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Limnological and Fishery Investigations Concerning Sockeye Salmon Production In Delight and Desire Lakes

by

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ABSTRACT

Delight Lake and Desire Lake are important producers of sockeye salmon *Oncorhynchus nerka* in lower Cook Inlet. In 1989, the *Exxon Valdez* oil spill (EVOS) contaminated the waters of Nuka Bay, and light oiling was observed near the outlets of Delight and Desire Lakes. Although there is no direct evidence that the oil spill affected sockeye salmon production, commercial catches of sockeye salmon in the East Nuka Bay subdistrict averaged 7,300 after the spill compared to 29,800 prior to the spill. In addition, the Delight Lake terminal harvest fishery has remained closed since 1991. Reduced harvests and inadequate sockeye salmon escapement prompted limnology and fishery (sockeye smolt and adult enumeration) investigations of the Delight Lake and Desire Lake systems to help evaluate nutrient enrichment or other restoration options for these stocks. Results from limnological surveys carried out in 1997 revealed that both lakes are nutrient poor (mean total phosphorus concentration (5 $\mu g\ L^{-1}$) and have low chlorophyll levels and zooplankton densities. Zooplankton biomass, an index of food availability, was very low in both lakes and six times less in Desire Lake (mean 17 mg m^{-2}) compared to Delight Lake (mean 102 mg m^{-2}). Age-1 smolt (the predominant age class in both lakes) production in Desire Lake (76,353) in 1997 was only about one-sixth that of Delight Lake (468,184), yet the brood-year escapement was estimated to be the same for both (15,000) suggesting a smaller rearing capacity in Desire Lake relative to that of Delight Lake. However, poor returns to Delight Lake are attributed to the decline in the East Nuka Bay sockeye harvest. Based on the 1997 weir estimate of sockeye escapements and observations of spawning activity in the two lakes, we speculate that aerial surveys underestimated escapements for Delight Lake in past years. We recommend validating historical escapement estimates prior to designing or implementing a nutrient enrichment program to accelerate the recovery of the Delight and Desire sockeye stocks.

Key Words: *Oncorhynchus nerka*, sockeye salmon, sockeye escapement, smolt, zooplankton, oligotrophic, nutrient enrichment, restoration, Lower Cook Inlet, East Nuka Bay

INTRODUCTION

In March 1989, the *Exxon Valdez* Oil Spill (EVOS) caused heavy oiling to the beaches and near shore waters at the entrance to East Nuka Bay, and light oiling was observed near the outlet streams of Delight Lake and Desire Lakes (ADNR 1989). Delight and Desire Lakes are important producers of sockeye salmon (*Oncorhynchus nerka*) and these two systems contribute to most of the commercial salmon catch within the East Nuka Bay subdistrict on the outer coast of the Kenai Peninsula (ADF&G 1996). During 1975-1989, the sockeye run (catch and escapement) for the two lakes combined averaged 50,500; however, between 1990 and 1997 the combined run averaged only 27,900. Since 1991, there has been no commercial fishing on the Delight Lake stock in order to achieve adequate escapement. In 1992 the escapement was estimated to be well below the minimum goal set for both Delight and Desire lakes, and in that year the commercial fishery in the East Nuka Bay subdistrict was never opened. Since the oil spill event, the annual commercial catch for the East Nuka Bay sockeye fishery averaged 7,300 compared to 29,800 for the 14 years prior to the spill. Although the Delight and Desire Lakes historically supported a much higher annual catch of sockeye salmon, there is no evidence to date that the recent run decline and poor harvests were directly or indirectly related to the oil spill.

The salmon resource of Delight and Desire Lakes is also important to the residents of the nearby villages of Port Graham and Nanwalek. Subsistence usage by these communities dates back to the early 1900s (Stanek 1977) and actively continues today. In addition, Delight and Desire Lakes support a popular fly-in sport fishery for sockeye and coho (*Oncorhynchus kisutch*) salmon, as well as Dolly varden trout (*Salvelinus malma*); however, inadequate salmon escapements in recent years may have reduced the sport and subsistence fisheries. The EVOS Trustee Council (EVOSTC) identified sockeye salmon and lost fishing time as injured biological resources and services, respectively. In 1996, EVOSTC recognized that the sockeye runs of Delight and Desire Lakes were depressed and approved funding for limnological and fisheries studies (EVOSTC 1996). The purpose of these studies was to evaluate the rearing habitat of these lakes and to assess the feasibility of a nutrient enrichment or other fish habitat restoration options to accelerate the recovery of these sockeye salmon stocks. Because Delight and Desire Lakes have the only known wild sockeye salmon stocks found in the Outer District that are of commercial importance, fry stocking was not recommended by ADF&G as an appropriate means of restoring sockeye production in these two lakes. Therefore, our approach to assessing fry rearing capacity was not to produce estimates of stocking rates, but rather to evaluate carrying capacity under current conditions and the potential of lake fertilization to increase sockeye salmon production.

Studies suggest that growth and survival of juvenile sockeye salmon in lakes are closely tied to zooplankton biomass (Hyatt and Stockner 1985; Olsson et al. 1992; Schmidt et al. 1994; Ashley et al. 1997), euphotic volume (Koenings and Burkett 1987), and temperature (Edmundson 1997). Given good light conditions and adequate rearing temperatures, the addition of nutrients to salmon nursery lakes is designed to increase the zooplankton forage base and enhance both fry growth and in-lake survival. In general, larger and more numerous smolts survive better at sea resulting in larger populations of returning adults (Stockner 1987; Koenings et al. 1993; Kyle et al. 1997). In the

Pacific Northwest and Alaska, nutrient enrichment techniques have been used extensively to restore or enhance the productivity of sockeye salmon nursery lakes (Stockner and Macissac 1996; Kyle et al. 1987; Kyle 1994; Edmundson et al. 1997). Lakes selected for fertilization are based typically on evidence of nutrient (nitrogen and phosphorus) limitation of plankton production or historically depressed sockeye runs. It is presumed that several years of low returns results in a loss of essential nutrients derived from decomposing adult carcasses causing them to become less productive for rearing sockeye fry (Donaldson 1966; Stockner 1987; Stockner and Macissac 1996). Because spawning area and lake rearing habitat have a crucial nexus in stock and recruitment of fishes (Rigler 1982; Luecke et al. 1996; Schmidt et al. 1997), assessing freshwater rearing capacity can also serve as a foundation for evaluating management options for restoration of sockeye nursery lakes.

During the 1997 open water season, comprehensive limnological and fisheries studies were conducted at Delight and Desire Lakes. In addition to monitoring physical conditions and obtaining baseline information on nutrients and plankton, we enumerated sockeye salmon smolt outmigration and adult escapement in both lakes. These data are not only designed to assess current rearing capacity for sockeye juveniles, but also to assess changes in lake trophodynamics induced by nitrogen and phosphorus additions. In 1981 (and sporadically in 1986 and 1987), ADF&G conducted limnology surveys at both Delight and Desire Lakes as part of a statewide program to prioritize candidate lakes for fertilization; however, there was little published limnological information and data analysis on these lakes. In this report, we present information on morphometry, light and temperature regimes, nutrient trends and status, and plankton populations in Delight and Desire Lakes.

Objectives

The objective of this project is to provide a comprehensive assessment of the physical, chemical, and biological aspects of Delight and Desire Lakes. This assessment includes a description and interpretation of the limnology of these two lakes, the historical salmon fisheries data, and recommendations regarding restoration potential through nutrient enrichment or other restoration techniques. Specifically, we compare limnological conditions between these two lakes to assess the existing and potential rearing capacity of juvenile sockeye salmon. We also examine juvenile and adult sockeye information to evaluate nutrient enrichment and management strategies to aid in the restoration of these sockeye stocks.

Study Site Description

Delight Lake (59° 34'N, 150° 15'W) and Desire Lake (59° 35'N, 150° 15'W) are located on the outer Kenai Peninsula within the East Nuka Bay drainage (Figure 1). Both lakes lie within the maritime zone where coastal mountains can produce up to 380 cm precipitation annually (Milner et al. 1997). This region is characterized by coastal temperate rainforests that are influenced by the oceanic currents of the North Gulf Coast. From a geologic perspective, the Delight and Desire Lakee drainages are relatively new, having been deglaciated since about the 1930s (Milner 1997)

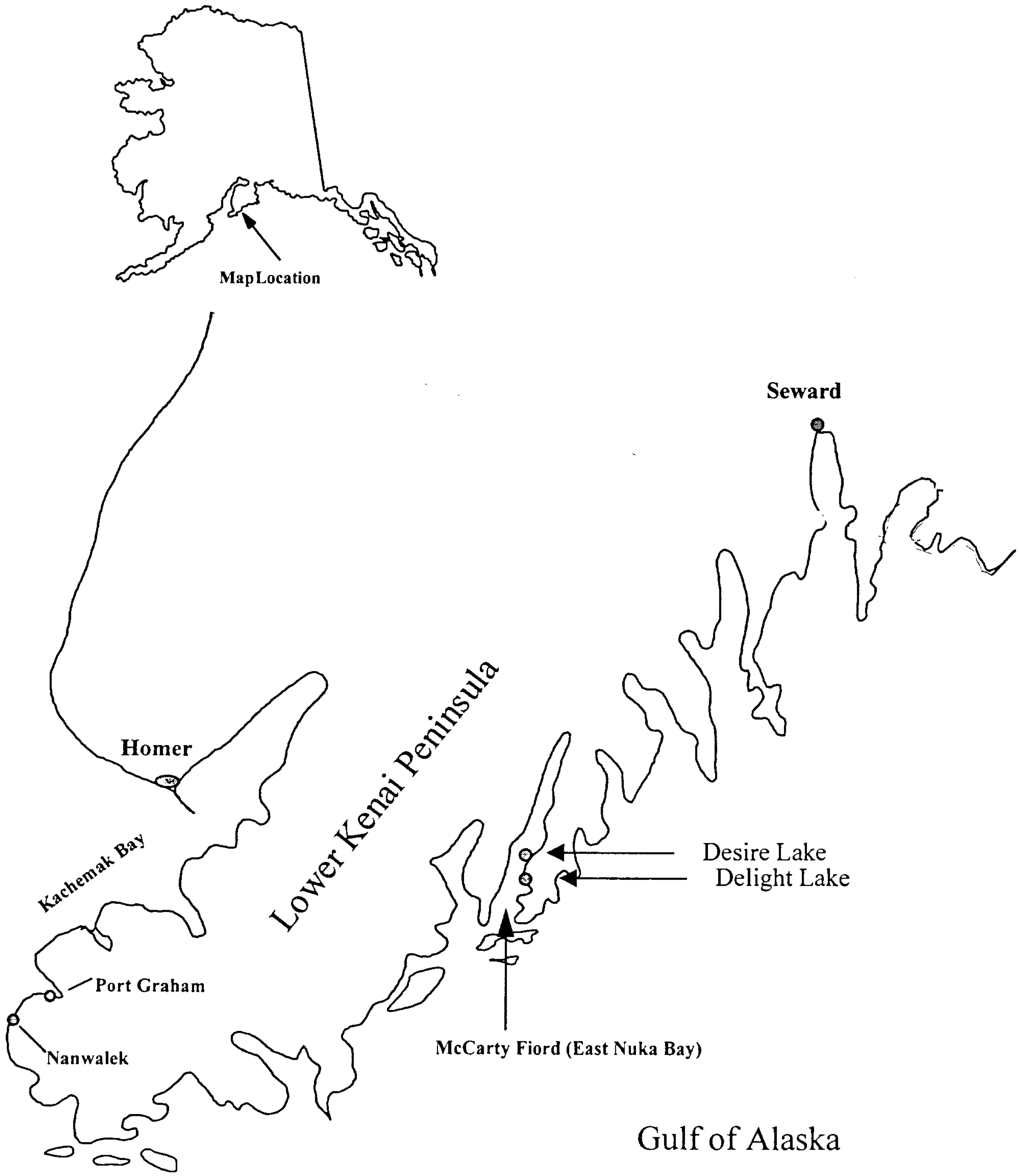

Figure 1. Geographic location of Delight and Desire Lakes, Kenai Peninsula.

The predominate vegetation type surrounding Delight Lake and its outlet stream is immature spruce (*Picea sitchensis*), whereas the vegetation within the Desire Lake drainage is largely old growth alder (*Alnus sp.*) (York and Milner 1996). Previously located within the Kenai Fjords National Park, the federal government recently conveyed lands bordering both lakes to the Port Graham Corporation, a private entity. Delight Lake is situated at an elevation of 15 m and its outlet flows approximately 3.5 km west into McCarty Lagoon. One small inlet creek enters the lake at the north end that drains a small, but very steep area. Desire Lake also lies at an elevation of 15 m and its outlet flows about 3 km before emptying into McCarty Fjord.

METHODS

Limnological Assessment

Morphometric data were calculated using bathymetric maps previously developed by ADF&G. At Delight Lake, we measured stream discharge using a Marsh-McBirney Model 201M water current meter, and at Desire Lake we used a Teledyne Gurley Model 700-flow velocity indicator. In addition, we measured water stage height at various flow rates using a graduated staff gauge anchored in the outlet stream of each lake. Drainage areas were delineated on USGS topographic maps and planimetered. Hydraulic residence time was estimated using multiple regression analysis of watershed characteristics (drainage area and mean annual precipitation) versus known system discharges within the Chugach National Forest (Anonymous 1979).

During 1997, we conducted five limnological surveys at Delight Lake (13 May, 17 June, 16 July, 13 August, and 01 October) and four surveys at Desire Lake. Poor weather precluded the 13 August survey at Desire Lake. Float-equipped aircraft were used for the sample trips. We located two primary sampling stations in each lake to reflect salient morphometric features (i.e., major basins and bays). Anchored buoys were not deployed; however, we were able to easily locate the sampling site by triangulating geographical landmarks and using depth soundings (Figures 2 and 3). At each of the main stations, we measured water column temperatures, dissolved oxygen levels, underwater irradiance and water transparency, and collected samples for water chemistry, nutrient, and plankton analysis. Zooplankton samples were collected at two additional sites on each lake.

Vertical profiles of temperature were measured at 1-m increments from the surface to the lake bottom using a YSI model 57 oxygen analyzer equipped with a thermistor. The onset and end of the growing season were estimated by fitting a 3rd order polynomial function to temperature (1-m) versus time (Julian day) plots and then projecting the X-intercepts where $f(x) = 4°$ C (Edmundson 1997). The length of the growing season is defined as the number of days between spring and fall isothermy (4° C). The Birgean summer heat budget was calculated as the difference between the maximum heat (volume × temperature) content and the amount of heat contained in the lake at 4° C isothermy (Wetzel and Likens 1991). The mean water column temperature was calculated by summing the seasonal average temperature for specified volumes of water and using interval volumes as the weighting factor (Edmundson 1997). YSI readings of dissolved oxygen concentration were taken at 1-m increments through the water column. On each survey, the oxygen content of the surface water, measured using the Winkler method (APHA 1985), was used to calibrate the oxygen YSI probe. Measurements of underwater light intensity, obtained using a Protomatic submarine photometer, were used to determine vertical light extinction coefficients and algal compensation depths. Light extinction coefficients (K_d) were estimated by fitting regression lines to the standard formula for exponential light extinction: $I_d = I_o e^{-Kd}$, where I_d is the light intensity at depth d (Kirk 1994). The euphotic zone depth (*EZD*) was calculated by substituting ln(100) into the regression equation. Water transparency was measured with a 20-cm black and white Secchi disk. Transparency was recorded as the mean depth where the disk disappeared and reappeared.

At each sampling station, we collected water from the 1-m stratum and at about 75% of the station depth. For each depth, approximately 8 liters of water were collected using a Van Dorn sampler. Samples were poured into separate (pre-cleaned) polyethylene carboys and transported to ADF&G in Homer where it was filtered and preserved. Samples for dissolved nutrients (filterable-P, filterable reactive-P, ammonia-N, and nitrate-N) and color were filtered under low vacuum pressure (15 psi) through a 0.7 μm-GFF filter 2-6 hr after collection and frozen until laboratory analysis. Unfiltered samples were stored refrigerated for determining general water chemistry (conductivity, pH, alkalinity, and turbidity), metals, (calcium, magnesium, and iron) and reactive silicon. Unfiltered samples for analysis of total Kjeldahl nitrogen and total phosphorus were stored frozen.

In the laboratory, conductivity (compensated to 25° C) was measured using a YSI conductance meter, and pH was measured with an Orion model 420A pH meter equipped with an automatic temperature compensation probe. Alkalinity was determined by acid (0.02 N H2SO4) titration to pH 4.5 units. Turbidity, expressed as nephelometric turbidity units (NTU) was measured with a HF model 00B meter, and color was determined on a filtered (GFF) sample 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, and total iron was analyzed by reduction of ferric iron with hydroxylamine during hydrochloric acid digestion. Reactive silicon was determined using the method of ascorbic acid reduction to molybdenum blue. Filterable reactive phosphorus (FRP) was analyzed by the molybdenum blue/ascorbic acid reduction procedure as modified by Eisenreich et al. (1975). Total phosphorus (TP) utilized the FRP procedure after acid-persulfate digestion. Nitrate + nitrite was analyzed as nitrite following cadmium reduction, and total ammonia utilized the phenylhypochloroite methodology. Total Kjeldahl nitrogen (TKN) was determined as ammonia following acid-block digestion. Total nitrogen (TN) was calculated as the sum of TKN and nitrate + nitrite. All chemical and nutrient methodologies are detailed in Koenings et al. (1987).

For analysis of chlorophyll *a* (chl *a*), we filtered 1-2 L aliquots of each water sample through a 0.7-μm GFF filter to which we added 2 ml of $MgCO_3$. The filters were stored frozen in plexiglass slides until analyzed. Algal pigments were subsequently extracted by grinding the filters in 90% acetone and refrigerating the slurry in the dark for 2 hr. Following centrifugation, chl *a* concentration (corrected for inactive phaeophytin) was determined by the fluorometric procedure using a calibrated (Sigma Co. chl *a* standards) Turner model 112 fluorometer (Koenings et al. 1987).

Four vertical zooplankton tows were collected on each survey date using a 20-cm diameter zooplankton net with 153 μm mesh. Zooplankton hauls were manually pulled from the bottom to the surface at approximately 0.5 m sec^{-1} and the contents preserved in 10% buffered formalin. Cladocerans and copepods were identified using standard taxonomic keys. Enumeration consisted of counting the animals in triplicate 1-ml subsamples taken with a Hansen-Stempel pipette in a 1-ml Sedgewick rafter cell. Zooplankton body length was measured to the nearest 0.01 mm for at least 15 individuals of each species in the subsample. Zooplankton biomass was estimated from species-specific regression equations derived between zooplankter body length and weight (Koenings et al. 1987).

Fishery Assessment

At Delight Lake, emigrating sockeye and coho smolt were captured with a fyke trap placed approximately 50 m downstream from the lake outlet. Smolts entered the trap through a 1.5 m^2 tunnel that narrowed to a cylindrical entrance at the trap. The trap was rectangular in shape with 1.0 m × 0.85 m × 0.80 m (L × W × H) dimensions and with a funnel-shaped entrance positioned on the upstream side. Baffles were installed to divert water current and provide resting areas for the fish. Meshed wings attached to the fyke trap extended from each side of the tunnel entrance to the north and south shores of the creek so that the trap effectively fished the entire stream width. The area fished was approximately 22 m wide with a maximum depth of about 0.8 m. We installed the fyke net on 12 May and began fishing at 2200 hr. The fyke system fished continuously until 29 June when we removed it from the creek. At Desire Lake a similar fyke net/trap system was installed approximately 20 m downstream from the lake outlet on 15 May and began fishing at 1200 hrs. The wings extended from the tunnel entrance to the east and west shores of the outlet creek and fished 100% of the outlet creek. During 18-20 May, we observed predation by river otters on trapped smolts; however, we made repairs and modifications to the fyke trap to prevent further predation. A large outmigration and a rapid increase in stream discharge occurred 05 June at Desire Lake, requiring us to remove a single fyke panel and the trap to relieve pressure on the fyke-trap system. The panel and trap were reinstalled 06 June at 1500 hr. On 14 June, high water also caused us to remove a fyke panel, and the entire fyke system was removed on 15 June. During these periods, smolt counts were estimated by linear interpolation. The fyke system at Desire Lake was reinstalled 17 June and fishing resumed at 1500 hr.

Throughout the smolt outmigration, we divided each day into four 6-hr periods beginning at 0000 hr (midnight) and we enumerated all smolt entering the trap during a 6-hr period. When numbers of smolt were manageable (e.g. <2,500), they were identified to species and counted by hand. When the number of smolt was large (e.g. 5,000), we subsampled using a biomassing procedure. All smolt entering the trap during a 6-hr period were weighed in a tared container. To calculate the total number of fish for a given 6-hr period, the total weight of the catch for that period was multiplied by the number of smolt in a randomly selected 0.45 kg (1 lb) subsample. All fish in the subsample were identified to species and the species composition for the whole sample was estimated by species proportion in the subsample. During peak emigration, several subsamples were taken during a 6-hr hour period to average the number of smolt per subsample. Additionally, we selected a random sample of 60 smolt (15 for each 6-hr period) to measure length (nearest 1 mm) and weight (nearest 0.1 g). Scale samples were also taken from the preferred area (below the posterior insertion of the dorsal fin and above the lateral line), mounted on microscope slides, and labeled. Smolt were not anesthetized prior to collecting size information and scale samples. Smolt collected during late hours were kept in a separate live box divided into four compartments for sampling at a more convenient time. Scale aging was accomplished using a microfiche reader. A total of 1,220 and 1,408 sockeye smolt from Delight Lake and Desire Lake, respectively were sampled for age and size estimation.

To facilitate enumeration and sampling of returning adult salmon, we installed an adult weir (fence) in Delight Lake Creek approximately 10 m downstream from the fyke trap on 4 June. The weir, which covered the entire stream width, consisted of vertical metal pickets spaced 1.9 cm apart and held in place by upper and lower horizontal metal stringers fastened to three wooden tripods. Several pickets were removed daily and fish were individually counted as they passed upstream through the weir. On 11 August, several weir pickets were removed because of high stream discharge and reinstalled 13 August. Nonetheless, we estimated escapement while the pickets were removed. At Desire Lake, a similar weir was installed approximately 10 m downstream from the fyke trap on 3 June. Both the Delight and Desire weirs remained in operation until 26 August when they were dismantled and removed from the creek.

Over the run duration, a total of 600 fish from each weir were sampled for age, weight, and length data. Fish to be sampled were captured in a small trap connected to the upstream side of the weir. When pickets were removed, fish moved into the trap on their own volition. Fish were measured to the nearest 1.0 cm and 0.5 kg. In addition, for each sampled fish we collected a scale sample from the preferred area. Scale samples were mounted onto numbered and labeled gummed cards, pressed onto acetate cards, and aged using a microfiche. Finally, we surveyed sockeye-spawning activity at each lake from a boat to determine if a significant amount of spawning occurs in deeper water. We speculated that past aerial surveys may have underestimated the escapement, particularly in Delight Lake, because prior observations showed that large numbers of adults appeared to spawn in deeper water and thus not easily observed via aerial surveys.

RESULTS

Limnological Assessment

Morphometry and Physical Environment

Delight Lake has a surface area of 2.8 km^2, a mean depth (Z) of 22 m, a maximum depth (Z_x) of 39.5 m, and a volume (V) of 60.2 x 10^6 m^3 (Figure 2). Desire Lake is smaller than Delight Lake and has an area of 1.8 km^2, an average depth of 14 m, a maximum depth of 27.4 m, and a volume of 24.8 x 10^6 m^3 (Figure 3). The Z:Z_x ratio gives values >0.5 for both lakes which is common of many fjord-type lakes. The depth-area plots for Delight and Desire Lakes (Figure 4a) indicate that both lakes are relatively steep and typical of deep lakes with a small littoral zone and volume. The

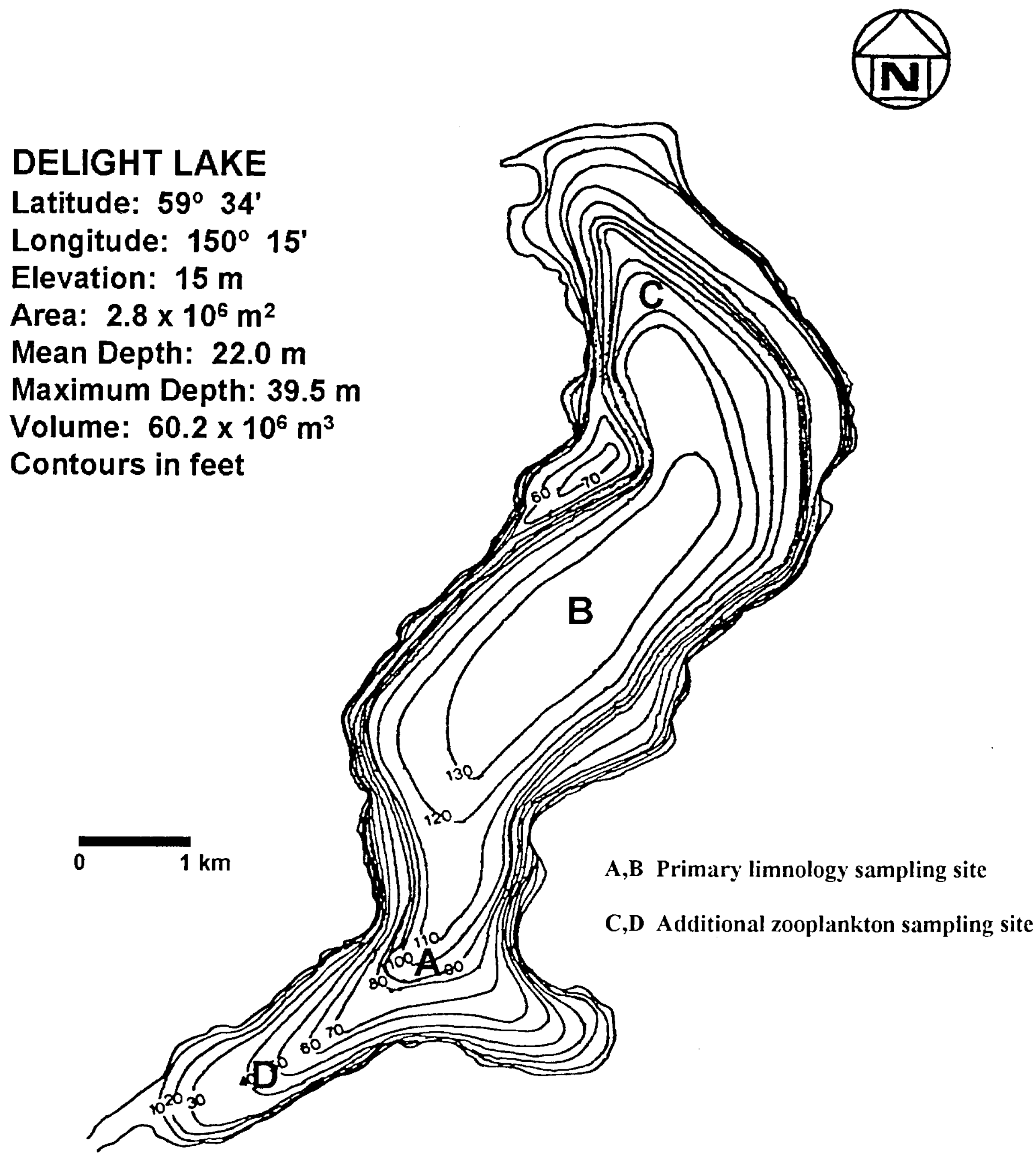

Figure 2. Bathymetric map of Delight Lake showing the location of limnology sampling stations.

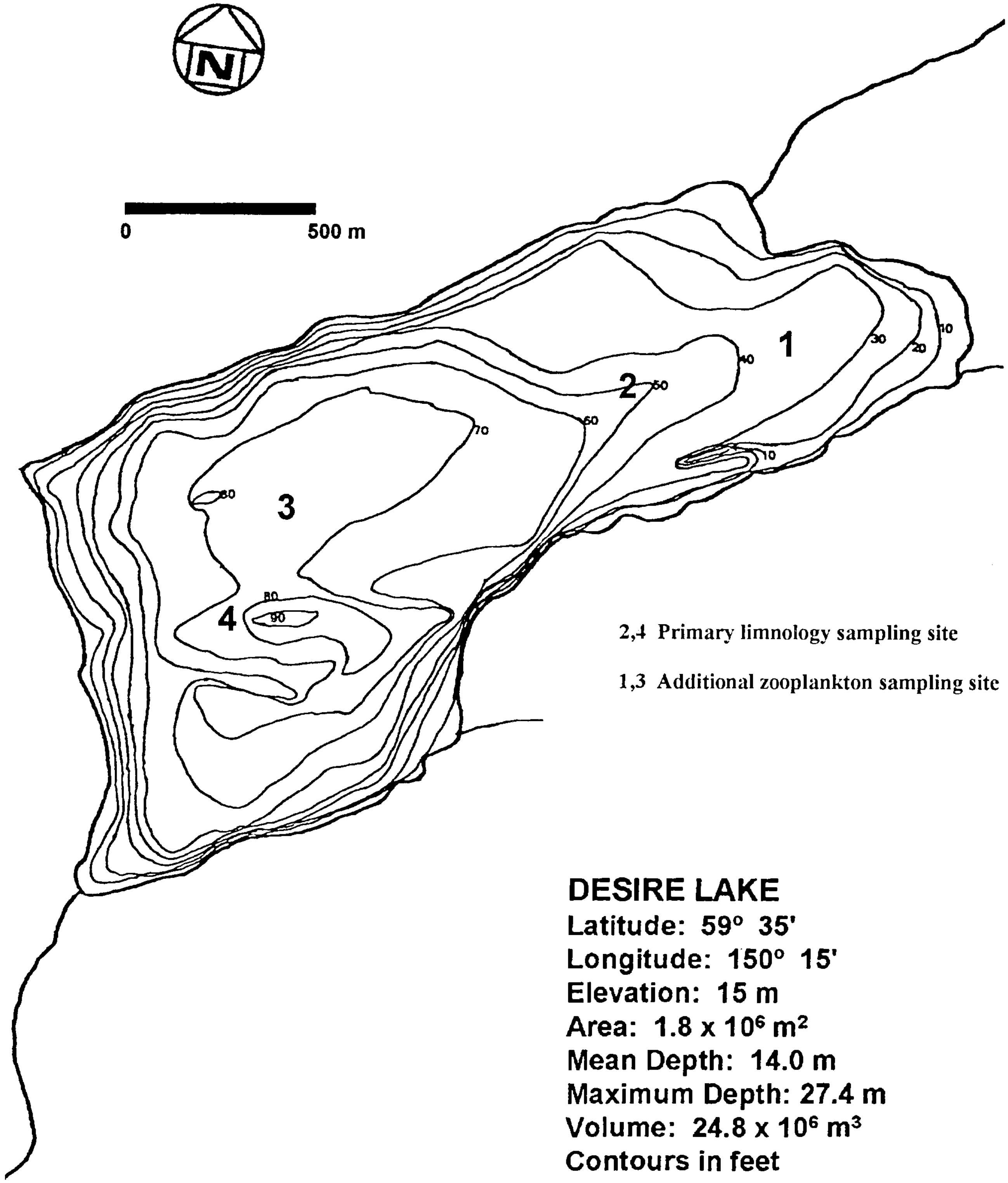

Figure 3. Bathymetric map of Desire Lake showing the location of limnology sampling stations.

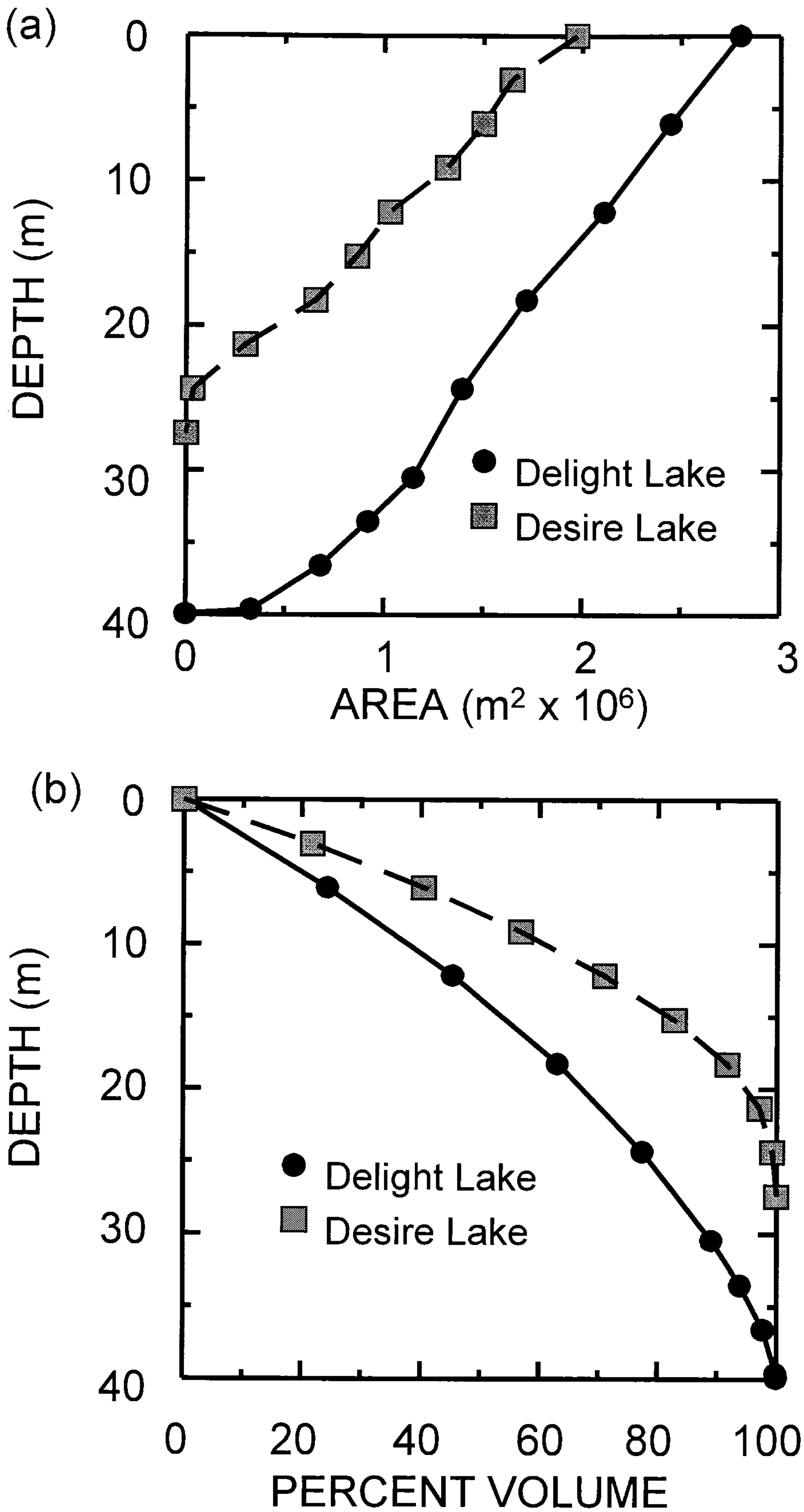

Figure 4. (a) Hypsometric and (b) depth-volume plots for Delight and Desire Lakes.

depth-volume relationship (Figure 4b) reveals that one-half of the water volume lies below a depth of 15 m in Delight Lake compared to 8 m in Desire Lake. In 1997, the summer outflow of Delight Lake ranged from 0.83 to 4.56 $m^3 sec^{-1}$ and was highest on 05 June. In comparison, the outflow from Desire Lake ranged from 0.40 to 3.50 $m^3 sec^{-1}$ and peaked on 23 May. Discrete flow measurements were linearly related to staff gage height (Figure 5a, b). The regression slope indicates that a 1-cm increase in gage height is equivalent to an increase in discharge of 0.1 $m^3 sec^{-1}$ in Delight Lake and 0.2 $m^3 sec^{-1}$ in Desire Lake. The estimated drainage area of each lake is approximately 11.2 km^2. Based on total volume and estimated total annual outflow, derived from drainage area and mean annual precipitation (300 cm), yields an estimated water residence time of 2.08 yr for Delight Lake and 0.86 yr for Desire Lake.

Both Delight and Desire Lakes are quite clear with light extinction coefficients (K_d) ranging from 0.11 to 0.48 m^{-1} (Figure 6a), euphotic zone depths (*EZD*) ranging from 9.6 to 41.9 m (Figure 6b), and secchi transparencies ranging from 2.8 to 10 m (Figure 6c). However, Delight Lake exhibited slightly greater light penetration than Desire Lake and had a median K_d value of 0.23 m^{-1} and a median *EZD* of 20.1 m. The median K_d and *EZD* values in Desire Lake were 0.27 m^{-1} and 17.1 m, respectively. The estimated euphotic volume (the volume above mean *EZD*) was 46.3 x 10^6 m^3 in Delight Lake and 21.9 x 10^6 m^3 in Desire Lake. Thus, euphotic volume represented 77% and 80% of the total volume in Delight and Desire Lakes, respectively. Secchi depths were deeper in Delight Lake (median 7.5 m) than in Desire Lake (median 5.3 m). There was little spatial (station) variation in water clarity in either lake, and seasonal differences were attributed to changing surface conditions (i.e., calm versus wavy) which may have affected our measurements rather than differences in plankton densities or sediment loading. From these data it appeared that light penetration in both lakes was slightly deeper and water clarity greater in 1997 than in 1981.

Both lakes were thermally stratified in the summer, but a thermocline was more pronounced in Delight Lake than in Desire Lake (Figure 7a-d). Thermal stratification was strongest in July, but a weak thermocline persisted through the end of August in both lakes. During July, the thermocline extended from about 5 m to 10 m and the lakes became isothermal at 8-9° C by mid-October. In 1997, surface warming (>4° C) in each lake was first detected about 09 May, whereas maximum temperatures occurred about 31 July. Maximum surface temperatures reached 16° C in Delight Lake, but temperatures were 1-2° C colder in Desire Lake (Table 1). Desire Lake reached 4° C isothermy on 21 October compared to 29 October for Delight Lake. Thus, the duration of the growing season is approximately 6 mo in both lakes. Although the growing season was slightly longer in 1981 compared to 1997, in both lakes mean water column temperature was warmer and the summer heat budget greater in 1997.

Water and Nutrient Chemistry

Delight and Desire Lakes are circumneutral with pH values of 5.2-6.9 and poorly buffered with total alkalinity of only 2-10 mg L^{-1} (Table 2). Both lakes also have low ion (dissolved solids) content as evidenced by small conductivity values of only 12-55 μmhos cm^{-1}. There was little difference in conductivity between the epilimnion (1-m) and hypolimnion, which indicated complete vertical

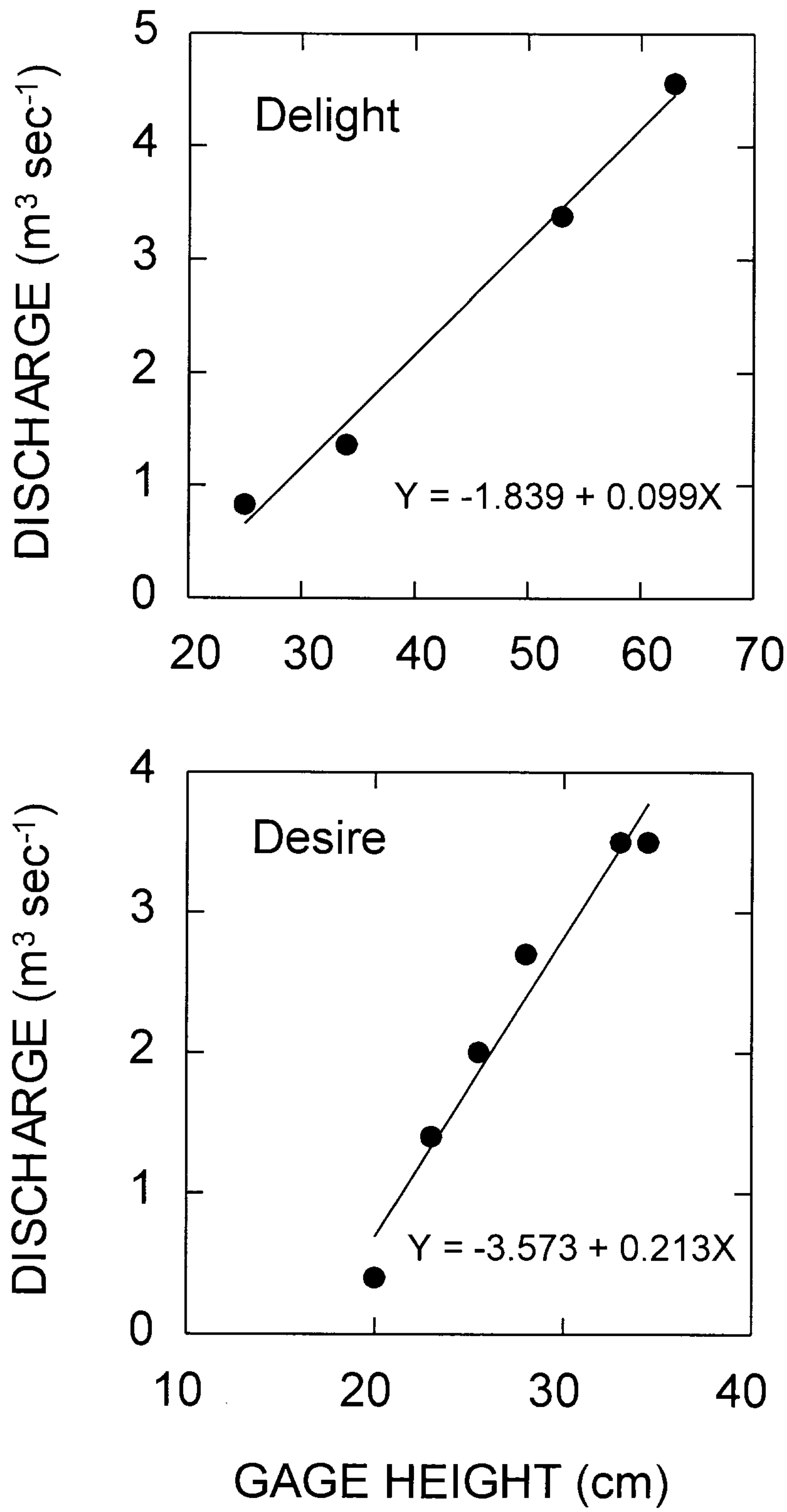

Figure 5. Relationship between staff gauge height and summer water discharge for Delight and Desire Lakes, 1997.

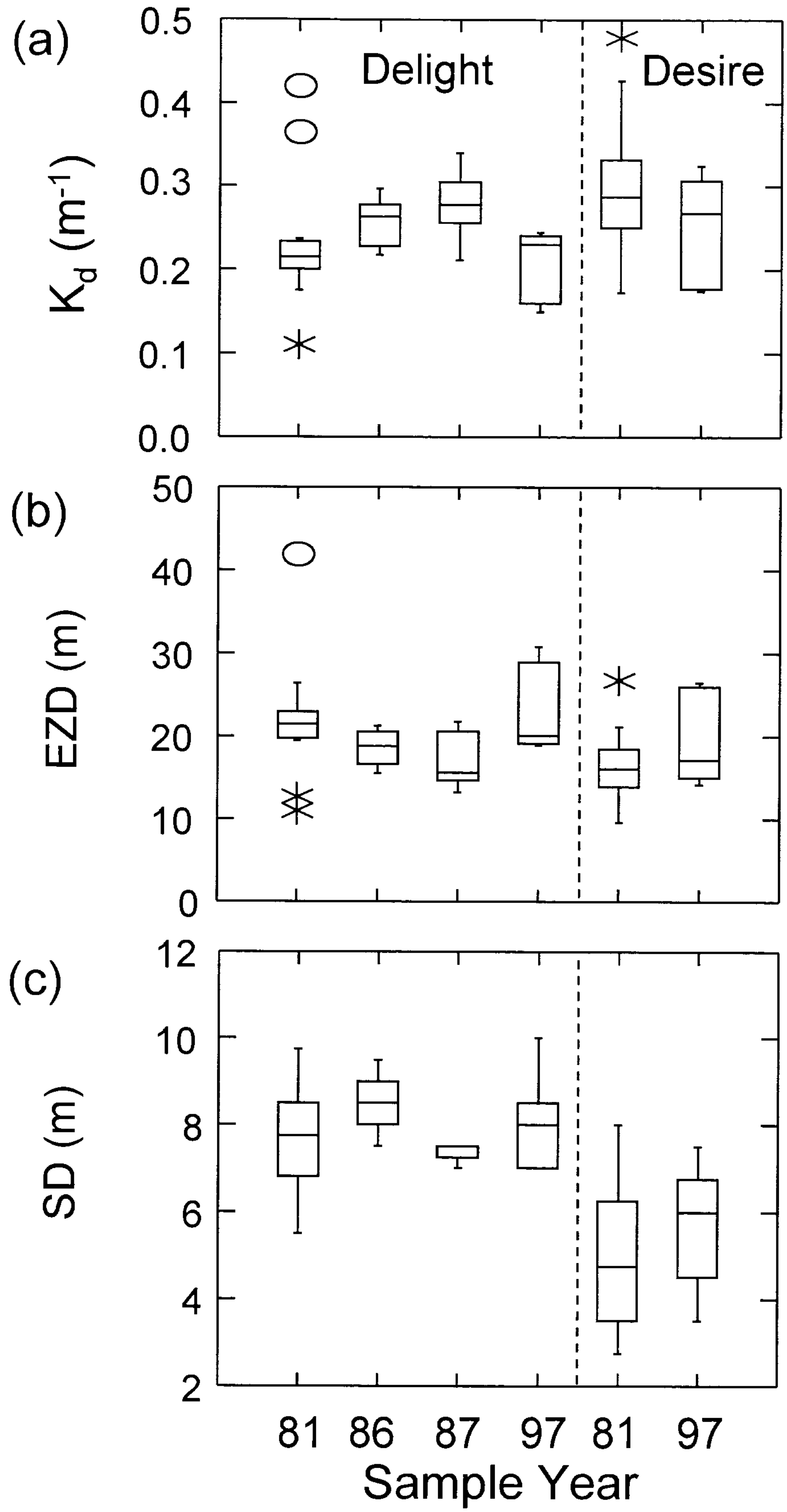

Figure 6. Box plots for the (a) vertical light-extinction coefficient (K_d), (b) euphotic zone depth (EZD), and (c) secchi disk (SD) transparency.

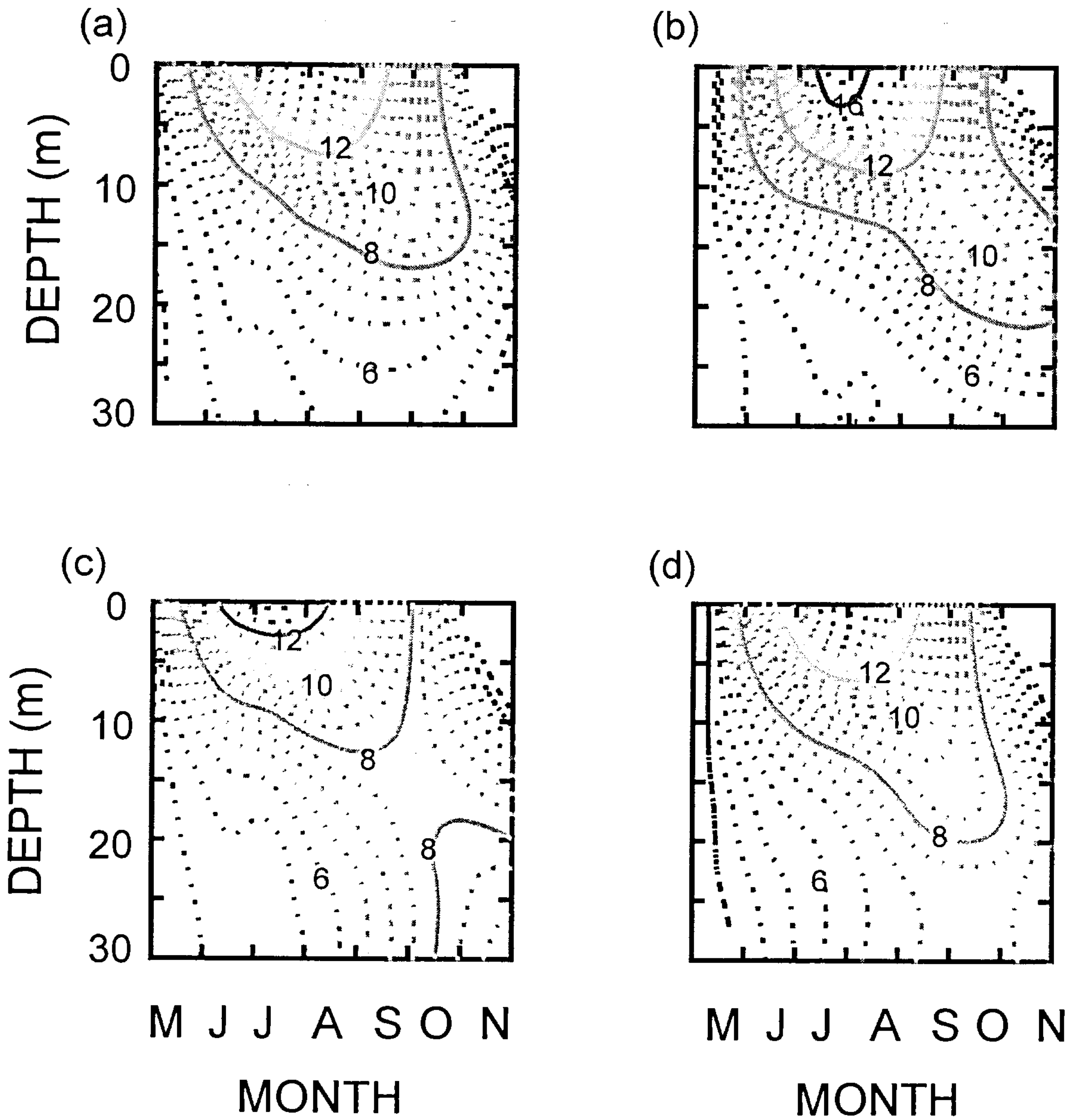

Figure 7. Depth-time isotherms (°C) for (a) Delight Lake 1981, (b) Delight Lake 1997, (c) Desire Lake 1981, and (d) Desire Lake 1997.

Table 1. Thermal characteristics of Delight and Desire Lakes, 1981 and 1997.

Characteristic	Delight Lake 1981	Delight Lake 1997	Desire Lake 1981	Desire Lake 1997
Projected Julian day of spring (4°C) isothermy	116	129	94	128
Projected Julian day of fall (4°C) isothermy	217	213	201	211
Projected Julian day of maximum heat content	294	302	307	294
Duration of growing season (d)	178	172	215	166
Maximum temperature at 1-m (°C)	16.0	16.3	13.2	15.5
Mean temperature at 1-m (°C)	11.8	12.2	8.9	11.7
Mean water column temperature (°C)	7.8	8.2	7.4	9.1
Summer heat budget (g-cal cm^{-2})	12,615	12,981	7,171	8,499

Table 2. Chemical characteristics of Delight and Desire Lakes. Values are means derived from measurements taken in 1981 and 1997.

Characteristic	Delight Lake	Desire Lake
Turbidity (NTU)	0.6	1.1
Color (Pt units)	5.6	4.6
pH (units)	6.2	6.3
alkalinity (mg L^{-1})	26	17
calcium (mg L^{-1})	1.8	1.8
magnesium (mg L^{-1})	0.4	0.4
hardness (mg L^{-1})	6.4	6.4
conductivity (μmhos cm^{-1})		
epilimnion	26	17
hypolimnion	32	20

mixing of the water column. Concentrations of soluble reactive silicon (RSI) in both Delight and Desire Lakes were < 1 mg L^{-1} and there was no apparent trend in RSI values. RSI concentrations were not considered low enough to limit phytoplankton (diatom) production. Given that light penetration is relatively deep, it is not surprising that turbidity levels were very low, averaging less than 1 NTU in Delight Lake and 0.5 NTU in Desire Lake. There was very little organic (humic) stain in either lake; color values ranged from 4-6 Pt units. Hence, both Delight and Desire Lakes are characterized as clearwater systems, as opposed to organically stained or turbid.

During 1997 and 1981, the two years of consistent (monthly) data, total nitrogen (TN) concentrations in Delight and Desire Lakes varied seasonally from 37-137 μg L^{-1} and 37-121 μg L^{-1}, respectively (Figure 8a-d). Nitrate concentrations in the epilimnion (1-m) tended to decrease over the course of the summer in the two lakes. In Delight Lake, nitrate concentrations ranged from 37-48 μg L^{-1} during the spring (May) overturn, decreasing to values of <2-19 μg L^{-1} by October. At spring turnover, concentrations were somewhat higher in Desire Lake, ranging between 54 and 84 μg L^{-1}, but then decreased to values of 13-33 μg L^{-1} by the end of the growing season. However, in Delight Lake both nitrate and TN concentrations dropped in July 1981 relative to the values in June, whereas the opposite trend occurred in Desire Lake. The difference between the two temporal shifts could be due to differential volumes of inflow. Total phosphorus (TP) concentrations were quite low, but varied considerably (Figure 9a-d). Epilimnetic TP concentrations as high as 6 μg L^{-1} in Delight Lake and 10 μg L^{-1} in Desire Lake were detected in the fall, but TP concentrations for the two sample years averaged 5.2 μg L^{-1} and 5.6 μg L^{-1}, respectively. In both lakes, total filterable phosphorus (TFP) concentrations did not fluctuate in concert with TP and ranged from 0.4-8.4 μg L^{-1}. Filterable reactive phosphorus levels (FRP) were very low and averaged about 1 μg L^{-1} in Delight Lake and 2 μg L^{-1} in Desire Lake. There was no obvious difference in TP concentrations in between 1981 and 1997 in eitherlake. TN:TP molar ratios in the two lakes ranged from a low of 15:1 to a high of 182:1, and the mean TN:TP ratio for both lakes was 48:1. Mean TN:TP values >15:1 indicate that phosphorus is the primary nutrient limiting productivity. Based on the low epilimnetic TP concentrations and high N:P ratios, both Delight and Desire Lakes are characterized as highly oligotrophic.

Chlorophyll

In 1981, the mean epilimnetic chl *a* concentration was 0.8 μg L^{-1} in Delight Lake and 0.7 μg L^{-1} in Desire Lake. The maximum epilimnetic concentration in each lake was 2.3 μg L^{-1} occurring 01 October (Figure 10a, c). It appeared that epilimnetic concentrations increased coincident with the breakdown of thermal stratification in the fall (September). In addition, mean epilimnetic chl *a* levels were substantially higher in 1997 averaging 1.3 μg L^{-1} in Delight Lake and 2.1 μg L^{-1} in Desire Lake (Figure 10b, d). In contrast to the 1981 season, the highest chl *a* concentration in 1997 occurred 06 May and reached 2.3 and 3.4 μg L^{-1}, respectively in Delight and Desire Lakes. In that year, epilimnetic concentrations decreased steadily throughout the summer and then increased markedly in the fall. There was little variation in chl *a* between sampling stations in either lake; however, there was considerable vertical heterogeneity, particularly in 1997 when concentrations

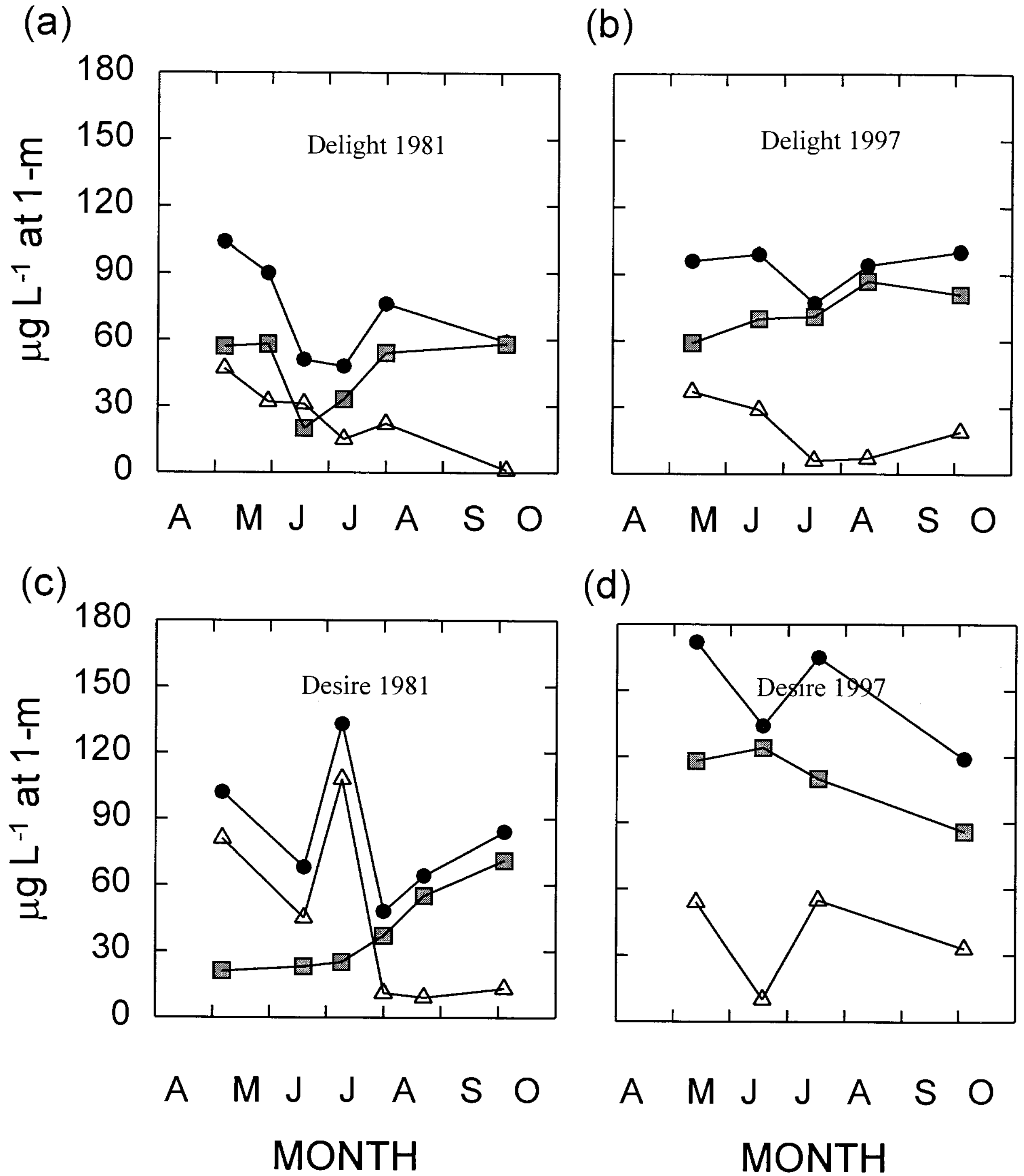

Figure 8. Seasonal changes in total nitrogen (solid circles), Kjeldahl (shaded squares), and nitrate (open triangles) nitrogen concentrations within the 1-m stratum; (a) Delight Lake 1981, (b) Delight Lake 1997, (c) Desire Lake 1981, and (d) Desire Lake 1997.

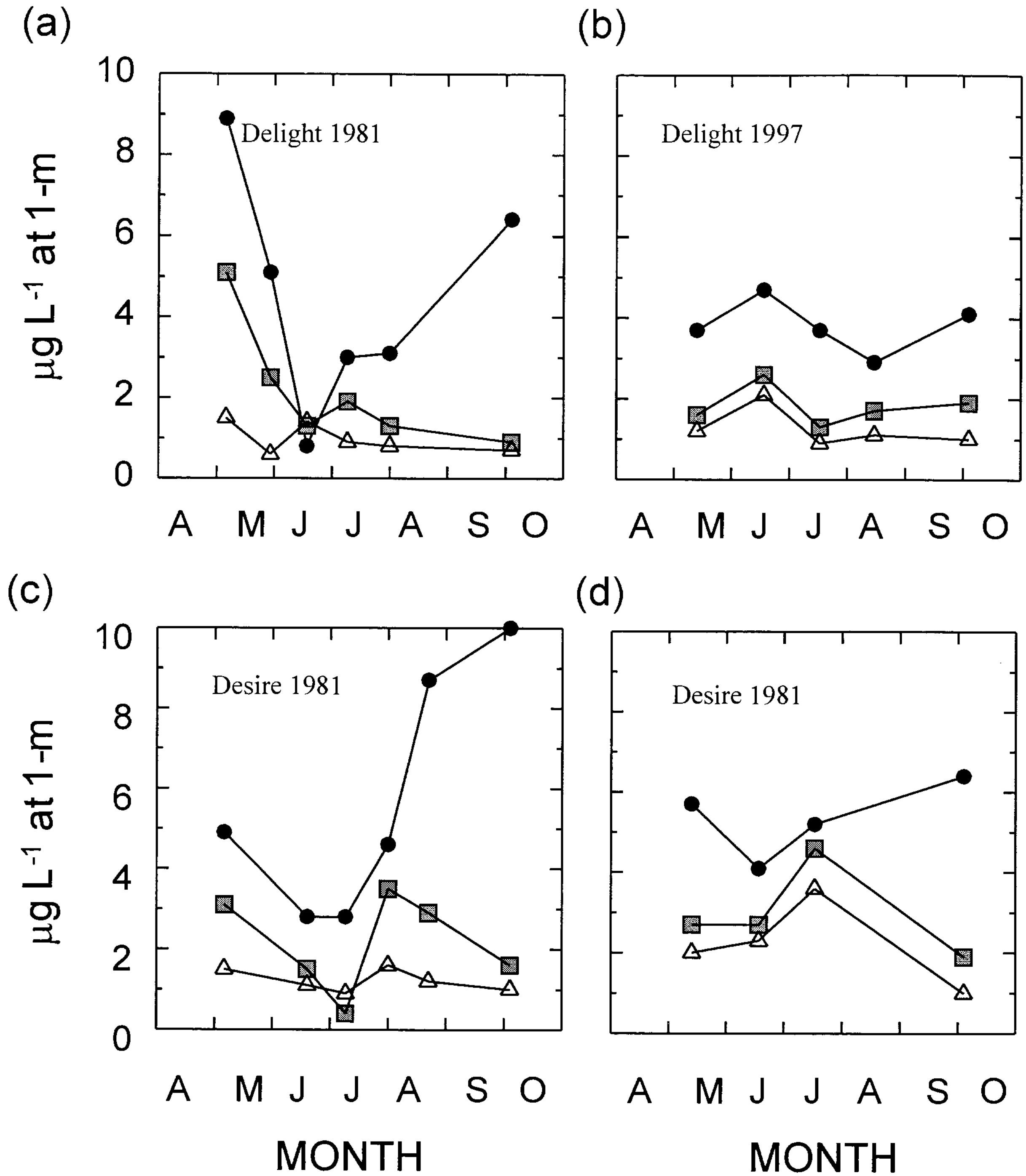

Figure 9. Seasonal changes in total (solid circles), total filterable (shaded squares), and filterable reactive (open triangles) phosphorus concentrations within the 1-m stratum; (a) Delight Lake 1981, (b) Delight Lake 1997, (c) Desire Lake 1981, and (d) Desire Lake 1997.

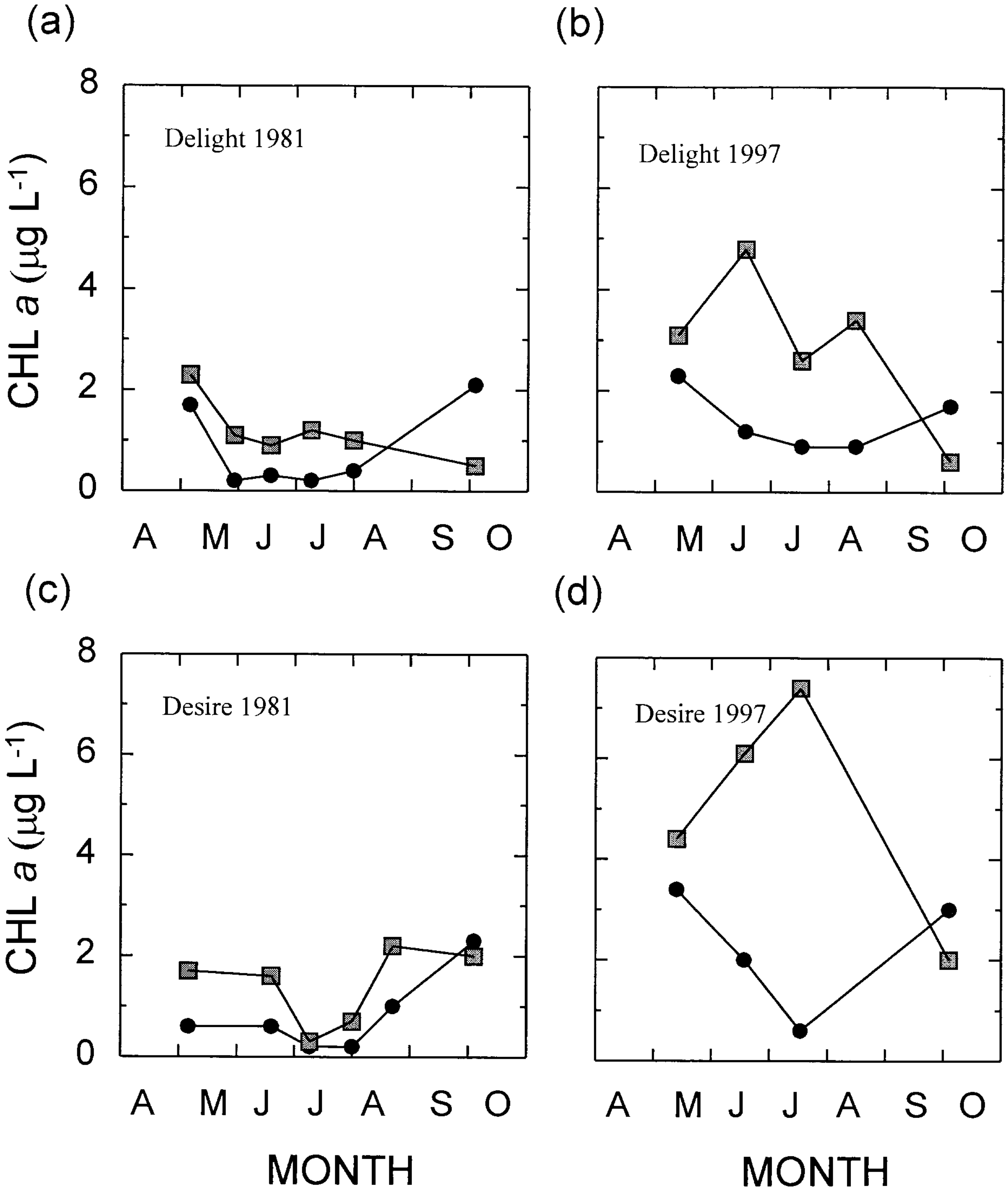

Figure 10. Seasonal changes in chlorophyll *a* (chl *a*) concentrations within the 1-m stratum (solid circles) and hypolimnion (shaded squares); (a) Delight Lake 1981, (b) Delight Lake 1997, (c) Desire Lake 1981, and (d) Desire Lake 1991.

were much (2-3 times) higher in the hypolimnion compared to the epilimnion (1 m). Deeper lying chl *a* concentrations averaged 2.9 $\mu g\ L^{-1}$ in Delight Lake and 5.0 $\mu g\ L^{-1}$ in Desire Lake.

Organic Particulates

In Delight Lake, particulate organic carbon (POC) concentrations did not track that of chl *a* indicating a large proportion of allochthonous loadings of POC (Figure 11a). In contrast, POC concentrations were positively and strongly related (r^2=0.90) to chl *a* in Desire Lake (Chl *a* = -0.723 + 0.021POC) indicating most of the POC content is of an autochthonous source (i.e., phytoplankton) (Figure 11b). Desire Lake had a slightly higher content of POC, as well as particulate nitrogen (PN) and phosphorus (PP) (Table 3). On average, Desire Lake had higher particulate POC:PN, POC:PP, and PN:PP molar composition ($\mu mol\ \mu mol^{-1}$) ratios compared to Delight Lake. Nonetheless, the mean POC:PN molar ratios for both Delight and Desire Lakes indicated no nitrogen deficiency. In contrast, the high POC:PP and PN:PP molar ratios are indicative of severe phosphorus deficiency in both lakes.

Zooplankton Species Composition, Density, and Biomass

The macrozooplankton community of Delight and Desire Lakes was relatively simple and composed three species of cladocerans - *Bosmina*, *Daphnia*, and *Chydorinae* - and one species of copepod - *Cyclops* (Table 4). The small (0.3 mm), herbivorous *Bosmina* dominated the macrozooplankton community in both lakes, accounting for about 95% of the total density andbiomass in Delight Lake, and nearly 80% of the density and biomass in Desire Lake. In both lakes, *Cyclops* populations were more abundant in 1981 compared to 1997, whereas small (0.26 mm) *Chydorinae* were more prevalent in 1997 than in 1981. *Daphnia* populations occurred sporadically throughout the two sample years in both lakes, but in very low numbers. Considering both years, the seasonal mean macrozooplankton abundance and biomass was 6-9 times greater in Delight Lake than in Desire Lake.

Total macrozooplankton densities were generally low (<50,000 m^{-2}) throughout the first part of the summer in both lakes; however, densities increased in the latter part of the season and peaked in the fall (Figure 12a-d). Seasonal changes in macrozooplankton biomass largely followed the same temporal trend (Figure 13a-d). In addition, both lakes exhibited considerable spatial (station) heterogeneity in zooplankton density and biomass. For example, the mean 1997 total macrozooplankton density and biomass by station (n = 4) ranged from 117,187-200,709 m^{-2} and 88-176 mg m^{-2}, respectively in Delight Lake. In comparison, station (n = 4) means ranged from 20,149-56,239 m^{-2} and 16-46 mg m^{-2} in Desire Lake.

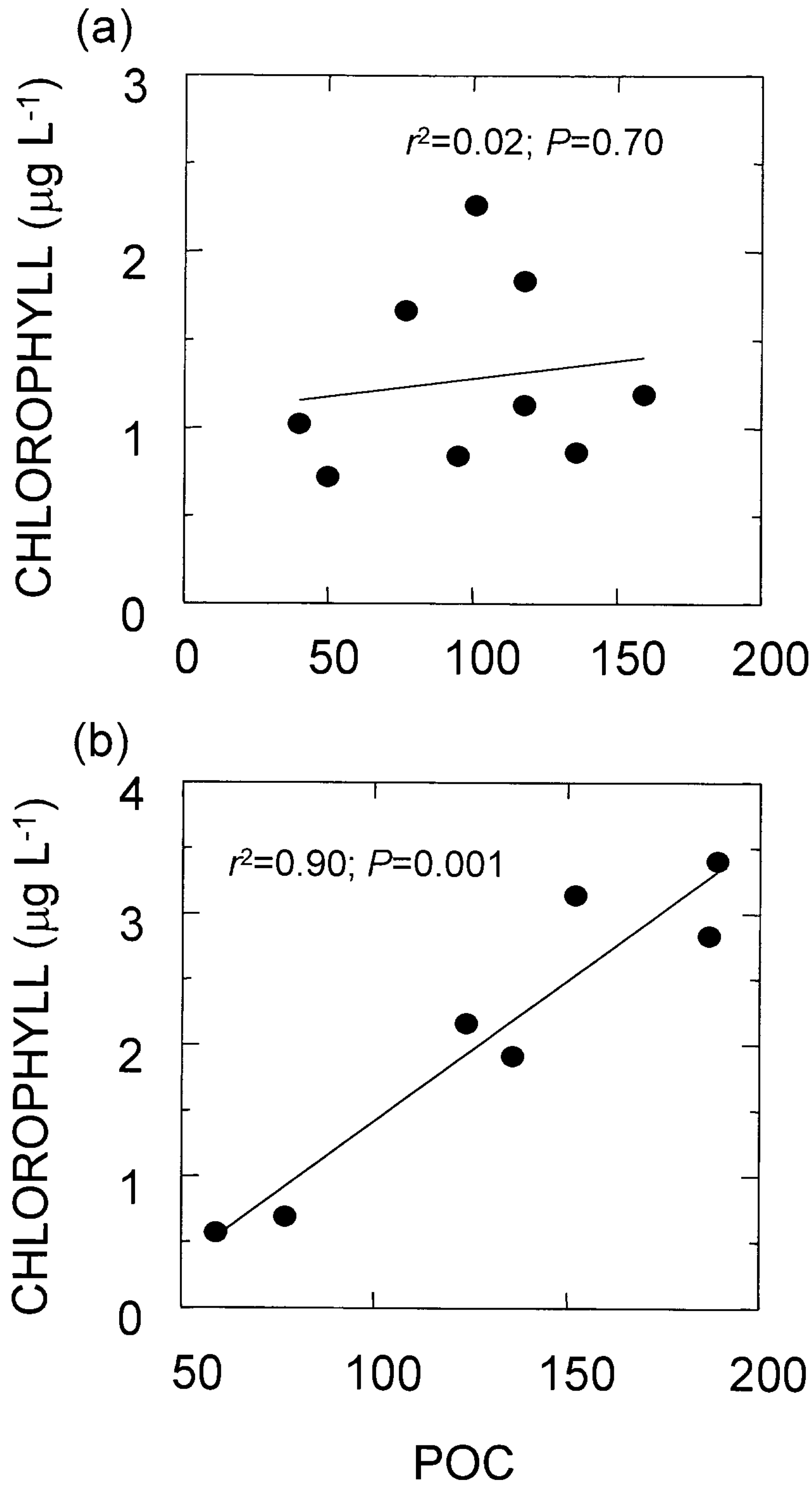

Figure 11. Relationship between chlorophyll *a* and particulate organic carbon (POC) concentration in (a) Delight and (b) Desire Lakes, 1997.

Table 3. Average particulate carbon (POC), nitrogen (PN), and phosphorus (PP) concentrations (μmoles L^{-1}) and molar composition ratios (μmoles $\mu moles^{-1}$) within the 1-m stratum in Delight (n=9) and Desire Lakes (n=7), 1997.

	Delight Lake		Desire Lake	
	Mean	Std. Dev.	Mean	Std. Dev.
POC	8.2	3.2	11.0	4.2
PN	2.8	0.9	5.0	1.9
PP	0.06	0.05	0.08	0.07
POC:PN	3.5	1.9	2.8	1.8
POC:PP	675	1322	233	125
PN:PP	156	217	186	200

Table 4. Mean density, biomass and body size of the major zooplankton taxa in Delight and Desire Lakes, 1981 and 1997.

Delight Lake

Taxon	1981 Density (animals m^{-2})	1981 Biomass (mg m^{-2})	1981 Body Size (mm)	1997 Density (animals m^{-2})	1997 Biomass (mg m^{-2})	1997 Body Size (mm)
Cyclops	3,670	4.5	0.60	1,107	1.0	0.54
Bosmina	57,924	61.0	0.34	163,119	132.2	0.30
Daphnia	11	0.1	0.95	0	0.0	na
Chydorinae	12	0.0	0.43	6,591	4.2	0.26
TOTAL	61,617	65.6	--	170,817	137.4	--

Desire Lake

Taxon	1981 Density (animals m^{-2})	1981 Biomass (mg m^{-2})	1981 Body Size (mm)	1997 Density (animals m^{-2})	1997 Biomass (mg m^{-2})	1997 Body Size (mm)
Cyclops	1,927	1.5	0.55	264	0.4	0.34
Bosmina	4,683	4.5	0.33	29,094	23.9	0.30
Daphnia	<1	0.5	--	0	0.0	0.66
Chydorinae	3	0.0	0.40	5,686	2.8	0.24
TOTAL	6,613	6.5	--	35,044	27.1	--

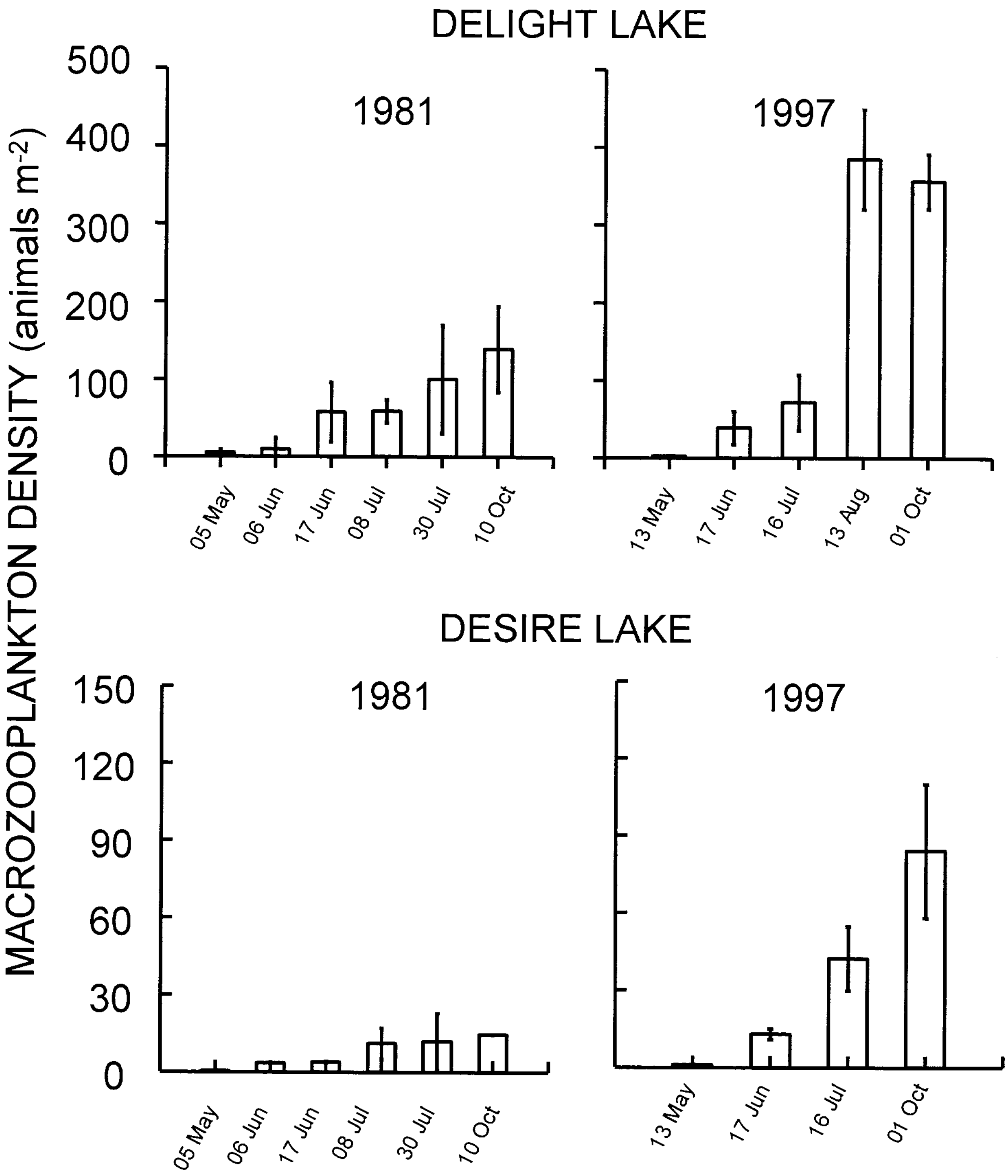

Figure 12. Average (±SE) total macrozooplankton density by sample date in Delight and Desire Lakes, 1981 and 1997.

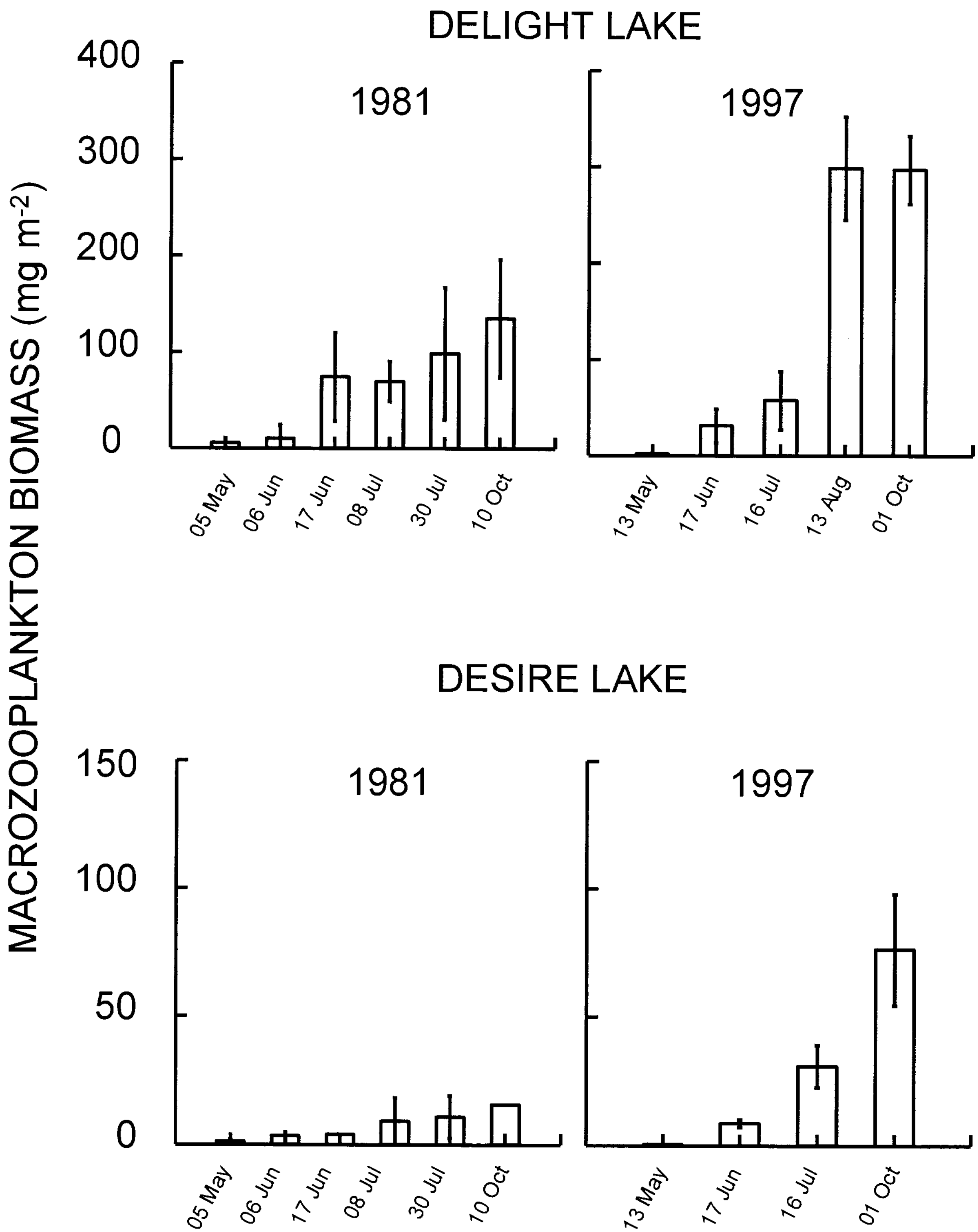

Figure 13. Average (±SE) total macrozooplankton biomass by sample date in Delight and Desire Lakes, 1981 and 1997.

Fisheries Assessment

Smolt Migration Patterns

Two peaks occurred in the daily fyke-net catches during the Delight Lake sockeye smolt outmigration; 06 June and 10 June when 78,922 and 69,083 smolt were captured (Figure 14a). Age-1 sockeye smolt comprised 83% of the total smolt in the first week of the emigration and 64% in the second week. By the third week, age-1 smolt represented 24% of the emigration. The peak daily coho catch coincided with the peak daily fyke-net catch of sockeye (Figure 14b). At Desire Lake, the highest daily catch of sockeyes occurred 05 June, when a total of 17,591 smolt were counted in a 24-hr period including 12,068 counted between 1800 and 2400 hr (Figure 14c). This peak coincided with a sharp increase in stream flow. During the first and second week of sampling, age-1 smolt comprised 81% and 57% of the sockeye emigration, respectively. The peak daily catch of coho smolts occurred 05 June when 3,698 smolts were counted (Figure 14d). Peak emigration timing of sockeye, i.e. when 50% of the emigration was reached, occurred 07 June in Delight Lake and 04 June in Desire Lake (Figure 15a). Peak coho emigration occurred 04 June in Delight Lake and 02 June in Desire Lake (Figure 15b). Thus, both sockeye and coho smolt emigration occurred slightly earlier in Desire Lake compared to Delight Lake.

Smolt Abundance, Size, and Age Composition

In 1997, an estimated 623,059 sockeye and 25,605 coho smolts emigrated Delight Lake in 1997 (Table 5). The sockeye smolt population consisted of an estimated 70% age-1 and 29% age-2 smolt. Age-1 sockeye smolt lengths and weights averaged about 69 mm and 2.5 g, and mean age-2 smolt size was 89 mm and 6.4 g. Age-2 smolt composed an estimated 54% of the coho migration from Delight Lake, and averaged 134 mm and 23.9 g. The remainder of the coho outmigration composed about equal proportions of age-1 (20%) and age-3 smolts (23%). Age-1 coho smolt sizes averaged about 124 mm and 18 g, whereas the age-3 sizes averaged 146 mm and 30 g. In comparison, 96,700 sockeye and 8,374 coho smolts migrated from Desire Lake in 1997. Age-1 smolts composed an estimated 79% of the total sockeye outmigration and age-2 composed 21%. Age-1 sockeye smolt sizes averaged 70 mm and 3.0 g, whereas age-2 smolt sizes averaged 92 mm and 7.3 g. The 1997 coho emigration consisted of an estimated 76% age-2 smolts with a mean size of 107 mm and 10.8 g. Age-3 and age-2 smolts represented about 7% and 5%, respectively of the coho outmigration.

Sockeye Salmon Escapement and Total Return

Qualitative spawning habitat surveys in Delight and Desire Lakes indicated that sockeye salmon are primarily shore or beach spawners. Boat surveys revealed that there is limited spawning habitat available on shallow beaches and within the small inlet streams entering both lakes. However, it appeared that there may be a substantial number of sockeye salmon spawning in deeper water that cannot be directly observed from the surveys. Comparisons of known numbers of adults passing

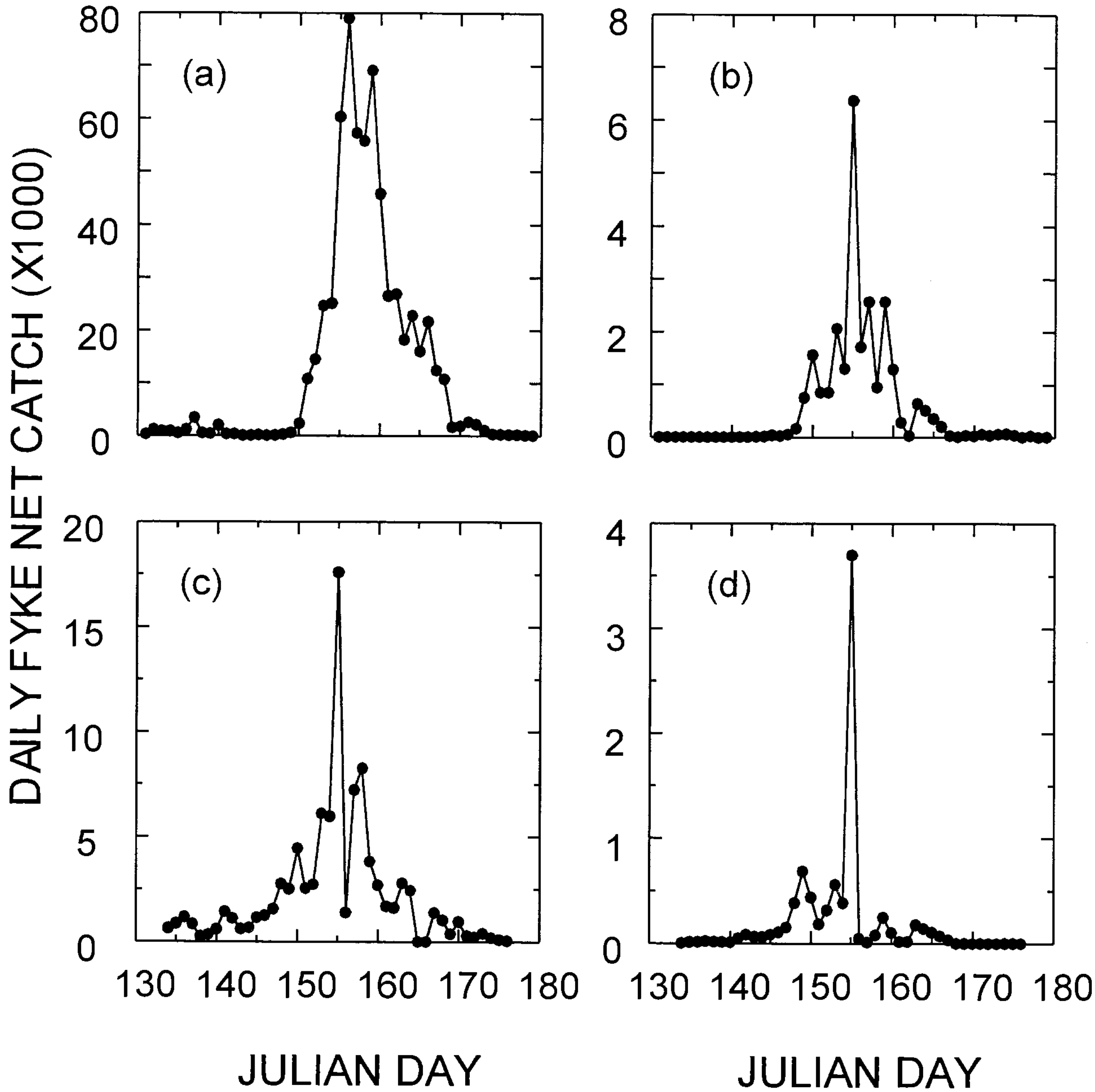

Figure 14. Daily fyke-net catch during the 1997 smolt outmigration; (a) Delight Lake sockeye, (b) Delight Lake coho, (c) Desire Lake sockeye, and (d) Desire Lake coho.

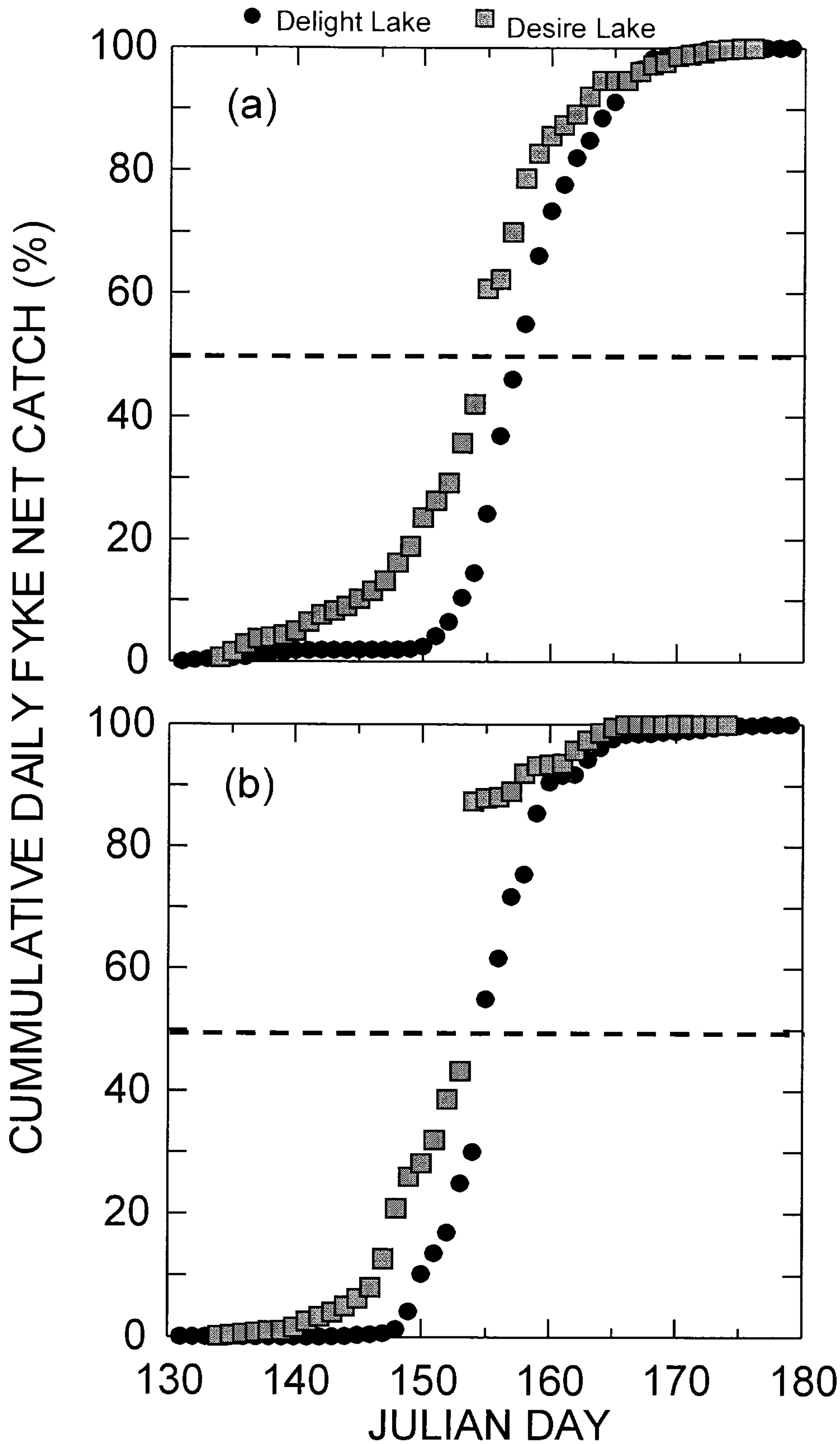

Figure 15. Cumulative daily fyke-net catch of (a) sockeye and (b) coho smolts during the 1997 outmigration in Delight (and Desire Lakes.

Table 5. Estimated number and size of migrating 1-, 2-, and 3-year old sockeye and coho salmon smolts from Delight and Desire Lakes in 1997.

	Delight Lake		Desire Lake	
	Sockeye	Coho	Sockeye	Coho
Age-1				
number of smolt	468,184	4,985	76,353	1,225
percent	70.3	19.5	78.9	5.4
length (mm)	69.0	124.0	70.0	86.0
weight (g)	2.5	17.7	3.0	5.4
Age-2				
number of smolt	181,811	14,728	19,850	6,332
percent	29.2	54.2	20.5	75.6
length (mm)	89.0	134.0	92.0	107.0
weight (g)	6.4	23.9	7.3	10.8
Age-3				
number	3,064	5,891	496	612
percent	0.5	23.0	0.5	7.3
length (mm)	114.0	146.0	119.0	129.0
weight (g)	13.5	29.7	14.4	18.6

through the weir with the number observed along the shores and beaches were inconsistent. We observed far fewer sockeye adults spawning in near-shore waters than were counted at the weir. Thus, we concluded that many adult sockeyes entering Delight Lake and Desire Lake spawn in deeper waters.

In 1997, the sockeye escapement into Delight Lake was 27,820. Peak migration occurred on 12 July when 6,468 sockeye passed through the weir. Another peak occurred on 09 August when 3,907 were enumerated. Five-year old fish dominated the sockeye run. The age composition of the escapement consisted of an estimated 54% age 1.3, 25% age 1.2, and 10% age-2.2 (Table 6). Six-year old (age 2.3) fish composed about 10% of the escapement. Lengths and weights for all age classes and both sexes combined averaged 54 cm and 2.2 kg, respectively. In comparison, the dominant age class (age 1.3.) averaged 56 cm and 2.4 kg. The sockeye escapement in Desire Lake was 14,665 and the peak count (2,324) occurred on 11 July. Five-year old fish also dominated the run. The age composition consisted of an estimated 72% age 1.3 and 26% age 1.2 (Table 7). Age 2.2 and 2.3 composed only about 1% of the sockeye escapement. Lengths and weights for all age classes and both sexes combined averaged 2.8 kg and 56.0 cm, respectively compared to 57 cm and 3.0 kg for the dominant age class (age 1.3).

The escapement of sockeye salmon into Delight Lake (27,820) was nearly three times the targeted escapement goal of 10,000 and it was the highest escapement into this system in the past 23 years (Figure 16a). In comparison, the lowest escapement occurred in 1988, one year prior to EVOS. Between 1985 and 1988, sockeye escapements into Delight Lake declined dramatically from 26,000 to 1,200. Over the next six years, sockeye escapements increased, averaging 5,600, but escapements remained well below the escapement goal. However, compared to the 23-yr mean escapement (9,700); escapements into Delight Lake averaged 9,900, and 9,400, respectively before (1975-1988) and after (1989-1997) the oil spill. In contrast, the 1997 sockeye escapement for Desire Lake of 14,665 was reasonably close to the escapement goal of 10,000 (Figure 16a). Historically, sockeye escapements in Desire Lake were much more similar to those of Delight Lake. During the past 23 years, escapements ranged from 6,500 to 18,000 and averaged 11,900. The highest escapement occurred in 1982 and the lowest in 1975. The mean sockeye escapement prior to EVOS was 12,500 compared to 11,100 after the oil spill. Results of an analysis-of-variance indicated no significant difference in sockeye escapement before and after the oil spill for either Delight Lake (P=0.84) or Desire Lake (P=0.77).

Commercial harvest data for sockeye salmon in the East Nuka Bay subdistrict, which includes the Delight and Desire sockeye stocks, are available since 1975 (Figure 16b). The 1997 commercial harvest of 6,300 sockeye in the East Nuka Bay fishery was well below the 23-yr average catch of 21,000. Since 1989, the commercial sockeye harvest averaged 7,300 compared to 29,800 for the 14 years prior to the oil spill. Although sockeye harvests have been much lower than expected since the oil spill (1989), sockeye catches began to rapidly decline from a high of 91,800 in 1985 to 9,500 in 1988, the year immediately preceding the oil spill. However, in the five years following the oil spill, sockeye harvests are the lowest on record for the Nuka Bay subdistrict. Thus, since 1975, total return for Delight and Desire Lakes combined ranged from 8,500 to 135,800 and averaged 42,700 (Figure 17). Total returns for the two lakes averaged 52,300 before the oil spill and 27,800 after the

Table 6. Age composition estimates and mean size of adult sockeye salmon sampled from Delight Lake, 1997.

	Age Class							
	1.2		1.3		2.2		2.3	
	Male	Female	Male	Female	Male	Female	Male	Female
Sample size	59	57	92	84	11	14	18	15
Percent of total	18.2	17.5	28.3	25.6	3.4	4.3	5.5	4.6
Length (cm)	51.0	51.0	57.0	54.0	51.0	48.0	59.0	54.0
Weight (g)	2.2	1.8	2.7	2.1	2.0	1.5	2.7	1.9

Table 7. Age composition estimates and mean size of adult sockeye salmon sampled from Desire Lake, 1997.

	Age Class							
	1.2		1.3		2.2		2.3	
	Male	Female	Male	Female	Male	Female	Male	Female
Sample size	37	50	116	128	1	2	0	5
Percent of total	10.9	14.7	34.1	37.7	0.3	0.6	0	1.5
Length (cm)	53.0	51.0	59.0	56.0	22.0	49.0	--	55.2
Weight (g)	2.5	2.1	3.3	2.7	2.6	1.8	--	2.6

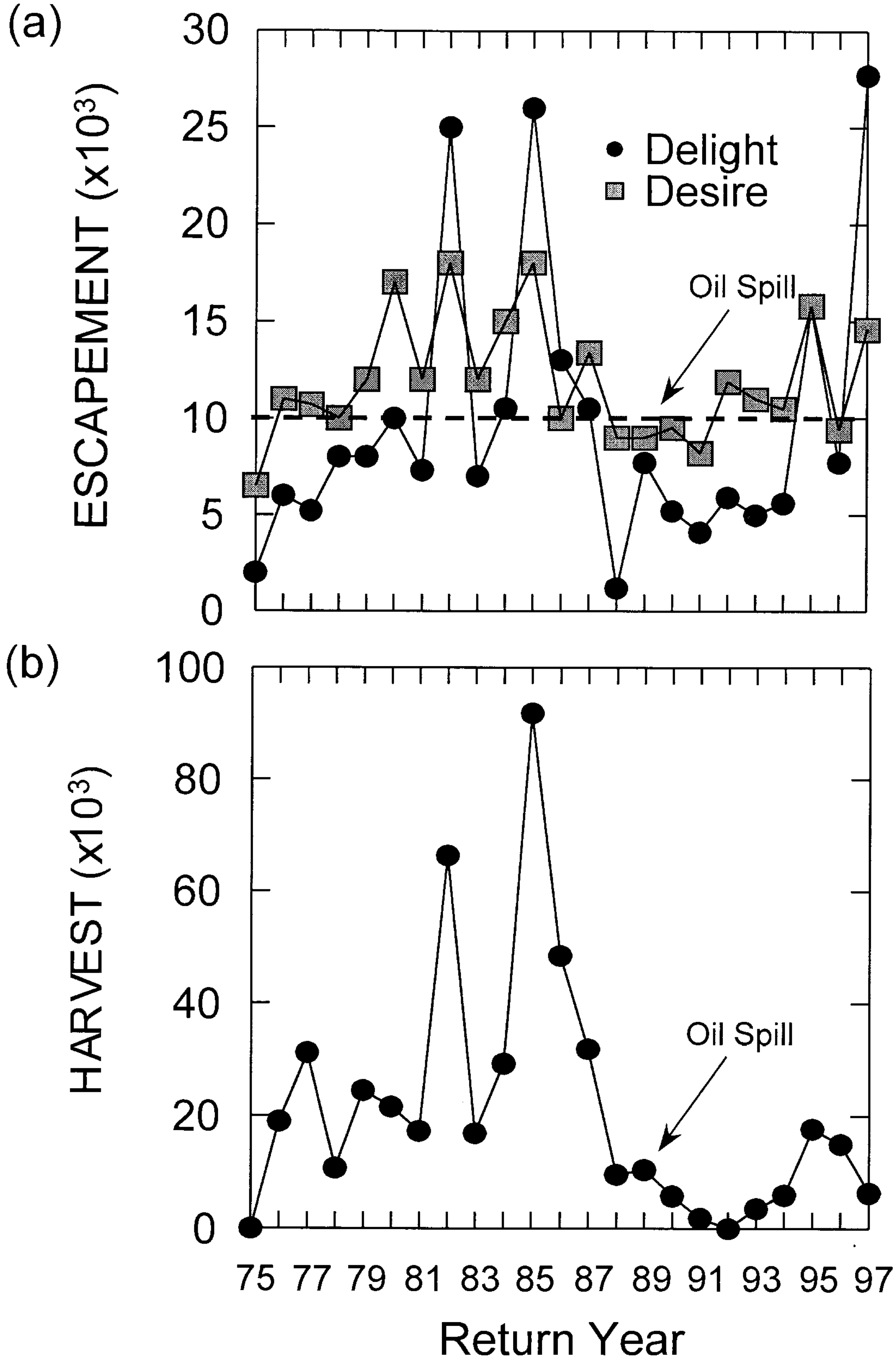

Figure 16. Annual sockeye salmon escapement into (a) Delight and Desire Lakes, and (b) the combined commercial sockeye harvest, 1975-1997. Dashed line represents the escapement goal.

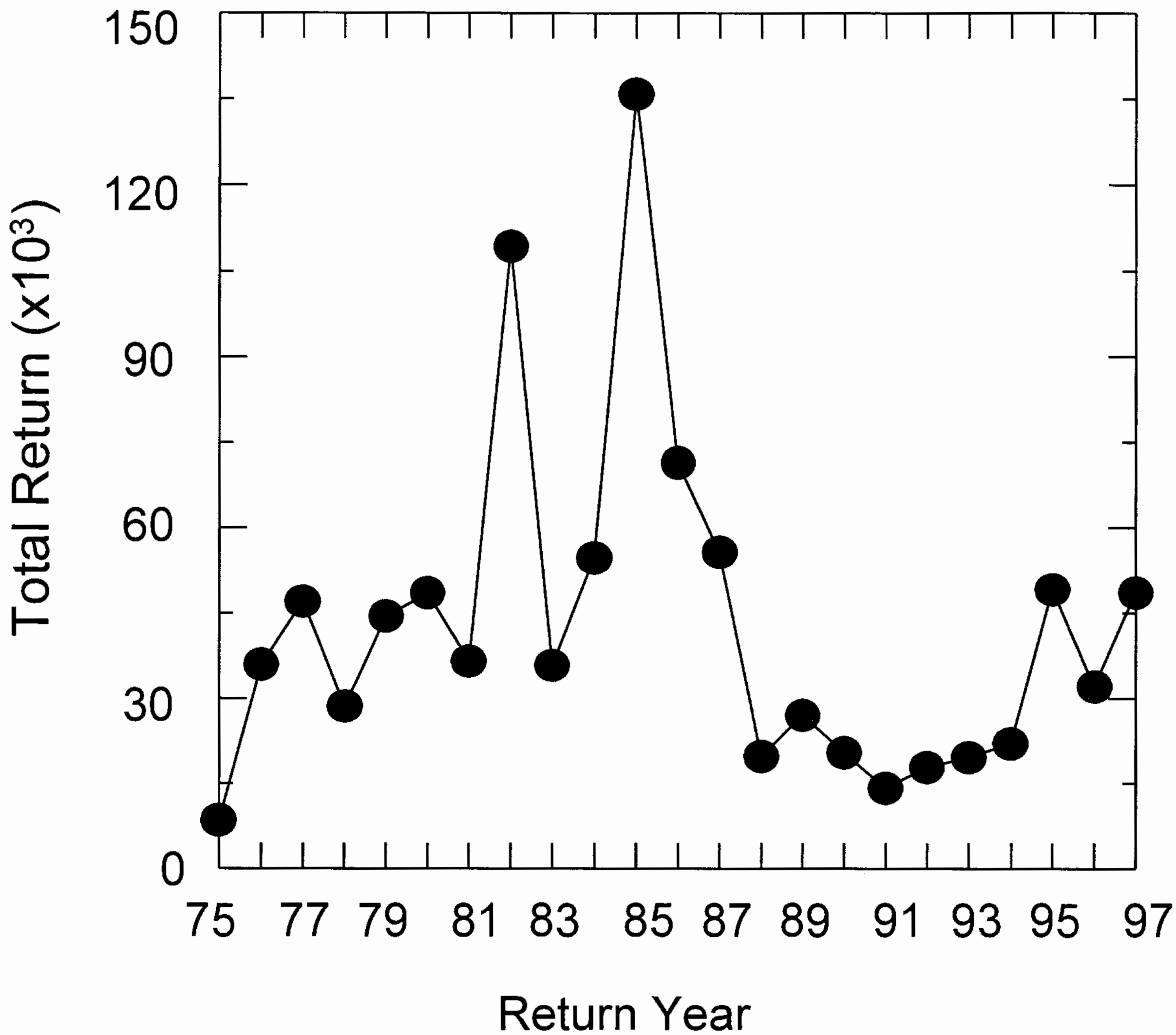

Figure 17. Total sockeye return for Delight and Desire Lakes, 1975-1997.

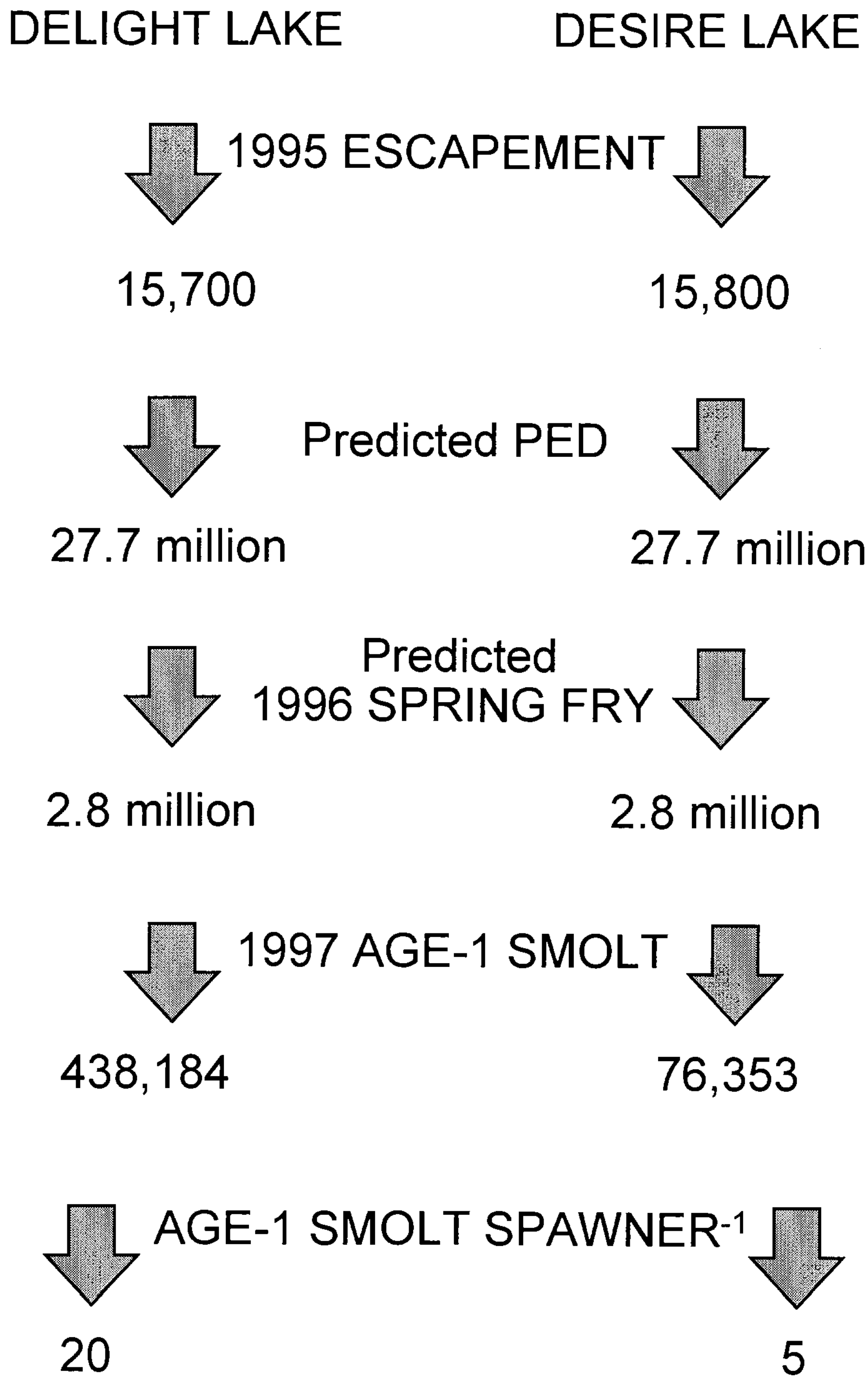

Figure 18. Proposed summary of freshwater survivals of juvenile sockye salmon relative to the 1995 brood-year escapement in Delight and Desire Lakes. Potential egg deposition (PED) is calculated using a fecunditiy of 3,500 eggs per female. Fry recruitment is based on a 10% survival from PED.

spill event. Nonetheless, analysis-of-variance indicated no significant difference (P=0.15) in sockeye returns before and after the oil spill.

DISCUSSION

Limnological Conditions Relative to Sockeye Salmon Production

Delight and Desire Lakes were formed during the 1920s and 1930s respectively, following the recession of McCarty Glacier (Milner 1997). Salmon colonization was rapid and by 1975 both lakes supported significant runs of sockeye salmon (Figure 17). ADF&G did limnological reconnaissance of Delight and Desire Lakes relative to fishery enhancement and management considerations in the late 1970s and 1980s. However, with the exception of 1981, the sporadic nature of the limnology surveys resulted in a lack of consistent data. Nonetheless, the information collected from the 1981 surveys provides a means to compare and contrast limnological conditions and productivity in Delight and Desire Lakes before and after EVOS (1989).

Results from our limnological studies indicate that both Delight and Desire lakes are quite suitable for juvenile sockeye rearing. Water column temperatures <20° C (Figure 7) and dissolved oxygen concentrations >5 mg L^{-1} are well within the tolerance limits for salmonids (Thurston et al. 1979). Although both lakes are stratified in summer (Figure 7), oxygen depletion does not occur in the lower layers. Thus, the entire water column can be utilized by rearing sockeye juveniles. Temperature has also been considered an important factor influencing productivity and juvenile sockeye growth and survival in Alaska lakes (Edmundson 1997). In Delight and Desire Lakes, length of growing season was not unusually short nor were water column temperatures exceptionally cold (Table 1); these values were nearly identical to mean values derived for 26 other Alaskan clearwater lakes (Edmundson 1997). In addition, light penetration in Delight and Desire Lakes is relatively deep (Figure 6b) providing zooplankters little refuge for visually attuned planktivores. For example, Levy (1990) found that sockeyes fed visually at depths equivalent to 0.1% of surface light in several British Columbia lakes. In Delight and Desire Lakes, most of the water column lies above the depth of 1% surface light. Thus, the underwater light climate in Delight and Desire Lakes indicates that during daylight hours sockeye juveniles should be able to efficiently forage on zooplankton.

Delight and Desire Lakes are similar in nutrient (Figure 8, 9) and chl *a* (Figure 10) concentrations and both are highly oligotrophic (nutrient poor). There is no obvious difference in TP values between 1981 and 1997 suggesting that fertility of the two lakes has changed little if any in recent years. The low TP levels and high N:P ratios coupled with low algal biomass (chl *a*) also suggests that sockeye salmon production in these lakes ultimately is limited by water column phosphorus (and nitrogen) concentration and primary production. Although we did not measure carbon fixation rates or oxygen consumption, there is a strong correlation between chl *a* and primary production (Kirk 1994). In addition, a considerable amount of primary production in lakes can occur within the metalimnion or hypolimnion (Pick et al. 1984; Kettle et al. 1987; Hurley and Garrison 1993). Given the vertical heterogeneity in chl *a* (Figure 10), concentrations determined from samples collected from the 1-m depth, as in this study, may not be the best estimate or index of primary production in these lakes.

The average macrozooplankton abundance and biomass in Delight and Desire Lakes (Table 4) are among the lowest recorded for Alaskan nursery lakes. According to a ranking of zooplankton characteristics for 23 sockeye lakes (Edmundson et al. 1992), the average zooplankton biomass for Delight Lake would rank 20th, whereas Desire Lake would rank last. The very low densities, and lack of a well defined seasonal pattern, suggests that low concentrations of algal particles (Figure 10) and other organic particulates (Table 3) limits the productivity and species composition of the macrozooplankton community in these two lakes. Because *Bosmnia* is known to be one of the most opportunistic cladoceran species in terms of selective filter feeding, and has a high reproductive potential (Vanni 1986), it is not surprising that this species is by far the most prevalent zooplankter in these two lakes (Table 4). Moreover, *Bosmina* are considered a preferred prey item for rearing juvenile sockeye, and given their ecological niche, this species would likely benefit under improved nutrient conditions.

Nutrient Enrichment and Management Strategies Relative to Sockeye Restoration

Our limnological data indicate that Delight and Desire Lakes are unproductive, suggesting that nutrient additions may enhance the growth and survival of rearing sockeye juveniles. In Alaska, application of liquid fertilizers to salmon nursery lakes has dramatically increased phosphorus and nitrogen levels, chl *a* concentration, and zooplankton densities and biomass resulting in larger or more abundant smolt (Kyle 1994a; Kyle 1994b; Kyle et al. 1997; Edmundson et al. 1997). Given their suitable water residence times (>0.2 yr), high light environment (deep *EZD*), low nutrient (TP) concentrations and zooplankton biomass, and the small smolt size (Table 5), supplemental additions of phosphorus would likely stimulate sockeye salmon production in both Delight and Desire Lakes. However, it should be stressed that although plankton production in these two lakes is limited by nutrients, there is no evidence that fertility has decreased in either Delight Lake or Desire Lake between 1981 and 1997 due, for example, to overfishing (loss of carcass nutrients), excessive grazing on the forage base from successive high escapements (top-down effects), or habitat (watershed) degradation. Therefore, any proposed nutrient enrichment program should be viewed as sockeye enhancement rather than restoration.

Both Delight and Desire Lakes are in ideal locations for assessing the results of a nutrient enrichment program. Although there is no formal stock separation program for the East Nuka Bay commercial fishery, most of the fishery involves seine catches off the mouth of the outlet creeks to Delight and Desire Lakes. Thus, the relative contribution of each run to the total harvest can be easily documented. In addition, the outlet creeks in both lakes are relatively easy to weir for monitoring migrating adult salmon, and fyke nets can be installed for a total smolt enumeration as done in this study. Accordingly, both lakes are suitable candidates for fertilization.

Of the two lakes, we initially considered Desire Lake as the preferred candidate for nutrient enrichment because of its lower fry survival and a scarcity of zooplankton. Based on the 1995 escapements (~15,000), which produced the 1997 age-1 smolt outmigration, and using standard survival estimates (0.1 egg to fry, 0.5 spring to fall fry, and 0.5 fall fry to smolt) (Foerester 1968), predicted fry recruitment is approximately 2.8 million for each lake (Figure 18). Though both lakes were estimated to have received the same escapement in 1995, the number of age-1 smolts produced in Desire Lake (76,358) was about one-sixth that of Delight Lake (468,184). It is interesting to note that average smolt sizes are very similar between the two lakes (Table 5); however, the effect of higher food abundance may not necessarily translate into larger smolt sizes, but rather to increased survival of smolts the following year (Foerster 1968; Edmundson et al. 1997). Considering the zooplankton standing crop in 1997 and differences in morphometry, there is presumably much less forage available per rearing fry in Desire Lake than at Delight Lake (Table 4), thus fry mortality should be higher in the former. However, the recent decline in sockeye catches in the East Nuka Bay fishery are attributed to poor returns to Delight Lake and not to Desire Lake (ADF&G 1996). Thus, it is difficult to explain why Desire Lake, with a smaller rearing capacity, seemingly supports (in recent years) higher sockeye production compared to Delight Lake.

Interestingly, the 1997 sockeye escapement to Delight Lake, based on enumeration at the weir, was the highest on record (Figure 16a). Prior to 1997, aerial surveys were used to estimate adult escapements in both Delight and Desire Lakes. In addition, our observations on the spawning grounds at Delight Lake indicated that a substantial number of fish appeared to spawn in deeper water and therefore could not be easily observed from aerial surveys, a situation or condition which is not as apparent in Desire Lake. This supports the notion that sockeye escapements in Delight Lake were somewhat higher than past aerial estimates indicate. If escapements are underestimated, then our estimate of the number of smolts produced per spawner in Delight Lake (20) would be lower and perhaps more comparable to Desire Lake (5) (Figure 18). Given that Delight Lake has a more favorable rearing environment, but sockeye production appears lower compared to Desire Lake, we question the accuracy of the aerial estimates of sockeye escapement into Delight Lake. Thus, before making recommendations (i.e., supplemental loading rates, type of fertilizer product, and application schedule) regarding a nutrient enrichment program for Delight and Desire Lakes, we recommend validating aerial index surveys at Delight and Desire Lakes. Only then can we assess how increasing the amount of nutrient can accelerate the recovery of the Delight and Desire Lake sockeye stocks.

CONCLUSIONS

Delight and Desire Lakes historically supported a much higher annual catch of sockeye salmon, yet there is no evidence to date that the recent decline is attributed to the oil spill from the *Exxon Valdez*. Although both lakes are excellent candidates for fertilization, the current forage base (zooplankton biomass) and freshwater growth and survival of juvenile sockeye salmon indicate that Desire Lake would likely benefit more from a modest fertilization program than Delight Lake. However, the recent decline in sockeye catches is attributed to poor returns to Delight Lake rather than Desire Lake. Our observations suggest that sockeye escapement estimates, derived via aerial surveys, are probably underestimated in Delight Lake more so than in Desire Lake. This difference is because of a larger number of sockeye salmon that spawn in deeper water in Delight Lake, which cannot be easily observed from aerial surveys. Until problems with estimating escapements can be solved, a nutrient enrichment program for the Delight and Desire Lakes sockeye salmon stocks is not recommended.

For the 1998 field season, we recommend that adult sockeye enumeration and sampling at both Delight and Desire Lakes be continued using a weir in conjunction with aerial escapement surveys to validate historical escapement estimates. If fertilization at one or both lakes is desired in the future, we recommend continuing field studies to obtain information on sockeye smolt abundance and population characteristics, lake physical conditions, nutrient trends, and plankton abundance and species succession. We believe this approach will further identify appropriate nutrient enrichment or management options concerning the restoration of the Delight and Desire sockeye salmon stocks.

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APPENDIX A.

Delight Lake daily smolt emigration by species, 1997.

Appendix A. Delight Lake daily smolt emigration by species, 1997.

	Sockeye		Coho		
Date	DAILY	CUMULATIVE	DAILY	CUMULATIVE	COMMENTS
12-May	233	233	0	0	Began fishing @ 1900 hrs
13-May	1,157	1,390	0	0	
14-May	847	2,237	0	0	
15-May	826	3,063	0	0	
16-May	504	3,567	0	0	
17-May	1,138	4,705	0	0	
18-May	3,357	8,062	0	0	
19-May	477	8,539	0	0	
20-May	391	8,930	0	0	
21-May	1,958	10,888	3	3	
22-May	292	11,180	1	4	
23-May	325	11,505	6	10	
24-May	56	11,561	10	20	
25-May	19	11,580	12	32	
26-May	116	11,696	40	72	
27-May	40	11,736	27	99	
28-May	108	11,844	52	151	
29-May	224	12,068	164	315	
30-May	604	12,672	750	1,065	
31-May	2,331	15,003	1,561	2,626	
1-Jun	10,812	25,815	852	3,478	
2-Jun	14,557	40,372	849	4,327	
3-Jun	24,678	65,050	2,064	6,391	
4-Jun	25,180	90,230	1,304	7,695	
5-Jun	60,352	150,582	6,372	14,067	
6-Jun	78,922	229,504	1,719	15,786	
7-Jun	57,299	286,803	2,570	18,356	
8-Jun	55,765	342,568	953	19,309	
9-Jun	69,083	411,651	2,568	21,877	
10-Jun	45,765	457,416	1,293	23,170	
11-Jun	26,536	483,952	284	23,454	
12-Jun	26,881	510,833	29	23,483	
13-Jun	18,225	529,058	636	24,119	
14-Jun	22,799	551,857	509	24,628	
15-Jun	15,992	567,849	357	24,985	
16-Jun	21,650	589,499	202	25,187	
17-Jun	12,419	601,918	32	25,219	
18-Jun	10,748	612,666	9	25,228	
19-Jun	1,656	614,322	37	25,265	
20-Jun	1,842	616,164	28	25,293	
21-Jun	2,598	618,762	58	25,351	
22-Jun	2,141	620,903	36	25,387	
23-Jun	1,049	621,952	62	25,449	
24-Jun	294	622,246	64	25,513	
25-Jun	261	622,507	44	25,557	
26-Jun	221	622,728	6	25,563	
27-Jun	208	622,936	29	25,592	
28-Jun	105	623,041	3	25,595	
29-Jun	18	623,059	10	25,605	Fyke removed

APPENDIX B.

Desire Lake daily smolt emigration by species, 1997.

Appendix B. Desire Lake daily smolt emigration by species, 1997.

	SOCKEYE		COHO		
DAILY	DAILY	CUMULATIVE	DAILY	CUMULATIVE	Comments
15-May	635	635	3	3	Began fishing at noon
16-May	858	1,493	11	14	
17-May	1,163	2,656	12	26	
18-May	825	3,481	21	47	Heavy otter predation on trapped smolts
19-May	243	3,724	15	62	Otter predation
20-May	328	4,052	13	75	Otter predation
21-May	597	4,649	10	85	
22-May	1,429	6,078	47	132	
23-May	1,114	7,192	82	214	
24-May	610	7,802	61	275	
25-May	660	8,462	60	335	
26-May	1,147	9,609	82	417	
27-May	1,249	10,858	105	522	
28-May	1,551	12,409	152	674	
29-May	2,750	15,159	385	1,059	
30-May	2,508	17,667	684	1,743	
31-May	4,449	22,116	436	2,179	
1-Jun	2,554	24,670	182	2,361	
2-Jun	2,730	27,400	314	2,675	
3-Jun	6,101	33,501	558	3,233	
4-Jun	5,964	39,465	384	3,617	
5-Jun	17,591	57,056	3,698	7,315	High water, one panel pulled
6-Jun	1,390	58,446	46	7,361	Panel reinstalled, fishing 100% @ 1530 hrs
7-Jun	7,217	65,663	14	7,375	
8-Jun	8,250	73,913	79	7,454	
9-Jun	3,820	77,733	248	7,702	
10-Jun	2,680	80,413	102	7,804	
11-Jun	1,680	82,093	17	7,821	
12-Jun	1,616	83,709	18	7,839	
13-Jun	2,784	86,493	176	8,015	
14-Jun	2,432	88,925	141	8,156	High water, pickets pulled in PM
15-Jun	1,744	90,669	106	8,262	Fyke not fishing, smolt numbers interpolated
16-Jun	1,056	91,725	71	8,333	Fyke not fishing, smolt numbers interpolated
17-Jun	1,376	93,101	36	8,369	Fyke fishing 85% @ 1500 hrs.
18-Jun	1,024	94,125	1	8,370	
19-Jun	366	94,491	1	8,371	
20-Jun	958	95,449	0	8,371	
21-Jun	290	95,739	1	8,372	
22-Jun	216	95,955	0	8,372	
23-Jun	399	96,354	0	8,372	
24-Jun	194	96,548	1	8,373	
25-Jun	107	96,655	1	8,374	
26-Jun	45	96,700	0	8,374	Fyke removed

APPENDIX C.

Summary of smolt age composition by sample period
at Delight and Desire Lakes, 1997.

Appendix C. Summary of smolt age composition by sample period at Delight and Desire Lakes, 1997.

DELIGHT LAKE

Sample Period	Sample Size	Age 1.0	Age 2.0	Percent Age 1.0
12 May-19 May	355	293	62	82.5
20 May-27 May	268	172	92	64.2
28 May-3 June	234	56	178	24.0
4 June-10 June	101	72	29	71.3
11 June-16 June	271	266	5	98.2
Total	1,229	859	366	69.9

DESIRE LAKE

Sample Period	Sample Size	Age 1.0	Age 2.0	Percent Age 1.0
15 May- 21 May	274	222	52	81.0
22 May-28 May	382	217	142	56.8
29 May-4 June	400	313	71	78.2
5 June- 11 June	230	209	21	90.1
12 June- 13 June	120	116	4	96.6
Total	1,406	1,077	290	76.5

APPENDIX D.

Delight Lake adult escapement, 1997.

Appendix D. Delight Lake adult spawning escapement, 1997.

	Sockeye	Accum sockeye	Pink	Accum pink	Coho	Accum Coho	Dolly Varden	Accum Dolly Varden	
35,588	1	1							
35,589	0	1							
35,590	0	1							
35,591	1	2							
35,592	1	3							
35,593	0	3							
35,594	1	4							
35,595	0	4							
35,596	66	70							
35,597	31	101							
35,598	6	107							
35,599	5	112							
35,600	0	112							
35,601	0	112							
35,602	0	112							
35,603	0	112							
35,604	0	112							Very low stream discharge
35,605	0	112							
35,606	0	112							
35,607	0	112							
35,608	0	112							
35,609	0	112							
35,610	114	226							
35,611	115	341							
35,612	0	341							
35,613	0	341							
35,614	0	341							
35,615	0	341							
35,616	0	341							
35,617	0	341							
35,618	0	341							
35,619	0	341							
35,620	0	341							
35,621	0	341							Rain,
35,622	2,632	2,973					3,659	3,659	discharge increases
35,623	6,468	9,441					3,950	7,609	
35,624	1,869	11,310					1,262	8,871	
35,625	2,468	13,778					173	9,044	
35,626	625	14,403					287	9,331	
35,627	246	14,649					100	9,431	
35,628	1,019	15,668					751	10,182	
35,629	179	15,847					206	10,388	
35,630	357	16,204					704	11,092	
35,631	54	16,258					10	11,102	
35,632	112	16,370					39	11,141	
35,633	217	16,587					21	11,162	
35,634	191	16,778					31	11,193	
35,635	202	16,980					58	11,251	
35,636	100	17,080					60	11,311	
35,637	0	17,080					0	11,311	
35,638	101	17,181					38	11,349	
35,639	0	17,181					0	11,349	
35,640	95	17,276					13	11,362	
35,641	0	17,276					0	11,362	
35,642	0	17,276					0	11,362	
35,643	828	18,104					446	11,808	
35,644	228	18,332					22	11,830	
35,645	369	18,701					37	11,867	
35,646	91	18,792	1	1			67	11,934	
35,647	20	18,812	0	1			2	11,936	
35,648	205	19,017	1	2			23	11,959	
35,649	191	19,208	0	2			81	12,040	
35,650	1,342	20,550	15	17			455	12,495	
35,651	3,907	24,457	39	56	1	1	745	13,240	
35,652	362	24,819	8	64	1	2	111	13,351	High water,
35,653	261	25,080	2	66	0	2	22	13,373	pickets pulled
35,654	0	25,080	0	66	0	2	0	13,373	
35,655	75	25,155	0	66	0	2	0	13,373	Reinstalled
35,656	110	25,265	11	77	1	3	5	13,378	pickets
35,657	317	25,582	16	93	1	4	13	13,391	
35,658	225	25,807	4	97	0	4	2	13,393	
35,659	441	26,248	22	119	8	12	0	13,393	
35,660	361	26,609	8	127	3	15	2	13,395	
35,661	250	26,859	12	139	3	18	2	13,397	
35,662	83	26,942	12	151	1	19	2	13,399	
35,663	139	27,081	2	153	0	19	0	13,399	
35,664	236	27,317	10	163	0	19	29	13,428	
35,665	61	27,378	1	164	0	19	1	13,429	
35,666	70	27,448	0	164	4	23	1	13,430	
35,667	0	27,448	0	164	0	23	0	13,430	
35,668	372	**27,820**	38	**202**	96	**119**	4	**13,434**	Weir removed

APPENDIX E.

Desire Lake adult escapement, 1997.

Appendix E. Desire Lake adult spawning escapement, 1997.

	Sockeye	Accum sockeye	Pink	Accum pink	Dolly Varden	Accum Dolly Varden	
3-Jun	1	1					
4-Jun	0	1					
5-Jun	0	1					
6-Jun	0	1					
7-Jun	0	1					
8-Jun	0	1					
9-Jun	2	3					
10-Jun	0	3					
11-Jun	19	22					
12-Jun	47	69					
13-Jun	751	820					
14-Jun	65	885					Pickets pulled due to high wate
15-Jun	0	885					Pickets out, no count
16-Jun	2	887					partial count, pickets reinstalled
17-Jun	0	887					
18-Jun	1	888					
19-Jun	326	1,214					
20-Jun	1,170	2,384					
21-Jun	30	2,414					
22-Jun	35	2,449					
23-Jun	431	2,880					
24-Jun	243	3,123					
25-Jun	685	3,808					
26-Jun	20	3,828					
27-Jun	95	3,923					
28-Jun	25	3,948					
29-Jun	259	4,207					
30-Jun	17	4,224					
1-Jul	375	4,599					
2-Jul	256	4,855					
3-Jul	315	5,170					
4-Jul	685	5,855			300*	300	*Estimated
5-Jul	178	6,033				300	
6-Jul	109	6,142				300	
7-Jul	933	7,075				300	
8-Jul	27	7,102				300	
9-Jul	126	7,228				300	
10-Jul	179	7,407				300	
11-Jul	2,324	9,731			620	920	
12-Jul	113	9,844			0	920	
13-Jul	151	9,995			0	920	
14-Jul	122	10,117			127	1,047	
15-Jul	318	10,435			446	1,493	
16-Jul	154	10,589			180	1,673	
17-Jul	355	10,944			317	1,990	
18-Jul	46	10,990			140	2,130	
19-Jul	47	11,037			150	2,280	
20-Jul	119	11,156			259	2,539	
21-Jul	113	11,269			196	2,735	
22-Jul	146	11,415			127	2,862	
23-Jul	62	11,477			63	2,925	
24-Jul	53	11,530			94	3,019	
25-Jul	110	11,640			205	3,224	
26-Jul	63	11,703			76	3,300	
27-Jul	97	11,800			83	3,383	
28-Jul	138	11,938			136	3,519	2 king salmon
29-Jul	219	12,157	2	2	79	3,598	3 king salmon
30-Jul	87	12,244	39	41	54	3,652	1 king salmon
31-Jul	571	12,815	40	81	671	4,323	
1-Aug	228	13,043	6	87	132	4,455	
2-Aug	4	13,047	0	87	0	4,455	1 coho salmon
3-Aug	0	13,047	2	89	0	4,455	
4-Aug	10	13,057	7	96	48	4,503	
5-Aug	217	13,274	74	170	312	4,815	
6-Aug	147	13,421	27	197	22	4,837	
7-Aug	125	13,546	3	200	87	4,924	
8-Aug	879	14,425	567	767	384	5,308	
9-Aug	240	14,665	267	1,034	152	5,460	Weir pulled at 1800 hrs

APPENDIX F.

Summary of sockeye harvest, escapement, and total return to Delight and Desire lakes, 1975-1997.

Appendix F. Summary of sockeye harvest, escapement, and total return to Delight and Desire Lakes, 1975-1997.

		Spawning Escapements		
Year	Harvests	Delight	Desire	Total Return
1975	0.0	2.0	6.5	8.5
1976	18.9	6.0	11.0	35.9
1977	31.1	5.2	10.7	47.0
1978	10.6	8.0	10.0	28.6
1979	24.4	8.0	12.0	44.4
1980	21.5	10.0	17.0	48.5
1981	17.2	7.3	12.0	36.5
1982	66.3	25.0	18.0	109.3
1983	16.8	7.0	12.0	35.8
1984	29.2	10.5	15.0	54.7
1985	91.8	26.0	18.0	135.8
1986	48.4	13.0	10.0	71.4
1987	31.8	10.5	13.4	55.7
1988	9.5	1.2	9.0	19.7
1989	10.3	7.7	9.0	27.0
1990	5.7	5.2	9.5	20.4
1991	1.8	4.1	8.2	14.1
1992	0.0	5.9	11.9	17.8
1993	3.5	5.0	11.0	19.5
1994	5.9	5.6	10.5	22.0
1995	17.6	15.7	15.8	49.1
1996	14.9	7.7	9.4	32.0
1997	6.3	27.7	14.6	48.6
Average	21.02	9.75	12.18	42.71