COMPLETION REPORT

AN INVESTIGATION INTO THE EXTENT AND CAUSE OF EUTROPHICATION IN GEORGETOWN LAKE, MONTANA

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INTRODUCTION

Georgetown Lake, located 15 miles west of Anaconda is the most heavily used lake in Montana for its size. The Montana Fish and Game Department estimates that Georgetown sustains 81,000 fishermen days per year. This is just under four percent of the total fishing pressure for the state. In addition to fishing, the drainage area provides summer residence, permanent residence, boating, swimming, skiing, horse-back riding, camping, and snowmobiling. The water is also used for irrigation, power supply and industrial purposes.

Increasing developmental trends in the Georgetown watershed were estimated by Lutey, et. al. (1974). Because of the concern for the status of the lake and the potential for development of the watershed the county commissioners and conservation districts from Deer Lodge and Granite Counties agreed that a study is needed to be conducted for an overall land use plan for the Georgetown Lake watershed.

Acknowledgments

The authors would like to express sincere gratitude to Dr. John C. Wright for his assistance throughout the course of this study.

Our sincere thanks is also extended to the Anaconda Mining Company for providing the hydrological and morphometric data. The Montana Power Company provided data concerning the structural aspects of the dam.

The specific objectives of this study were:

1) to determine the present oxygen consuming power of the lake as related to organic content, and to determine the reservoir of plant nutrients in the underlying sediments and the rate at which these nutrients become available for plant growth as related to the oxygen regime of the lake.

2) to determine the nutrient cycle in the lake with particular reference to the mud-water and plant-water interfaces.

3) to determine the seasonal course and rate of organic production in the lake and to determine the relative importance of phytoplankton versus macrophytes in supplying oxidizable organic material to the bottom muds.

History and Description of Georgetown Lake

Mining was established in the Georgetown area as early as 1862. Cattle were first grazed on Georgetown flats in 1872. In 1885 a small earth dam was built across Flint Creek by the Montana Water Electric and Power Company to produce power for the Bi-Metallic Mining Company at Phillipsburg and Granite. The area flooded was a large hay meadow with practically no timber. Very little of the area was patented or surveyed. The Anaconda Copper Mining Company (AMC) purchased the dam in 1901 and built a masonry dam to an elevation of 6424.5 feet above mean sea level. In the same year, the Montana Power Company (MPC) put in a power house to supplement their power demand. In 1919, the AMC raised the dam to the present level of 6429.5 feet. The entire project was deeded to the MPC in 1925. The MPC strengthened the dam and built a two-lane highway across it in 1966.(Beal, 1953, and Georgetown Lake Pre-Study, 1973). Currently, rights to the water in Georgetown Lake are shared by the AMC, and irrigation concerns in the Phillipsburg valley.

Georgetown Lake Dam is located at lat. 46°10'16", long. 113° 10' 42" in sec. 16, T. 5 N, R. 13W, in Deer Lodge County approximately 17 miles west of Anaconda, Montana. Currently the masonry core structure has a crest length of 94.5 m, top width of 2.2 m (7.2 ft) and a maximum base width of 10 m (32.8 ft). Puddled clay seals the lake side of the structure with rock fill support on the downstream side.

The Montana Power Company maintains three outlets at the dam; (1) intake to a power house, 0.85 $m^3.sec^{-1}$ (30 cfs) capacity, (2) 0.76 m (30 in) valve 4.39 $m^3.sec^{-1}$ (155 cfs) capacity and (3) headgate, 3.54 $m^3.sec^{-1}$ (125 cfs) capacity. The spillway, elevation 1959.7 m (6429.5 ft), 0.76 m valve and headgate were not used for discharge during the entire study. Anaconda Mining Company controls pumping into Silver Lake, capacity 1.27 $m^3.sec$ (45 cfs), and the Hardtla Creek return flume, capacity 1.13 $m^3.sec^{-1}$ (40 cfs) (AMC data).

At full capacity, the MPC has the potential to use the entire reservoir, 5,914 x 10^7m^3 (47,924 acre.ft), while the AMC is limited to 4.529 x 10^7m^3 (36,700 acre.ft). Table 1 summarizes the data associated with the structures on Georgetwon Lake.

At maximum pool elevation the lake is 7.05 Km (4.38 mi) long with a maximum and mean breadth of 3.64 Km (2.26 mi) and 1.72 Km (1.07 mi), respectively. The mean depth is 4.89 m (16.03 ft) with a maximum depth of 10.67 m (35.0 ft). The values are maximums however, due to fluctuating water levels.

Table 1. Morphometric and Hydrologic Data

	Elevation		Surface Area		Capacity		Discharge[1]	
	meter	feet	Ha	(Acre)	x $10^7 m^3$	(acre ft)	x $10^7 m^3$	(acre ft)
Spillway	1959.7	(6429.5)	1479.2	(2990)	5.914	(47,924)	0	
Intake to MPC Power House	1949.0	(6394.5)	0		5.914	(47,924)[2]	2.280	(18480)
Intake to Head-gate	1956.5	(6418.97)	1106.6	(2237)	3.686	(29,870)[2]	0	
Anaconda Pump House to Silver Lake	1955.2	(6414.6)	938.0	(1896)	4.529	(36,700)[2]	2.813	(22800)
Dead Storage-MPC	1949.0	(6394.5)	0		0		-	
Dead Storage-AMC	1955.2	(6414.6)	941	(1902)	1.385	(11,225)	-	
Montana Power Co. Power House	1740.8	(5711.3)	-		-		-	
Silver Lake (Full Lake)	1976.6	(6485)	159.3	(322)	1.621	(13138)	3.464	(2807)[3]
North Fork Flint Creek Drainage Area	-		4895	(12096)	-		1.436	(11640)
Stewart Mill Creek Drainage Area	-		4222	(10432)	-		1.468	(11890)

[1] Recorded during entire study, 10 July 1973-16 June 1974

[2] Above Intake

[3] From Silver Lake to Georgetown Lake via Hardtla Creek

Table 2 gives the ranges of morphometric data observed during the study.

North Fork of Flint Creek drains an area approximately 4895 Ha (12,096 acres). Flint Creek originates in the area of Fred Burr Pass and flows past old mines and the most developed section of the lake watershed.

Stewart Mill Creek originates from a spring approximately 200-300 m from the lake. The spring receives its flow from a drainage area of approximately 4222 Ha (10432 acres).

Since the entire drainage area of Georgetown Lake is 13728 Ha (33920 acres). The remaining area (excluding Flint Creek and Stewart Mill) presumably discharges ground water to the lake. Surface streams to the south of the lake disappear and other surface water is negligible.

A general geological description of the study area can be found in Alt and Hyndman (1972).

Five sampling stations were established within the lake. Station I was located in the main channel in the vicinity of the dam. Stations II and III were off Rainbow Point and Piney Point, respectively. Station IV was in Jericho Bay and Station V was located at the mouth of Stewart Mill Bay (Figure 1).

In addition to sampling points within the reservoir, North Fork of Flint Creek was sampled at the bridge on Highway 10A; Stewart Mill Creek samples were taken at the bridge on the road to the south of the lake; and Flint Creek below the lake was sampled where the creek flowed out of the power house.

Table 2. Morphometric Data during the study.

		Full Capacity	Range[1]
Maximum Depth		10.67 m (35.0 ft)	9.27 - 10.27 (30.4 - 33.7 ft)
Mean Depth [2]		4.89 (16.03 ft)	3.9 - 4.6 m (12.80 - 15.09)
Maximum Length		7.05 Km (4.38 mi)	7.00 - 7.03 Km (4.33 - 4.37 mi)
Maximum Breath		3.64 Km (2.26 mi)	3.60 - 3.56 Km (2.24 - 2.21 mi)
Mean Breath [2]		1.72 Km (1.07 mi)	1.56 - 1.67 Km (097 - 1.04 mi)
Length of Shoreline		26.87 Km (16.7 mi)	24.6 - 26.2 (15.3 - 16.3 mi)
Shoreline [2] Development		2.18	2.11 - 2.16
Mean Retention Time	summer	804 days	337 - 6112 days
	winter	493 days	

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[1] Range was maximum and minimum during 10 July 1973 - 16 June 1975

[2] Definition of these parameters in Reid (1961)

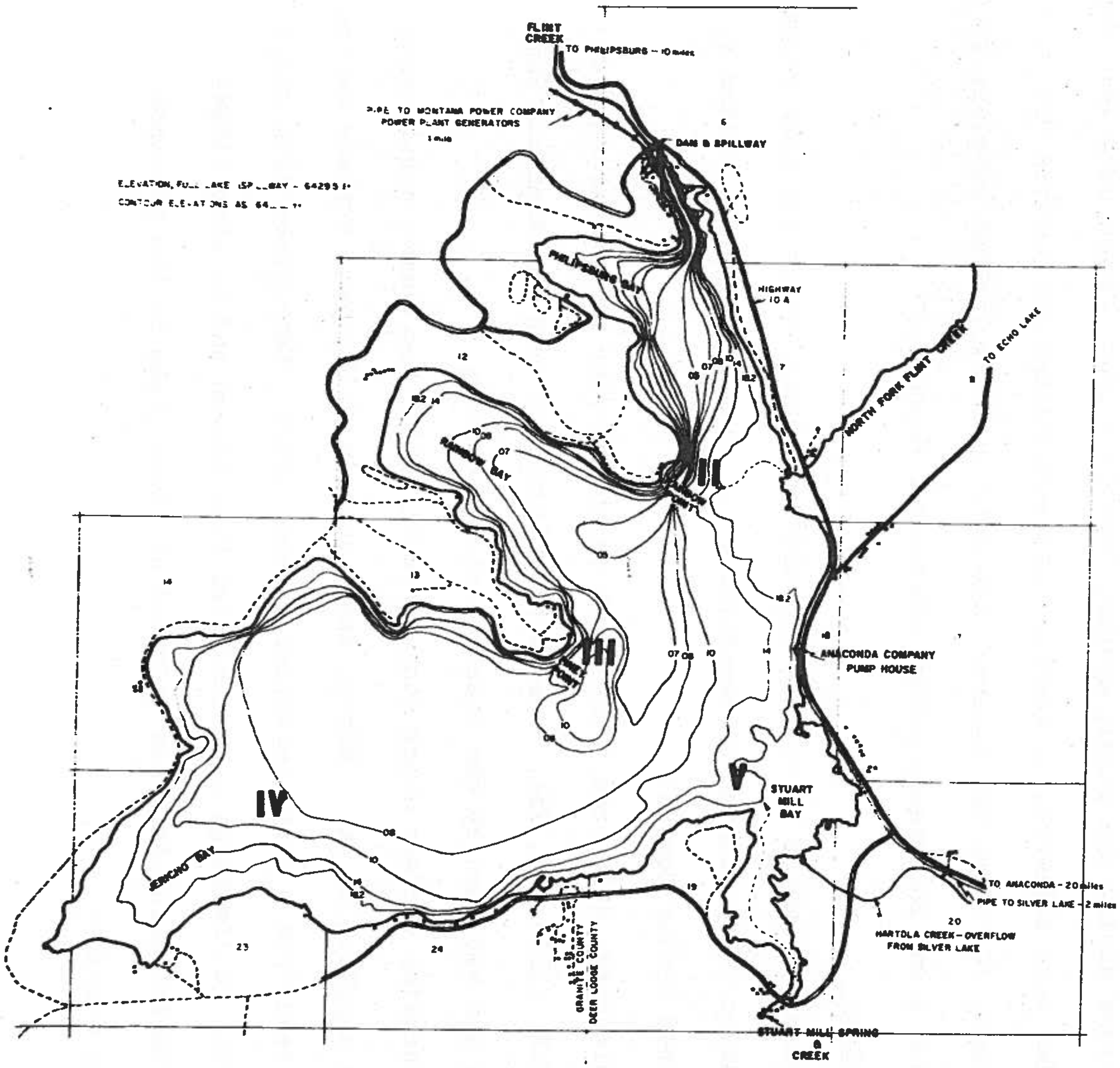


Figure 1. A map of the study area showing the locations of the sampling Stations I-V

METHODS

All samples were collected at biweekly intervals from all lake and creek locations during the summer months, July 73 - Sept. 73 and June 74 - Aug 74. Samples were collected at monthly intervals during the periods Oct 73 - May 74 and Sept. 74 - June 75, however, ice cover usually limited sampling to only Station I and the creeks during the winter months.

Hydrology

Reservoir water elevations recorded on a daily basis and lake volumes and areas corresponding to reservoir water elevations were supplied by the Anaconda Mining Company.

Discharge data from Flint Creek below the lake were obtained from the U.S.G.S. (1973, 74, 75). Discharge information from the Anaconda Pump House was supplied by the Anaconda Mining Company.

Incoming surface water stage records during the summer months were again supplied by AMC. Winter stage records on incoming surface waters were read from a gauge installed on each creek. Conversion from stage readings to discharge was calculated from Bowman and Lessley (1968).

Precipitation data was recorded at Silver Lake by the Anaconda Mining Company.

Light

Total daily solar radiation incident upon the reservoir surface was measured by either a Kipp and Zonen Model CM-3 or a Kahl pyranometer and recorded with an Esterline Angus, Model 80-M, recorder; these were installed at the Montana Fish and Game Department Cabins located on N. Fork Flint Creek. Daily radiation was converted to Langley day^{-1} as described by the Kipp and Zonen instrument manual.

A vertical profile of light penetration at one meter intervals through the water column was obtained by a Kahl submarine photometer containing a selenium photocell. The mean extinction coefficient was calculated by the method of Hutchinson (1957)

Temperature and conductivity

Temperature was recorded at every sampling location at one meter intervals using a Yellow Spring Oxygen Meter equipped with an electronic thermistor.

Conductivity measurements, corrected to μmhos.cm^{-1} at 25°C, was measured in the laboratory at a frequency of 1 KH$_z$ with a Yellow Spring AC Conductivity Bridge, Model 31.

Water Chemistry

The influent and effluent waters were collected directly into reagent bottles. All water samples in the lake, with the exception of oxygen, were collected with a 3-liter polyvinyl chloride Van Dorn Type water bottle. Samples at Station I were collected at two meter intervals, collection at all other stations were made at three meter intervals.

Immediately upon collection of water samples, one liter of water was filtered through a Gelman type A glass fiber filter and 0.5 liter was saved in an acid-washed glass reagent bottle for chemical analysis. The filter was immersed in 5 ml of 90% acetone contained in a darkened centrifuge tube for chlorophyll a determinations. A 300 ml glass reagent bottle was filled with unfiltered water for alkalinity, chloride, and conductivity determinations.

Concentrations of Na, K, Ca, and Mg were determined by atomic emmission absorption spectroscopy using an Instrumentation Laboratory AA/AE Model 131 spectrophotometer. Alkalinity and chloride were determined titrimetrically as described by APHA (1971). Sulfate was determined turbidimetrically as described by APHA (1971) using Hach Chemical Co. Sulfate Ver$^{(R)}$III. pH was determined with a Beckman Expanded Scale pH meter, Model 76. Inorganic carbon species were estimated by calculation involving pH total alkalinity and temperature, using the equations of Rainwater and Thatcher (1960).

Concentrations of N and P species were determined colorimetrically with a Klett-Summerson spectrophotometer using the following tests: NH_3-N, hypochlorite oxidation method of Strickland and Parsons (1972); NO_3-N, reduction method of Mullin and Riley (in Barnes, 1962); NO_2-N, Hach Chemical Co. reagents and procedures; total nitrogen-N, acid digestion, hypochlorite oxidation method of Strickland Parsons (1972); O-PO_4-P, combined reagent method in Strickland and Parsons (1972); total phosphorus -P, acid and persulfate digestion, combined reagent method in Strickland and Parsons (1972).

Iron and silica were determined colorimetrically with a Klett-Summerson spectrophotometer using the following tests: Iron, Hach Chemical Co. Ferro Zine $^{(R)}$; silica, molybdosilicate complex method in APHA (1971)

Flouride was analyzed colorimetrically using Hach Chemical Co. SPANS reagent.

Total organic carbon was measured using a Beckman Laboratory Carbonaceous Analyzer.

Oxygen concentrations were either measured <u>in situ</u> with a Yellow Springs Oxygen Meter or by the Winkler method described in Strickland and Parsons (1972).

Sediments

Sediment samples were collected at the same given lake stations as the water samples. Samples were collected from 12 September 1973 to 7 January 1975 generally at the same time and place as the water samples. Single grab samples were collected with an Ekman dredge. The sampler generally collected a mixed sample to a depth of 10-15 cm. However, at Stations II, III, IV, and V during periods of large macrophytic growth, sampling was more difficult. At these times the dredge only penetrated the bottom sediment a few centimeters, therefore, 3-4 samples were composited into one sample.

Sampling error may be much greater when collecting sediments than when gathering water samples. This is because water is generally more homogenous horizontally than sediments. Because it was not possible to mark the stations with permanent markers the samples were not always collected in the same exact place. Because of the great variability of the bottom, results were sometimes non-comparable. Station I was generally sampled in the same area because it was located near a dock. However, at the other stations the sampling area was much larger thereby increasing the sampling errors.

After the samples were collected they were dried in an oven at 60-70 C and ground with a porcelain mortar and pestle to pass through a 100 mesh sieve.

Chemistry

Total phosphorus and inorganic phosphorus were determined using the extraction method of Mehta et al (1954). Total phosphorus in the combined extracts was converted to inorganic phosphorus with potassium persulfate sulfuric acid, and heating in an autoclave as described by the Environmental Protection Agency (1971). The inorganic phosphorus was analyzed by the

Single Reagent Method (Environmental Protection Agency, 1971). The difference between the total phosphorus and the inorganic phosphorus was reported as the total organic phosphorus.

Total nitrogen was extracted by the Kjeldahl digestion method and determined using steam distillation (Bremner, 1960). Total organic nitrogen was determined by the method of Bremner (1965) in conjunction with steam distillation. Total inorganic nitrogen was determined as the difference between total nitrogen and total organic nitrogen.

Organic carbon was determined using the Walkley-Black method modified by heating the sample to 150 C (Allison, 1965). This actually determines the chemical oxygen demand of the sample. The organic carbon content was determined by multiplying a correction factor of 1.12 as recommended for soils of western United States (Allison, 1965).

The initial volatile solids were determined by weight loss after combustion at 600 C for one hour. Prior to combustion the samples were dried at 110 C.

Iron oxides were extracted using the sodium dithionite method of McKittrick and Hope (1963). Exchangeable iron was extracted with neutral 1 N ammonium acetate (Chapman 1965). The iron extracted by these procedures was determined using the orthophenanthroline method of Olson (1965).

Aluminum oxides were extracted using the sodium dithionite method (McKittrick and Hope, 1963). Exchangeable aluminum was extracted with 1 N KCl as described by Syers et al. (1971). The aluminum extracted by these methods was determined using the methylthymol blue method (Arshad et al, 1972).

Exchangeable calcium, magnesium, manganese, and zinc were extracted with neutral 1 N ammonium acetate (Chapman, 1965). These cations were determined using atomic absorption spectroscopy as described in APHA (1971)

The hydrogen ion activity was determined on the samples after they had been frozen and then thawed, with a Beckman Expanded Scale pH meter (Model 76).

All colorimetric determinations for the sediment chemistry were made with a Klett-Summerson colorimeter.

Phytoplankton Standing Crop and Metabolism

Phytoplankton samples were collected simultaneously with water chemistry samples. A 125 ml aliquot was preserved with acetic Lugol's solution. Later in the laboratory, samples collected at the same station and on the same date were combined to form a composite sample. The composite sample was uniformly resuspended and an appropriate volume was concentrated and tabulated according to the membrane filter technique as described in APHA (1971).

Phytoplankton organisms were identified to the lowest taxonomic division as possible. Prescott (1962), Smith (1950) and Ward and Whipple (1959) were used for identification of all taxa except the Bacillariophycae. The diatoms were identified by use of FWPCA Bulletin (1966), Patrick and Reimer (1966) and Hustedt (1930).

Phytoplankton were measured to obtain mean cell volumes per taxa by assuming appropriate geometric volumes. Standing crop estimates were expressed as cell volume per liter ($mm^3 \ell^{-1}$).

Standing crop of phytoplankton was also estimated by $chlorophyll_a$ concentration corrected for phaeopigments, by the method of Strickland and Parsons (1972).

Photosynthesis and respiration, were measured by changes of oxygen in light and darkened BOD bottles. The samples were resuspended at the depth from which they were collected. After incubation, the change in oxygen was determined by the Winkler method. A microburrette was used for all oxygen titrations. This technique closely followed that described by Strickland and Parsons (1972).

RESULTS

Hydrology

Figure 2 illustrates the surface elevation of water in Georgetown Lake throughout the course of the study. The lake had less water in 1973 than in 1974 and 1975. On a yearly basis, the lake is lowest in April and highest in June. The decrease in volume of the lake from January to April was a function of the pumping rate and duration of pumping of the Anaconda Mining Company. The increase of volume from April to June was associated with the spring runoff and snowmelt. Generally, throughout the summer and fall the lake remains fairly constant, indicating equal inflows and outflows.

The above qualitative statements can be expressed quantitatively by the following:

$$\begin{aligned}\text{Lake Vol}_{T+1} - \text{Lake Vol}_{T} = {} & \text{Surface Inflow}_{T \text{ to } T+1} - \text{Surface Outlfow}_{T \text{ to } T+ 1} \\ & + \text{Precipitations}_{T \text{ to } T+1} + \text{Groundwater}_{T \text{ to } T+1} \\ & - \text{Evaporation}_{T \text{ to } T+1}\end{aligned}$$

where

T = a beginning time

and T + 1 = a time after T

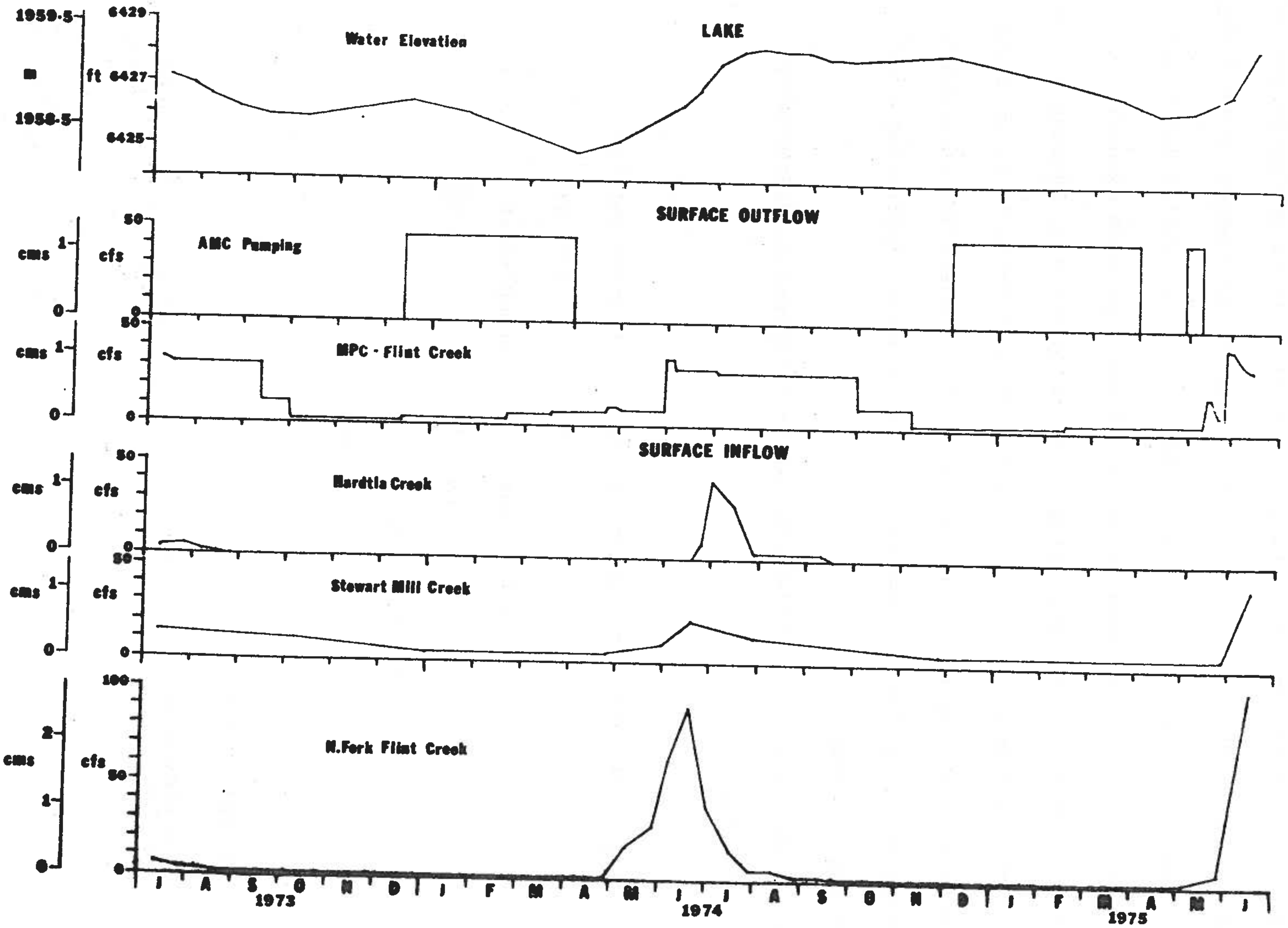


Figure 2. Reservoir surface water fluctuation and discharges of inflowing and outflowing surface waters.

Since daily precipitation rates, groundwater flows, and evaporation rates are not known for Georgetown Lake, an exact hydrological budget cannot be made. However, yearly budgets have been estimated, (Table 2), by the assumption that precipitation and evaporation directly affecting the lake during the ice covered period is negligible. Ground water flows were then calculated. Extrapolation of mean groundwater flow over the entire time period with the addition of precipitation data yielded an evaporation estimate.

Table 3 shows the relative importance of all the inflows and outflows. Flint Creek irrigation and power withdrawals, Anaconda Co. pumping activity, and evaporation caused essentially the same percentages of water loss from the reservoir. Groundwater inflows for 1973-74 and 1974-75 were 55.2 and 41.6 percent, respectively, of the total water input to Georgetown lake for these two years. Hardtla Creek return from Silver Lake amounted to 1.1 and 6.1 percent of the yearly imputs, while N. Fork of Flint Creek and Stewart Mill Creek added 11.5 to 21 percent. Also evident from Table 3 is that inflows were substantially higher the second year as compared to the first year. This can easily be related to the greater precipitation the second year.

Table 3

Hydrological Data

		10 July 73 - 5 June 74 Volume of Water (m^3)	Percent	5 June 74 - 16 June 75 Volume of Water (m^3)	Percent
Inflow	Hardtla Creek Overflow	3.678×10^5	1.1	3.096×10^6	6.1
	Stewart Mill Creek	6.446×10^6	19.7	8.232×10^6	16.3
	North Fork Flint Creek	3.761×10^6	11.5	1.060×10^7	21.0
	Precipitation	4.114×10^6	12.6	7.492×10^6	14.9
	Ground Water	1.809×10^7	55.2	2.097×10^7	41.6
	Total	3.278×10^7	100.1	5.039×10^7	99.9
Outflow	Flint Creek	9.522×10^6	26.8	1.328×10^7	30.5
	Anaconda Pump into Silver Lake	1.337×10^7	37.6	1.476×10^7	33.9
	Evaporation	1.269×10^7	35.7	1.554×10^7	35.7
	Total	3.558×10^7	100.1	4.358×10^7	100.1

Light

The total daily solar radiation recorded for Georgetown lake is given in Table 4. The values ranged from a low of 78 Langley.day^{-1} in December to 712 Langley.day^{-1} in June. More meaningful to the organisms within the lake is the actual amount of light energy received. The percentage of incident solar radiation that was reduced by snow and ice cover ranged from a high of 82.8% reduction in February to 54.2% reduction in November and May.

The mean extinction coefficient is a measure of the absorption of light through a column of water. Generally, the extinction coefficient is a function of particulate material (both living and dead), suspended solids and dissolved or colloidal material (Hutchinson 1957). Through the summer months phytoplankton standing crops were large and had a substantial effect on the extinction coefficient. During the winter months, however, the extinction coefficient is probably more of a function of bacteria and suspended and dissolved solids.

Verduin (1964) and Odum (1971) defined the euphotic zone as the depth of surface water at which photosynthesis just balances respiration. Parsons and Takahashi (1973) estimate that about 5 Langley.day^{-1} represents the compensation point.

Table 4 Light Data

Month	Monthly Mean Daily Solar Radiation (Ly.day^{-1})	Monthly Mean Daily Incident Radiation Upon Water Surface (Ly.day^{-1})	Mean Extinction Coefficient (m^{-1})	Depth of Euphotic Zone (m)	Depth of Euphotic Zone (ft)	Area of Lake above, lower limit of Euphotic Zone (Ha)	(Acres)	(%)
January	97	20	0.71	1.95	(6.40)	190	(469)	16.7
February	227	39	0.60	3.42	(11.22)	341	(843)	30.1
March	404	79	0.73	3.78	(12.40)	387	(944)	34.6
April	654	122	0.85	3.76	(12.34)	390	(963)	35.1
May	585	268	0.93	4.28	(14.04)	451	(1114)	39.8
June	712	712	0.61	8.13	(26.67)	1136	(2807)	99.0
July	658	658	0.71	6.87	(22.54)	1115	(2755)	96.2
August	593	593	0.75	6.37	(20.90)	1032	(2550)	89.8
September	462	462	0.67	6.76	(22.18)	1105	(2731)	96.2
October	327	327	0.45	9.29	(30.48)	1112	(2749)	99.9
November	97	44	0.43	5.06	(16.60)	539	(1331)	46.0
December	78	27	0.59	2.86	(9.38)	280	(691)	24.4

Using 5 Langley.day $^{-1}$ as the lower limit of the euphotic zone, the mean daily incidence radiation upon the water surface and the mean extinction coefficient, the depth of the euphotic zone on a monthly basis was calculated and given in Table 4. The depth of the euphotic zone ranged from a low of 1.95 m (6.4ft) in January to 9.29 m (30.48 ft) in October. Reduction of total incident solar radiation coupled with a higher extinction coefficient drastically reduced the euphotic zone in the winter months.

To estimate the amount of underlying sediments exposed within the euphotic zone, the mean euphotic zone depth was used to calculate a mean area of sediments exposed to at least 5 Langley.day^{-1} light intensity. These values are also presented in Table 4. The percentage of the area of lake bottom in the euphotic zone ranged from a low of 16.7% in January to a high of 99.9% in October. Winter (ice-cover) months averaged 32.4% of the bottom within the euphotic zone, while summer (ice-free) months averaged 96.2% of the lake sediments exposed.

<u>Temperature and Conductivity</u>

Figure 3 illustrates the temporal variation of temperature at Station I throughout the course of the study. There was no significant temperature difference between stations. As soon as the ice melted, a rapid period of warming existed which resulted in temperatures between 16°C and 20°C for two months. Rapid cooling was observed in October. Thermal stratification was non-existent during the ice-free season and a very weak stratification pattern was observed during the ice-covered periods. Hutchinson (1941) attributes a rise in temperature under the ice to heat exchange from the bottom sediments, this was observed in Georgetown from the onset of ice-cover. Also, a slight depression of the isoclines during March indicates some degree of ice melt.

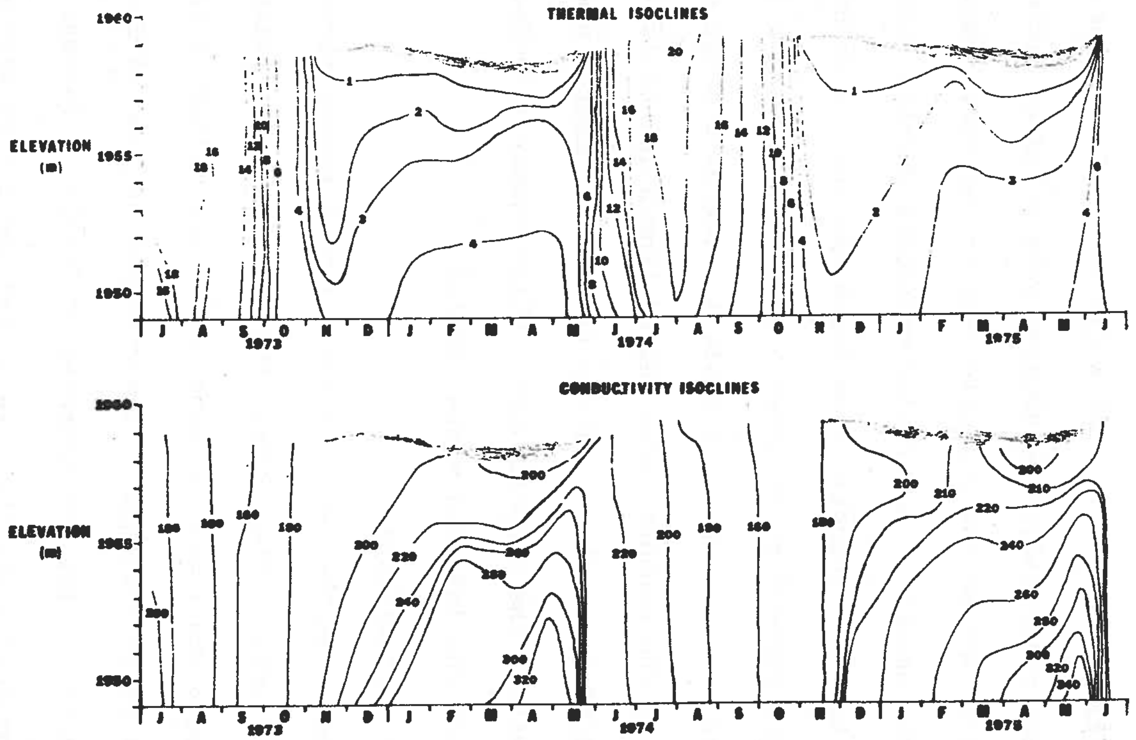


Figure 3. Seasonal isoclines of temperature (°C) and conductivity(μmhos-cm^{-2}).

Conductivity isoclines at Station I for the same time period as temperature, indicate chemical stratification did not exist during the ice-free period. However, about a month after the onset of ice-cover chemical stratification was observed and continued to increase as the ice-cover persisted. When the ice melted a very rapid loss of stratification and chemical content occured. The process of chemical release from the sediments under the ice is a function of the oxidative state of the sediments, hence dependent upon the dissolved oxygen in the free water. Hutchinson (1941) also points out the importance of density currents which tend to accumulate dissolved materials in the lower depressions of lakes.

Water Chemistry

The ranges and means of the concentrations of chemical analyses are presented in Table 5. Generally, the concentrations of most parameters were higher when the lake was ice-covered. Dilution of inflowing surface waters by snow-melt effectively reduced concentrations at that time. Exept for low-dissolved oxygen concentrations under the ice, the lake and its tributaries did not exhibit concentrations of any parameter that could be considered harmful to the biota. (FWPCA, 1968).

Dissolved Gases and pH

As shown in Figure 4, dissolved oxygen concentrations are relatively high during the ice-free months. Slight oxygen deficits in the lower 3-4 meters during the early summer were probably a result of oxygen utilization by biological respiration. Later in the summer, oxygen values were at or near 100% saturation with the atmosphere and relatively homogenious with depth. High plant production coupled with vertical mixing probably

Table 5. Chemical Data.

Analysis	Georgetown Lake	Stewart Mill Creek (Inflow)	North Fork Flint Creek (Inflow)	Flint Creek (Outflow)
Temperature (°C)	0 - 20.6 (8.9)	4.8 - 10.0 (6.4)	0.3 - 18.1 (7.5)	2.5 - 19.0 (9.5)
Conductivity (umhos.cm^{-2})	140 - 348 (212)	175 - 317 (268)	134 - 275 (217)	168 - 335 (245)
pH	7.20 - 9.28 (8.61)	7.57 - 8.30 (7.90)	7.74 - 8.52 (7.96)	7.59 - 9.13 (7.92)
Dissolved gases:				
Oxygen (mg.l^{-1})	0 - 13.26 (5.60)	7.65 - 11.6 (9.93)	5.87 - 10.94 (9.22)	5.75 - 11.16 (8.96)
Carbon Dioxide (mg.l^{-1})	0.09 - 25.2 (0.67)	1.95 - 9.65 (4.50)	0.75 - 7.20 (2.32)	0.15 - 13.1 (3.15)
Cations:				
Calcium (mg.l^{-1})	18.2 - 47.0 (28.4)	34.9 - 42.0 (37.6)	21.0 - 37.0 (31.0)	18.4 - 45.2 (33.5)
Magnesium (mg.l^{-1})	8.8 - 17.0 (10.6)	9.6 - 14.8 (12.4)	5.6 - 11.1 (7.6)	6.8 - 16.5 (10.6)
Sodium (mg.l^{-1})	1.1 - 1.9 (1.6)	0.8 - 1.8 (1.4)	1.0 - 1.7 (1.2)	1.3 - 1.9 (1.7)
Potassium (mg.l^{-1})	0.7 - 2.2 (1.4)	1.1 - 2.0 (1.6)	0.7 - 2.4 (1.4)	1.0 - 2.1 (1.8)
Iron (ug.l^{-1})	1 - 850 (35.6)	0 - 10 (2.0)	5 - 120 (53)	18 - 830 (170)
Anions:				
Bicarbonate (mg.l^{-1})	85.2 - 225 (126)	126 - 181 (164)	80.6 - 176 (121)	92.8 - 236 (140)
Carbonate (mg.l^{-1})	0.09 - 6.41 (1.57)	0.17 - 0.93 (0.5)	0.15 - 1.71 (0.26)	0.21 - 4.30 (0.32)
Sulfate (mg.l^{-1})	2.5 - 10.2 (6.3)	4.8 - 10.2 (7.9)	3.8 - 7.9 (5.2)	1.0 - 9.0 (6.3)
Chloride (mg.l^{-1})	0.1 - 1.0 (0.6)	0.1 - 0.4 (0.2)	0.1 - 0.5 (0.2)	0.1 - 0.9 (0.5)
Fluoride (mg.l^{-1})	0 - 0.3 (0.10)	0 - 0.3 (0.1)	0 - 0.3 (0.1)	0 - 0.3 (0.1)

Table 5. Chemical Data (continued)

Analysis	Georgetown Lake	Stewart Mill Creek (Inflow)	North Fork Flint Creek (Outflow)	Flint Creek (Outflow)
Silica ($mg.1^{-1}$)	0.2 - 18.2 (6.1)	3.7 - 14.4 (4.7)	6.7 - 14.5 (11.2)	3.2 - 18.2 (7.4)
Nutrients:				
Total Phosphorus ($ug.1^{-1}$)	12 - 165 (28.7)	3 - 32 (13.5)	4 - 38 (18.3)	17 - 134 (46.8)
Ortho-Phosphorus ($ug.1^{-1}$)	0 - 114 (5.2)	1 - 23 (5.2)	0 - 13 (5.2)	0 - 97 (18.8)
Total Nitrogen ($ug.1^{-1}$)	30 - 1560 (370)	0 - 350 (145)	0 - 355 (163)	100 - 1015 (493)
Nitrate-Nitrogen ($ug.1^{-1}$)	0 - 95 (9.8)	16 - 63 (48)	0 - 36 (7.0)	0 - 46 (10.2)
Nitrite-Nitrogen ($ug.1^{-1}$)	0 - 19 (2.3)	0 (0.0)	0 (0.0)	0 (0.0)
Ammonia-Nitrogen ($ug.1^{-1}$)	0 - 208 (19.3)	0 - 9.0 (3.6)	0 - 16 (2.9)	0 - 410 (54.4)
Organic Carbon ($ug.1^{-1}$)	1.9 - 14.3 (5.9)	0 - 4.3 (1.2)	0.5 - 6.9 (3.7)	2.0 - 15.5 (4.1)

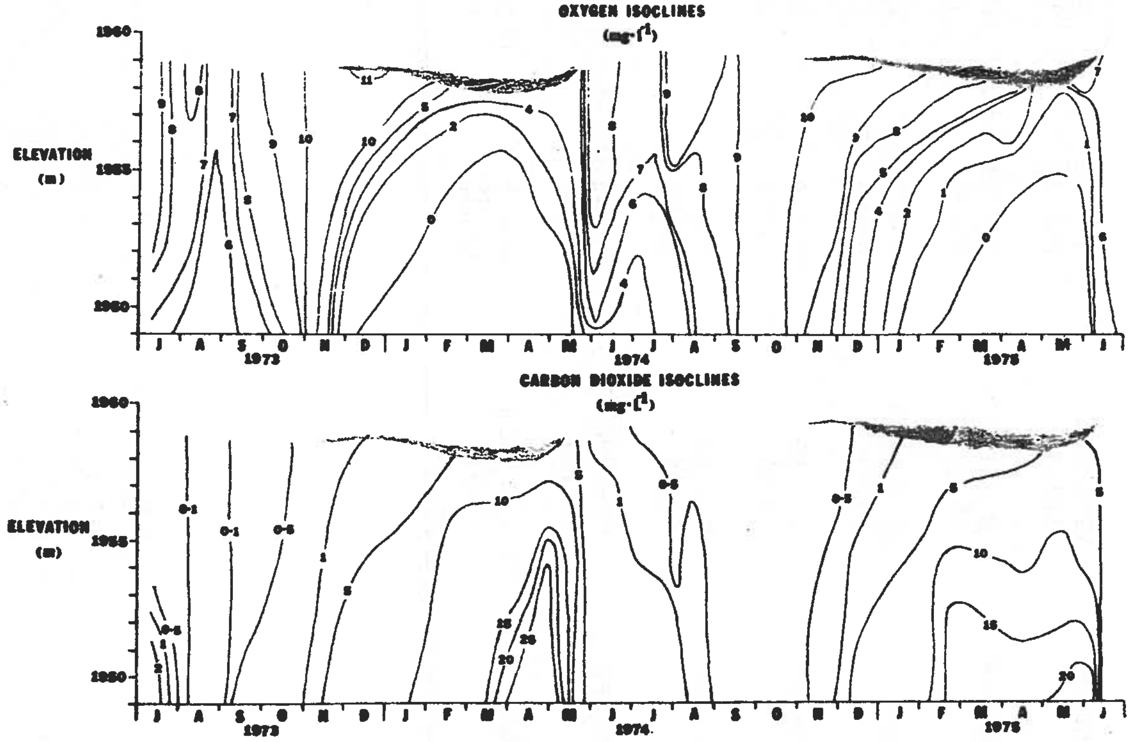


Figure 4. Seasonal isoclines of oxygen ($mg.l^{-1}$) and carbon dioxide ($mg.l^{-1}$).

accounted for the high oxygen concentrations. With the onset of ice-cover oxygen content rapidly decreased. An anoxic zone, ie.zero oxygen, began to develop in December 1973, and February 1974. The differences between the two years is most likely a function of the degree of plant production the previous summer and subsequent decomposition. Due to increased turbulent mixing associated with ice-melt, oxygen was rapidly replenished to the water column.

Patterns of pH changes were similar to those for oxygen. The pH, (as with oxygen), was highly dependent upon the relative metabolic rates, ie respiration compared to photosynthesis, and the carbonate equilibrium system. High pH values, associated with photosynthetically removed carbon dioxide, are observed during the summer. These pH values are conducive to $CaCO_3$ precipitation. Under the ice, the minimum observed pH was 7.20. Indicating a net input of CO_2 from biological respiration. $CaCO_3$ has the potential to become redissolved at these lower pH values. Generally, pH fluctuations are small in hardwater lakes due to the buffering capacity of $CaCO_3$.

Carbon dioxide isoclines are also presented in Figure 4. Typically carbon dioxide concentrations showed the inverse pattern as for oxygen. Again, relative respiratory and photosynthetic rates control the amount of carbon dioxide in the water column. As expected, during high photosynthetic action in the summer, CO_2 is effectively reduced to less than 0.1 $mg.1^{-1}$. Under the ice when respiration predominates, carbon dioxide levels rise to over 25 $mg.1^{-1}$. Carbon dioxide concentrations continued to increase in the anoxic zone, indicating anaerobic respiration.

Comparing the two summers, CO_2 concentrations reached a lower minimum in 1973 than in 1974. Qualitatively, primary production was probably greater in the summer of 1973 than 1974. This observation agrees with the hypothesis of the increased rate of oxygen depletion and development of the anoxic zone under the ice during the respective winters.

Cations and Anions

Table 5, in addition to other parameters, give the ranges and mean values of the major cations and anions. Chloride, carbonate and fluoride account for less than 0.4% of the anions; sodium and potassium accounted for less than 4% of the cations. All of the water sampled can be classified as a calcium bicarbonate type. The bicarbonate ion accounted for over 95% of the total alkalinity since the carbonate ion concentration was low at the observed pH values.

The mean relative abundance of cations and anions in Georgetown lake is the same as that reported by Hutchinson (1957) for the mean values of freshwater. Typically, waters that have the above relative abundance drain from geological formations of sedimentary origin. The geological hystory described by the Georgetown Lake Pre-Study Committee (1973) included the deposition of sedimentary deposits rich in limestone and gravel.

Since most of the dissolved solids were shown to be calcium and bicarbonate ions, the calcium and bicarbonate isocline illustrated in Figure 5 resemble those for conductivity. The yearly trend is similar for calcium and bicarbonate as was observed for CO_2. Bicarbonate and calcium ions decreased throughout the summer indicating photosynthetically induced $CaCO_3$

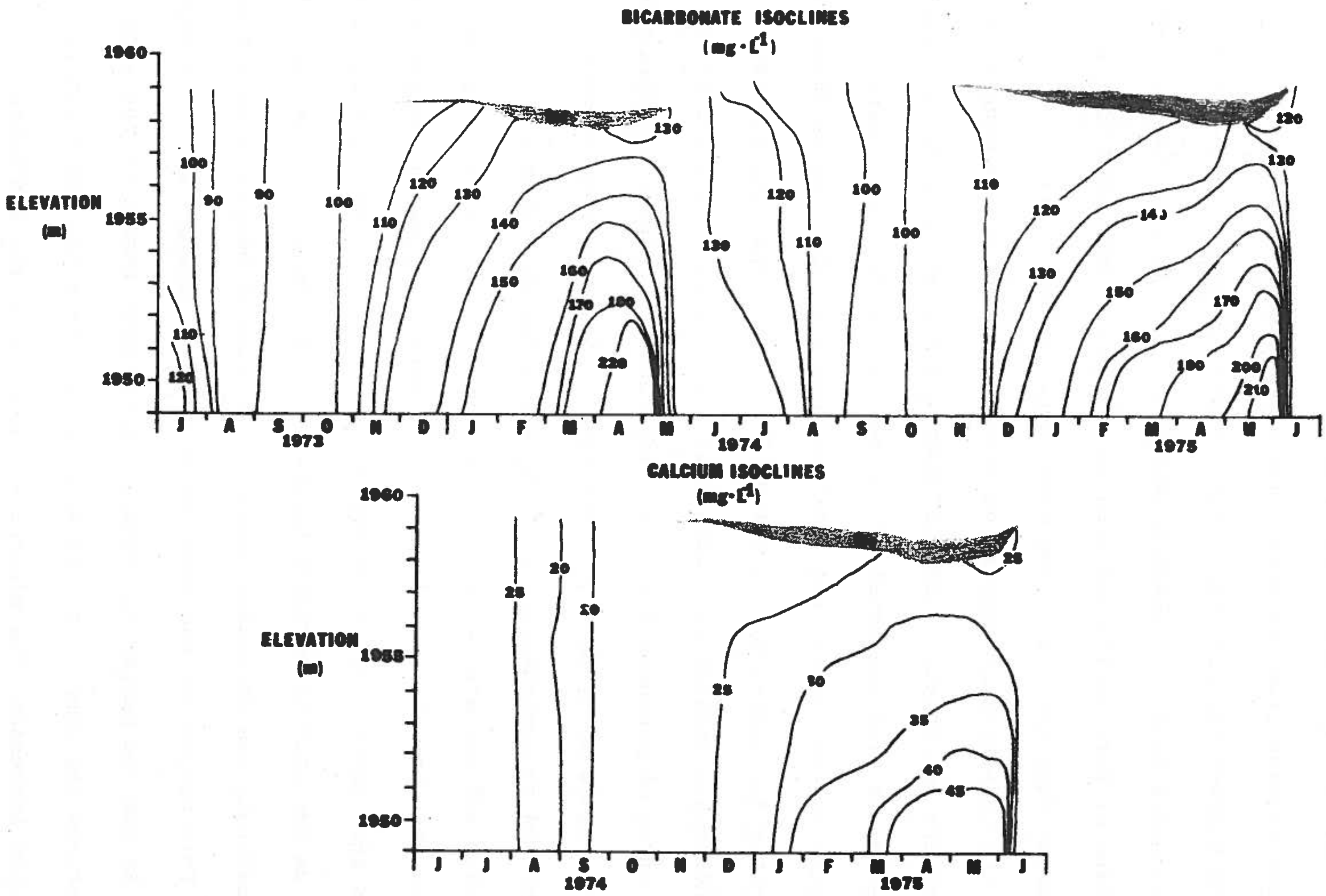


Figure 5. Seasonal isoclines of bicarbonate ($mg.l^{-1}$) and calcium ($mg.l^{-1}$).

precipitation. Both calcium and bicarbonate concentrations increased under the ice. This increase was probably due to $CaCO_3$ dissolution and release of adsorbed calcium from the underlying sediments.

Figure 6 shows the seasonal isoclines for silica and iron. Silica concentrations were above the minimum requirement for diatoms (Lund, 1964). Accumulation of both silica and iron under the ice and rapid loss to the sediments when the ice melted were observed both years.

With the exception of sodium, chloride, fluoride and carbonate, all of the cations and anions increased under the ice and were rapidly lost to the sediments with the onset of ice melt and subsequent oxygenation of the water column. Thus, the chemical nature of the lake is directly or indirectly influenced by the metabolism of the organisms present. Oxygen and carbon dioxide concentrations are directly regulated by the relative rates of photosynthesis and respiration. Calcium and bicarbonate levels are regulated by thermodynamic equilibrium reactions which in turn are influenced by concentrations of CO_2 and hence pH. Magnesium, potassium, silica, iron and sulfate concentrations appear to be regulated by the relative adsorptive capacity of the under-lying sediments. Stumm and Morgan (1970) discussed the reducing and oxidyzing potential of the mud-water interface. Briefly, as the over-lying water became reduced, the adsorptive capacity of the sediments was decreased causing a release of compounds to the over-lying waters. This phenomenon was observed both years during the ice-covered period. As the ice melted and with the subsequent mixing of the water column, oxygen entered the water from the atmosphere. Thus the mud-water interface was oxidized increasing the adsorptive capacity of the sediments.

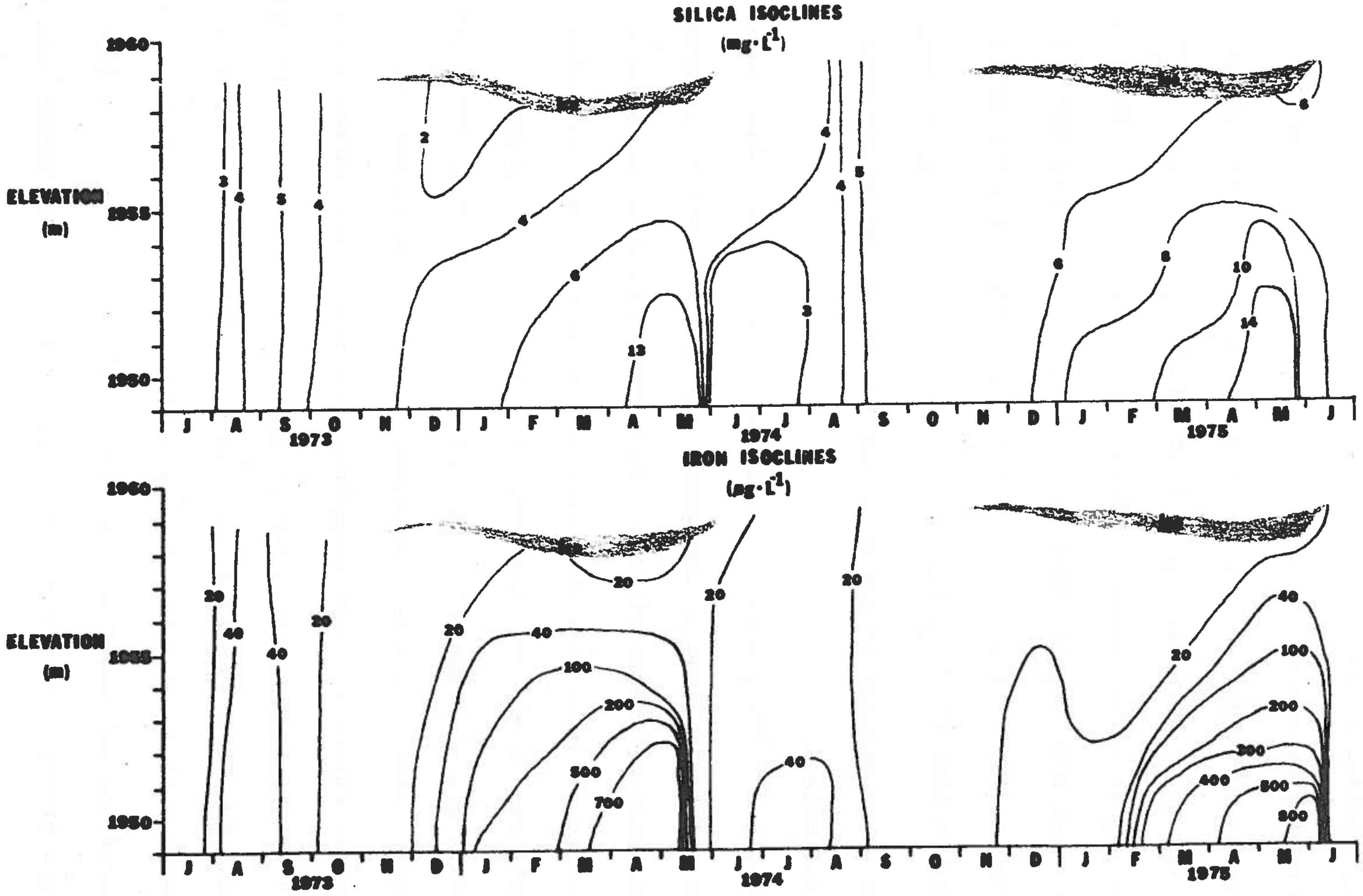


Figure 6. Seasonal isoclines of silica ($mg.l^{-1}$) and iron isoclines ($\mu g.l^{-1}$).

Nitrogen and Phosphorus

Since plant metabolism is highly dependent upon nitrogen and phosphorus, the availability of these nutrients to plants becomes paramount in the determination of the fertility of a water mass. Hutchinson (1957), Odum (1971), Sverdrup et al. (1942), Stumm and Morgan (1970) and other authors have discussed the role and recycling of plant nutrients in lakes. Briefly, biological productivity removes inorganic nutrients from the water as they are incorporated into organic material. Inorganic nutrients are released through bacterial decomposition. Stumm and Morgan (1970) gave the molar ratio of algal protoplasm of: $C_{106}\ H_{263}\ O_{110}\ N_{16}\ P_{1}$, and a biological oxygen demand through decomposition of 140 mg oxygen for every 100 mg dry weight of algal protoplasm.

Figure 7 shows that most of the nutrients are organically combined. Similar seasonal trends of inorganic nitrogen and phosphorus closely followed that of carbon dioxide. Both inorganic phosphorus and inorganic nitrogen levels were very much reduced during the ice-free period indicating high utilization of both nutrients by plants. Accumulation of inorganic phosphorus and nitrogen under the ice, as with CO_2, suggests mineralization of organic material through bacterial decomposition during this time. As shown in Figure 7, total phosphorus concentrations varied slightly around 0.1 g/m^2 with the maximum variation approximately 2 fold. Generally, organically combined phosphorus was slightly greater in the summer and just proceeding the break-up of ice-cover. Organic nitrogen exhibited two major peaks, both occurring in August of each year. As will be discussed later, these peaks are probably a result of nitrogen fixation by *Anabaena flos-aquae*. Two lesser peaks of organic nitrogen occurred in January of both years. During the remainder of the year, total nitrogen per square meter was approximately 1.2 grams.

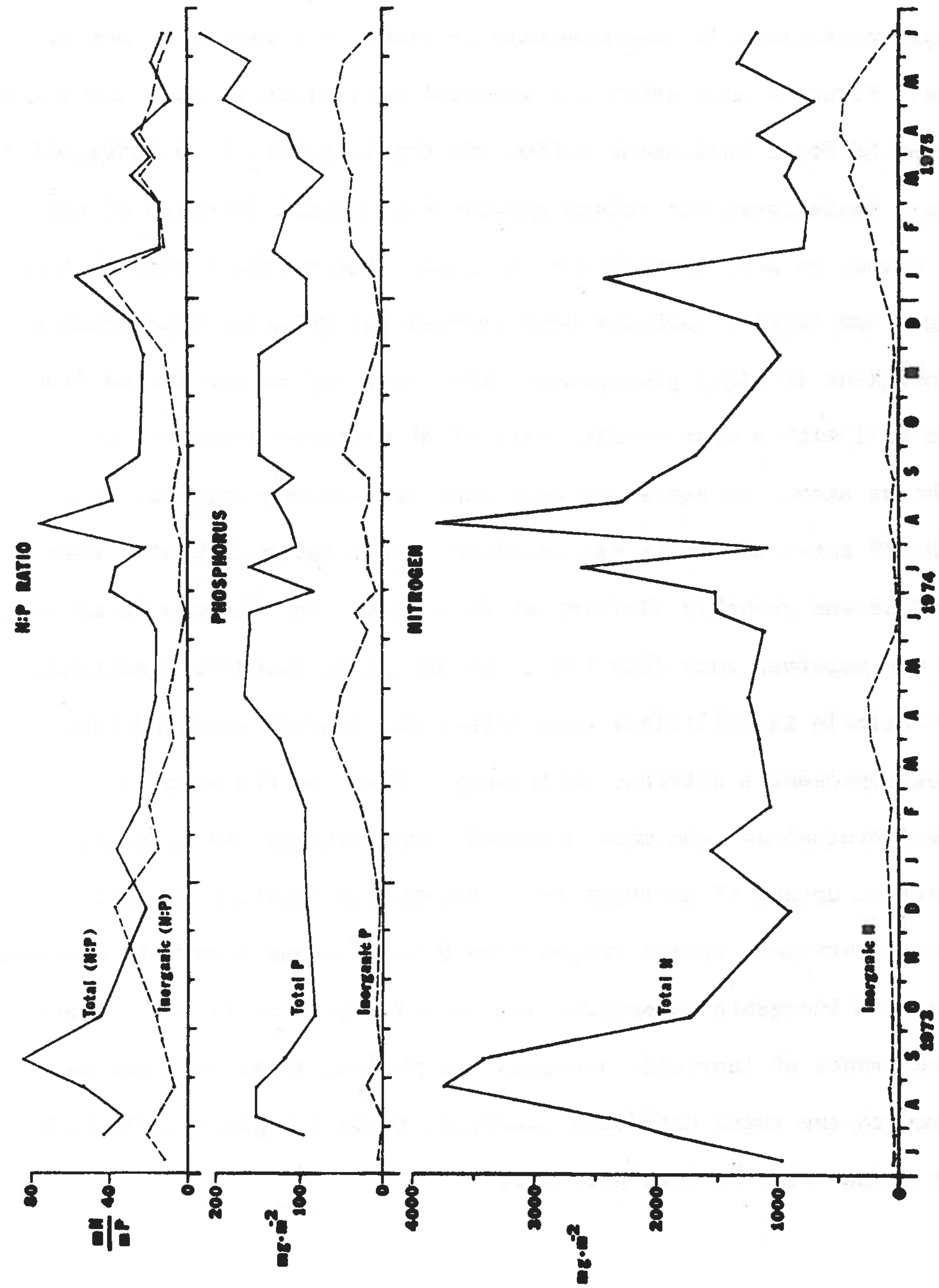
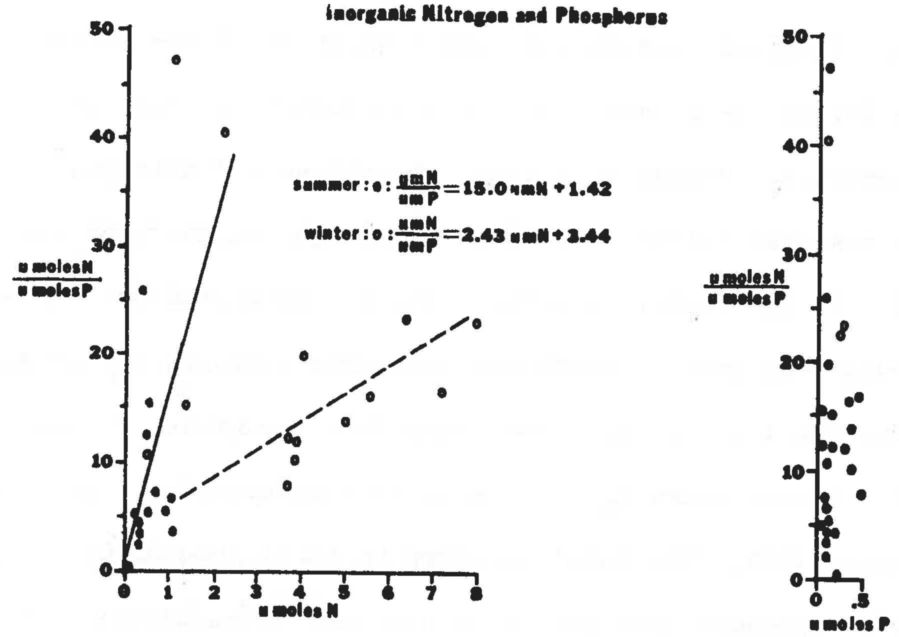


Figure 7. Seasonal distribution of total and inorganic phosphorus and nitrogen and nutrient ratios.

Of more importance in assessing the relative importance of nitrogen and phosphorus to plant production is the nitrogen to phosphorus ratio. As was discussed above, the mean molar ratio of nitrogen to phosphorus in algal protoplasm is approximately 16 atoms of nitrogen to one of phosphorus. Figure 8 also shows the seasonal variations of both the total nitrogen to total phosphorus ratios and the inorganic N to inorganic P ratios. Since inorganic values represented a small fraction of the total amount of nutrients that were present the ratios involving total nitrogen and total phosphorus best express the relative importance of each nutrient in algal protoplasm. The total N:P ratios varied from 8:1 to 85:1 with a mean atomic ratio of 31 nitrogen atoms to one phosphorus atom. In August of each year the maximum observed ratio of 80N: 1P total nutrients was attained. This ratio indicates that phosphorus was probably limiting at this time. The minimum total nutrient ratio was observed late into ice-cover and since inorganic nutrients were available in sufficient quantities, the minimum ratio probably did not represent a nutrient deficiency. Based on the mean 16:1 ratio in algal protoplasm, the mean observed total nutrient ratio indicates a luxurient uptake of nitrogen and a phosphorus limiting situation. Inorganic nutrients ratios ranged from 0 to 47 atoms inorganic nitrogen to one atom inorganic phosphorus with a mean ratio of 13.3:1. Since the occurrence of inorganic nitrogen and phosphorus was minimal as compared to the total nutrients observed, these inroganic ratio indicate a high uptake rate of both nutrients.



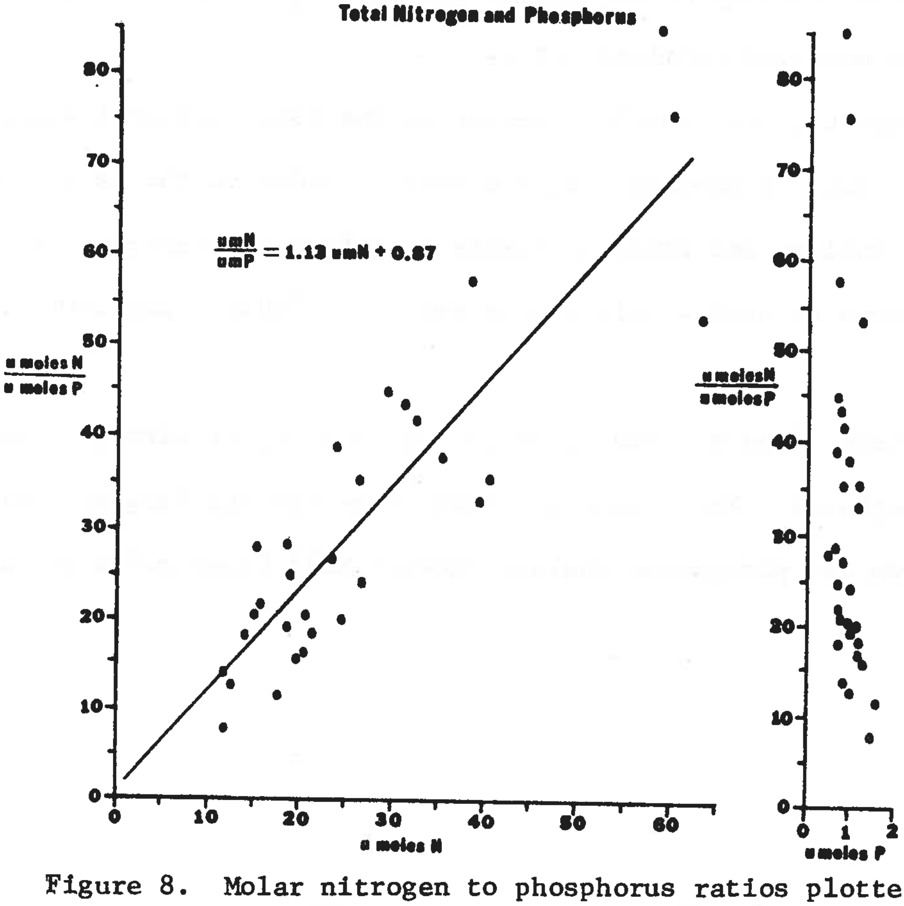


Figure 8. Molar nitrogen to phosphorus ratios plotted against nitrogen and phosphorus concentrations.

To determine if the nutrient ratios are a function of the nitrogen or phosphorus concentrations, Figure 8 was constructed from the results of a regression analysis between the ratios and respective nutrient concentrations. Inorganic ratios were not a function of the phosphorus concentrations during the summer. Nitrogen accounted for only 34% of the observed variance. During that time, phosphorus and nitrogen concentrations remained fairly constant, eventhough the nutrient ratio varied 47 fold. In the winter, however, nitrogen accounted for 56% of the observed ratio variance. Eventhough inorganic nitrogen and phosphorus accumulate under the ice, the plot indicates that inorganic nitrogen accumulates at a faster rate, <u>ie</u> the ratio is more dependent upon inorganic nitrogen concentrations. The total nitrogen to total phosphorus ratio was consistantly dependent upon the total nitrogen concentration. Since total phosphorus concentrations remained nearly constant, nitrogen accounted for 77% of the observed nutrient ratio.

Another aspect of the nutrient regime is the total nutrient budget for the lake. Table 6 presents total nutrients added to the lake from surface water inflows and total nutrients lost from the reservoir during the entire course of study. All of the values in Table 6 are corrected for discharge.

Inflow waters added 931,000 kg of carbon, 6190 kg of nitrogen, and 563 kg of phosphorus. North Fork of Flint Creek was the largest contributor of nitrogen and phosphorus whereas Stewart Mill Creek added the most carbon.

Table 6 Inflow and Outflow Chemistry

		Total Carbon	Total Nitrogen	Total Phosphorus
INFLOW	North Fork Flint Creek (kg)	333,000	2,330	262
	Stewart Mill Creek (kg)	490,000	2,130	198
	Hardtla Creek (kg)	108,000	1,730	1030
	Total (kg)	931,000	6,190	563
	Atomic Ratio	1650	11.0	1.0
OUTFLOW	Anaconda Co. Pump House (kg)	898,000	6.650	621
	Flint Creek (kg)	532,000	11,200	1,060
	Total (kg)	1,430,000	17850	1,680
	Atomic Ratio	2200	23.5	1.0
	Difference (kg)	-499,000	-11660	- 1120
	Atomic Ratio Atoms lost to 1 gained	1.4	2.9	3.0

Outflow surface waters removed 1,430,000 kg of carbon, 17,859 kg of nitrogen and 1.680 kg of phosphorus. The Anaconda Company pumping activity removed the most carbon, and Flint Creek outflow removed the most nitrogen and phosphorus. This was probably a result of deep water withdrawal.

Immediately apparent is that more nutrients were lost compared to nutrients gained. Expressed as atoms, the reservoir lost 1.4 atoms of carbon for every atom that was gained, 2.9 and 3.0 atoms of nitrogen and phosphorus, respectively, for every atom gained. These values are only for surface waters and are not corrected for precipitation inputs, biological nitrogen fixation nor ground water inputs. Precipitation inputs, based on Hutchinson's (1975) estimate of 0.7 $mg.1^{-1}$ nitrogen, amounted to only 8 kg nitrogen during the two year study. Nitrogen fixation by <u>Anabaena flos-aquae</u> undoubtedly occurs. Based on chemical analyses of ten ground water wells on 24 July, 1975, and estimates of total groundwater flow (see Results - Hydrology section), the total maximum nutrient input to Georgetown Lake during the course of study was: $0\text{-}PO_4\text{-}P$, 1180 kg; $NO_3\text{-}N$, 4062 kg; $NH_3\text{-}N$, 1480 kg. These values would change the budget to an equal input - output rate of phosphorus and a net loss of 6118 kg of nitrogen. However, Powell and Densmore (1971) stated that phosphorus movement in groundwater is very limited due to soil interaction and chemical activity of the phosphorus ion. Ammonia would also show limited movement. Nitrate, on the other hand, is very leechable and therefore moves in groundwater with little interference.

Based on surface waters, the mean observed annual loss of phosphorus was 0.010%. Mean nitrogen loss per year was estimated to be 0.085%.

Sediment Chemistry

The sediments of Georgetown Lake are neutral to slightly acidic and noncalcarous. These sediments could be classified as gyttja, being almost entirely of autochthonous in origin. The organic carbon content is relatively high. This is caused by the fact that the flooded area was originally a hay meadow and the lake presently supports considerable plant growth, both macrophytic and algal.

The sediments are very heterogeneous throughout the lake. This is mainly due to the large macrophytic growth which varies from sheltered to exposed areas, and also to part of the lake having virtually no macrophytic growth. Additionally, prior to the flooding part of the area was a hay meadow and part was a marshy area. For these reasons the sediment parameters vary a great deal throughout the whole lake. Because of the heterogeneity of the sediments, representative sampling was difficult and large sampling errors sometimes resulted.

To obtain a reasonable picture of the sediment characteristics of the whole lake a weighted mean was calculated. The areas represented by the five sampling sites were estimated in terms of their percentage of the total lake area. This mean is sometimes biassed because at some times, particularly during ice cover, only Station I was sampled, and at other times only Station I, IV, and V were sampled.

Cations:

Table 7 gives the ranges and means of the cations in the sediments of Georgetown Lake.

Iron oxides were consistantly higher at Station I than at the other stations. At Station I they were generally at least twice as great as the other stations. Here, too, concentrations ranged from 8.500 $mg/_g$ to

TABLE 7. RANGES AND MEANS OF SOME CHEMICAL AND PHYSICAL PARAMETERS OF THE SEDIMENT OF GEORGETOWN LAKE.

Parameters	Station I	Station II	Station III	Station IV	Station V	weighted mean of Lake
Fe_2O_3 (mg/g)	8.500-22.800 12.426	4.125 - 9.250 6.189	3.200 - 6.375 4.482	1.625 - 4.250 2.806	0.460 - 7.350 2.546	4.254 - 15.464 8.786
Al_2O_3 (mg/g)	0.047-0.164 0.116	0.045 - 0.120 0.082	0.037 - 0.091 0.0062	0.038 - 0.076 0.058	0.002 - 0.068 0.027	0.043 - 0.164 0.084
Ex-Ca (mg/g)	2.50 - 7.45 3.93	-	-	1.90 - 13.80 7.73	-	2.89 - 12.00 5.39
Ex - Mg mg/g	0.620-1.360 0.948	0.600 - 1.163 0.890	0.540 - 1.043 0.757	0.863 - 1.750 1.297	0.038 - 0.688 0.478	0.620 - 1.412 0.995
Ex-Mn (mg/g	0.016-0.181 0.097	0.066 - 0.259 0.166	0.099 - 0.313 0.151	0.058 - 0.166 0.113	0.012 - 0.124 0.075	0.041 - 0.197 0.110
Ex-Fe (mg/g)	0.001-0.022 0.006	0.004 - 0.012 0.008	0.005 - 0.008 0.006	0.001 - 0.018 0.006	0.005 - 0.010 0.007	0.001 - 0.011 0.006
Ex - Al (mg/g)	0.004-0.019 0.011	0.004 - 0.017 0.010	0.005 - 0.021 0.010	0.007 - 0.020 0.010	0.005 - 0.016 0.008	0.004 - 0.019 0.011
Ex - Zn (mg/g)	0.016-0.114 0.055	0.011 - 0.121 0.057	0.006 - 0.086 0.039	0.004 - 0.060 0.039	0.001 - 0.069 0.034	0.008 - 0.096 0.049
pH	6.2 - 7.2 6.9	6.8 - 7.4 7.1	6.9 - 7.2 7.0	6.7 - 7.2 7.0	6.9 - 7.3 7.1	6.2 - 7.3 7.0

22.800 mg/g with a mean of 12.426 mg/g. The iron oxide concentrations ranged from 4.254 mg/g to 15.464 mg/g for the whole lake with a mean of 8.786 mg/g. In the sediments for the lake Fe_2O_3 did not show any distinctive trends. Instead the concentrations remained generally the same throughout the sampling period. However, at Station I, which is the deep water station that becomes anaerobic, Fe_2O_3 was lower during the later part of the ice cover period. When the ice melted and the oxygen concentration in the water increased Fe_2O_3 in the sediments increased, although not to the levels recorded earlier. As shown in figure 9, when the sediment iron was decreasing the iron in the overlying water column was increasing greatly. Conversely, when the iron increased in the sediments in June the iron concentrations dropped drastically in the overlying water. Exchangeable iron was present in very low concentrations throughout the whole sampling period. It ranged from 0.001 mg/g to 0.011 mg/g with a mean of 0.006 mg/g.

As with iron oxides, aluminum oxides were present at higher concentrations but were not as high as iron, ranging from 0.043 mg/g to 0.164 mg/g with a mean of 0.084 mg/g. As with Fe_2O_3 , the mean concentrations decrease as the station numbers increase; ie. $I \geq II \geq III \geq IV \geq V$. Aluminum oxides were similar to Fe_2O_3 in that they did not show any distinctive trends in the lake as a whole. However, at Station I the trend was similar as the trend for Fe_2O_3. During the later part of ice cover Al_2O_3 decreased rapidly but with the ice breakup the Al_2O_3 concentration drastically increased and remained about the same through the summer. Unfortunately aluminum concentrations were not determined in the overlying water so the sediment and water concentrations could not be correlated.

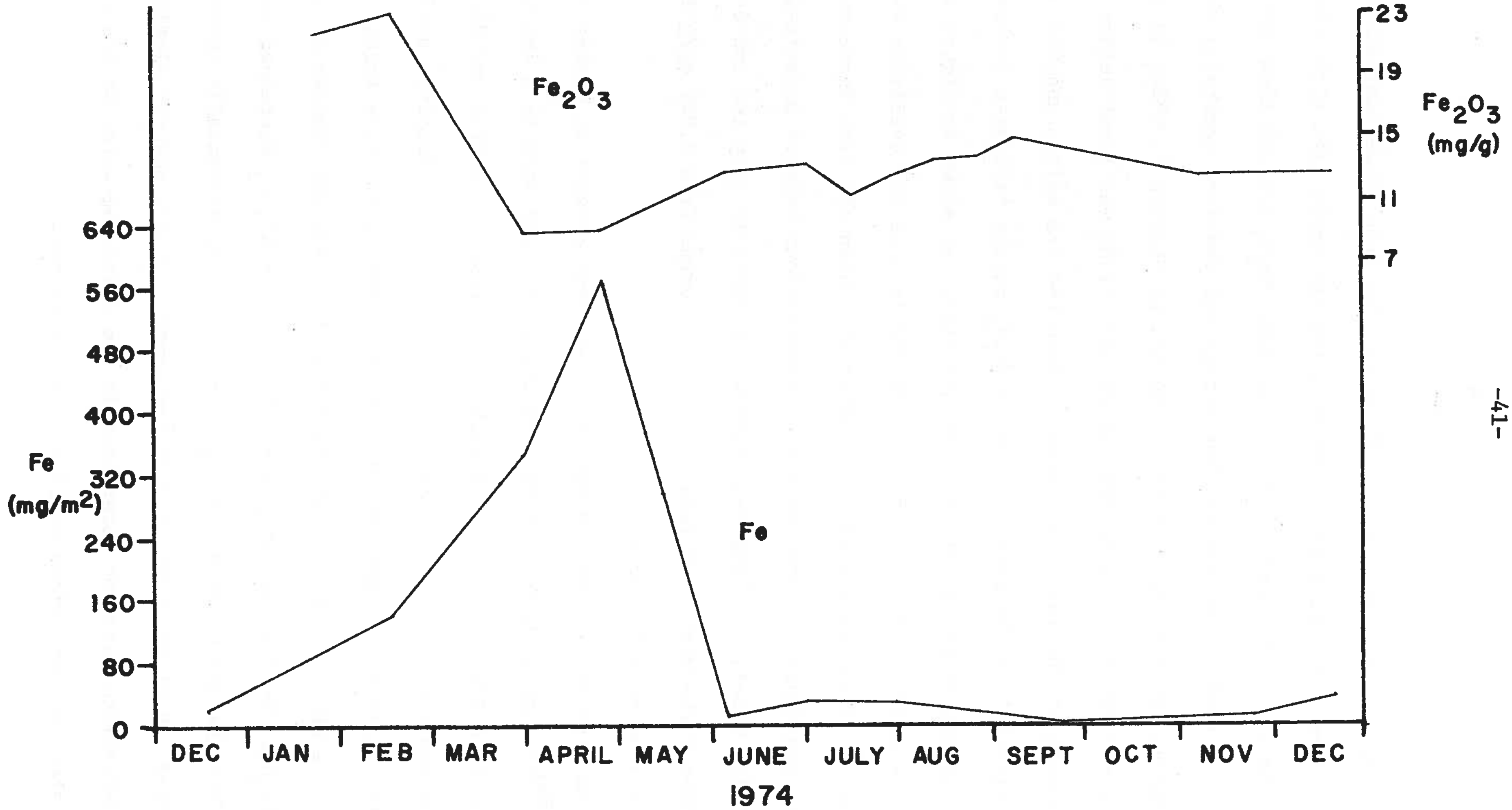


Figure 9. The relationship of iron in the bottom waters and iron oxides in the sediments at Station I.

As with exhangeable iron, the exchangeable aluminum concentrations were low. However, exchangeable aluminum was present in slightly higher concentrations, ranging from 0.004 mg/g to 0.019 mg/g with a mean of 0.011 mg/g.

Exchangeable calcium was only determined at Stations I and IV. The calcium was much higher at Station IV than at Station I. At Station IV the mean was 7.73 mg/g and at Station I the mean was 3.93 mg/g. The calcium concentrations in the sediments tended to be higher during the summer than during the winter, especially at Station IV. Heald (1965) states that the procedure used partially, measures $CaCO_3$. This increase could be partially due to the $CaCO_3$ precipitation which occurred during the summer.

Exchangeable magnesium exhibited the same trend as exchangeable calcium throughout the lake, being higher at Station IV that at Station I. The difference was not as great, the means being 0.948 mg/g and 1.297 mg/g at Stations I and IV respectively. The weighted mean for the lake was 0.995 mg/g. Magnesium tended to increase during ice cover but it fell drastically in June. Throughout the summer, Mg increased but it never reached the concentrations observed during the previous winter months.

Exchangeable manganese was present in concentrations comparable to those of the aluminum oxides. Concentrations in the lake as a whole ranged from 0.041 mg/g to 0.197 mg/g with the weighted mean being 0.110 mg/g. As shown in figure 10, in the lake as a whole manganese showed a general decrease during the period of ice cover and a drastic increase in June. This same trend was exhibited at Station I. As mentioned previously, during the period of ice cover, esp. January - April, the bottom waters become anaerobic (Figure 4). Although manganese was not measured in the overlying water, it has been well documented (Mortimer,

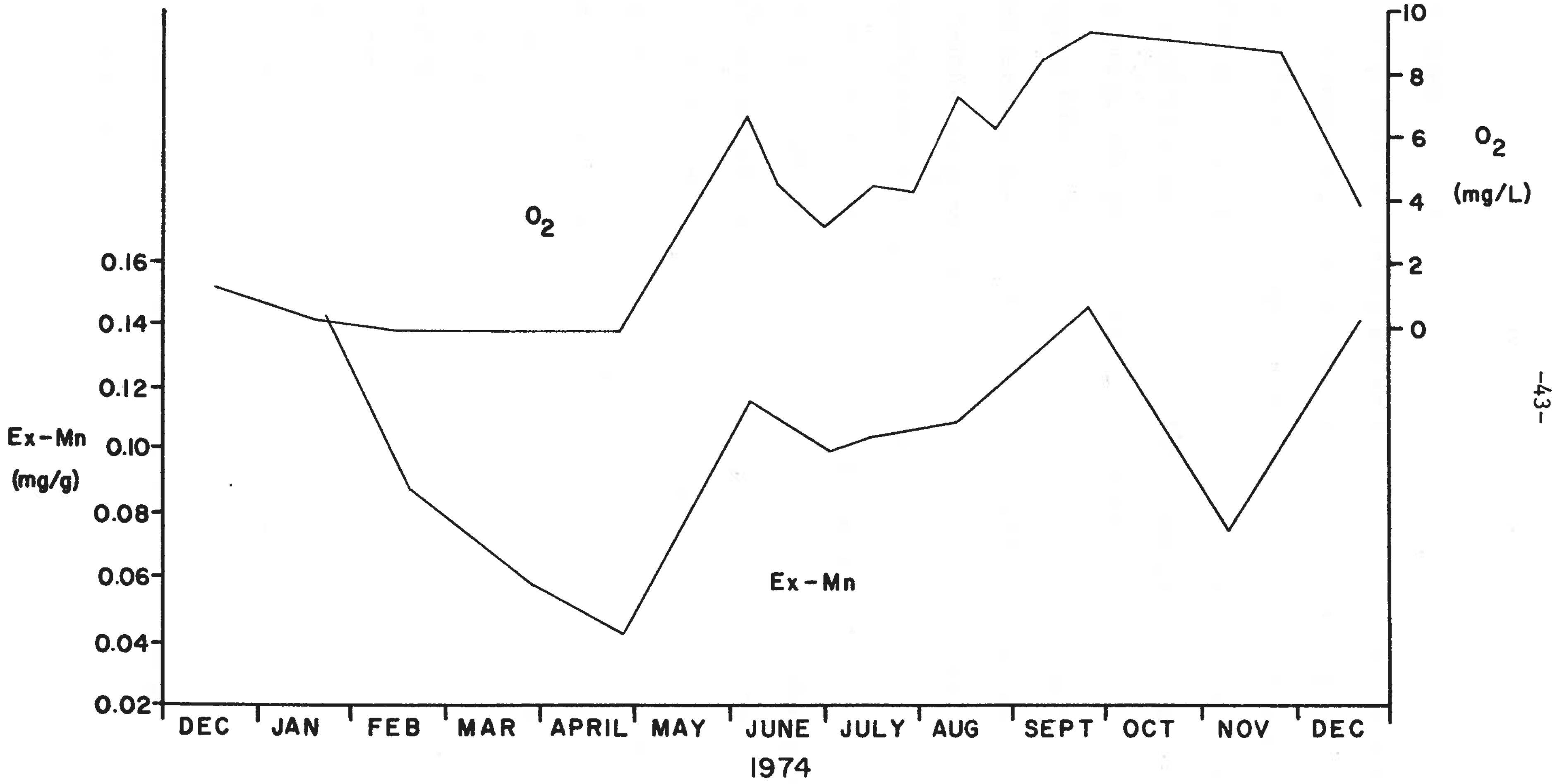


Figure 10. The relationship of dissolved oxygen in the bottom waters at Station I and Ex-Mn in the sediments in the whole lake.

1941 and 1942; Hutchinson, 1957; Wetzel, 1975) that in a reducing environment, as with iron, manganese is released into the water from the sediments. It can be assumed then as the bottom waters become anaerobic manganese is released into the overlying waters with a resultant decrease in the exchangeable manganese in the sediments. Exchangeable manganese (Mn II) decreases because it is adsorbed on clay and humic colloids. Mn II is the only form of manganese which is readily soluble in water.

Station I represents the deepest area in the lake. Therefore, the bottom waters are presumably more likely to become anaerobic. As mentioned in the water chemistry section, the rest of the lake contains more oxygen; therefore the bottom waters may not become as reduced as at Station I. Stumm and Morgan (1970) have noted that Mn IV is reduced at a higher redox potential than Fe III. This may explain why in the lake as a whole manganese decreases in the sediments during ice cover but iron does not, although iron oxides do at Station I.

Exchangeable zinc was present in low concentrations although it was higher than either exchangeable iron or aluminum. In the sediments zinc ranges from 0.008 mg/g to 0.096 mg/g with an average of 0.049 mgm/g. In the lake as a whole and at Station I, zinc tended to remain constant during ice cover and then increased during the summer and return to ice cover levels during the fall.

Delfino et.al. (1969) have shown that Mn, P, and Fe are positively correlated with the depth of the water. This is due to current patterns and particle size differentiation. Davis (1968) showed that pollen grains were deposited 2-4 times before being burried deeply enough to escape further disturbance. Davis (1968) stated that apparently the sediments in the shallower areas are stirred up and resuspended. The ultimate result is that finely grained particles are being carried into the deeper areas of the lake. Delfino et.al. (1969) stated that Fe, Mn and P are associated with finely graded particles which would settle out very slowly. As shown in Table 7, $Fe_2 0_3$ is highest at Station I,apparently because it is the deepest station. Manganese is higher at Station IV that at Station I but this may be due to biological concentration (Oborn, 1964). Although Delfino et.al. (1969) did not discuss aluminum, apparently its distribution is similar to iron since it is highest at Station I. Delfino et.al.(1969) found a slight positive correlation with Mg and depth. This may explain why Station I has the second highest Mg concentration, Station IV being highest. They did not find any correlation with Ca and depth. Although Ca was only determined at Stations I and IV, it was much higher at Station IV.

Organic - Carbon:

The ranges and means of organic carbon and the initial volatile solids (IVS) for the lake and the five stations are given in Table 8. Organic carbon ranged from 56.7 to 268.9 mg/g with a weighted mean of 161.4 mg/g. Station IV was consistently much higher than the other four stations. With the exception of Station V, the macrophytic biomass was much greater here than at either Station I, II, or III.(Garrett, personal communications).

Organic carbon was relatively low at Station V because the bottom was much more gravelly. Stewart Mill Creek enters the lake at this station. Apparently when the lake was formed this area was a stream bottom and not a hay meadow or marsh as the other stations originally were. The original

Table 8. Ranges and means of some chemical and physiological parameters of the sediments of Georgetown Lake.

Parameters	Station I	Station II	Station III	Station IV	Station V	Weighted mean of lake
Organic - C (mg/g)	56.7 - 187.8 125.5	120.0 - 227.6 165.9	75.8 - 211.0 149.7	202.1 - 352.7 276.5	44.3 - 138.6 91.0	56.7 - 268.9 161.4
IVS (mg/g)	132.17 - 312.43 207.86	176.08 - 325.21 264.05	167.81 - 325.16 243.47	342.99 - 669.33 493.22	78.08 - 224.43 161.71	132.17 - 423.30 270.29
Total - P (mg/g)	0.663 - 1.088 0.789	0.563 - 1.606 1.150	0.675 - 1.219 0.939	0.938 - 1.438 1.190	0.306 - 1.163 0.680	0.706 - 1.211 0.918
Inorganic - P (mg/g)	0.434 - 0.634 0.522	0.347 - 1.100 0.731	0.384 - 0.825 0.555	0.522 - 0.919 0.646	0.181 - 0.747 0.414	0.434 - 0.742 0.566
Organic - P (mg/g)	0.178 - 0.491 0.267	0.216 - 0.581 0.419	0.290 - 0.469 0.384	0.416 - 0.637 0.542	0.109 - 0.416 0.265	0.178 - 0.548 0.352
Total - N (mg/g)	4.69 - 13.72 9.02	9.57 - 19.52 13.48	9.00 - 15.92 12.12	16.84 - 24.84 21.18	3.85 - 10.86 7.49	4.69 - 20.40 12.25
Inorganic- N (mg/g)	1.70 - 5.22 3.43	4.09 - 7.45 5.28	3.00 - 6.16 4.35	5.91 - 12.02 8.25	0.86 - 3.70 2.09	1.70 - 7.53 4.44
Organic - N (mg/g)	2.989 - 8.681 5.696	5.480 - 12.073 8.148	5.996 - 9.764 7.764	10.172 - 15.812 13.509	2.916-8.172 5.026	2.989 - 12.873 7.452

gravelly substrate apparently is the reason the sediments of Station IV are similar to Station I in organic carbon, nitrogen,and phosphorous concentrations even though Station V is shallow and has a dense macrophytic growth.

As shown in Figure 11 organic carbon was higher during ice cover and lower during the summer months. The higher carbon during ice cover is a result of fall deposition of macrophytes. Wetzel (1975) stated that when oxygen is absent, as during ice cover, the rate of carbon mineralization is slower than at times when oxygen is abundant.

The initial volatile solids exhibit a similar trend, organic carbon being much higher at Station IV than at the other stations (Table 8) The mean IVS concentration at Station IV was 493.22 mg/g whereas the weighted mean for the lake was 270.29 mg/g. IVS follows the same trend throughout the year as carbon. These two parameters have a correlation coefficient of 0.942 which is significant to the 0.01% level. This is not surprising since IVS estimates total organic matter. This organic matter includes carbohydrates, lignens, proteins, fats, waxes, etc. Although organic carbon makes up the majority of this, it is not the only constituent. Nitrogen, P, S, etc. are also included. This is why the IVS is higher than organic C. Brady (1974) states that the organic matter content is about 1.7 times the organic carbon content. This holds true for Georgetown Lake as the IVS is about 1.7 times the organic C.

<u>Phosphorus</u>:

Total sediment phosphorus is composed of total inorganic and total organic phosphorus. Throughout the year organic phosphorus accounted for 38% of the total phosphorus and inorganic phosphorus accounted for 62%.

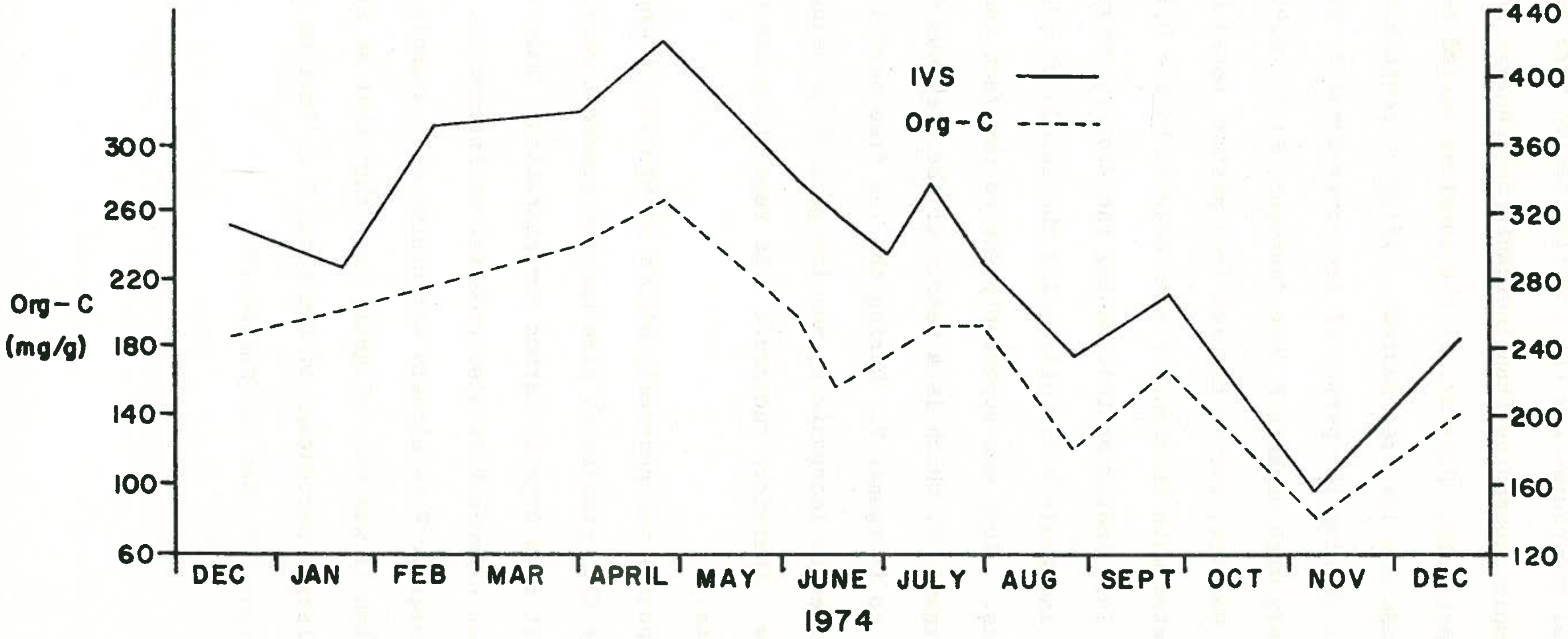


Figure 11. The relationship of IVS and organic -C in the lake sediments.

Changes in total phosphorus for the sampling period were more closely correlated with organic phosphorus than inorganic phosphorus; r = 0.878 and r = 0.780 respectively. However, if the sampling period is divided into ice cover periods and ice free periods, different constituents become more important. During the period of ice cover total P was correlated much more closely with organic P than inorganic P; r = 0.955 and r = 0.718 respectively. However, during the ice free period. total P was more closely correlated with inorganic P than organic P, r = 0.906 and r = 0.850 respectively. This indicates that during the winter, organic P was more important than inorganic P in influencing the levels of total P that are in the sediments. This was apparently due to the fact that during ice cover little organic P, which is a result of the previous fall's deposition, is mineralized to inorganic P. During the ice free period, organic P is being mineralized to inorganic P, and inorganic P is being utilized by the macrophytes. Therefore inorganic P is regulating the total P level in the sediments.

Total phosphorus was generally higher at Station IV than the other stations (Table 8). Station IV also had the greatest macrophytic biomass and the greatest mean organic carbon concentration. This is supported by the fact that organic P is also greatest at Station IV. As will be detailed later, organic P is closely correlated with organic C. The total mean P at Station II was only slightly less than that at Station IV. This was because a larger percentage of the total P at Station II was attributable to inorganic P than at Station IV.

As with organic C, total P was lowest at Station I with the exception of Station V. The low phosphorus at Station V is a result of the same factors that resulted in low organic C concentrations. Station I is the only station that was in the limnetic zone of the lake. Therefore there was little macrophytic growth at this station. Because the total biomass deposition was lower here, the total P in the sediments was lower. Also, as will be discussed later, there was a general loss of total phosphorus from the sediments because of this station's proximity to the dam's deep water withdrawel.

Seasonal changes in total, inorganic and organic phosphorus in the sediments are depicted in figure 12. Total P in the entire lake increased during ice cover primarily because of organic P. This is due to the accumulation of detritus in the fall and early winter when the macrophytes and phytoplankton died. Total P decreased during the summer as inorganic P was being utilized by the macrophytes. At the end of September total P increased as less inorganic P was being utilized and the macrophytes and algae were dying.

Since most of the lake is relatively shallow (Table 3), figure 12 represents what would be expected in the littoral zone of the lake. However, in the deeper areas of the lake, examplified by Station I, a different seasonal pattern is evident (figure 13). At this station total P declined during ice cover, from a high in December 1973. This was due to a decline in both organic and inorganic P. Total P increased during the summer as organic P is mineralized to inorganic P. Because there is little macrophytic

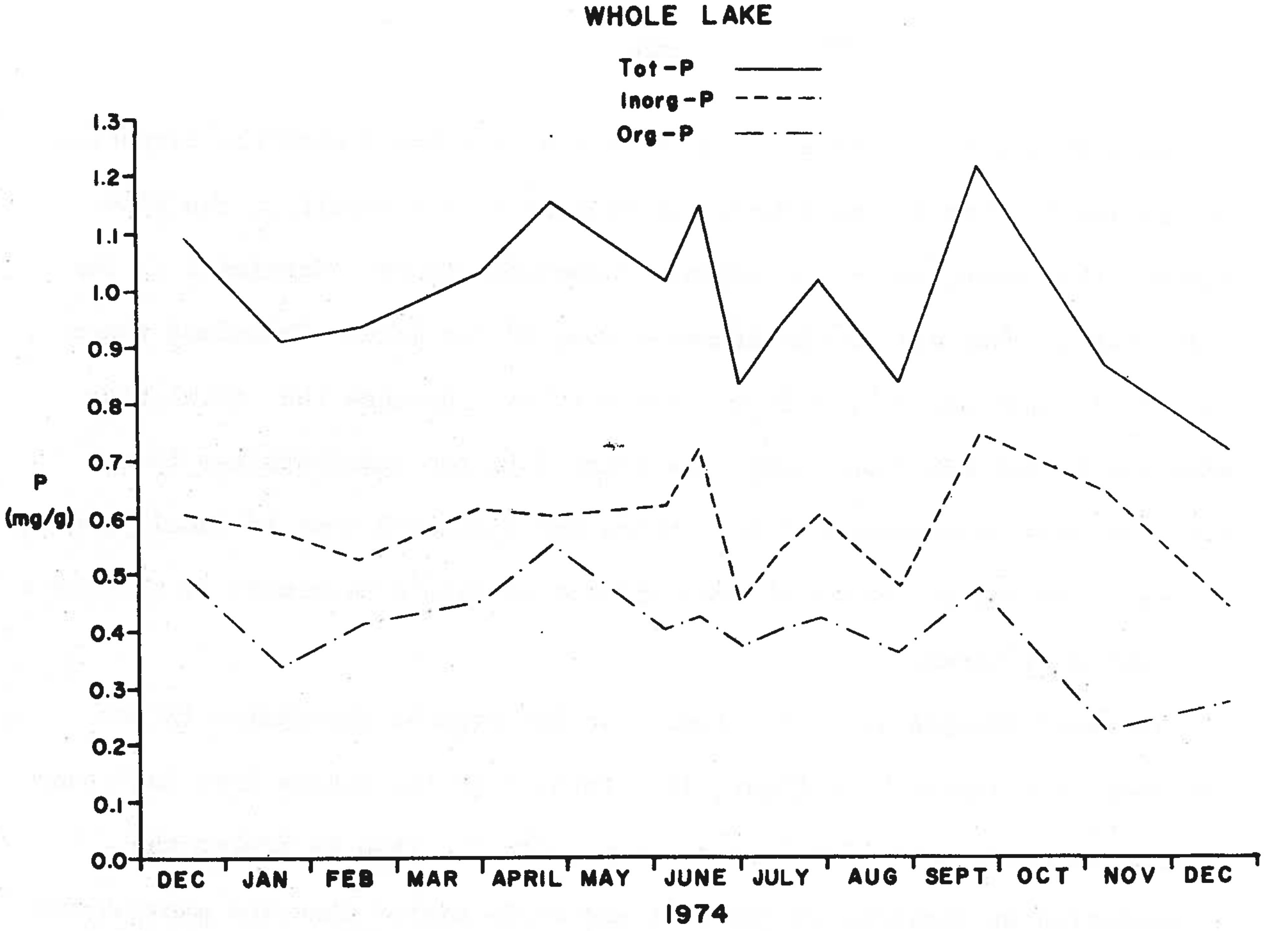


Figure 12. Sediment phosphorus in the whole lake.

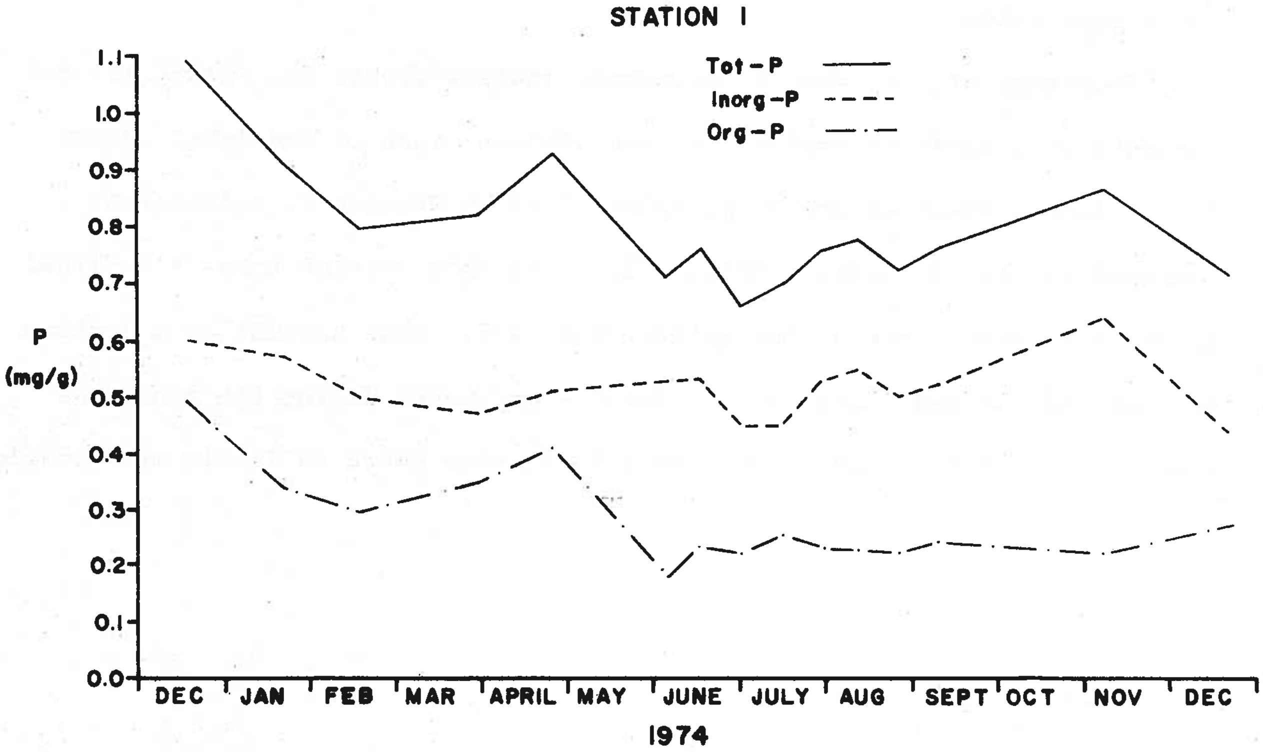


Figure 13. Sediment phosphorus at Station I.

growth at this station inorganic P was not being utilized appreciably.

Inorganic phosphorus was highest at Station II with a mean concentration of 0.731 mg/g. This may be due to higher phosphorus in this area when the lake was formed. Station IV was consistently higher in inorganic nitrogen and most other nutrient parameters.

Inorganic phosphorus in the sediments increased from January through June. (figure 12) This seems to be a result of mineralization of organic P. Mineralization was slow during ice cover but increased in June as oxygen became more abundant and the water temperature increased. During the summer inorganic P fluctuates but there was a general decrease until the end of September. The general decrease was probably due to inorganic P being utilized by the macrophytes. Inorganic P was higher in the fall due to rapid mineralization of organic P from decomposing macrophytes and algae.

Inorganic P at Station I had a somewhat different seasonal patterns (figure 13). During ice cover inorganic P decreased until April. Although mineralization of organic P probably preceeded at a slow rate as in the rest of the lake. As shown in figure 14 inorganic P at this time was being released into the overlying water which caused the sediment inorganic P to decrease. Through the latter part of ice cover (18 Feb - 25 April) organic P had increased and mineralization may have been rapid enough to increase the sediment inorganic P even though it was being released into the overlying water.

Organic phosphorus was highest at Station IV, having a mean of 0.542 mg/g. Organic carbon was also highest at Station IV. This relationship is not

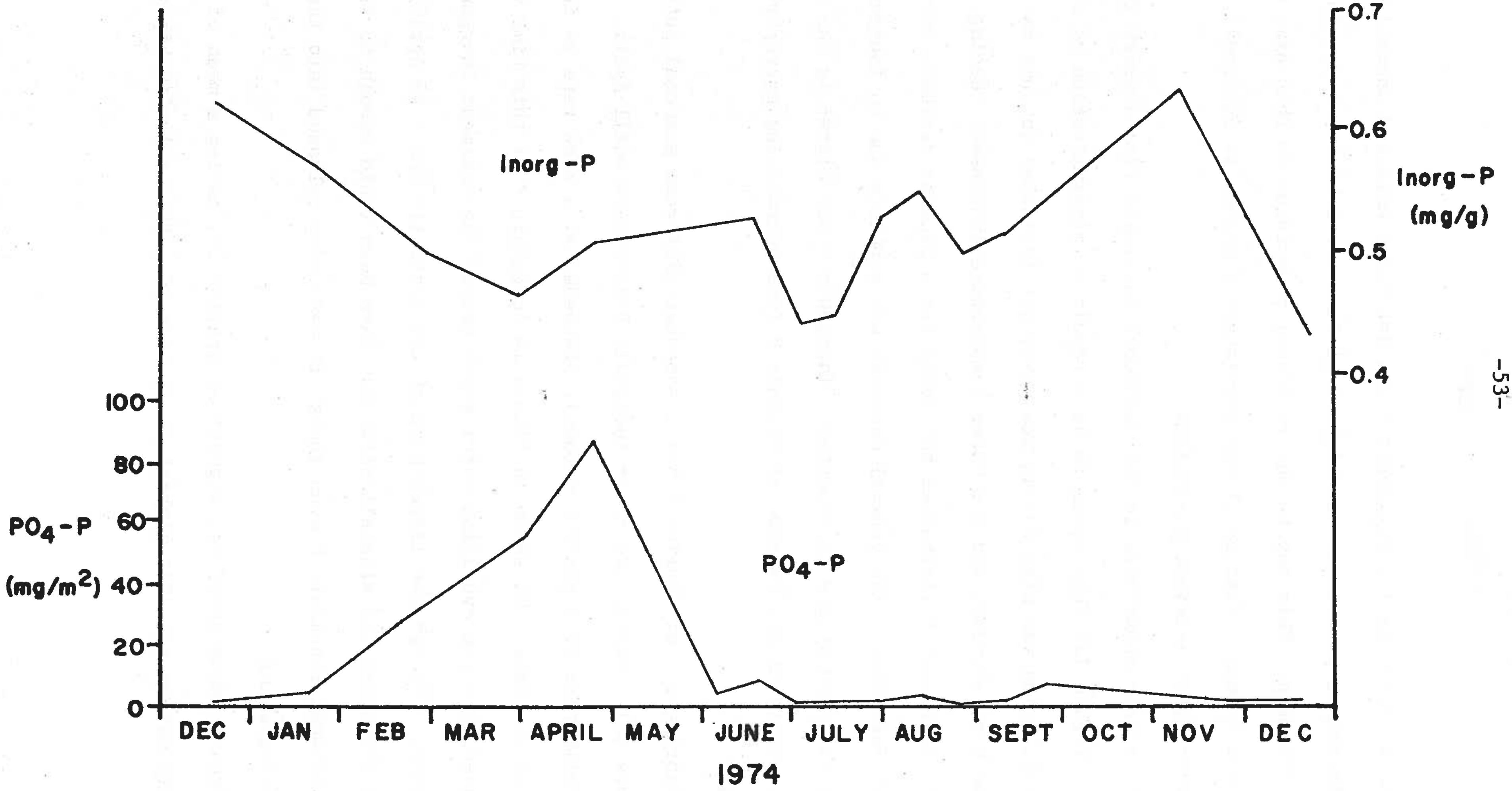


Figure 14. The relationship of sediment inorganic P and the inorganic P in the bottom waters at Station I.

surprising as organic P is generally correlated with organic C (Williams, et. al.; 1971; Wildung and Schmidt, 1973; Syers et.al, 1973; and Wetzel, 1975). Figure 15 shows the relationship between organic C and organic P. The correlation coefficient was 0.842 which is significant to the 0.05 level. Organic P increased during ice cover. During the summer organic P fluctuated but showed an increase in the fall probably due to deposition of macrophytes and algae.

Nitrogen

Like total phosphorus, total sediment nitrogen was composed of total organic N and total inorganic N. Throughout the year, inorganic N comprised 38% of the total N and organic N 62% of the total nitrogen. Inorganic N made up a larger percentage of the total N content than most reported studies in the literature. Keeney, et. al. (1970) and Kemp and Mudrochova (1972) reported inorganic N comprised at the most, only 10% of the total N. The lakes that these authors generally discuss were deeper than Georgetown Lake and their bottom waters became anaerobic in the summer. Wetzel (1975) has stated that during low oxygen, mineralization of organic carbon is slower than when oxygen is abundant. During the summer when the sediment temperatures are warmer oxygen is abundant in Georgetown Lake. Therefore since the environment is better suited for microbial activity more organic N may be mineralized in the course of a year. This could result in inorganic N making up a greater percentage of the total N.

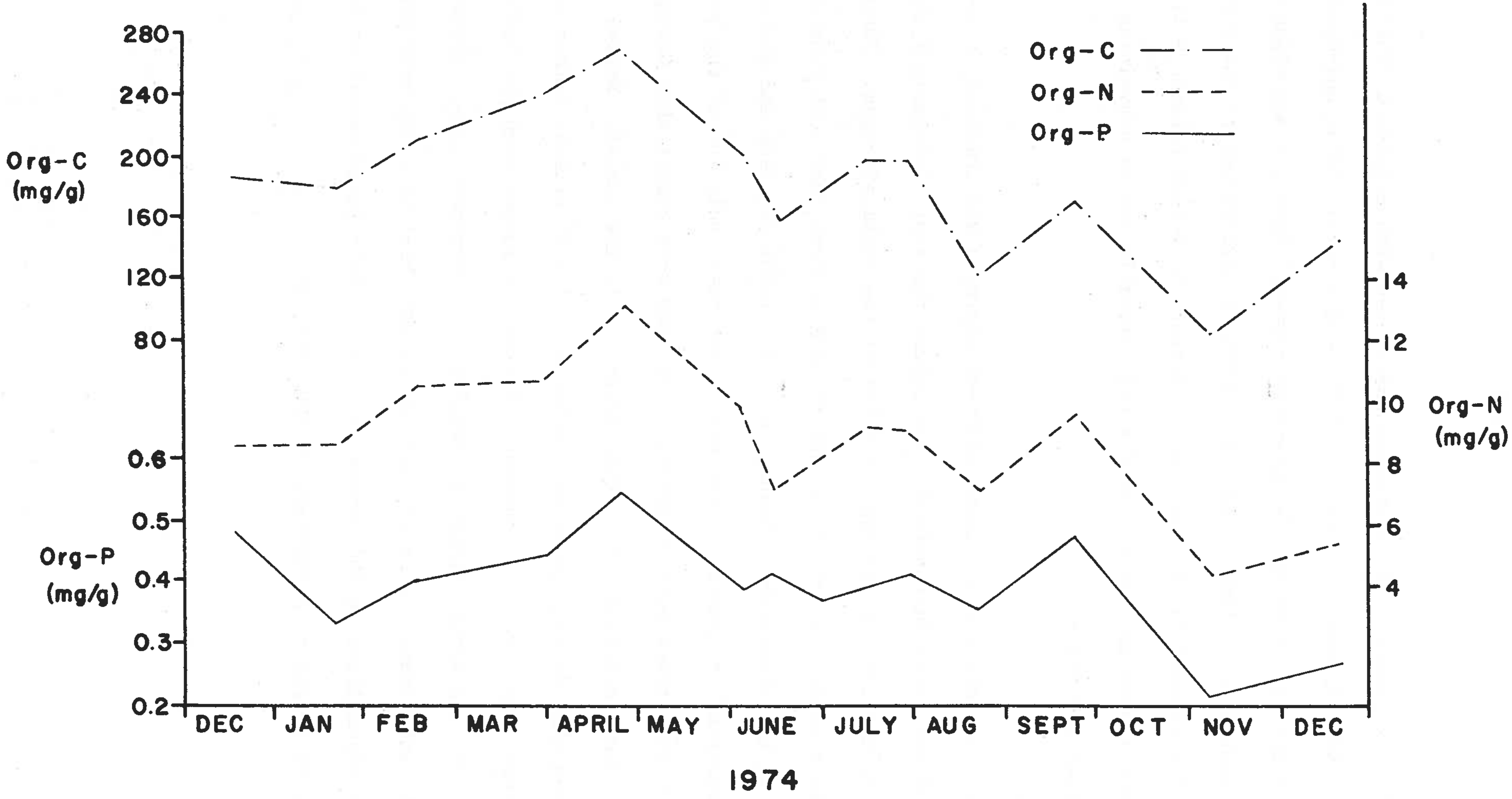


Figure 15. Relationship of organic -C, organic -N, and organic -P in the lake sediments.

Table 9. Mean atomic ratios for the sediments of Georgetown Lake.

	N:P[1]	$N_I:P_I$[2]	C : N[3]	C : N : P[4]
Station I	26.1	15.0	16.2	424:26:1
Station II	26.8	16.5	14.4	385:27:1
Station III	29.5	17.9	14.4	425:30:1
Station IV	40.7	29.2	15.2	620:41:1
Station V	25.2	11.5	14.2	357:25:1
Weighted mean of the whole lake	30.5	17.9	14.9	469:31:1

1. Total N: Total P
2. Inorganic N: Inorganic P
3. Organic C: Total N
4. Organic C: Total N: Total P

Changes in total nitrogen were closely correlated with both inorganic N and organic N; 0.975 and 0.991 respectively.

Total nitrogen was consistently much higher at Station IV than at the other five stations. This is consistent with higher organic carbon and total phosphorus. As discussed earlier, this is the station that has the largest macrophytic growth. Station I was lower in total N than the other stations with the exception of Station V. Again this points to the importance of the deep water withdrawl in removing nutrients from the sediments.

Total nitrogen was much greater than total phosphorus throughout the lake. The weighted mean of total N was 12.25 mg/g and the weighted mean of total P was 0.918 mg/g. The N:P ratio for the whole lake averaged 31:1. Wildung and Schmidt (1973) obtained a N:P ratio of 30:1 and Neel et. al (1973) obtained a N:P ratio of 24:1 for lake sediments. These ratios are much higher than N:P ratios usually associated with algae or macrophytes which is 12:1 (Wetzel, 1975). Since nitrogen and phosphorus is being depleted from the sediments this indicates that phosphorus is being lost more rapidly due to utilization by the primary producers. This is indicated by the fact that the inorganic N to inorganic P ratio is higher at Station IV that at Station I (Table 9). Macrophytes are very abundant at Station IV and therefore seem to be utilizing phosphorus at a faster rate than nitrogen.

The average C:N ratio for the whole lake was 15:1. Wildung and Schmidt (1973) reported C:N ratios of 8:1 in Upper Klamath Lake, Oregon and Neel et.al(1973) reported C:N ratios of 12:1 for Lake Sallie, Minnesota. Kemp (1971) found while studying Lakes Ontario, Erie, and Huron that their C:N ratios varied from 7 to 13:1. All of these values are less than the C:N ratios found in Georgetown Lake. As will be discussed in the following section organic carbon is accumulating in the sediments but nitrogen is being depleted. This could explain the unusually high C:N ratios.

The average C:N :P ratio in the sediments was 469:31:1. This ratio is much higher than those reported in the literature. Neel et.al. reports C:N:P ratios of 286:24:1 and Wildung and Schmidt (1973) report ratios of 236:30:1 in the sediments. The ratios for algal protoplasm is usually quoted as 105:15:1 (Strickland, 1969). The ratios in the sediments of Georgetown Lake are similar to those observed in the macrophytes. Garrett (personal communication) using some preliminary data observed ratios of 442:29:1. Neel et. al. at Lake Sallie observed ratios in macrophytes of 326:24:1. Since the majority of the primary preducers are macrophytes this would explain the C:N:P ratios. The higher ratios in Georgetown lake again indicate that N and P is being lost from the lake while organic C is being accumulated.

Seasonal changes in total, inorganic and organic nitrogen are depicted in figure 16. Total nitrogen generally increased during ice cover but was less during the summer. The general increase in total nitrogen at the end of September was probably due to macrophytic deposition as the plants died. This is evidenced by the concurrent increase in organic carbon and organic phosphorus.

As shown in figure 17 the seasonal pattern of total, inorganic and organic nitrogen was somewhat different at Station I. During the winter total N did not increase although it increased throughout the whole lake. During the summer total N was lower but it did not fluctuate as much as it did in the whole lake. Like total P, total N is influenced by the inorganic fraction being released into the water.

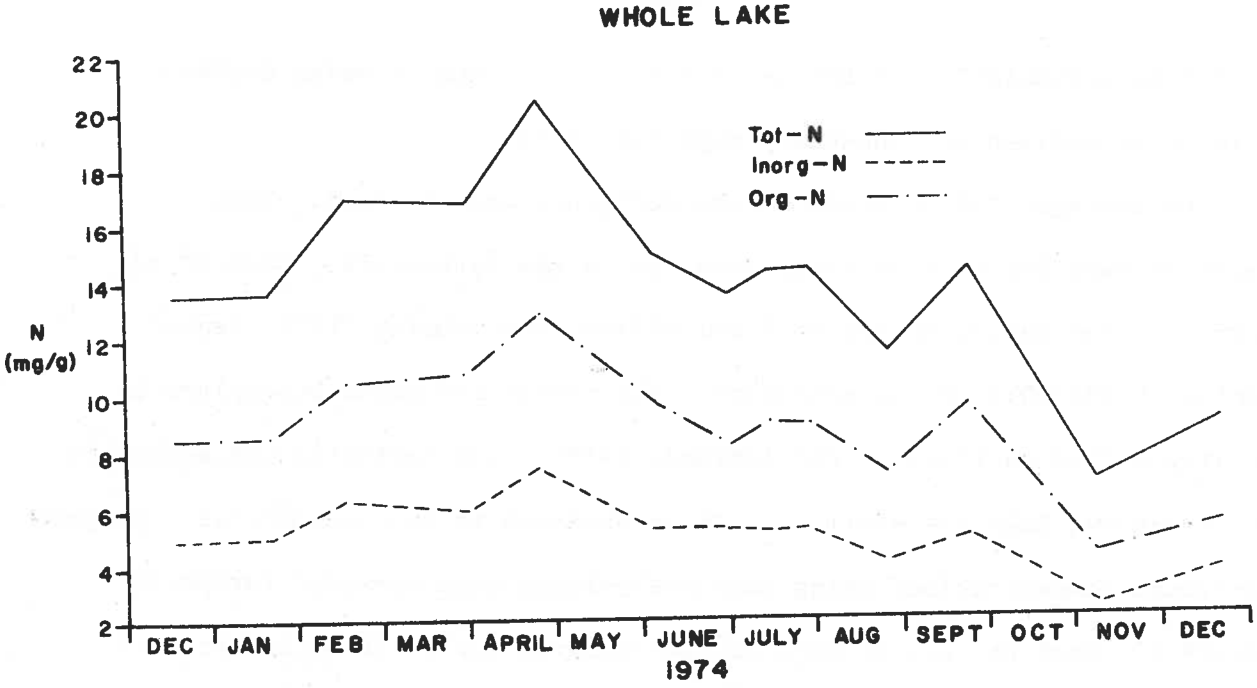


Figure 16. Sediment nitrogen in the whole lake.

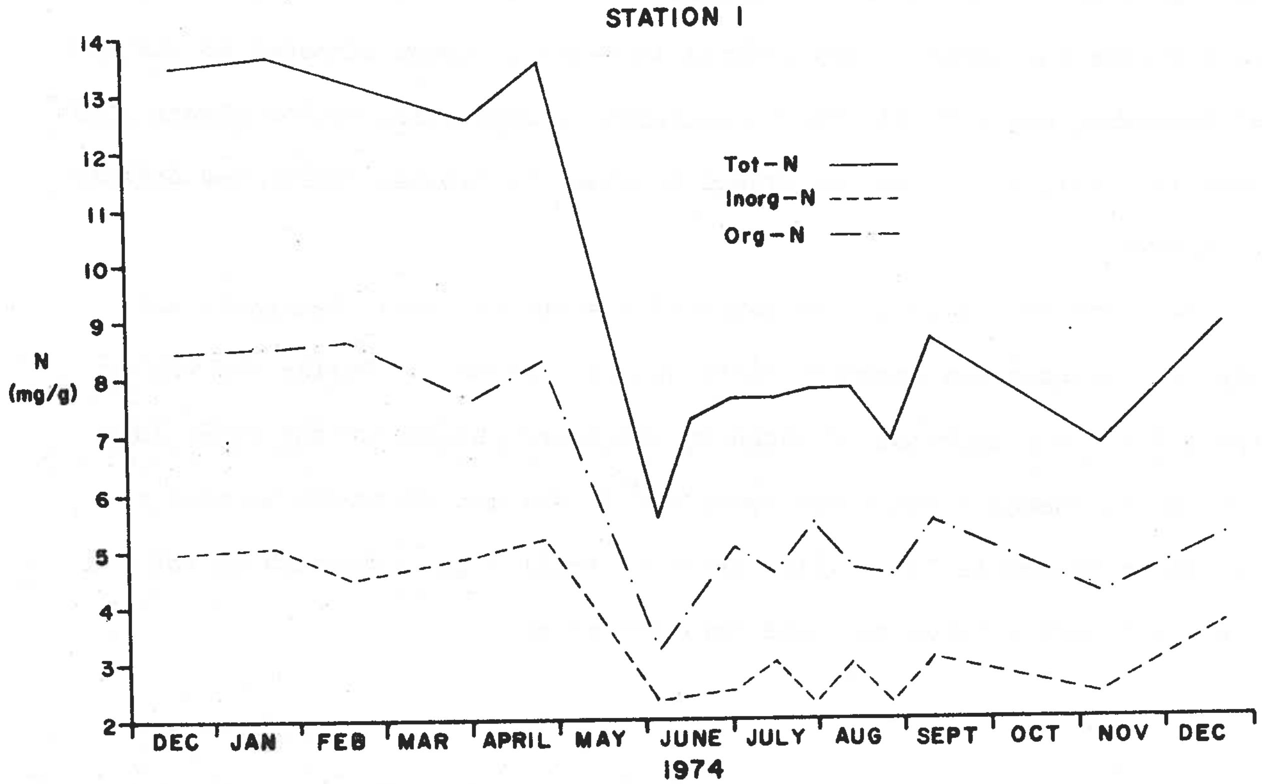


Figure 17. Sediment nitrogen at Station I.

Unlike inorganic phosphorus, inroganic nitrogen was higher at Station IV than at Station II. This is consistent with organic N which is also highest at Station IV. The weighted means inorganic-N for the lake was 4.44 mg/g.

Inorganic N generally increased during the period of ice cover (figure 16), although conditions at this time were not optimal for microbial activity some mineralization of organic N was probably occurring. This same trend was exhibited by inorganic P. During the summer inorganic N generally decreased. Although organic N mineralization was occurring, apparently more inorganic N was being extracted from the sediments by the macrophytes than was formed by mineralization.

Inorganic N at Station I shows a somewhat different seasonal pattern. As shown in figure 18, from December until the end of May, ammonia was being released from the sediments into the overlying water. Although inorganic P showed a decrease during the winter, inorganic N did not show a decrease. This may be due to: (1) organic N may have been mineralized at a similar rate to that being released into the water. Inorganic N did not show an increase from January to April at Station I as it did in the rest of the lake. (2) The amount of ammonia being released into the overlying water was very small compared to the total inorganic N that was present in the sediments. Therefore the relative decrease in total inorganic N would not be great. Conversely the inorganic P that was released into the water was a larger percentage of the total inorganic P.

As with organic carbon and organic phosphorus, organic nitrogen was much higher at Station IV than at the other stations. As with the other two parameters macrophytic growth was the greatest here. Organic N was closely correlated with organic C just as organic P was (figure 15). The

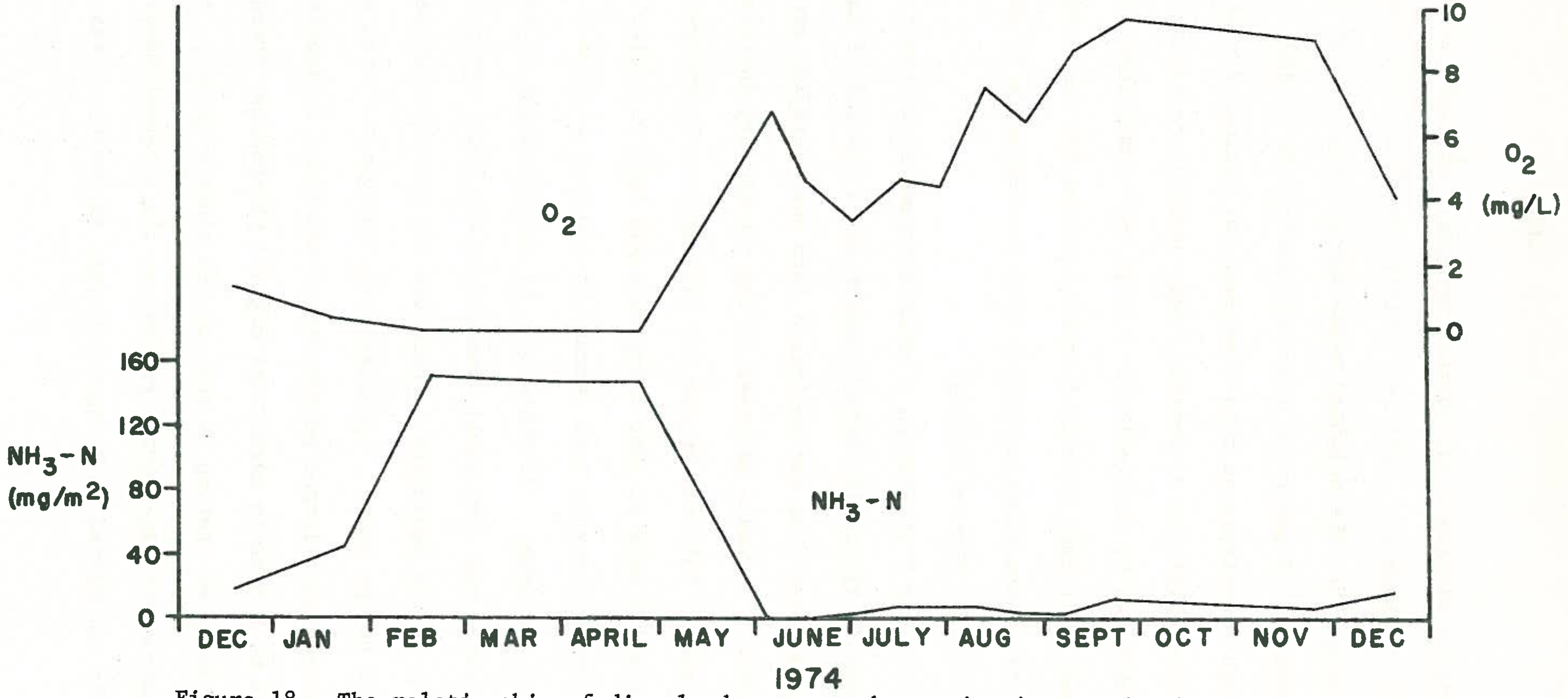


Figure 18. The relationship of dissolved oxygen and ammonia-nitrogen in the bottom waters at Station I.

correlation coefficient was 0.935 which is significant to the 0.01 level. Organic N was better correlated with organic C and IVS than organic P.

Organic nitrogen increased during the period of ice cover but during the summer the concentration decreased. The decrease can be attributed to mineralization. Organic N showed a sharp increase at the end of September. As with organic C and organic P this was probably due to the deposition of macrophytes.

Sediment Trends.

In order to estimate the annual trends of the previously discussed sediment parameters we computed the net gain or loss from the sediments. These annual trends for the whole lake and station I are presented in Table 10. To obtain these trends we determined the changes for each parameter between two consecutive sampling dates. The differences were then summed for the year 17 December 1973 to 21 December 1974 to obtain annual trends. Trends during specific periods of the year can also be determined in this way. Using this method we attempted to obtain gross qualitative changes in the sediments.

As can be seen in Table 10, some of the cations in the sediments increased and some decreased during the year. Iron oxides, $Al_2,0_3$,Ex-Ca, Ex-Mg, and Ex Mn increased during the year and Ex-Al and Ex-Zn decreased. Ex-Fe, which was present in low concentrations, did not show a significant change. Oborn (1964) showed that macrophytes can concentrate both iron and manganese in the encrustations found on the external parts of macrophytes.

This may partially explain why iron oxides and exchangeable manganese are being accumulated in the sediments.

Organ carbon and IVS both are accumulating in the sediments. This is not surprising as this is the result of the natural aging process of the lake (Wetzel, 1975 and Hutchinson, 1957). Organic C and IVS are a determination of the organic matter. During the lifetime of a lake, as the aqutic biomass grows and dies it accumulates on the bottom. Gradually through the years the sediments build up little by little until the lake eventually fills and ceases to be a lake. The greatest increases in organic matter in the sediments occurred from 12 September 1973 - 17 December 1973, 10 Sept. 1974 - 24 Sept. 1974, and 8 November 1974 - 21 December 1974. This is not surprising as these are the times when the majority of the macrophytes and much of the phytoplankton die.

As can be seen in Table 10 both the total phosphorus and total nitroggen decreased in the sediments. This is unusual because many workers have noted that the sediments serve as a sink for phosphorus (Bortelson and Lee, 1972, Golterman, et.al. 1969; and Syers et.al. 1973). This loss is due exclusively to inorganic P which is released into the overlying water and then removed through the dam. It appears that with the exception of Station I the lake sediments are accumulating total P. However, so much is being removed from the sediments at Station I that there is a net loss of phosphorus from the sediments.

Inorganic phosphorus does not show an annual change in the lake as a whole but organic P does. Apparently more organic P is mineralized to inorganic P annually than is being formed biologically. This results in a net loss of P from the lake. However, at Station I both organic and inorganic P show an annual loss. The amounts are larger here than in the lake as a whole which again indicates that the deep water withdrawal is causing the removal of phosphorus.

Table 10. Trends of some chemical parameters of the sediments of Georgetown Lake from 17 December 1973 - 21 December 1974.

Parameters	mg/g[1] Station I	 Whole Lake
Fe_2O_3	0.000	+8.719
Al_2O_3	+0.011	+0.056
Ex-Ca	-0.20	+6.25
Ex-Mg	-0.187	+6.25
Ex-Mn	+0.101	+0.056
Ex-Fe	-0.001	+0.012
Ex-Al	-0.014	-0.025
Ex-Zn	-0.045	-0.116
Organic-C	-44.2	+27.2
IVS	-64.25	+26.86
Total-P	-0.382	-0.020
Inorganic-P	-0.163	-0.001
Organic-P	-0.219	-0.019
Total-N	-4.62	-0.63
Inorganic-N	-1.35	+2.25
Organic-N	-3.271	-3.442

[1] + indicates annual gain; - indicates annual loss

Total nitrogen also shows an annual loss in the sediments. As with phosphorus, nitrogen, both inorganic and organic, show a greater loss at Station I than in the rest of the lake. In the lake as a whole, inorganic N shows an annual increase. However, at Station I inorganic N is decreasing. It appears then, that organic N is being mineralized more rapidly than inorganic N is being lost through the dam. However, organic N is being lost more rapidly than inorganic N is accumulating.

It would seem that the sediments of Georgetown Lake should be very low in phosphorus and nitrogen. The fact that this is not so is probably caused by the original substrate. As discussed earlier this area was originally a hay meadow. As such it was probably high in nitrogen and phosphorus.

This phenomenon is probably a result of the deep water withdrawl at the dam. Wright (1967) has shown that reservoirs with deep water withdrawls liberate higher concentrations of nitrogen and phosphorus that surface water withdrawls. This is generally because change during summer stratification, higher concentrations of N and P are present in the hypolimnion than in the epilimnion. This is not true in the summer in Georgetown Lake but is true during ice cover. As discussed earlier during the ice cover period the bottom waters become anaerobic thus causing certain sediment chemicals to be released from the sediments. Among these are inorganic P and ammonia. Because the water withdrawl is near the lake bottom, as these chemicals are being released they are being removed permanently from the lake. This is substantiated by the high concentrations in the outflow during most of the period of ice cover.

As can be seen in Table 10 the greatest loss of total phosphorus from the sediments is at Station I. This is the station near the dam. Using the sum of the differences it is evident that total phosphorus is lost during the ice covered period but gained during the ice free period.

Phytoplankton Standing Crop

The phytoplankton taxa and respective mean cell volumes are listed in Table 11. As can be noted from Table 11, most species of the phytoplankton community were rare, with a few forms dominating the standing crop. This is undoubtedly not a complete list since the occurance of rare species is a function of the enumeration technique and of sample size (Hurlbert, 1971).

The division chlorophyta (green algae) was represented by at least 22 genera and 21 species. Euglenophyta was encountered in only one sample, with *Phacus* being the only genera found. Chrysophyta was the most diverse division being represented by three classes, 22 genera and 61 species. *Dinobryen sertularia*, *Cyclotella bodanica*, *Stephanodiscus astrea*, *Asterionella formosa*, *Fragilaria crotenensis* and *Synedra* sp. accounted for the majority of the Chrysophyta biomass. Four species were found of the division Pyrrophyta (dino flagellates). Due to the large cell volumes, eventhough the numbers of dinoflagelattes were low, they made a noticeable contribution to the total biomass. The Cyanophyta (blue-green algae) were represented by five genera with seven species. *Anabaena flos-aqua* reached the largest standing crop of any phytoplankton. The cryptophyceae were present in all the samples. *Cryptomonas ovata* made a substantial contribution to the total biomass in every sample.

Table 11. List of the Phytoplankton Taxa in Georgetown Lake, Montana. 1973-1975.

Taxa	Mean Cell Volume $u^3.m^{-3}$
Division Chlorophyta	
Class Chlorophyceae	
Order Volvocales	
Family Chlamyomonadaceae	
Chlamydomonas[o] sp. Ehrenberg	35
Carteria[o] sp. Diesing	440
Family Volvocaceae	
Eudorina unicocca[o] Smith	900
Pandorina morum[o] Bory	525
Order Tetrasporales	
Family Palmellaceae	
Gleocystis gigas (Kuetz) Lagerheim	2150
Sphaerocystis schroeteri Chodat	900
Order Ulotrichales	
Family Ulotrichaceae	
Ulothrix variabilis[o] Kuetzing	300
Family Protococcaceae	
Protococcus[o] sp. Agardh	30
Order Chlorococcales	
Family Micractiniaceae	
*Golenkinia radiata** (Chodat) Wille	4200
Family Dictyosphaeriaceae	
Dictyosphaerium pulchellum[o] Wood	310
Family Hydrodictyaceae	
Pediastrum duplex[4] Meyer	3000
*Sorastrum americanum** (Bohlin) Schmidle	30
Family Oocystaceae	
Ankistrodesmus falcatus (Corda) Ralfs	100
A. spiralis[o] (Turner) Lemmermann	70
Chlorella[o] sp. Beijerinek	40
Chodatella longiseta[o] Lemm.	1000
Oocystis gloeocystiformis Borge	40
O. pusilla[o] Hansgirg	2450
Planktosphaeria gelatinosa Smith	65
Tetraedron minimum (A.Braun) Hansgirg	50
T. trigonum (Naeg.) Hansgirg	1750
Family Scenedesmaceae	
Scenedesmus bijuga (Turp.) Lagerheim	4300
S. quadricauda (Turp.) de Brebisson	60
Order Zygnematales	
Family Zygnemataceae	
Mougeotiopsis calospora[o] Palla	226,200
Family Desmidiaceae	
Cosmarium tumidum[o] Wolle	202,700
Stauratrum aspinosum Wolle	3225
S. eustephanum[o] (Ehrb.) Ralfs	268,000

Table 11. (continued)

Taxa	Mean Cell Volume $u^3.m^{-3}$
Unidentified Chlorophyta	
microplankton$_a$	35
microplankton$_b$	65
microplankton$_c$	525
microplankton$_d$	85
microplankton$_e$	12
Division Euglenophyta	
Class Euglenophyceae	
Order Euglenales	
Family Euglenaceae	
Phacus[o] sp. Dujardin	4400
Division Chrysophyta	
Class Xanthophyceae	
*Botryococcus braunii** Kutzing[1,4]	3550
Class Chrysophyceae	
Order Chrysomonadales	
Family Ochromonadaceae	
Dinobryon sertularia Ehrenberg[o]	580
Class Bacillariophyceae[2]	
Order Centrales	
Family Coscinodiseaceae	
*Cyctolella antiqua** W.Sm.	5300
C. comta (Ehr.) Kutz	1950
C. bodanica Eulenst	6870
C. glomerata Bachmann	150
*C. meneghiniana** Kutz	3150
Melosira distans (Ehr.) Kutz	950
*M. granulata** (Ehr.) Ralfs	570
Stephanodiscus astrea (Ehr.) Grun	760
Order Pennales	
Suborder Fragilarineae	
Family Diatomaceae	
*Diatoma hiemale** (Roth)	2750
Family Fragilariaceae	
Asterionella formosa Hass	235
*Fragilaria brevistriata** (Pat.) Hust	90
F. capucina Desm	450
F. construens (Ehr.) Grun	135
F. crotenensis Kitton	565

[1] There is disagreement as to the classification of *Botryococcus*, for discussion, see Smith (1950) and Prescott (1962).

[2] Patrick and Reimer (1966) consider the Bacillariophyta as a division, with a class Bacillariophceae, the orders not being the Centrales and Pennales, but rather what Smith (1950) defines as suborders.

Table 11. (continued)

Taxa	Mean Cell Volume $u^3.m^{-3}$
Synedra capitata* Ehr.	35,350
S. parasitica* (W.Sm.) Hust	135
S. ulna (Nitz.) Ehr.	3050
S. sp.	80
Family Achnanthaceae	
Achnanthes hungarica* (Grun.) Grun	170
A. lancolata (Breb.) Grun	625
A. minutissima Kutz	70
Cocconeis diminuta* Pant	450
C. placentula Ehr.	8600
Rhoicosphenia curvata* (Kutz.) Grun	650
Family Tabellariaceae	
Tabellaria fenestrata* (Lyrgb.) Kutz	5450
Suborder Naviculineae	
Family Naviculaceae	
Navicula bacillum* Ehr.	2350
N. cryptocephala Kutz	150
N. cuspidata* (Kutz.) Kutz	12,500
N. pupula* Kutz	200
N. radiosa* Kutz	2050
N. rhynchocephala Kutz	875
N. salinarum* Grun	450
N. tripunctata (O.F. Mull) Bory	2000
Pinnularia biceps* Greg	6200
P. nodosa* (Ehr.) W.Sm.	4400
Family Gomphonemataceae	
Gomphonema acuminatum Ehr.	1450
G. constrictum Ehr.	1450
G. olivaceum (Lyngbye) Kutz	500
G. parvulum* (Kutz.) Grunow	400
G. sphaerophorum Ehr.	1650
G. subtile* Ehr.	900
Family Cymbellaceae	
Amphora ovalis* Jutz	14,500
Cymbella affinis Kutz	1800
C. microcephala Grun.	100
C. prostrata (Berkeley) Cleve	2750
C. turgida *(Greg.) Cleve	17,700
C. ventricosa Kutz	1400
Epithemia sorex Kutz	3150
E. turgida (Ehr.) Kutz	35,600
E. zebra (Ehr.) Kutz	35,000
Rhopalodia gibba (Ehr.) O. Mull.	31,500
Suborder Surirellineae	
Family Nitzschiaceae	
Nitzschia filiformis* (W.Smith) Hust	700
N. fonticola Grun	160

Table 11. (continued)

Taxa	Mean Cell Volume $u^3.m^{-3}$
*N. hantzschiana** Rabh.	650
N. linearis W. Smith	3050
N. palea (Kutz.) Smith	550
*N. sigmoida** (Ehr.) W. Smith	17,800
N. sublinearis Hust.	2275
Family Surirellaceae	
*Cymatopleura solea** (Breb.) W. Smith	290,300
Division Pyrrophyta	
Class Dinophyceae	
Order Gymnodiniales	
Family Gymnodiniaceae	
Gymnodinium pulustre Schilling	88,400
Order Peridiniales	
Family Glenodiniaceae	
Glenodinium pulvisculus (Ehr.) Stein	5500
Family Peridiniaceae	
Peridinium gatunense Nygaard	130,900
Family Ceratiaceae	
*Ceratium hirundinella** (O.F. Muell.) Dujardin	73,800
Division Cyanophyta[3]	
Class Myxophyceae	
Order Chroococcales[4]	
Family Chroococcaceae	
*Anacystis cyanea** (Kutz.) Drouet and Daily	413,100
A. incerta° (Lemm.) Drouet and Daily	
A. marina (Hansgirg) Drouet and Daily	225
Gomphosphaeria lacustris Chodat	365
Order Oscillatoriales[5]	
Suborder Oscillatorineae	
Family Oscillatoriaceae	
Oscillatoria rubescens° de Candolle	5025
Suborder Nostochineae	
Family Nostocaceae	
Anabaena flos-aquae (Lyngbye) Debrebisson	1350
Family Scytonemataceae	
Fremyella diplosiphon° (Gomont) Drouet	6350
Unidentified Cyanophyta[5]	210

[3] The taxonomy of the Cyanophyta is based on revisions made by Drouet and Daily, in Edmondson, ed. (1959).

[4] Mean cell volume was based on the average number of cells per colony.

[5] Mean cell volume was based on a trichome length of 100 um.

Table 11. (continued)

Taxa	Mean Cell Volume $u^3.m^{-3}$
Division Uncertain	
Class Cryptophyceae[6]	
Order Cryptomonadales	
Family Cryptochrysidaceae	
Rhodomonas lacustris Pascher, Ruttner	100
Family Cryptomonadaceae	
Cryptomonas erosa Ehrenberg	575
C. ovata Ehrenberg	5500

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[*] Taxa were encountered in only a few samples.

[o] Identification and/or the presence of taxa were based on living samples.

[6] Prescott (1962) considers this class belonging to the division Pyrrophyta, however, *Rhodomonas* is not mentioned by Prescott (1962).

Figures 19 and 20 illustrate the respective cell volumes by division for 1973-74 and 1974-75, respectively. The results are expressed on an areal basis. Both years exhibited a maximum algal standing crop in August and September. Lowest standing crops were observed under the ice. Anabaena flos-aquae reached the highest standing crop of 190,000 $mm^3.m^{-2}$ on 10 September, 1973. The following year the maximum observed standing crop of Anabaena flos-aquae was approximately 20 times less. Cryptophyceae standing crops were also observed to be greater the first year, especially under the ice. The chemical data did not show a difference between the two years, indicating other factors influence algal populations. Higher standing crops can be qualitatively explained by the difference in water levels between the two years (Figure 2). With less water in the reservoir, more water would be in contact with the sediments, indicating that growth promoting substances were released from the bottom sediments. Chrysophyta standing crops were slightly greater the second summer, possibly indicating an antagonistic interaction with the Cyanophyta. Both years showed an increase of standing crop before the ice melted.

The taxa which were observed to contribute more than 15% of the total cell volume are graphically illustrated in Figure 21 and 22. Dinobryon sertularia, a form which is inhibited by high phosphate concentrations, attained 28% of the total biomass on 1 July 1974. On the 29th of July, 1974, Fragilaria crotenensis, a common planktonic diatom reached a maximum standing crop of 19,850 $mm^3.m^{-2}$, representing 73% of the total biomass on that day. Anabaena flos-aquae bloomed on the 26 August, 1974. Anabaena flos-aguae is capable of atmospheric nitrogen fixation and therefore would be relatively unaffected by existing nitrogen concentrations. The Anabaena

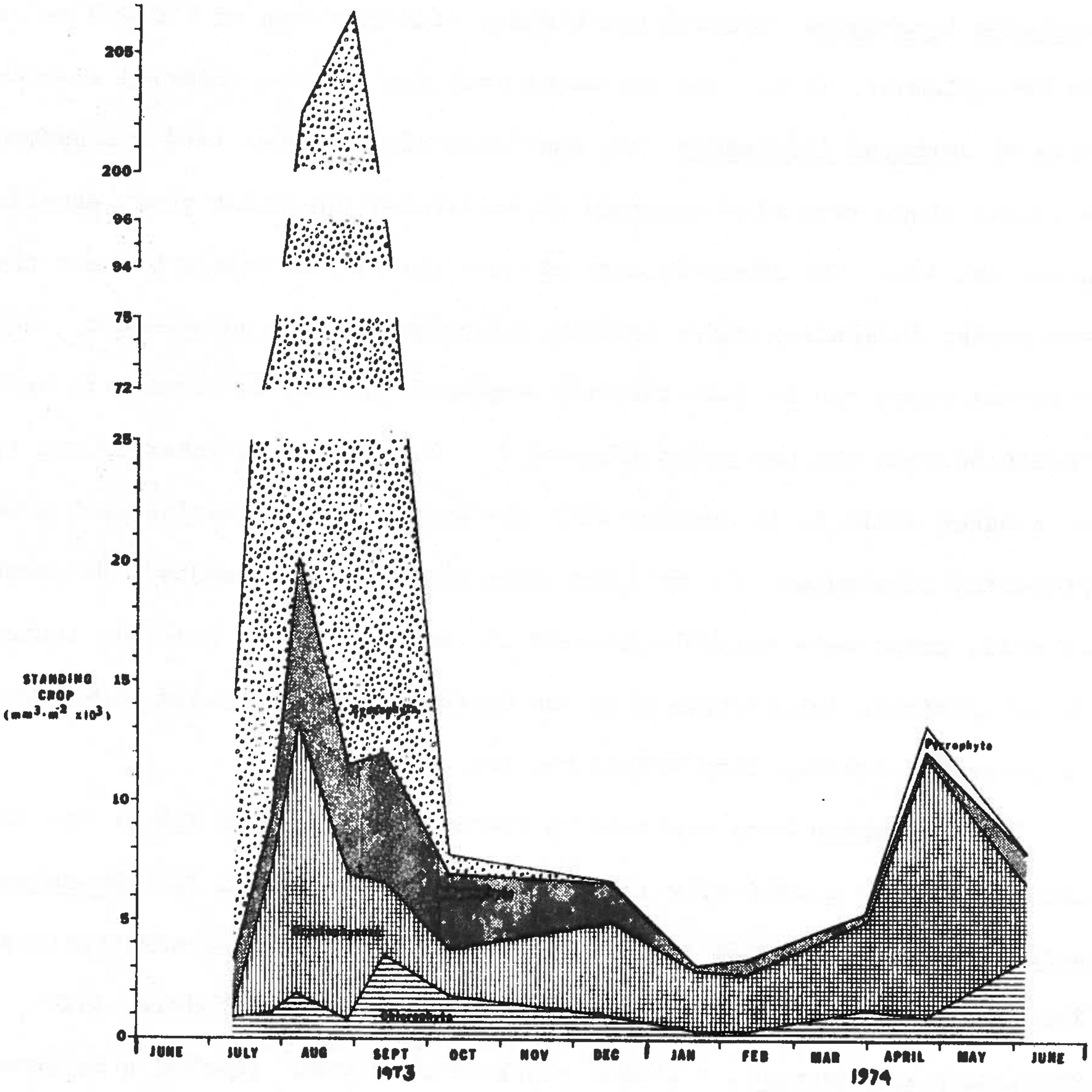

Figure 19. Seasonal distribution of divisional phytoplankton standing crops, 1973-74.

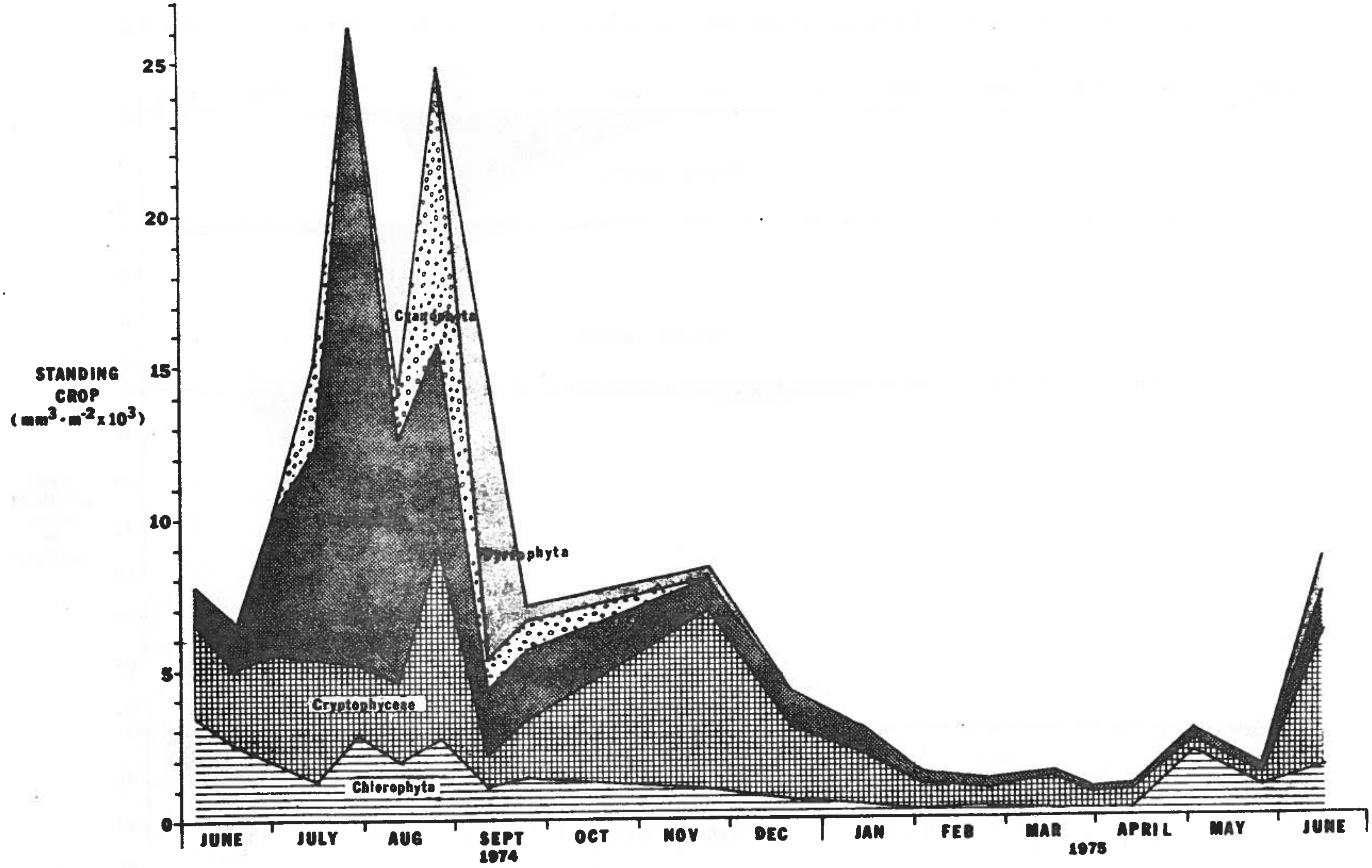

Figure 20. Seasonal distribution of divisional phytoplankton standing crop. 1974-75.

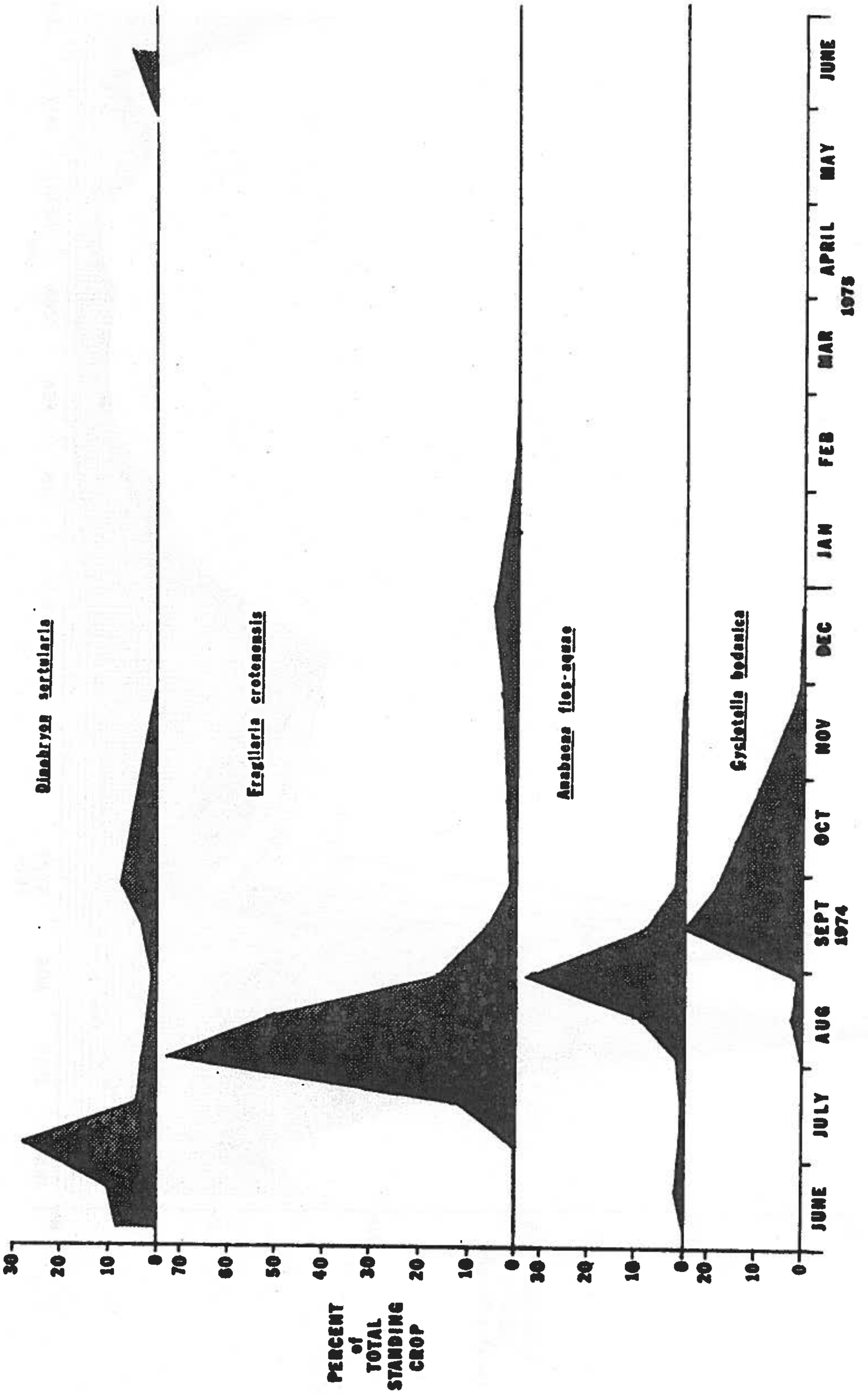

Figure 21. Relative seasonal abundance of the major phytoplankton species, 1973-75.

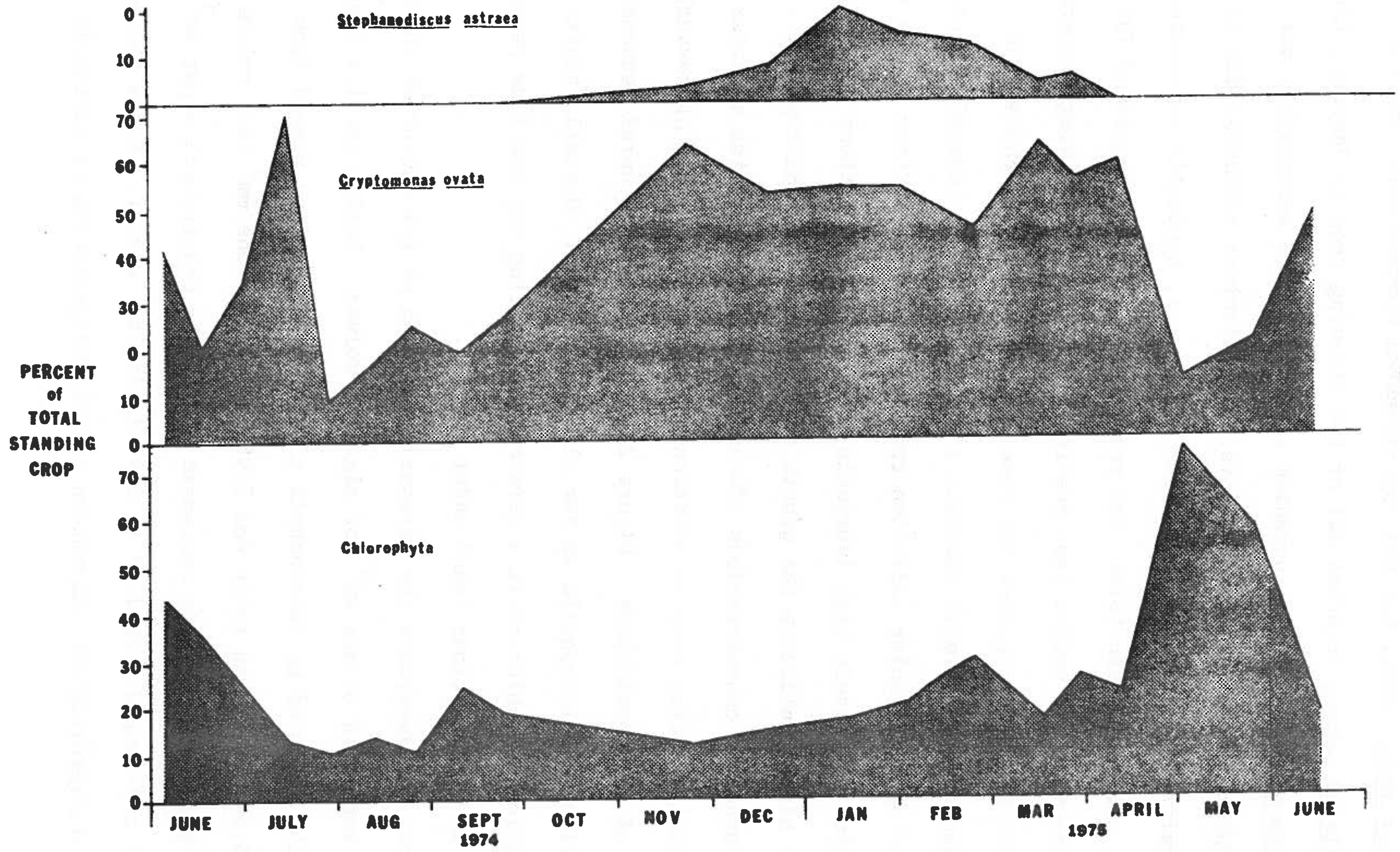

Figure 22. Relative seasonal abundance of the major phytoplankton species, 1973-75.

pulse was followed by an increase of Cyclotella bodanica. Eventhough Cryptomonas ovata dominated the Phytoplankton biomass under the ice, Stephanodiscus astrea reached 20% of the standing crop in January, 1975. Cryptomonas ovata , a motile organism capable of both autotrophic and heterotrophic growth, appeared to have had a distinct advantage due to its diversified habits. The division Chlorophyta, typically represented by small, unidentifiable forms, was present all year, but achieved 70% of the observed cell volume just previous to ice melt. Although heterotrophic growth has been reported for some forms of the Chlorophyta, the data presented in Figure 22 indicate a light - nutrient induced effect. The amount of daily solar radiation reaching the light surface (Table 4) coupled with relatively high inorganic nutrient concentrations (Figure 7), appear to highly influence the growth rate of the small Chlorophyta.

Chlorophyll a concentrations of the phytoplankton provide an index to the algal standing crop in addition to an estimate of the photosynthetic capacity of the populations. Figure 23 shows the same general seasonal distribution of chlorophylla as for algal biovolumes. Overall, higher concentrations of chlorophyll a were observed during the ice free period compared to cocentrations found under the ice.

Figure 23 illustrates the seasonal variation of the amount of chlorophyll a contained by one mm^3 of algal biovolume. During the ice free period, the ratio of µg chlorophyll a per mm^3 cell volume ranged from 0.17 to 5.64. The mean ratio was 2.08 µg Chl a to one mm^3 cell volume. The mean value of the ratio increased to 4.65 µg Chlorophyll a per mm^3 biovolume and ranged from 1.63 to 8.98 during the winter. These values indicate a physiological adaptation of the Phytoplankton to partially over -

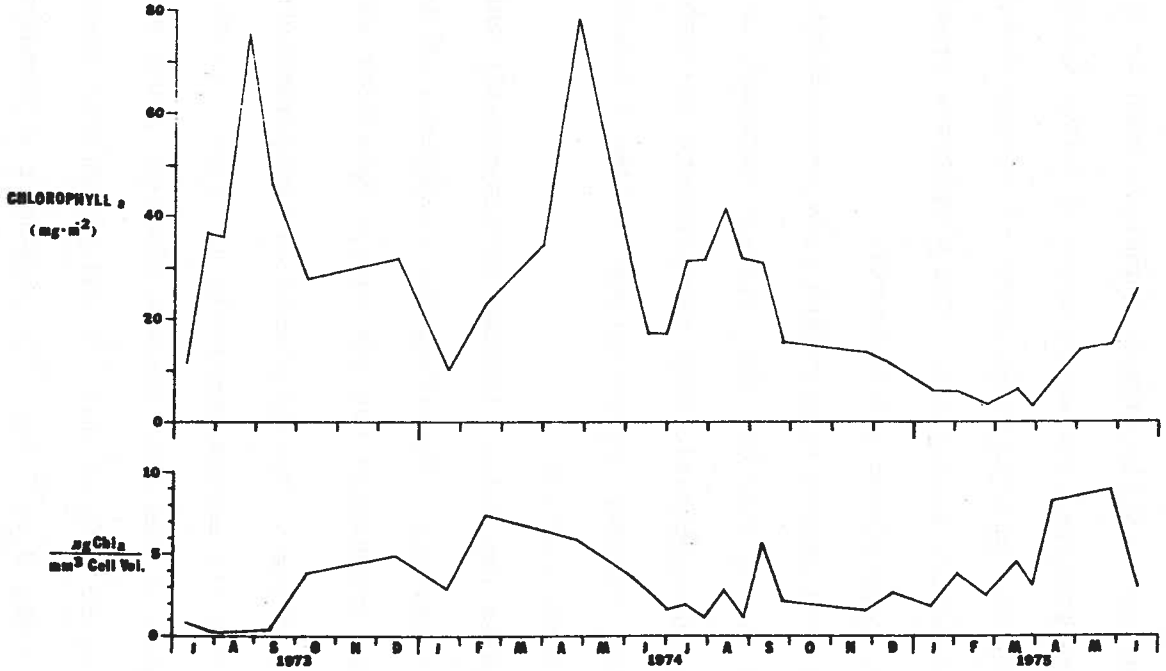

Figure 23. Seasonal variation of chlorophyll a concentration and chlorophyll a to cell volume ratios, 1973-75.

come light deficiencies during the ice-covered period, ce more chlorophyll to absorb light.

PLANKTON PHOTOSYNTHESIS AND RESPIRATION

Since the light and dark bottle oxygen technique used to measure metabolic rates of plankton involved the entrainment of water collected at each depth in the lake, the *in situ* measurement of oxygen changes reflected the total plantonic community metabolism. The planktonic organisms entrained include phytoplankton, zooplankton and bacteria.

Oxygen rates were used rather than carbon rate measurements for two reasons: (1) oxygen metabolism in the lake was the critical interest in Georgetown Lake, and; (2) oxygen photosynthetic rate measurements are more dependent upon the light reaction, whereas carbon uptake is also a function of chemosynthesis and heterotrophic uptake.

Figure 24 illustrates the daily plankton photosynthetic and respiratory rates for the entire reservoir. Utilizing the techniques of Sorokin (1969), total planktonic oxygen production for the entire reservoir was estimated at 6.967×10^6 kg 0_2 per year. Yearly planktonic respiration was estimated at 1.717×10^7 kg 0_2 for the entire reservoir per year. These values divided by the mean area of the lake yielded plankton gross production of 0.604 kg $0_2 . m^{-2} . yr^{-1}$ (1.61 g $0_2 . m^2 . day^{-1}$) and planktonic respiration at 1.49 kg $0_2 . m^{-2} . yr^{-1}$ (3.96g $0_2 . m^{-2} . day^{-1}$). Assuming a photosynthetic quotient of 1.2, the gross primary production values can be expressed as 0.188 kg $C . m^{-2} . yr^{-1}$ and 0.50 g $C . m^{-2}$.day

Rodhe's(1969) suggested that naturally entrophic cakes tend to have average rates of net production of 0.3 - 1.0 g $C . m^{-2} . day^{-1}$ Based on Rhode's values of net production, Georgetown Lake could be classified

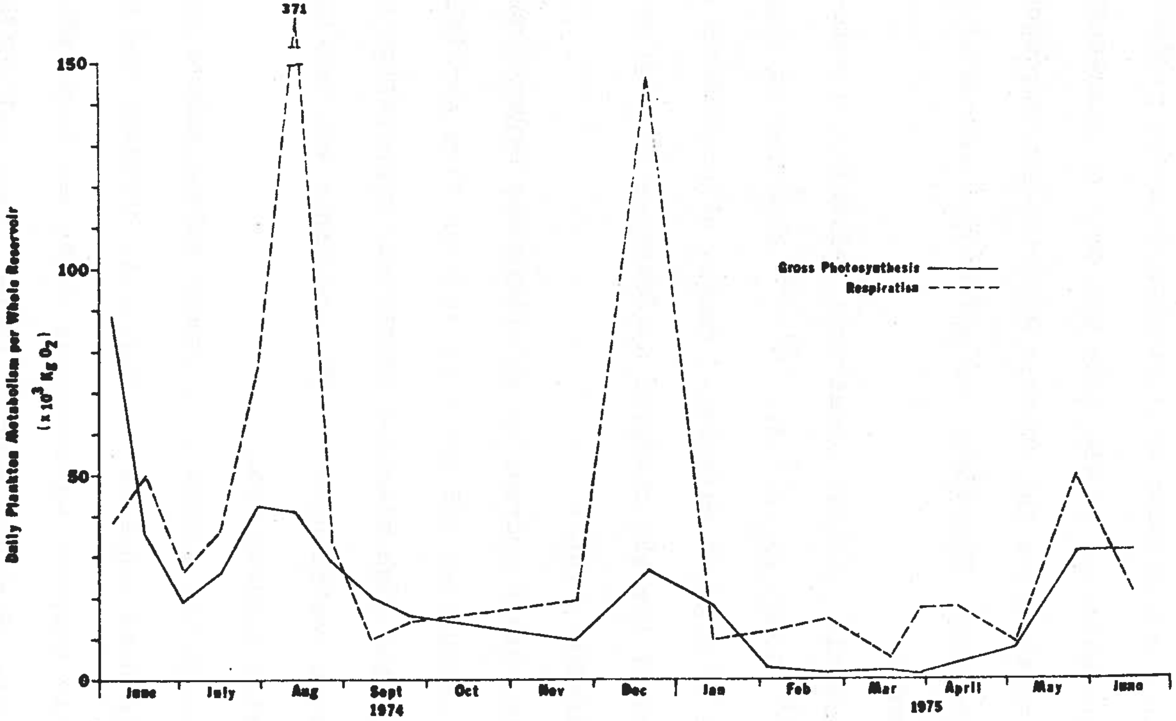

Figure 24. Mean daily rates of planktonic gross photosynthesis and respiration per whole reservoir, 1974-75.

as moderately productive in phytoplankton, especially when gross production was compared to net production.

Figure 24, as well as the above estimated values, show that planktonic respiration was greater than planktonic gross production. Theoretically, if the organic material in the lake was only of planktonic origin, plankton could not exist since the organic material was decomposed at a greater rate than it was produced. Therefore, an additional source of organic material must have been present.

Allochthonous organic material input from inflowing streams averaged 0.0169 g $C.m^{-2}.day^{-1}$ (0.045 $gO_2.m^{-2}.day^{-1}$) are required to completely oxidize this amount of organic material. Hence, allochthonous organic material cannot account for the observed differences between gross production and respiratory rates.

Besides plankton, other sources of autochthonous organic material include macrophyte production and sediment release from partially decomposed organics. However, the high observed planktonic respiration rates indicate that the plankton contribution to the sediments was negligible compared to that of macrophytic accumulation.

Attempts to analyze the causes of seasonal phytoplankton production and biomass fluctuations have centered on physical, chemical and biological influences. Physical factors, particularly light and temperature regimes, tend to set the limits of photosynthetic rates. Chemical influences, most notably nitrogen and phosphorus, may limit productivity within the limits set by lights and temperature. Biological activity of the phytoplankton themselves can influence productivity, such as the physiological condition, adaptation (Parsons and Takahshi, 1971), and density dependent factors (Wright, 1960).

The knowledge of either standing crop of the primary productivity of a phytoplankton population gives little information as to the inherent "production intensity" or "vitality" of the population (Strickland, 1960). Verduin (1956) demonstrated that large standing crops may be producing little organic material and, conversely, small standing crops may be producing large amounts of organic matter. Strickland (1960), therefore, recommends both the standing crops and production data to decide on the fertility of a water mass.

Figure 25 shows the seasonal distribution of absolute phytoplankton gross production rates per average square meter, phytoplankton assimilation ratios and a slight variation of the phtotosynthetic index described by Strickland (1960). The assimilation ratios (mgO_2 produced per mg $Chlorophyll_a$ per day) corrects the absolute daily gross production rates for the standing crops of phytoplankton. The assimilation ratios divided by the incident light intensity yielded the photosynthetic index. Strickland (1960) recommended the use of this index for evaluating the limitations of the standing crop to produce organic material. Eventhough photosynthetic rates are not directly proportional to light at high light intensities, the photosynthetic index is useful since most of the phytoplankton occurred at depth were light intensities were sub-optimal, ie. the linear portion of the light saturation curve.

The absolute gross plankton production curve indicates four periods at which photosynthesis was the greatest. The photosynthetic pulse during late July and August became negligible when corrected for the standing crop. The assimilation ratio curve coupled with figure 24 showing that late July

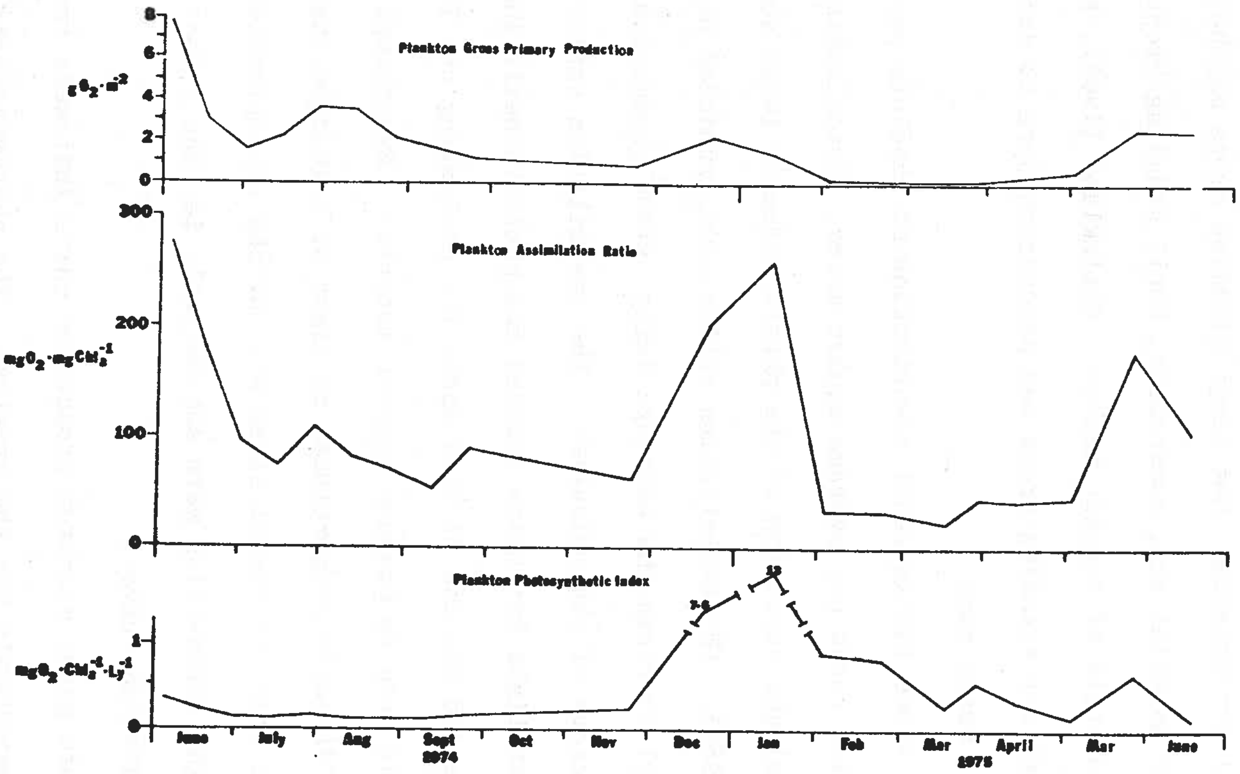

Figure 25. Seasonal areal gross photosynthesis, assimilation ratios, and photosynthetic index, 1974-75.

and August was the period of maximum standing crop, indicates that density dependent factors as described by Wright (1960) were possibly effecting production rates. Summer values of the photosynthetic index had a mean value of 0.15, indicating that the high photosynthetic rates observed in June were a function of light and that the entire phytoplankton population was limited by other factors during the summer. Possible influential factors reducing the photosynthetic index during the summer were low carbon dioxide tensions, low inorganic nitrogen and phosphorus concentrations and the low total phosphorus relative to total nitrogen. Of these, total phosphorus appeared to be a substantial factor since total nitrogen to total phosphorus ratios were very high compared to that found in algal protoplasm (see Results-Nutrient section). Algae can use free carbon dioxide, bicarbonate and carbonate as inorganic carbon sources. Since the minimum concentration of the total inorganic carbon was 80 $mg.l^{-1}$, carbon does not appear to be limiting (Parsons and Takahashi, 1973).

The photosynthetic pulse that was observed in December and January became stronger with each additional correction. The phytoplankton that occurred at this time were in the best physiological condition than cells that occurred during any other time of the year. As evident by low inorganic nutrient concentrations, phosphorus and nitrogen were probably incorporated into the cells as fast as they were released through decomposition. As the ice-cover persisted, the photosynthetic index dropped, indicating another limitation. Since inorganic concentrations were relatively high, the phytoplankton probably became more inhibited by lower oxygen tensions, ie. exposed to a more reducing condition.

The phytoplankton, mainly chlorophyta, that occurred just previous to ice-melt, were well adapted physiologically, as evident by a more pronounced peak of the assimilation ratio. However, this peak was diminished by correcting the assimilation ratio for light intensity. The reduction indicates a light induced effect.

Oxygen Budget

As was pointed out in the introduction to the water chemistry section, low dissolved oxygen concentrations observed under the ice was the only chemical parameter that seriously jeopardized Georgetown Lake. Therefore, a model has been proposed to account for the oxygen regime in the reservoir.

The following equation was used to quantitatively define the various factors which influence the dissolved oxygen in the reservoir:

$$\pm \frac{\Delta \text{ Lake}}{t} = \frac{\text{Inflow}}{t} - \frac{\text{Outflow}}{t} \pm \frac{\Delta\text{Chemical}}{t} \pm \frac{\Delta \text{ Physical}}{t} \pm \frac{\Delta \text{ Biological}}{t} \qquad (1)$$

where;

t = time in days

Δ Lake = measured change of oxygen concentration in the lake during time t

Inflow and Outflow = the measured mean oxygen concentration input or output, respectively, from surface waters during time t

Δ Chemical = the average change of oxygen concentration in the lake due to chemical redox reactions during time t

Δ Physical = the average change of oxygen concentration due to physical action in the lake during time t

Δ Biological = the average change of oxygen concentration due to biological metabolism during time t

The use of the equation (1) to partition the changes of oxygen involves limitations since all of the above parameters were not measured. The first assumption was that the chemical redox reactions involving oxygen was negligible during the entire study. This assumption becomes more valid when the rates of biological activity compared to the probable quantities and rates involved with purely chemical reactions. Also, equation (1) assumed that complete, instantaneous mixing occurred with the inflowing surface waters. The third assumption involved the physical influence on the oxygen concentrations. Since the lake is essentially 100% saturated with oxygen during the ice free period, Figure 4 the net gain or loss of oxygen cannot be corrected. Qualitatively, as determined from the carbon dioxide isoclines Figure 4 photosynthesis occurs at a greater rate than respiration during the summer. Hence, a loss of oxygen to the atmosphere probably occurred during the summer. However, the physical interaction of the atmosphere and water column became negligible during the ice-covered period. Since the winter was the critical period with respect to oxygen, an oxygen budget for this period was critical.

Since the chemical and physical influences were negligible during the ice-covered period, equation (1) reduces to:

$$\frac{\Delta \text{ Lake}}{t} = \frac{\text{Inflow}}{t} - \frac{\text{Outflow}}{t} \pm \frac{\Delta \text{ Biological}}{t} \qquad (2)$$

Correcting the observed oxygen changes in the lake for inflow and outflow surface waters, equation (2) can then be solved for biological activity.

$$\frac{\Delta \text{ Lake} - (\text{Inflow}-\text{Outflow})}{t} = \frac{\Delta \text{ Biological}}{t} \qquad (3)$$

The biological activity can be partitioned into net plankton production, net macrophyte production and sediment microbial activity. Substituting the net plankton production (gross photosynthesis-respiration) into equation (2) yields:

$$\frac{\Delta \text{ Lake} - (\text{Inflow}-\text{Outflow})}{t} \pm \frac{\text{Net Plankton Production}}{t} = \pm \frac{\text{Net Influx}}{t} \qquad (4)$$

Table 12 gives the quantitative values for equation (4) during the ice-covered period for the second year of the study.

Correcting the observed lake changes for surface waters had little effect during the winter. A greater difference was observed early in the winter than later into ice-cover. This was probably due to deep water withdrawal. Early in the season the discharges removed oxygen while later on the outflow was removing water from the anoxic zone.

Figure 26 graphically illustrates columns (4) and (7) from Table 12 and the potential amount of oxygen that would have been contained in the water column at 100% saturation. As expected, oxygen deficits became more pronounced as the ice-cover persists. The predicted values represent the oxygen content that would occur if only the plankton had been responsible for the oxygen concentrations. Based on this prediction, the entire water column would have been anoxic by the first of December.

Observed oxygen content was substantially greater than those values predicted from plankton metabolic rate measurements, indicating additional oxygen inputs to the lake. The shaded area of Figure 26 represents the amounts of oxygen that was unaccounted for by measured values. This amount of oxygen, expressed as daily influx rates, is presented in Column (8) of Table 12.

Ground water, as was shown in the hydrology section, imputed a substantial percentage of water to the lake. However, groundwater oxygen concentrations would have to had averaged 330 $mg.l^{-1}$ to account for the calculated influx of oxygen. Typically, groundwater is very low in dissolved oxygen, and probably accounts for less than one percent of the total influx.

Table 12 Oxygen Balance

Date	(1) observed O_2 lake (g O_2.m^{-2})	(2) Δ Lake per day (g O_2.m^{-2}.day^{-1})	(3) Inflows-Outflows per day (g O_2.m^{-2}.day^{-1})	(4) (2)-(3)= corrected $\bar{O}_2$ in lake per day (g O_2.m^{-2}.day^{-1})	(5) (4)t = corrected O_2 in lake (g O_2.m^{-2})	(6) Net plankton production per day (g O_2.m^{-2}day^{-1})	(7) (6)t+(5)= predicted O_2 (g O_2.m^{-2})	(8) -[(4) + (6)]= influx of O_2 per day (g O_2.m^{-2}.day)
Nov 74	48.80				48.80		48.80	
(24)		-0.179	+0.170	-0.349		-0.78		+ 1.13
5 Nov 74	44.50						30.08	
(26)		-0.289	+0.064	-0.225		-5.56		+5.79
1 Dec 74	36.98				34.58		-114	
(23)		-0.351	+0.064	-0.287		-4.81		+5.10
3 Jan 75	28.89				27.99		-225	
(20)		-0.428	+0.053	-0.375		-0.01		+0.39
Feb 75	20.33				20.49		-226	
(21)		+0.009	-0.025	+0.035		-0.97		+0.94
3 Feb 75	20.52				21.23		-246	
(22)		-0.466	+0.011	-0.455		-0.71		+1.17
Mar 75	10.27				11.22		-261	
(12)		-0.050	+0.006	-0.044		-0.82		+0.86
Mar 75	9.67				10.69		-271	
(14)		-0.296	+0.010	-0.306		-1.09		+1.40
Apr 75	5.52				6.41		-289	
(21)		-0.182	-0.009	-0.191		-0.66		+0.85
May 75	1.69				2.39		-303	
(23)		+0.260	-0.013	+0.247		-0.87		+0.62
May 75	7.66				8.08		-323	
(21)		+1.095	-0.088	+1.007		-0.36		-0.65
June 75	30.65				29.23		-331	

e value 48.80 was determined as the oxygen content of the water column assuming 100% saturation at the onset of ice-cover

lumn (1) was determined from Figure

lumn (6) was determined from Figure
corrected for mean depth

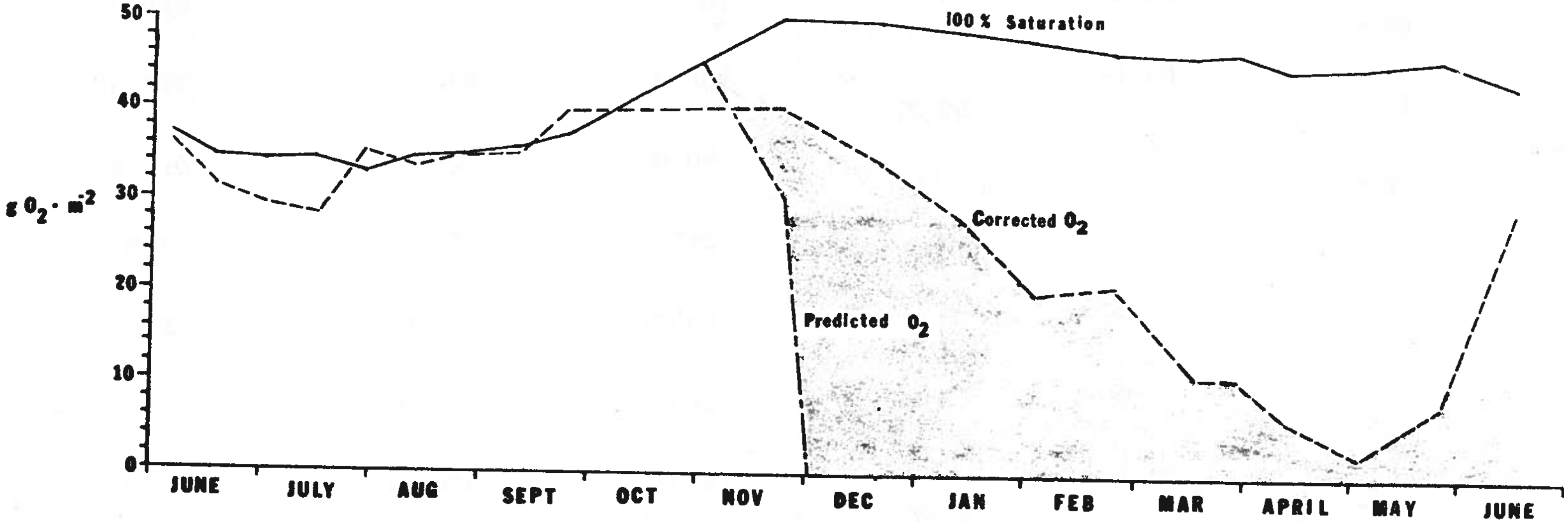

Figure 26. Seasonal areal oxygen concentrations at 100% saturation, oxygen concentration corrected for inflow-outflow and predicted oxygen concentration resulting from phytoplankton metabolic activity, 1974-75.

The biological activity from equation (3) was partitioned into net plankton production, net macrophyte production and sediment microbial activity. Since plankton metabolic rates were accounted for in equation (4) the calculated positive influx of oxygen was probably due to a positive net macrophyte production under the ice. Sediment microbial activity would tend to decrease the oxygen concentrations even more than the negative net plankton production. Hutchinson (1941) observed density currents tending to accumulate heavier water in the depression of Linsley Pond. Accompanying the flow of more dense water was a return of surface water to the shallower areas. Since shallow water (0-2 meters) in Georgetown Lake was never observed to be anoxic, a sediment oxygen demand from recirculating density currents to the shallow sediments probably accounted for additional oxygen consumption. This additional oxygen sink would tend to increase the macrophytic production to account for the calculated oxygen influx presented in column (8), Table 12.

As was postulated from the temperature isoclines (Figure 3), some degree of ice melt probably occurred from March through May, 1975. Conductivity, bicarbonate, calcium, silica and iron isoclines also showed a decrease in concentration directly under the ice during this time, indicating percolation of water around the ice crystals. Since some degree of ice melt and percolation was evident from March through May, oxygen probably entered the water column from the surface ice. This probable additional oxygen imput would tend to minimize the macrophyte production under the ice from March through May.

With the above qualitative judgements, equation (4) can then be rewritten as:

$$\frac{\text{Net Influx}}{t} = \frac{\text{Net Macrophyte Production}}{t} - \frac{\text{Sediment Demand}}{t} + \frac{\text{Input from Surface Ice}}{t} \quad (5)$$

Therefore, the values presented in column (8), Table 12, reflect the net rate composed of the three parameters given in equation (5).

Since oxygen is a highly non-conservative element, the relative contribution of photosynthesis and respiration is of prime importance in a summary of the oxygen budget. When photosynthesis ≃ respiration the organic material is decomposed by respiratory (heterotrophic) activity as fast as it was produced photosynthetically; O_2 produced by photosynthesis can be used for respiration, Stumm and Morgan (1970). The phytoplankton appeared to approach this condition since measured respiratory rates were consistently greater than photosynthesis, However, evidence of greater photosynthetic activity during the summer was apparent from carbon dioxide and bicarbonate data. This photosynthetic activity was due to macrophytic growth as evident by negative net plankton production. Oxygen was apparently lost from the system at this time. Anoxic conditions under the ice resulted from respiration being greater than photosynthesis. However, on an annual basis photosynthesis was greater than respiration, indicating an accumulation of organic matter in the underlying sediments. This conclusion was also substantiated by an increase of organic carbon in the bottom sediments on an annual basis.

A steady state between photosynthesis and respiration is a prerequisite for the maintenance of a constant chemical composition of the water (chemostasis), Stumm and Morgan (1970). Most reported lakes have a special separation of photosynthesis and respiration, ie. epilimnetic versus hypolimnetic stratification of photosynthesis and respiration, ie. summer versus winter. Chemostasis has not been reached in Georgetown Lake for several reasons: (1) a stoichiometric imbalance occurred when oxygen was lost from the system during the summer, ie. oxygen was unavailable during the winter, (2) since macrophytes appeared to be regulating the metabolic reactions in the lake and have the capacity to incorporate nutrients unavailable to the phytoplankton, ie. from bottom sediments, nutrients availability to bacterial populations was enhanced, and (3) deep water withdrawal resulted in a net loss of nitrogen and phosphorus expressed on an annual basis.

SUMMARY

1) Ground water accounted for ≃ 50% of the input water, surface runoff ≃ 37%, and precipitation ≃ 13%. The output was equally divided between Anaconda Mining **Company** pumping, Montana Power Company usage and evaporation.
2) Surface incident light was highest in June and lowest in December. The highest light reduction by the ice cover was 83%. The percentage of the bottom in the euphotic zone ranged from a low of 17% in January to a high of 99.9% in October.
3) During the summer there was no thermal or chemical stratification. During ice cover there was slight thermal stratification and strong chemical stratification both years.
4) Oxygen was the only critical element; the bottom water becoming anaerobic during ice cover. CO_2 data indicates high photosynthesis during the summer, and relatively high respiration during the winter.
5) The order of abundance of cations was: $Ca > Mg > Na > K$
The order of abundance of anions was: $HCO_3 >> Si > SO_4 > CO_3 > Cl > F$.
All data indicates that there was an accumulation of total dissolved solids at low depth.
6) N:P ratios indicate that the ratio is regulated by nitrogen.
7) More essential nutrients are being lost than gained:
    1.4 atoms carbon lost per 1 gained
    2.9 atoms nitrogen lost per 1 gained
    3.0 atoms phosphorus lost per 1 gained
The annual percentage loss of phosphorus is 0.01%; nitrogen loss is 0.085%.
8) As a reducing environment develops during ice cover, inorganic N and inorganic P was released from the sediments.
9) In the sediments organic C, P, and N were higher during the winter but decreased in the summer due to mineralization.

10) C:P ratios indicate that N and P are being lost from the sediments.

11) Because of the deep water withdrawl at the dam there is a loss of N and P from the lake sediments, especially at Station I.

12) Phytoplankton standing crop was very diverse with respect to the total taxa. Only about 15 species accounted for an average of 95% of the total standing crop.

13) _Anabaena flos-aquae_ had the highest observed biomass. This species is capable of nitrogen fixation, therefore it has a nitrogen source.

14) _Cryptomonas ovata_, due to its diversified characteristics, appeared to have the greatest ecological advantage throughout the entire year.

15) The phytoplankton appeared to adapt to the low light levels under the ice cover.

16) Plankton respiration rates were greater than the plankton gross photosynthetic rates which indicates that there is rapid decomposition of dead phytoplankton and additional autochthonous inputs, ie. macrophytes.

17) Annual average daily gross photosynthesis was 0.5 $g.C.m^{-2}.day$.

18) Plankton production during the winter was light limited. Phosphorus was apparently more limiting than N during the summer eventhough both nutrients were reduced to very low levels.

19) Oxygen depletion under the ice was due to both sediment and plankton respiration rates.

20) Additional oxygen input under the ice was required to compensate for the respiration rates. Macrophytic production and to a limited degree, ice-melt are responsible for the oxygen input during ice cover.

21) The lake was not in a steady state since annual photosynthetic rates were greater than annual respiration rates. This indicates organic matter is accumulating in the sediments.

22) Macrophytic production is of major importance in regulating the lake metabolism.

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