twice the desired level (60,000). Excessive sockeye fry recruitment (escapement) above a lake's rearing capacity can lead to changes in zooplankton species composition, size and biomass, thereby lowering smolt growth and survival (Kyle et al. 1988; Koenings and Kyle 1991). Smolt studies were initiated in several KMA systems including Akalura Lake in order to monitor changes in smolt size, abundance and age composition in response to the high 1989 escapement (Barrett et al. 1993). In general, Barrett et al. found that since 1990 both smolt size and abundance in Akalura Lake has steadily declined. In addition, although Akalura Lake produced predominantly (>90%) age-2 smolt, they observed a slight shift in age composition from relatively few age-1 smolt to more age-3 smolt. Such an increase in the proportion of holdovers can indicate a less than optimum rearing environment (Koenings and Burkett 1987; Barrett et al. 1993).

It is known that sockeye salmon production is associated with lake fertility through food-chain linkages (Foerster 1968; LeBrasseur et al. 1978; Hyatt and Stockner 1985; Koenings and Burkett 1987; Kyle et al. 1991). In addition, many sockeye salmon nursery lakes support robust populations of stickleback within the pelagic and littoral zones. As both sockeye salmon juveniles and stickleback exhibit dietary overlap, competition for food can be an important mechanism influencing sockeye salmon production (Rogers 1961; Ruggles 1965; Manzer 1976; O'Neill and Hyatt 1987). Honnold (1993) conducted hydroacoustic and townet surveys in 1990 and 1991 and found an abundant population of stickleback present in Akalura Lake. As such, interactions between juvenile sockeye salmon and stickleback, and insufficient forage (zooplankton) are factors to consider for the decline in sockeye salmon smolt production. In 1987, the Alaska Department of Fish and Game (ADF&G) began limnological investigations in Akalura Lake to determine the lake's rearing capacity. This report summarizes adult information, data from the smolt research project (Barrett et al. 1993), information from the hydroacoustic/townet surveys (Honnold 1993), and limnological data to provide an assessment of the historical, current, and potential sockeye salmon production in Akalura Lake.

Description of Study Area

Akalura Lake is located 120 km southwest of the city of Kodiak (57° 12' N 154° 12' W) on the north side of Olga Bay (Figure 1). The area has a maritime climate and the annual precipitation is estimated at 152 cm. Other than sockeye salmon, fish within the Akalura Lake drainage include: pink salmon *Oncorhynchus gorbuscha*, coho salmon *Oncorhynchus kisutch*, rainbow or steelhead trout *Oncorhynchus mykiss*, Dolly Varden *Salvelinus malma*, three-spine stickleback *Gasterosteus aculeatus*, and freshwater sculpin *Cottus aleuticus*.

METHODS

Sockeye Salmon Escapement and Harvest

During 1923-1958, sockeye salmon escapement was monitored using a weir operated by the U.S. Bureau of Commercial Fish. For the next 11 years (1959-1969), the escapement was not monitored. Beginning in 1970, ADF&G operated a weir each year to count sockeye salmon, except during 1975-1985 when no counts were made. Annual escapements during 1923-1971 were obtained from Hennick and Bevan (1970), whereas the 1972-1993 data were derived from ADF&G annual reports. Each year since 1987, 500-1,000 adult sockeye salmon were sampled at the weir site for age composition. A scale was taken from each fish, and ages were determined from acetate impressions using a microfiche projector. The historical harvest of Akalura Lake sockeye salmon is not available because this stock is caught in a mixed-stock fishery. However, because the total harvest in the Alitak Bay District is known and comprises mainly Frazer, Upper Station, and Akalura lakes, the harvest of Akalura Lake sockeye salmon were estimated by using the ratio of the number of fish that escaped into Akalura and Upper Station lakes. For example, if there were 10,000 fish in Akalura Lake and 100,000 in Upper Station, 10% of the Upper Station commercial catch was attributed to Akalura Lake. However, we recognize that there may be error associated with this method for assessing the stock of origin in a terminal catch, e.g. within the Inner Akalura Section. Harvest records from 1986 to 1988 were obtained from Swanton (1992), and subsequent harvest data were provided by Barrett (per. comm. ADF&G, Kodiak, AK).

Spawning Habitat

Blackett (1971) evaluated the available spawning habitat in the major tributaries of Akalura Lake (Figure 2) to estimate the number of sockeye salmon this system could support. Two transects were randomly selected in each section of each tributary stream and the cross-sectional area was measured. The distance between each transect along each bank was measured, thus giving rectangular dimensions. The dimensions of the two banks as well as the two transects were averaged, and the resulting dimensions (W x L) were used to estimate the total section area (m^2). The total usable spawning habitat was determined by estimating the percentage of usable spawning habitat in each survey section, and multiplying by the estimated total area. Usable spawning habitat was defined as flows of approximately 0.5 m sec^{-1}, water depth of 0.3-0.5 m, gravel size of 6-150 mm with <25% by volume of the gravel $\leq$6 mm, and minimal compactness (Chambers et al. 1955). The lakeshore spawning area was estimated based on a maximum depth of 1.5 m, and the area was determined by planimetry.

Hydroacoustic/Townet Surveys

Hydroacoustic surveys were conducted on 29 September 1990 and 06 October 1991 to estimate the number and distribution of juvenile fish. Surveys consisted of collecting (recording) data along six transects orthogonal to the longitudinal axis of Akalura Lake (Figure 2). The lake was divided into three equal areas (A-C), and two transects per area were selected randomly. Data were recorded along each transect at night when juvenile sockeye salmon are more likely to be distributed in the upper to middle part of the water column (Narver 1970; McDonald 1973; Eggers 1978; Simpson et al. 1981; Nunnallee 1983; Burczynski and Johnson 1986; Levy 1987). A 4.9-m Achilles raft powered by a 30-hp outboard engine was utilized for the surveys. Survey speed along each transect was maintained at 1.5 m sec^{-1} and monitored by the use of a portable Marsh-McBirney flow meter. Transect direction was maintained by compass bearing and by the use of flashing strobe lights at one end of each transect. A BioSonics model-105 echosounder with a model-171 tape recorder interface system with 6/15° dual-beam transducer was used. Fish signals were recorded electronically using a Sony digital audio tape recorder (Model TCD-D10), and on chart paper using a BioSonics model-115 recorder. The specific instrumentation for data acquisition is described by Honnold (1993). Analysis of the recorded hydroacoustic tapes was conducted by BioSonics, Inc. using procedures described by Kyle (1990) and Honnold (1993).

Townetting was conducted along the axis of the lake at depths where the highest numbers of acoustic targets were observed using a 2 x 2-m townet (Gjernes 1979). A minimum of 3 tows, ranging from 20 to 30 minutes in duration were conducted during each survey. Fish were enumerated and weighed to the nearest 0.1 g. When greater than 200 stickleback were captured, a random sample of 100 to 150 were counted and weighed to determine mean fish weight. The total number of stickleback was calculated by dividing the total biomass by the average weight. Juvenile sockeye salmon caught in 1991 were preserved in ethyl alcohol. These preserved samples were measured for fork length (to the nearest 1.0 mm), weighted, and used to determine the condition coefficient (Bagenal 1978). Ages were determined after Mosher (1969) from scale smears mounted on glass slides using a microfiche projector. No age or size information was collected from the 1990 townet samples.

Smolt Sampling

During 1969-1977, sockeye salmon smolt were collected using a fyke net with a 1.2-m square opening and sampled for age, weight, and length (AWL). During 1990-1993, a Canadian fan trap (Ginetz 1977) equipped with a live box was used to estimate the number of migrating smolt and to sample for AWL information (Barrett et al. 1993). Smolts were anesthetized in a tricaine methanesulfonate (MS-222) solution, measured for fork length to the nearest 1.0 mm, and weighed to the nearest 0.1 g. A scale smear was taken from each measured fish, placed on a glass slide, and aged using a microfiche projector. During the latter period, smolt population estimates were derived using a mark and recapture method after Rawson (1984).

Lake Morphometry, Sampling, and Physical Features

Lake depth contours were recorded with a fathometer along numerous transects, and used to develop a bathymetric map (Figure 2). The area of each depth strata was determined with a polar planimeter, and the total volume was computed as the sum of the volume of the strata at successive depths (Hutchinson 1957). The mean depth was calculated as the total volume divided by the surface area. The water residence time was estimated via multiple regression analysis for watershed characteristics (drainage and annual precipitation) versus known discharges (Anonymous 1979; Koenings et al. 1987).

During 1987-1993, limnological surveys were conducted at approximately one-month intervals from May through October. Transportation to and from Akalura Lake was provided by a float-equipped aircraft, and sampling was conducted after mooring to a permanent station. A single station was sampled in 1987, 1988 and 1989; however, two stations were utilized for subsequent surveys. Light penetration was measured using a Protomatic submarine photometer at 0.5-m increments to a depth of 5 m, and at subsequent 10-m increments to a depth equivalent to 1% of the subsurface light reading. The euphotic zone depth (EZD), defined as the depth at which 1% of the subsurface light (photosynthetically available radiation [400-700 nm]) penetrates (Schindler 1971), was calculated from the relationship of light transmission through water: light extinction (K_d) = ($\ln I_o - \ln I_z$)/z (Wetzel and Likens 1979). Water clarity was measured with a 20-cm Secchi disk by recording the depth at which the disk disappeared from view. Lake temperature profiles and dissolved oxygen levels were measured using a YSI model-57 temperature/oxygen analyzer at 1-m increments from the surface the lake bottom.

Water Chemistry

Lake water samples were collected from both the 1 m (epilimnion) and the 10-20 m (hypolimnion) strata using a non-metallic Van Dorn sampler. Approximately eight liters of water collected from each depth were stored in pre-cleaned translucent carboys, transported to Kodiak, and filtered and/or preserved for laboratory analysis. A portion of the water samples was refrigerated for general tests and metals, another portion was frozen for Kjeldahl nitrogen and total phosphorus testing, and a final portion was filtered through a Whatman GFF glass-fiber filter and frozen for analysis of dissolved nutrients. All samples were contained in pre-cleaned polybottles and sent to the Limnology Laboratory in Soldotna for analysis as detailed by Koenings et al. (1987).

Conductivity (temperature compensated to 25° C) was measured with a YSI model-32 conductance meter, and pH was measured with a Corning model-A specific ion meter. Alkalinity levels were determined by acid titration (0.02 N H_2SO_4) to pH 4.5 (AHAP 1985). Turbidity, expressed as nephelometric turbidity units (NTU), was measured using a HF model-DRT100 turbidimeter, and color was determined on filtered samples by measuring the spectrophotometric absorbance at 400 nm and converting to equivalent platinum-cobalt (Pt) units. Calcium and magnesium were determined from separate EDTA (0.01 N) titrations after Golterman (1969), and total iron was analyzed by reduction of ferric iron with hydroxylamine during hydrochloric acid digestion after Strickland and Parsons (1972). Filterable reactive phosphorus (FRP) was analyzed by the molybdate-blue/ascorbic-acid method of Murphy and Riley (1962), as modified by Eisenreich et al. (1975). Total phosphorus was determined using the FRP procedure, after persulfate digestion. Nitrate and nitrite (NO_3 + NO_2) were determined as nitrite after cadmium reduction and diazotization with sulfanilamide, and total ammonia was determined using the phenylhypolchlorite methodology (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 calculated as the sum of TKN and NO_3 + NO_2. Finally, reactive silicon was determined using the method of ascorbic acid reduction to molybdenum blue after Stainton et al. (1977).

Phytoplankton and Chlorophyll a

Samples for phytoplankton analysis were preserved in Lugol's acetate solution (Koenings et al. 1987) and analyzed by Eco-Logic Ltd., Vancouver, British Columbia. Phytoplankton were counted using an inverted microscope equipped with phase-contrast optics. A portion of the sample was placed in a 25-ml counting chamber and allowed to settle. Transects at 1250X magnification were counted. The counts were converted to number of cells m^{-3} and to volume (mm^3 m^{-3}). Phytoplankton volumes were determined using values calculated by Evans and Stockner (1972). Algal standing crop was estimated by the algal pigment chlorophyll *a* (chl *a*). Samples were prepared by filtering 1-2 L of lake water through a Whatman 4.25-cm GFF glass-fiber filter, to which 1-2 ml of saturated $MgCO_3$ solution were added just prior to completion of filtration. The filters were then stored frozen in individual plexislides for later analysis. Pigment was extracted after homogenizing glass-fiber filters in 90% acetone using a tissue grinder and pestle. Chl *a* concentrations (corrected for inactive phaeophytin) were determined using the fluorometric procedure of Strickland and Parsons (1972). The low-strength acid addition recommended by Riemann (1978) was used to estimate phaeophytin.

Zooplankton

Replicate near bottom-to-surface zooplankton hauls were taken using a 0.2-m diameter, 153-µ mesh, conical net. The net was pulled manually at a constant ~0.5 m sec^{-1}, and rinsed prior to removing and preserving all specimens in neutralized 10% formalin (Koenings et al. 1987). Identification of *Daphnia* followed Brooks (1957), *Bosmina* after Pennak (1978); and the copepods were identified using keys of Wilson (1959) and Yeatman (1959). Enumeration consisted of counting triplicate 1-ml subsamples taken with a Hansen-Stempel pipette in a 1-ml Sedgewick-Rafter cell. Zooplankton body sizes were obtained by measuring the length to the nearest 0.01 mm of at least 10 individuals along a transect in each 1-ml subsample (Koenings et al. 1987). Finally, zooplankton biomass, weighted by organism density, was estimated from specie-specific regressions of zooplankter body length and weight after Koenings et al. (1987).

RESULTS

Total Adult Run and Exploitation Rate

Over the past 70 years, sockeye salmon escapements in Akalura Lake ranged from a high of 252,193 in 1937 to a low of 1,828 in 1956 (Table 1). The estimated harvest ranged from 424,414 in 1937 to 0 in 1989 when the fishery was closed due to contamination of the fishing grounds from the *Exxon Valdez* oil spill. As a result of this closure, the 1989 escapement exceeded 116,000, and was the highest observed since 1945. During 1923-1949, both the escapement and harvest averaged ~70,000. The commercial exploitation rate during 1923-1936 averaged a relatively low 37%, and from 1937 to 1949 increased to an average of 58%. Subsequently, total adult run strength over the next 25 years decreased by more than 90%. That is, during 1950-1975 the escapement and harvest averaged only 9,000 and 4,000, respectively. No data are available during 1976-1985; however, recent adult runs (1986-1993) have increased and approximate the level of runs during 1923-1949. Recent sockeye salmon escapements (1986-1993) averaged ~45,000, which is within the current escapement goal (40,000-60,000), and the harvest during this period has averaged 75,500, which represents the highest average exploitation rate (68%) for this system.

Adult Run Timing and Spawning Habitat

Akalura Lake sockeye salmon exhibit a bimodal migration and a spawning time which is similar to the sockeye salmon runs in nearby Upper Station and Karluk lakes. During May and June, a small population of ~3,000 sockeye salmon migrate into the lake, but do not spawn until late July and early August, primarily in Eagle, Falls, and Crooked creeks (Figure 2). The tributary spawning area was estimated at 12,115 m^2. The second or late run fish are much more numerous and migrate into the lake during late July and August. The late run of fish spawn mainly along the lakeshore northwest of Crooked Creek in late October/early November. The useable shore spawning area was estimated at 74,900 m^2, and combined tributary and shore spawning areas comprise ~87,000 m^2. Based on an optimal spawning density of 2 m^2 per female (Burgner et al. 1969), ~440,000 sockeye salmon would be produced (i.e., 87,000 spawners at a 50:50 sex ratio, a fecundity of 2,500 eggs/female, a potential egg deposition to emergent fry survival of 10% (Foerster 1968), and a 4% spring fry to smolt survival).

Adult Age Composition and Return Per Spawner

Sockeye salmon of Akalura Lake comprise 11 different age classes for the early and late runs (Table 2). As a group, four- and five-year old fish dominate the early sockeye run as together they accounted from 59% to 94% of the composition since 1986. The age-1.2 sockeye comprised ~50% of the early run in 1987 and 1990, whereas the age-1.3 class comprised 89% in 1988 and

52% in 1992 and 1993. In contrast, three-year old fish (age 1.1) were the largest component (23%) of the early run in 1986 and age classes 1.2, 1.3, and 2.2 comprised equal portions (~19%). Excluding the 1987 return, five and six-year old fish comprised 81% to 99% of the late run. Age-2.2 and age-2.3 fish accounted for 23 to 83% of the late run, whereas 3% to 48% of this run was comprised of age-2.3 fish. In 1987, four-year old fish (age 1.2) accounted for 60% of the late run. Return per spawner (R/S) data are only available for the 1986 and 1987 broodyears and equalled 16.3 and 23.6, respectively. However, based on the averaged broodyear return of six-year old fish (17%), and attributing this to the 1988 broodyear escapement, a projected R/S for 1988 would be 2.2.

Fry Abundance, Size, and Age Composition

The hydroacoustic survey conducted 29 September 1990 in Akalura Lake revealed a total fish population estimate of 3,950,101 (Table 3). The population in the northern basin (Figure 2) represented by area C (transects 5 and 6) was estimated to be 1,720,390 compared to 1,483,006 and 746,705 in areas B (transects 3 and 4) and A (transects 1 and 2), respectively. The 06 October 1991 survey revealed a total fish population estimate of 3,171,891. In contrast to 1990, fish populations in 1991 were highest in area B (1,707,640) compared to area C (907,625) and area A (556,626). In both surveys, nearly 80% of the fish were distributed within the top 10 m of the lake (Table 4). In addition, most of the fish were distributed within the pelagic (middle) sections as opposed to the littoral (nearshore) areas; however, ~33% of the fish were also observed within the northern and eastern sections. During the 1990 survey, a total of 237 juvenile sockeye salmon and 4,252 stickleback were caught by townetting, which represented 5% and 95% of the catch, respectively (Table 5). Using this catch data, the October 1990 juvenile sockeye salmon population was an estimated 209,350 compared with 3.7 million stickleback. Unfortunately, due to improper fish preservation, age composition and size data were not available in 1990. In May 1991, 54 juvenile sockeye salmon and 387 stickleback were collected by townetting. Of the juvenile sockeye salmon sampled, 6.8% were age-0, 54.5% were age-1, and 38.6% were age-2 (Table 6). The age-0 fish averaged 0.2 g and 29 mm, which equates to a condition coefficient (K) of 0.79 (Table 6). Age-1 fish averaged 1.0 g and 50 mm in size (K = 0.78), and age-2 fish averaged 2.4 g and 68 mm (K = 0.74). During the October 1991 survey, 147 juvenile sockeye were captured, which represented only 1.4% of the total catch; the remainder (98.6%) comprised 10,765 stickleback (Table 5). Based on this catch data, the October 1991 juvenile sockeye salmon and stickleback populations were an estimated 44,380 and 3.1 million fish, respectively. The age-0 fish comprised 37% of the townet catch and averaged 1.4 g and 52 mm in size, whereas the age-1 fish comprised 63% of the townet catch and averaged 3.8 g and 74 mm (Table 6).

Smolt Abundance, Size, and Age Composition

Since 1990, the number of sockeye salmon smolt emigrating Akalura Lake has decreased from 474,790 to 88,874 (Table 7). On average, age-2 smolt comprised more than 90% of the total outmigration; however, there has been a decrease in the proportion of age-1 smolt and a gradual increase in the proportion of age-3 smolt. In 1990, age-1 smolt comprised 14% (66,460) of the total outmigration and there were no age-3 smolt. In contrast, in 1993 age-3 smolt comprised 14% (12,315) of the total outmigration and age-1 smolt comprised <4% (3,259). A six-fold increase in escapement in 1988 compared to 1987 produced 374,604 smolt; 10% less than the 409,582 smolt produced from the 1987 escapement (Table 8). Both 1987 and 1988 escapements produced about twice the number of smolt compared to the much larger 1989 escapement (~116,000) which produced only 204,364 smolts. The 1990 escapement (47,181) produced even fewer smolt, as combined age-1 and age-2 smolt (no age-3 until 1994) totalled ~75,000. Based on the age composition in previous years, neither age-3 nor age-4 smolt produced from this escapement will substantially increase the 1990 broodyear production of smolt. During 1969-1977, age-1 smolt averaged 83 mm (range 75-94 mm) and 5.2 g (range 3.8-6.7 g) whereas, age-2 smolt averaged 95 mm (range 92-99 mm) and 7.6 g (range 6.4-8.6 g) (Table 9). During 1990-1992, age-1 smolt were smaller and averaged 76 mm and 3.9 g. In 1993, age-1 smolt were the smallest on record, averaging 62 mm and 2.2 g. Except for 1993, the recent (1990-1993) average age-1 smolt sizes are within the historical (1969-1977) size range (3.9-7.6 g; 75-94 mm). In contrast, recent (1990-1993) age-2 smolt sizes are considerably smaller than previously (1969-1977) observed (6.4-8.6 g; 92-99 mm). The 1990 age-2 smolt averaged 5.7 g and 86 mm, whereas in 1991 and 1992 both age-1 and age-2 smolt were quite similar in size (~4 g; 77 mm). Also, in contrast to the age-1 smolt in 1993, the age-2 smolt were the largest (5.7 g; 86 mm) sampled in four years.

Lake Morphometry and Physical Features

Akalura Lake has a surface area of 4.9 km^2, a mean depth of 9.9 m, a maximum depth of 22 m, and a total volume of 48 km^3 (Figure 2). The water residence time is an estimated 1.3 years, or conversely, the flushing rate is 0.8 yr^{-1}. This lake is defined as a clearwater system based on low amounts of color and turbidity (Table 10). The euphotic zone depth (EZD) varied considerably both on a seasonal basis and within season (Table 9). In particular, the EZD was shallowest in 1989 (mean 7.2 m) and deepest in 1992 (mean 12.0 m). In addition, the EZD was somewhat deeper in the spring (8-15 m) and summer (8-14 m) compared to the fall (4-12 m). Overall, the EZD ranged from 3.7 to 16.1 m and averaged 10.0 m. Thus, the mean euphotic volume (EV) is 45 x 10^6 m^3 or 45 EV units, which equates to ~94% of the total lake volume. The Secchi disk (SD) transparency exhibited little temporal variation, and differences between stations were minimal. Overall, the SD transparency was relatively shallow and ranged from 1.8 to 4.8 m, with a mean of 3.1 m. Due to the relatively deep light (EZD) penetration and shallow basin, temperatures during July typically reach ~16° C at the surface (Figure 3). Lake temperatures gradually (<1.0 C° m^{-1}) decreased with depth (~15 m) to ~10° C, thus forming a weak thermocline. Dissolved oxygen (D.O.) concentrations within the upper layers (<15 m) generally ranged from 7 to 13 mg L^{-1} and were 70-100% saturated. Although there is only slight thermal stratification, D.O. levels within the deeper strata (>15 m) in July are quite low (<5 mg L^{-1}) and can become anaerobic near the bottom of the lake as exemplified in 1990 (Figure 3). In addition, oxygen depletion occurred in August as evidenced by D.O. levels of <4 mg L^{-1} near the lake bottom. However, by September when the lake was isothermal at 10° C, D.O. concentrations increased to 8 mg L^{-1} (70% saturation) throughout the water column.

General Water Chemistry and Nutrient Levels

A summary of water chemistry parameters, nutrient concentrations, and algal biomass is presented for the epilimnion (1 m) and hypolimnion in Tables 10 and 11, respectively. For ease of comparison, these parameters are discussed below in terms of seasonal mean values unless noted otherwise. The pH was usually less than neutral and ranged from 6.6 to 7.1 units. Conductivity ranged from 50 to 61 µmhos cm^{-1}, and alkalinity ranged from 13 to 15 mg L^{-1}. Turbidity was very low and ranged from 1 to 2 NTU, and there was minimal color in the lake (mean 7 Pt units). Both calcium and magnesium concentrations were quite stable and averaged 4.8 and 1.3 mg L^{-1}, respectively. In contrast, iron levels (mean 285 µg L^{-1}) within the hypolimnion were nearly double the epilimentic concentrations (mean 177 µg L^{-1}).

Overall, nitrate + nitrite ($NO_3 + NO_2$) concentrations ranged from 5 to 30 µg L^{-1} in the epilimnion and from 5 to 42 µg L^{-1} in the hypolimnion. The lowest $NO_3 + NO_2$ levels occurred in 1992 and 1993 when spring and summer concentrations remained below the detection limit (<4 µg L^{-1}). On a seasonal basis, mean ammonia concentrations were generally quite low and ranged from 7 to 16 µg L^{-1} in the epilimnion and from 8 to 118 µg L^{-1} in the hypolimnion. However, ammonia concentrations in excess of 200 µg L^{-1} occurred in the hypolimnion during the summer of 1989 and 1990. Total Kjeldahl nitrogen (TKN) ranged from 148 to 279 µg L^{-1}, and there was little difference between stations or by depth. The average total phosphorus (TP) concentration in the epilimnion of Akalura Lake was about twice that for other sockeye salmon nursery lakes in Alaska. The epilimnetic TP in Akalura Lake averaged 13.4 µg L^{-1} (range 11.0-17.8 µg L^{-1}), and in the hypolimnion averaged 16.2 µg L^{-1} (range 12.6-20.2 µg L^{-1}). Filterable reactive phosphorus (FRP) or orthophosphate levels were relatively low and ranged from 1.4 to 4.8 µg L^{-1}. Finally, the nitrogen-to-phosphorus ratio (N:P) averaged ~33:1; however, in 1992 when $NO_3 + NO_2$ levels were extremely low the ratio dropped to 23:1, which was still within the range for optimum phytoplankton growth.

Phytoplankton Composition and Biomass

The phytoplankton community of Akalura Lake is quite diverse in composition (Table 12). On a numerical basis, the diatoms and chrysophyceans were the most abundant groups found in Akalura Lake (Table 13). The most common diatoms were *Stephanodiscus niagare*, *Tabellaria fenestrata*, and *Melosira* sp., while the most common chrysophyceans were *Chromulinas* sp., and *Dinobryon lorica*. Together these two groups accounted for >90% of the total cell number. *Anabaena* sp. was the most dominant of the blue-greens, and in June and July of 1991 comprised most of the phytoplankton assembledge at Station 2. Of the other major taxon present, *Staurastrum* sp. and *Scenedesmus* sp., were the two dominant chlorophytes; *Chroomonas acula* and *Rhodomonos* sp., were the dominant cryptophytes, and *Peridinium* sp. and *Gymnodinium* sp. were the common flagellates (pyrrophyceans). By far, diatoms comprised the greatest proportion of phytoplankton volume, and were surpassed only by the blue-greens during June and July 1991. Except for 1991, phytoplankton samples were too few and inconsistent to describe any meaningful spatial distribution or temporal change. However, since 1987 seasonal mean algal biomass, as indexed by chlorophyll *a* (chl *a*), ranged from 2.8 to 6.0 µg L^{-1} in the epilimnion (Table 10) and from 2.0 to 5.6 µg L^{-1} in the hypolimnion (Table 11). In general, chl *a* concentrations were highest during the spring (range 1.4-10.6 µg L^{-1}) and fall (range 3.0-14.9 µg L^{-1}) turnover periods. There was no apparent trend in seasonal mean chl *a* concentrations over the years sampled.

Zooplankton Abundance, Size, and Biomass

The macrozooplankton community in Akalura Lake consists of four copepods and three cladocerans (Table 14). The copepods present are *Cyclops* sp., *Epischura* sp., *Ergaslius* sp., and *Eurytemora* sp., and cladocerans include *Bosmina* sp., *Chydorinae* sp., and *Daphnia* sp. The total mean macrozooplankton (TMZ) density (number m^{-2}) for the samples collected throughout the season was highest in 1987 (289,383) and lowest in 1992 (28,371). The lower densities in 1991 and 1992 were followed by an increase in 1993 (mean 94,713), which was still less than the 8-year mean (130,887). Except for 1990, the TMZ density was higher at station 1 compared to station 2 (Figure 2). Numerically, *Bosmina* and *Eurytemora* were the two most abundant taxa, and together they accounted from 63% to 93% of the seasonal mean TMZ density. *Epischura* and *Cyclops* were the next most numerous, and comprised an average of 11% and 8%, respectively of the TMZ density. *Ergasilus*, *Chydorinae*, and *Daphnia* appeared sporadically and occurred in relatively low numbers. Although *Bosmina* were the most numerous zooplankter, the body sizes were very small and averaged <0.3 mm, which is considered below the minimal threshold size for elective foraging by sockeye salmon fry (Koenings and McDaniel 1983). *Eurytemora* were much larger with a mean body size of ~0.9 mm, and *Epischura* was the largest-sized zooplankter with a mean body size of 0.96 mm. *Cyclops* averaged ~0.6 mm, both *Ergasilus* and *Daphnia* averaged ~0.5 mm, and *Chydorinae* were extremely small with a mean size of only 0.26 mm. The seasonal mean zooplankton biomass (like the density) was highest in 1987 (725 mg m^{-2}) and lowest in 1992 (mean 67 mg m^{-2}) (Table 15). During 1988-1990, the biomass levels were consistent and ranged between 221-273 mg m^{-2}, and over all years averaged 263 mg m^{-2}. The 1991 TMZ biomass (mean 132 mg m^{-2}) decreased by 50% compared to 1990 (mean 251 mg m^{-2}) and the 1992 biomass decreased by 50% compared to 1991. The 1993 TMZ biomass (mean 174 mg m^{-2}) was only slightly less than the overall 8-year average. Although *Eurytemora* were less abundant than *Bosmina* in 1993, they comprised 54% of the seasonal TMZ biomass.

DISCUSSION

Over the past 70 years, Akalura Lake sockeye salmon runs have fluctuated considerably (Table 1). Although no escapement and harvest data are available during 1959-1969, it is evident that this stock was severely depressed from the 1950's through the early 1970's. Blackett (1971) believed that overfishing during 1939-1953 decreased subsequent returns. However, the average exploitation rate (57%) through the 1940's is not considered excessive, as Chapman (1986) indicated that a 63% exploitation rate is optimal for Alaska sockeye salmon stocks. Nonetheless, the escapement and harvest remained low until the late 1980's. Recent (1986-1993) runs (mean 110,00) have increased to near historic levels (mean 135,000), and it appears that current production is at the lake's potential. That is, based on 2,300 adults per euphotic volume (EV) unit (Koenings and Burkett 1987), Akalura Lake which has an average EV of 45 units (Table 9), would be expected to produce ~100,000 sockeye salmon. Substantially increasing the exploitation rate would make the present escapement goal difficult to achieve and lead to a long-term decrease in production as occurred during 1950-1975. Although the escapement goal (40,000-60,000) has been largely maintained in recent years (1990-1993), smolt production appears to have steadily declined following the 1989 overescapement. As a result, future escapement deficits may occur regardless of harvest rates.

Kyle et al. (1988) showed that in nearby Frazer Lake, successive high escapements and subsequent large fry recruitments altered zooplankton species composition and decreased zooplankton biomass which lowered smolt growth and survival. In Akalura Lake, the excessive escapement (~116,000) in 1989 did not initially impact the macrozooplankton community as both the species composition, sizes, and seasonal mean biomass remained relatively unchanged in 1990 compared to the previous three years (Tables 14 and 15). However, as Akalura Lake produces predominantly age-2 smolt, the large number of fry rearing in the lake in 1990, concomitant with a large number of holdovers from the 1989 broodyear escapement reduced the 1991 total macrozooplankton (TMZ) biomass by 50%. The decline in TMZ biomass continued in 1992 even after moderate escapements in 1990 (47,000) and 1991 (44,000). As the age-2 holdovers from the 1989 escapement outmigrated, we believe that the low seasonal mean TMZ biomass during 1992 reflected a low recruitment of zooplankton. Copepods, which dominate the macrozooplankton community of Akalura Lake, typically produce only a single brood annually (Pennak 1953; Williamson 1991). As a result, we feel the recovery of the macrozooplankton community was delayed following consecutive years of heavy grazing by sockeye salmon juveniles. This is consistent with the finding of Barrett et al. (1993) that the 1993 age-1 smolt scale pattern was atypical, in that the pattern lacked an annulus and age-2 and age-3 smolt scales exhibited little plus growth, suggesting a lack of food (zooplankton) during 1992. In addition, the 1993 age-1 smolt were the smallest size on record, and the age-2 smolt were the largest size in the last four years, albeit fewer in number (Table 9). Quite possibly, the larger age-2 fish were able to outcompete the smaller age-1 fish, which may explain the different growth trends in the 1993 smolt population.

Based upon the number of spawners, the 1990 age-2 smolt population (408,330) produced from the 1987 broodyear escapement of 6,116 represents a relatively high freshwater survival. That is, assuming a 50:50 sex ratio, a fecundity of 2,500 eggs/female, and a potential egg deposition to emergent fry survival of 10% (Foerester 1968), this escapement would be estimated to produce ~765,000 spring fry. Given a spring fry-to-smolt survival of 20% (Koenings and Burkett 1987), this number of spring fry would yield only ~152,000 smolt. Thus, the 1990 smolt population estimate (474,790) was nearly 3 times more than expected. Nonetheless, post-1990 smolt production is much less than expected.

A significant relationship has been derived between sockeye salmon smolt production and zooplankton biomass (Kyle et al. 1993). Considering the TMZ biomass (mean 247 mg m^{-2}) during 1988 and 1989, we would expect Akalura Lake to have produced ~2,500 kg of smolt, which approximated the 1990 total smolt biomass (2,403 kg). Based on the mean age-2 smolt size (5.3 g), this would translate to ~450,000 smolt which is consistent with the estimated 1990 age-2 smolt production (408,000). Furthermore, using a smolt-to-adult survival of 21% (Koenings et al. 1993), this would equate to a total return of ~95,000 adults, which is also consistent with the potential sockeye salmon production (~100,000) based on euphotic volume. However, the 1991 age-2 smolt which reared under similar forage levels (mean 236 mg m^{-2}) during 1989 and 1990 were considerably smaller (4 g), and totalled only ~300,000. If this decrease in smolt size (and abundance) resulted from overgrazing, then we would expect differences in zooplankton size and species composition between the years of high and low sockeye salmon fry densities (Goodlad et al. 1974; Mills and Schiavone 1982). Instead, we observed no change in the zooplankton community structure in the year following the 1989 overescapement. Surprisingly, the 1991 age-2 smolt were smaller in size (4.0 g) than the 1991 age-1 smolt (4.3 g). We know of no other sockeye salmon system in which this has occurred; however, the age-1 smolt weight and length data may be biased by the relatively small sample size (n = 41). Although the recent (1991 and 1992) age-1 smolt sizes were within the historical (1969-1977) range, the 1991 and 1992 age-2 smolt sizes were not. Thus, this discrepancy remains an anomaly. In addition, the 1991 age-2 smolt were much larger (4 g) than the age-2 juveniles (2.4 g) caught on 11 May 1991 via townetting. It is unlikely that these pre-smolts (age-2) increased in size by 1.6 g or nearly 70% between early and late May when most of the outmigration occur. However, the townet sample may not be representative of the age-2 smolt population if it is assumed that the larger fish could more easily avoid the townet. Also, it is possible that not all age-2 fry outmigrated, but some held over for an additional year of rearing. Nonetheless, the total smolt biomass produced in 1991 (1,200 kg) was only ~50% of that produced in 1990, and in both 1992 and 1993 smolt biomass decreased even further (721 kg and 424 kg, respectively). However, based on the respective forage (zooplankton biomass) levels, the predicted smolt biomass (Kyle et al. 1993) for the last three years exceeded the actual smolt biomass. Thus, there is apparently some other mechanism(s), in addition to the level of forage, that is responsible for the apparent decline in smolt production.

It has been suggested that competitive interaction between stickleback and sockeye salmon fry for zooplankton within the pelagic zone of a lake may reduce juvenile sockeye growth and survival (Rogers 1968; Goodlad et al. 1974; O'Neill and Hyatt 1987). Such interspecific competition would be most severe during periods of reduced food supply, e.g during winter or prior to the spring zooplankton bloom. Since diet studies have not been conducted in Akalura Lake, it is difficult to assess the degree of interspecific (or intraspecific) competition. Although we lack population estimates of stickleback (and sockeye salmon fry) prior to 1990, it is possible that the relative abundance of each species has changed over time. We suggest that the very large stickleback population in the limnetic zone of Akalura Lake, as evidenced by the hydroacoustic/townet surveys, may at times influence food availability to juvenile sockeye salmon through changes in feeding behavior when (or where) food resources are low. In addition, the relatively shallow depth, warm temperatures, and high nutrient levels provide a favorable environment for stickleback growth, and contribute to the large population in Akalura Lake.

Finally, we reject the idea that increased nutrient (phosphorus) loading from the large number of carcasses deposited in the lake from the 1989 escapement differentially benefited stickleback populations at the expense of sockeye salmon smolt production. Since monitoring began in 1987 seasonal TP levels have remained >10 µg L^{-1}, which indicates that Akalura Lake is relatively productive compared to other sockeye salmon nursery lakes. In fact, this lake is considered a mesoeutrophic system based on both TP and algal biomass (chl *a*) levels (Carlson 1977; Lambou et al. 1982; Woods 1986). In addition, the phytoplankton assemblage is dominated by large numbers of diatoms including *Stephanodiscus*, *Fragilaria*, and *Melosira* as well as periodic blooms of the blue-green *Anabaena*. These phytoplankton species represent an energy sink as they are considered immune from zooplankton grazing (Gliwicz 1975; Infante and Litt 1985). Thus, given the current fertility of Akalura Lake, increasing nutrient loading through a lake fertilization project could increase the biomass of the less desirable (inedible) phytoplankton species (Watson et al. 1992) without benefiting zooplankton or juvenile sockeye salmon growth (Stockner and Hyatt 1984). If zooplankton availability to sockeye salmon fry is influenced by the presence of stickleback, then ensuring sufficient fry recruitment by maintaining the current escapement goal would lessen the intensity of competition and should lead to increased smolt production.

RECOMMENDATIONS

It appears that the current forage base in Akalura Lake is sufficient to produce more smolt than has been observed in recent years. Interspecific competition between juvenile sockeye salmon and sticklebacks may limit smolt production; however, juvenile sockeye salmon are known to have a competitive advantage. Consequently, we recommend targeting the upper level (60,000) of the current escapement goal range to maximize fry production. We also recommend continued qualitative smolt sampling to further assess sockeye salmon smolt size and age of outmigrants. Lastly, limnological sampling should continue monthly to assess lake productivity.

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Table 1. Sockeye salmon escapement, commercial harvest, total run, and exploitation rate for Akalura Lake, 1923-1993.

Year	Escapement[a]	Harvest[b]	Total	Exploitation Rate (%)
1923	15,855	15,682	31,537	50
1924	19,867	15,706	35,573	44
1925	40,910	16,788	57,698	29
1926	105,142	43,071	148,213	29
1927	87,949	48,103	136,052	35
1928	72,550	36,591	109,141	34
1929	18,094	12,022	30,116	40
1930	9,907	4,343	14,250	30
1931	29,100	22,129	51,229	43
1932	72,106	66,012	138,118	48
1933	90,448	ND[c]	ND	ND
1934	145,219	ND	ND	ND
1935	85,025	34,677	119,702	29
1936	100,447	ND	ND	ND
Mean 1923-1936	**63,759**	**28,648**	**79,239**	**37**
1937	252,193	424,414	676,607	63
1938	97,455	73,079	170,534	43
1939	59,486	86,469	145,955	59
1940	73,517	117,628	191,145	62
1941	46,609	48,451	95,060	51
1942	48,521	87,650	136,171	64
1943	ND	ND	ND	ND
1944	79,638	100,549	180,187	56
1945	118,234	79,137	197,371	40
1946	47,900	77,943	125,843	62
1947	50,068	99,079	149,147	66
1948	39,856	83,015	122,871	68
1949	19,862	27,877	47,739	58
Mean 1937-1949	**77,778**	**108,774**	**186,553**	**58**
1950	6,180	6,139	12,319	50
1951	5,888	1,911	7,799	24
1952	16,793	14,890	31,683	47
1953	15,053	6,595	21,648	30
1954	2,105	1,841	3,946	47
1955	2,128	1,258	3,386	37
1956	1,828	899	2,727	33
1957	5,740	1,826	7,566	24
1958	5,658	2,292	7,950	29
1959-1969	ND	ND	ND	ND
1970	3,992	5,919	9,911	60
1971	3,618	4,295	7,913	54
1972	9,001	1,178	10,179	12
1973	5,769	434	6,203	7
1974	35,112	7,238	42,350	17
1975	16,129	3,246	19,375	17
Mean 1950-1975	**9,000**	**3,997**	**12,997**	**33**
1976-1985	ND	ND	ND	ND
1986	13,440	83,380	93,180	89
1987	6,116	9,067	15,183	60
1988	38,618	86,541	125,159	69
1989	116,029	0[d]	ND	ND
1990	47,181	114,575	161,756	71
1991	44,189	95,689	139,878	68
1992	63,296	70,271	133,567	53
1993	30,691	68,660	99,351	69
Mean 1986-1993	**44,945**	**75,455**	**109,725**	**68**
Mean 1923-1993	**47,357**	**49,079**	**90,517**	**46**

[a]Source for 1923-1971 data was Hennick and Bevan (1970), and 1972-1993 data was ADF&G annual reports.

[b]Harvest during 1923-1975 was projected on relative proportions of escapements into Upper Station and Akalura lakes; 1986-1988 data from Swanton (1992); and 1990-1993 data from Barrett (per. comm. ADF&G, Kodiak, AK).

[c]Indicates no data.

[d]Fishing was closed due to the *Exxon Valdez* oil spill.

Table 2. Age composition of the early and late run adult sockeye salmon escapement in Akalura Lake, 1986-1993.

Return Year	Run	Sample Size	Percent/ Number	Age Class											Total
				0.2	1.1	0.3	1.2	2.1	1.3	2.2	3.1	1.4	2.3	3.2	
1986	Early	211	%	0.5	23.2	0.5	18.5	3.3	19.4	18.0	0.0	0.0	16.6	0.0	100.0
			n	17	845	17	673	121	707	656	0	0	604	0	3,640
	Late	145	%	0.0	0.0	0.7	2.1	0.0	22.8	55.2	0.0	0.0	17.9	1.4	100.0
			n	0	0	68	203	0	2,229	5,402	0	0	1,756	135	9,792
1987	Early	192	%	0.0	5.2	0.5	49.5	4.2	27.1	2.1	0.0	0.0	11.4	0.0	100.0
			n	0	144	14	1,370	115	750	58	0	0	317	0	2,769
	Late	173	%	0.6	0.6	0.6	60.1	1.7	6.4	23.1	0.0	0.0	6.9	0.0	100.0
			n	19	19	19	2,012	58	213	774	0	0	232	0	3,347
1988	Early	346	%	0.0	0.9	0.0	2.6	0.9	88.7	2.0	0.0	0.3	4.6	0.0	100.0
			n	0	37	0	110	37	3,743	85	0	12	195	0	4,219
	Late	380	%	0.0	0.0	0.0	3.9	0.5	10.3	81.8	0.0	0.0	3.4	0.0	100.0
			n	0	0	0	1,358	181	3,530	28,153	0	0	1,177	0	34,399
1989[a]	Late	441	%	0.0	0.0	0.2	1.4	0.5	4.8	44.4	0.0	0.0	47.8	0.9	100.0
			n	0	0	263	1,579	526	5,525	51,568	0	0	55,515	1,052	116,029
1990	Early	311	%	0.0	17.7	0.0	50.1	3.2	4.8	23.2	0.0	0.0	1.0	0.0	100.0
			n	0	590	0	1,674	107	161	773	0	0	32	0	3,338
	Late	767	%	0.0	0.0	0.4	9.6	0.0	3.8	64.0	0.0	0.0	21.4	0.6	100.0
			n	0	0	196	4,225	18	1,686	28,080	0	0	9,385	252	43,843
1991[a]	Late	584	%	0.0	0.0	0.0	9.7	0.7	9.2	71.0	0.0	0.0	9.4	0.0	100.0
			n	0	0	0	4,051	312	3,817	29,524	0	0	3,895	0	41,598
1992	Early	418	%	0.0	0.5	0.0	13.5	1.4	51.9	21.9	0.0	0.7	10.0	0.0	100.0
			n	0	12	0	335	36	1,289	543	0	17	248	0	2,484
	Late	553	%	0.0	0.0	0.0	0.9	0.0	2.4	82.5	0.0	0.0	13.4	0.7	100.0
			n	0	0	0	574	27	1,485	50,153	0	0	8,133	441	60,812
1993	Early	99	%	0.0	0.0	0.0	5.1	0.0	51.5	17.2	0.0	0.0	24.2	1.9	100.0
			n	0	0	0	92	0	930	311	0	0	438	35	1,807
	Late	661	%	0.0	0.1	0.0	18.2	0.3	4.3	45.5	0.1	0.0	31.4	0.1	100.0
			n	0	22	0	5,251	85	1,252	13,145	22	0	9,083	22	28,885

[a]No early run samples.

Table 3. Density and population estimate of juvenile fish in Akalura Lake by transect for the 1990 and 1991 hydroacoustic surveys.

Transect	Density (no. m^{-2} x 1000)	Area (x 10^3 m^2) Transect	Total	Weighted Density (no. m^{-2} x 1000)	Density Variance	Population	Pop. Variance
1990							
1	154.60	612					
2	640.56	1,018	1,630	458.1	5.54 x10^4	7,467,056	1.5 x10^{11}
3	803.30	948					
4	847.80	851	1,799	824.2	4.94 x10^2	1,483,006	1.6 x10^9
5	123.30	872					
6	1,066.20	600	1,472	1,168.7	7.24 x10^3	1,720,390	1.6 x10^{10}
Total		**4,901**				**3,950,101**	**1.68 x10^{11}**
				95% Confidence Interval (+/-)		802,403	
1991							
1	455.03	593					
2	499.64	574	1,167	477.0	4.97 x10^2	556,626	6.8 x10^8
3	767.64	1,514					
4	564.63	966	2,480	688.6	9.80 x10^3	1,707,640	6.0 x10^{10}
5	802.92	745					
6	603.24	501	1,255	723.2	9.56 x10^3	907,625	1.5 x10^{10}
Total		**4,901**				**3,171,891**	**7.60 x10^{10}**
				95% Confidence Interval (+/-)		540,335	

Table 4. Vertical distribution of fish density by depth strata for the 1990 and 1991 fall hydroacoustic surveys at Akalura Lake.

Survey year	Strata (m)	Density (no. m^{-2} x 1000)	Relative Percent
1990	2-5	5,241	36.0
	5-9.5	5,273	36.2
	9.5-14.0	2,245	15.4
	14.0-18.5	1,599	11.0
	18.5-23.0	203	1.4
	23.0-27.0	0	0.0
	Total	**14,562**	**100.0**
1991	2-5	5,988	54.0
	5-9.5	3,452	31.2
	9.5-14.0	1,206	10.9
	14.0-18.5	419	3.8
	18.5-23.0	15	0.1
	23.0-27.0	0	0.0
	Total	**11,079**	**100.0**

Table 5. Summary of the number of fish caught, percent composition, and catch-per-unit (CPUE) in Akalura Lake based on townetting in 1990 and 1991.

Date	Tow Duration (min)	Sockeye Catch	Sockeye %	Sockeye CPUE	Stickleback Catch	Stickleback %	Stickleback CPUE
09/29/90	70	237	5.3	3.4	4,252	94.7	60.7
05/11/91	72	50	11.4	0.69	387	88.6	5.4
10/05/91	75	147	1.3	2	10,765	98.7	143.5

Table 6. Age, size, and condition coefficient of juvenile sockeye salmon collected in Akalura Lake during the 1991 townet surveys.

Date	Number	Age	Percent composition	Weight (g)	Length (mm)	Condition Coefficient (K)
11-May	3	0	6.8	0.2	29	0.79
	24	1	54.5	1.0	50	0.78
	17	2	38.6	2.4	68	0.74
Total	**44**[a]					
5-Oct	54	0	36.7	1.4	52	0.95
	93	1	63.3	3.8	74	0.93
Total	**147**					

[a]10 of the 54 sockeye salmon fry caught were not sampled.

Table 7. Population estimates and age compositions of sockeye salmon smolt out-migrating from Akalura Lake, 1990-1993.

Smolt Year	**Number and Relative (Percentages) of Smolt by Age Class**				**Total No. Smolt**	**95% Confidence Interval**	
	1	**2**	**3**	**4**		**Low**	**High**
1990	66,460	408,330	0	0	474,790	318,734	630,846
	(14)	(86)	(0)	(0)			
1991	9,085	299,591	1,251	0	309,928	237,981	381,875
	(2.9)	(96.7)	(0.4)	(0)			
1992	1,921	182,963	8,315	0	193,199	153,765	232,638
	(0.9)	(94.7)	(4.3)	(0)			
1993	3,259	73,062	12,315	238	88,874	35,943	141,802
	(3.7)	(82.3)	(13.9)	(0.1)			

Table 8. Sockeye salmon escapement and number of smolt produced by broodyear for Akálura Lake, 1988-1993.

Brood Year	Escapement	Smolt Produced by Age Class 1	2	3	4	Total No. Smolts
1986	9,800	[a]	[a]	0	0	[a]
1987	6,116	[a]	408,331	1,251	0	409,582[b]
1988	36,618	66,460	299,591	8,315	238	374,604
1989	116,029	9,086	182,963	12,315	[c]	204,364
1990	47,181	1,921	73,062	[c]	[c]	74,983
1991	44,189	3,259	[c]	[c]	[c]	3,259
1992	63,296					
1993	30,692					

[a]Smolt outmigration not monitored.

[b]Incomplete broodyear data.

[c]Smolt of this age class have not outmigrated.

Table 9. Summary of mean length and weight by age class of smolt sampled in Akalura Lake during 1969-1977 and 1990-1993.

Smolt Year	Age-0 N	Age-0 Length (mm)	Age-0 Weight (g)	Age-1 N	Age-1 Length (mm)	Age-1 Weight (g)	Age-2 N	Age-2 Length (mm)	Age-2 Weight (g)	Age-3 N	Age-3 Length (mm)	Age-3 Weight (g)	Age-4 N	Age-4 Length (mm)	Age-4 Weight (g)
1969	0			575	80.0	4.2	0								
1970	0			78	94.0	7.6	845	99.0	8.4	0			0		
1971	0			541	77.0	3.8	82	96.0	7.3	0			0		
1972	0			835	83.0	4.8	25	95.0	7.2	0			0		
1973	0			485	90.0	6.7	466	98.0	8.6	0			0		
1974	0			53	88.0	6.2	890	96.0	8.2	0			0		
1975	0			106	78.0	3.9	611	92.0	6.4	0			0		
1976	0			10	81.0	5.2	297	92.0	7.7	0			0		
1977	0			2	75.0	4.2	462	94.0	7.3	0			0		
													0		
1990	0			577	73.9	3.6	748	85.9	5.3	0			0		
1991	0			41	77.2	4.3	1,382	77.5	4.0	22	97.3	8.9	0		
1992	1	59	1.5	25	75.7	3.7	2,014	78.8	3.9	61	86.4	4.9	0		
1993	0			74	91.8	2.2	992	85.8	5.7	94	90.8	6.8	2	101.5	10.12

Table 10. Seasonal mean and standard deviation (S.D.) of general water-chemistry parameters, metals, nutrient concentrations and atom ratios, and algal pigments within the epilimnion (1 m) of Akalura Lake, 1987-1993.

	1987 (n=5)		1988 (n=3)		1989 (n=4)		1990 (n=6)				1991 (n=6)				1992 (n=6)				1993 (n=5)			
	Sta 1		Sta 1		Sta 1		Sta 1		Sta 2		Sta 1		Sta 2		Sta 1		Sta 2		Sta 1		Sta 2	
Parameter	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Sp. Cond. (umhos cm^{-1})	50	4	54	2	60	1	60	2	59	2	58	2	58	1	57	1	57	1	59	0	60	1
pH (Units)	6.8	0.2	6.7	0.4	7.0	0.2	7.2	0.2	7.1	0.2	7.1	0.1	7.1	0.1	6.9	0.2	7.0	0.1	6.8	0.1	6.9	0.1
Alkalinity (mg L^{-1})	14.0	0.7	13.7	1.5	13.8	1.9	14.8	1.1	15.0	0.8	13.9	2.2	14.2	1.9	15.1	2	14.6	0.7	14.9	0.2	15.0	0.4
Turbidity (NTU)	2.0	0.8	0.7	0.3	1.4	0.4	1.0	0.3	1.0	0.4	1.7	1.4	1.3	0.5	1.0	0.3	1.9	2.7	1.2	0.5	1.5	0.4
Color (Pt units)	6	3	8	2	8	1	7	2	7	2	6	1	9	3	5	2	6	2	7	7	6	4
Calcium (mg L^{-1})	4.4	0.5	NA[a]	--	3.6	2.4	4.9	0.5	5.6	2.7	4.8	0.7	5.0	0.8	5.3	1.1	5.3	0.8	4.8	0.1	4.7	0.6
Magnesium (mg L^{-1})	1.6	1.7	NA	--	0.8	0.9	1.5	0.5	1.2	0.6	1.5	0.7	1.0	0.6	0.9	0.7	1.3	0.7	1.6	0.2	1.5	0.2
Iron (ug L^{-1})	102	32	31	21	141	100	136	53	435	758	67	33	61	35	91	26	84	40	52	16	90	46
Total - P (ug L^{-1})	17.8	4.2	12.1	5.6	11.0	2.4	11.4	3.2	11.3	2.2	11.8	1.6	11.9	3.1	16.4	0.9	15.5	2.3	14.1	3.0	14.1	3.5
Total filterable - P (ug L^{-1})	6.8	2.8	5.7	0.5	5.2	1.7	3.2	1.5	3.6	2.3	3.9	0.7	8.4	6.8	4.9	0.8	5.5	1.2	7.1	4.0	6.2	3.4
Filterable reactive -P (ug L^{-1})	2.5	1.9	2.3	1.1	2.3	0.7	1.5	0.4	1.4	1.1	1.5	0.7	4.5	3.7	2.2	0.6	2.5	0.9	4.8	4.3	3.3	2.1
Total Kjeldahl - N (ug L^{-1})	229	22	164	74	146	13	174	29	159	20	161	23	158	17	167	21	156	30	195	16	197	21
Ammonia (ug L^{-1})	6.9	7.4	16.2	17.2	8.0	6.9	15.6	21.4	15.9	20.1	11.5	12.2	12.6	12.4	7.4	8.2	6.6	10.8	9.9	14.0	9.0	13.9
Nitrate+nitrite (ug L^{-1})	29	35	20	15	21	17	30	27	21	20	20	27	18	27	5	5	5	6	9	13	8	12
N:P atom ratio	33	5	34	5	34	5	40	8	36	8	34	3	34	6	23	3	23	4	33	4	33	3
Reactive silicon (ug L^{-1})	292	187	325	159	394	356	441	245	316	198	283	252	284	244	789	401	769	426	656	401	615	429
Chlorophyll *a* (ug L^{-1})	6.0	3.4	3.5	2.8	4.2	3.2	3.9	1.8	4.3	1.7	5.1	5.1	3.6	2.2	3.0	2.0	2.8	2.0	5.2	2.5	4.7	4.9
Phaeophytin (ug L^{-1})	2.6	2.7	1.1	0.8	2.5	2.5	1.4	0.5	1.4	0.5	1.3	1.5	1.5	0.9	1.6	0.9	1.7	1.1	0.8	0.6	1.1	0.7

[a]Indicates not available

Table 11. Seasonal mean and standard deviation (S.D.) of general water-chemistry parameters, metals, nutrient concentrations and atom ratios, and algal pigments within the hypolimnion of Akalura Lake, 1987-1993.

	1987 (n=5)		1988 (n=3)		1989 (n=4)		1990 (n=6)				1991 (n=6)				1992 (n=6)				1993 (n=5)			
	Sta 1		Sta 1		Sta 1		Sta 1		Sta 2		Sta 1		Sta 2		Sta 1		Sta 2		Sta 1		Sta 2	
Parameter	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
Sp. Cond. (umhos cm^{-1})	52	2	55	3	61	1	60	3	58	4	59	2	58	3	58	2	57	6	61	2	61	2
pH (Units)	6.7	0.2	6.6	0.3	7	0.1	6.9	0.4	6.8	0.3	6.9	0.2	6.9	0.2	6.9	0.2	6.9	0.2	6.6	0.2	6.6	0.2
Alkalinity (mg L^{-1})	14.6	0.5	14.0	1.0	14.8	1.0	16.0	1.7	15.8	1.1	14.3	2.1	14.4	2.0	14.8	0.6	13.4	2.7	15.7	1.2	15.0	0.7
Turbidity (NTU)	2.2	1.2	1.6	1.2	1.5	1	2	1	2	0	1.4	0.5	1.3	0.5	1.1	0.3	0.9	0.5	1.8	0.8	1.6	0.3
Color (Pt units)	5	3	11	4	9	1	9	2	7	3	7	3	7	3	8	3	6	2	5	3	4	2
Calcium (mg L^{-1})	3.8	1.8	NA[a]	--	5.4	1.6	5.1	0.9	4.8	0.6	5.1	0.8	4.6	0.5	5.1	0.9	4.6	0.6	4.6	0.5	4.9	0.1
Magnesium (mg L^{-1})	1.2	0.3	NA	--	1.0	0.7	1.5	0.8	1.5	0.3	1.1	0.7	1.6	0.4	0.9	0.7	1.3	0.6	1.6	0.2	1.5	0.2
Iron (ug L^{-1})	142	46	875	1409	232	174	381	413	288	257	172	173	179	216	185	129	142	139	301	290	245	241
Total - P (ug L^{-1})	18.6	4.7	17.8	8.6	12.6	2.8	15.0	4.1	13.7	2.4	13.2	3.1	13.7	4.5	20.2	3.2	16.1	5.8	20.0	7.6	17.7	6.3
Total filterable - P (ug L^{-1})	4.8	0.9	6.4	2.9	4.9	1.8	4.5	1.2	3.6	2.2	4.3	1.2	4.5	1.3	7.5	4.0	5.8	2.6	5.9	2.2	5.0	1.8
Filterable reactive -P (ug L^{-1})	1.4	0.1	3.2	1.6	2.3	0.4	2.1	0.9	1.6	0.5	1.9	1.2	2.0	1.3	3.8	2.6	3.0	1.7	3.2	1.3	2.7	1.4
Total Kjeldahl - N (ug L^{-1})	225	12	243	154	221	57	279	107	262	83	166	32	168	34	148	17	156	19	235	57	214	49
Ammonia (ug L^{-1})	20.8	28.7	63.4	75.7	89.5	98	117.5	110.5	101.1	94.5	38.5	27.3	40.4	37.4	10.2	9.5	7.9	8.5	51.3	46.9	42.1	41.1
Nitrate+nitrite (ug L^{-1})	29	31	22	19	42	25	35	24	29	15	37	29	36	30	5	5	15	18	17	17	17	17
N:P atom ratio	32	8	33	6	44	16	48	13	48	15	35	4	34	6	17	3	28	17	29	3	30	4
Reactive silicon (ug L^{-1})	413	183	661	554	487	398	576	388	535	420	427	311	426	351	895	423	798	524	880	582	984	525
Chlorophyll *a* (ug L^{-1})	5.6	3.7	4.2	4.3	2.0	1.7	3.0	2.2	3.5	3.1	4.4	3.3	4.2	3.3	4.3	2.9	3.4	1.9	4.4	4.1	4.1	3.4
Phaeophytin (ug L^{-1})	1.6	0.8	1.8	1.1	0.9	0.3	1.5	0.5	1.4	0.6	1.5	0.8	1.3	0.4	1.3	0.5	1.9	1.0	1.1	0.6	0.9	0.6

[a]Indicates not available

Table 12. Major phytoplankton taxa found in Akalura Lake.

DIATOMS	CHRYSOPHYTES	CYANOPHYTES
Achnanthes	Chromulina	Anabaena
Asterionella formosa	Chrysochromulina	Chroococcus
Fragilaria crotonensis	Cryptomonas	Microcystis
Fragilaria	Dinobryon lorica	Oscillatoria
Synedra	Dinobryon cell	
Melosira	Mallomonas	
Tabellaria	Kephyrion	
Cyclotella	Crucigenia	
Stephanodiscus	Quadriguia	
Nitzschia	Bitrichia	
CHLOROPHYTES	**CRYPTOPHYTES**	**PYRROPHYTES**
Ankistrodesmus	Chroomonas acula	Gymnodinium
Cosmarium	Rhodomonos	Peridinium
Scenedesmus		
Staurastrum		

Table 13. Summary of phytoplankton density and volume for major taxa found within the epilimnion (1 m) of Akalura Lake, 1988-1991.

		DIATOMS		CHRYSOPHYTES		CYANOPHYTES		OTHERS		MICRO-ALGAE		TOTAL	
Date	Station	Cell number ($x\ 10^9\ m^{-3}$)	Cell volume ($mm^3\ m^{-3}$)	Cell number ($x\ 10^9\ m^{-3}$)	Cell volume ($mm^3\ m^{-3}$)	Cell number ($x\ 10^9\ m^{-3}$)	Cell volume ($mm^3\ m^{-3}$)	Cell number ($x\ 10^9\ m^{-3}$)	Cell volume ($mm^3\ m^{-3}$)	Cell number ($x\ 10^9\ m^{-3}$)	Cell volume ($mm^3\ m^{-3}$)	Cell number ($x\ 10^9\ m^{-3}$)	Cell volume ($mm^3\ m^{-3}$)
06/06/88	1	1.78	804.5	0.25	10.7	0	0	0.31	59.9	1.99	13.9	4.3	889.0
08/09/88	1	1.11	1074.6	1.68	248.5	0.07	35.7	0.18	29.3	3.99	22.5	7.0	1410.6
09/30/88	1	0.94	769.8	0.64	79.9	0	0	0.23	67.1	3.72	21.6	5.5	938.4
05/10/89	1	1.18	1714.0	3.01	354.3	0	0	1.20	1704.7	8.39	64.1	13.8	3837.1
06/26/89	1	3.53	1422.7	2.20	249.3	0.07	6.7	1.20	403.7	3.73	30.1	10.7	2112.5
05/16/91	1	7.52	1371.4	0.99	94.8	1.57	117.9	0.05	4.8	4.05	8.1	14.2	1597.0
05/16/91	2	3.92	569.6	0.99	102.7	1.58	118.8	0.13	7.5	3.54	7.1	10.2	805.7
06/11/91	1	1.30	168.3	1.30	74.8	0	0	0.17	19.5	0	0	2.8	262.6
06/11/91	2	1.33	165.5	0.76	15.2	6.86	514.3	0.38	42.9	0	0	9.3	737.9
07/07/91	1	0.18	42.3	1.46	53.6	1.56	117.3	0.18	26.2	1.79	3.6	5.2	243.0
07/07/91	2	0.75	152.5	2.13	106.3	7.04	528.1	0.63	75.4	0.87	8.8	11.4	871.1
08/05/91	1	0.37	55.6	1.19	25.7	0	0	0.37	63.7	7.48	27.5	9.4	172.5
08/05/91	2	0.13	37.7	0.72	33.2	0	0	0.31	54.1	0.26	2.6	1.4	127.6
09/10/91	1	1.87	366.7	0.33	5.0	0	0	0.27	16.0	1.20	47.4	3.7	435.1
09/10/91	2	2.00	283.3	1.17	31.0	0	0	0.83	10.8	5.49	146.0	9.5	471.1

Table 14. Seasonal mean macrozooplankton density (number m^{-2}) and body size (mm) by taxa in Akalura Lake, 1987-1993.

	1987 (n=5)		1988 (n=3)		1989 (n=4)		1990 (n=6)			
	Sta 1		Sta 1		Sta 1		Sta 1		Sta 2	
Taxa	Density	Size	Density	Size	Density	Size	Density	Size	Density	Size
y s	16,242	0.57	7,741	0.63	6,403	0.56	9,554	0.56	4,140	0.62
pisc ura	41,242	0.99	25,035	0.95	10,152	0.71	3,892	1.23	4,671	1.19
r asilus	0	–	0	–	465	0.56	487	0.51	531	0.48
urytemora	108,386	0.97	45,471	0.85	49,662	0.84	47,682	0.86	55,361	0.87
osmina	122,452	0.30	59,934	0.28	80,912	0.30	78,512	0.30	81,422	0.3
ydorinae	1,061	–	0	–	266	0.30	841	0.26	743	0.25
ap nia	0	–	0	–	66	–	44	0.56	0	–
TOTAL	**289,383**		**138,181**		**147,926**		**141,012**		**146,868**	

	1991 (n=6)				1992 (n=6)				1993 (n=5)			
	Sta 1		Sta 2		Sta 1		Sta 2		Sta 1		Sta 2	
	Density	Size	Density	Size	Density	Size	Density	Size	Density	Size	Density	Size
y s	5,600	0.62	6,086	0.55	4,582	0.65	4,158	0.69	8,217	0.61	9,098	0.57
pisc ura	5,989	0.97	7,360	1.08	7,369	0.82	1,575	1.01	11,274	0.82	12,166	0.97
r asilus	239	0.50	168	0.49	195	0.50	257	0.52	265	0.50	860	0.48
urytemora	19,896	0.87	17,560	0.92	11,332	1.02	9,952	0.86	42,972	0.83	24,501	0.89
osmina	44,197	0.29	39,048	0.30	9,687	0.30	6,989	0.31	45,308	0.29	31,221	0.30
ydorinae	292	–	770	0.26	531	0.47	97	0.25	1,921	0.24	977	0.26
ap nia	142	0.50	53	0.51	18	0.66	0	0.76	382	0.55	265	0.66
TOTAL	**76,355**		**71,045**		**33,714**		**23,028**		**110,339**		**79,088**	

Table 15. Summary of seasonal mean macrozooplankton biomass (mg m^{-2}) by taxa in Akalura Lake, 1987-1993.

	1987 (n=5)	1988 (n=3)	1989 (n=4)	1990 (n=6)		1991 (n=6)		1992 (n=6)		1993 (n=5)	
Taxa	**Sta 1**	**Sta 1**	**Sta 1**	**Sta 1**	**Sta 2**	**Sta 1**	**Sta 2**	**Sta 1**	**Sta 2**	**Sta 1**	**Sta 2**
Cyclops	18	10	7	10	5	7	6	6.5	7	10	10
Epischura	178	97	18	32	34	25	41	19	7	29	51
Ergasilus	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.6
Eurytemora	431	124	129	133	158	59	60	51	28	111	75
Bosmina	98	42	67	65	64	33	31	7.8	6	34	25
Chydorinae	0	0	0	0	0	0	0.5	1.1	0.1	1	0.6
Daphnia	0	0	0	0	0	0	0.1	0	0	0.5	0
TOTAL	725	273	221	240	261	124	139	86	48	186	162

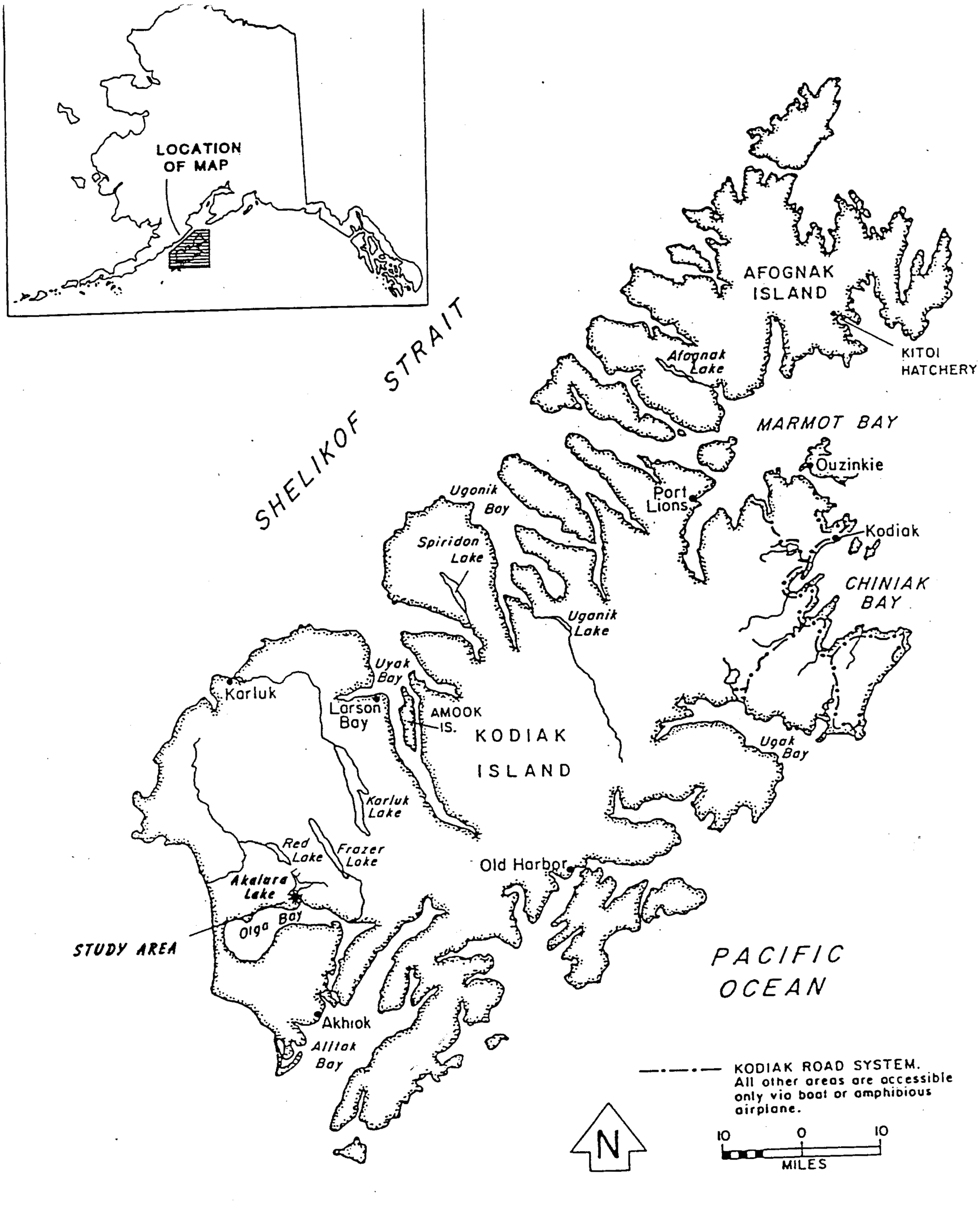

Figure 1. Location of Akalura Lake on Kodiak Island.

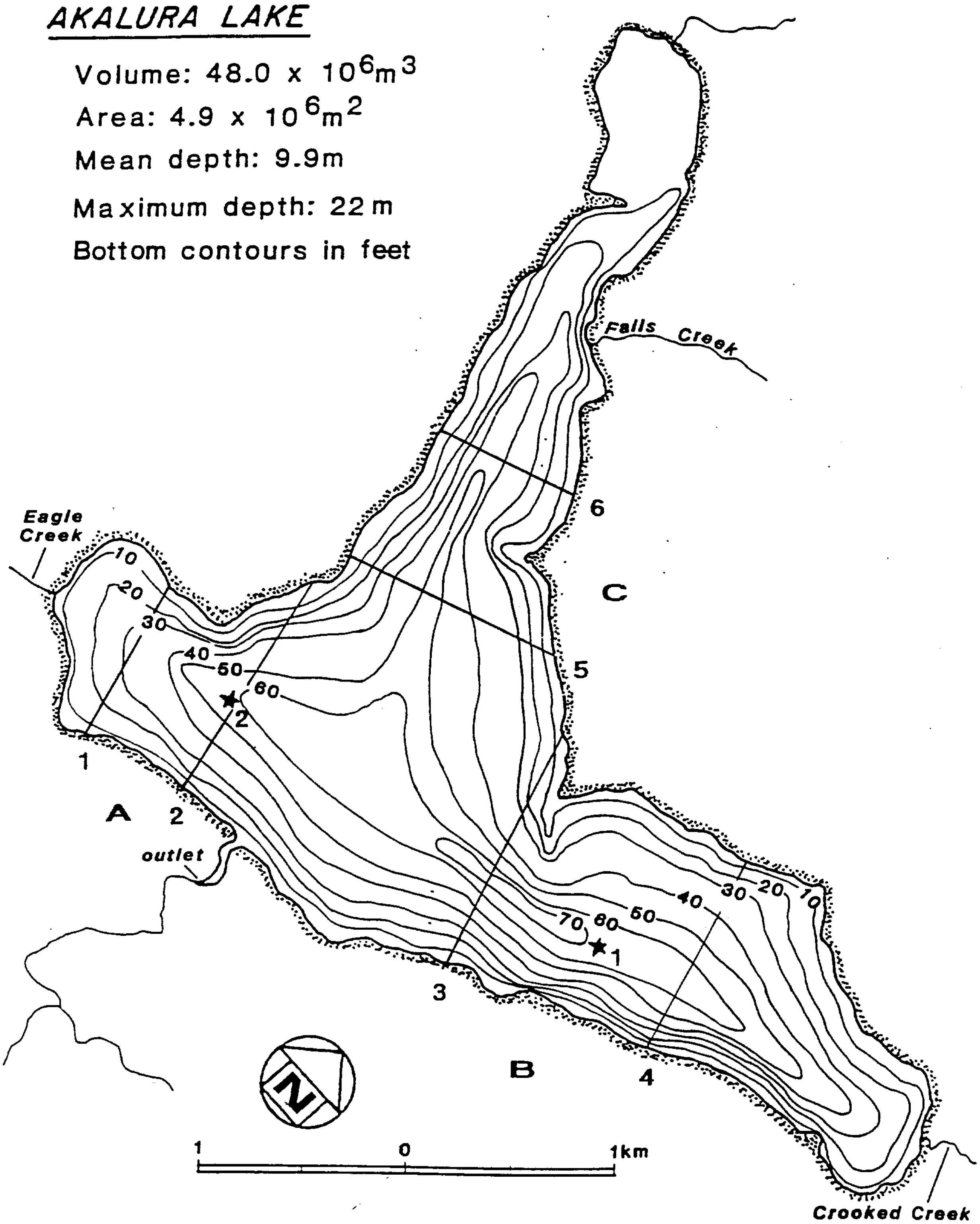

Figure 2. Bathymetric map of Akalura Lake showing the location of the limnology sampling stations, hydroacoustic areas (A-C), and transects (1-6).

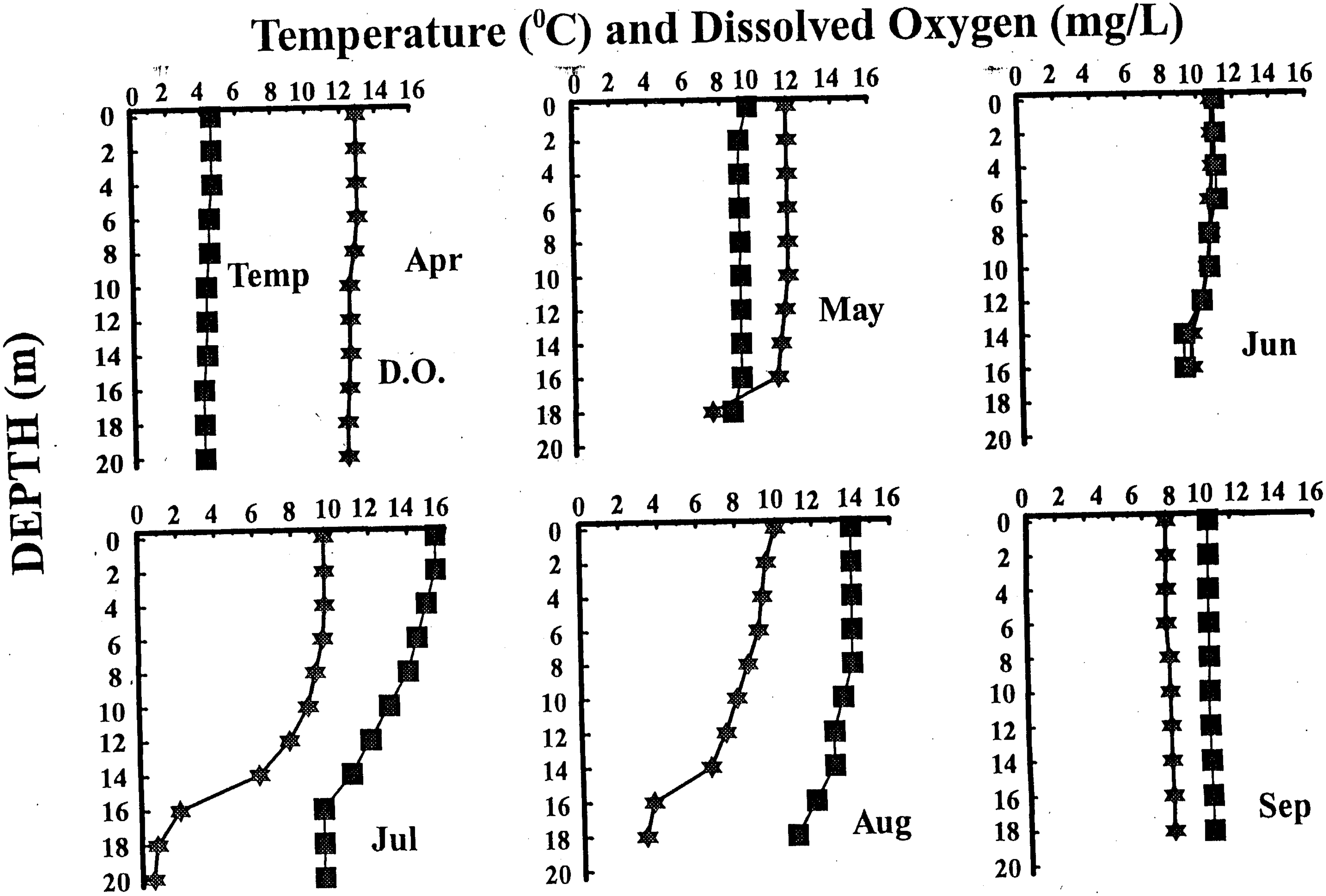

Figure 3. Seasonal changes in temperature and dissolved oxygen (D.O.) concentrations in Akalura Lake, 1990.