Exxon Valdez Oil Spill
Restoration Project Final Report

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

Restoration Project 97254
Final Report

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Study History: Restoration Project 97254 was initiated to assess the feasibility of nutrient enrichment (fertilization) to restore sockeye salmon production in Delight and Desire Lakes. During 1997, comprehensive limnological surveys were conducted (Restoration Project 97254) to characterize the physical environment, water chemistry, nutrient condition, and plankton abundance and biomass in Delight and Desire Lakes. In addition, Alaska Department of Fish and Game (ADF&G) conducted studies of sockeye salmon smolts and adults in these two lakes. Restoration Project 98254 involved analyses of the limnological data and evaluation of current and historical fisheries data relative to restoration of the Delight and Desire sockeye salmon populations.

Abstract: The 1989 *Exxon Valdez* oil spill 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 spill affected sockeye salmon production, commercial catches of sockeye in the East Nuka Bay subdistrict averaged 7,300 after the spill compared to 29,800 prior to the spill. 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 low zooplankton densities. Zooplankton biomass 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 (1995) escapement was estimated to be the same for both lakes (15,000) suggesting a smaller rearing capacity in Desire Lake compared to Delight Lake. Based on the 1997 weir estimate of sockeye escapements and observations of spawning activity in the two lakes, we speculate that aerial surveys underestimated Delight Lake escapements in past years.

Key Words: East Nuka Bay, limnology, Lower Cook Inlet, nutrient enrichment, sockeye salmon smolts and adults.

Project Data: *Description of data* - Two sets of data were developed during the study: (1) limnological characteristics (e.g., morphometry, temperature, light penetration, water chemistry, nutrients, phytoplankton and zooplankton); and (2) information on sockeye and coho salmon populations including adult escapement, harvest, age composition, and the 1997 smolt outmigration estimate for Delight and Desire Lakes. *Format* - Data used in this report are stored electronically in dBASE, Foxprow, or Microsoft (MS) Excel formats. Data presented in the accompanying figures are in MS PowerPoint 97 presentation files and tabular data are in MS Excel 97 files. Text files are in MS Word 97. *Custodian* - Contact Jim A. Edmundson, Alaska Department of Fish and Game, 43961 K-Beach Road, Suite B, Soldotna, AK 99669, work phone

(907) 260-2917, fax (907) 262-4709, email jim_edmundson@fishgame.state.ak.us. *Availability* - There are no restrictions upon supplying copies of the data.

Citation:

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EXECUTIVE SUMMARY

Delight and Desire Lakes support anadromous salmonid stocks, which contribute to most of the commercial salmon catches within the East Nuka Bay subdistrict along the outer coast of the Kenai Peninsula. These lakes also provide ample opportunities for subsistence and recreational fishing. Prior to the 1989 *Exxon Valdez* oil spill (EVOS), Delight and Desire Lakes supported much higher runs (catches and escapements) of sockeye salmon (*Oncorhynchus nerka*) compared to recent years. During 1975-1989, sockeye salmon runs to Delight and Desire Lakes combined averaged 50,500; however between 1990 and 1997 the return averaged only 27,900 sockeyes. Evidence to date suggests that the decline was neither directly nor indirectly attributed to EVOS because sockeye catches began to decrease several years before the oil spill. Nonetheless, in 1996 EVOS Trustee Council recognized that the sockeye runs of Delight and Desire Lakes were depressed and approved funding for limnological and fisheries studies. Delight and Desire Lakes were studied intensively during the 1997 open water season to examine limnological conditions relative to sockeye salmon production. We conducted monthly limnological surveys in both lakes to assess physical (e.g., light and temperature) characteristics, nutrient status, and plankton abundance, biomass and community structure. In addition, we enumerated sockeye (and coho) smolt outmigrations and adult escapements into both Delight and Desire Lakes. The purpose of these investigations was to determine whether a nutrient enrichment program or other restoration techniques could accelerate the recovery of these depressed sockeye salmon stocks.

Results from our limnological surveys indicated that Delight (2.8 km^2) and Desire (1.8 km^2) Lakes were very oligotrophic with an average photic depth of 20 m, a mean total phosphorus concentration of about 5 $\mu g\ L^{-1}$, and algal biomass (chlorophyll *a*) levels less than 1 $\mu g\ L^{-1}$. The macrozooplankton communities in Delight and Desire Lakes were dominated (>80%) both numerically and in terms of biomass by the small (0.3 mm) herbivore *Bosmina*. During 1997, the seasonal mean total macrozooplankton biomasses in Delight and Desire Lakes averaged 137 $mg\ m^{-2}$ and 27 $mg\ m^{-2}$, respectively, which are low compared to many other Alaskan sockeye nursery lakes. In 1997, an estimated 623,059 sockeye smolt (70% age-1) emigrated Delight Lake, whereas 96,700 sockeye (79% age-1) smolts emigrated Desire Lake. Based on the 1995 escapement (which produced the 1997 age-1 smolt outmigration) estimated to be 15,000 for each lake, the number of age-1 smolts produced in Desire Lake was about one-sixth that of Delight Lake.

Given that nutrients limit lower trophic level production (algal and zooplankton biomass) and ultimately influence freshwater growth and survival of juvenile sockeye salmon, supplemental additions of nutrients could benefit sockeye production in Delight and Desire Lakes. Both lakes are ideally located for assessing the results of a nutrient enrichment program in that harvest, escapement, and smolt information are relatively easy to obtain. Of the two lakes, we considered Desire Lake as the preferred candidate for a nutrient enrichment program because of its apparent lower fry survival and much smaller forage base (zooplankton biomass). However, the historical escapement data derived from aerial surveys for Delight Lake may be biased low, but by an

unknown amount. Our 1997 ground surveys indicated that in Delight Lake a large number of sockeye spawned in deeper water that could not be observed from aerial surveys. This problem was not as serious in Desire Lake. Although Delight Lake seemed to have a more favorable rearing environment (greater zooplankton biomass) than Desire Lake, sockeye production appeared lower. We therefore recommend validating aerial index surveys at Delight and Desire Lakes before implementing or determining an appropriate nutrient enrichment program.

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, (1989-1997) the annual commercial catch for the East Nuka Bay sockeye fishery averaged 7,300 compared to 29,800 for the 14 years (1975-1988) 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, hatchery-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 euphotic volume (Koenings and Burkett 1987), temperature (Brett 1971; Beauchamp et al. 1989; Edmundson and Mazumder 2001), photosynthetic rates (Shortreed et al. 2000), and zooplankton biomass (Hyatt and Stockner 1985; Stockner 1987; Kyle and Koenings 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 1994ab; Kyle et al. 1997; 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 1967; 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 the sockeye salmon smolt outmigration and adult escapement in both lakes. These data are not only designed to help assess current rearing capacity for sockeye juveniles, but also to detect future or potential 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.

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 precipitation up to 380 cm 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 Lakes drainages are relatively new, having been deglaciated since about the 1930s (Milner 1997). 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

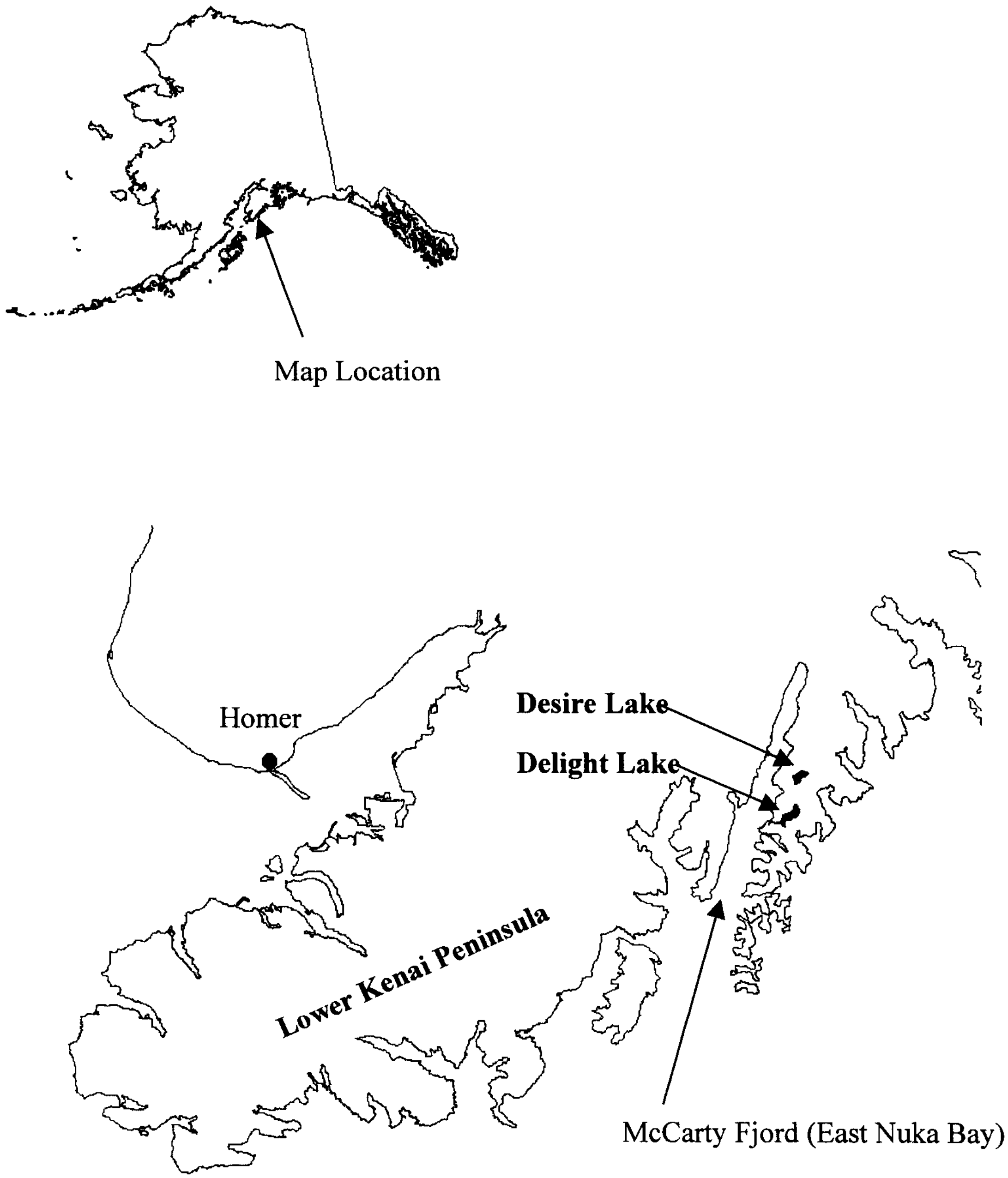

Figure 1. Geographic location of Delight and Desire Lakes, Kenai Peninsula

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.

OBJECTIVES

The objective of the report funded 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.

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 3^{rd} order polynomial function to temperature (1-m) versus day-of-year plots and then projecting the X-intercepts where $f(x) = 4°$ C

(Edmundson 1997). The lengths of the growing season were 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 irradiance (I) were obtained using a Protomatic submarine photometer. The rate of attenuance of I with depth (d) is K_d, the light-extinction coefficient, and was calculated from the equation: $I_d = I_o e^{-Kd}$ or $\ln I_o - \ln I_d = K_d$, where I_o is the irradiance at the surface and I_d is the irradiance at depth, d (Kirk 1994). The value of the depth of 1% light penetration or euphotic zone depth (*EZD*) is given by $4.6/K_d$ (Kirk 1994). Water transparency was measured with a 20-cm black and white Secchi disk.

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 (temperature compensated to 25° C) was measured using a YSI conductivity 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 phenylhypochlorite 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 (4°C) 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 using an ocular micrometer to the nearest 0.02 mm for at least 15 individuals of each species in the subsample. Zooplankton body mass was estimated from species-specific regression equations derived between zooplankter body length and dry weight (Koenings et al. 1987). To calculate species biomass, the species density was multiplied by the mean mass.

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 was reinstalled 17 June and fishing resumed at 1500 hr. On 26 June, the fyke net in Desire Lake was removed for the season.

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 number of smolts in the 0.45 kg subsample were multiplied by the ratio of total weight to subsample weight. 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. Smolts 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 sockeye smolt from Delight Lake and 1,408 from Desire Lake 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, because stream visibility was good, 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 greater than 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 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), we computed 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 (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 and a median *EZD* of 20.1 m. The median K_d and *EZD* values in Desire Lake were 0.27 and 17.1 m, respectively (Figure 6a-c). 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 transparency 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 transparency 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,

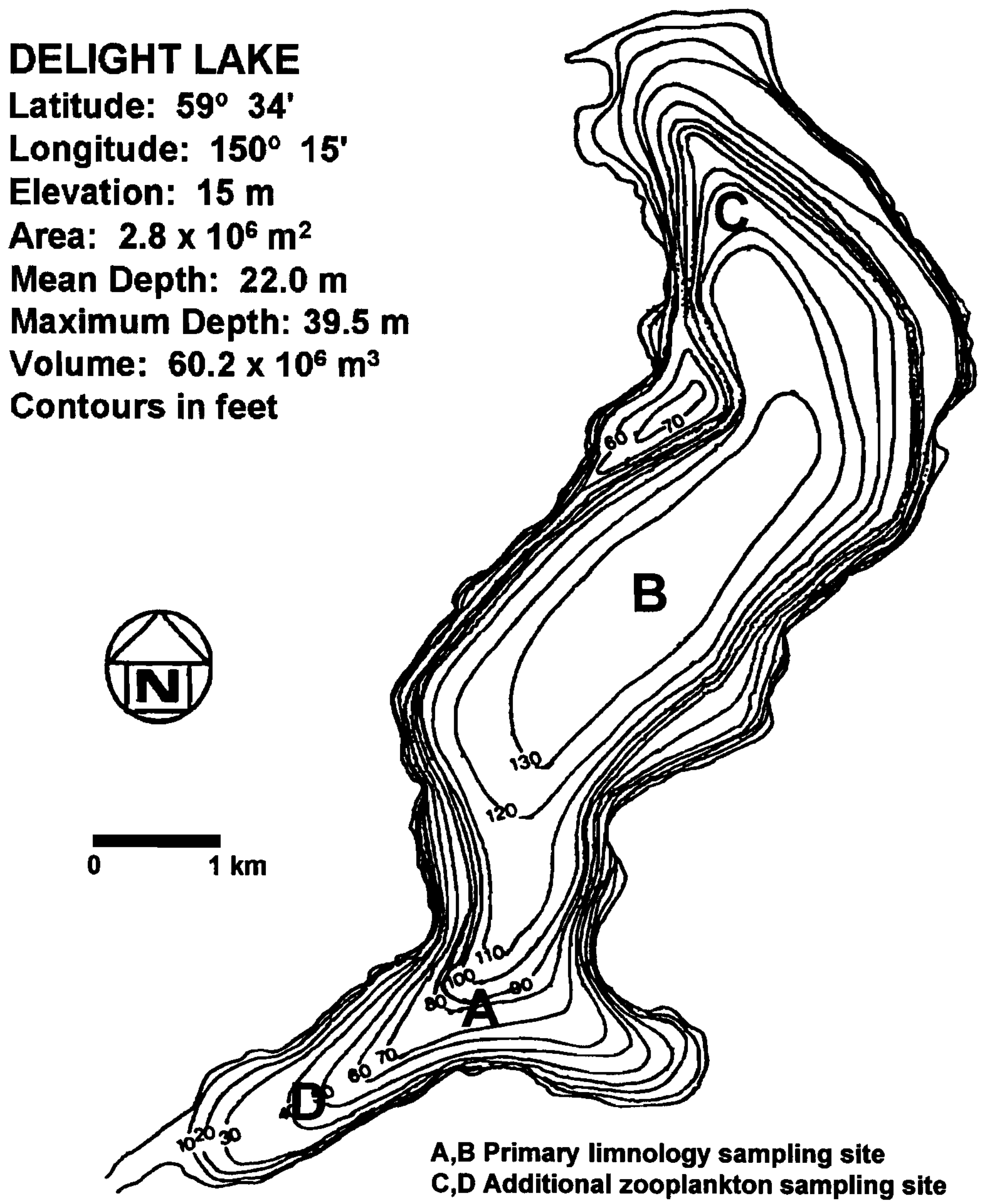

Figure 2. Bathymetric map of Delight Lake showing the location of the limnology sampling stations.

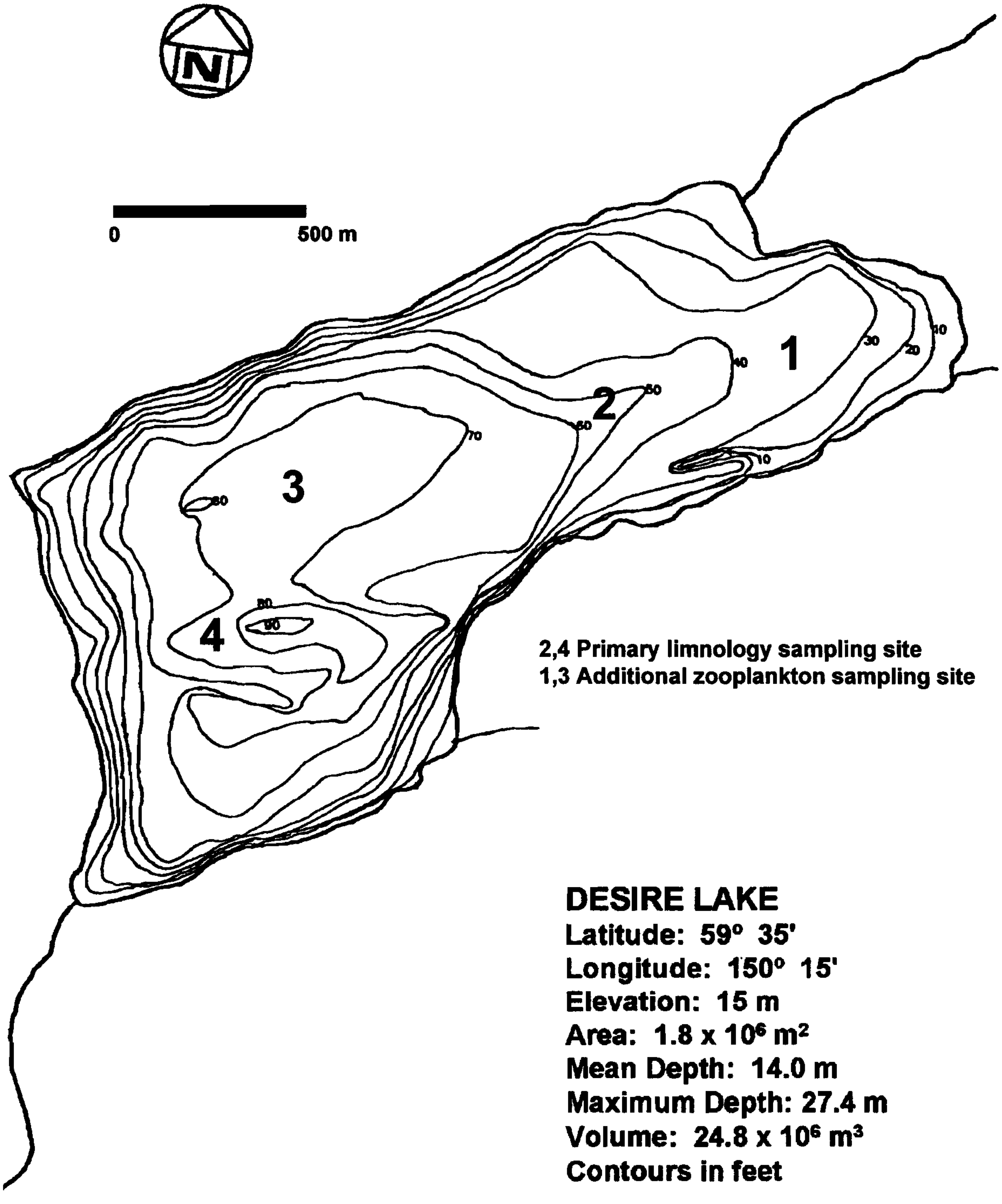

Figure 3. Bathymetric map of Desire Lake showing the location of the limnology sampling stations.

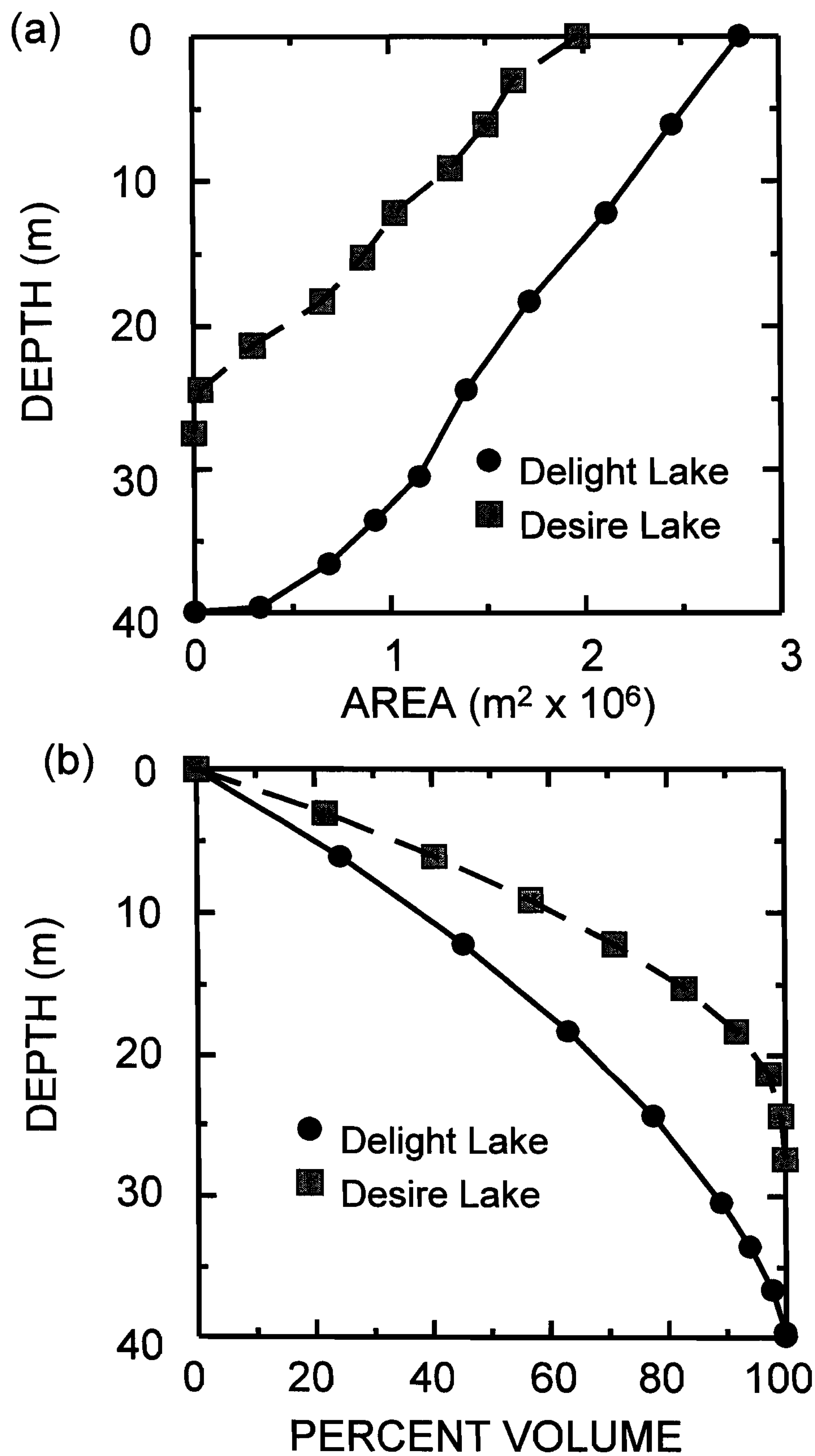

Figure 4. (a) Hypsometric and (b) depth-volume plots for Delight and Desire Lakes.

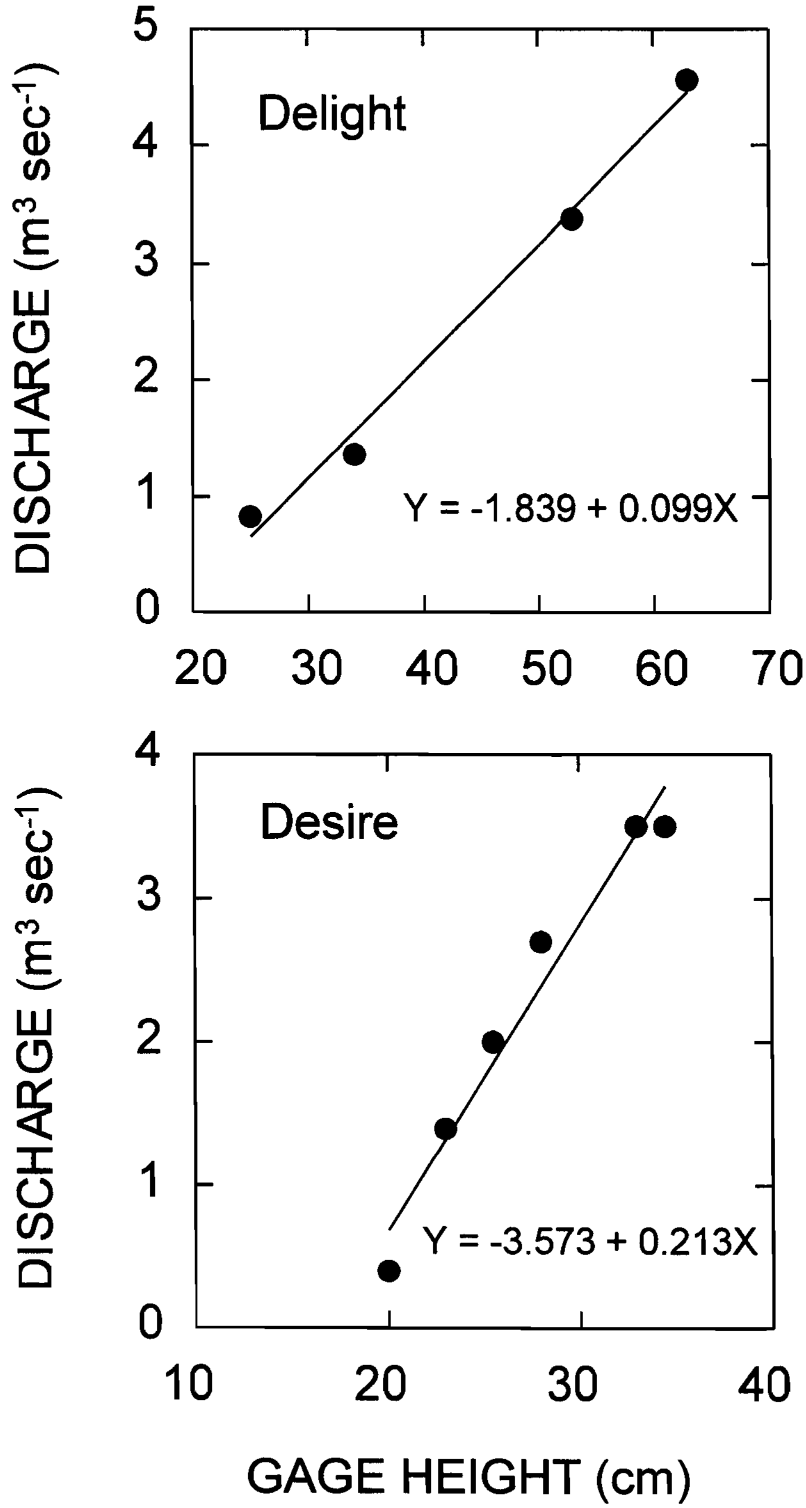

Figure 5. Relationship between staff gauge height and summer water discharge for Delight and Desire Lakes, 1997.

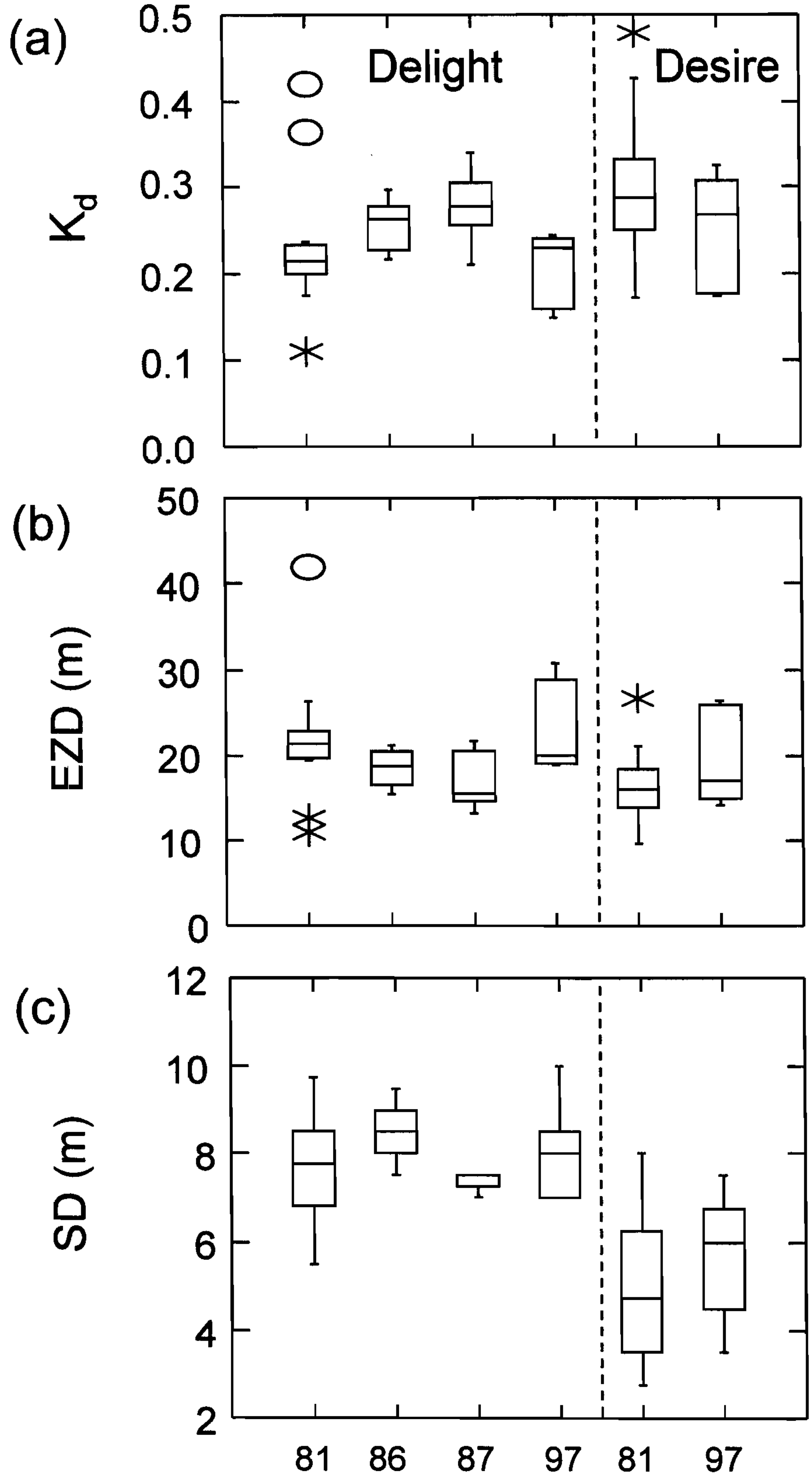

Figure 6. Box plots for the (a) vertical light-extinction coefficient (K_d), (b) euphotic zone depth (*EZD*), and (c) Secchi disk (*SD*) transparency. Asterisks are values greater than 1.5 times the interquartile range, ovals greater than 3 times the interquartile range.

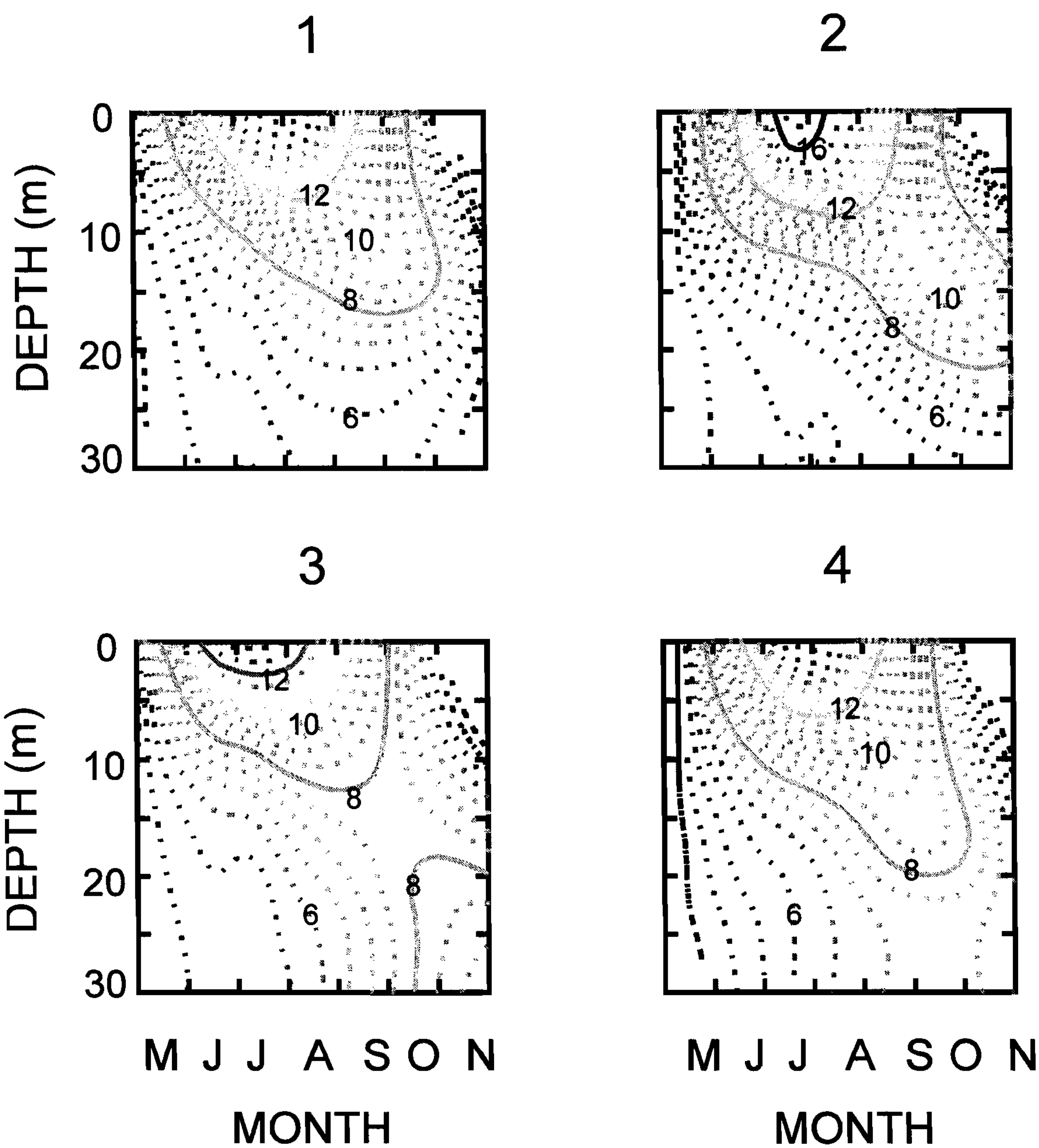

Figure 7. Temperature (°C) isopleths for (1) Delight Lake 1981, (2) Delight Lake 1997, (3) Desire Lake 1981, and (4) Desire Lake 1997.

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 in both lakes the growing season was shorter in 1997 than in 1981, water temperatures were warmer and heat budgets greater in 1997.

Water and Nutrient Chemistry

Delight and Desire Lakes were slightly below neutral with pH values ranging from 5.2 to 6.9 and poorly buffered as total alkalinity ranged from 2 to 10 mg L^{-1} (Table 2). Both lakes also had 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 mixing of the water column. Concentrations of soluble reactive silicon (RSI) in both Delight and Desire Lakes were less than 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 was relatively deep, it was 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 to 137 µg L^{-1} and from 37 to 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 to 48 µg L^{-1} during the spring (May) overturn and ranged from 2 to 19 µg L^{-1} in October. At spring turnover, nitrate concentrations were somewhat higher in Desire Lake, ranging between 54 and 84 µg L^{-1}, but by the end of the growing season concentrations ranged from 13 to 33 µg L^{-1}. 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 only 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 to 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 between 1981 and 1997 in either lake. 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 greater than 15:1 indicate that phosphorus is the primary nutrient limiting productivity (Smith

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 day of year of spring (4°C) isothermy	116	129	94	128
Projected day of year of fall (4°C) isothermy	217	213	201	211
Projected day of year 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

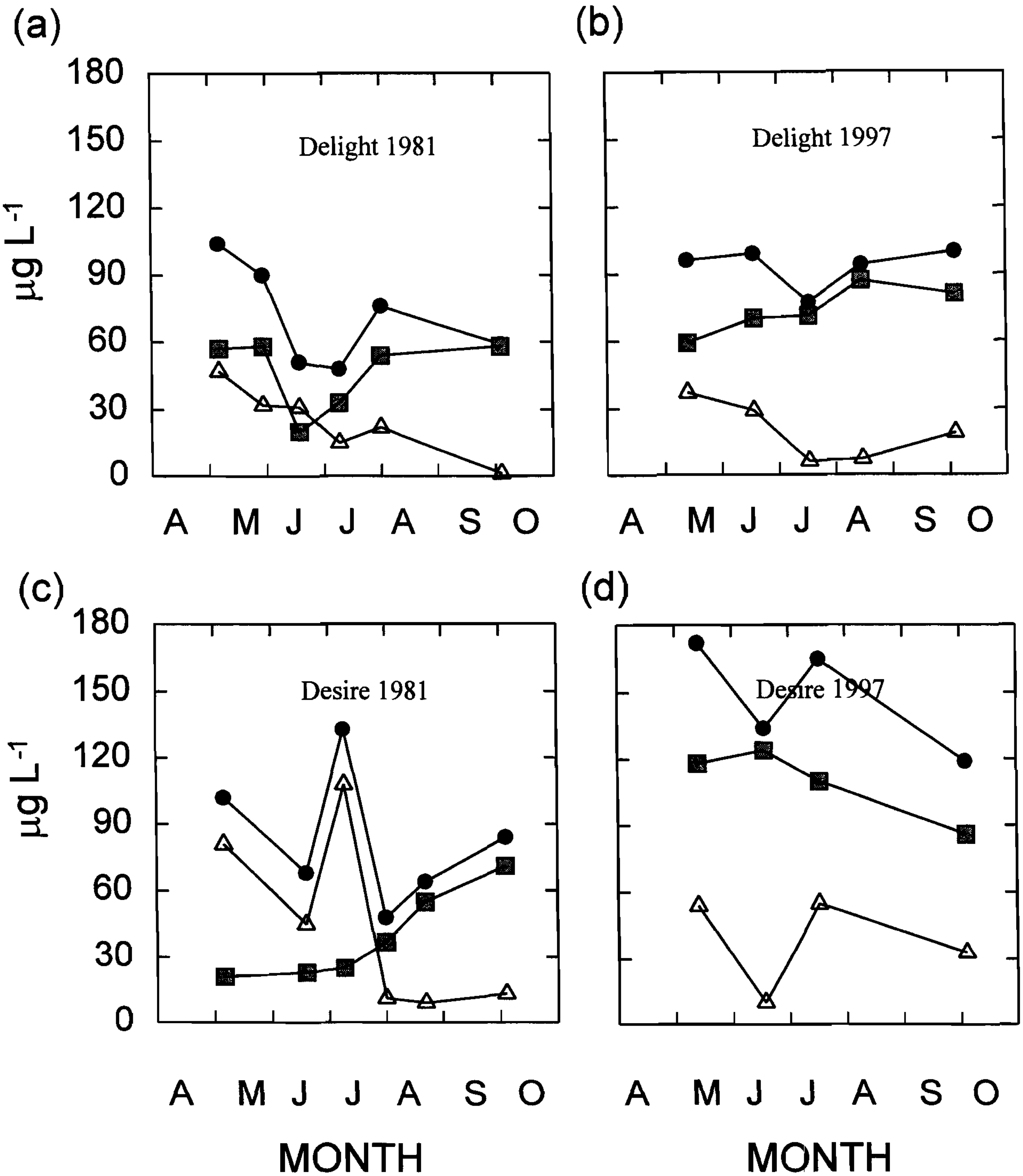

Figure 8. Seasonal changes in total nitrogen (circles), Kjeldahl (squares), and nitrate (triangles) nitrogen concentrations within the 1-m stratum; (a) Delight Lake 1981, (b) Delight Lake 1997, (c) Desire Lake 1981, and (d) Desire Lake 1997.

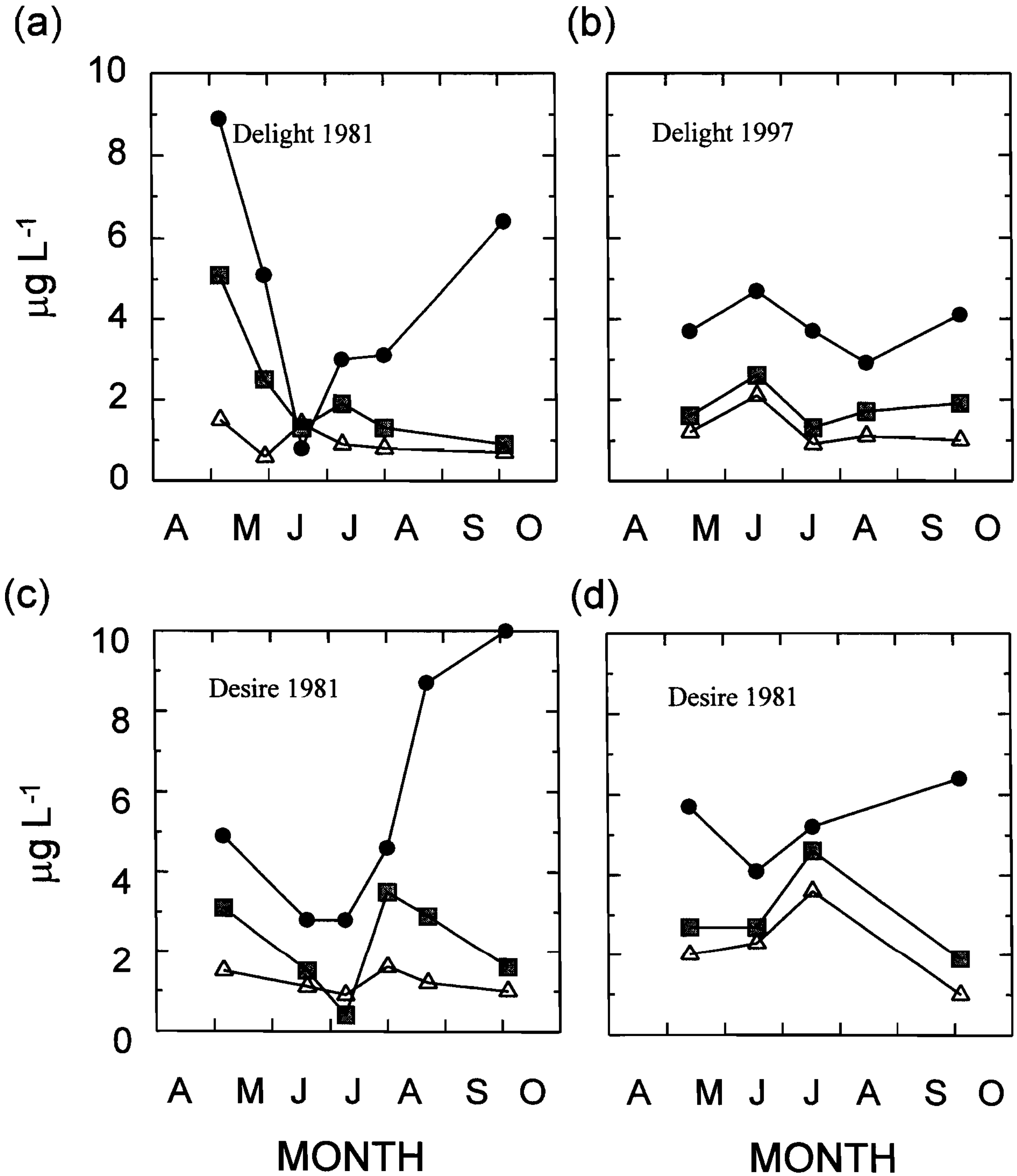

Figure 9. Seasonal changes in total (circles), total filterable (squares), and filterable reactive (triangles) phosphorus concentrations within the 1-m stratum; (a) Delight Lake 1981, (b) Delight Lake 1997, (c) Desire Lake 1981, and (d) Desire Lake 1997.

1982). Based on the low epilimnetic TP concentrations and high TN:TP 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 were much (2-3 times) higher in the hypolimnion compared to the epilimnion (1 m). Deeper lying chl *a* concentrations averaged 2.9 µg L^{-1} in Delight Lake and 5.0 µg 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 (µmol μmol^{-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 these cladocerans - *Bosmina* sp., *Daphnia* sp., and *Chydorinae* sp. - and one copepod, *Cyclops* sp. (Table 4). The small (0.3 mm), herbivorous *Bosmina* dominated the macrozooplankton community in both lakes, accounting for about 95% of the total density and biomass 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

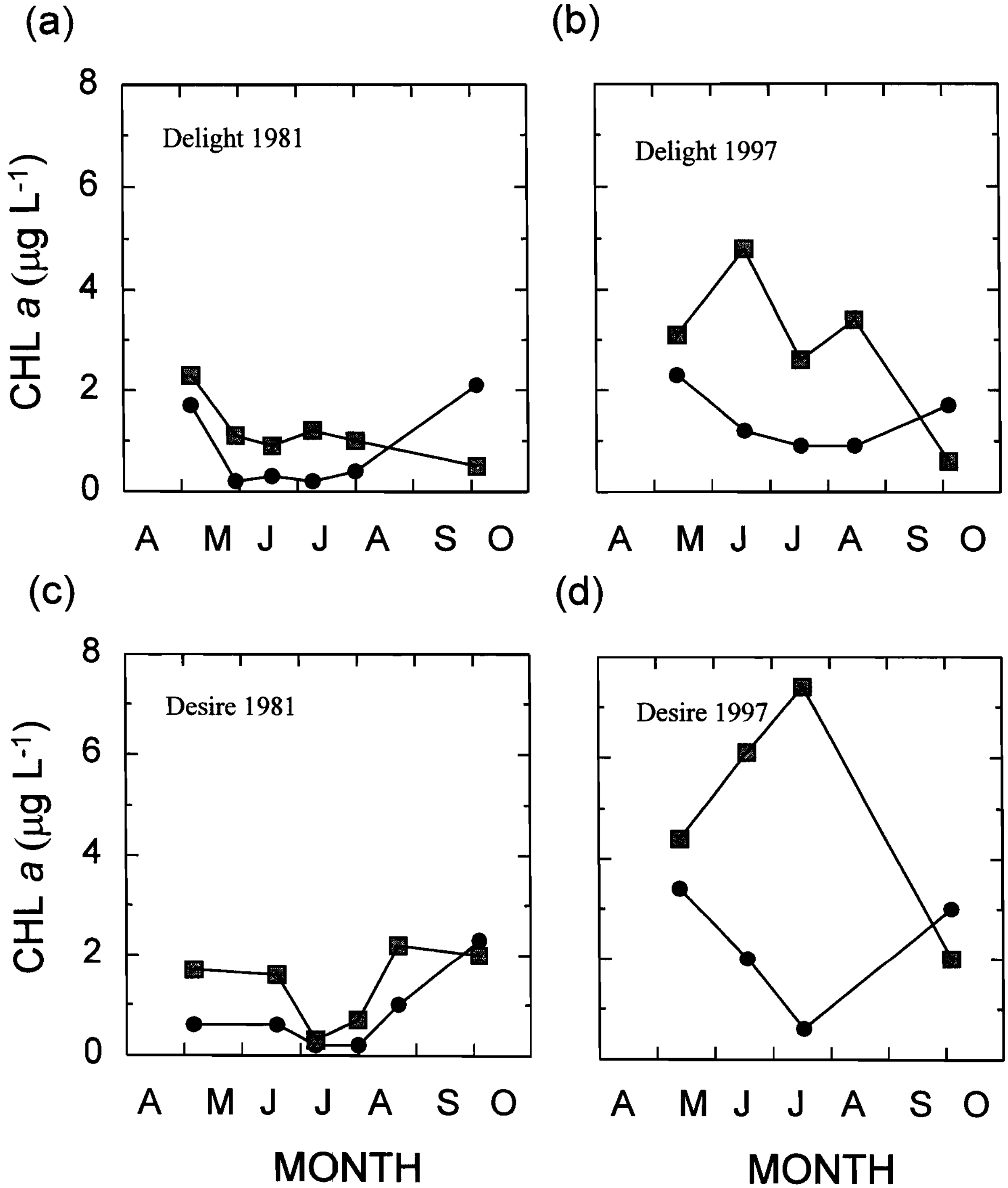

Figure 10. Seasonal changes in chlorophyll *a* (chl *a*) concentrations within the 1-m stratum (circles) and hypolimnion (squares); (a) Delight Lake 1981, (b) Delight Lake 1997, (c) Desire Lake 1981, and (d) Desire Lake 1997.

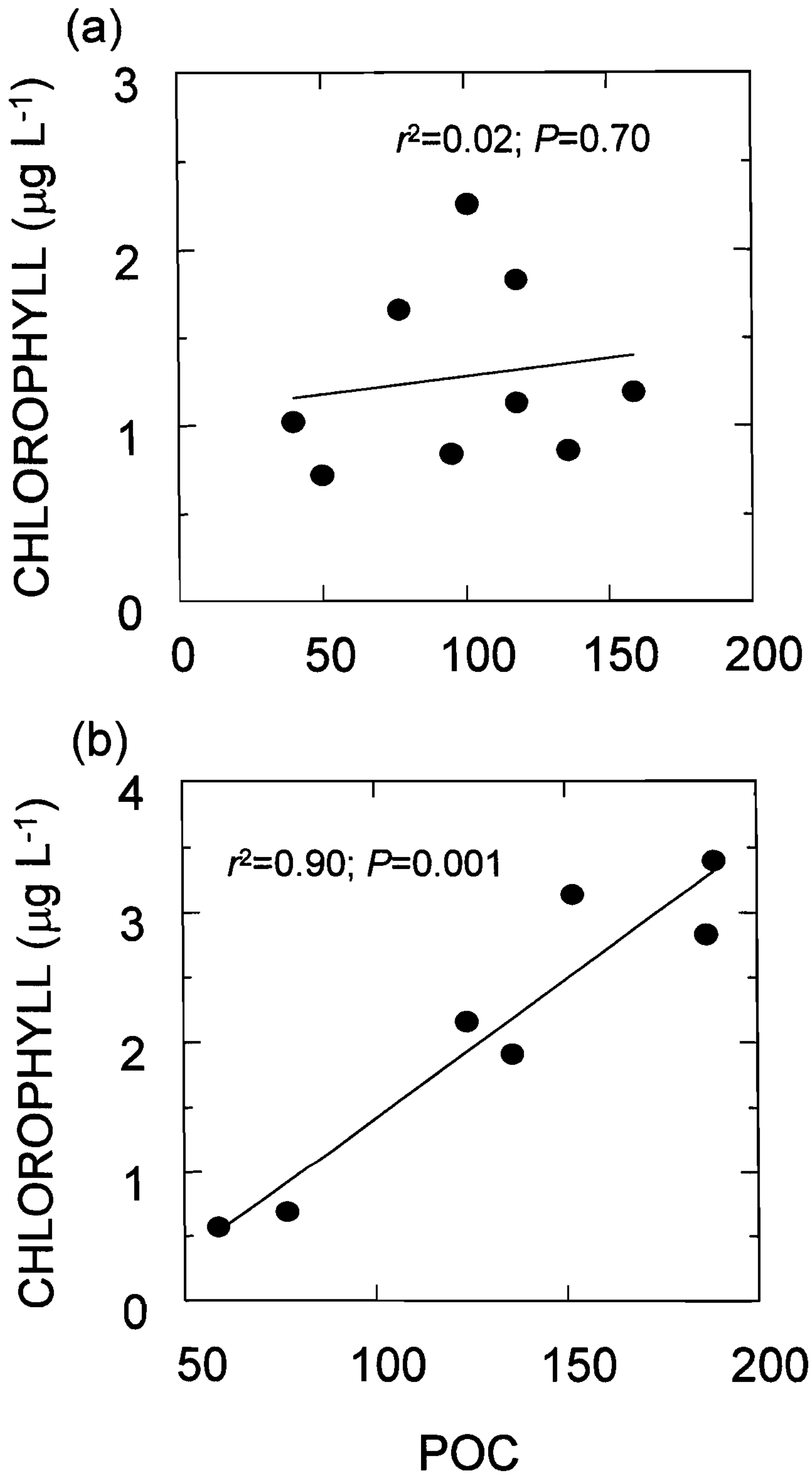

Figure 11. Relationship between chlorophyll *a* and particulate organic carbon (POC) concentration in (a) Delight and (b) Desire Lakes, 1997.

Table 3. Mean particulate carbon (POC), nitrogen (PN), and phosphorus (PP) concentrations (µmoles L^{-1}) and molar composition ratios (µmoles $µmoles^{-1}$) within the 1-m stratum in Delight (*n*=9) and Desire Lakes (*n*=7), 1997. S.D. is one standard deviation.

	Delight Lake		Desire Lake	
	Mean	S.D.	Mean	S.D.
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

	1981			1997		
Taxon	Density (animals m^{-2})	Biomass (mg m^{-2})	Body Size (mm)	Density (animals m^{-2})	Biomass (mg m^{-2})	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[\a]
Chydorinae	12	0.0	0.43	6,591	4.2	0.26
TOTAL	61,617	65.6	--	170,817	137.4	--

Desire Lake

	1981			1997		
Taxon	Density (animals m^{-2})	Biomass (mg m^{-2})	Body Size (mm)	Density (animals m^{-2})	Biomass (mg m^{-2})	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	na	0	0.1	na
Chydorinae	3	0.0	0.40	5,686	2.8	0.24
TOTAL	6,613	6.5	--	35,044	27.2	--

a/na indicates not available.

(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). This is a common seasonal pattern of development for cladoceran populations. 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 to 200,709 m^{-2} and 88 to 176 mg m^{-2}, respectively in Delight Lake. In comparison, station ($n = 4$) means ranged from 20,149 to 56,239 m^{-2} and 16 to 46 mg m^{-2} in Desire Lake.

Fisheries Assessment

Smolt Migration Patterns

Two peaks occurred in the daily fyke-net catches during the Delight Lake sockeye smolt outmigration; 06 June and 09 June when 78,922 and 69,083 smolt were captured (Figure 14a, Appendix Table A). However, the catch on 06 June was probably less than recorded because one of the fyke-net panels was removed for a portion of the day and because the catch was so high on 05 June. 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). However, the number of coho smolts recorded for 06 June was probably underestimated because of the panel removal. 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, Appendix Table B). 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). However, the numbers of both sockeye and coho smolts that outmigrated 05-06 June from Desire Lake were probably underestimated because of the missing fyke-net panel. 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.

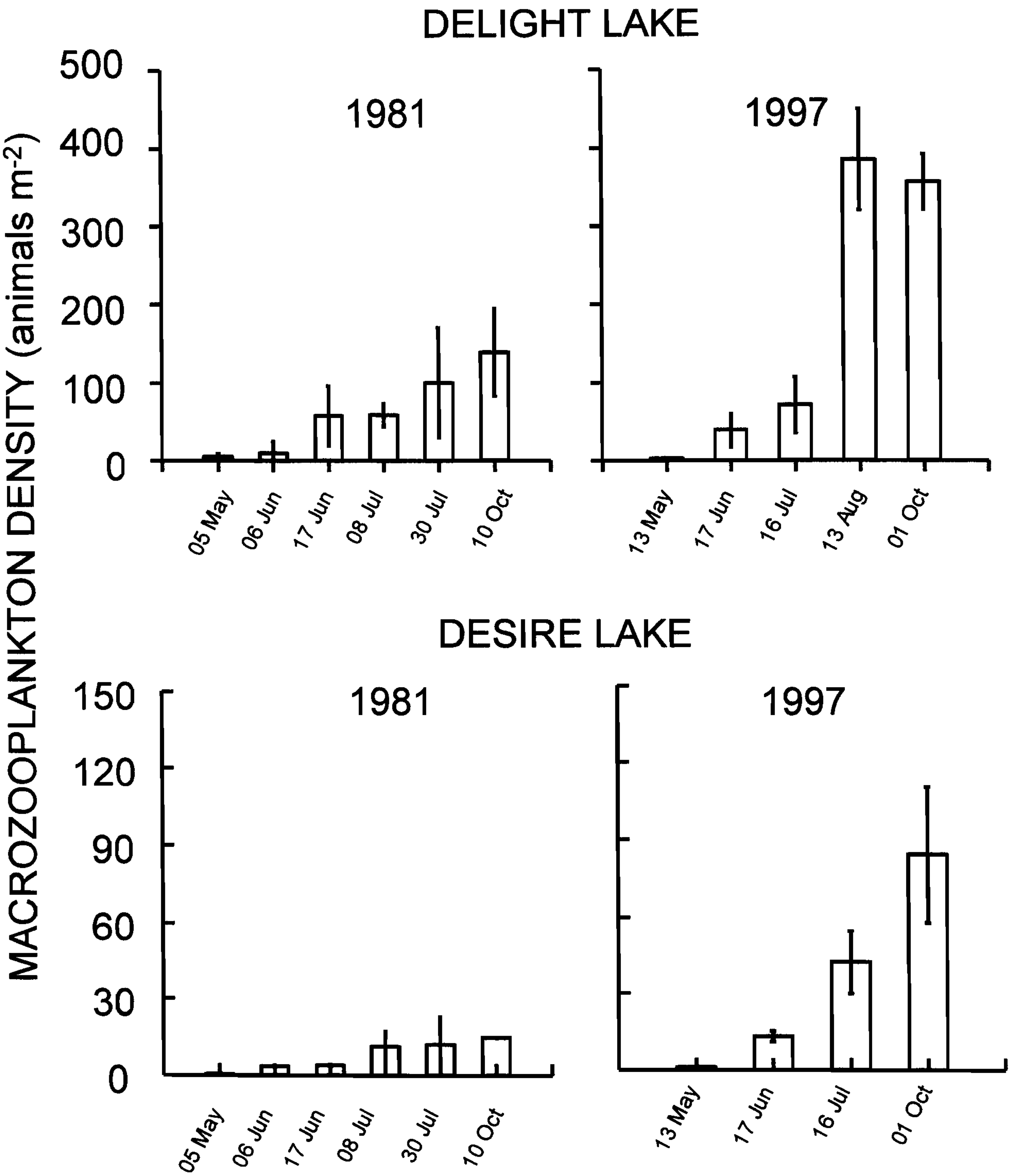

Figure 12. Average total macrozooplankton density by sample date in Delight and Desire Lakes, 1981 and 1997. Vertical lines are one standard error.

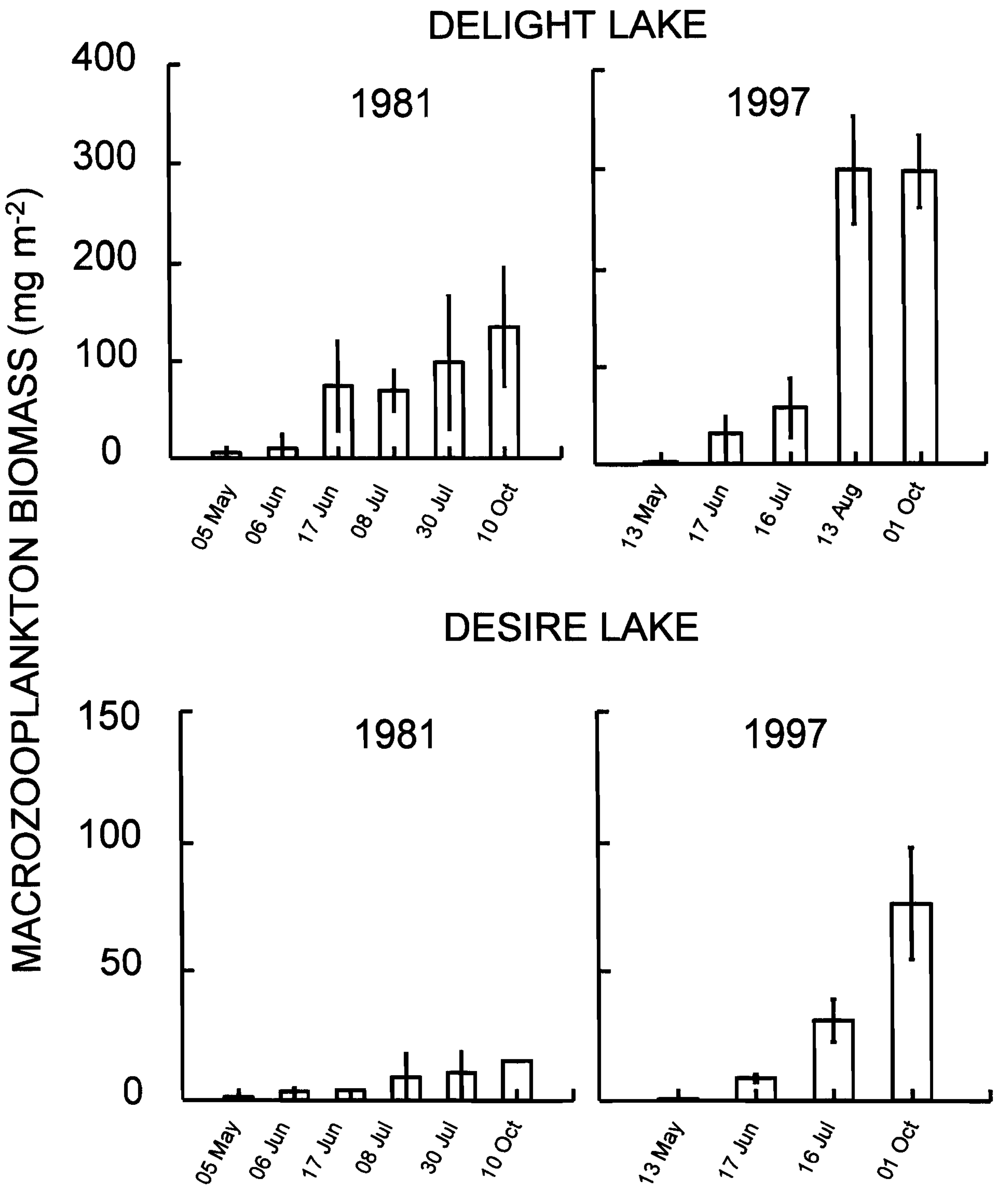

Figure 13. Average total macrozooplankton biomass by sample date in Delight and Desire Lakes, 1981 and 1997. Vertical lines are one standard error.

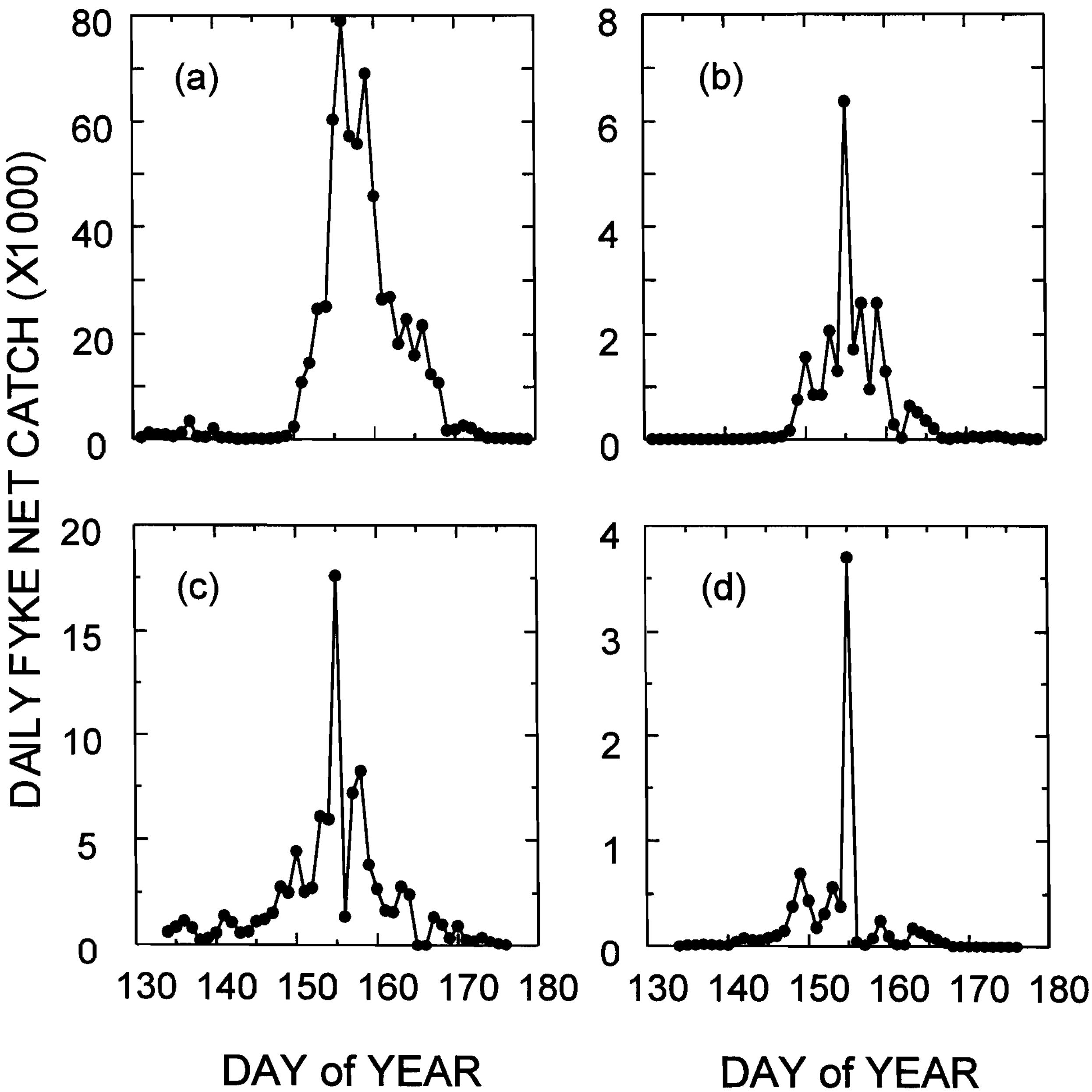

Figure 14. Daily fyke-net catch during the 1997 smolt outmigration; (a) Delight Lake sockeye, (b) Delight Lake coho, (c) Desire Lake sockeye, and (d) Desire Lake coho.

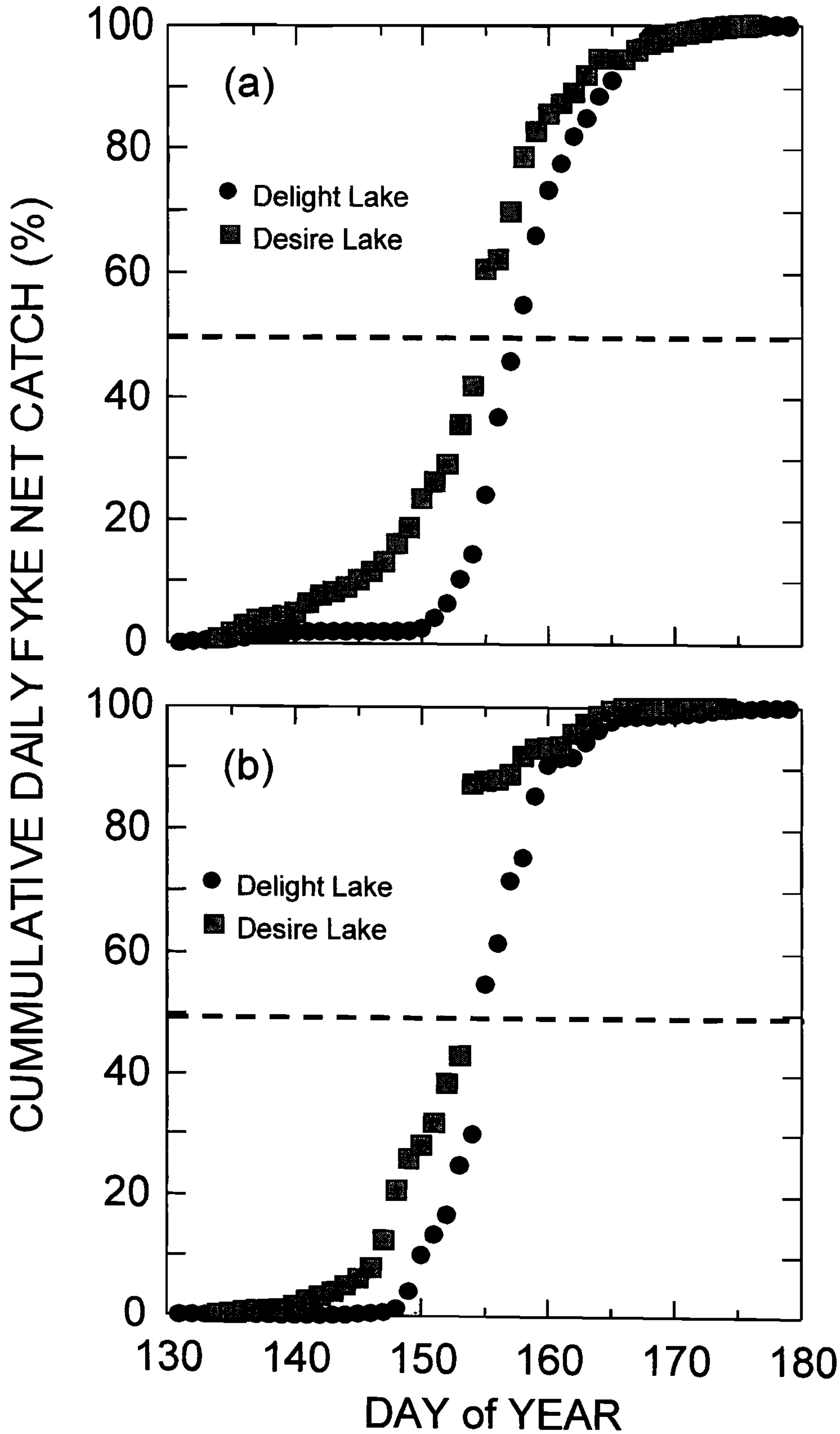

Figure 15. Cumulative daily fyke-net catch of (a) sockeye and (b) coho smolts during the 1997 outmigration in Delight and Desire Lakes.

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 were primarily shore or beach spawners. Boat surveys revealed that there was limited spawning habitat available on shallow beaches and within the small inlet streams entering both lakes. However, it appeared that in Delight Lake there might have been a substantial number of sockeye salmon spawning in deep water near shore. Comparisons of known numbers of adults passing through the weir with the number observed along the shores and beaches of Delight Lake via cursory surveys at the lake were inconsistent. That is, we observed far fewer sockeye adults spawning in near-shore waters than were counted at the weir, though total counts of the number of spawners at the lake were not made. Nonetheless, from our visual assessment we concluded that many adult sockeye entering Delight Lake may not be detected by aerial surveys suggesting that the historical escapement (1975-1996) estimates may be biased low, albeit by some unknown amount. This situation or discrepancy was not as apparent in nearby Desire Lake.

In 1997, the sockeye escapement (weir count) 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

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

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

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 (Figure 16a). During the 22 years of aerial surveys, the lowest escapement occurred in 1988 (1,200), one year prior to EVOS. The highest occurred in 1985 (26,000). Between 1985 and 1988, sockeye escapements into Delight Lake declined dramatically from 26,000 to 1,200. Over the next six years, sockeye escapements averaged 5,600, well below the escapement goal. However, compared to the 22-yr mean escapement (8,900); escapements into Delight Lake averaged 10,000 before the spill (1975-1988) and 7,100 after the spill (1989-1996). In comparison, the 1997 sockeye escapement for Desire Lake of 14,665 was reasonably close to the escapement goal of 10,000 (Figure 16a). During the 22-yr period (1975-1996) of aerial surveys, the highest sockeye escapement occurred in 1982 (18,000), the lowest in 1975 (6,500). The mean sockeye escapement prior to EVOS (1975-1988) was 12,500 compared to 10,700 after the oil spill (1989-1996). Results of analysis-of-variance (ANOVA) using only the aerial survey data (n=22) suggested no significant difference in sockeye escapement before and after EVOS for either Delight Lake (P=0.32, F=1.1) or Desire Lake (P=0.21, F=1.7).

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 (1975-1997) average catch of 22,000. During 1989-1997, the annual commercial sockeye harvest averaged 7,300 compared to 29,800 for the 14 years prior to the oil spill (1975-1988). Although sockeye harvests have been much lower than expected since the oil spill, catches began to decline rapidly 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 (1989-1993), sockeye harvests were the lowest on record for the Nuka Bay subdistrict. In the 14 years before the oil spill (1975-1988), total sockeye returns for the Nuka Bay subdistrict (Delight and Desire Lakes combined) ranged from 8,500 (1975) to 135,800 (1985) and averaged 52,300 (Figure 17). After the spill (1989-1996), total returns ranged from 14,100 (1991) to 49,100 (1995) and averaged 25,200. Results of ANOVA (n=22), using only catch and aerial escapement data, suggested that total returns were higher before the oil spill than after the spill (P=0.043, F=4.7). However, the reported P-value was very close to our prescribed significance level (α=0.05), so we could not emphatically declare that sockeye returns were significantly different between these two periods. The 1997 estimated total return of sockeye, estimated from the Nuka Bay catch plus weir counts for the Delight and Desire Lakes, was 48,600.

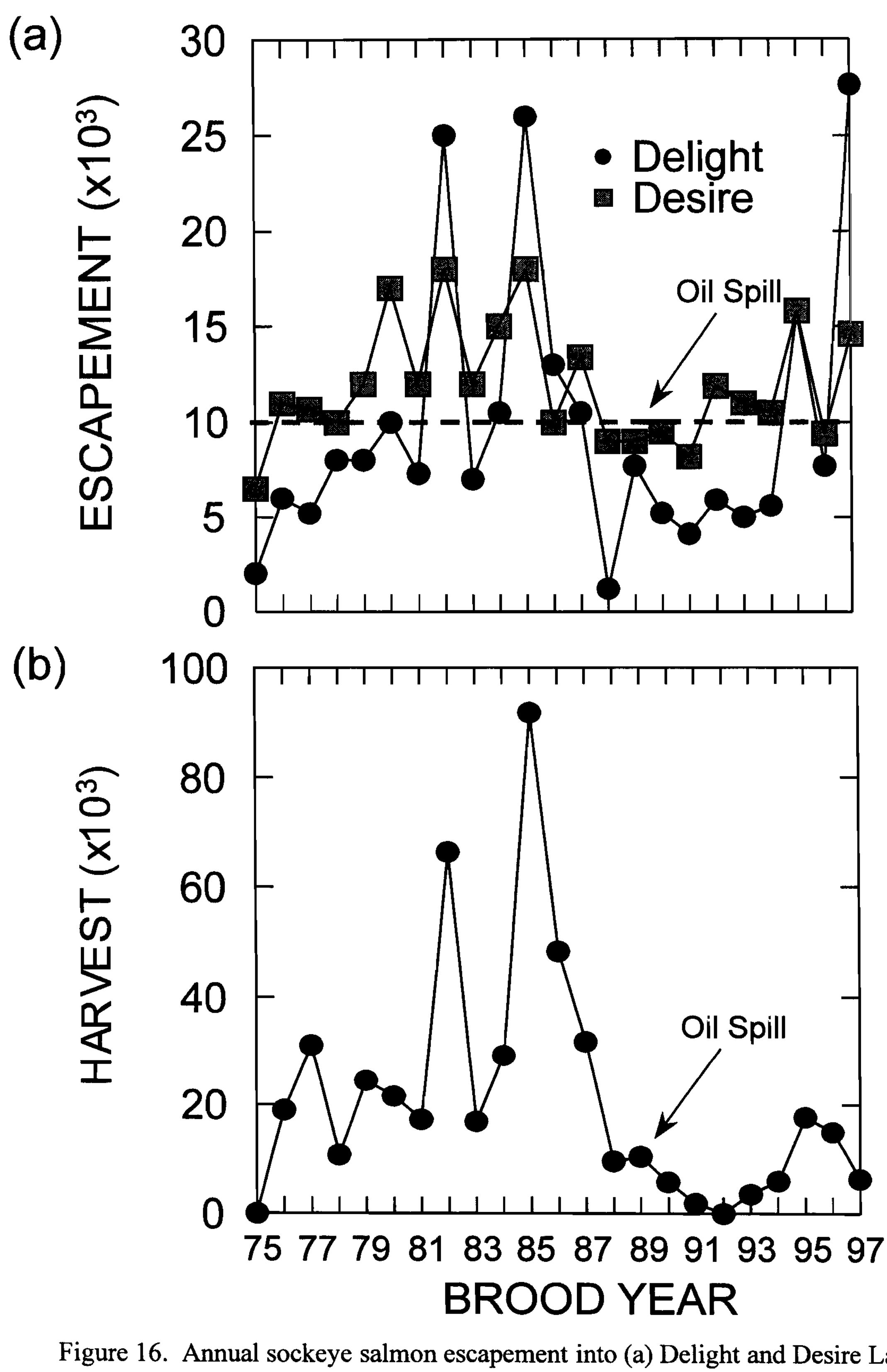

Figure 16. Annual sockeye salmon escapement into (a) Delight and Desire Lakes, and (b) the combined commercial sockeye harvest, 1975-1997. Dashed line represents the current escapement goal.

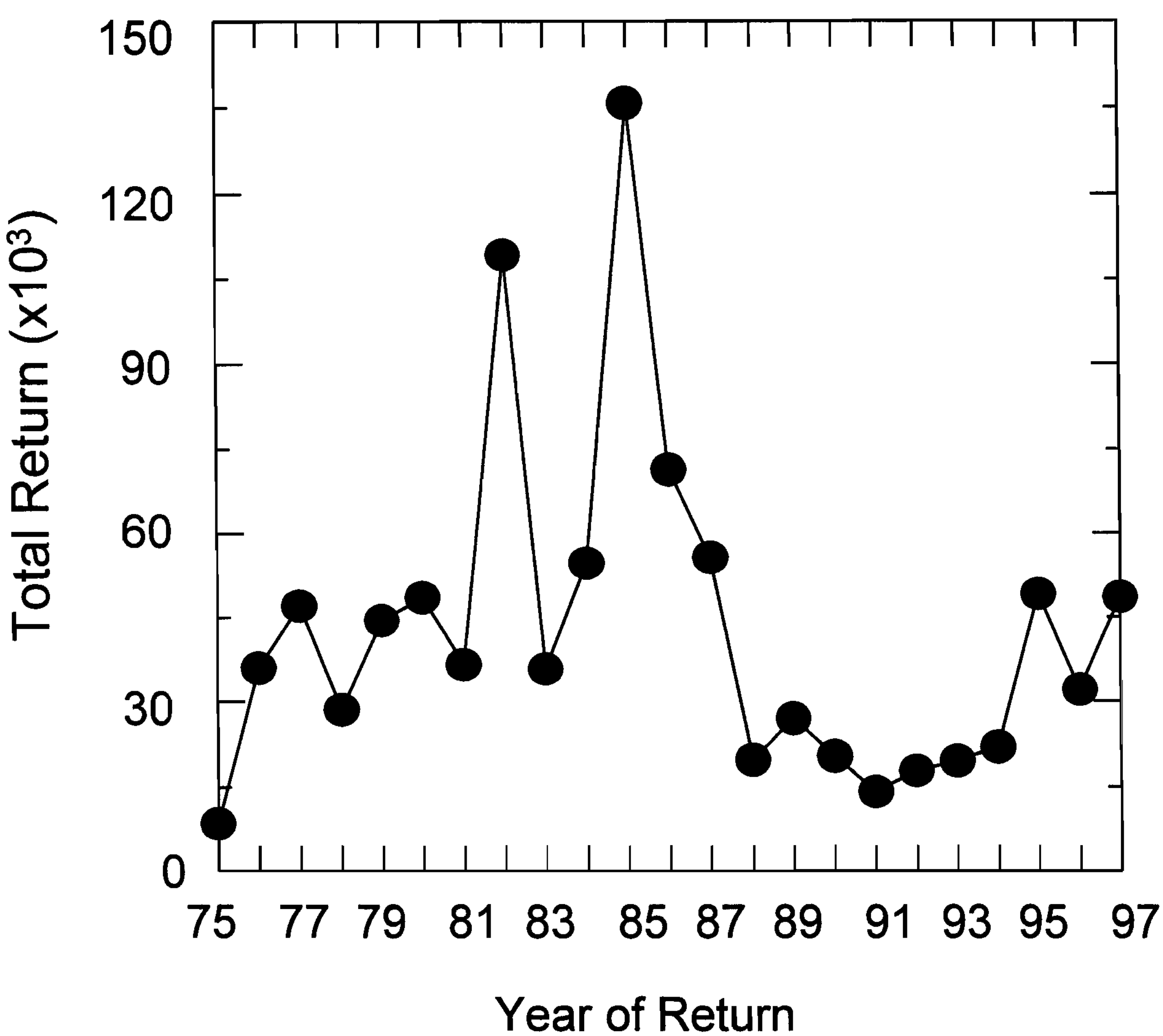

Figure 17. Total sockeye return for Delight and Desire Lakes, 1975-1997.

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).

Physical conditions of Delight and Desire Lakes are quite suitable for juvenile sockeye rearing. For example, water column temperatures were always below 20° C (Figure 7) and dissolved oxygen concentrations were always above 5 mg L^{-1}. That is, the summer water temperatures and dissolved oxygen levels were well within the known tolerance limits for salmonids (Thurston et al. 1979). Although both lakes stratified in summer (Figure 7), oxygen depletion did not occur in the lower layers. Potentially, the entire water column can be utilized by rearing sockeye juveniles. Studies have shown that temperature is an important factor relative to sockeye smolt size in Alaskan lakes (Burgner 1987; Edmundson and Mazumder 2001). In Delight and Desire Lakes, length of growing season was not unusually short nor were water column temperatures exceptionally cold or warm (Table 1); these values were nearly identical to mean values derived for 26 other Alaskan clearwater lakes (Edmundson and Mazumder 2001). In addition, light penetration in Delight and Desire Lakes was relatively deep (Figure 6b) providing zooplankters little refuge for visually attuned planktivores. For example, Levy (1990) found that sockeye 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, in both lakes it appears that sockeye juveniles can effectively forage on zooplankton.

Delight and Desire Lakes were similar in nutrient (Figure 8, 9) and chl *a* (Figure 10) concentrations; i.e., both were highly oligotrophic (nutrient poor). There was 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*) suggests that sockeye salmon production in these lakes is probably limited by water column phosphorus concentration and primary production (Stockner 1987; Koenings and Burkett 1987; Kyle et al. 1997). Although we did not measure carbon fixation rates nor estimate oxygen consumption in these lakes, other studies have shown there is a strong correlation between chl *a* and primary production in freshwater (Kirk 1994). In addition, a considerable amount of primary production in lakes can occur within the metalimnion or hypolimnion (Pick and Nalewajko 1984; Kettle et al. 1987; Hurley and Garrison 1993). Given the vertical heterogeneity in chl *a* (Figure 10) as exhibited in both Delight and Desire Lakes, chl *a* 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) were among the lowest recorded for Alaskan nursery lakes. According to a ranking of zooplankton characteristics for 23 representative 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 particulate material (Table 3) limits the productivity and species composition of the macrozooplankton community in these two lakes. However, there was some evidence for heavy grazing of the forage base in both lakes. In 1997, compared to 1981, *Cyclops* were reduced both in density and body size. In addition, *Daphnia* density (though extremely low on all sampling dates) decreased and the small herbivores *Bosmina* and *Chydorinae* increased in density, but their mean body size decreased (Table 4). This suggests that larger zooplankton disappeared and smaller ones have increased, a classic response of zooplankton to fish predation (Zaret 1980; Kyle et al. 1988; Sorrano et al. 1993). Whether bottom-up (nutrients) or top-down (consumer) forces are more important in determining growth and survival of juvenile sockeye salmon in Delight and Desire Lakes, sockeye smolt sizes nonetheless were very small (Table 5) and near the known threshold size for smoltification (~2 g, 60 mm) (Koenings and Burkett 1987). Thus, we propose there is a potential for increasing the rearing capacity of both lakes either through lake fertilization or perhaps reducing the density of rearing sockeye juveniles (escapement).

Nutrient Enrichment and Management Strategies Relative to Sockeye Restoration

Our phosphorus, nitrogen, chl *a*, and zooplankton data indicated that lower trophic level production in Delight and Desire Lakes was low, suggesting that supplemental nutrient additions may enhance the growth and survival of rearing sockeye juveniles. In Alaska and British Columbia, application of liquid fertilizers to many salmon nursery lakes dramatically increased nutrient levels, primary production, and macrozooplankton densities resulting in larger or more abundant smolt (Stockner 1987; Kyle 1994a; Kyle 1994b; Stockner and Macisaac 1996; Kyle et al. 1997; Edmundson et al. 1997; Edmundson et al. 1999). Given their suitable water residence times (>0.2 yr), deep light penetration, low nutrient (TP) concentrations and zooplankton biomass, and the small size of smolts (Table 5), supplemental additions of phosphorus could 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 to overfishing (i.e., loss of carcass nutrients) or habitat (watershed) degradation (e.g., increases in inorganic turbidity). 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; however, harvest data would need verification of stock separation, which could be accomplished through an adult tagging program. In addition, the outlet creeks in both lakes are relatively easy to weir for monitoring migrating adults, 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 largely because of its scarcity of zooplankton (Table 4) and assumed lower fry survival. For instance, based on the 1995 escapement estimates (~15,000), which produced the 1997 smolt outmigration, an average fecundity of 3,500 eggs per female, and using standard freshwater survival estimates (e.g., 10% egg to fry; 10% fry to smolt) (Foerster 1968), the predicted fry recruitment is approximately 2.8 million for each lake (Figure 18). In turn, we would project that each lake would produce approximately 275,000 smolt. However, the actual number of sockeye smolts produced was more than twice that predicted for Delight Lake (623,059), but it was only about one third of that predicted for Desire Lake (96,700). This exercise suggested to us that fry survival was lower in Desire Lake than Delight Lake. Though we concede that the escapement estimates for Delight Lake are probably biased low, so fry survival may be low in both lakes. Nonetheless, considering the zooplankton standing crop in 1997 and differences in morphometry (size) between the two lakes (Figure 2, Figure 3), there is presumably less forage available per rearing fry in Desire Lake than Delight Lake (Table 4). Thus, although actual fry survival rates are unknown to us, we believe juvenile sockeye growth rates and survival are lower in Desire Lake than Delight Lake.

It is interesting to note that the recent decline in sockeye catches in the East Nuka Bay fishery were attributed to poor returns to Delight Lake and not to Desire Lake (ADF&G 1996). However, it is known that sockeye salmon mill in the mouths of non-home streams prior to returning to their natal streams to spawn (Foerster 1968). Thus, the paradox of declining returns to Delight Lake based on Nuka Bay harvests could be explained by a lack of definitive stock identification information. However, such spawning behavior of sockeye between these two systems has not been documented nor observed. Also, a detailed analysis of smolt scales, which may have revealed growth differences, might have helped to explain the mortality schedules between the two lakes.

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 were underestimated, then our estimate of the number of smolts produced per spawner in Delight Lake (40) would be lower and perhaps more comparable to Desire Lake (6) (Figure 18). Given that Delight Lake has a more favorable rearing environment (greater zooplankton biomass), but sockeye production appears lower

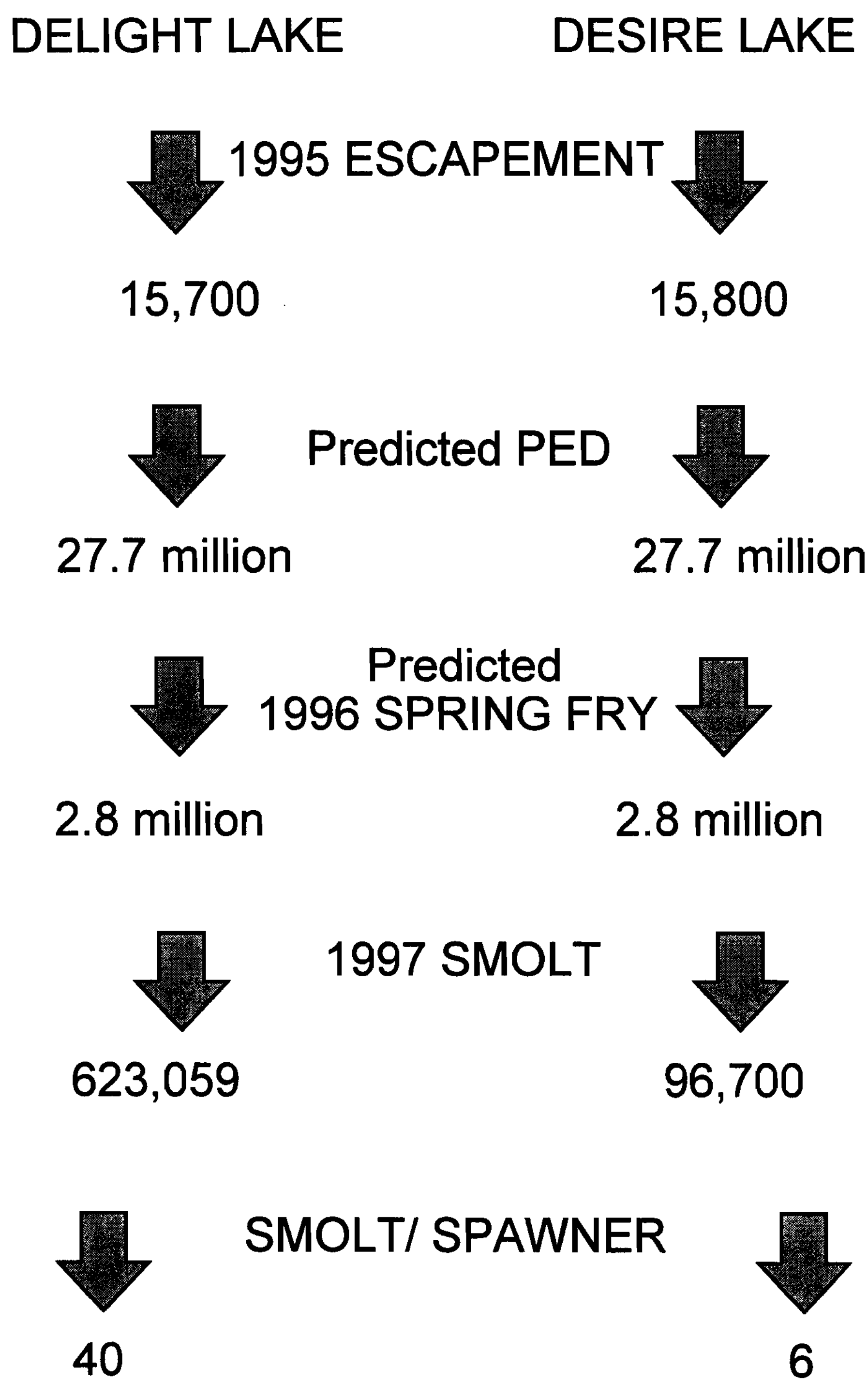

Figure 18. Proposed summary of freshwater survivals of juvenile sockye salmon relative to the 1995 brood-year escapement in Delight and Desire Lakes. Potential egg deposition (PED) is calculated using a fecunditiy of 3,500 eggs per female. Fry recruitment is based on a 10% survival from PED.

compared to Desire Lake, we question the accuracy of the aerial estimates of sockeye escapement into Delight Lake. Good catch and escapement data are required to determine the effectiveness of a nutrient enrichment program. 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. We recognize that this would only be possible if the aerial surveys were consistently biased, which is probably unlikely given different observers and variability in lake surface conditions. Nonetheless, index surveys are typically biased low and reasonably good correlations between aerial estimates and enumerated escapements are still possible (Symons and Waldichik 1984). In addition, use of a correction for observer efficiency and adjusting for stream life can significantly improve estimates of salmon escapement (Bue et al. 1998). If we can obtain more accurate estimates of the number of spawners, then we can better assess how increasing the amount of nutrients 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 can be attributed to the 1989 oil spill from the *Exxon Valdez*. Although both lakes are excellent candidates for fertilization, the current forage base (zooplankton biomass) and small smolt sizes suggest Desire Lake is the preferred candidate for any fertilization program. In turn, nearby Delight Lake could be used as a control system. However, our field observations suggest that sockeye escapement estimates, derived via aerial surveys, are probably underestimated in Delight Lake more so than in Desire Lake. We believe this difference is because a larger number of sockeye salmon spawn in deep water in Delight Lake, and this spawning activity cannot be easily observed from aerial surveys. Therefore, until problems with estimating escapements can be resolved, a nutrient enrichment program for the Delight and Desire Lakes sockeye salmon stocks is not recommended.

Recommendations

In future years, 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 help 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.

Daily sockeye and coho smolt emigration for Delight Lake, 1997.

Appendix A. Daily sockeye and coho smolt emigration for Delight Lake, 1997.

Date	Sockeye		Coho	
	Daily	Cumulative	Daily	Cumulative
5/12	233	233	0	0
5/13	1,157	1,390	0	0
5/14	847	2,237	0	0
5/15	826	3,063	0	0
5/16	504	3,567	0	0
5/17	1,138	4,705	0	0
5/18	3,357	8,062	0	0
5/19	477	8,539	0	0
5/20	391	8,930	0	0
5/21	1,958	10,888	3	3
5/22	292	11,180	1	4
5/23	325	11,505	6	10
5/24	56	11,561	10	20
5/25	19	11,580	12	32
5/26	116	11,696	40	72
5/27	40	11,736	27	99
5/28	108	11,844	52	151
5/29	224	12,068	164	315
5/30	604	12,672	750	1,065
5/31	2,331	15,003	1,561	2,626
6/1	10,812	25,815	852	3,478
6/2	14,557	40,372	849	4,327
6/3	24,678	65,050	2,064	6,391
6/4	25,180	90,230	1,304	7,695
6/5	60,352	150,582	6,372	14,067
6/6	78,922	229,504	1,719	15,786
6/7	57,299	286,803	2,570	18,356
6/8	55,765	342,568	953	19,309
6/9	69,083	411,651	2,568	21,877
6/10	45,765	457,416	1,293	23,170
6/11	26,536	483,952	284	23,454
6/12	26,881	510,833	29	23,483
6/13	18,225	529,058	636	24,119
6/14	22,799	551,857	509	24,628
6/15	15,992	567,849	357	24,985

Appendix A. (continued)

Date	Sockeye		Coho	
	Daily	Cumulative	Daily	Cumulative
6/16	21,650	589,499	202	25,187
6/17	12,419	601,918	32	25,219
6/18	10,748	612,666	9	25,228
6/19	1,656	614,322	37	25,265
6/20	1,842	616,164	28	25,293
6/21	2,598	618,762	58	25,351
6/22	2,141	620,903	36	25,387
6/23	1,049	621,952	62	25,449
6/24	294	622,246	64	25,513
6/25	261	622,507	44	25,557
6/26	221	622,728	6	25,563
6/27	208	622,936	29	25,592
6/28	105	623,041	3	25,595
6/29	18	623,059	10	25,605

APPENDIX B.

Daily sockeye and coho smolt emigration for Desire Lake, 1997.

Appendix B. Daily sockeye and coho smolt emigration for Desire Lake, 1997.

Date	Sockeye		Coho	
	Daily	Cumulative	Daily	Cumulative
5/15	635	635	3	3
5/16	858	1,493	11	14
5/17	1,163	2,656	12	26
5/18	825	3,481	21	47
5/19	243	3,724	15	62
5/20	328	4,052	13	75
5/21	597	4,649	10	85
5/22	1,429	6,078	47	132
5/23	1,114	7,192	82	214
5/24	610	7,802	61	275
5/25	660	8,462	60	335
5/26	1,147	9,609	82	417
5/27	1,249	10,858	105	522
5/28	1,551	12,409	152	674
5/29	2,750	15,159	385	1,059
5/30	2,508	17,667	684	1,743
5/31	4,449	22,116	436	2,179
6/1	2,554	24,670	182	2,361
6/2	2,730	27,400	314	2,675
6/3	6,101	33,501	558	3,233
6/4	5,964	39,465	384	3,617
6/5	17,591	57,056	3,698	7,315
6/6	1,390	58,446	46	7,361
6/7	7,217	65,663	14	7,375
6/8	8,250	73,913	79	7,454
6/9	3,820	77,733	248	7,702
6/10	2,680	80,413	102	7,804
6/11	1,680	82,093	17	7,821
6/12	1,616	83,709	18	7,839
6/13	2,784	86,493	176	8,015
6/14	2,432	88,925	141	8,156
6/15	1,744	90,669	106	8,262
6/16	1,056	91,725	71	8,333
6/17	1,376	93,101	36	8,369
6/18	1,024	94,125	1	8,370
6/19	366	94,491	1	8,371

Appendix B. (continued)

Date	Sockeye		Coho	
	Daily	Cumulative	Daily	Cumulative
6/20	958	95,449	0	8,371
6/21	290	95,739	1	8,372
6/22	216	95,955	0	8,372
6/23	399	96,354	0	8,372
6/24	194	96,548	1	8,373
6/25	107	96,655	1	8,374
6/26	45	96,700	0	8,374

APPENDIX C.

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

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

Delight Lake

Period	Total	Age 1		Age 2	
	n	*n*	Percent	*n*	Percent
12 May - 19 May	355	293	82.5	62	17.5
20 May - 21 May	268	172	64.2	92	34.3
28 May - 03 June	234	56	23.9	178	76.1
04 June - 10 June	101	72	71.3	29	28.7
11 June - 16 June	271	266	98.2	5	1.8
Total	1,129	859		366	

Desire Lake

Period	Total	Age 1		Age 2	
	n	*n*	%	*n*	%
15 May - 21 May	274	222	81.0	52	19.0
22 May - 28 May	382	217	56.8	142	37.2
29 May - 04 June	400	313	78.3	71	17.8
05 June - 11 June	230	209	90.9	21	9.1
12 June - 13 June	120	116	96.7	4	3.3
Total	1,406	1,077		290	

APPENDIX D.

Sockeye escapement for Delight and Desire Lakes, 1997.

Appendix D. Sockeye escapement for Delight and Desire Lakes, 1997.

Delight Lake			Desire Lake		
Date	Daily	Cumulative	Date	Daily	Cumulative
6/7	1	1	6/3	1	1
6/8	0	1	6/4	0	1
6/9	0	1	6/5	0	1
6/10	1	2	6/6	0	1
6/11	1	3	6/7	0	1
6/12	0	3	6/8	0	1
6/13	1	4	6/9	2	3
6/14	0	4	6/10	0	3
6/15	66	70	6/11	19	22
6/16	31	101	6/12	47	69
6/17	6	107	6/13	751	820
6/18	5	112	6/14	65	885
6/19	0	112	6/15	0	885
6/20	0	112	6/16	2	887
6/21	0	112	6/17	0	887
6/22	0	112	6/18	1	888
6/23	0	112	6/19	326	1,214
6/24	0	112	6/20	1,170	2,384
6/25	0	112	6/21	30	2,414
6/26	0	112	6/22	35	2,449
6/27	0	112	6/23	431	2,880
6/28	0	112	6/24	243	3,123
6/29	114	226	6/25	685	3,808
6/30	115	341	6/26	20	3,828
7/1	0	341	6/27	95	3,923
7/2	0	341	6/28	25	3,948
7/3	0	341	6/29	259	4,207
7/4	0	341	6/30	17	4,224
7/5	0	341	7/1	375	4,599
7/6	0	341	7/2	256	4,855
7/7	0	341	7/3	315	5,170
7/8	0	341	7/4	685	5,855
7/9	0	341	7/5	178	6,033
7/10	0	341	7/6	109	6,142
7/11	2,632	2,973	7/7	933	7,075
7/12	6,468	9,441	7/8	27	7,102

Appendix D. (continued)

Delight Lake			Desire Lake		
Date	Daily	Cumulative	Date	Daily	Cumulative
7/13	1,869	11,310	7/9	126	7,228
7/14	2,468	13,778	7/10	179	7,407
7/15	625	14,403	7/11	2,324	9,731
7/16	246	14,649	7/12	113	9,844
7/17	1,019	15,668	7/13	151	9,995
7/18	179	15,847	7/14	122	10,117
7/19	357	16,204	7/15	318	10,435
7/20	54	16,258	7/16	154	10,589
7/21	112	16,370	7/17	355	10,944
7/22	217	16,587	7/18	46	10,990
7/23	191	16,778	7/19	47	11,037
7/24	202	16,980	7/20	119	11,156
7/25	100	17,080	7/21	113	11,269
7/26	0	17,080	7/22	146	11,415
7/27	101	17,181	7/23	62	11,477
7/28	0	17,181	7/24	53	11,530
7/29	95	17,276	7/25	110	11,640
7/30	0	17,276	7/26	63	11,703
7/31	0	17,276	7/27	97	11,800
8/1	828	18,104	7/28	138	11,938
8/2	228	18,332	7/29	219	12,157
8/3	369	18,701	7/30	87	12,244
8/4	91	18,792	7/31	571	12,815
8/5	20	18,812	8/1	228	13,043
8/6	205	19,017	8/2	4	13,047
8/7	191	19,208	8/3	0	13,047
8/8	1,342	20,550	8/4	10	13,057
8/9	3,907	24,457	8/5	217	13,274
8/10	362	24,819	8/6	147	13,421
8/11	261	25,080	8/7	125	13,546
8/12	0	25,080	8/8	879	14,425
8/13	75	25,155	8/9	240	**14,665**
8/14	110	25,265	(weir removed 8/9)		
8/15	317	25,582			
8/16	225	25,807			
8/17	441	26,248			

Appendix D. (continued)

Delight Lake			Desire Lake		
Date	Daily	Cumulative	Date	Daily	Cumulative
8/18	361	26,609			
8/19	250	26,859			
8/20	83	26,942			
8/21	139	27,081			
8/22	236	27,317			
8/23	61	27,378			
8/24	70	27,448			
8/25	0	27,448			
8/26	372	**27,820**			
(weir removed 8/26)					

APPENDIX E.

Summary of sockeye escapement, catch, and total return
for Delight and Desire Lakes, 1975-1997.

Appendix E. Summary of sockeye escapement, catch, and total return for Delight and Desire Lakes, 1975-1997. Numbers are in thousands.

Year	Escapement Delight	Escapement Desire	Catch	Total return
1975	2.0	6.5	0.0	8.5
1976	6.0	11.0	18.9	35.9
1977	5.2	10.7	31.1	47.0
1978	8.0	10.0	10.6	28.6
1979	8.0	12.0	24.4	44.4
1980	10.0	17.0	21.5	48.5
1981	7.3	12.0	17.2	36.5
1982	25.0	18.0	66.3	109.3
1983	7.0	12.0	16.8	35.8
1984	10.5	15.0	29.2	54.7
1985	26.0	18.0	91.8	135.8
1986	13.0	10.0	48.4	71.4
1987	10.5	13.4	31.8	55.7
1988	1.2	9.0	9.5	19.7
1989	7.7	9.0	10.3	27.0
1990	5.2	9.5	5.7	20.4
1991	4.1	8.2	1.8	14.1
1992	5.9	11.9	0.0	17.8
1993	5.0	11.0	3.5	19.5
1994	5.6	10.5	5.9	22.0
1995	15.7	15.8	17.6	49.1
1996	7.7	9.4	14.9	32.0
1997	27.7	14.6	6.3	48.6
Average	**9.8**	**11.9**	**21.0**	**42.7**