FRED Reports

BEAR LAKE NUTRIENT ENHANCEMENT
(PRE-FERTILIZATION) REPORT
by
Gary B. Kyle, (Part I)
J.P. Koenings, (Part II)
Number 15

Alaska Department of Fish & Game
Division of Fisheries Rehabilitation,
Enhancement and Development

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ABSTRACT

Bear Lake has undergone detailed limnological investigations since 1979 to determine if this lake is a suitable candidate for a nutrient enrichment program. The fisheries data has been summarized in Part I of this report and contains data since the inception of the Bear Lake coho salmon program in 1963. Part II summarizes the water quality and pelagic productivity of Bear Lake.

At present, Bear Lake is in a transitional state between an oligotrophic and mesotrophic system and as such is considered a phosphorus-rich system. Consequently, the N:P atom ratio must be raised to increase the competitive advantage of non blue-green algal species. This would result in a more productive capacity of the lake by providing more edible species of phytoplankton for the zooplankton such as the green and diatom species.

The recommendations for this lake are to increase the supply of nitrogen by application of a nitrate-ammonium fertilizer and to limit the loading of phosphorus to minimum levels.

INTRODUCTION

This report is designed primarily to summarize sockeye and coho production in the Bear Lake system. Major emphasis is directed toward such salmon production data as origin of stocks, smolt and adult production, size, and age of fish produced. The effects of the 1963 and 1971 lake rehabilitation on subsequent coho fingerling releases, and to a lesser extent, on sockeye productivity, are discussed.

Bear Lake (180 hectares or 445 acres) is the largest stable body of clear fresh water in the Resurrection River drainage. Since 1961, the Resurrection Bay coho sport fishery has developed into the largest marine sport fishery for the species in Alaska (McHenry 1978). In 1963 the Sport Fish Division (ADF&G) decided to rehabilitate Bear Lake with rotenone to eradicate its predator and competitor fish species. Without predation and interspecific competition, it was believed that through annual coho fingerling releases, coho smolt production could be increased and that adult returns would increase to satisfy the growing angler demand.

Before the 1963 rehabilitation, upstream and downstream fish migrations were monitored by a temporary weir located in lower Bear Creek. Annual upstream migrations averaged 921 adult coho (1961-1964), 4,801 adult sockeye (1961-1965), and 10,543 Dolly Varden (1961-1962). Downstream migrations (1962-1963) averaged 5,421 coho smolts, 51,232 sockeye smolts, and 17,838 Dolly Varden. Threespine stickleback were not counted at the temporary weir, but beach seining in Bear Lake indicated this specie was abundant. Table 1 lists fish species present in the Bear Lake drainage.

Following detoxification of the lake, the first stocking of Bear Lake with coho fingerlings took place in November and December of 1963. Coho fingerling releases continued until 1968, afterwhich the second Bear Lake rehabilitation was planned and conducted. Following the 1971 lake rehabilitation, fingerling releases resumed and are currently being conducted.

The 1964 earthquake destroyed the outlet dam in Bear Creek which allowed unobstructed entry of all fish migrating upstream into Bear Lake. Following the earthquake, Bear Lake gradually became reinfested with a considerable population of threespine stickleback. It is not known whether the reinfestation was caused by the destruction of the Bear Lake dam or by insufficient rotenone treatment. The take-over of the rearing environment by stickleback apparently decreased coho and sockeye smolt production and size, and also changed the age structure from age-1 to predominantly age-2.

Before the rapid expansion of the stickleback population, salmonid smolt production in Bear Lake increased several fold as a result of favorable rearing conditions during 1964-1966. This smolt production increased abundances of adult sockeye by 11 times and coho by 3.5 times after rehabilitation. Specifically, coho smolt biomass production attained 4.2 kg for each kg of fingerlings released in 1964. Smolt survival from

Table 1. List of fish species present in the Bear Lake drainage*.

Common Name	Scientific Name
Dolly Varden	*Salvelinus malma*
Rainbow-steelhead trout	*Salmo gairdneri*
Sockeye salmon	*Oncorhynchus nerka*
Coho salmon	*Oncorhynchus kisutch*
Chum salmon	*Oncorhynchus keta*
Pink salmon	*Oncorhynchus gorbuscha*
Threespine stickleback	*Gasterosteus aculeatus*
Prickly sculpin	*Cottus asper*
Coastrange sculpin	*Cottus aleuticus*
Slimy sculpin	*Cottus cognatus*

* Taken from Logan and McHenry (1973).

stocked coho fingerlings in Bear Lake was 43.5% and 48.1% from the 1964 and 1965 releases, respectively. Correspondingly, smolt to adult survivals from the 1964 and 1965 releases were 13.7% and 17.4%, respectively. After 1967, coho fingerling releases were terminated (until 1972) because of poor smolt production which was due presumably to the increasing stickleback population.

Bear Lake was rehabilitated again in 1971, primarily to eradicate the excessive population of stickleback. The lake remained toxic throughout the winter of 1971-1972 and finally detoxified shortly after the spring overturn. Coho fingerling releases resumed in 1972 at stocking densities thought to be conservative. During 1972-1975, Bear Lake was stocked at densities ranging from 2,461-2,503 per surface hectare. As a result of these stocking densities, intense intraspecific competition among fingerlings occurred, causing depressed growth rates, lowered survivals, and extended rearing to smoltification. Thus, it appears that the cumulative effect of stocking Bear Lake at these densities resulted in overtaxing the rearing capacity. Since 1976, Bear Lake has been stocked at approximately one-half the 1972-1975 densities (1,247-1,265 per surface hectare) to prevent overcrowding of the rearing area.

The selection of coho brood stocks used after the initial (1963) lake rehabilitation was limited to sources most readily available. The brood stocks used during the 1963-1967 fingerling releases included Bear Creek, Dairy Creek-Seward Lagoon, Ketchikan Creek-Southeast Alaska, Swanson River-Kenai Peninsula, Pasagshak River-Kodiak, and one out-of-state stock from Big Creek, Oregon. Following the 1971 lake rehabilitation, most of the fingerling releases have been from Bear Lake, except during 1973 and 1974 when brood stock from Kodiak was used.

In 1966, coho smolt releases in the Resurrection Bay area were initiated for the purpose of increasing adult returns for the demanding marine sport fishery. Coho smolts have been and currently are being released in Seward Lagoon, lower Bear Creek and Grouse Lake. Total adult returns for these smolt release sites have attained 15.1% for Seward Lagoon, 6.1% for lower Bear Creek, and 7.8% from smolts released in Grouse Lake.

Brood stocks used in the coho smolt release program at Seward Lagoon, lower Bear Creek and Grouse Lake were of Bear Lake origin, except for the following: Kodiak brood stock was used in 1970 and 1972 at Seward Lagoon and in 1970 at lower Bear Creek, the Big Creek, Oregon brood stock was used in the 1968 and 1969 releases at Seward Lagoon and in the 1969 release at lower Bear Creek. All smolt releases in Grouse Lake were of Bear Lake system origin.

SOCKEYE SALMON PRODUCTION

Post 1963 Lake Rehabilitation

Following the 1963 lake rehabilitation, sockeye salmon smolt production dramatically increased. In 1964, 1,287,471 smolts migrated from Bear Lake, which represented a 15.2% potential egg-to-smolt survival (Table 2). As previously noted, these fish were reared in Bear Lake during the time of low stickleback abundance. Age-1 smolt size increased from a mean of 63.5 mm in 1962-1963 to 120.3 mm in 1965 and 82.0 mm in 1966. Concurrently, the age structure of these smolts changed predominantly from age-2 to age-1 (Table 2). In addition, adult production peaked as a result of the 1963 and 1964 brood years with respective smolt to adult survivals of 23.3% and 19.6% (Table 2). Total sockeye salmon adult returns from one life cycle before the 1963 rehabilitation averaged 4,801 (1961-1965) fish. After lake rehabilitation, the mean adult return increased to 53,527 sockeye salmon for the next life cycle (1966-1970). Thus, adult production following the 1963 lake rehabilitation increased to the point that commercial and subsistence fisheries were opened in Resurrection Bay. Catches in 1968 and 1969 reached 74,473 and 99,859 adult sockeye, respectively (Table 3).

However, after 1967, sockeye smolt production began showing a marked decline in abundance, size and percentage of age-1 smolts. By 1969, sockeye smolt production was lower than that measured before rehabilitation. Smolt mean length decreased from 120.3 mm to 66.3 mm for age-1 fish. Similarly, the age structure had reverted to age-2 smolts becoming more prevalent.

As a result of decreased smolt production, total adult returns also decreased dramatically (Table 3). The 1971 and 1972 returns of 2,520 and 803 sockeye salmon, respectively, were much lower than those measured before rehabilitation.

Consequently, because of the above trends, Sport Fish Division decided in 1970 that Bear Lake should be rehabilitated again if high salmon production was ever to be achieved. In 1971, Bear Lake was rotenoned to reclaim the juvenile salmon rearing potential.

Post 1971 Lake Rehabilitation

Following the 1971 rehabilitation and detoxification of Bear Lake, the largest coho salmon fingerling release (450,000) was conducted. In subsequent years (1971-1974), coho fingerling releases averaged 450,000 per year for a total release of 1.8 million coho fingerlings.

It is believed that the cumulative effects of the high coho salmon fingerling stocking densities and the declining adult sockeye returns resulting from poor rearing conditions (stickleback take-over after 1967), caused sockeye production to remain depressed following the 1971 Bear Lake rehabilitation. For example, potential egg-to-smolt survival rates for sockeye after the 1971 lake rehabilitation never surpassed 1.0% (Table 2).

Table 2. Summary of sockeye salmon smolt production following the 1963 and 1971 Bear Lake rehabilitation.

Brood Year	Potential Egg Deposition	Smolt Production			Smolt Age Composition %			Smolt Mean Length (mm)			Adult Production	
		Number	No./ha	% Survival	1	2	3	1	2	3	Total Number	Smolt to Adult Survival (%)
1963	12,216,340	23,378	129.9	0.19	52.4	47.6		120.3	151.8		5,456	23.3
1964	8,484,320	1,287,477	7,152.7	15.17	85.6	14.4		82.0	101.6		252,110	19.6
1965	6,425,820	95,456	530.3	1.49	71.8	28.2		90.6	96.3		7,266	7.6
1966	3,677,480	37,448	208.0	1.02	81.5	18.5	1/	78.4	98.6	1/	3,760	10.0
1967	1,481,760	5,877	32.7	0.40	71.2	28.8		75.5	95.0		421	7.2
1968	71,357,720	4,847	26.9	0.007	72.4	27.6		66.3	79.9		2/	2/
1969	40,310,500	1,897+2/	10.5	0.005+2/	2/	2/		69.1	2/		2/	2/
1972	1,375,220	13,097	72.8	0.95	33.6	29.9	36.5	109.3	149.7	173.5	614	4.7
1973	515,580	2,485	13.8	0.48	42.0	34.9	23.1	104.4	157.5	187.7	26	1.0
1974	128,160	538	3.0	0.42	1.1	52.8	46.1	119.5	177.0	182.2	5	0.9
1975	3/											
1976	796,740	12,403		1.6	94.2	5.6	0.2	108.1	149.3	214	---	---

1/ No significant age-3 smolts were produced until the 1971 Bear Lake rehabilitation.
2/ Total adult and smolt production could not be determined due to the 1971 Bear Lake rehabilitation.
3/ Only jacks returned in 1975.

Table 3. Summary of Bear Lake adult sockeye salmon returns.

Year	Sex Ratio M/F	Number of Males	Number of Females	Adult Return[1/] Escapement	Harvest[2/]	Total
1961	1.0:1	1,512	1,511	3,023	Closed	3,023
1962	1.0:1	1,782	1,781	3,563	Closed	3,563
1963	1.4:1	5,202	3,717	8,919	Closed	8.919
1964	0.8:1	2,094	2,618	4,712	Closed	4,712
1965	1.0:1	1,893	1,894	3,787	Closed	3,787
1966	0.8:1	827	1,033	1,860	Closed	1,860
1967	3.2:1	2,487	785	3,272	294	3,566
1968	1.0:1	30,063	28,901	58,964	74,473	133,437
1969	0.7:1	8,995	12,210	21,205	99,859	121,064
1970	1.0:1	2,927	2,904	5,831	1,876	7,707
1971	1.1:1	211	192	403	2,117	2,520
1972	0.8:1	333	391	724	77	803
1973	0.6:1	94	145	239	Closed	239
1974	0.7:1	25	36	61	Closed	61
1975	1.0:1	7	0	7	Closed	7
1976	1.1:1	307	271	578	Closed	578
1977	1.7:1	22	13	35[3/]	Closed	35
1978	0.5:1	9	18	27	Closed	27
1979	2.0:1	12	6	18	Closed	18

1/ Includes "jack" salmon.
2/ Includes estimated commercial and subsistence harvest.
3/ An electrical ground problem prevented adult sockeye from migrating to the weir.

Even though the mean length of age-1 and age-2 sockeye smolts after 1971 significantly increased following rehabilitation (age-1 from 66.3 to 109.3 mm, age-2 from 79.9 to 149.9 mm), the age composition included a significant proportion of age-3 sockeye smolts (Table 2). The occurrence of age-3 sockeye smolts may superficially suggest that this was a result of competition with the high density coho fingerling releases. However, the occurrence of age-3 sockeye smolts, concurrent with the significant increase in length, may have been the result of possible development of a residual population of sockeye in Bear Lake at that time.

Only three total sockeye adult returns have occurred since the 1971 rehabilitation (Table 2). The largest return was from the 1972 brood stock, in which 614 adults were produced from 13,097 smolts, for a survival of 4.7%. The sockeye adult returns from the 1973 and 1974 brood stocks were much lower. Smolt to adult survivals were 1.0% and 0.9%, respectively.

COHO SALMON PRODUCTION

Fingerling Releases

Post 1963 Lake Rehabilitation:

In the years following the initial (1963) lake rehabilitation (until 1968), Bear Lake was stocked annually with coho salmon fingerlings from various brood stocks, of various release size, and at different times of the year. Thus, comparisons of survivals should be viewed accordingly. In addition, similar to the sockeye smolt production in Bear Lake following the 1963 rehabilitation, coho smolt production increased during 1964-1966. Also, after 1966, the high stickleback abundance apparently caused a decrease in coho smolt production.

The top portion of Table 4 shows that, as a result of the variable brood stocks being released at different times and different sizes in Bear Lake, and the growing stickleback problem, the fingerling-to-smolt survival (during post 1963 lake rehabilitation) varied from a high of 48.1% in 1965 to a low of 5.5% in 1967. Peak coho smolt production coincided with peak sockeye smolt production following the 1963 lake rehabilitation. For example, in 1964 and 1965 coho smolt survivals from fingerling releases were 43.5% and 48.1% respectively. In addition, coho smolt size increased from a mean of 86.4 mm in 1962-1963 to 121.2 mm in 1964 and 107.3 mm in 1965 for age-1 smolts, and from a mean of 118.0 mm in 1962-1963 to 155.7 mm in 1964 and 131.5 mm in 1965 for age-2 coho smolts. The high coho smolt to adult survival in 1964 and 1965, (13.9% and 17.4% respectively) indicated that marine survival was related to the size of seaward migrating smolts. Finally, the dominant age structure also changed, from age-2 to age-1 smolts.

Similar to the sockeye smolt production, by 1969 coho salmon smolts experienced a similar decline in both abundance and size, although to a lesser degree. The 1965 brood year (1968 smolt emigration) age structure had reverted to age-2 fish (90.6%) being dominant (Table 4).

Table 4. Summary of Bear Lake coho salmon fingerling releases.

Brood Year	Dates of Releases	Origin	Number of Fish Released	Mean Number per Pound	Smolt Production			Smolt Age Composition		Smolt Mean Length (mm)		Adult Production[1/]		
					Number	No./ha	% Survival	1 (%)	2	1	2	Total Number	Fingerling to Adult Survival (%)	Smolt to Adult Survival (%)
1962	11/13-12/8 1963	Diary Cr. Bear Cr. Swanson R.	148,057	88	15,197	84.4	10.3	55.9	44.1	91.4	161.4	1,789	1.2	11.8
1963	9/16 1964	Swanson R. Ketchikan Cr.	43,000	168	18,699	103.9	43.5	73.0	27.0	121.2	155.7	2,605	6.1	13.9
1964	8/25-9/3 1965	Swanson R.	69,800	95	33,205	184.5	48.1	81.7	18.3	107.3	131.5	4,947	7.1	17.4
1965	7/11-8/9 1966	Swanson R.	360,800	504	50,199	278.9	13.9	9.4	90.6	71.8	114.9	1,953	0.5	3.9
1966	8/8-8/30 1967	Big Cr. Ore. Pasagshak R[2/]	246,400	165	13,723	76.2	5.5	6.9	93.1	83.6	147.9	94	0.04	0.7
1968 - 1971 NO FINGERLING RELEASES														
1971	6/26 1972	Bear L.	450,000	862	86,637	481.3	19.3	89.2	10.8	107.5	147.6	5,040	1.1	5.9
1972	6/20 1973	Bear L. L. Rose Tead[2/]	443,300	727	218,661	1,214.8	49.3	29.5	70.5	117.8	143.4	3/	3/	3/
1973	7/16 1974	Upper Station[2/]	450,800	489	43,384	241.0	9.6	31.1	68.9	107.3	134.9	3/	3/	3/
1974	6/19-7/1 1975	Bear L.	450,000	495	112,819	676.8	25.1	56.8	43.2	106.3	129.5	3/	3/	3/
1975	6/10-6/14 1976	Bear L.	224,600	363	66,209	367.8	29.5	75.1	24.9	113.1	134.8	3/	3/	3/
1976	6/16 1977	Bear L.	227,700	292	89,186	495.5	39.2	90.8	9.2	120.0	146.2	3/	3/	3/
1977	6/20 1978	Bear L.	225,800	337	117,438	652.4	52.0	82.7	17.3	120.6	134.8	3/	3/	3/
1978	5/24 1979	Bear L.	225,500	663	54,580	303.2	24.2[4/]			121.8		3/	3/	3/
1979	6/12 1980	Bear L.	150,000	248	5/	5/	5/	5/	5/	5/	5/	5/	5/	5/

1/ Includes sport harvest estimates and "jack" salmon. There is no commercial harvest of coho salmon in Resurrection Bay.
2/ These systems are located on Kodiak Island.
3/ After the 1974 adult return, no scale analysis was conducted on returning adults so survivals cannot be computed.
4/ Includes only age-1 smolt production.
5/ No production has occurred to date.

Post 1971 Lake Rehabilitation:

From 1972-1975, Bear Lake was stocked with coho fingerlings (mainly Bear Lake brood stock) at high densities (i.e. >2,400 per surface hectare). The cumulative effect of these stocking densities critically overtaxed the lake's coho rearing habitat in just three years.

Intense intraspecific competition among the released fingerlings apparently depressed growth rates, lowered survival and extended rearing duration. Although the largest coho smolt emigration ever recorded for Bear Lake occurred from the 1972 brood year (Table 4), 70.5% were age-2 smolts in relatively poor condition. The increased stress from overcrowding led to a greater susceptibility of rearing fingerlings to natural diseases in Bear Lake. Consequently, many (13%) of the 1972 age-2 coho smolts migrating from Bear Lake died either from "eye fluke", *Diplostromulum spathaceum*, or fungus, *Saprolegnia sp.*, diseases at the weir (McHenry 1978).

Finally, biomass ratios of smolts produced per fingerling release (Table 5) show the abrupt decline from 16.0:1 (1973 release) to 3.1:1 (1974 release). Similarly, coho smolt survival decreased from 49.1% in 1973 to 9.6% in 1974.

From these findings, it was evident that a reduction in Bear Lake's coho fingerling stocking density was necessary. Stocking densities, beginning with the 1976 release, were reduced to one-half previous levels or approximately 1,250 per hectare. This resulted in increased smolt length and survival, and an age structure change to predominately age-1 smolts. Specifically, the 1975 and 1976 brood years (1976 and 1977 releases) showed an increasing trend in fry-to-smolt survivals (29.5% and 39.2%, respectively) and a shift in the age composition to predominately age-1 (75.1% for the 1976 release and 90.8% for the 1977 release) (Table 4). Similarly, mean lengths for age-1 and age-2 coho smolts from the 1976 and 1977 releases increased from 113.1 to 120.6 mm for age-1, and from 134.8 to 146.2 mm for age-2 fish.

Conversely, smolt biomass yield since the reduced coho fingerling stocking in 1976 has not shown an expected increase (Table 5). Instead, from the 1976-1978 releases, biomass ratios of smolts produced per fingerling have generally leveled off: 4.4:1 (1976 release), 4.7:1 (1977 release). The 1978 release however, increased to 7.6:1.

Smolt Releases in Resurrection Bay Area

Coho smolt releases in Seward Lagoon, lower Bear Creek and Grouse Lake are summarized in Tables 6 and 7. The 1970 release of 39,750 smolts in Seward Lagoon produced a return of 6,006 adults for a return percent of 15.1%. Lower Bear Creek produced its highest adult return of 2,145 fish (6.1%) from the 1977 release of 35,100 coho smolts. The 1977 release in Grouse Lake of 35,100 smolts also produced its highest adult return of 2,750 fish (7.8%). Thus, smolts released in Seward Lagoon produced the largest total adult return percentage of the three release sites.

Table 5. Summary of Bear Lake coho salmon smolt abundance and biomass produced since 1972 from annual fingerling releases.

Year of Release	Number of Fingerlings and Weight (kg)	Total Smolt Yield From Brood-Year			Survival to Smolt (%)1/
			No./ha	Kg/ha	
1972					
Number	450,000	86,637	481.3		19.3
Weight (kg)2/	237.0	2,439.1		13.6	
Weight ratio3/		1:10.3			
1973					
Number	443,300	218,661	1,214.8		49.3
Weight (kg)	295.5	4,716.5		26.2	
Weight ratio		1:16.0			
1974					
Number	450,800	43,384	241.0		9.6
Weight (kg)	418.1	1,279.5		7.1	
Weight ratio		1:3.1			
1975					
Number	450,000	112,819	626.8		25.1
Weight (kg)	412.7	1,988.7		11.0	
Weight ratio		1:4.8			
1976					
Number	224,600	66,209	367.8		29.5
Weight (kg)	280.3	1,219.5		6.8	
Weight ratio		1:4.4			
1977					
Number	227,700	89,186	495.5	9.3	39.2
Weight (kg)	353.7	1,677.8			
Weight ratio		1:4.7			
1978					
Number	225,800	117,438	652.4		52.0
Weight (kg)	303.9	2,312.8		12.8	
Weight ratio		1:7.6			

1/ A low percentage of natural smolt production was observed but not included (i.e., <8,000 smolts per year).
2/ Number times mean weight per individual for combined age classes.
3/ Fingerling to smolt ratio.

Table 6. Summary of hatchery-reared coho salmon smolt releases in Seward Lagoon.

Brood Year	Origin	Release Date	Number of Fish	Mean Number per Pound	Adult Return Data 1/ 0+ Ocean (jacks) No.	0+ Ocean (jacks) %	1-Ocean No.	1-Ocean %	Total Number	Return Percent
1966	Oregon	4/18-4/22 1968	42,200	18.2	0	0.00	15	0.04	15	0.04
1967	Oregon	5/6-5/7 1969	27,100	14.6	1	0.00	6	0.02	7	0.03
1968	Bear L.	5/19-5/27 1970	39,750	10.8	952	2.4	5,114	12.8	6,006	15.1
1969	Bear L.	5/17 1971	10,900	14.2	3	0.03	1,519	13.9	1,522	14.0
1970	Kodiak	5/31 1972	66,500	16.8	915	1.4	2,963	4.5	3,878	5.8
1971	Seward Lag.	5/7-5/9 1973	30,200	8.9	140	0.5	125	0.4	265	0.9
1972	Kodiak	5/6-5/11 1974	100,000	9.4	4,764	4.8	3,885	3.9	8,649	8.7
1973	Seward Lag.	5/15-5/19 1975	100,700	9.1	2,610	2.6	1,971	2.0	4,581	4.6
1974	Bear L.	5/4-5/10 1976	100,600	12.8	600	0.6	4,513	4.5	5,113	5.1
1975	Bear L.	5/6-5/13 1977	100,450	10.3	1,622	1.6	7,710	7.7	9,332	9.3
1976	Seward Lag.	5/1-5/5 1978	125,979	9.9	147	0.12	1,080	0.9	1,227	1.0
1977	Bear L.	5/14-5/15 1979	97,840	29.0	0	0.00	3,956	4.0	3,956	4.0
1978	NO SMOLTS RELEASED									
1979	Bear L.	5/25-5/26 1980	100,800	39.1	2/	2/	2/	2/	2/	2/

1/ Includes sport harvest estimates.
2/ Denotes no production has occurred to date.
3/ Initial year of age-0 smolt releases.

Table 7. Summary of hatchery-reared coho salmon smolt releases in lower Bear Creek and Grouse Lake.

Brood Year	Origin	Release Date	Number of Fish	Mean Number Per Pound	Adult Return Data 1/ 0+ Ocean (jack) No.	0+ Ocean (jack) %	1-Ocean No.	1-Ocean %	Total Number	Return Percent
1967	Oregon	5/8-5/13 1969	47,470	13.8	8	0.02	17	0.04	25	0.05
1968	Bear L.	5/27 1970	6,400	10.3	76	1.2	285	4.5	361	5.6
1969	Bear L.	5/18-5/21 1971	51,100	14.2	14	0.03	178	0.4	192	0.4
1970	Kodiak	5/15-5/24 1972	155,500	14.8	155	0.1	470	0.3	625	0.4
1974	Bear L.	5/12-5/14 1976	35,600	11.4	16	0.1	756	2.1	772	2.2
1975	Bear L.	5/13-5/15 1977	35,100	10.5	436	1.2	1,709	4.9	2,145	6.1
1976	Seward Lag.	5/31 1978	28,574	10.0	153	0.5	1,343	4.7	1,496	5.2
1977	Bear L.	5/15 1979	40,400	25.0	0	0.0	881	2.2	881	2.2
1978	NO SMOLTS RELEASED									
1979	NO SMOLTS RELEASED									
Grouse Lake										
1974	Bear L.	5/10-5/12 1976	35,200	12.2	50	0.1	1,498	4.3	1,548	4.4
1975	Bear L.	5/15-5/17 1977	35,100	10.1	446	1.3	2,304	6.6	2,750	7.8
1976	Seward Lag.	5/30 1978	53,555	11.3	118	0.2	801	1.5	919	1.7
1977	Bear L.	5/16 1979	44,000	28.4	0	0.0	1,337	3.0	1,337	3.0
1978	NO SMOLTS RELEASED									
1979	Bear L.	6/26 1980 3/	50,286	34.0	0	0.0	2/	2/	2/	2/

1/ Includes sport harvest estimates.
2/ Denotes no production has occurred to date.
3/ Initial year of age-0 smolts releases.

Various brood stocks have been used in the Resurrection Bay smolt releases. However, the highest adult returns for the three release sites were from the Bear Lake brood stock. The lowest adult returns from smolt releases in Seward Lagoon and lower Bear Creek occurred from the 1969 releases when brood stock from Oregon was used. Logan (pers. comm. 1980) explained that the major reason that this brood stock produced poor adult returns was late migration timing.

The total adult production (for years of completed returns) from all smolts released in Seward Lagoon, lower Bear Creek and Grouse Lake are summarized in Table 8. Again, Seward Lagoon displayed the highest total smolt-to-adult return survival (5.3%) during 1968-1980. Grouse Lake, during 1976-1980, displayed a 3.9% smolt-to-adult return survival while coho smolt releases in lower Bear Creek from 1969-1980 displayed the poorest smolt-to-adult return survival (1.6%). The total adult return from coho smolts released at these three sites was 57,602 which represented a total smolt-to adult return of 4.1%.

DISCUSSION

Since the 1976 reduced stocking density of coho fingerling releases in Bear Lake, coho smolt production has shown an increasing trend (Table 4). Age composition of recent Bear Lake smolt emigrants reverted to the highest percentage of age-1 fish ever recorded. Fingerling-to-smolt survivals have increased to approximately 40% and smolt-to-adult survivals, since 1976, have increased 270% due to healthier, seaward migrating smolts (McHenry 1978).

At present, without further results of the effects of reduced stocking, the optimum smolt production levels suggested by McHenry (1978) of not to exceed 100,000 coho smolts annually should be adhered to. Although Bear Lake has produced slightly less than 100,000 smolts annually since the 1977 release, total smolt biomass has generally leveled off. In fact, in three out of four years when fingerling releases were nearly double in size compared to the 1976-1978 releases, the total biomass of smolts produced from both levels of release were not that different. For example, the average total biomass of smolts (>70% age-2), at nearly 450,000 fingerlings released each year, averaged 1,902 kg, compared to an average smolt (>70% age-1) biomass of 1,737 kg, when the stocking density was approximately 225,000 fingerlings. Thus, it appears that Bear Lake's rearing potential for coho is roughly at or below 2,000 kg (11.1 kg/ha) of smolts produced per year (Table 5).

The leveling off of coho smolt biomass production at high and intermediate stocking densities, and the resulting change in smolt weight, length and age suggests that to increase the production of smolt biomass from Bear Lake, the rearing capacity has to be increased. To this end, FRED Division, in cooperation with Sport Fish Division, has been conducting a pre-fertilization program at Bear Lake since July 1979. It is hoped that by increasing nutrient input, zooplankton densities (biomass) will increase as a result of a stimulation of primary production. The end result would be additional food for rearing fry.

Table 8. Summary of total adult production for years of completed returns from smolts released in Seward Lagoon, lower Bear Creek and Grouse Lake.

Number of Smolts Released	Total Adult Return	Return Percent
842,249	Seward Lagoon 1968-1980	
	44,551	5.3
400,144	Lower Bear Creek 1969-1980	
	6,497	1.6
167,855	Grouse Lake 1976-1980	
	6,554	3.9
1,410,248	Total	
	57,602	4.1

Superficially, the decline in the sockeye escapement would appear to be related to nutrient depletion in Bear Lake. For example, from 1961-1967 the run of sockeye averaged 4,100 fish (Table 3). The potential effect of the carcasses on the yearly phosphorus loading would be an additional 21 mg/m^2. After 1971, the average return of adults decreased to 232 fish for a loading of 1 $mg/m^2/yr$. However, the present loading of phosphorus into the system is 209 $mg/m^2/yr$. Thus, the drop in phosphorus loading would be less than 10%, an amount not insignificant but certainly not alarming, especially since coho adult returns to the lake have increased since 1971.

Indirectly, the lower number of sockeye fry may have decreased coho smolt production since sockeye fry have been suggested to be an excellent food source for rearing coho fingerlings (Foerster 1968). Compounding the above changes are other occurrences to these fish stocks over the same period: 1) reoccurring stickleback problems, 2) a history of different coho stocks since 1962, 3) different sizes of stocked fry, 4) two rotenone treatments, and 5) changing ratios of coho fry to sockeye fry which would bear on competition for food. Correspondingly, the most consistent data are from 1972 and these data should be considered the more relevent information on which to evaluate Bear Lake for inclusion into a nutrient enrichment program.

Finally, since the first stocking of Bear Lake through 1975 (the years of completed adult returns), a total of 2,661,300 fingerlings have been released to produce 31,670 adults for a return percent of 1.19. Comparatively, the 57,602 adults produced from 1,410,248 smolts released in Seward Lagoon, lower Bear Creek and Grouse Lake represented a return percent of 4.1. The smolt releases yielded nearly a 4-fold increase in number of adults produced compared to the fingerling releases in Bear Lake. Thus, an evaluation of increasing smolt releases should be considered as an alternate and/or complimentary program to lake enrichment of Bear Lake proper.

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Bear Lake Report

Water Quality and Pelagic Productivity

Part II

by

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INTRODUCTION

Bear Lake has been under detailed limnological investigation since July 1979 to determine if the lake is a suitable candidate for a nutrient enrichment program. The purpose of nutrient enhancement (primarily nitrogen and phosphorus) is to raise the primary productivity of a system in order to produce more pelagic food (zooplankton) for rearing coho and sockeye fry. The nutrient additions would increase the production of endemic species of desirable phytoplankton, which are then available to grazing zooplankton.

Detailed pre-fertilization studies are necessary not only to determine pre-existing nutrient loading and the permissible increase, but also to ascertain the species and numerical abundance of the phytoplankton and zooplankton. In addition, chemical and physical parameters are followed on a seasonal basis to determine, as a whole, the basis for the productive capacity of the lake. The purpose of the Bear Lake study is to determine the present productive status of the system, to determine any potential increase in the permissible loading of phosphorus, and to determine the feasibility of increasing the quality of the lake as a rearing area for coho salmon.

METHODS

Limnological sampling trips to Bear Lake were made every three weeks during the period of ice-on to ice-out as well as one to three trips during the ice-over period. One station was sampled from July 1979 to June 1980 at which time a second station was added. The lake was sampled for algal nutrients (nitrogen, phosphorus, silicon and carbon) as well as other water quality parameters (see Alaska Department of Fish and Game, Lake Fertilization Guidelines) from both the 1 m and mid-hypolimnetic zones. Water samples consisted of multiple (4) casts of a non-metallic Van Dorn sampler which were pooled, stored in 8-10 liter transluscent carboys, cooled, and transported immediately to Soldotna for analysis. Both the chemical and biological samples were analyzed by methods detailed in the Alaska Department of Fish and Game limnology manual.

Filterable reactive phosphorus (FRP) was analyzed by the molybdate blue-ascorbic acid method of Strickland and Parsons (1972) 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 following Stainton et al. (1977) after cadmium reduction of nitrate. Ammonium analysis followed Stainton et al. (1977) using the phenolhypochlorite methodology, while silica analysis followed the procedure of Strickland and Parsons (1972). Inorganic carbon was calculated according to Saunders et al. (1962) after determining alkalinity by acid titration to pH 4.5 using a Corning model 399A specific ion meter.

To estimate particulate nutrients, appropriate sample volumes (1-2 liters) were filtered through pre-cleaned 4.2 cm GF/F filters and stored frozen in plexislides. Filtered and unfiltered water samples were stored either refrigerated or frozen in acid cleaned polybottles.

Primary production (standing crop) was estimated by chlorophyll a analysis after Strickland and Parsons (1972) using the low strength acid addition recommended by Reimann (1978) to estimate phaeophytin. Samples (1-2 liters) were filtered through 4.2 cm Whatman GF/F filters to which a few mls of saturated $MgCO_3$ solution were added during filtration, and then were frozen in plexislides.

Primary productivity (rate of production) was assayed by use of radioactive carbon (C^{14}) following the method of Saunders et al. (1962.) Samples (two light, one dark, and one dark-killed) were placed in situ for four hours at 1 m, mid-euphotic and 1% incident light levels during mid-day incubation periods (10:00 a.m. to 2:00 p.m.). After incubation, the samples (100 ml) were fixed with 1 ml of Lugols-acetate and transported to the Soldotna lab for analysis. Filtering was on 2.4 cm GF/F glass fiber filters under low vacuum to prevent cellular rupture. The filters were placed in plastic scintillation vials, acidified with 1N HCL (Lean and Burnison 1979) to remove residual inorganic carbon-14, and assayed after adding 10 ml of Aquasol scintillation fluor on a Packard Tri-carb liquid scintillation spectrometer.

Zooplankton were collected from duplicate bottom to surface vertical tows using a 0.5 m diameter, 153 μ mesh conical zooplankton net. The net was pulled at a constant 1m/sec, and washed well before preserving the organisms in 10% neutralized sugar-formalin (Haney and Hall 1973). Identification followed that of Brooks (1959) and Wilson and Yeatman (1959), while enumeration consisted of counting triplicate 1 ml subsamples taken with a Hansen-Stempel pipette in a 1 ml Sedgewick-Rafter cell.

Photosynthetic available radiation (PAR) was determined with a Protomatic underwater photometer (Wetzel and Likens 1979) which measures only the 400-700 nm wavelengths of light. Temperature and dissolved oxygen profiles were determined with a YSI model 57 meter equipped with a 30 m cable.

RESULTS

Bear Lake is located approximately 9 km north of Seward, Alaska and drains into Resurrection Bay via Bear Creek (Figure 1). The lake is small (180 ha) and shallow (maximum depth is 20 m before the 1964 earthquake and 18 m after the earthquake) with a generally forested mountainous watershed. The lake is morphometrically a potentially productive system having a mean depth of 11 m and a water renewal (or retention) time of 0.8 years. Water renewal is primarily by ice and snow melt in the spring and by rainfall in the fall (Oct. - Nov.) The ice-free period is from May through October or November with an approximately 1 m accumulation of ice and snow during the ice-over period. Maximum flow through the lake usually occurs in the fall with the total discharge of Bear Creek increasing 5-fold during the spring to summer period.

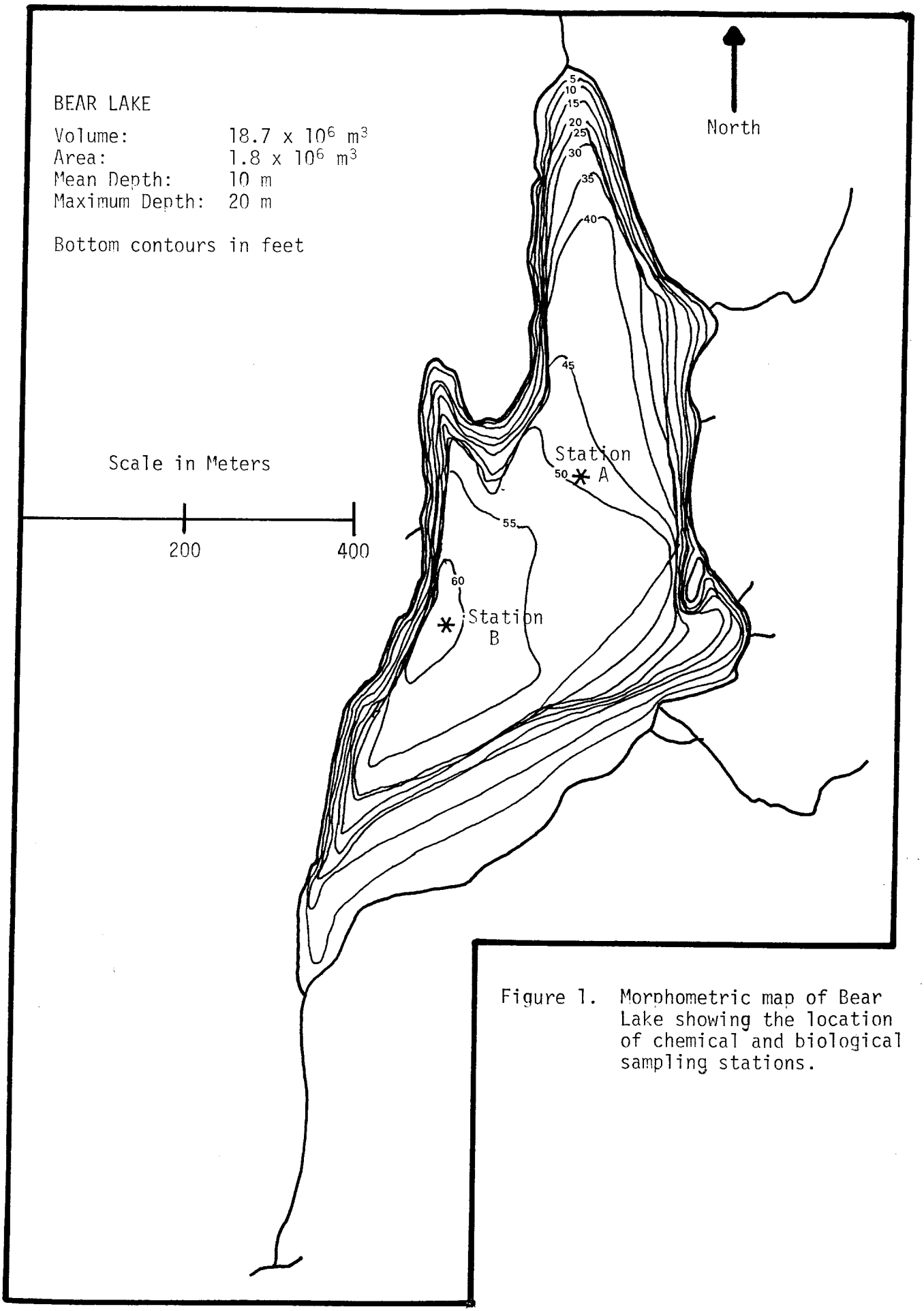

Figure 1. Morphometric map of Bear Lake showing the location of chemical and biological sampling stations.

Physical Parameters

Temperature:

The lake aperiodically mixes from top to bottom after ice out due to a slow warming of the lake in layers of 5°-6°C before rapidly developing a complete thermocline in June (Figure 2). The thermocline then deepens to approximately 10 m during July and August. Cooling begins in September and by October the lake is isothermal at nearly 7°C. During November, the lake continues to cool from top to bottom as complete mixing (overturn) progresses through the fall. Under the ice during the winter, the lake temperatures (from surface to bottom) often remain at <2°C.

During summer stagnation, the hypolimnion is 7-8 m deep, and the epilimnion nearly 10 m. Maximum epilimnetic temperatures are achieved in July and can exceed 20°C with temperatures above 15°C not uncommon from late June to August. Hypolimnetic temperatures approach 7-10°C in late summer, but are highest during the initial period of fall overturn when warm surface water is initially mixed with the cooler hypolimnetic layer. Finally, there is evidence for the introduction of ground water (6°C) at the bottom of the lake during the late summer and early fall period (Figure 2).

Discharge:

Timing and rate of system flushing has important consequences for the nutrient economy of Bear Lake. The lake flushes rapidly with an estimated water retention time of 0.8 years. Usually, the maximum rate of Bear Creek discharge occurs in the fall with total discharge of spring to summer (May through July) being only 15% of the total discharge for the May through mid-November period. An example of this typical cycle is seen in the discharge for 1979 (Figure 3). In 1980, not only did the total discharge increase by 20%, but more importantly, the discharge during the spring to summer period increased to 60% of the total May through mid-November discharge. That is compared to 1979 when the spring period discharge increased by nearly 400% while the fall flushing decreased by 40%.

Following the lowered fall flushing in 1980, the spring discharge in 1981 was very low as a result of near record low snowfall during the 1980-81 winter. However, in both years (1979 and 1980) the lowest rate of discharge occurred in the September to October period with a subsequent rapid increase in October through the middle of November.

Light Levels:

Light penetration [photosynthetically available radiation (PAR)] varied considerably in the lake with deepest penetration (10-11 m) occuring in the summer period (Figure 4). A general decrease occurred in the depth of the euphotic zone (i.e., surface to 1% of incident light) to <5 m during the spring and fall periods. At these times, snow and ice melt along with rainfall contributed noticeable amounts of debris to the lake from the mountainous watershed which restricted light penetration. In addition,

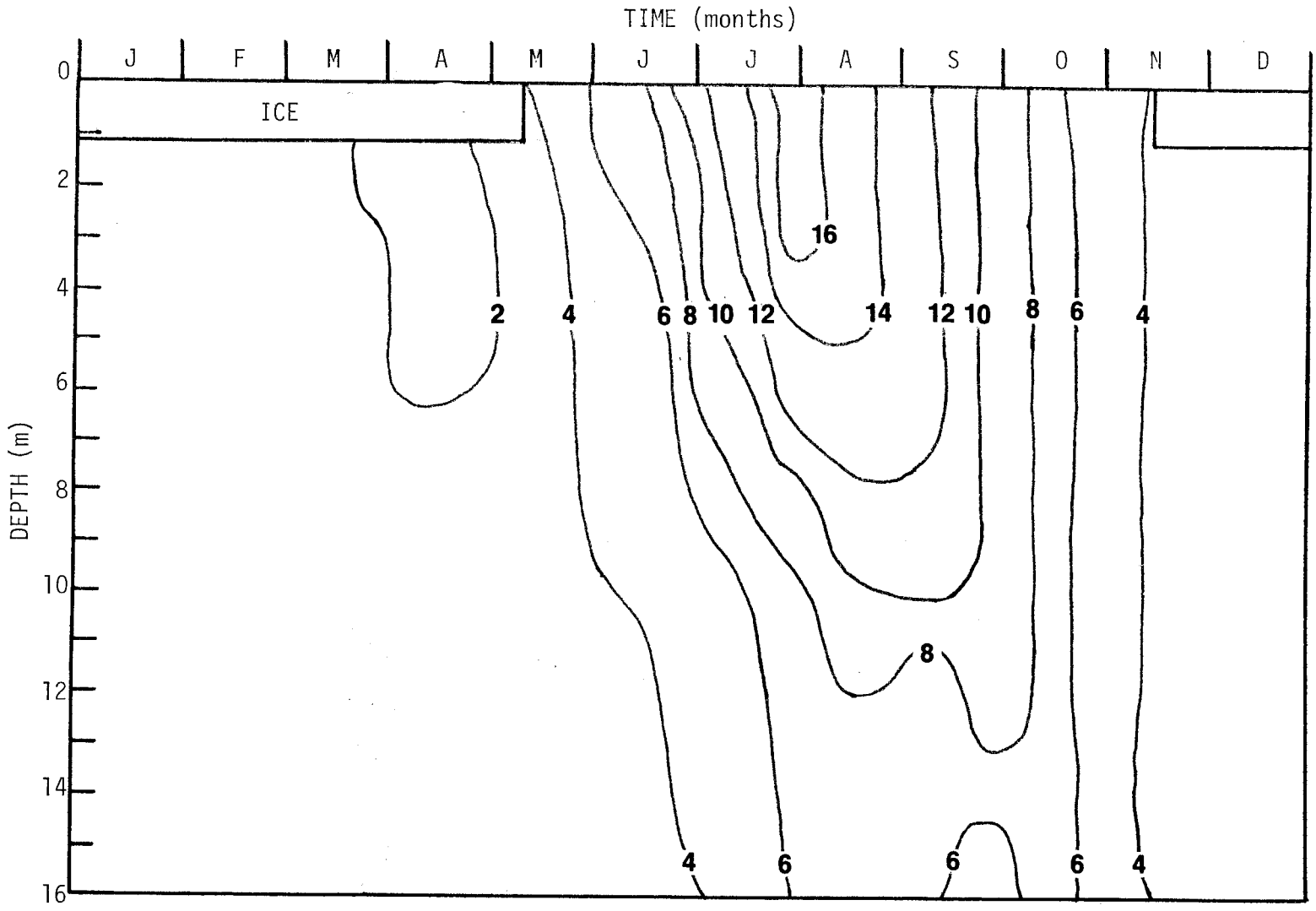

Figure 2. Representative temperature (°C) isotherms for Bear Lake in 1980.

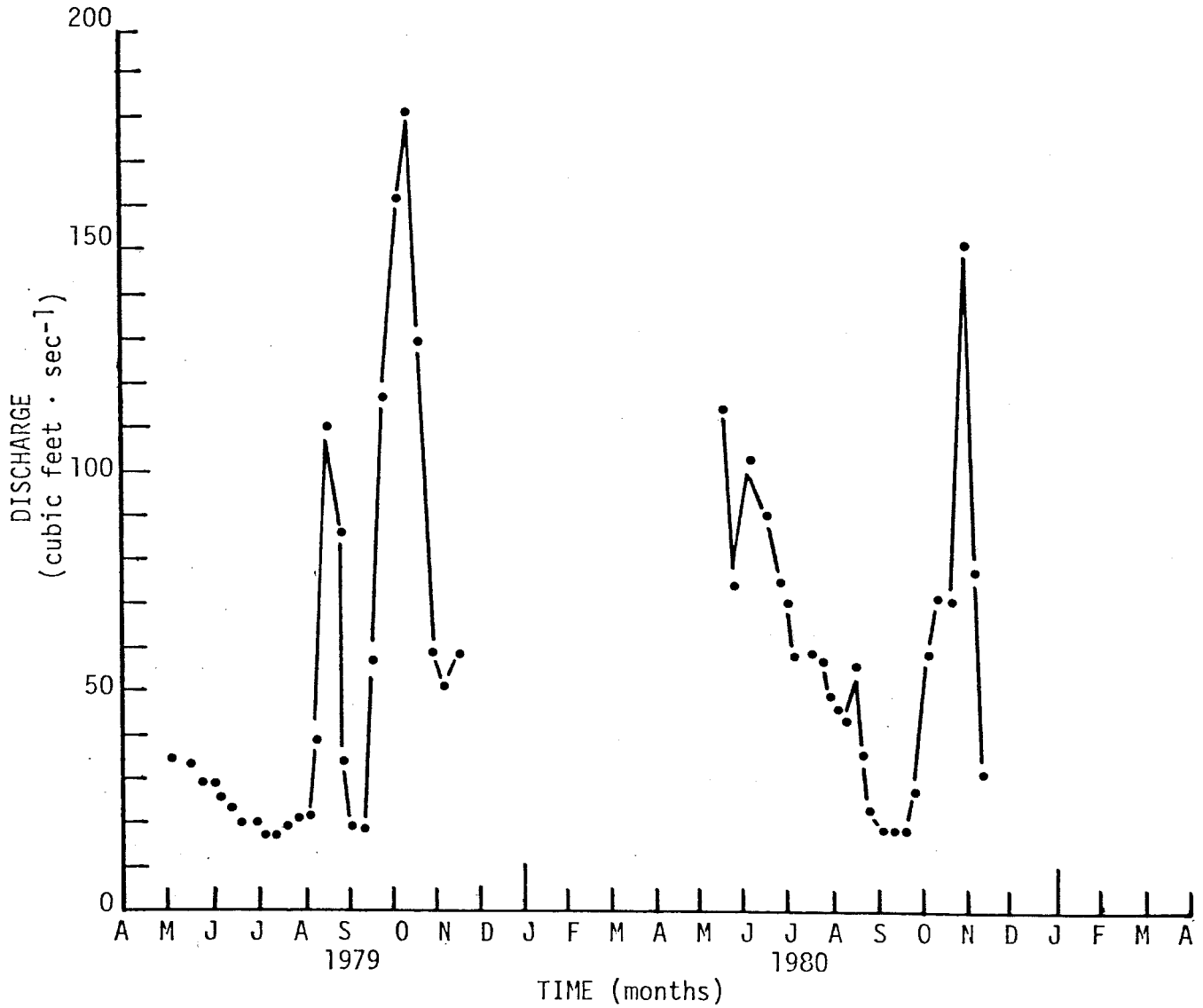

Figure 3. Discharge estimates of Bear Creek as measured at the Bear Creek weir. Points are weekly averages of daily readings.

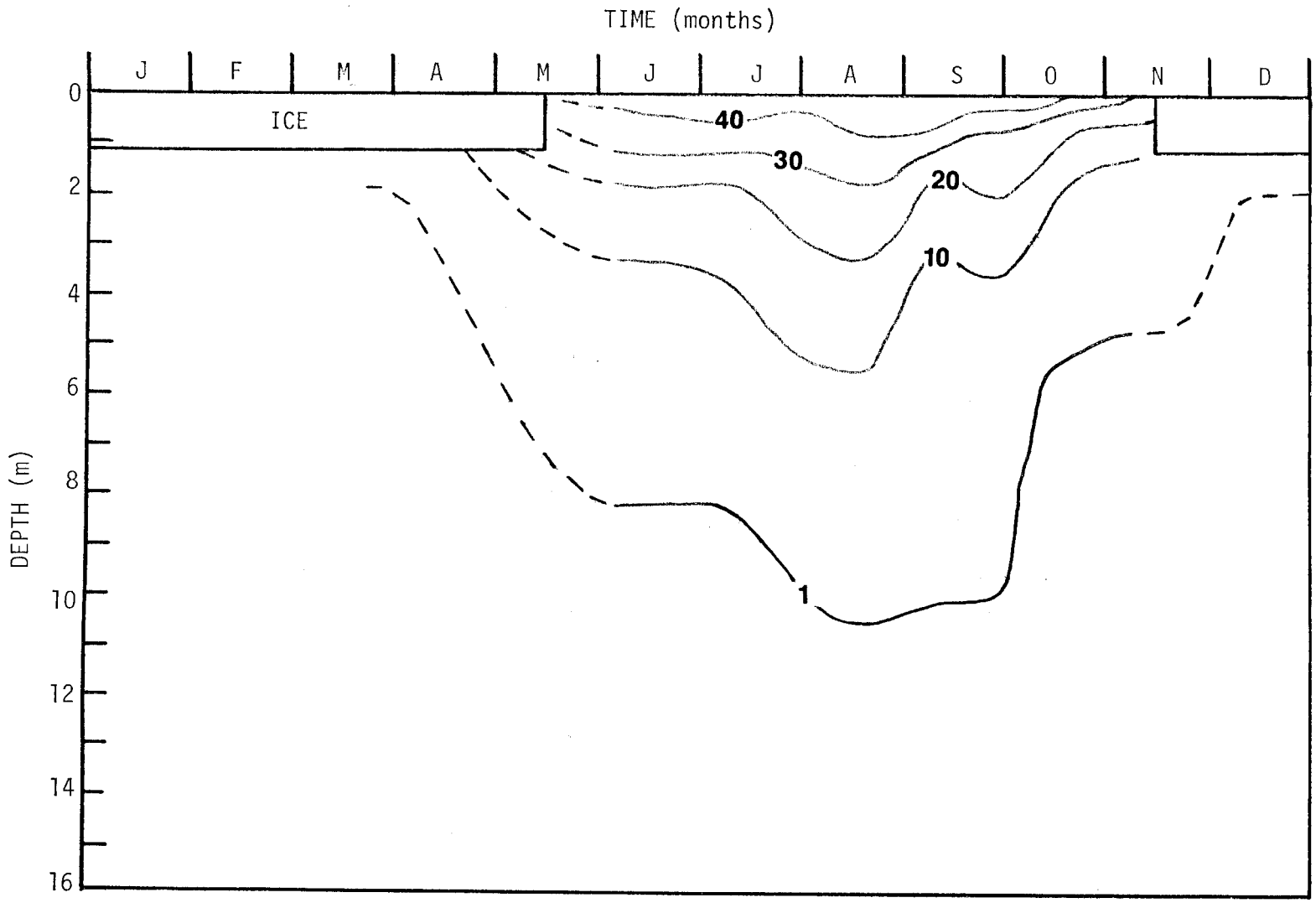

Figure 4. Photosynthetically available radiation in Bear Lake for 1980 (values are in percent of incident light).

the lake underwent partial spring and complete fall mixing which contributed significant amounts of hypolimnetic algae to the water column, thus further reducing light penetration. Secchi disk depths range from 3-11 m and were generally at the 6% incident light level. In Bear Lake, 1% PAR levels were generally double the secchi disk depth.

Chemical Parameters

Dissolved Oxygen:

Dissolved oxygen (D.O.) profiles indicated a well saturated epilimnion throughout the year while a definite depression of D.O. occurred near the bottom of the lake. Maximum recorded levels of D.O. occurred at 10-11 m in August where values greater than 140% oxygen saturation were achieved. Minimum levels were recorded in September at <7% saturation near the bottom of the lake.

Phosphorus:

Total phosphorus (total-P) values for the epilimnion of Bear Lake are generally high, but exhibit a definite seasonal trend (Figure 5A). Concentrations were above 10-11 $\mu g\ L^{-1}$, during the fall (1979 and 1980) and spring (1981) overturn periods, 5-6 $\mu g\ L^{-1}$ during the spring overturn period (1980), and fell to a low of (<3 $\mu g\ L^{-1}$) during the summer period (July and August). In the hypolimnion (i.e., >10 m), the quantity of total-P rose dramatically to >24 $\mu g\ L^{-1}$ with a definite peak during the summer period i.e., between spring and fall overturn. This lower layer exhibited a seasonal cycle that was just the opposite of the 1 m layer, with phosphorus levels increasing over the summer growing season.

During the turnover periods, levels of total-P decreased in the bottom layer and increased in the surface as water from both layers completely mixed. Thus, the epilimnetic water reached 9-10 $\mu g\ L^{-1}$ during both fall overturn periods and the hypolimnion decreased to 8-10 $\mu g\ L^{-1}$.

Like the seasonal trend in total-P concentrations, the amount of particulate phosphorus (part-P) in the epilimnion reached a low (<3 $\mu g\ L^{-1}$) during the summer growing season, but rose as turnover approached (Figure 5B). In contrast, the hypolimnion exhibited much higher part-P levels (>18 $\mu g\ L^{-1}$) during the summer period. During fall overturn, part-P levels of the epilimnion increased as hypolimnetic levels decreased to an intermediate level in both layers of 6-7 $\mu g\ L^{-1}$.

The physical mixing of upper and lower layers during the spring and fall overturn periods is extremely important as it can redistribute the concentration of nutrients within a lake. For example, during periods of complete mixing, phosphorus levels are generally increased within the epilimnion during the spring (e.g., 1981) however, as in 1980, an incomplete spring overturn reduced phosphorus input to the epilimnion. Since the calculated volumes of the epilimnion (44% of the total) and hypolimnion (56% of the total) in Bear Lake are roughly equal, physical mixing alone can result in an equalization of phosphorus levels found within discrete layers before overturn. This is exactly what has been

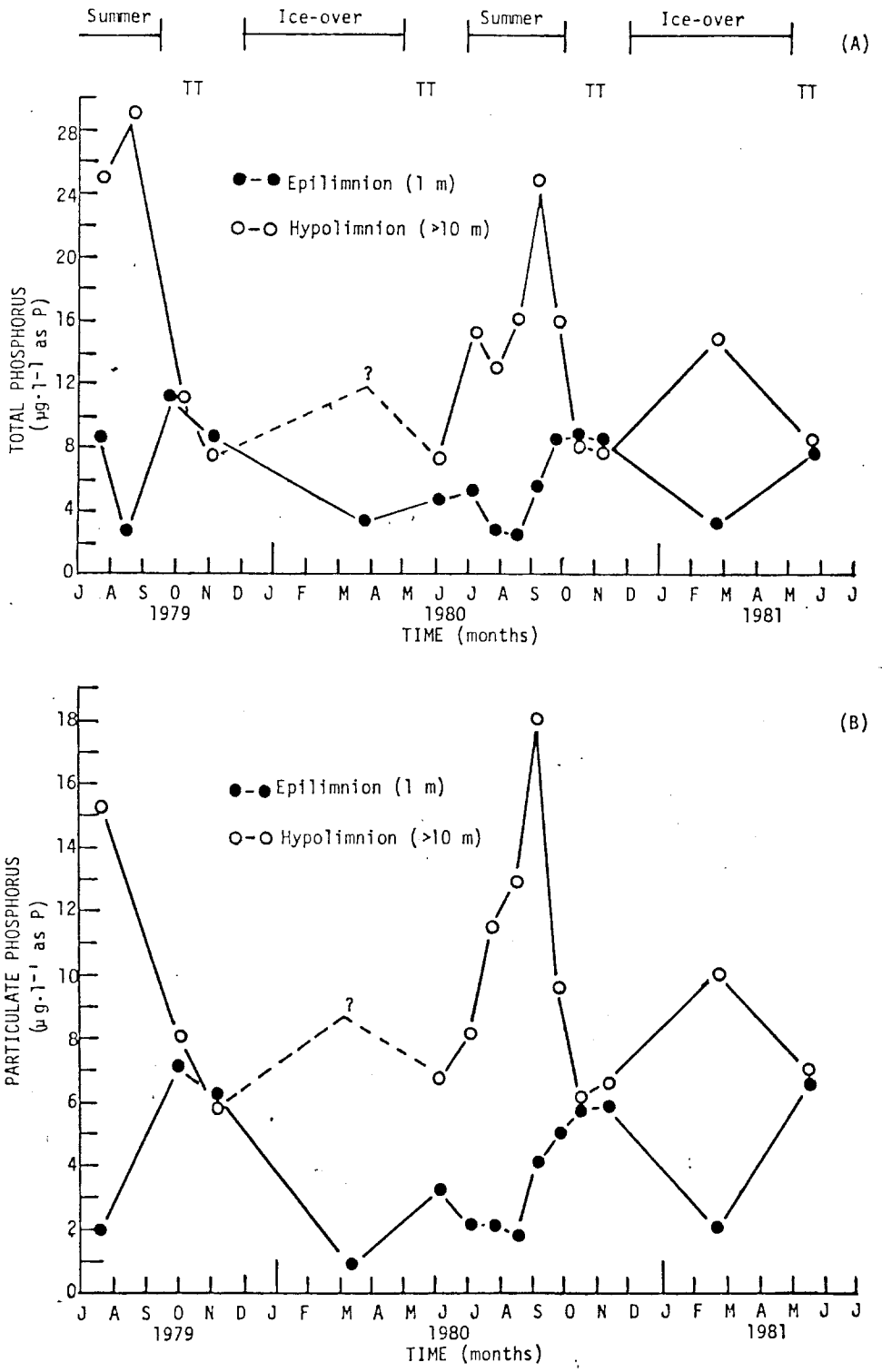

Figure 5. The seasonal cycle of total phosphorus (A), and particulate phosphorus (B) within the epilimnetic and hypolimnetic zones of Bear lake. Lake turnover periods are indicated by the symbol TT.

found to also occur in Bear Lake during the fall overturn periods. The mixing reduced the hypolimnetic accumulation of phosphorus, and potentially could further reduce the concentration of phosphorus within the lake when overturn is coupled with periods of high rainfall. In combination, these two factors could substantially flush nutrients from the entire system.

Reactive phosphorus (or inorganic phosphate) was consistently low to undetectable in Bear Lake at levels <1 $\mu g\ L^{-1}$. These low levels are due to the high demand for inorganic phosphate by the plankton. Because of this, and the fact that phosphorus is cycled very rapidly between the water and the plankton, total-P levels are used as a more relevant measure of the phosphorus capable of being metabolized in fresh water.

Inorganic Nitrogen:

Nitrate + nitrite levels (predominantly nitrate) were low in the epilimnion of Bear Lake, but like total-P exhibited a definite seasonal cycle (Figure 6). In general, during both years nitrate levels began to increase just beofre the fall overturn from a low the previous summer. The nitrate concentration builds to a maximum of <60 $\mu g\ L^{-1}$ under the ice just prior to spring overturn, and then decreases dramatically to a low of <0.5 $\mu g\ L^{-1}$ during the mid-summer period.

In contrast to the nitrate cycle, ammonium concentrations in the epilimnion reached a maximum during the summer period at 20 $\mu g\ L^{-1}$ (1979), and then decreased at approximately the same rate as the nitrate increased to reach a low (<0.5 $\mu g\ L^{-1}$) in June 1980 (Figure 6). Ammonium values then rose to a small summer maximum, decreased, and then rose slightly during the winter ice-over period of 1980. The lower concentration found for the fall period of 1980 (6 $\mu g\ L^{-1}$) compared to 1979 (20 $\mu g\ L^{-1}$) could have resulted from the greater rate of lake flushing that occurred in 1980 compared to 1979.

Nitrogen to Phosphorus Ratio:

Since inorganic phosphorus is utilized very rapidly and can be stored in excess of immediate needs by the phytoplankton, the total amount of phosphorus is used as the more reliable index to the phosphorus available to the plankton (Lund 1965). In addition, the relative requirements of healthy populations of phytoplankton are known for some of the essential nutrients; for example, carbon, nitrogen and phosphorus are used in atom ratios of 100:15:1 (Lund 1965, Fuhs 1972, Golterman 1975). Thus, I calculated seasonal inorganic nitrogen to total phosphorus ratios for Bear Lake (Figure 7).

Adequate epilimnetic concentrations of inorganic nitrogen for the amount of phosphorus present were found only in the winter period (i.e., N:P ratio >15:1). Nutrient ratios fell below 1:1 during the summer period, indicating a definite low supply of inorganic nitrogen or an over supply of phosphorus. However, total-P values reached minimal levels (Figure 5A) of 3 $\mu g\ L^{-1}$ during the summer period suggesting that the problem lies more in a low supply of inorganic nitrogen. Such an imbalance can cause the competitive advantage for nutrients to shift from desirable species of phytoplankton to undesirable species.

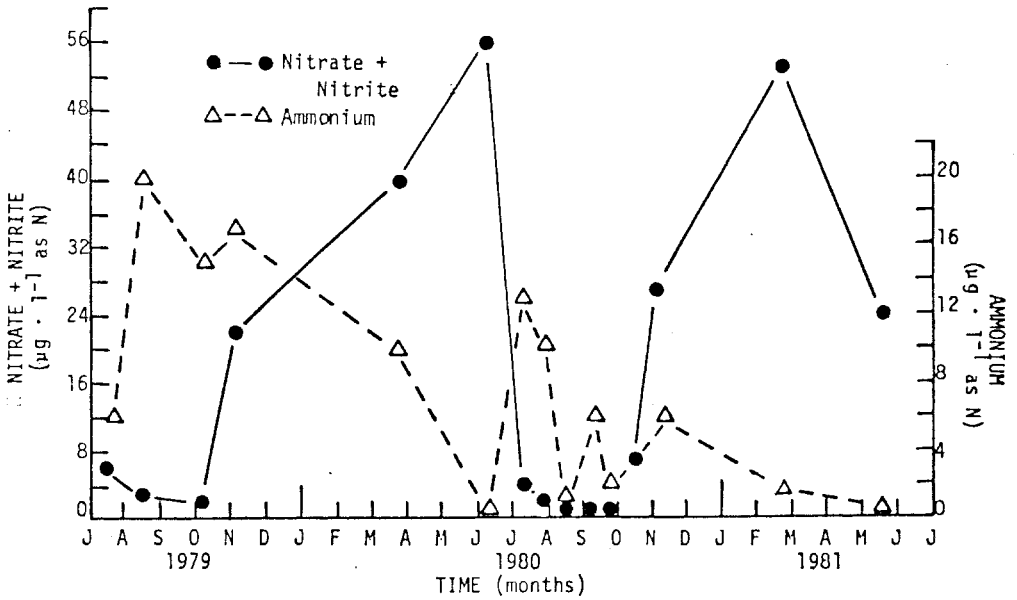

Figure 6. Seasonal levels of inorganic nitrogen (ammonium and nitrate + nitrite) within the epilimnion of Bear Lake.

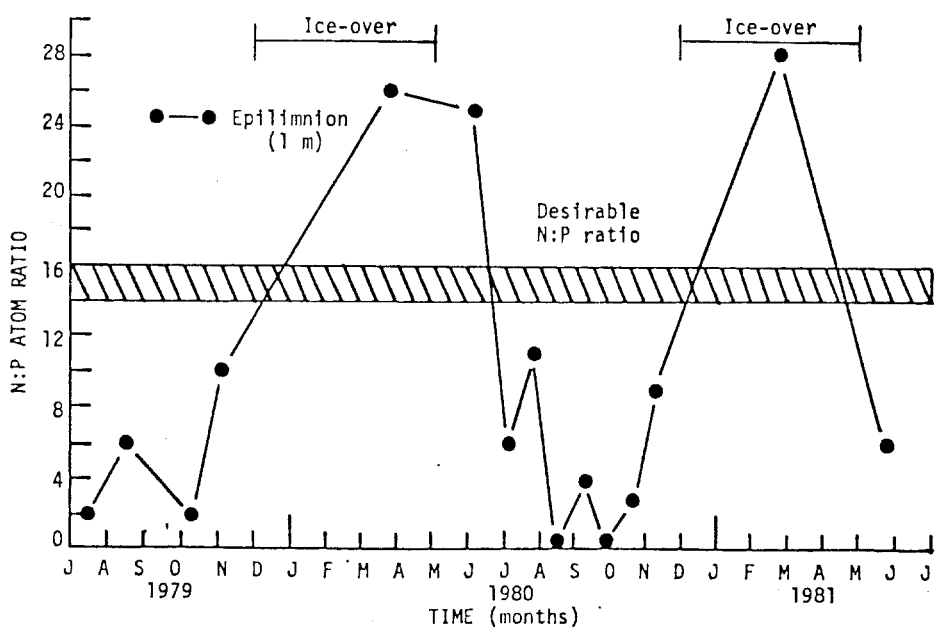

Figure 7. Seasonal trends in the ratio of inorganic nitrogen (ammonium and nitrate + nitrite) to total phosphorus by atoms within the epilimnion of Bear Lake.

Silica and Inorganic Carbon:

Silica levels (Figure 8A) remained fairly consistent throughout 1980, however, the bottom water contained slightly elevated levels (>2,000 $\mu g\ L^{-1}$) compared to the surface water (<4,000 $\mu g\ L^{-1}$) during the summer period. Yet in 1979, silica values in the epilimnion decreased to a low point (<400 $\mu g\ L^{-1}$) in October and November when the chlorophyll a levels were at their seasonal maximum. Since development of populations of diatoms is accompanied almost invariably by a marked decrease in the amount of silica in solution (Lund 1965), it is suggested that in 1979 the low silica concentraions were caused by a population of diatoms which were not a major part of the plankton community in the fall of 1980.

Inorganic carbon levels also increased seasonally in Bear Lake. They were lower in the spring and summer and rose during the fall especially during overturn (Figure 8B). In addition to the seasonal cycle, there appears to be a trend for higher concentrations of inorganic carbon in the hypolimnion when compared to the epilimnion. However, during the ice-free period of 1980 (i.e., June-November) the epilimnion contained a mean value of 8,130 $\mu g\ L^{-1}$ (n=14) while the hypolimnion contained a mean value of 8,830 $\mu g\ L^{-1}$ (n=14). The overall difference is slight, but one reason for this observed trend may be the presence of a larger quantity of organic acids in the hypolimnion which could be detectable (and thus be an artifact) by the acid titration used to determine the amount of inorganic carbon.

Biological Paramters

Chlorophyll:

Phytoplankton standing crop (primary production) exhibited both a definite seasonal cycle, and large differences between the epilimnion (1 m) and the hypolimnion (>10 m) (Figure 9). Chlorophyll a (chl a) levels in the epilimnion were generally less than 1 $\mu g\ L^{-1}$ during the summer of 1979, and increased to nearly 7 $\mu g\ L^{-1}$ at the beginning of the fall overturn period. In contrast, the levels of chl a in the hypolimnion ranged from 5-7 $\mu g\ L^{-1}$ during the summer, remained at that level through the fall overturn, and decreased before freeze-up.

In the spring of 1980 and through the summer, chl a remained <2 $\mu g\ L^{-1}$ in the epilimnion and again climbed during the fall overturn period to 7-8 $\mu g\ L^{-1}$. In the hypolimnion, chl a equalled the epilimnetic concentration at 2 $\mu g\ L^{-1}$ during the spring, but climbed to >18 $\mu g\ L^{-1}$ in the summer. During the fall overturn, hypolimnetic chl a levels dropped to 7-8 $\mu g\ L^{-1}$, a level equal to that of the epilimion. It is important to note that chl a levels were minimal during the summer period in the epilimnion and increased to their maximum levels in the fall during lake overturn by mixing with the dense hypolimnetic concentration of chl a. In contrast to the epilimnion, hypolimnetic chl a reached a maximum during the summer and subsequently decreased during overturn.

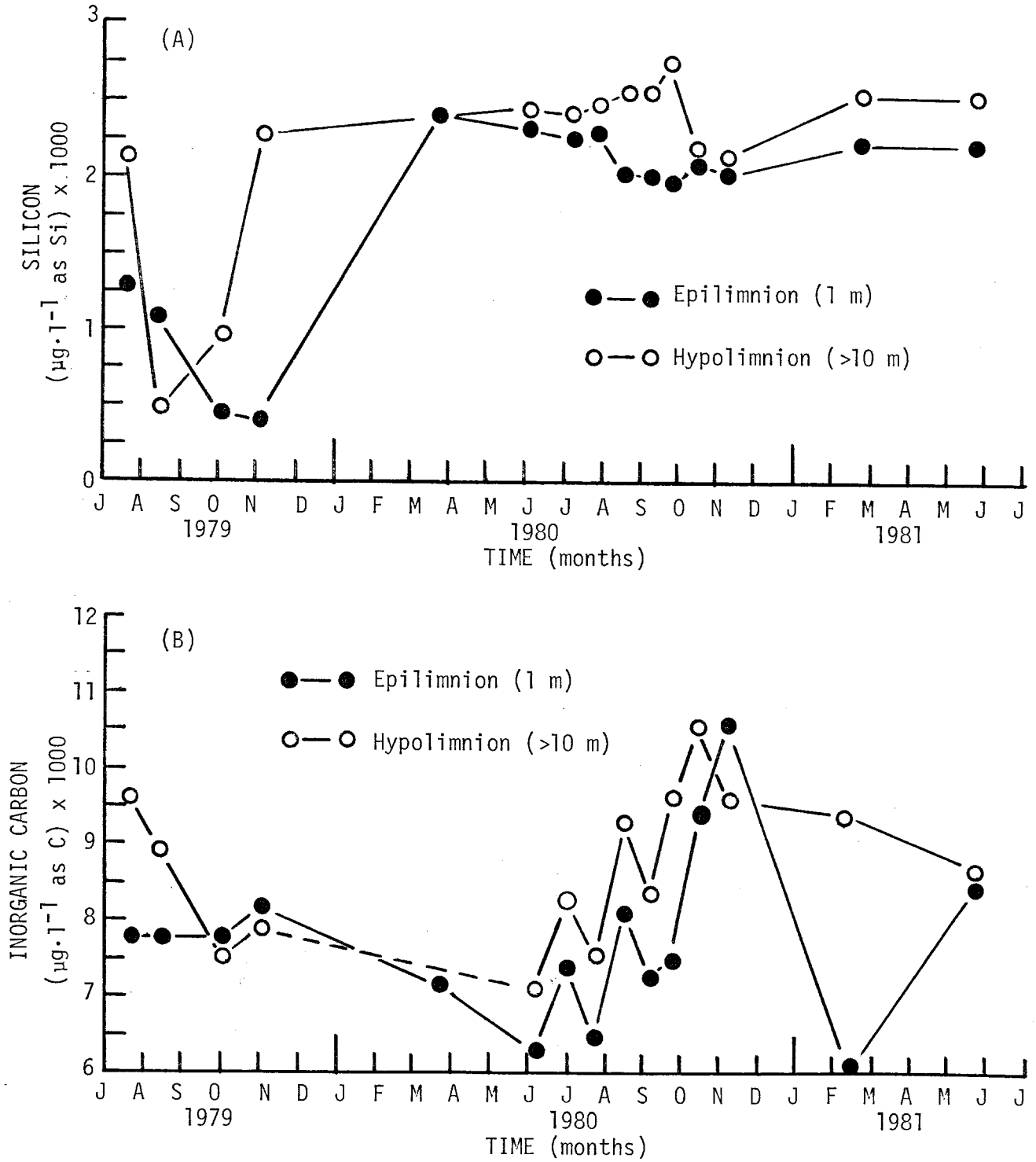

Figure 8. The seasonal cycle of silica (A) and inorganic carbon (B) within the epilimnetic and hypolimnetic zones of Bear Lake.

Carbon Uptake Rates:

By the use of carbon-14, we were able to determine the rate of carbon incorporation by the phytoplankton (Figure 10B). It is apparent that maximum rate of plankton production occurred in the epilimnion in the spring and fall with minimal acitivity during the summer period. Thus, both algal standing crop (chl a) (Figure 9) and rate of carbon incorporation (Figure 10B) within the epilimnion were minimal in the summer and reached maximum levels in the spring and fall overturn periods.

By incubating samples at varying depth-related light intensities (0.5 m, 1.0 m and 1% incident light level), the relative productivity of each stratum could be estimated (Figure 10A). Again, the general trend of increasing carbon incorporation from July through November is indicated however, from July to early September, the bottom layer was the most productive, followed by the 1 m layer and then by the 0.5 m stratum. At the end of September, the rate of carbon uptake begins to become higher in the upper layers, and then dramatically increases in October and November. That is, algal production is largely confined to the upper layers of the euphotic zone only during fall overturn and reaches a maximum in October.

This partitioning of the productivity of the lake into layers is reflected in the light penetration and secchi disk visibility. In the summer, when production is greater in the lower layers (hypolimnion), the epilimnion remains clear of plankton and the 1% incident light level increases to 10-11 m. In the fall, maximum production takes place in the upper euphotic zone which decreased light penetration, and thus the 1% incident light level fell to <5 m.

Algal Taxa and Numerical Abundance:

The algae dominating the flora of Bear Lake during the spring are species of the diatom *Cyclotella*, and species of the blue-green alga *Oscillatoria* (Figure 11). Blue-green algae represent nearly 70% of the volume (biomass) of the plankton and almost 40% of the total number of algal cells. Diatoms (principally *Cyclotella*) account for only 17% of the total volume (biomass) and 33% of total numbers. Green algae represent only 7% of the algal flora by volume and 22% by numbers.

The phytoplankton preferred (i.e., diatoms and greens) by grazing zooplankton represent less than one-quarter of the primary production (biomass) within the epilimnion of the lake. This means that over 75% of the biomass is contained within non-edible phytoplankton. Thus, much of the productive capacity of Bear Lake is currently being channeled into a biological dead-end.

Zooplankton:

The zooplankton community consisted of four important taxa (excluding rotifers), two copepods and two cladocerans. Calanoid copepods formed a signigficant portion of the population, but cyclopoid copepods were present at only trace levels (Figure 12). Thus, the two major taxa were *Daphnia*

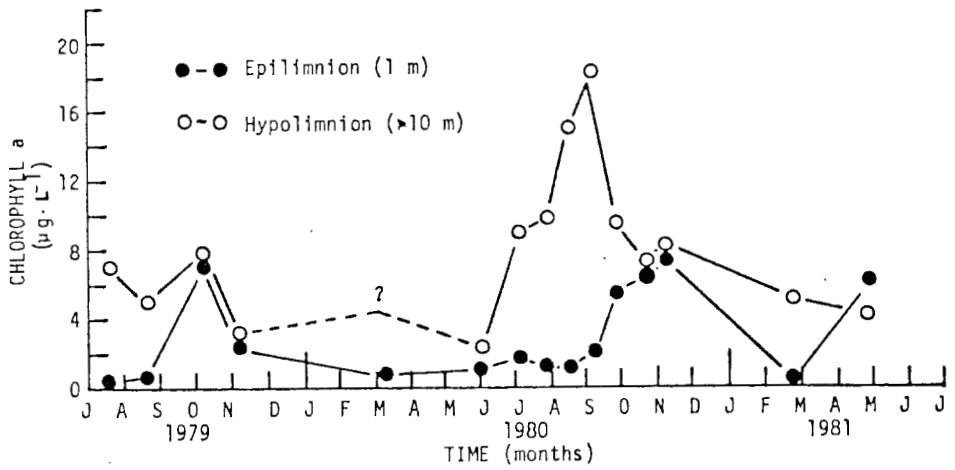

Figure 9. Seasonal levels of chlorophyll a within the epilimnetic and hypolimnetic zones of Bear Lake.

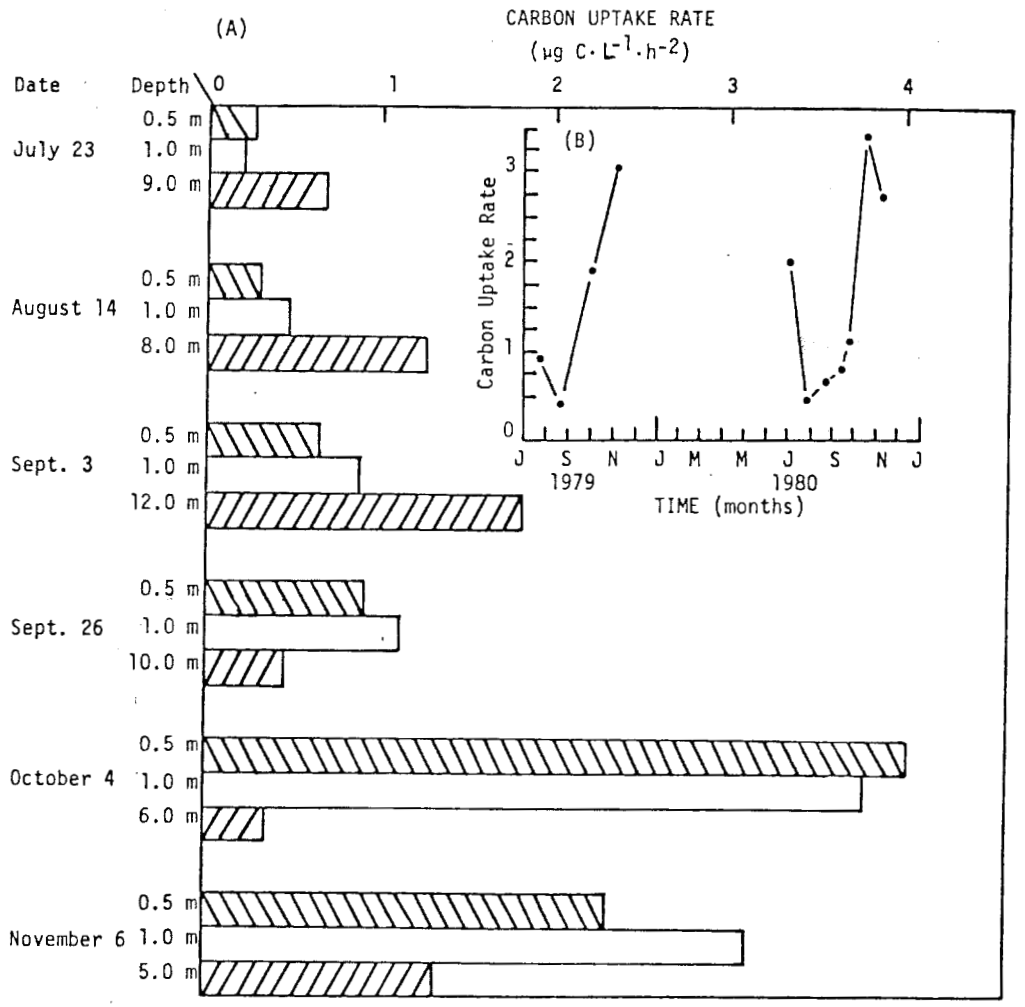

Figure 10. A comparison of carbon uptake rates by the plankton of Bear Lake at varying depths in 1980 (A), and seasonal levels of productivity within the epilimnion (B). Note that the lower incubation depth in (A) is at the 1% incident light level.

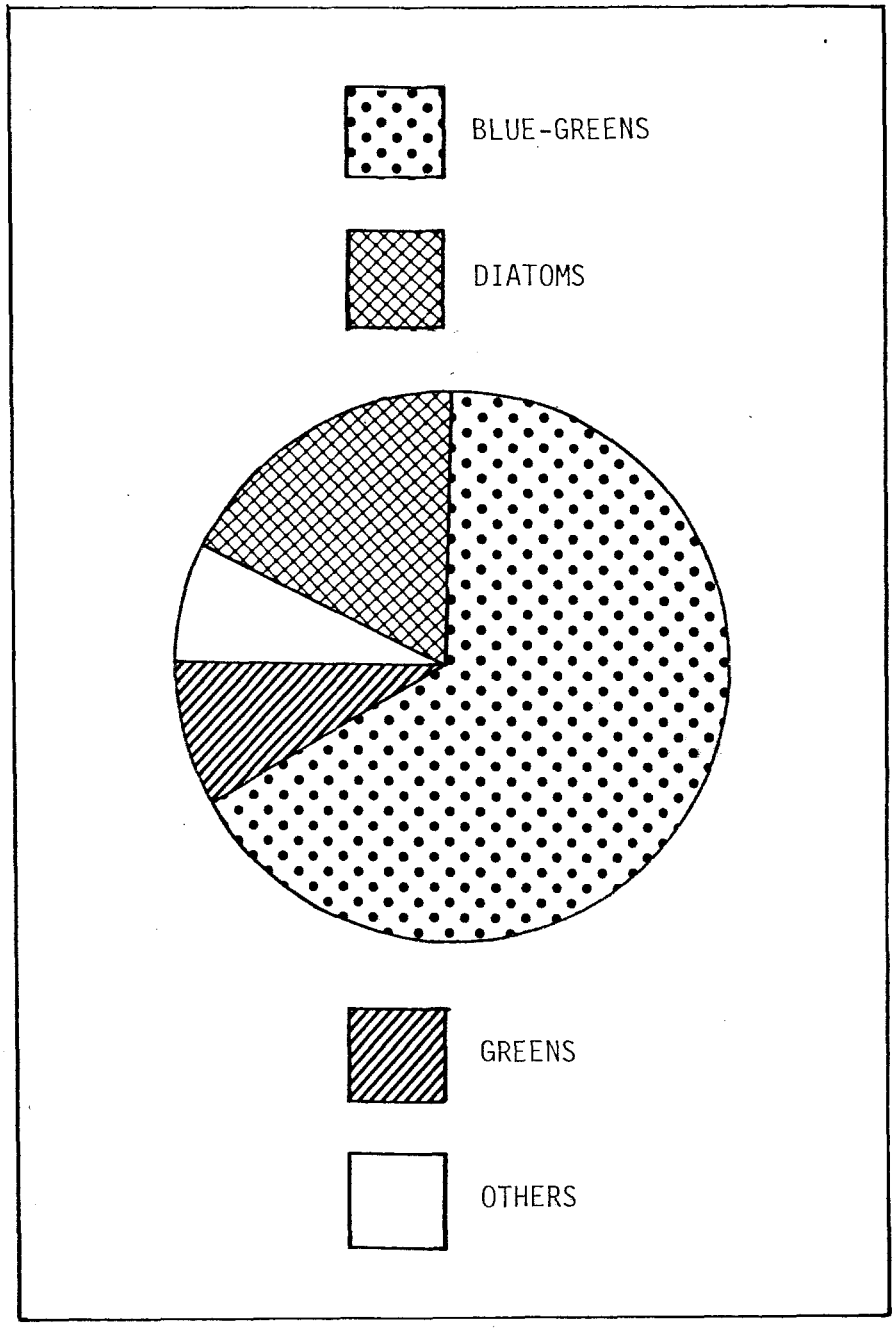

Figure 11. The composition of the epilimnetic spring phytoplankton (by volume) within Bear Lake.

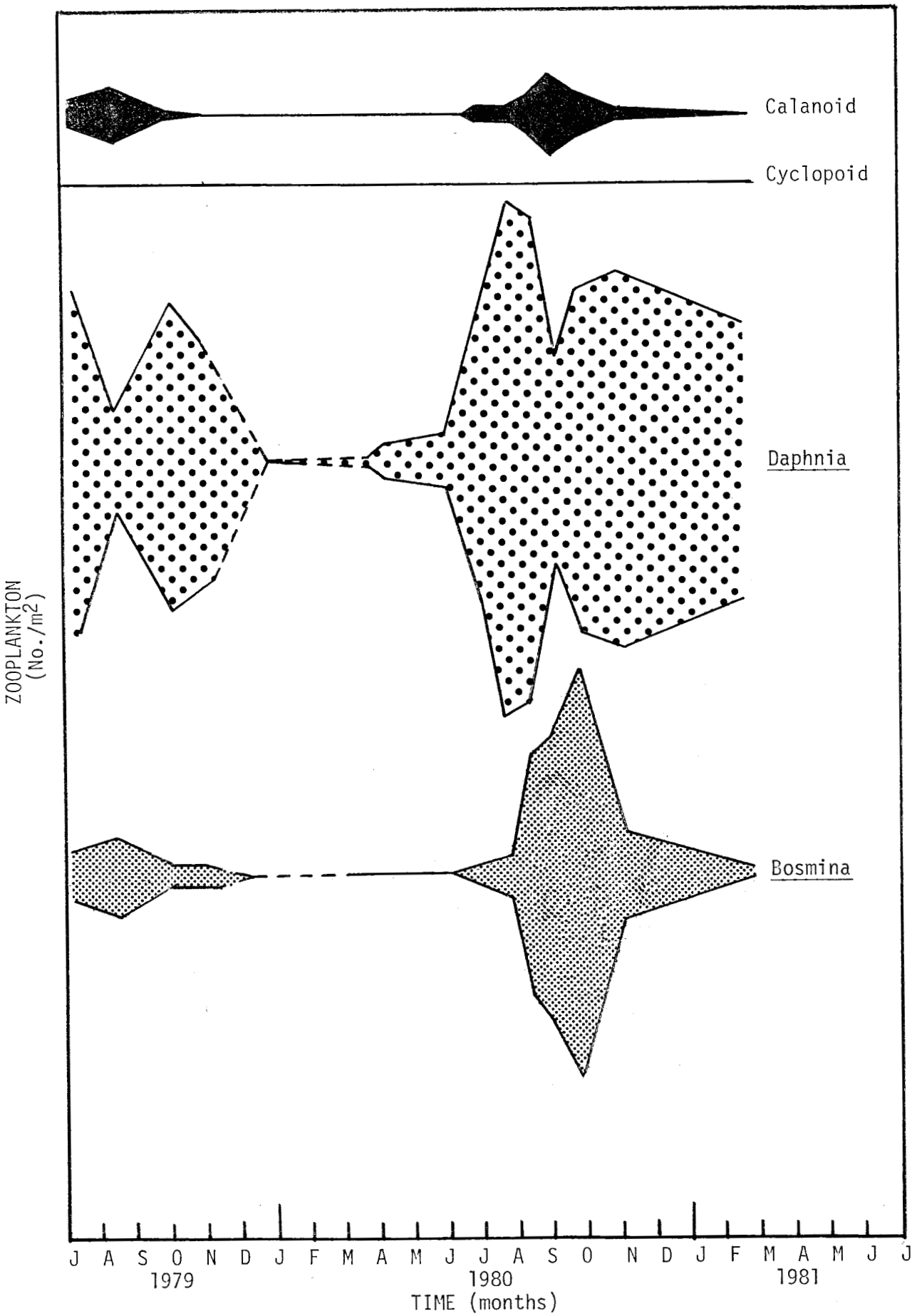

Figure 12. Seasonal abundance of zooplankton by taxa within Bear Lake.

and *Bosmina* which generally reached combined maximum numbers (>250,000/m^2) and densities (>16,000/m^3) in the late summer (August) through the fall (October) and then decreased with the onset of winter.

In 1979, zooplankton levels in September decreased by 60% from a high of 9,500/m^3 during August, and showed only a moderate increase during the turnover period in October to 7,000/m^3 (Figure 13). Under the ice, in March 1980, the zooplankton population was very low <500/m^3 but slowly began to build after ice-out into the first week of June. Beginning in July, the density of zooplankton rapidly increased from levels slightly less than 7,000/m^3 to over 12,000/m^3 in late July. From August through October, levels fluctuated around 16,000/m^3 before decreasing to <9,000/m^3. The mean total numbers of zooplankton in the July to November period of 1979 equalled 23,000/m^2 or 5,700/m^3 (n=4) compared to 43,300/m^2 or 15,000/m^3 (n=8) during the same time period of 1980. It should be noted that biomass estimates of the zooplankton were also made, but because of the large (and variable) amounts of filimentous blue-green algae, the values were not meaningful. In addition, zooplankton net efficiencies were drastically altered by algae clogging the net, and subsequent counting of organisms was extremely difficult. Thus, the numbers of organisms presented above may not be strictly comparable from one date to another.

However, it is evident that the rapid increase in zooplankton in the spring of 1980 came primarily from Daphnid and Bosminid zooplankton--both filter feeders with parthanogenic reproductive stategies. The generation time for cladocerans can be measured in weeks so dramatic increases in population numbers can be acheived in very short time periods, as was evident in Bear Lake (Figure 12). In contrast, copepods reproduce sexually with generation times measured in terms of months. Population increases are thus less dramatic and occur over longer periods of time.

DISCUSSION

Algal succession overtime is triggered or caused by a variety of factors namely temperature, light, flushing rate, nutrients, dissolved oxygen, zooplankton grazing, and organic matter all of which lead to changing competitive advantages of one species over another (Porter 1977). Not all increases in algal productivity are desirable. Blooms of some green and blue-green algae represent dead-ends in planktonic food chains because they are not immediately available to planktonic herbivores. Thus, the composition as well as the quantity of algae will have to be monitored (and regulated) in management programs that seek to maintain and/or increase water quality. Since the changing combination of the above factors leads to seasonal changes in the water quality of Bear Lake, a detailed discussion of these inter-relationships is presented below.

Lake Stratification, Flushing, and Oxygen

It is evident from the dissolved oxygen and temperature profiles (Figure 14) that Bear Lake is not a classic oligotrophic system. In the spring, the lake undergoes overturn except for a small layer below 12 m that remains at <4°C and is below 100% oxygen saturation (e.g., 6 June 1980). Later in

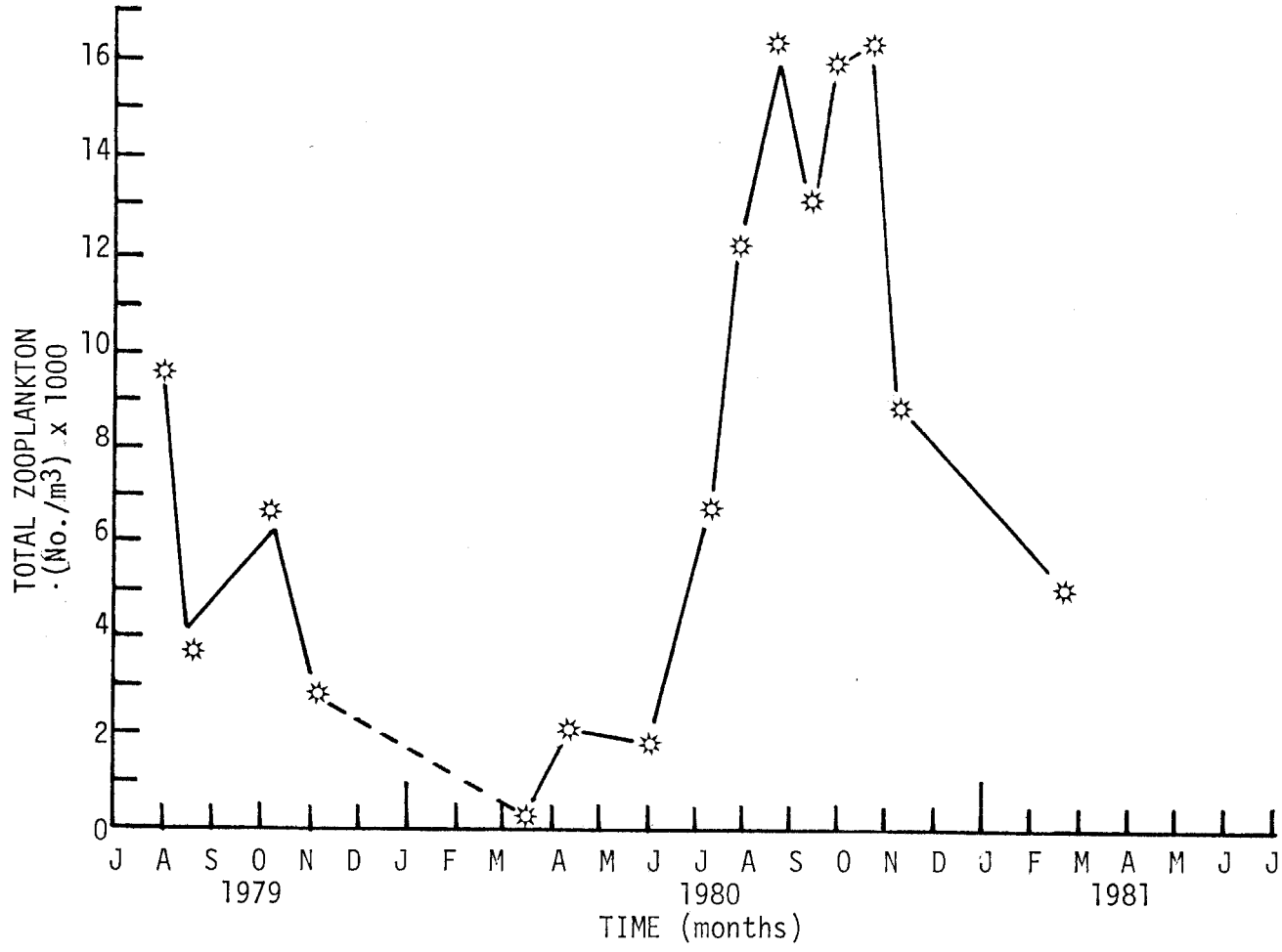

Figure 13. Density of zooplankton (minus rotifers) showing changing population levels over time.

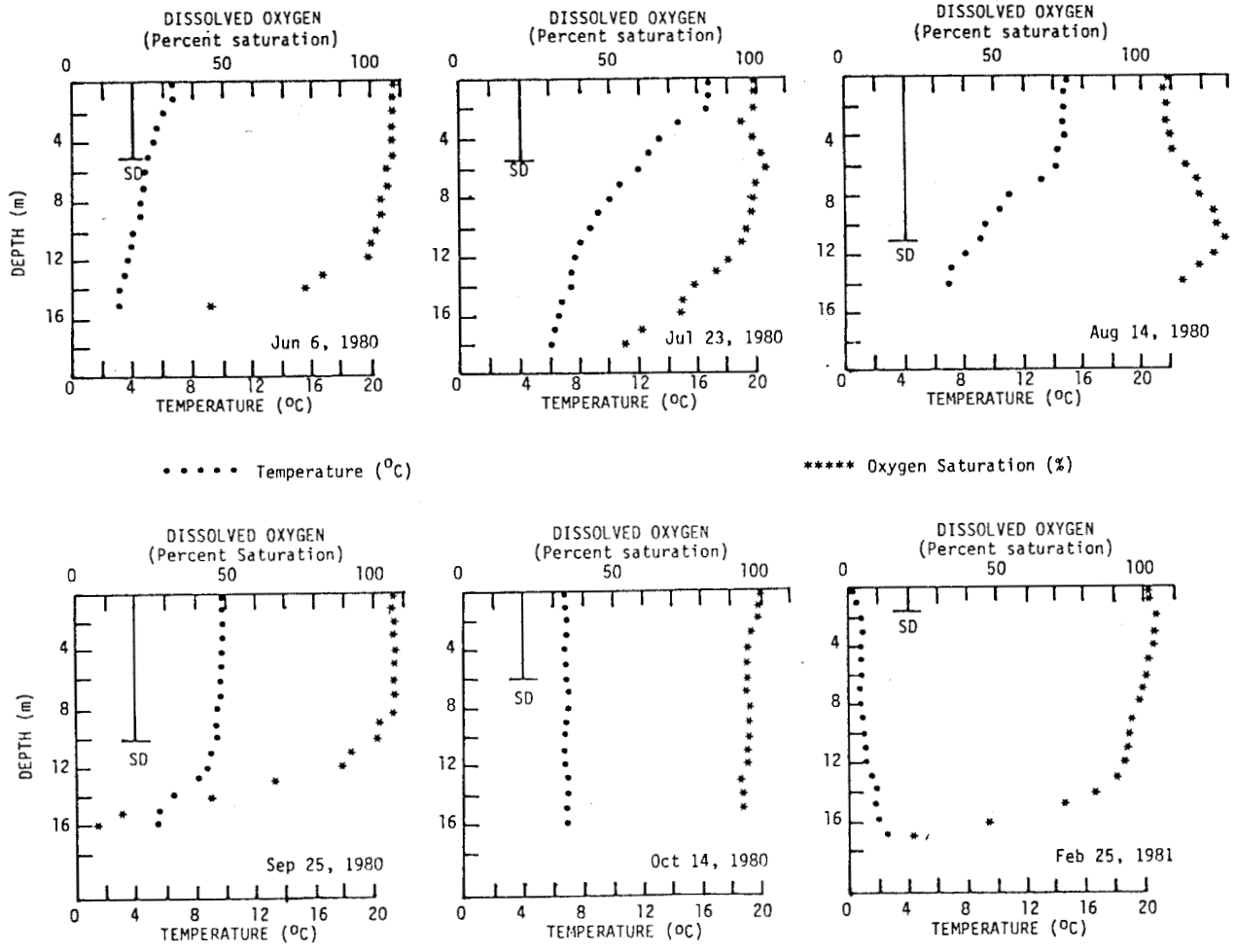

Figure 14. Temperature and dissolved oxygen profiles plus secchi disk depth (SD) of Bear Lake at representative time periods through 1980-81.

the summer (July 23, 1980), the lake warms to nearly 17°C (maximum recorded surface temperatures approach 20°C) and the bottom layers warm to 6°C. However, D.O. levels remain at <100% saturation below the 12 m level. By August 1980, the epilimnion has deepened to 8 m and has cooled to 14°C. At the same time, oxygen is close to 100% saturation at the surface, but exceeds 125% saturation (140% at station B) at the 10-11 m depth just at or below the 1% light level. By early fall (i.e., September 1980, the lake continues to cool as the epilimnion decreases to 9°C, and the thermocline has deepend to 13 m. Below 8 m, the D.O. begins to rapidly decrease as the plankton bloom (responsible for the 125-140% oxygen saturation noted at 10-11 m in August) decline and begins to decompose and use oxygen. Later in the fall (October 1980), the lake becomes isothermal at 7°C and is in the overturn period Consequently, D.O. levels are very close to 100% saturation at all depths. As winter approaches the lake rapidly cools to below 4°C and rapidly flushes due to the heavy rains. Following freeze-up (February, 1981), the lake remains well below 4°C from top to bottom which helps to reduce the rate of microbial decomposition and allows the lake to remain well oxygenated except, again, for the layer below 12 m.

The warming of the hypolimnion above 4°C in the summer, and subsequent cooling below 4°C before freeze-up in the winter is typical of shallow lakes with a great deal of wind generated, early spring and late fall mixing. The increased temperature of the hypolimnion during the summer promotes rapid planktonic growth which accounts for the oxygen supersaturation noted in August. The rapid cooling of the lake during the later part of the summer and early fall, plus the tendency of the lake to rapidly flush at this time (due to fall rains), enables the lake to remain saturated with oxygen above the 10 m depth, and most importantly, flushes out much of summer's plankton production. As a consequence of the fall flushing and low winter water temperatures, which retard the rate of microbial decomposition, the lake remains well supplied with oxygen, except for the >10 m stratum of water.

Nutrients and Algal Abundance

Because of the basin configuration and location of inflowing streams [e.g., the primary inlet is stream #3 (Figure 1) in the southeast part of the watershed], a layer of non-renewed water develops in summer and winter below the 12 m depth. During periods of incomplete spring mixing, this lower layer prevents the return of nitrogen and phosphorus to the epilimnion, reducing subsequent primary production within the euphotic zone during the spring to summer period. In addition, intense zooplankton grazing further reduces the standing crop of desirable species of phytoplankton. Thus, epilimnetic chl a levels were reduced to below 2 $\mu g\ L^{-1}$. This is seen in the drastic increase in light penetration (Figure 4) and secchi disk depths (Figure 14) during August and early September. At the same time, total-P and part-P concentrations were reduced to 3-5 $\mu g\ L^{-1}$ and 2-3 $\mu g\ L^{-1}$ respectively, and inorganic nitrogen values (especially nitrate and nitrite) fell to undetectable levels. In contrast, chl a levels in the shallow hypolimnion reached 18 $\mu g\ L^{-1}$, nearly 10 times that found in the epilimnion. Likewise, total-P values rose to nearly 26 $\mu g\ L^{-1}$ and part-P increased to 18 $\mu g\ L^{-1}$. However, like the epilimnion, inorganic nitrogen values were very low.

Interestingly enough, even though a large difference existed between the primary production of the two layers, silica values of the hypolimnion in 1980 were very close to, or even slightly higher than those within the epilimnion. The reason for this slight rise may be ground water seepage which was detected in the 6°C bottom water isotherm (Figure 2). Since the bloom of phytoplankton that developed at or below 12 m did not depress the hypolimnetic level of silica (as seen in 1979), the increase could not have come from the growth of diatoms. In addition, the bloom developed below the 1% incident light level (or light compensation depth) under severely low N:P ratios. Thus, conditions were ideal for the growth of filimentous blue-green algae.

Algal Production and Zooplankton Abundance

Blue-green algae are not desirable food for filter feeding cladocerans which dominate the zooplankton community of Bear Lake (Figure 12). Because of intense zooplankton grazing, the levels of edible species of phytoplankton were drastically reduced leaving the plankton community dominated by blue-greens (Figure 11). This intense cropping of desirable species maintained chl a levels in the epilimnion below 2 $\mu g\ L^{-1}$ during the summer, and allowed the zooplankton populations to expand their numbers into July and August. However, by early September the zooplankton began to deplete the level of desirable food, and zooplankton numbers began to decline. By the later part of September and early October, the lake began to cool and increased rainfall began to flush nitrogen into the lake. At this point in time, epilimnetic chl a levels were rising (as the lake began to mix) from senescent cells of hypolimnetic blue-green algae (Figure 9). The actual turnover of carbon (Figure 10) was in part from these blue-greens, but also consisted of more edible species of phytoplankton which allowed the zooplankton to maintain maximum densities through October.

This unusual situation of a hypolimnetic maximum of primary production developed because blue-green algae can develop shade adapted species which thrive at <0.01% of surface irradiance (Wetzel and Likens 1979), and their faculative photoheterotrophy may help to explain why blue-greens are often found below the thermocline as in Bear Lake. In such strata, the irradiance is low and mineralization processes result in the release of organic substances or molecules, some of which may form a substrate for heterotrophic nutrition of blue-green algae such as *Oscillatoria* (Golterman 1975). In addition, nitrogen fixation does occur in nonheterocyst containing filamentous algae (such as *Oscillatoria*) and in unicellular blue-green algae, but only in micro-aerophilic conditions i.e., organisms which grow optimally at lower oxygen concentrations (Golterman 1975, Saunders 1972). Usually, cyanophyta (blue-greens) are only abundant in summer and autumn, however, a few species (mainly those of *Oscillatoria*) do appear much earlier (Lund 1965). It is interesting that *Oscillatoria* (possibly *Oscillatoria rubesins*) has been identified within Bear Lake during the spring (Figure 11).

Nitrogen-fixation by blue-greens has also been positively correlated with concentrations of dissolved organic nitrogen (DON) occurring in the water. Algae secrete many simple and complex organic carbon and nitrogen compounds

i.e., secretion of the DON reflects the growth of the blue-green algal populations and concurrant N-fixation (Wetzel 1976). This release of organic substances may account for the slight rise (and apparent anomally) in inorganic carbon observed in the hypolimnion during the summer-fall period of 1981 (Figure 8B).

Trophic Level and Water Quality

Bear Lake was initially deceiving because the usually productive trophogenic zone of the lake (euphotic zone) is almost oligotrophic in nature whereas the usually tropholytic zone (hypolimnion) is the most productive zone and meso-eutrophic to eutrophic in nature. This is just the opposite of most, if not all, deep water lakes studied in Alaska. In essence, the lake is not phosphorus limited since it is at 100-110% of its permissible P loading (Vollenweider 1976), but does develop severely low levels of inorganic nitrogen. Thus, the application of phosphorus to Bear Lake would not increase the production of desirable species of phytoplankton, in fact, it would further deteriorate the water quality of the lake.

Currently, most of the pelagic primary production is channeled into non-edible (by zooplankton) algae and thus, is non-transferable up the food chain to ultimately feed rearing coho fry. To be more specific, the problem lies not in a lack of production, but rather centers on the low quality phytoplankton (or zooplankton food) being produced.

Finally, any decrease in the flushing rate would compound an already serious condition of diminishing oxygen levels and increasing phosphorus concentrations. A decrease in the flushing rate (either during the spring or fall) in combination with a warm sunny summer could result in a drastic reduction in water quality, and may result in near winter kill conditions during the following winter. The potential for this to occur is readily seen by comparing total phosphorus values during fall and spring turnover periods (Figure 5). During fall overturn, concentrations of total-P were at 10-11 $\mu g\ L^{-1}$ (mostly part-P from the summer's plankton production). However, spring turnover values (after heavy fall and spring flushing) only reached 5 $\mu g\ L^{-1}$ in 1980, but in 1981 reached 10-11 $\mu g\ L^{-1}$, which was a result of low fall and spring rainfall suppressing the flushing of decomposable plankton (phosphorus) out of the lake.

As a whole, Bear Lake is transitional between an oligotrophic and a meso-trophic system and, at present, cannot be considered as a candidate for a phosphorus enrichment program. The lake can also be viewed as being in a transitional state to a non-salmonid system unless the trend in evidence for the last two years is reversed. This reversal should begin with an increase in the flushing rate (and cooling) of the system, if possible, and the changing of nutrient ratios within the lake. The N:P atom ratio must be raised to increase the competitive advantage of non blue-green species of algae. This would result in more of the pre-existing productive capacity of the lake being channeled into zooplankton edible species of phytoplankton, i.e., greens and diatoms instead of a biological dead-end such as blue-greens.

RECOMMENDATIONS

1) Ensure that a decrease in the flushing rate of Bear Lake does not occur either by inflow diversion and/or damming or by additional groundwater drawdown by well operation from a growing Bear Creek subdivision.

2) Ensure that there is not an increase in phosphorus loading to the lake via septic systems or farming activities.

3) Increase the supply of nitrogen to the system by judicious application of nitrate-ammonium fertilizer. This would increase the competitive advantage of non blue-green algae.

4) Unless the above can be accomplished, the long term use of the lake as a major coho rearing system should be viewed as a very unsure proposition and alternatives should be identified.

5) Continue monitoring Bear Lake to judge the effects of N-addition on the phyto-and zooplankton communities.

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