FRED Reports

Limnological and Fisheries Evidence
for Rearing Limitation of
Sockeye Salmon, Oncorhynchus nerka,
Production from Lake Tokun,
Lower Copper River (1981-1984)
by

J. P. Koenings, Ph.D.
T. McDaniel
D. Barto *

Number 55

Alaska Department of Fish & Game
Division of Fisheries Rehabilitation,
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TABLE OF CONTENTS

(Part I)

Section	Page
ABSTRACT	1
INTRODUCTION	4
Study Site Description	5
MATERIALS AND METHODS	5
Sockeye Smolt Enumeration	7
Age-Weight-Length Sampling	8
Adult Sockeye Enumeration	9
RESULTS	9
Sockeye Smolt Enumeration	9
Population Characteristics of Sockeye Smolts	11
Adult Sockeye Enumeration and Population Characteristics	11
DISCUSSION	15
ACKNOWLEDGEMENTS	22
REFERENCES	23
APPENDIX A	26

LIST OF TABLES

Table		Page
1	Mean length (mm), weight (g), standard deviation (SD), sample size (n), and population estimate per five-day sample period of age-1.0 sockeye smolts, Tokun Lake, 1983 and 1984	13
2	Estimated age composition of the adult sockeye escapement to Tokun Lake in 1983 and 1984	16
3	Estimated number of sockeye smolt and biomass production per hectare (a) and per euphotic volume (b) from Tokun Lake, 1983 and 1984	18
4	Mean lengths and weights of age-1.0 and age-2.0 sockeye smolt from different clear-water systems in Alaska as compared to 1983 and 1984 mean lengths and weights of sockeye smolt from Tokun Lake	20

LIST OF FIGURES

Figure		Page
1	The location of Tokun Lake within the Copper River delta area of southcentral Alaska............	6
2	Average number of sockeye smolts migrating from Tokun Lake during five-day periods from 11 May through 20 June 1983, and water temperatures as recorded on the listed dates.......................................	10
3	Average number of sockeye smolts migrating from Tokun Lake during five-day periods from 3 May through 29 June 1984, and water temperatures as listed on the recorded dates.......................................	12
4	Length frequency distribution of sockeye smolts sampled from Tokun Lake in 1983 and 1984.....	14

TABLE OF CONTENTS
(Part II)

Section	Page
INTRODUCTION	30
Study Site Description	30
METHODS	32
RESULTS	36
Light Regimes and Heating/Cooling Cycles	36
Dissolved Gases	42
General Water Quality Indicators	42
Nutrient Cycles	45
Nutrient Ratios	50
Algal Biomass	52
Zooplankter Density and Body Size	54
DISCUSSION	60
Existing Limnetic Production Patterns	60
Tokun Lake Nutrient Loading	65
Recommendations	66
ACKNOWLEDGMENTS	68
REFERENCES	69
APPENDIX B	75

LIST OF TABLES

Table		Page
1	The penetration of photosynthetically available radiation (PAR) which defines the lower limit of the euphotic zone (compensation point), depth of the metalimnion, and the depth at which the Secchi disk is no longer visible at Stations 1 and 2 during 1982 and 1983...............	37
2	Dissolved oxygen percent saturation levels for Stations 1 and 2 at Tokun Lake, 1981-1983....................................	43
3	Summarized concentrations and/or units for general water quality parameters found for the epilimnion (1 m) and hypolimnion (14 - 20 m) within Tokun Lake in 1982 (n=14) and 1983 (n=16). Values cited are mean levels followed by the range of values found over the experimental period........................	44
4	The ratio of inorganic nitrogen (ammonium + nitrate and nitrite) to total phosphorus (by atoms) within the epilimnion (1 m) and hypolimnion (20 m and 14 m) during 1982 and 1983 at Stations 1 and 2 respectively...........	53

LIST OF TABLES (continued)

Table		Page
5	The concentration of chlorophyll *a* (chl *a*) and phaeophytin, by date, within the epilimnion (1 m) of Lake Tokun at Stations 1 and 2 during 1981, 1982, and 1983	53
6	Changes in the seasonal density (organisms/m^2) of zooplankters by taxa within Lake Tokun at Station 1 and Station 2 during 1982	55
7	Changes in the seasonal density (organisms/m^2) of zooplankters by taxa within Lake Tokun at Station 1 and Station 2 during 1983	56
8	The seasonal changes in bodylength (mm) of macro-zooplankters within Lake Tokun at Stations 1 and 2 during 1982 and 1983. Mean values by sample date are followed by seasonal mean values calculated by simple averaging and by weighting bodylengths by the number of organisms within a sample date	59
9	A comparison of the euphotic volume of sockeye rearing lakes throughout Alaska in relation to total lake volume, surface area, and water clarity	63

LIST OF FIGURES

Figure		Page
1	Location of Lake Tokun relative to Prince William Sound, the Copper River, and the State of Alaska	31
2	Morphometric map of Lake Tokun showing the location of major basins and the limnological sampling Stations 1 and 2	33
3	Temperature profiles within Lake Tokun at Station 1 for 1982 and 1983 showing the seasonal heating and cooling cycles, the location of the metalimnion, and the depth of the compensation point	39
4	Temperature profiles within Lake Tokun at Station 2 for 1982 and 1983 showing the seasonal heating and cooling cycles, the location of the metalimnion, and the depth of the compensation point	40
5	The seasonal cycle of essential nutrients within the epilimnion (1 m) and hypolimnion (20 m) at Station 1 in Lake Tokun during 1981, 1982, and 1983	47

LIST OF FIGURES (continued)

Figure		Page
6	Changes in the magnitude of total phosphorus and its component fractions [namely particulate (part-P), filterable unreactive phosphorus (FUP), and filterable reactive phosphorus (FRP)] within the epilimnion (1 m) and hypolimnion (20 m) at Station 1 of Tokun Lake during 1982 and 1983	49
7	Morphometric map of Lake Tokun showing the recommended fertilizer application zone in relation to the location of the limnological sampling Stations 1 and 2	67

ABSTRACT

In order to apply the appropriate sockeye salmon, *Oncorhynchus nerka*, enhancement strategy at Tokun Lake, an assessment was made of the fisheries and limnological conditions that determine successful rearing of juveniles to smolt. We utilized a two-tier approach that specifically addresses fishery ecology (Part I) and limnetic production patterns (Part II).

Only relatively small age-1.0 sockeye smolts migrated from Tokun Lake in both 1983 and 1984. Specifically, the smolts sampled in 1983 averaged 63 mm in length and 2.1 g in weight; whereas, smolts sampled in 1984 were slightly larger, having a mean length of 69 mm and a mean weight of 2.7 g. Finally, of the returning adults sampled in 1983, 84% were age 1.3 and 15% age 1.2; in 1984, 92% were age 1.3 and 8% age 1.2. Thus, when considering the age composition of both the smolts and the adults, Tokun Lake currently produces a large percentage of small 1-year-old freshwater and 3-year-old saltwater fish.

Tokun is an oligotrophic, clear-water lake with summer-period light-compensation depths greater than 25 m, a surface temperature less than 15° C, and a stable epilimnion, lying at ≅10 m to 12 m from June through mid-September. At the same time, epilimnetic total phosphorus levels reached seasonal lows at 2 $\mu g\ L^{-1}$ to 4 $\mu g\ L^{-1}$, IN:TP ratios were reduced to as low as 1:1, and chlorophyll a levels fell below 0.5 $\mu g\ L^{-1}$. Finally, the herbivorous zooplankters, *Daphnia* and *Bosmina*, dominate the limnetic zooplankton assembledge; *Daphnia* peak early in the summer, followed by a fall peak of *Bosmina*. In addition, both zooplankters exhibit small body sizes when compared to the larger bodysizes found in lakes supporting less dense populations of rearing sockeye fry and/or producing less numerous but larger smolts.

In summary, the sockeye smolt population characteristics of threshold size, minimal age, and high density are closely aligned with the oligotrophic condition of the lake, particularly total phosphorus loading; and the small body size of the zooplankters signifies a rearing limitation of sockeye production.

Key Words: Sockeye salmon, *Oncorhynchus nerka*, lake enrichment, rearing limitations, smolt production, euphotic volume, nutrient loading

PART I: LAKE TOKUN FISHERIES PROGRAM

by

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INTRODUCTION

In 1981 a systematic lake inventory and assessment project was initiated to define the potential for increasing sockeye salmon, *Oncorhynchus nerka*, production in the Copper River drainage. This multi-agency project was part of a comprehensive proposal aimed at rehabilitation and enhancement of sockeye, chinook, *O. tshawytscha*, and coho, *O. kisutch*, salmon in the Copper River/Prince William Sound area.

During the first project field season, information was collected on several sockeye lake systems in the lower Copper River drainage to determine the feasibility of potential enhancement projects in this area. Limnological sampling data collected at Tokun Lake indicated a potential for increasing sockeye production by the addition of chemical fertilizer: a process that stimulates primary productivity and enhances natural zooplankton populations, the primary food source for rearing sockeye juveniles (Juday et al. 1932; Barnaby 1944; Foerster 1968; and Hall and Hyatt 1974).

Extensive baseline studies are required prior to the implementation of artificial enrichment techniques. Numerous chemical, biological, and climatic influences as well as morphometric characteristics must be identified and evaluated. In Alaska, the lake-enrichment policy quidelines require at least two years of chemical and biological data collection so that a fertilization program can be evaluated from its effect on all trophic levels.

As part of the pre-fertilization studies, the Alaska Department of Fish and Game, Fisheries Rehabilitation, Enhancement and Development Division (FRED), in cooperation with the Prince William Sound Aquaculture Corporation (P.W.S.A.C.) and the U. S.

Forest Service (U.S.F.S.), conducted sockeye salmon smolt and adult enumeration studies at Tokun Lake in 1983 and 1984. The purpose of these studies was to determine sockeye smolt and adult population characteristics in order to assess if sockeye production was limited by a lack of adequate freshwater rearing.

Study Site Description

Tokun Lake (lat.60°24'N., long.144°17'W.) is located approximately 45 miles east of Cordova and drains westward into the Martin River (Figure 1). The lake lies at an elevation of 54 m and has a surface area of 181.3 ha, or 448 acres (*see* Part II of this report for further details). Species present in Tokun Lake, in addition to sockeye salmon, include coho salmon, Dolly Varden, *Salvelinus malma*, lake trout, *Salvelinus namaycush*, cutthroat trout, *Salmo clarki*), coastrange sculpin, *Cottus aleuticus*, and threespine stickleback, *Gasterosteus aculeatus*.

MATERIALS AND METHODS

Outmigrant sockeye smolts were captured daily during May and June at a downstream weir located approximately 75 m below the outlet of Tokun Lake. The weir consisted of 1.2- x 2.4-m panels constructed with 1.3-cm square-mesh plastic netting placed diagonally across the stream. The weir diverted smolts through the dewatering nets into a 1- x 1-m dual-chamber collection trap. The trap was equipped with manually operated selective doors that opened into each chamber. The larger capture chamber was used to hold downstream migrants for enumeration, while the smaller bypass chamber allowed smolts to pass directly through the trap and to continue downstream migration. The weir fished the total width of the river, and all emigrating smolts were diverted into the trap.

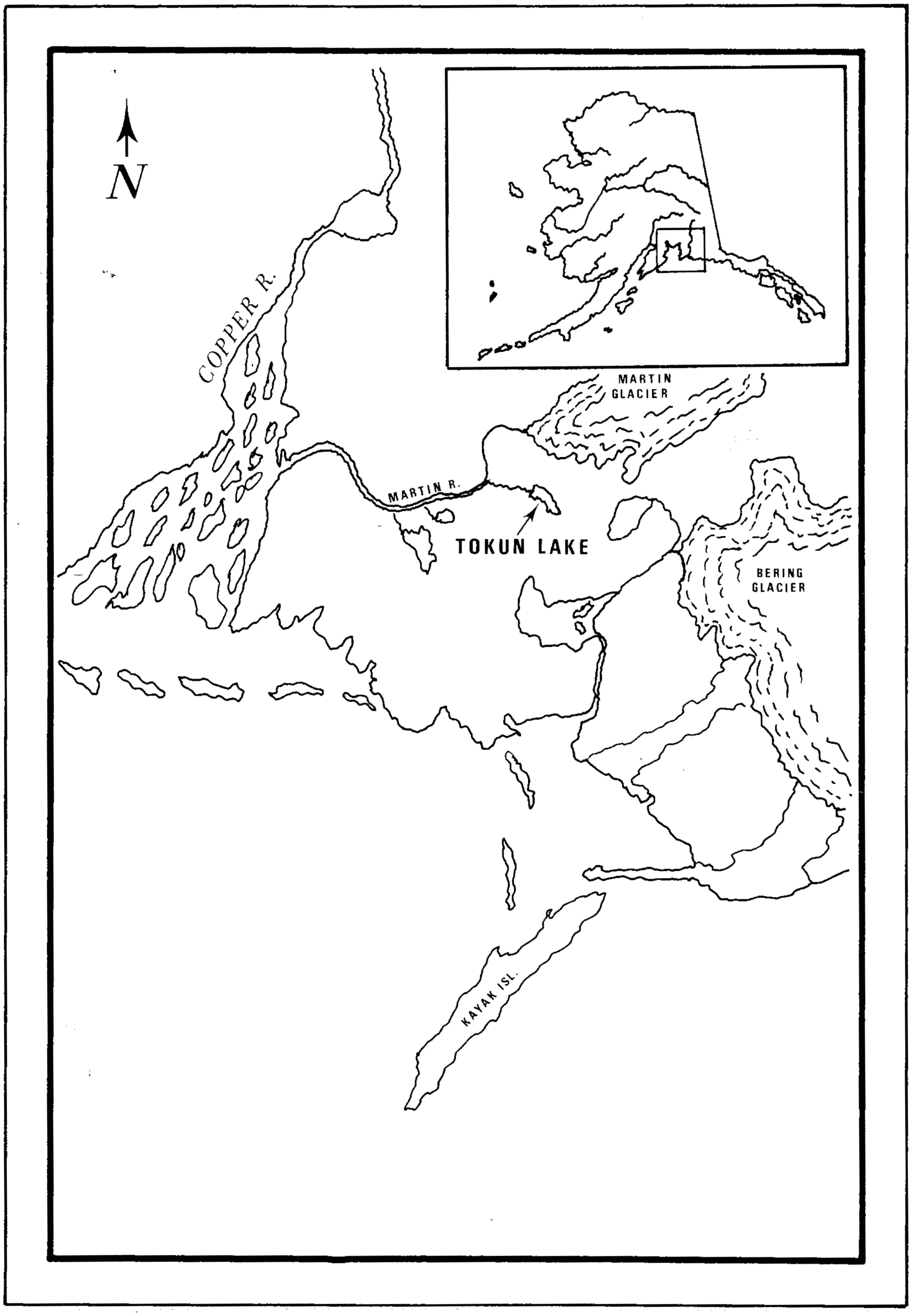

Figure 1. The location of Tokun Lake within the Copper River delta area of Southcentral Alaska.

Sockeye Smolt Enumeration

A stratified sampling method, based on the migratory habits of sockeye smolts, was utilized to minimize handling while providing an accurate estimate of the number of emigrating smolts.

During peak daily migration (generally between 2000 h and 0200 h) when the numbers of smolts emigrating became too cumbersome to hand tally, a five-minute subsample for each 30 minutes was collected in the holding chamber, enumerated, and released. During the remaining 25-minute period smolts were allowed to pass freely through the trap and to continue downstream migration. Daily hand counts and hourly sub-samples were pooled to yield daily and total population estimates.

In 1984 a similar procedure was used; however, we deleted all hand counts. The sampling frequency was increased to three, 2-minute sub-samples per hour for each hour between 2000 h and 0200 h. For the remaining 18 hours of the day, a 10% sampling period (108 minutes) was randomly selected for collection and enumeration of smolts. During the remaining time of the "day" period, smolts were allowed to pass freely through the trap. This sample design provided a consistent daily and seasonal estimate. Sockeye smolt population estimates and 95% confidence intervals for both years were calculated according to the following formulas (Rawson, personal communication):

$$\hat{Y} = \sum_{i=1}^{d} (pn \sum_{i=1}^{n} \bar{x}_i)$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i, \text{ where:}$$

$\hat{Y}$ = total population estimate of timed sub-samples

x = number of smolts captured per sample

p = proportion of time smolts were collected

n = number of samples

d = number of days sub-sampling occurred

$$95\%\ CI = \hat{Y} \pm t_{0.05/2}\ [[d-1]\ \sqrt{\hat{Y}(s^2)}\ \text{where:}$$

$$\hat{Y}(s^2) = \frac{(pn)^2}{n} \sum_{i-1}^{d} s^2_{\bar{x}}$$

That is, the total population estimate is the sum of the timed sub-sample estimate and the total number of smolts that were hand counted.

Age-Weight-Length Sampling

A sample of 20 sockeye smolts was collected without known bias during the peak of daily migration for age, weight, and length analyses. Smolts were anesthetized with MS-222, fork lengths recorded to the nearest millimeter, weights recorded to the nearest 0.1 g, and a scale sample removed. Scales were mounted on glass microscope slides and later viewed under a microfiche reader for age determination. Scale patterns were interpreted using criteria developed by Mosher (1968).

Adult Sockeye Enumeration

Returning adult sockeye were enumerated on a daily basis through an aluminum-conduit counting fence placed at the same location as the smolt weir. A portion of the adult return was sampled for length and age data as part of the Copper River sockeye stock-separation program.

RESULTS

Sockeye Smolt Enumeration

Smolt enumeration and sampling were scheduled to being on 1 May 1983, but because of ice conditions, Tokun Lake was not accessible until 10 May. Between 11 May and 20 June 1983, an estimated 350,200 (95% CI: 287,500 to 412,900) outmigrant sockeye smolts were enumerated. Approximately 3,100 sockeye smolts were captured on 11 May during the first 24-hour sampling period, and it is assumed that smolt emigration had begun during breakup, which was prior to installation of the smolt weir. Also, an undetermined number of smolts migrated between 29 May and 3 June when the weir was inoperable because of high lake discharge. Smolt migration increased sharply on 6 June as water temperatures approached 10°C (Figure 2). The highest daily smolt catch was recorded on 8 June when an estimated 56,200 sockeye smolts were enumerated. Approximately 56% of the smolts migrated in a ten-day period from 4 June through 15 June. Smolt enumeration was discontinued on 20 June when counts dropped to less than 100 sockeye per day. In addition to sockeye smolts, 1,930 coho juveniles, 227 Dolly Varden, and 35 lake trout were captured. Population estimates for these species were not calculated because most fish captured appeared to be rearing juveniles.

In 1984 smolt enumeration began on 3 May and continued through 29 June. An estimated 526,600 (95% CI: 443,200 to 609,800) sockeye

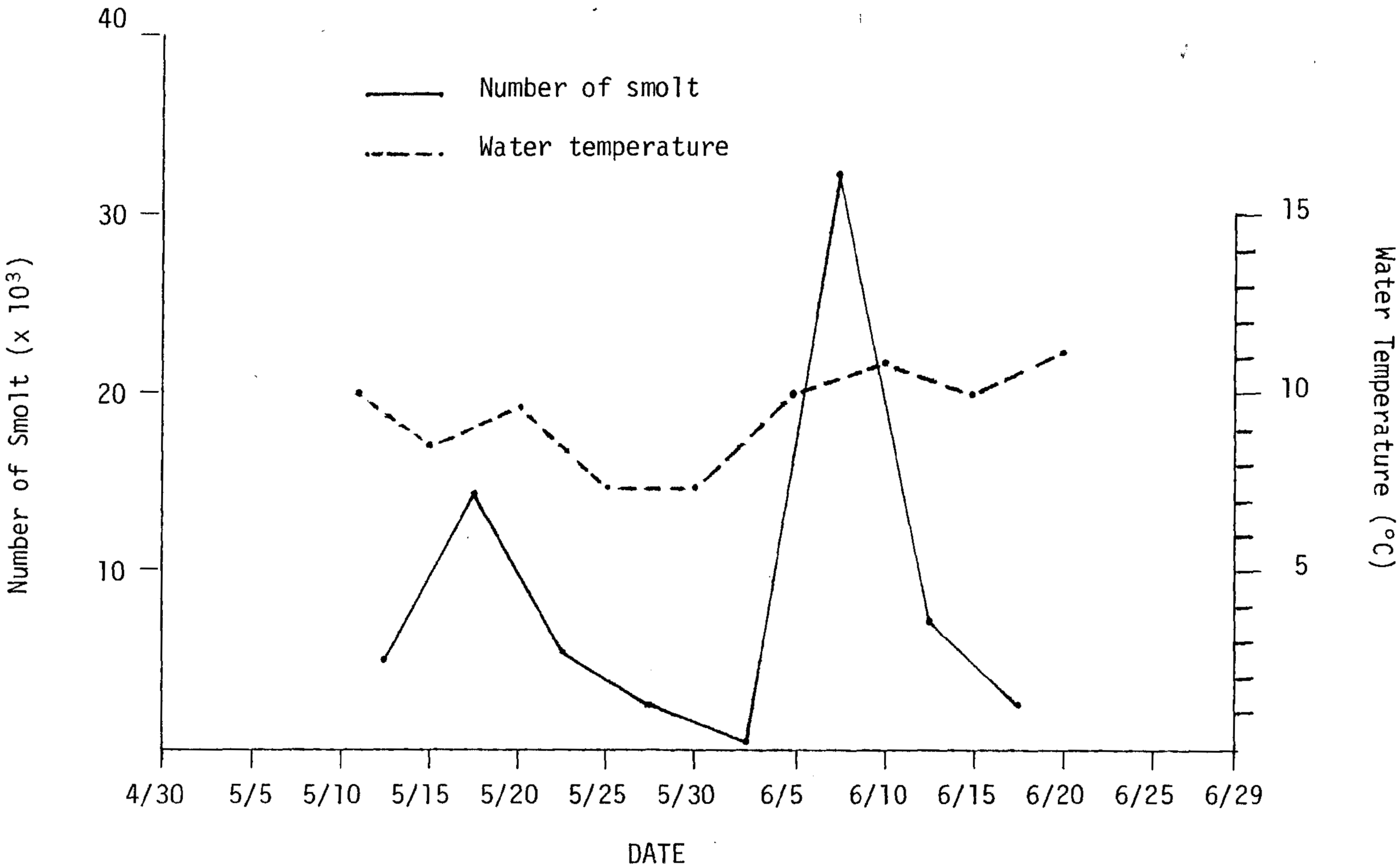

Figure 2. Average number of sockeye smolts migrating from Tokun Lake during five-day periods from 11 May through 20 June 1983 and water temperatures as recorded on the listed dates.

smolts were enumerated; approximately 15,420 smolts passed through the weir in the first 24 hours of operations. The highest daily smolt catch occurred on 5 May, three days after the weir was installed. A second pulse occurred in June, peaking on 6 June when an estimated 12,550 smolts were enumerated (Figure 3). Overall, 28% of the smolts enumerated migrated during the period from 3 May through 11 May. In addition to sockeye smolt, 530 coho juveniles, 177 Dolly Varden, 2 lake trout, and 2 cutthroat trout were captured.

Population Characteristics of Sockeye Smolts

In 1983 a total of 399 sockeye smolts were sampled for age, weight, and length analyses. All smolts sampled (with the exception of one age-2.0 smolt) were age 1.0 and had a population mean length of 63 mm and a mean weight of 2.1 g. The mean length and weight of migrating smolts remained relatively constant throughout the sample period (Table 1); approximately 65% of the smolt sampled were 61 mm to 70 mm in length (Figure 4).

Adult Sockeye Enumeration and Population Characteristics

In 1983 a total of 7,645 adult sockeye were counted through the weir between 31 May and 11 August (*see* Table A-1). A peak daily escapement count of 1,213 sockeye was recorded on 2 July, and by 8 July 72% of the total run had entered the lake. In 1984 a total of 27,441 sockeye were enumerated between 11 May and 20 August. This was the second largest sockeye escapement into Tokun Lake since observations began in 1981 (*see* Appendix Table A-2). A peak count of 1,727 sockeye was recorded on 13 June. The 1984 return was earlier than the 1983 return, with 70% of the escapement entering the lake prior to 21 June.

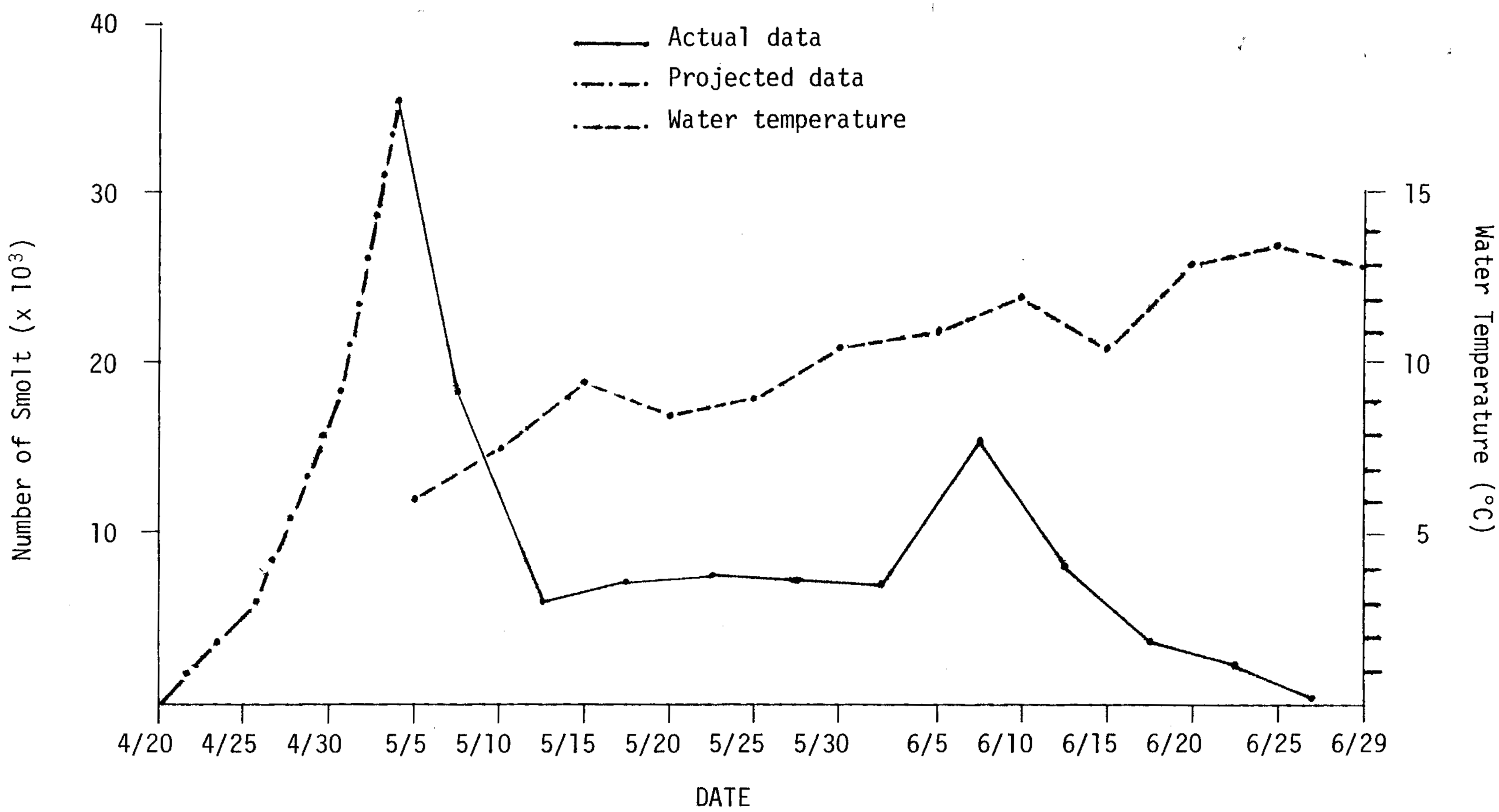

Figure 3. Average number of sockeye smolts migrating from Tokun Lake during five-day periods from 3 May through 29 June, 1984 and water temperatures as listed on the recorded dates.

Table 1. Mean length (mm), weight (g), standard deviation (SD), sample size (n), and population estimate per five-day sample periods of age-1.0 sockeye smolts, Tokun Lake, 1983 and 1984.

Sample Period	n	Mean Length(mm)	SD	Mean Weight(g)	SD	Population Estimate
1983						
5/11-5/15	20	62	5.2	1.8	0.5	24,850
5/16-5/20	60	62	5.4	1.9	0.5	71,840
5/21-5/25	20	61	4.4	2.0	0.6	26,580
5/26-5/30	100	65	4.6	2.1	0.5	13,160
5/31-6/04	39	65	4.9	2.3	0.6	1,830
6/05-6/09	40	63	5.0	2.6	0.6	136,780
6/10-6/14	80	62	4.4	2.1	0.5	59,130
6/15-6/20	40	63	4.9	2.3	0.7	16,030
Totals	399					350,200
1984						
5/03-5/07	99	63	4.0	1.8	0.4	140,690
5/08-5/12	99	63	4.2	1.8	0.4	76,170
5/13-5/17	100	64	4.3	1.9	0.5	26,780
5/18-5/22	98	65	4.8	2.2	0.5	47,300
5/23-5/27	100	66	3.9	2.3	0.5	18,500
5/28-6/01	99	68	4.6	2.6	0.6	35,630
6/02-6/06	100	70	5.2	2.9	0.8	43,030
6/07-6/11	100	71	3.8	3.1	0.6	75,130
6/12-6/16	100	72	3.9	3.2	0.5	34,470
6/17-6/21	100	73	4.0	3.1	0.6	16,150
6/22-6/26	100	73	4.0	3.4	0.7	11,020
6/27-6/29*	60	74	4.6	3.6	0.8	1,630
Totals	1,155					526,500

* Three days only

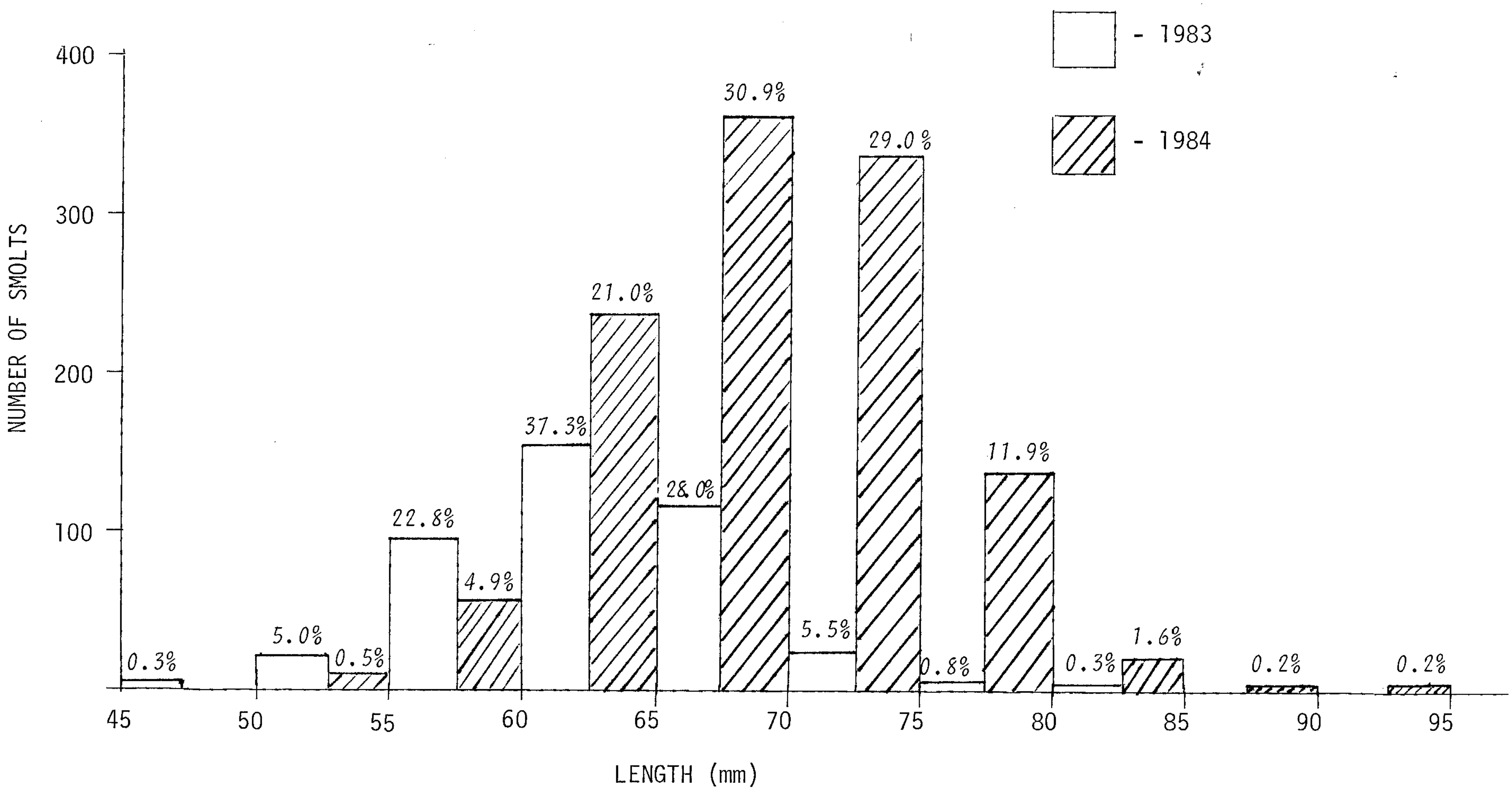

Figure 4. Length frequency distribution of sockeye smolts sampled from Tokun Lake in 1983 and 1984.

Estimated age composition for the sockeye salmon escapement to Tokun Lake was summarized by Sharr et al. (1983) for the 1983 return and by Sharr (personal communication) for the 1984 return. The dominant age class of sockeye returning to Tokun Lake in both 1983 and 1984 was age 1.3; 84.1% and 91.7% of the total returns were comprised of this age group, respectively. In contrast, age-1.2 sockeye represented 15.3% and 7.7% of the total return in 1983 and 1984, respectively (Table 2).

DISCUSSION

For many years, declines in the yield (or stock strength) of sockeye salmon were related solely to over fishing, simply because it resulted in insufficient egg deposition (Rounsefell 1958). However, the negative effects of a reduction in spawned-out carcasses and, therefore, of fertility in the rearing area have been added to this previously exclusive effect of over fishing (Juday et al. 1932; Nelson and Edmondson 1955; Krokhin 1967; LeBrasseur et al. 1978). That is, the amount of nutrients (principally nitrogen and phosphorus) released from the carcasses of the spawned-out salmon can be directly related to the fertility of the lake at the time the brood-year fry subsequently rear (Mathisen 1972; Richey et al. 1975). When dealing with the production of sockeye salmon, this relationship introduces the concept that aquatic productivity can be expressed as a functional variable in equations. Thus, Mathisen (1972) and Rigler (1982) argued that the standard spawner-recruit relationship can not be considered a closed loop, but that it must be based on an understanding of changing lake productivities.

In beginning an assessment of the current sockeye production characteristics of Tokun Lake, we concentrated on the production of smolts; i.e., the end product of the freshwater-rearing phase. We did not attempt to estimate smolt production as it relates to

Table 2. Estimated age composition of the adult sockeye salmon escapement to Tokun Lake in 1983 and 1984.

	Brood year and age group			
	1978		1979	
	1.3	2.2	0.3	1.2
1983 Return				
Percent	84.1	0.2	0.4	15.3
Escapement	6,438	12	24	1,171

	1978		1979		1980
	1.4	2.3	1.3	2.2	1.2
1984 Return					
Percent	0.2	0.4	91.7	0.1	7.7
Escapement	44	109	25,154	17	2,117

parent-year escapement, because brood-year escapement counts for the 1983 and 1984 smolt migrations were calculated from aerial surveys in 1981 and 1982. The variability in these escapement counts (aerial surveys of spawning sockeye in deep-water lake systems) is too large to construct meaningful spawner/smolt production ratios. Thus, in an effort to develop an understanding of the current production characteristics of Tokun Lake, the number and biomass of smolts produced per unit of lake surface area and per-unit euphotic volume were estimated (Table 3). Biomass production estimates were calculated using the mean weight of smolts sampled each year. Biomass production nearly doubled in 1984 because of the increase in both the number and mean weight of migrating smolts. Thus, in 1984 Tokun Lake produced 2,910 smolt/ha, or 7.9 kg/ha, compared to 1,935 smolt/ha, or 4.1 kg/ha, in 1983 (Table 3). Likewise, production of age-1.0 smolts based (or normalized) on euphotic volume was greater in 1984, when compared to that in 1983 (Table 3). This indicated that lake productivity may have increased in 1984, because the increased number of successfully reared smolt were also larger in weight.

Earlier ice break-up and warmer lake water temperatures (mean water temperature in 1984 = 10.3°C versus 9.0°C in 1983) may have attributed to improved rearing conditions and larger average smolt size in 1984 as compared to 1983. It was noted during our age analysis that a large percentage of smolts sampled in 1984 showed additional growth prior to migration; a large proportion of smolts had deposited up to three circulii after the winter check. Such an indication of growth during early spring and before actual migration was not observed in the 1983 sample. In addition, concommitant with the scale-pattern differences, a gradual increase in smolt size throughout the smolt migration was observed in 1984; little or no size difference between early and late migrating smolts was noted in 1983. Finally, the 1982 rearing period, which would produce the 1983 smolts, had

Table 3. Estimated number of sockeye smolts and biomass production per hectare (a) and per unit euphotic volume (b) from Tokun Lake, 1983 and 1984.

Year	Population estimate	Range @ 95% CI	Estimated number of smolt produced (per ha)	Range (per ha)	Estimated biomass production (kg/ha)	Range (kg/ha)
(a)						
1983	350,200	287,500-412,900	1,935	1,590- 2,280	4.1	3.3- 4.8
1984	526,500	443,200-609,800	2,910	2,450- 3,370	7.9	6.6- 9.1

Year	Population estimate	Range 95% C.I.	Estimated number of smolt produced (per unit E.V.)	Range (per unit E.V.)	Estimated biomass production (kg/unit E.V.)	Range (kg/ha)
(b)						
1983	350,200	287,500-412,900	12,034	9,880-14,189	25.5	20.5-29.8
1984	526,500	443,200-609,800	17,727	14,923-20,532	48.1	40.2-55.4

considerably more precipitation than that observed for the 1983 rearing period; i.e., 1983 precipitation dropped by nearly 25%, when compared to that in 1982. The residence time of the lake water, therefore, was considerably greater in 1983 than in 1982. The increased residence time coupled with more photosynthetically available radiation increased water temperatures and, ultimately, the biological production within the lake; i.e., the 1983 sockeye fry rearing capacity expanded. Compared to the rearing conditions existing in 1982-1983, the rearing environment in the lake during 1983-1984 allowed for larger-sized smolts, even with the presence of a greater density of rearing fry.

Over twice as many sockeye smolts migrated from Tokun Lake in 1984 than in 1983, both migrations showed similar seasonal patterns in migration timing. In both years, smolts began leaving the system immediately after ice break-up or when the outlet area became ice free. Migration curves for both years exhibited an initial peak in early-to mid-May and a second peak during the second week of June. However, in 1984 a significant number of smolts may have migrated from the lake prior to initiation of the enumeration project. To estimate the magnitude of the pre-enumeration smolt migration, we projected the portion of the migration curve from 20 April through 3 May (Figure 3). The projected curve was plotted as a symmetrical function of the known curve from 3 May through 12 May. By calculating the area under the projected curve, it is estimated that approximately 165,000 smolts may have left the lake prior to 3 May. Finally, the mean size of sockeye smolts leaving Tokun Lake was smaller in both years when compared to the mean size of smolts from other clear-water systems in southcentral Alaska (Table 4). In general, the average size of age-1.0 smolts from Tokun Lake is similar to those reported by Koenings et al. (1984) for lakes in southeast Alaska and by Kyle and Koenings (1982) for glacial lakes in the Cook Inlet area.

Table 4. Mean lengths and weights of age-1.0 and age-2.0 sockeye smolts from different clear-water systems in Alaska as compared to 1983 and 1984 mean lengths and weights of sockeye smolts from Tokun Lake.

Location	Mean Length (mm)		Mean Weight (g)	
	Age 1.0	Age 2.0	Age 1.0	Age 2.0
Hidden Lake	143	200	27.3	83.9
Big Lake	132	166	25.5	48.1
Naknek River	100	113	9.2	12.6
Kvichak River	89	110	6.1	10.1
Togiak Lake	85	101	5.5	9.5
Red Lake	85	111	5.8	12.8
Russian River	84	93	5.1	6.5
Brooks Lake	83	109	5.2	10.1
Desire Lake	74	92	4.7	8.8
Delight Lake	71	81	3.6	5.4
Eshamy Lake (1982)	73	97	3.2	7.1
Eshamy Lake (1983)	77	100	3.7	8.4
Tokun Lake (1983)	63		2.1	
Tokun Lake (1984)	69	87*	2.7	5.2*

* sample size of 3

The 1983 and 1984 returns of adult sockeye consisted almost entirely of one-year freshwater fish, which is consistent with finding the 1983 and 1984 smolts to be entirely age-1.0 fish. While the smolts and adults were not of the same brood year, this information indicates that Tokun Lake has produced a large percentage of age-1.0 smolts in previous years. In addition, the dominating presence of age-1.3 adult fish in the 1983 return (84%) and in the much larger 1984 return (92%) may indicate that these broodyear smolts were small (Koenings et al. 1984) as was observed for both the 1983 and 1984 smolts.

Given concurrence in Part II of this report, the addition of nutrients to the epilimnion of Lake Tokun may increase the growth rate of the rearing fry by stimulating production of zooplankton (Raleigh 1963). If so, the resulting smolts will be larger (Barraclough and Robinson 1972), which may lead to a higher marine survival (Foerster 1954; Eicher and Rounsefell 1957; Ricker 1962) and a higher percentage of age-1.2 adults.

ACKNOWLEDGEMENTS

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PERSONAL COMMUNICATION

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Sharr, S. 1984. Alaska Department of Fish and Game, Commercial Fisheries Division, Stock Biology Section, Anchorage, Alaska.

APPENDIX A

Table A-1. Tokun Lake daily adult sockeye salmon weir counts, 1983 and 1984.

Date	Number of fish 1983	Number of fish 1984	Date	Number of fish 1983	Number of fish 1984
5/11		1	7/01	799	195
5/12		0	7/02	1,213	259
5/13		0	7/03	93	360
5/14		0	7/04	347	117
5/15		0	7/05	306	120
5/16		0	7/06	656	505
5/17		0	7/07	176	0
5/18		0	7/08	50	186
5/19		7	7/09	7	310
5/20		0	7/10	31	63
5/21		0	7/11	23	49
5/22		12	7/12	10	1
5/23		0	7/13	73	4
5/24		26	7/14	77	43
5/25		202	7/15	2	63
5/26		165	7/16	0	159
5/27		201	7/17	12	78
5/28		248	7/18	21	117
5/29		108	7/19	113	169
5/30		235	7/20	112	28
5/31	75	614	7/21	73	37
6/01	0	302	7/22	190	33
6/02	0	234	7/23	121	47
6/03	0	777	7/24	238	70
6/04	0	1,294	7/25	173	141
6/05	0	769	7/26	229	38
6/06	0	1,376	7/27	80	71
6/07	0	1,148	7/28	19	22
6/08	0	780	7/29	47	7
6/09	103	1,324	7/30	115	86
6/10	124	872	7/31	10	10
6/11	30	1,164	8/01	32	30
6/12	128	658	8/02	39	47
6/13	88	1,727	8/03	39	17
6/14	59	1,669	8/04	29	12
6/15	96	1,527	8/05	28	27
6/16	176	859	8/06	52	35
6/17	86	402	8/07	44	8
6/18	79	557	8/08	24	0
6/19	27	681	8/09	11	8
6/20	0	608	8/10	10	8
6/21	0	191	8/11	41	17
6/22	0	421	8/12	--	12
6/23	7	395	8/13	--	91
6/24	28	228	8/14	--	13
6/25	34	568	8/15	--	45
6/26	74	372	8/16	--	10
6/27	65	334	8/17	--	30
6/28	84	162	8/18	--	13
6/29	84	106	8/19	--	106
6/30	433	111	8/20	--	89
Total				7,645	27,441

Table A-2. Sockeye salmon aerial escapement estimates in Tokun Lake, 1961-1984.

Year	Escapement
1961	5,000
1962	8,000
1963	10,000
1964	8,900
1965	31,000
1966	4,900
1967	-
1968	3,500
1969	700
1970	19,800
1971	23,000
1972	1,850
1973	3,455
1974 (Weir)	2,170
1975 (Weir)	1,200
1976	11,200
1977	5,500
1978	6,600
1979	6,500
1980	17,000
1981	8,500
1982	7,000
1983 (Weir)	7,645
1984 (Weir)	27,800
Mean	9,220

PART II. THE LAKE TOKUN LIMNOLOGY PROGRAM

by

J.P. Koenings

David Barto

INTRODUCTION

Successful sockeye salmon fry rearing requires preferred forage items to be seasonally available to fry entering the rearing area and for that forage to be of sufficient density and size to allow for efficient fry growth rates (LeBrasseur and Kennedy 1972; Hall and Hyatt 1974; Goodlad et al. 1974; Vinyard 1982). If these conditions are not met, fry growth will be curtailed, and smolts will either emerge as small age-1.0 fish or will hold over for a second year of freshwater rearing (Krogius 1961). Both of the above results are undesirable because small smolt size has been linked to reduced marine survival (Foerster 1954; Ricker 1962; Barraclough and Robinson 1972), and protracted freshwater residence has been tied to drastically reduced freshwater survival (Barnaby 1944; Johnson 1965; Foerster 1968).

The intent of lake enrichment is to either boost the size and/or number of smolts from rearing-limited systems and/or to decrease freshwater residence time (Nelson 1959; McAllister et al. 1972). The mechanism driving this desired product is the addition of nutrients to the trophogenic zone (Nelson 1959; Stockner 1981). By this approach, the forage density can be increased (Raleigh 1963; McAllister et al. 1972; Milbrink and Holmgren 1981) and the maxima of zooplankton densities advanced seasonally to more appropriately match fry emergence patterns or timing (Rankin et al. 1979).

The purpose of this report is to define limnological conditions within the lake that may limit the efficiency of fry feeding and to recommend programs to correct those deficiences.

Study Site Description

Lake Tokun [ADF&G No. 212-30-924 (lat.60°24'N; long.144°17'W)] is located in the Lower Copper River Delta and lies at an elevation of 57 m (Figure 1). The lake has a surface area of 183 ha (448 acres), a

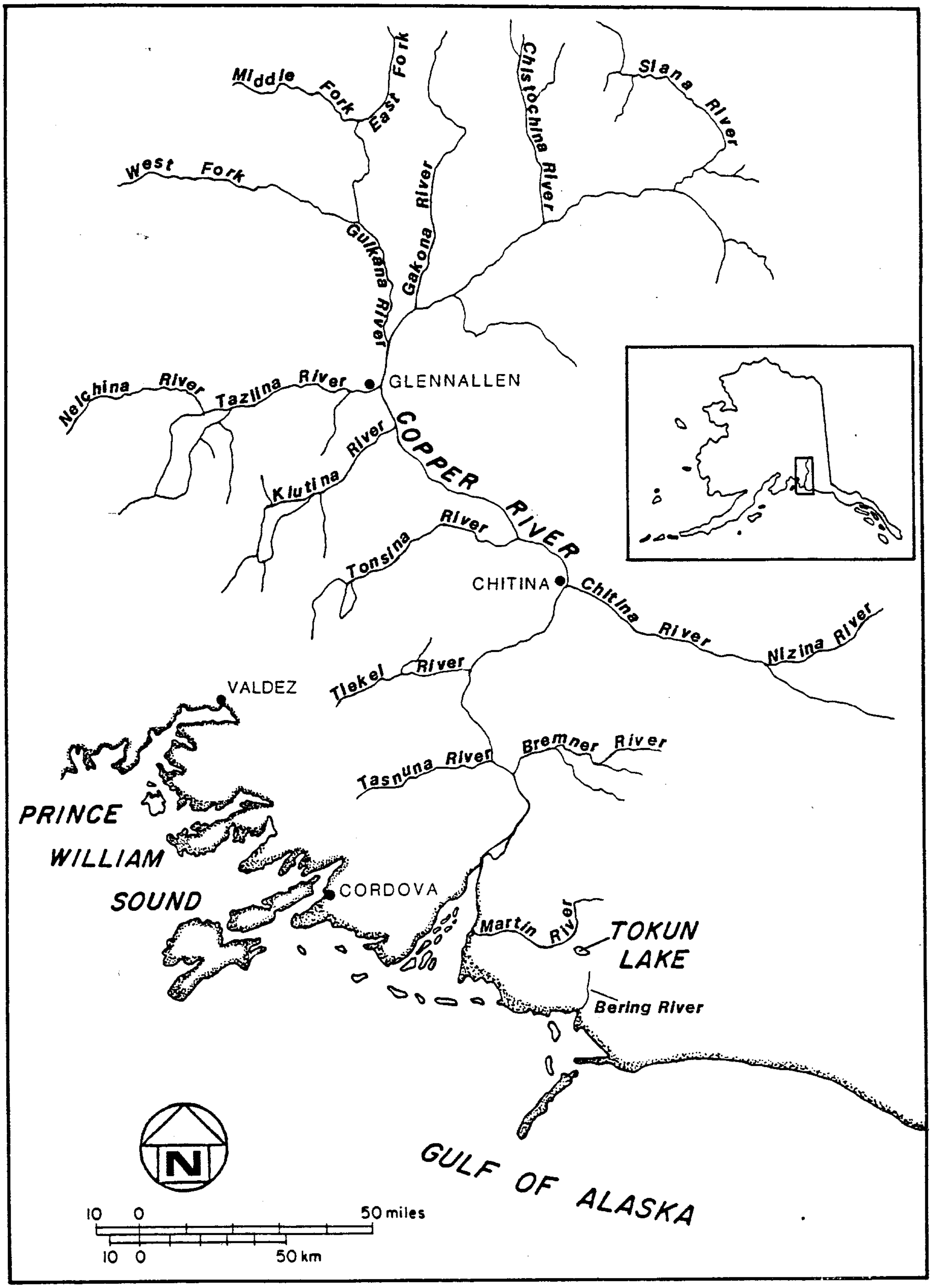

Figure 1. Location of Lake Tokun relative to Prince William Sound, the Copper River, and the State of Alaska.

volume of $38.0 \times 10^6\ m^3$, and a mean depth of 21 m (Figure 2). The calculated annual discharge out of the 1958 ha watershed surrounding Lake Tokun is estimated to be $39.0 \times 10^6\ m^3$, which results in a theoretical water residence time for the lake of ≅1.0 yr. The lake has one central basin; two limnological sampling sites were placed to characterize the lake at the upper (Station 2) and lower (Station 1) ends (Figure 2). Finally, the shoreline is steep sided, especially along the northern and southern shores; however, both the eastern and western (outlet) ends have small percentages of littoral area.

METHODS

Transportation to and from Lake Tokun was provided by a float-equipped aircraft; during all surveys, limnological samples were collected after mooring to the permanent sampling stations. The frequency of sampling was designed to characterize the lake at three-week intervals from ice-off in the spring to ice-on in the winter. The lake was sampled for algal nutrients (nitrogen, phosphorus, silicon, and carbon) as well as for other water quality parameters (*see* Alaska Department of Fish and Game, Lake Fertilization Guidelines) from both the epilimnetic and mid-hypolimnetic zones. Water samples from multiple (4) casts with a nonmetalic Van Dorn sampler were pooled, stored in 8-10 liter transluscent carboys, cooled, and immediately transported in light-proof containers to Cordova for filtering and preservation. Subsequent filtered and unfiltered water samples were stored either refrigerated or frozen in acid-cleaned, prerinsed polybottles. The preprocessed water samples were then sent to the Soldotna Limnology Laboratory for analysis.

All chemical and biological samples were analyzed by methods detailed by Koenings et al. (1985a). In general, filterable reactive phosphorus (FRP) was analyzed by the molybdate-blue/ ascorbic-acid method of Murphy and Riley (1962), as modified by Eisenreich et al. (1975). Total phosphorus was determined by the FRP procedure, after persulfate digestion. Nitrate and nitrite were determined as nitrite,

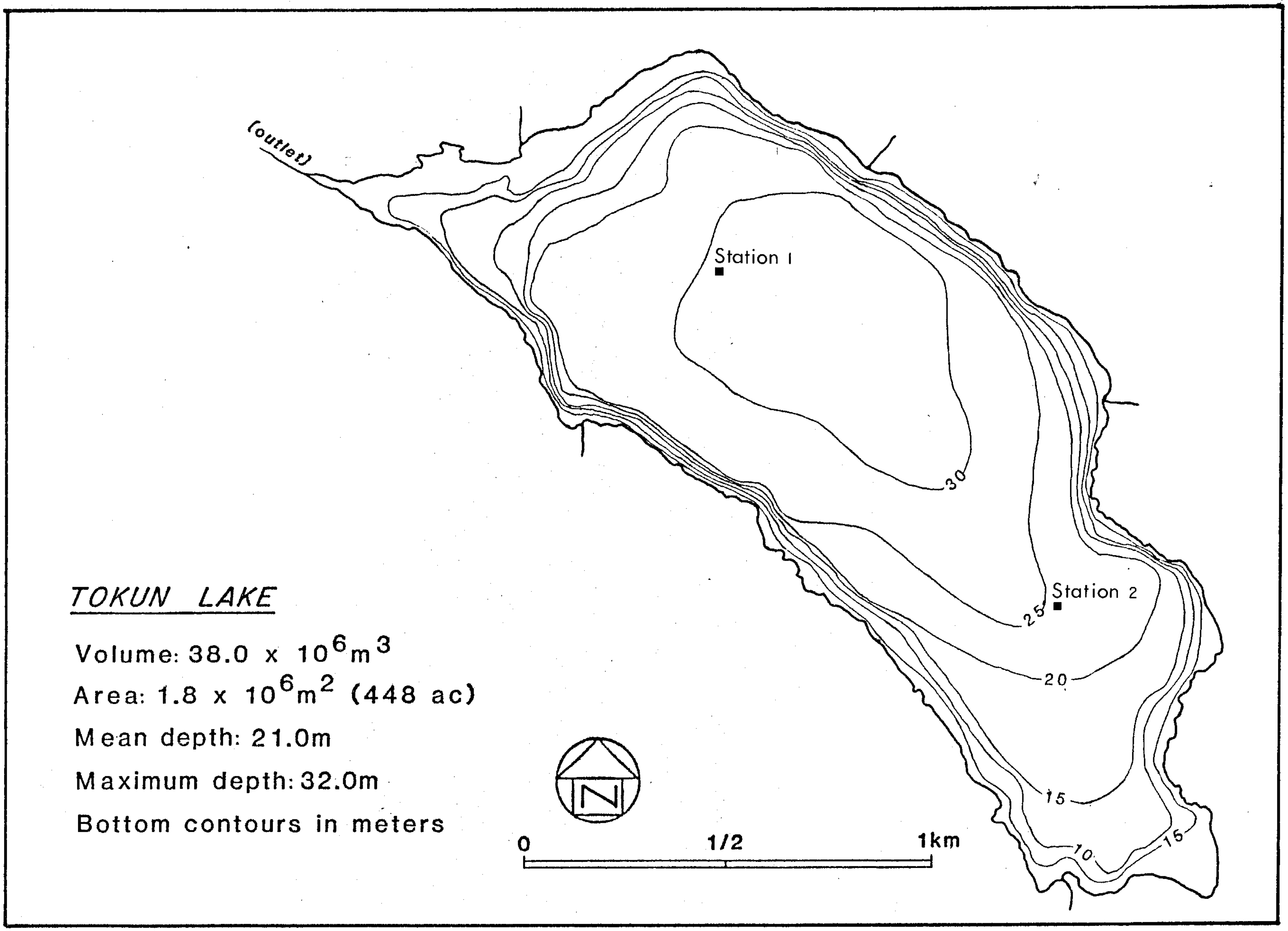

Figure 2. Morphometric map of Lake Tokun showing the location of major basins and the limnological sampling Stations 1 and 2.

following Stainton et al. (1977), after cadmium reduction of nitrate. Using the phenolhypochlorite methodology, ammonium analysis followed Stainton et al. (1977), while reactive silicon analysis followed the procedure of Strickland and Parsons (1972). Alkalinity levels were determined by acid titration (0.02 N H_2SO_4) to pH 4.5, using a Corning model-399A specific ion meter.

Particulate carbon, nitrogen, and phosphorus were estimated directly from filtered seston that was prepared by drawing 1 to 2 liters of lake water through precleaned 4.2-cm GF/F filters. The filters were stored frozen in individually marked plexislides until analyzed.

Primary production (algal standing crop) was estimated by chlorophyll a (chl a) analysis, after the fluorometric procedure of Strickland and Parsons (1972). The low-strength acid addition recommended by Riemann (1978) was used to estimate phaeophytin. Water samples (1-2 liters) were filtered through 4.25-cm GF/F filters to which a 1 to 2 mls of a saturated $MgCO_3$ solution were added just prior to the completion of filtration. The filters were then stored frozen in individual plexislides for later analysis.

Zooplankton were collected from either duplicate bottom-to-surface or surface-to-50-m vertical tows, using a 0.5-m diameter, 153-μ mesh conical zooplankton net. The net was pulled at a constant 1 m/second and washed well before removing; the organisms were preserved in 10% neutralized sugar-formalin (Haney and Hall 1973).

Identification of the genus *Daphnia* followed Brooks (1957), of the genus *Bosmina*, Pennak (1978), and of the copepods, Wilson (1959), Yeatman (1959), and Harding and Smith (1974). Enumeration consisted of counting triplicate 1-ml subsamples taken with a Hansen-Stempel pipette in a 1-ml Sedgewick-Rafter cell. Size (length) of the individual zooplankters was obtained by counting at least ten individuals along a transect in each of the 1-ml subsamples used in identification and enumeration. Zooplankters were measured to the nearest 0.01 mm as described in Edmondson and Winberg (1971).

Bottom profiles were recorded with a fathometer along several lake transects, and from these depth recordings a bathymetric map was developed. The area of component depth strata was determined with a polar planimeter, and lake volume (V) was computed by summation of successive strata, after Hutchinson (1957):

$$\text{Lake Volume} = \sum_{i=1}^{n} \frac{h}{3} \left(A_1 + A_2 + \sqrt{A_1 A_2}\right)$$

Where: $\sum_{i=1}^{n}$ = sum of strata volumes i through n

A_1 = surface area of upper depth strata (m^2)

A_2 = surface area of lower depth strata (m^2)

h = distance between A_1 and A_2 (m)

Lake mean depth ($\bar{z}$) was calculated as:

$$\bar{z} = V/A_L$$

Where: $\bar{z}$ = lake mean depth (m)

V = lake volume ($\cdot 10^6 m^3$)

A_L = lake surface area ($\cdot 10^6 m^2$)

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

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

Where: T_w = theoretical water residence time (years)

V = total lake volume ($\cdot 10^6 m^3$)

TLO = total lake outflow ($\cdot 10^6 my3_{yr}$)

The collection of physical data included the measurement of lake temperatures and light penetration at both Stations 1 and 2. Lake-temperature profiles were measured using a YSI temperature/dissolved-oxygen model-57 meter. These recordings were taken at 1-m increments from the surface to 5 m, at 2-m increments from 6 to 12 m, and at 10-m increments from 20 to 50 m. The algal light-compensation point was defined as the depth at which 1% of the subsurface light (photosynthetically available radiation [400-700 mm]) penetrated (Schindler 1971a), and it was measured by using a Protomatic submersible photometer. Recordings were taken at several depths between the surface and the compensation depth. Using these data, the natural logarithm of light intensity was plotted against depth, and the slope of this line was used to calculate the light-extinction coefficient by date. In addition, water transparency was estimated, using a 20-cm Secchi disk. Finally, in both the Tables and Figures we have used the designation of either mg L^{-1} or µg L^{-1} to report concentration data. However, in the body of the report we have used either parts per million (ppm) in lieu of mg L^{-1} or parts per billion (ppb) in lieu of µg L^{-1}. We have made this conversion in order to reduce the handling time of the report by our support staff.

RESULTS

Light Regimes and Heating/Cooling Cycles

The depth of the euphotic zone ranged between 7 and 25 m at Station 1 and from 9 to 24 m at Station 2 during the 1982 open-water period (Table 1). In addition, the compensation depth appeared to deepen at

Table 1. The penetration of phytosynthetically available radiation (PAR) which defines the lower limit of the euphotic zone (compensation point), depth of the metalimnion, and the depth at which the Secchi disk is no longer visible at Stations 1 and 2 during 1982 and 1983.

	Station 1			Station 2		
Date	Compensation point (m)	Metalimnion (m)	Secchi disk (m)	Compensation point (m)	Metalimnion (m)	Secchi disk (m)
1982						
04/07	11	Isothermal	--	11	Isothermal	--
06/25	13	5	6	15	6	6
07/26	20	10	8	21	10	9
08/12	21	12	11	20	12	9
08/31	25	12	10	24	12	9
09/24	14	Isothermal	5	9	26	5
10/13	14	Isothermal	6	14	Isothermal	5
11/05	--	Isothermal	--	16	Isothermal	6
1983						
04/26	15	Isothermal	6	13	Isothermal	6
05/18	21	Isothermal	8	21	Isothermal	7
06/05	19	5	8	19	5	7
06/27	30	10	12	24	10	11
07/15	26	10	15	25	10	15
08/17	25	15	11	21	15	11
09/05	21	15	10	21	15	11
09/26	11	Isothermal	6	11	27	5
10/19	11	Isothermal	4	10	Isothermal	4
11/07	18	Isothermal	7	16	Isothermal	7

both stations from the spring into August and then to shallow during the fall period. The mean compensation level for 1982 was 16.6 m, which resulted in a euphotic volume of 25.6 x 10^6 m^3, or nearly 67% of the total volume of the lake.

In 1983 the depth of the euphotic zone ranged between 11 and 30 m at Station 1 and between 10 and 25 m at Station 2. As was observed in 1982, light penetration increased in depth from April (during the spring overturn) and reached 24 to 30 m by late June. Thereafter, the photic zone again shallowed, reaching only 10 to 11 m by the end of September and October; but then it expanded to 16 to 18 m in November. Overall, the compensation level in 1983 averaged 18.9 m, which resulted in a euphotic volume of 28.5 x 10^6 m^3, or nearly 75% of the total volume of the lake.

For comparison to the depth of the photic zone, which was estimated from a submarine photometer, we estimated the depth of light penetration with a Secchi disk. In 1982 the light-penetration pattern followed, on a seasonal basis, that obtained with the photometer. That is, a relatively shallow spring photic zone was followed by a doubling of the photic depth in the summer and then by a decrease to spring levels by fall. Secchi-disk depths ranged from 6 to 11 m in 1982 and from 4 to 1 m in 1983; both sites had similar patterns for both years.

For example, Station 1 had a seasonal-mean Secchi-disk depth of 7.7 m in 1982 and 8.5 m in 1983, while Station 2 averaged 7.2 m and 8.5 m in 1982 and 1983, respectively. As such, the zone of light penetration defined by the Secchi disk depth was 45% of that defined by submarine photometer in both 1982 and 1983.

Temperature profiles taken in 1982 indicate that the lake began to form a thermocline, or metalimnion, by the end of June at 5 m (Figures 3 and 4). Thereafter, the lake warmed as the metalimnion deepened to

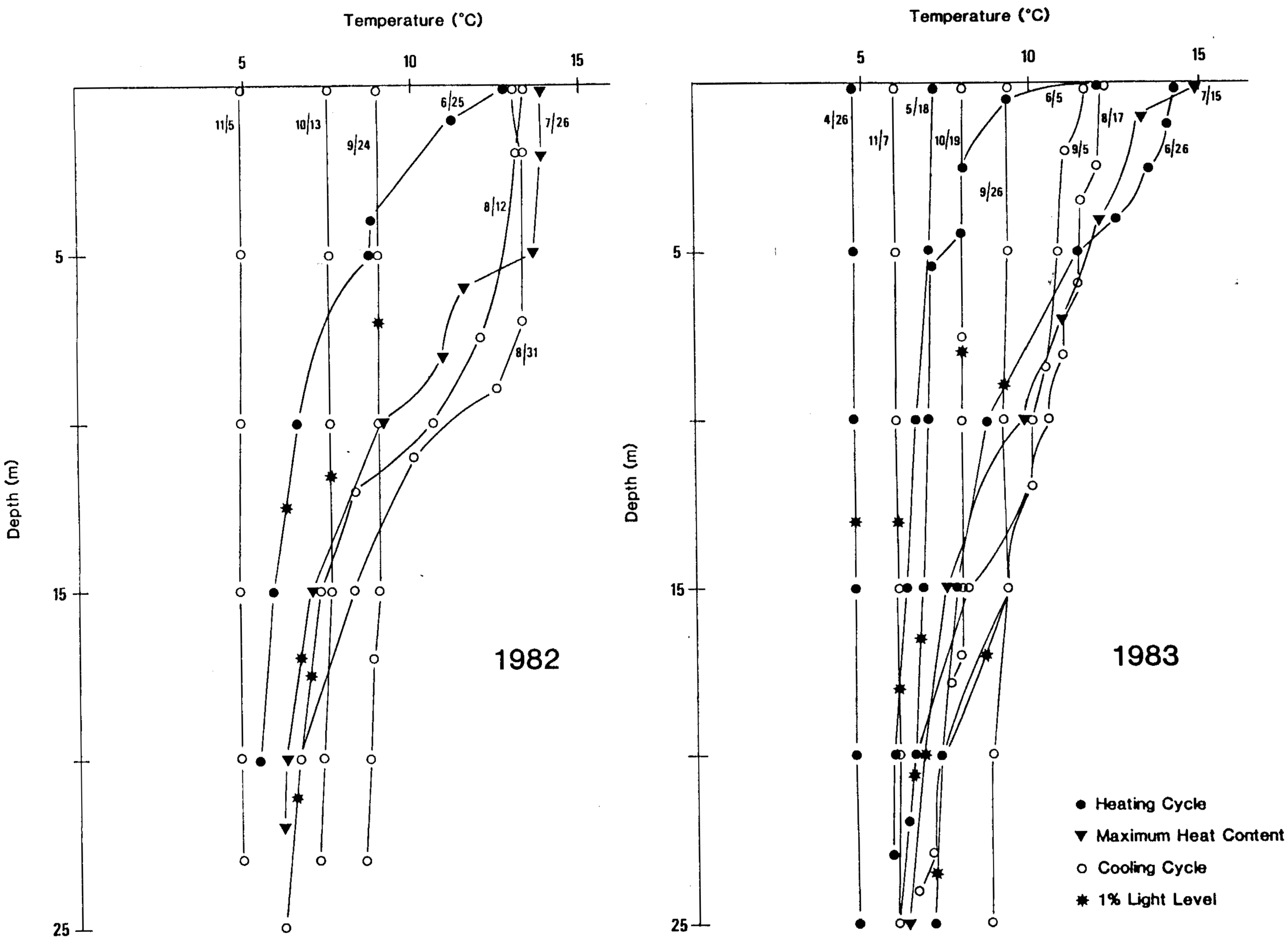

Figure 3. Temperature profiles within Lake Tokun at Station 1 for 1982 and 1983 showing the seasonal heating and cooling cycles, the location of the metalimnion, and the depth of the compensation point.

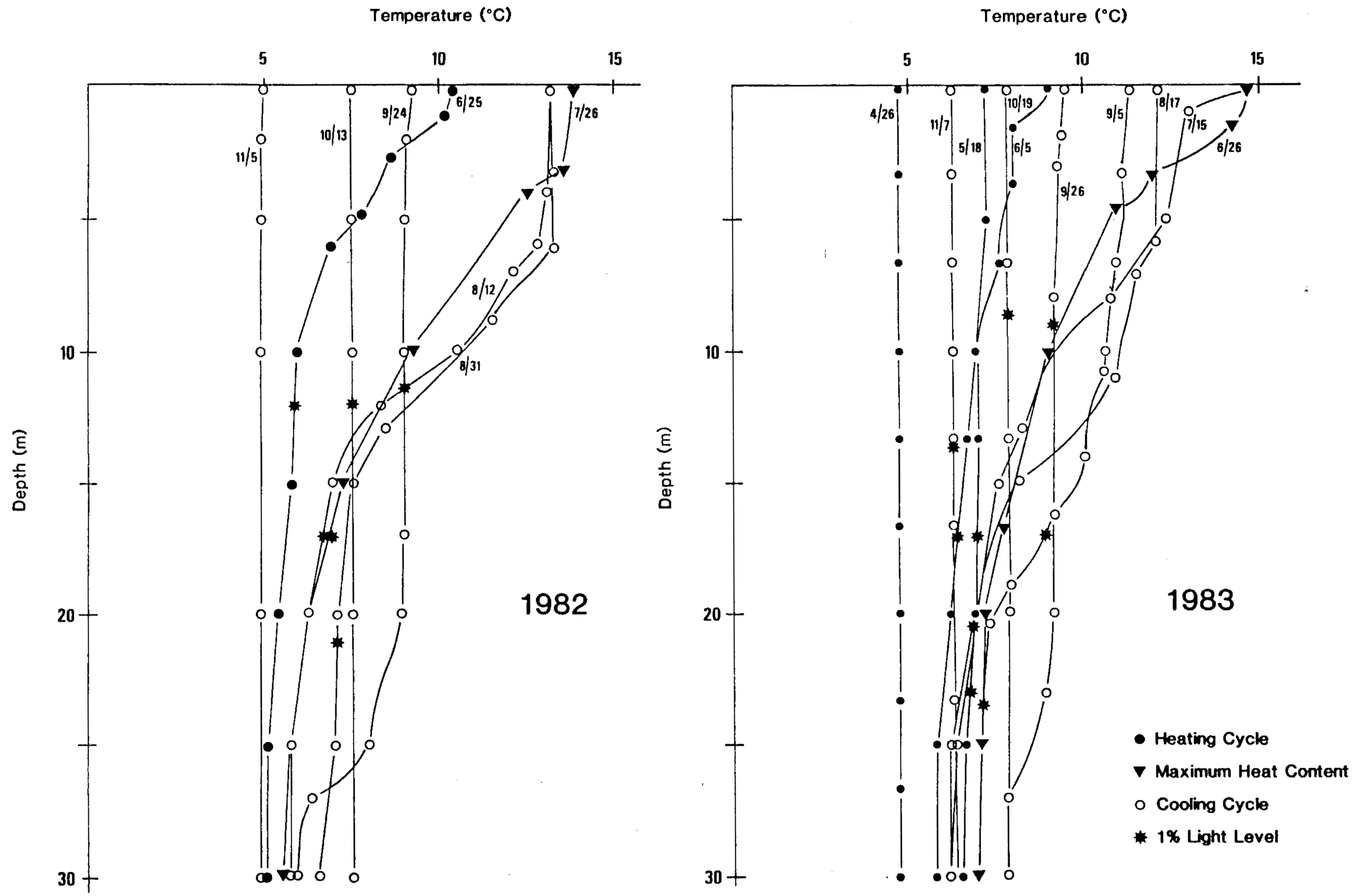

Figure 4. Temperature profiles within Lake Tokun at Station 2 for 1982 and 1983 showing the seasonal heating and cooling cycles, the location of the metalimnion, and the depth of the compensation point.

10 m by the end of July; surface temperatures reached nearly 14°C. After July, surface temperatures began to cool as the diel convection and wind-generated currents pushed the epilimnion down to 12 m by the end of August. At this time, the heat content of the lake reached a seasonal maximum, with surface temperatures peaking at just below 15°C and hypolimnetic temperatures rising to 8°C. Temperatures within the deeper layers increased still further as the lake mixed from the surface down to the bottom at Station 1 and to 26 m at Station 2. Three weeks later, the lake was holomictic at 7°C, cooling further to 5°C by the first week in November.

In 1983 we found essentially the same pattern that was observed in 1982 (Figures 3 and 4). That is, the lake began to heat as a homogeneous mass after iceout in the spring, reaching nearly 7°C by the middle of May. By the first week in June, the epilimnion began to form, exhibiting a stair-step pattern as episodic weather patterns established, deepened, and then dissipated any transient thermal structure that had begun to develop. However, by the end of June the surface layers had warmed to 14°C; maximal temperatures were achieved at 15°C by the middle of July. At this time a stable metalimnion had been established at 10 m, and the lake contained its maximal amount of heat. Later in August, the lake began to cool; the metalimnion was forced deeper into the lake, reaching 15m by the first week of September. By the end of September, the lake was homogeneous, mixing at an isothermal 9°C. Thereafter, isothermal conditions existed as the entire water mass cooled from 9°C to 6°C by November.

In general, we found that a stable metalimnion was established at 10 to 12 m during the summer period, while the light defined compensation point was at 13 to 30 m. Thus, autotrophic production was not necessarily limited to the epilimnion but could take place within a respectable proportion of the hypolimnion as well. Finally, we found Tokun Lake to be well mixed; however, a stable thermal structure existed from only the middle of June to the middle of September.

Dissolved Gases

The dissolved oxygen (D.O.) profiles at both stations were consistently high, both at the surface and within the hypolimnion (Table 2). Values (expressed as percent of saturation) ranged from 86% to 112% of saturation at the surface and from 77% to 107% of saturation within the hypolimnion (except for a 73% of saturation found at Station 2 on 7 November 1982). However, near the bottom of the lake, we observed definite reductions in oxygen saturation. For example, at the deeper Station 1, oxygen levels dropped to 36%, 32%, and 26% of saturation in August of 1981, 1982, and 1983, respectively. At the same time, Station 2 experienced a lowering of oxygen levels that were only to 61%, 74%, and 40% of saturation in 1981, 1982, and 1983, respectively. Thus, we observed that oxygen levels remained high within a considerable volume of the lake, even under the winter ice cover.

However, oxygen levels did sag near the bottom of the lake at the deeper sampling depth, but only during the late summer stagnation period.

General Water Quality Indicators

In general, water quality indicators were intermediate in magnitude (relative to Alaskan lakes statewide) and were very consistent in showing little variation in terms of both depth and time-related changes (Table 3). For example, in 1983 conductivity values ranged from 36 μmhos cm^{-1} to 48 μmhos cm^{-1} within the epilimnion and from 34 μmhos cm^{-1} to 48 μmhos cm^{-1} in the hypolimnion. In addition, conductivity levels averaged 45 μmhos cm^{-1} within the epilimnion (n=14) in 1982 and 45 μmhos cm^{-1} within the epilimnion (n=16) during 1983. Similarly, alkalinity levels were low to intermediate in value (relative to statewide concentrations); mean levels were 17 ppm (n=14) in the epilimnion and 18 ppm (n=14) within the hypolimnion in 1982 and

Table 2. Dissolved oxygen percent saturation levels for Stations 1 and 2 at Tokun Lake, 1981-1983.

Date	Station 1			Station 2		
	Depth			Depth		
	1 m	20 m	Bottom[1]	1 m	15 m	Bottom[1]
1981						
08/13	96	84	36	87	82	61
10/02	91	89	84	92	89	81
11/13	98	97	91	97	96	70
1982						
01/19	109	97	87	107	94	89
03/03	86	77	45	87	84	84
04/07	103	90	76	102	94	90
06/25	102	93	90	98	94	82
07/26	95	84	70	102	91	88
08/12	107	92	46	103	98	67
08/31	99	82	32	95	82	74
09/24	101	94	40	97	94	80
10/13	92	92	89	91	91	87
11/05	---	---	--	73	73	70
1983						
04/26	95	95	89	100	100	93
05/18	103	101	95	105	101	97
06/05	105	104	87	112	104	101
06/26	111	102	65	110	106	85
07/05	108	104	85	110	107	72
08/17	105	90	26	102	87	40
09/05	100	83	77	101	99	76
09/26	89	87	37	88	87	57
10/19	98	98	54	98	97	84
11/07	102	97	80	101	98	97

[1]Dissolved oxygen measurements collected 1.0 m above the lake bottom. At Station 1 the bottom varied from 21-30 meters, and at Station 2 the bottom varied from 18-26 meters.

Table 3. Summarized concentrations and/or units for general water quality parameters found for the epilimnion (1 m) and hypolimnion (14 - 20 m) within Tokun Lake in 1982 (n=14) and 1983 (n=16). Values cited are mean levels followed by the range of values found over the experimental period.

Parameter	1982 (June-November)		1983 (June-November)	
	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion
Conductivity (μmhos cm^{-1})	45(36-48)	44(34-48)	45(43-47)	46(44-48)
Alkalinity (mg L^{-1} as $CaCO_3$)	18(15-30)	17(15-20)	17(13-20)	17(14-24)
pH* (units)	7.2(7.0-7.4)	7.1(6.7-7.3)	7.1(6.6-7.3)	7.0(6.8-7.2)
Calcium (mg L^{-1})	6.8(5.2-7.7)	6.8(4.8-9.4)	6.9(5.8-10.1)	6.7(5.4-8.2)
Magnesium (mg L^{-1})	0.5(<0.3-1.9)	0.3(<0.3-0.6)	0.7(<0.3-2.1)	0.7(<0.3-1.5)
Iron (μg L^{-1})	26(10-47)	25(6-46)	24(<2-73)	28(<2-69)

*Simple mean of log values.

17 ppm lake wide in 1983. Calcium levels ranged from 4.8 to 9.4 ppm in 1982 and from 4.5 to 10.1 ppm in 1983, while magnesium was generally undetectable (i.e., <0.3 ppm); iron levels were within the range expected (15 ppb to 30 ppb) for oligotrophic clearwater lakes. Finally, pH levels were neutral to slightly acidic, ranging in unit values from 6.7 to 7.4 in 1982 and 6.6 to 7.3 in 1983.

Nutrient Cycles

The seasonal nutrient-concentration cycles of primary interest are inorganic nitrogen (ammonium and nitrate + nitrite), reactive silicon, reactive phosphorus, and total phosphorus (*see* Appendix B).

We found reactive-silicon (as Si) levels to fall within the median range for Alaskan lakes, ranging from 750 ppb to nearly 1,400 ppb during 1982 and centering on approximately 1,000 ppb during 1983 (Figure 5). From overwinter-high levels of nearly 1,400 ppb, silicon concentrations decreased during the 1982 spring-summer period to approximately 900 ppb; however, from early November 1982, when silicon concentrations were below 800 ppb, concentrations of reactive silicon never rebounded to the maximal levels found in November 1981 (over 1,200 ppb). Consequently, relatively low levels of silicon (1,000 ppb) were found by our first sampling (late in April of 1983.) Furthermore, from late April, through the summer, and into November of 1983, silicon concentrations remained virtually unchanged in both the epilimnion and the hypolimnion.

Inorganic nitrogen concentrations in 1981-82 showed two distinct patterns that were dependant upon form; i.e., nitrate versus ammonium. Nitrate concentrations followed that of reactive silicon; seasonally low values occured in the fall (<10 ppb) and spring (<2 ppb), and seasonally high levels occurred during the winter (70 ppb to 80 ppb).

Although we observed a seasonally distinct cycle involving nitrate nitrogen, concentrations of nitrate were consistently low (relative to other Alaskan lakes). Inorganic-nitrogen recharge appears to take place, in part; however, inlake regeneration of organic nitrogen, the primary vehicle of nitrogen input, appears to be that exported from the surrounding watershed. If watershed inputs decrease because of a lack of rainfall or the advent of a premature cold winter, nitrate levels would never rebound from summer lows. Apparently, such was the case during the fall of 1982, when November concentrations of nitrate rose to become slightly greater than 30 ppb; this amount was almost 1/3 less than that recorded in the fall of 1981. Consequently, the following spring (late April) levels of nitrate were undetectable within the epilimnion and the hypolimnion. Undetectable nitrate concentrations persisted throughout the summer, although slightly higher levels occurred during the spring and fall; the levels then rose slightly to approximately 20 ppb by the first week in November.

Ammonium concentrations were always low (<12 ppb) throughout 1981, 1982, and 1983; values were consistently below 5 ppb for all three years. The consistent features of the ammonium cycle within the hypolimnion and the epilimnion were the uniformly low levels and the slight fall increase in concentrations from summer minimums. Thus, even after combining both inorganic forms, levels of inorganic nitrogen were extremely low in Lake Tokun throughout the year.

Reactive phosphorus (FRP) concentrations generally cycled between 0.5 ppb (our detection limits) and 3.5 ppb; values usually (as in 1982 and 1983) centered around concentrations of 1.0 ppb to 2.0 ppb. Because of these consistently low values, seasonal cycles were hard to define; however, reactive phosphorus concentrations appeared to sag during the summer period (Figure 5). Because consistently low concentrations of reactive phosphorus make realistic trend analysis difficult and because phosphorus is rapidly cycled between the inorganic phase (lake water) and particulate phase (algae), total phosphorus levels are used here to indicate the level of biologically available phosphorus (Koenings et al. 1985b).

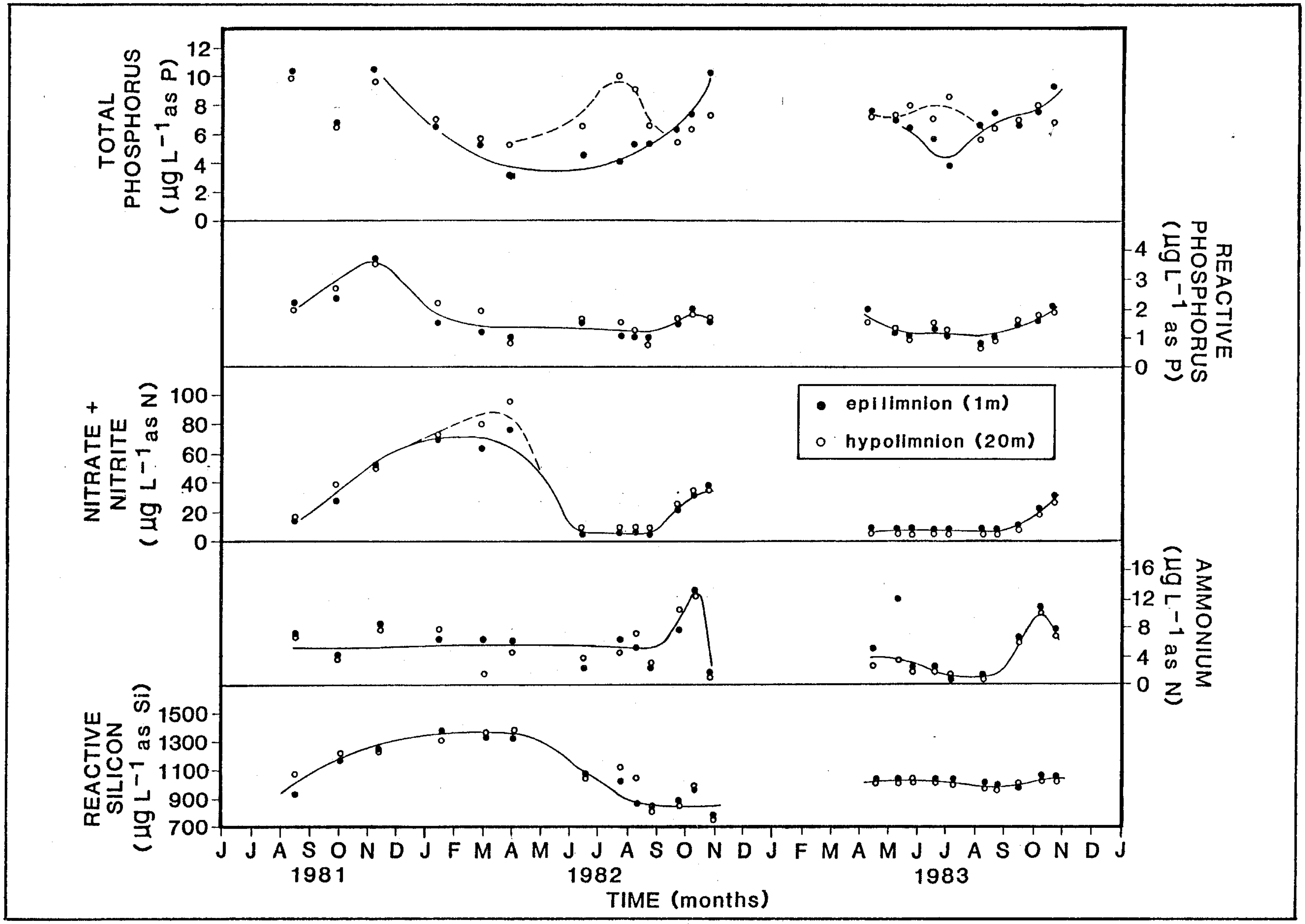

Figure 5. The seasonal cycle of essential nutrients within the epilimnion (1 m) and hypolimnion (20 m) at Station 1 in Lake Tokun during 1981, 1982, and 1983.

Total phosphorus (total-P) levels increased dramatically in mid-August of 1981 to over 20 ppb because of a heavy load of silt entering the lake as a result of heavy summer rains. After the silt settled, total-P levels dropped to 6-7 ppb, but during the subsequent fall overturn, total-P increased to 16 ppb and reactive P levels increased to 3.5 ppb, the highest concentration recorded for inorganic phosphate. Thereafter, total-P concentrations cycled between 3 and 10 ppb; generally higher values were found during the spring and fall overturn periods. However, distinct seasonal differences in total-P levels between the epilimnion and the hypolimnion were found in both 1982 and 1983. Epilimnetic total-P levels tended to decrease from higher spring concentrations and to reach seasonally low levels in July through August (Figure 5). In contrast, we found that hypolimnetic total-P levels increased from the spring period and reached seasonal maximal values in August (1982) and in July (1983).

As this vertical segregation in phosphorus concentrations was not observed in the FRP profiles, the cause of these differences must have involved the organic fraction. Indeed, we looked at FRP levels in both strata when the lake was thermally stratified, and we found little difference in FRP between the layers in either year. However, we did find consistent differences to exist between the layers in terms of filterable unreactive phosphorus (FUP); i.e., organic phosphorus in solution and particulate phosphorus (Figure 6). The FUP fraction dominated the phosphorus pool within the epilimnion, representing 61% (1982, n=4) and 60% (1983, n=5) of the total-P present. In contrast, FUP represented only 22% (1982, n=4) and 26% (1983, n=5) of the total-P present in the hypolimnion. Whereas FUP dominated the phosphorus pool within the epilimnion, part-P dominated the phosphorus contained within hypolimnion, representing 61% (1982, n=4) and 69% (1983, n=5) of total-P. In the epilimnion, part-P represented only 29% (1982, n=4) and 21% (1983, n=5) of the total-P pool. In addition, after thermal stratification broke down in the fall (e.g., 1982), part-P levels equalized in the lake at 51% (n=3) and 59% (n=3) of total-P within the upper (1 m) and the hypolimnetic

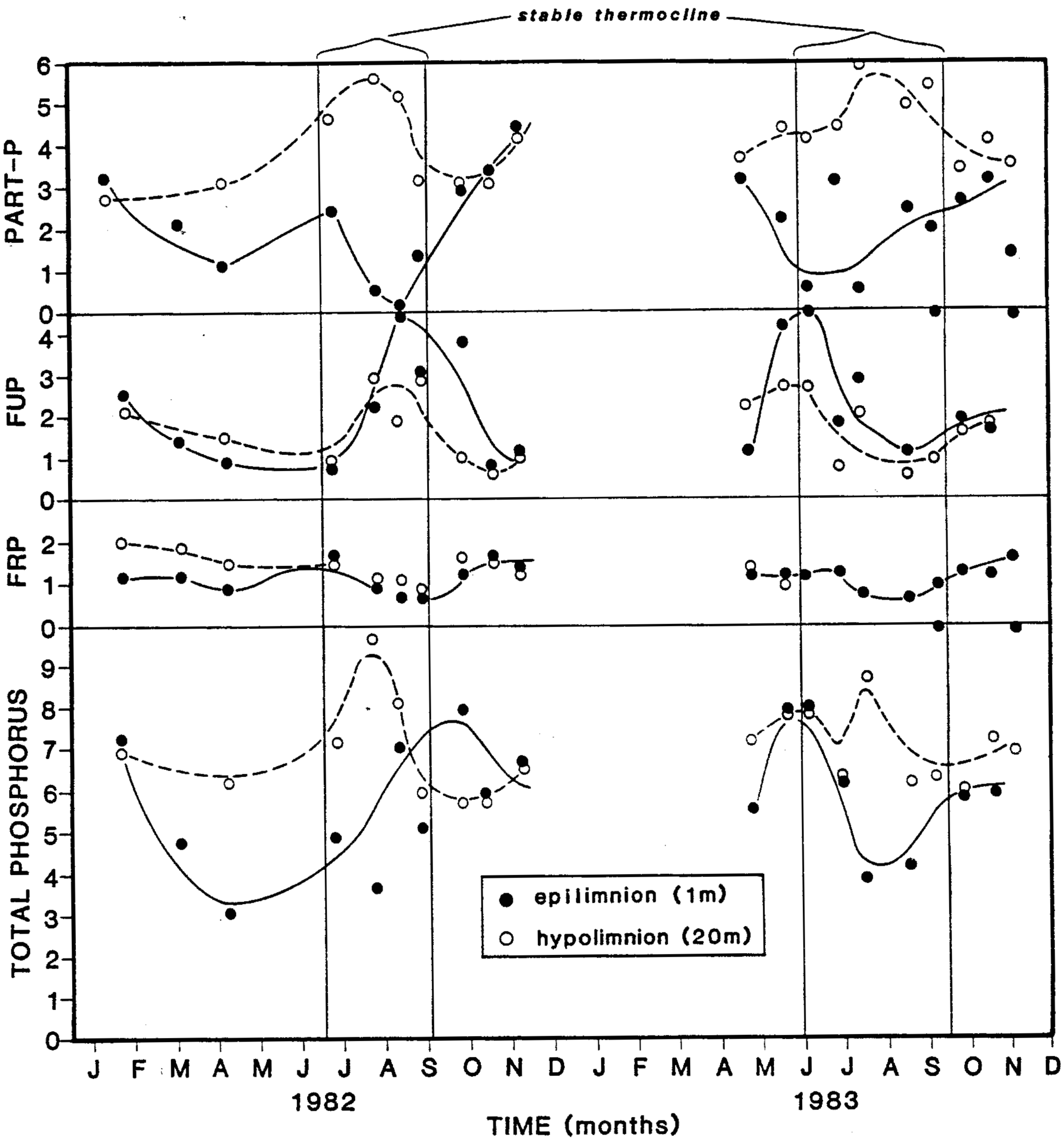

Figure 6. Changes in the magnitude of total phosphorus and its component fractions(namely,particulate [part-P], filterable unreactive phosphorus [FUP], and filterable reactive phosphorus [FRP]) within the epilimnion (1 m) and hypolimnion (20 m) at Station 1 of Tokun Lake during 1982 and 1983.

(20 m) strata. Thus, we observed that the epilimnetic phosphorus pool changed during the summer, decreasing in magnitude and exhibiting an enhancement in the FUP pool concommitant with a reduction in the part-P fraction. In contrast, within the hypolimnion, the part-P pool was enhanced; whereas, the FUP fraction remained fairly stable, resulting in a significant rise in total-P.

Nutrient Ratios

The ratio of inorganic nitrogen (nitrate/nitrite and ammonium) to total-P underwent considerable changes (Table 4). In addition, the seasonal variation was not limited to the epilimnion, because the hypolimnetic strata showed changes similar to those within the upper layers. Overall, the seasonal trends noted for both the epilimnion and the hypolimnion were similar at both sites.

In 1981 the lake was sampled only during the late summer and fall period, and we found that the initial inorganic nitrogen (IN): total-P ratio (by atoms) taken in August was very low at 2:1. Thereafter, as fall cooling progressed and the lake underwent overturn, the ratios equalized in all depths at approximately 14:1. In 1982 we were able to complete the seasonal pattern of IN:total-P changes; during the winter, the ratios increased dramatically under the ice, reaching 39:1 to 63:1 by early April. However, soon after ice-out, the atom ratios plummeted within the epilimnion and hypolimnion to values ranging from 7:1 to 1:1. These low nutrient ratios persisted until late September, when the lake began to overturn and the runoff increased dramatically from fall rains. As a consequence, the IN:total-P ratios rose to around 14:1, or to the level found in the fall of 1981.

During early spring in 1983, the nutrient ratios within the lake were extremely low; that is, either the nutrient regeneration/ input to the

Table 4. The ratio of inorganic nitrogen (ammonium + nitrate and nitrite) to total phosphorus (by atoms) within the epilimnion (1 m) and hypolimnion (20 m and 14 m) during 1982 and 1983 at Stations 1 and 2 respectively.

	Station 1		Station 2	
Date	1 m	20 m	1 m	14 m
1981				
08/14	2:1	2:1	2:1	2:1
10/02	13:1	13:1	14:1	13:1
11/13	6:1	14:1	14:1	14:1
1982				
01/19	24:1	24:1	27:1	25:1
03/03	32:1	--	27:1	31:1
04/07	63:1	39:1	50:1	47:1
06/25	2:1	5:1	1:1	2:1
07/26	2:1	3:1	7:1	1:1
08/12	2:1	4:1	3:1	1:1
08/31	1:1	3:1	2:1	1:1
09/24	7:1	13:1	10:1	14:1
10/13	17:1	15:1	9:1	14:1
11/05	12:1	12:1	--	10:1
1983				
04/26	3:1	3:1	2:1	2:1
05/18	6:1	1:1	1:1	1:1
06/05	<1:1	1:1	1:1	1:1
06/27	1:1	<1:1	1:1	1:1
07/15	<1:1	<1:1	<1:1	<1:1
08/17	<1:1	<1:1	<1:1	<1:1
09/05	<1:1	<1:1	<1:1	<1:1
09/26	5:1	5:1	3:1	3:1
10/19	10:1	8:1	6:1	6:1
11/07	6:1	10:1	11:1	10:1

lake during the winter was dramatically reduced or, by the time the lake was first sampled, the ratio had already been lowered by a combination of autochthonous production and low spring rainfall. Nonetheless, the ratios were exceptionally low throughout the summer and were consistently below 1:1 in both the epilimnion and hypolimnion from the end of June to the first week in September. However, by the end of September, the nutrient ratios rose only to 10:1, not 14:1; i.e., levels that were characteristic of the lake in the fall of both 1981 and 1982.

Algal Biomass

Seasonal changes in algal biomass were followed by pigment analysis for both chlorophyll *a* (chl *a*) and phaeophytin *a* concentrations within the epilimnion (1 m). As both Station 1 and Station 2 showed similar trends and concentrations of chl *a* (Table 5), averaged levels of chl *a* were used to describe the seasonal trends in the amount of algal standing crop.

In 1981 chl *a* increased from a mean level of 0.68 mg/m^3 in August to 1.14 mg/m^3 in October and then to a high of 1.56 mg/m^3 in November (Table 5). In 1982 we were able to define a complete seasonal cycle for the first time; spring and summer standing stocks of phytoplankton were below 0.90 mg/m^3 and 0.50 mg/m^3, respectively. The anticipated spring pulse in chl *a* was not evident; although we did see a slight rise in chl *a* at Station 1 on 7 April, a similar increase was not observed at Station 2. However, by the end of August, we observed a rise in chl *a* concentrations at Station 1 to 1.15 mg/m^3; this was followed by an increase to 1.45 mg/m^3 at Station 2 by the end of September. The concentration of chl *a* then peaked at both stations during November, reaching a mean level of 3.51 mg/m^3.

The seasonal pattern in chl *a* distribution established in 1982 was repeated in 1983 with one important addition. At the end of April, we

Table 5. The concentration of chlorophyll *a* (chl *a*) and phaeophytin, by date, within the epilimnion (1 m) of Lake Tokun at Stations 1 and 2 during 1981, 1982, and 1983.

	Station 1		Station 2	
Date	Chl a	Phaeophytin	Chl a	Phaeophytin
1981				
08/14	0.66	0.27	0.69	0.21
10/02	1.28	0.33	0.99	0.50
11/13	1.53	0.27	1.38	0.79
1982				
01/19	0.79	0.18	0.79	0.18
03/03	0.59	0.29	0.59	0.21
04/07	0.89	0.21	0.49	0.11
06/25	0.39	0.09	0.33	0.16
07/26	0.33	0.22	0.36	0.22
08/12	0.32	0.09	0.49	0.21
08/31	1.15	0.37	0.18	1.26
09/24	1.41	0.53	1.45	0.39
10/13	1.49	0.41	1.49	0.39
11/05	3.46	0.53	3.56	1.08
1983				
04/26	4.17	1.65	3.29	1.63
05/05	0.34	0.34	0.29	0.34
06/05	0.57	0.25	0.92	0.37
06/27	0.36	0.07	0.33	0.07
07/15	0.22	0.08	0.37	0.12
08/17	0.83	0.01	0.75	0.09
09/05	1.30	0.34	0.70	0.09
09/26	1.01	0.23	0.79	0.28
10/19	1.68	0.33	1.88	0.34
11/07	2.27	0.63	1.88	0.42

found a major pulse in chl a at both Station 1 (4.17 mg/m^3) and at Station 2 (3.29 mg/m^3). Either this was an unusual pulse in chl a or our sampling protocol in 1982 missed the spring pulse; i.e., the spring pulse could have occurred during most of April, all of May, and in much of June without being detected. However, following the April pulse, chl a levels dropped dramatically throughout the summer to concentrations similar to those found in 1982. As in 1982, August of 1983 brought increasing concentrations of chl a, which were initiated earlier in the year at Station 1 (mid-August) than at Station 2 (mid-October). Chl a concentrations subsequently peaked in early November, reaching 2.27 mg/m^3 at Station 1 and 1.88 mg/m^3 at Station 2. Finally, in August we compared chl a concentrations at the lower limits of the euphotic zone (well within the hypolimnion) to those at the top of the euphotic zone (within the epilimnion); the chl a content within the hypolimnion at 20 m equalled 1.68 mg/m^3, compared to 0.83 mg/m^3 at 1 m (Station 1); and it equalled 4.60 mg/m^3 at 14 m compared to 0.75 mg/m^3 at 1 m (Station 2).

Zooplankter Density and Body Size

The zooplankton community within the lake was represented by four species of macro-zooplankton and an equal number of rotifers (Tables 6 and 7). The macro-zooplankters consisted of three species of cladocerans; namely, the dominant *Daphnia longiremus*, the sub-dominent *Bosmina longirostris*, and the rare *Holopedium gibberum*. In addition to the cladocerans, we found two copepods, *Cyclops strenuus* and the apparently rare *Acanthocyclops vernalis*. *Acanthocyclops* appeared in the samples, but mature adults needed to fix the proportion of the species within the population were rare. Finally, the rotifers were represented by *Kellicottia longispina*, *Asplanchna* sp., *Conochiloides* sp., and the sporatically occurring *Keratella* sp.

In 1982 the macro-zooplankton community at both Stations 1 and 2 were

Table 6. Changes in the seasonal density (organisms/m^2) of zooplankters by taxa within Lake Tokun at Station 1 and Station 2 during 1982.

Station 1 Date (1982)	Number/m^2 1/19	3/03	4/07	6/25	7/26	8/12	8/31	9/24	10/13	11/05
Bosmina longirostris	6,369	1,035	279	306	1,070	10,252	54,061	142,118	136,844	--
Daphnia longiremis	92,676	73,806	85,868	33,622	392,257	472,491	724,522	530,653	254,075	--
Sub total (cladocera)	99,045	74,841	86,147	33,928	393,327	482,743	778,583	672,771	390,919	--
Cyclops strenuus										
(Anthoscyclops vernalis)	239	Rare	1,035	7,132	4,636	5,795	12,818	30,255	28,528	--
Sub total (copepod)	239	Rare	1,035	7,132	4,636	5,795	12,818	30,255	28,528	--
Total macro-zooplankton	99,284	74,841	87,182	41,060	397,963	488,538	791,401	703,026	419,447	--
Kellicottia longispina	2,627	9,037	2,229	4,076	16,760	40,117	148,806	39,809	345,899	--
Asplanchna sp.	11,386	2,787	2,150	18,340	369,791	919,575	360,032	121,020	225,994	--
Conochiloides sp.	--	1,035	120	2,038	2,140	5,795	72,453	21,099	173,841	--
Keratella sp.	--	--	--	--	--	1,337	1,672	--	1,337	--

Station 2 Date (1982)	Number/m^2 1/09	3/03	4/07	6/25	7/26	8/01	8/31	9/24	10/13	11/05
Bosmina longirostris	3,583	239	--	535	1,337	18,722	27,707	213,774	137,657	62,405
Daphnia longiremis	77,508	27,349	52,031	90,932	310,686	575,994	386,121	208,200	236,424	73,103
Holopedium gibberum	--	--	--	Rare	--	--	Rare	--	--	--
Sub total (cladocera)	81,091	27,588	52,031	91,467	312,023	594,716	413,828	421,974	374,081	135,508
Cyclops strenuus										
(Anthoscyclops vernalis)	1,075	Rare	120	3,923	--	1,872	12,739	23,885	29,598	4,457
Sub total (copepod)	1,075	Rare	120	3,923	--	1,872	12,739	23,885	29,598	4,457
Total macro-zooplankton	82,166	27,588	52,151	95,390	312,023	596,588	426,567	445,859	403,679	139,965
Kellicottia longispina	2,906	9,953	2,110	14,532	24,070	64,227	158,280	51,752	169,740	188,997
Asplanchna sp.	7,843	5,693	1,871	40,385	640,537	896,753	218,790	136,545	211,819	136,844
Conochiloides sp.	279	120	--	1,516	1,337	37,443	44,586	14,730	196,129	127,929
Keratella sp.	--	--	--	--	1,337	--	--	--	1,070	5,995
Other sp.	--	--	--	--	--	--	--	--	--	1,337

Table 7. Changes in the seasonal density (organisms/m2 of zooplankters by taxa within Lake Tokun at Station 1 and Station 2 during 1982.

Station 1	Number/m^2									
Date (1983)	4/26	5/18	6/05	6/27	7/15	8/17	9/05	9/26	10/19	11/07
Bosmina longirostris	--	637	1,656	8,380	154,674	168,046	110,100	80,029	80,235	40,652
Daphnia longiremus	4,840	7,361	26,108	70,785	336,093	595,962	727,904	635,634	471,154	346,969
Holopedium gibberum	179	701	--	535	10,252	15,155	4,458	--	Rare	--
Sub total (cladocera)	5,019	8,699	27,764	79,700	501,019	779,163	842,462	742,663	551,389	387,621
Cyclops strenuus										
(Acanthocyclops vernalis)	8,304	3,783	1,720	6,062	24,070	13,372	7,578	3,120	Rare	--
Sub total (copepod)	8,304	3,785	1,720	6,062	24,070	13,372	7,578	3,120	Rare	--
Total macro-zooplankton	13,323	12,482	29,484	85,762	525,089	792,535	850,040	724,783	551,389	387,621
Kellicottia longispina	19,206	41,608	67,499	95,746	127,930	65,079	20,950	71,320	84,692	88,080
Asplanchna sp.	6,113	15,448	76,223	138,538	362,838	270,123	89,150	80,235	145,759	80,948
Conochiloides sp.	4,585	22,186	76,223	50,459	28,082	162,252	276,363	299,986	221,536	82,018
Keratella sp.	153	344	1,019	2,496	--	4,457	--	2,674	3,120	4,992
Other sp.	77	186	4,203	7,132	2,674	--	--	--	--	1,070

Station 2	Number/m^2									
Date (1983)	4/26	5/18	6/05	6/27	7/15	8/17	9/05	9/26	10/19	11/07
Bosmina longirostris	255	1,528	2,738	15,512	31,292	40,920	122,135	110,099	41,722	33,342
Daphnia longiremis	3,414	6,113	26,363	74,886	196,842	386,997	267,448	532,221	388,245	275,650
Holopedium gibberum	77	382	--	--	6,152	7,221	4,457	--	--	--
Sub total (cladocera)	3,746	8,023	29,101	90,398	234,286	435,138	394,040	642,320	429,967	308,992
Cyclops strenuus										
(Acanthocyclops vernalis)	5,349	611	1,911	3,031	5,349	12,570	--	--	--	2,318
Sub total (copepod)	5,349	611	1,911	3,031	5,349	12,570	--	--	--	2,318
Total macro-zooplankton	9,095	8,634	31,012	93,429	239,635	447,708	394,040	642,320	429,967	311,310
Kellicottia longispina	19,689	35,647	42,282	98,064	134,527	65,792	41,455	89,150	118,747	55,986
Asplanchna sp.	8,737	21,281	50,497	187,748	270,123	120,352	89,150	59,285	106,534	60,087
Conochiloides sp.	3,414	18,607	50,752	40,296	24,873	131,050	105,642	254,076	162,876	32,094
Keratella sp.	77	1,261	637	1,248	--	803	1,337	--	3,655	2,853
Other sp.	179	382	2,738	--	--	--	1,337	--	--	--

numerically dominated by the cladoceran, *Daphnia longiremus*, followed by *Bosmina longirostris* and the copepod, *Cyclops strenuus* (Table 6).

Within the six-month open-water period of June through November, *Daphnia* represented 85% and 78% of the zooplankton enumerated at Station 1 and Station 2, respectively. At Station 1, *Daphnia* densities ranged from a low of $33,622/m^2$ in June to a high of $724,522/m^2$ in late August: a seasonal mean density of 401,270 (n=6). In comparison, *Bosmina* densities ranged from a low of $306/m^2$ in late June to a high of $142,118/m^2$ in late September: a mean density of $57,442/m^2$ (n=6). Finally, adult *Cyclops* densities ranged from a low of 4,636 in July to a high of $30,255/m^2$ in late September, which resulted in a mean density of 14,861 (n=6). Zooplankter densities at Station 2 were similar to those found at Station 1, except that *Daphnia* densities peaked at $575,994/m^2$ and averaged $268,780/m^2$ (n=7), or only 67% of the density found at Station 1. In contrast, *Bosmina* densities were slightly higher at Station 2; the densities of *Cyclops* were basically the same at both stations.

In 1983 (considering only the same time interval as in 1982) *Daphnia* densities represented 82% and 84% of the total organisms enumerated at Station 1 and Station 2, respectively (Table 6). At Station 1, *Daphnia* densities averaged $401,326/m^2$ (n=8); a peak density of $727,904/m^2$ occurred in early September. *Bosmina* densities averaged $80,472/m^2$ (n=8); a peak density of $168,046/m^2$ occurred in mid-August, while *Cyclops* densities peaked in mid-July at $24,070/m^2$ and averaged only $6,990/m^2$. At Station 2, *Daphnia* densities decreased more than at Station 1, averaging only $268,582/m^2$ (n=8); a subdued peak of $532,221/m^2$ occured at the end of September. Again, *Bosmina* densities followed those of *Daphnia*, averaging only $49,720/m^2$ (n=8); *Cyclops* densites were even lower, averaging $3,148/m^2$ (n=8).

Thus, we found that *Daphnia* population densities were very uniform between years at both stations, but consistent differences were found to exist within each year between the two stations; i.e., Station 2 contained fewer organisms per m^2 (based upon both seasonal averages and peak densities). *Bosmina* populations were somewhat more variable; peak and average densities varied between stations, yet seasonal mean densities for both years hovered between $50,000/m^2$ and $80,000/m^2$.

Cyclops densities proved to be the most variable; 1982 densities were 2 to 3 times those found in 1983, and again, as for *Daphnia* Station 1, contained within the same year a greater number of adults than Station 2.

In general, peak densities of the macro-zooplankton community occurred in the August and September period at both sites and during both years. However, when compared to an occurrence in 1982, we observed a major seasonal advance of the zooplankter density pulse in 1983. This increase was carried, in large part, by the earlier advance of *Bosmina* densities from the late-fall/early winter period in 1982 to the late-spring/early summer period of 1983.

Finally, *Daphnia* was not only the most numerous but also the largest zooplankter by body size within the zooplankton community (Table 8). In 1982 *Daphnia* ranged in body size from 0.61 to 0.88 mm and averaged 0.77 mm at Station 1; the body-size range was from 0.60 to 0.83mm (mean of 0.76 mm) at Station 2. In comparison, *Bosmina* exhibited a body size ranging from 0.35 to 0.44 mm; the average body size of 0.36 mm at Station 1 was virtually equivalent to that at Station 2. The body size of *Cyclops* was larger than that of *Bosmina*, averaging 0.61 mm and 0.62 mm at Stations 1 and 2, respectively. In 1983 both the mean body size and range of body sizes for *Bosmina* remained basically the same as in 1982. In contrast, we found that the mean body sizes and the range in sizes of *Cyclops* and *Daphnia* were lower in 1983 than in 1982. Specifically, whereas the largest body size for *Daphnia* approached 0.90 mm (0.88 mm and 0.83 mm at Stations 1 and 2, respectively) in 1982, the largest body sizes observed in 1983 were only 0.71 mm at

Table 8. The seasonal changes in body length (mm) of macro-zooplankters within Lake Tokun at Stations 1 and 2 during 1982 and 1983. Mean values by sample date are followed by seasonal mean values calculated by simple averaging and by weighting body lengths by the number of organisms within a sample date.

Station 1											Seasonal mean	
Date (1982)	1/19	3/03	4/07	6/25	7/26	8/12	8/31	9/24	10/13	11/05	Simple	Weighted
Bosmina longirostris	.44	.43	--	--	--	.39	.35	.35	.36	--	.39	.36
Daphnia longiremis	.72	.61	.62	.69	.88	.80	.76	.74	.71	--	.73	.77
Cyclops sp.	--	--	.61	.83	.86	.59	.55	.57	.59	--	.66	.61

Station 2											Seasonal mean	
Date (1982)	1/19	3/13	4/07	6/25	7/26	8/12	8/31	9/24	10/13	11/05	Simple	Weighted
Bosmina longirostris	.45	--	--	--	--	.38	.36	.35	.37	.40	.39	.37
Daphnia longiremis	.69	.60	.63	.80	.83	.77	.71	.66	.67	.62	.70	.76
Cyclops sp.	.51	--	--	.96	--	--	.54	.65	.60	.51	.63	.62

Station 1											Seasonal mean	
Date (1983)	4/26	5/18	6/05	6/27	7/15	8/17	9/05	9/26	10/19	11/07	Simple	Weighted
Bosmina longirostris	--	.37	.42	.35	.34	.34	.39	.42	.41	.41	.38	.37
Holopedium gibberum	--	.57	--	.82	.70	.83	--	--	--	--	.73	.77
Daphnia longiremis	.60	.65	.67	.71	.62	.67	.66	.62	.66	.62	.65	.65
Cyclops sp.	.59	.73	.67	.67	.51	.63	.57	--	--	--	.62	.58

Station 2											Seasonal mean	
Date (1983)	4/26	5/18	6/05	6/27	7/15	8/17	9/05	9/26	10/19	11/07	Simple	Weighted
Bosmina longirostris	.34	.38	.41	.39	.34	.39	.38	.41	.43	.43	.39	.40
Holopedium gibberum	--	--	--	--	.79	.91	.75	.65	.64	.66	.82	.83
Daphnia longiremis	.69	.66	.69	.71	.62	.62	.62	--	--	--	.66	.64
Cyclops sp.	.59	.65	.61	.58	.54	.53	.59	--	--	--	.58	.56

both stations. *Cyclops* followed, although to a lesser degree, the trend established by *Daphnia*. That is, while seasonal-mean body sizes of adult *Cyclops* in 1983 were only slightly smaller than those established in 1982, the maximal lengths (0.86 to 0.96 mm) observed in 1982 were reduced to only 0.65 to 0.73 mm in 1983.

DISCUSSION

Existing Limnetic Production Patterns

In order for nutrient enrichment to result in an increased survival and/or growth of rearing salmon juveniles, the rearing environment within the lake must be limiting to or at least restricting to successful smoltification. Specifically, the critical features or variables within the rearing equation that serve to reduce successful foraging by rearing fry must be altered or changed by the addition of nutrients. Thus, our prefertilization studies are designed to allow us to determine if altering the rearing environment by the addition of nutrients would result in a significantly increased probability of producing greater smolt biomass (McAllister et al. 1972).

Lake Tokun presently provides for the successful rearing of both sockeye and coho smolts (*see* Part I of this report); sockeye smolts numbered more than 350,000 in 1983 and approximately 600,000 in 1984. During the same period, coho smolts numbered under 10,000; so the indication is that the lake has tended to support a greater rearing density of sockeye juveniles than of coho. Thus, rearing conditions of primary interest are those that determine successful sockeye rearing; i.e., those of the open-water or pelagic region. One part of the rearing equation consists of in-lake temperature regimes, because biological activities, including growth and feeding, are related to temperature (Goodlad et al. 1974). That is, within limits, increased temperatures provide increased rearing capacity; fish are potentially able to forage over greater areas for an increased period of time and, during this period, can additionally metabolize food more efficiently. The winter of 1981-82 was one of the coldest winters on record; lake ice, under deep snow, was nearly 1 m in depth as late as early April. Consequently, ice-out was delayed until early June (compared to mid-April in 1983 and late April in 1984). Underneath the snow and ice, during the spring of 1982, primary production was low; chl a levels never exceeded 0.9 mg/m^3, nutrient ratios were high, and zooplankton densities were pauperate. Following ice-off, temperatures slowly began to rise, exceeding 10°C by the end of June. The chl a levels dropped as the lake began to flush with the heavy spring runoff from melting snow. In 1983, however, the ice was clear of the lake in mid-April, and chl a levels were greater than 3 mg/m^3 at Station 2 and even higher (>4 mg/m^3) at Station 1. In addition, in 1983 the lake had warmed to nearly 15°C by 26 June compared to just above 10°C by 25 June 1982. The lake contained its maximal amount of heat as early as 15 July in 1983 and as late as 31 August in 1982.

The greater temperature units within the lake in 1983 (compared to 1982) resulted from an early ice-off, which allowed the lake to absorb light for a greater time period, beginning with the rapidly increasing day-length period in April. As a consequence, algal populations bloomed by the end of April; this, in turn, allowed the herbivorous zooplankters to increase in density earlier in the year. For example, on 25 June 1982, *Bosmina* population densities equalled 306/m^2 at Station 1 and 535/m^2 at Station 2; *Daphnia* densities were equal to 33,000/m^2 and 91,000/m^2 at the same sites, respectively. In contrast, on 26 June 1983, *Bosmina* densities were 8,400 at Station 1 and 15,500 at Station 2; this was nearly 30 times the densities that were recorded at the same sites in 1982. Similarly, *Daphnia* densities on 26 June 1983 exceeded 70,000 at Station 1 and almost 75,000 at Station 2, which doubled the 1982 density at Station 1 but only comprised 80% of that at Station 2.

One of the interesting features of the zooplankton community during the winter of 1981-1982 was the presence of a large overwintering population of adult *Daphnia* that was not present during the same time period in 1982-1983, when the lake was ice free. It appears that the extended spring period of ice cover in 1982 not only reduced light penetration, which resulted in lower temperatures and lowered chl a levels, but it also resulted in higher zooplankton densities (relative to 1983). In the spring of 1983, the earlier ice-off conditions produced early warm temperatures, increased light, an early bloom in phytoplankton, and until the end of June, depressed densities of *Daphnia*. After considering the blooming algal populations in 1983, the cause of reduced densities of zooplankton in 1983 may have come from predation by rearing juveniles. Because of the dark and cold under the ice in 1982, visual predation would have been less successful and, thus, zooplankton densities would have remained high. As such, 1983 should prove to be a better rearing year for sockeye fry than 1982; and if equal numbers of rearing fry entering the lake were approximately the same in both years, the lake could produce more smolt biomass in the spring of 1984 than in the spring of 1983.

A second variable that powers autochthonous primary production within the growth equation is light energy. Compared to other sockeye nursery lakes, especially organically stained systems (e.g., Packers Lake), light penetration in Lake Tokun was extended beyond the depth of the metalimnion to include a substantial portion of the hypolimnion. Thus, the euphotic volume of this clear-water lake represented from 67% to 75% of the total lake volume, which is a substantially greater percentage than that of glacial or organically stained systems (Table 9). This feature adds to the potential of any clear-water lake to increase annual primary production (Oglesby 1977), since nutrient shortages and phytoplankton washouts associated with the epilimnion need not affect hypolimnetic populations of phytoplankton (Kiefer et al. 1972). Extremely low N:P ratios were observed within the hypolimnion and the epilimnion in 1982, indicating that the demand for nutrients by the plankton exceeded supply even within the hypolimnion (Schindler 1971b, 1977). A reduction in nutrient demand that occurred during the snowy, cold winter of 1981-1982 was probably responsible for the increased N:P ratios that were found in the lake prior to ice-out. However, the absence of light under the ice, which reduces algal demand for nutrients, was not present in the winter or spring of 1983; and, consequently, nutrient ratios that dropped early

Table 9. A comparison of the euphotic volume of sockeye rearing lakes throughout Alaska in relation to total lake volume, surface area, and water clarity.

Lake	Volume ($m^3 \times 10^{+6}$)	Lake type (water clarity)	Surface area ($m^2 \times 10^{+6}$)	Surface area (acres)	Water residence time (yr)	Light compensation level (m)	Euphotic volume ($m^3 \times 10^{+6}$)	Euphotic volume (% of total)
Trail Lakes	124	Glacial	8.1	1,754	0.19	0.5	3.6	3
Tustumena	37,000	Glacial	295.0	73,944	17.20	1.0	295.0	<1
Skilak	N.A.	Glacial	99.0	24,463	N.A.	1.5	148.5	<1(est.)
Kenai	N.A.	Glacial	56.0	13,837	N.A.	4.0	224.0	<1(est.)
Crescent	98	Semi-Glacial	3.3	805	0.2	8.0	26.4	27
Eklutna	512	Semi-Glacial	14.0	3,458	1.8	3.0	42.0	8
Ptarmigan	125	Semi-Glacial	3.0	750	1.1	6.0	15.6	17
Crescent	389	Semi-Glacial	16.2	4,002	0.3	5.5	89.1	23
Bakewell	67	Organic Stain	2.8	692	--	4.5	12.6	19
Hugh Smith	198*	Organic Stain	3.2	800	1.1	5.0	16.0	8
Packers	26	Organic Stain	2.1	519	3.0	4.0	8.4	32
McDonald	197	Organic Stain	4.2	1,035	0.7	7.5	31.5	16
Falls	30	Organic Stain	1.0	254	0.5	9.5	9.0	29
Bear	19	Clear	1.8	445	0.8	9.5	17.1	90
Hidden	138	Clear	6.8	1,680	11.2	15.0	102.0	74
Upper Russian	122	Clear	4.6	1,137	1.1	13.0	51.0	42
Karluk	1,920	Clear	39.0	9,637	6.0	20.0	780.0	41
Tokun	38	Clear	1.8	448	1.0	16.0	25.0	65
Eshamy	122	Clear	3.6	890	2.7	20.0	72.0	59
Leisure	23	Clear	1.1	259	0.3	18.0	19.8	86
Larson	29	Clear	1.8	445	1.7	9.5	17.1	59
Sea Lion Cove	0.32	Clear	0.08	19	0.3	6.9	0.26	80
Nunavauguluk	4,489	Clear	79.0	19,513	6.0	25.0	1,975	44
Cultus	201	Clear	6.3	1,550	N.A.	23.0	145	72

*Volume of the mixolimnion

in the spring never rebounded from the summer lows established in 1982.

A third variable of interest to efficient in-lake sockeye juvenile growth is nutrient loading, particularly that of phosphorus. Phosphorus loading has been linked to the degree (or magnitude) of algal production (Vollenweider 1976), to zooplankton (Dermott et al. 1977), and, ultimately, to fish yield (Hanson and Leggett 1982). Thus, an increase in phosphorus loading accompanied by nitrogen should result in the stimulation of primary production and then, in turn, to that of the secondary producers, the zooplankton.

In Lake Tokun we observed a definite sag in phosphorus levels during the open-water period beginning in late spring. At the same time, we found the amount of inorganic nitrogen to be less than that necessary to balance the uptake of phosphorus. In addition, chl a concentrations were very low during the summer season, and inorganic nutrient levels sagged in the face of warm-water temperatures and long periods of intense daylight. Zooplankters certainly contributed to the low-standing stock of algae because herbivorous forms dominated both the micro-and the macro-zooplankton community. Thus, a stimulation of primary production channeled into edible forms of algae could enhance the density of zooplankton, especially that of the cladocerans (*Daphnia longiremus* and *Bosmina longirostris*). While these organisms numerically dominated the macro-zooplankton, the mean body size of each was similar to that in Upper Russian Lake and Falls Lake, which are intensely grazed by rearing sockeye juveniles. In contrast, the body size is smaller than that found for the same species occurring in Hidden Lake, a sockeye-rearing but escapement-limited system. This provides some indication that the sockeye juveniles can utilize the zooplankton as forage; i.e., the zooplankters are being challenged by an effective planktivore (Brooks and Dodson 1965; Brooks 1968; Zaret 1980). Overall, the results indicate that additional loading of phosphorus (in combination with inorganic nitrogen) could lead to the stimulation of zooplankter biomass by increasing either the body size, the density, or both (LeBrasseur and Kennedy 1972). Finally, it is extremely important to assess the degree to which nutrient loading of the lake (nutrient type) either exceeds or falls below the demand exerted by the phytoplankton. For example, healthy nutrient demand typically follows the 106:16:1 ratio of carbon, nitrogen, and phosphorus atoms. If the inorganic nutrient ratios within the lake fall below these levels, algal demand will exceed supply, which may result in a change in algal species (Schindler 1971b; Barica et al. 1980). Such changes may have profound effects on zooplankter populations, because certain genera of algae are more edible or available as forage for herbivorous plankters (Porter 1975, 1977). The effects of either a less or more available food base on zooplankter densities and species composition (i.e., the quality and quantity of forage for rearing juveniles) are key factors influencing efficient juvenile growth.

Lake Tokun Nutrient Loading

The present loading of phosphorus into Lake Tokun equals 153 mg $P/m^2/yr$, compared to a critical loading rate of 420 mg $P/m^2/yr$ (Vollenweider 1976). Thus, the lake is currently at 36% of critical loading. The loading rate will be increased to 80% of critical loading (336 mg $P/m^2/yr$) and will require the yearly addition of 329 kg of phosphorus.

The inorganic fertilizer to be used is a special blend of a liquid product (27:7.6:0) containing 27% nitrogen, 7.6% phosphorus (as P_2O_5), and 0% potash with an atom N:P ratio of 18:1. The material weighs approximately 5.44 kg/gal (0.18 kg of phosphorus per gallon). Thus, we require 329 kg of phosphorus to be provided by the fertilizer; this equals 2,056 gallons of product in 28 gallon barrels; i.e., approximately 73 barrels of fertilizer.

Based on limnological studies, Lake Tokun has a stable thermal structure, coinciding with phosphorus depletion within the epilimnion and lasting from the first or second week of June until the first week in September (a period of only 11-12 weeks). Fertilization should begin after the first week of June and extend until at least the first of September (fertilization period of 12 weeks). Thus, there are approximately 85 days in which to add 73 barrels of fertilizer; i.e., one barrel per day.

During application of the product, the littoral zone should be avoided and the fertilizer confined to the east half of the lake (Station 2 [Figure 7]). The littoral zone and Station 1 should be left out of the immediate application zone. The product should be mixed with epilimnetic water at a water-to-fertilizer ratio of 80:1; it should be sprayed onto the surface of the lake, using a pump supplied with a spray bar.

Recommendations

1) Apply inorganic fertilizer (a high N:P atom ratio product) at a rate that will result in an increase in the phosphorus loading from 37% to 80% of critical.

2) Begin fertilizer addition no earlier than the first week in June and continue until the first part of September; i.e., fall overturn.

3) Closely monitor the inorganic nitrogen levels in order to either prevent an unfavorable lowering of the inorganic nitrogen:total-P ratio or to indicate the need to add pure nitrogen to the system.

4) Continue the detailed limnological and fisheries monitoring in order to assess the impact of the increased nutrient loading on the capacity of Lake Tokun to produce an increase in smolt biomass.

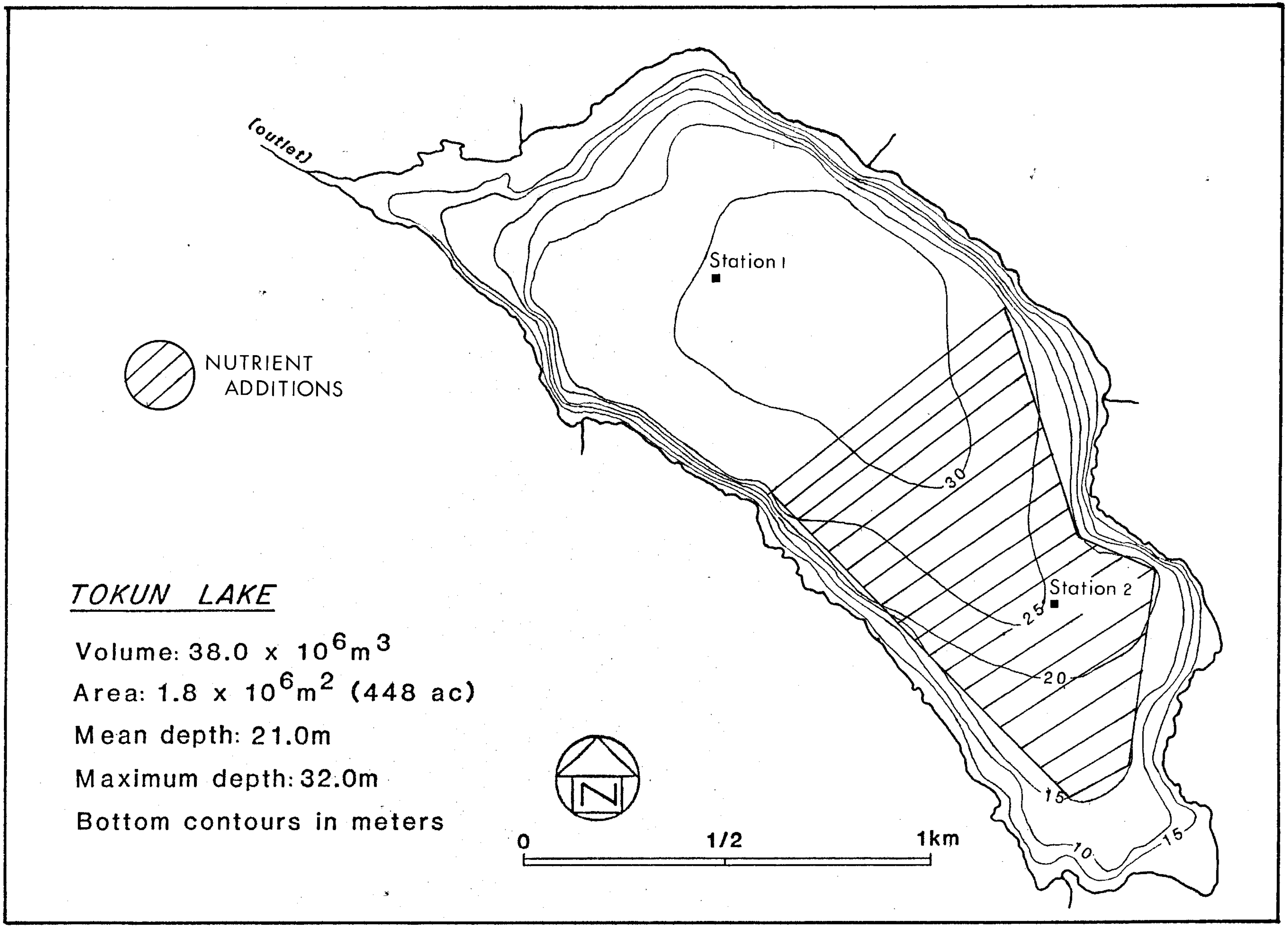

Figure 7. Morphometric map of Lake Tokun showing the recommended fertilizer application zone in relation to the location of the limnological sampling Stations 1 and 2.

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APPENDIX B

Appendix Table B-1. A summary of water quality analysis results within the epilimnion and hypolimnion of Tokun Lake during 1981, 1982, and 1983 at Stations 1 and 2.

Date	08/14/81				10/02/81				11/13/81			
Station	1		2		1		2		1		2	
Depth/Parameter	1 m	20 m	1 m	14 m	1 m	20 m	1 m	14 m	1 m	20 m	1 m	14 m
Conductivity (μmhos cm^{-1})	32	30	34	32	35	35	34	35	35	35	36	36
ph	6.3	6.1	6.3	6.3	6.7	6.8	6.7	6.7	6.3	6.2	6.4	6.6
Alkalinity (mg L^{-1} as $CaCO_3$)	13	13	13	13	14	14	14	14	16	18	16	18
Calcium (mg L^{-1})	7.2	7.2	7.2	7.2	1.6	1.6	3.4	6.0	6.7	5.0	6.2	5.4
Magnesium (mg L^{-1})	<0.3	<0.3	<0.3	<0.3	<0.3	2.9	<0.3	<0.3	<0.3	<0.3	<0.3	2.3
Iron (μg L^{-1})	344	504	330	472	42	37	23	27	29	29	28	28
Total Phosphorus (μg L^{-1} as P)	18.4	20.9	18.3	21.2	7.3	7.3	6.5	6.6	21.8	9.3	9.2	8.3
Total Filterable Phosphorus (μg L^{-1} as P)	4.6	3.0	7.5	5.3	7.7	7.6	4.2	3.3	16.2	4.4	4.0	3.0
Filterable Reactive Phosphorus (μg L^{-1} as P)	1.7	1.3	2.4	1.6	2.5	3.7	2.2	2.0	3.2	2.0	3.9	4.0
Nitrate + Nitrite (μg L^{-1} as N)	10	14	11	12	39	39	38	37	51	51	53	50
Ammonium (μg L^{-1} as N)	9	6	5	7	4	4	3	3	8	8	8	6
Reactive Silicon (μg L^{-1} as Si)	845	1,064	1,028	1,114	1,191	1,213	1,196	1,189	1,252	1,259	1,245	1,242

Appendix Table B-1 (continued)

Date	06/25/82				07/26/82				08/12/82			
Station	1		2		1		2		1		2	
Depth/Parameter	1 m	14 m	1 m	12 m	1 m	20 m	1 m	14 m	1 m	20 m	1 m	14 m
Conductivity (μmhos cm^{-1})	36	34	36	35	48	46	46	48	48	47	47	46
pH	7.2	7.2	7.3	7.2	7.1	6.9	7.0	7.2	7.2	7.0	7.0	7.0
Alkalinity (mg L^{-1} as $CaCO_3$)	15	15	15	15	20	20	20	20	20	20	20	20
Calcium (mg L^{-1})	5.5	4.8	5.2	5.5	6.5	6.5	6.9	7.4	6.9	6.5	6.4	5.9
Magnesium (mg L^{-1})	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.6	<0.3
Iron (μg L^{-1})	26	37	10	6	23	24	20	23	22	26	19	20
Total Phosphorus (μg L^{-1} as P)	4.8	7.0	4.1	6.0	3.6	9.6	4.4	10.4	7.0	8.0	3.4	10.9
Total Filterable Phosphorus (μg L^{-1} as P)	2.4	2.4	1.9	1.7	3.1	4.0	3.6	6.2	7.1	2.9	2.9	3.0
Filterable Reactive Phosphorus (μg L^{-1} as P)	1.6	1.4	1.3	1.4	0.9	1.1	0.9	1.6	0.6	1.0	0.9	1.4
Nitrate + Nitrite (μg L^{-1} as N)	2	12	<2	2	<2	7	4	2	<2	7	<2	<2
Ammonium (μg L^{-1} as N)	2	3	2	4	3	5	10	4	5	8	4	6
Reactive Silicon (μg L^{-1} as Si)	1,113	1,138	1,076	1,047	1,012	1,208	1,008	1,002	942	1,146	961	918

Appendix Table B-1 (continued)

Date	01/19/82				03/03/82				04/07/82			
Station	1		2		1		2		1		2	
Depth/Parameter	2 m	20 m	2 m	14 m	2 m	20 m	2 m	20 m	2 m	20 m	2 m	14 m
Conductivity (μmhos cm^{-1})	36	38	37	39	39	41	40	40	40	42	40	40
pH	6.8	6.8	6.8	6.8	6.9	6.8	6.7	6.7	7.2	7.2	7.2	7.2
Alkalinity (mg L^{-1} as $CaCO_3$)	17	17	16	16	16	16	16	16	15	17	15	16
Calcium (mg L^{-1})	6.3	5.4	7.2	8.1	5.7	6.2	6.2	6.2	7.2	7.2	6.4	6.8
Magnesium (mg L^{-1})	<0.3	0.9	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Iron (μg L^{-1})	6	30	8	31	8	39	30	16	16	64	26	29
Total Phosphorus (μg L^{-1} as P)	7.1	6.9	5.8	7.1	4.7	--	5.5	5.6	3.0	6.1	3.1	4.2
Total Filterable Phosphorus (μg L^{-1} as P)	3.7	4.2	3.7	3.2	2.5	--	3.5	3.1	1.8	3.0	2.2	2.2
Filterable Reactive Phosphorus (μg L^{-1} as P)	1.2	1.9	1.8	2.6	1.1	1.9	1.1	1.7	0.9	1.5	0.9	0.6
Nitrate + Nitrite (μg L^{-1} as N)	68	69	68	72	61	78	62	78	82	102	71	86
Ammonium (μg L^{-1} as N)	8	8	4	7	7	1	5	2	7	6	5	3
Reactive Silicon (μg L^{-1} as Si)	1,238	1,291	1,534	1,314	1,303	1,391	1,334	1,338	1,327	1,443	1,303	1,327

Appendix Table B-1 (continued)

Date	08/31/82				09/24/82				10/13/82				11/05/82			
Station	1		2		1		2		1		2		1		2	
Depth/Parameter	1 m	20 m	1 m	14 m	1 m	20 m	1 m	14 m	1 m	23 m	1 m	15 m	1 m	23 m	1 m	15 m
Conductivity (μmhos cm^{-1})	48	47	48	47	44	44	46	45	45	45	45	45	44	46	47	46
pH	7.1	6.7	7.1	6.9	7.3	7.1	7.3	7.3	7.4	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Alkalinity (mg L^{-1} as $CaCO_3$)	16	16	16	16	16	16	17	16	16	16	16	16	20	18	20	20
Calcium (mg L^{-1})	7.4	9.4	6.9	6.1	6.8	6.8	7.7	6.8	7.7	6.3	6.8	7.7	7.5	8.3	7.1	6.7
Magnesium (mg L^{-1})	<0.3	<0.3	<0.3	<0.3	0.9	<0.3	<0.3	0.6	<0.3	<0.3	1.9	<0.3	<0.3	<0.3	<0.3	<0.3
Iron (μg L^{-1})	42	35	38	9	21	46	18	22	12	14	47	16	35	40	32	26
Total Phosphorus (μg L^{-1} as P)	5.0	5.9	5.4	7.2	7.9	5.6	5.6	4.9	5.7	5.4	8.2	6.5	6.5	6.7	16.3	7.9
Total Filterable Phosphorus (μg L^{-1} as P)	3.6	2.9	3.4	4.0	5.0	2.6	2.9	1.9	2.4	2.4	5.0	2.9	2.7	2.3	14.3	3.9
Filterable Reactive Phosphorus (μg L^{-1} as P)	0.6	0.6	0.9	0.6	1.3	1.6	1.5	1.4	1.6	1.6	1.8	1.7	1.4	1.3	1.4	1.5
Nitrate + Nitrite (μg L^{-1} as N)	<2	5	2	<2	15	21	18	22	31	25	23	30	34	33	37	33
Ammonium (μg L^{-1} as N)	2	3	2	2	8	12	7	8	14	11	11	11	1	3	2	2
Reactive Silicon (μg L^{-1} as Si)	954	834	741	794	871	833	916	937	951	957	960	968	746	733	749	724

Appendix Table B-1 (continued)

Date	04/26/83				05/18/83				06/05/83			
Station	1		2		1		2		1		2	
Depth/Parameter	1 m	23 m	1 m	15 m	1 m	23 m	1 m	15 m	1 m	20 m	1 m	16 m
Conductivity (μmhos cm^{-1})	43	48	47	47	48	49	49	44	47	47	47	46
pH	6.7	6.8	6.6	6.6	7.0	6.5	6.8	6.6	6.6	6.8	6.8	6.8
Alkalinity (mg L^{-1} as $CaCO_3$)	20	20	20	20	19	19	21	21	20	24	20	20
Calcium (mg L^{-1})	8.2	8.2	7.7	8.2	8.2	8.2	8.2	8.2	8.2	7.7	8.2	8.2
Magnesium (mg L^{-1})	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Iron (μg L^{-1})	91	35	27	46	26	--	20	--	20	34	16	20
Total Phosphorus (μg L^{-1} as P)	5.5	7.1	9.7	7.2	7.8	7.8	5.9	6.4	7.9	7.7	4.4	8.1
Total Filterable Phosphorus (μg L^{-1} as P)	2.3	3.5	6.0	4.2	5.5	3.5	2.9	2.8	7.4	3.5	2.6	3.4
Filterable Reactive Phosphorus (μg L^{-1} as P)	1.2	1.3	2.2	1.4	1.3	0.9	0.7	1.0	1.1	0.9	0.7	0.9
Nitrate + Nitrite (μg L^{-1} as N)	3	5	4	4	<2	<2	<2	<2	<2	<2	<2	<2
Ammonium (μg L^{-1} as N)	4	3	6	2	21	3	2	2	1	2	2	2
Reactive Silicon (μg L^{-1} as Si)	1,024	1,006	996	1,015	1,041	1,083	1,036	998	1,046	1,046	1,054	1,028

Appendix Table B-1 (continued)

Date	06/27/83				07/15/83				08/17/83			
Station	1		2		1		2		1		2	
Depth/Parameter	1 m	20 m	1 m	16 m	1 m	20 m	1 m	16 m	1 m	20 m	1 m	16 m
Conductivity (μmhos cm^{-1})	46	46	47	46	43	46	46	46	42	44	46	45
pH	7.3	7.2	6.9	7.2	7.3	7.2	7.3	7.2	7.3	7.0	7.2	7.0
Alkalinity (mg L^{-1} as $CaCO_3$)	17	17	20	14	16	16	16	16	17	17	17	16
Calcium (mg L^{-1})	9.1	8.1	10.1	7.1	6.7	7.1	7.1	7.1	6.0	5.5	6.5	6.5
Magnesium (mg L^{-1})	<0.3	<0.3	<0.3	<0.3	0.5	0.8	0.5	0.5	1.5	1.5	1.2	<0.3
Iron (μg L^{-1})	16	7	5	31	7	7	18	15	<2	<2	<2	<2
Total Phosphorus (μg L^{-1} as P)	6.0	6.3	4.9	7.5	3.9	8.6	3.7	8.0	4.2	6.2	9.1	5.0
Total Filterable Phosphorus (μg L^{-1} as P)	2.9	1.9	1.9	2.2	3.4	2.8	1.8	1.9	1.8	1.3	0.4	1.4
Filterable Reactive Phosphorus (μg L^{-1} as P)	1.2	1.1	1.1	1.4	0.7	0.8	0.7	1.1	0.6	0.7	0.7	0.6
Nitrate + Nitrite (μg L^{-1} as N)	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Ammonium (μg L^{-1} as N)	2	1	2	2	<0.5	<0.5	<0.5	2	<0.5	<0.5	<0.5	<0.5
Reactive Silicon (μg L^{-1} as Si)	1,006	1,028	1,021	--	1,015	988	1,005	998	996	964	1,008	976

Appendix Table B-1 (continued)

Date	09/05/83				09/26/83				10/19/83				11/07/83			
Station	1		2		1		2		1		2		1		2	
Depth/Parameter	1 m	20 m	1 m	16 m	1 m	20 m	1 m	16 m	1 m	20 m	1 m	16 m	1 m	20 m	1 m	16 m
Conductivity (μmhos cm^{-1})	46	48	47	45	44	45	45	45	45	45	45	46	45	45	45	45
pH	7.2	7.1	7.0	7.1	7.0	6.9	6.9	6.9	6.9	7.0	6.9	7.0	7.1	7.1	7.1	7.1
Alkalinity (mg L^{-1} as $CaCO_3$)	17	17	15	17	13	17	16	15	16	16	16	17	17	15	16	16
Calcium (mg L^{-1})	6.0	6.5	6.9	6.0	5.8	5.8	5.8	5.4	5.8	5.8	6.5	6.9	6.5	7.4	6.5	6.5
Magnesium (mg L^{-1})	2.1	1.5	<0.3	1.2	0.8	1.1	1.3	1.3	0.5	0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Iron (μg L^{-1})	<2	<2	<2	<2	46	44	42	47	69	67	73	69	34	44	35	35
Total Phosphorus (μg L^{-1} as P)	10.5	4.8	4.2	7.8	5.7	5.8	7.0	7.5	5.9	7.3	8.3	8.3	11.9	6.8	6.2	6.5
Total Filterable Phosphorus (μg L^{-1} as P)	8.5	1.4	1.4	2.3	3.1	2.9	4.6	2.8	2.8	3.1	5.0	2.8	10.5	3.3	3.2	2.2
Filterable Reactive Phosphorus (μg L^{-1} as P)	0.9	0.5	0.7	1.1	1.3	1.4	1.3	1.4	1.2	1.5	1.4	1.3	1.6	1.7	2.3	1.7
Nitrate + Nitrite (μg L^{-1} as N)	<2	<2	<2	<2	6	6	5	5	18	16	16	16	23	24	25	25
Ammonium (μg L^{-1} as N)	<0.5	<0.5	<2	<2	6	6	6	6	9	9	8	7	7	7	7	5
Reactive Silicon (μg L^{-1} as Si)	1,001	992	964	945	947	988	958	965	1,056	1,060	1,057	1,054	1,083	1,092	1,088	1,083