CHEMICAL INTERACTIONS IN A EUTROPHIC LAKE

by

Donald B. Aulenbach, Ph.D.
Rensselaer Polytechnic Institute
Troy, New York

August 1976

Presented at
172nd American Chemical Society National Meeting
SanFrancisco, Calif.
Sept. 1, 1976

FWI Report No. 76-6

Abstract

CHEMICAL INTERACTIONS IN A EUTROPHIC LAKE

by

Donald B. Aulenbach
Rensselaer Polytechnic Institute
Troy, New York 12181

Saratoga Lake in eastern New York is a eutrophic lake which receives nutrients from several population centers in addition to non-point source nutrients from farmlands on the watershed. A large portion of the lake has shallow water in which weeds have grown. There are two deep portions of the lake, one 45 ft (14 m) and the other 95 ft (29 m). A peculiarity of the lake is that the inlet and the outlet are in the same quadrant of the lake.

Measurements were made of carbon dioxide, oxygen, light penetration, iron, phosphate, organic, ammonia, and nitrate nitrogen, silica, and the predominant algal forms. During the period of summer stratification, the hypolimnion is devoid of oxygen. On a calm day, there is a marked deficiency in oxygen below the 6 meter (10 ft) level in the epilimnion. The presence of the dissolved oxygen in the upper portions of the epilimnion defines the euphotic zone. The chemical measurements were correlated with the presence or absence of oxygen in the water and with biological productivity.

Control measures were evaluated for improving the quality of Saratoga Lake. A major step is the elimination of raw, partially and fully treated sewage effluents from the influent stream. Consideration was made of the feasibility of using chemical additives to reduce the phosphorus content and change the N:P ratio of the lake so as to lessen the productivity, and to add silicon to support diatom growth at the expense of the blue-green algae. Cost estimates indicate that control by the addition of chemicals would be very costly.

CHEMICAL INTERACTIONS IN A EUTROPHIC LAKE

by Donald B. Aulenbach

Introduction

A lake is a complex ecosystem involving physical, chemical and biological interactions. It is difficult to separate the system into any one of these three processes; however, this paper will try to discuss primarily the chemical interactions within a eutrophic lake with the appreciation that the chemical interactions are frequently controlled or moderated by biological and physical processes.

The model used for this study was Saratoga Lake, located in the southern foothills of the Adirondack Mountains approximately 48 km (30 mi) north of Albany, New York and 19 km (12 mi) west of the Hudson River, as shown in Figure 1. Since the drainage basin is an important factor in the contribution of chemical nutrients to a lake, this is indicated in Figure 1 with the relationship of the lake itself to its main drainage basin. The main stream tributary to Saratoga Lake is the Kayaderosseras Creek which has its origin in the Adirondack Park. The one outlet of Saratoga Lake, Fish Creek, flows into the Hudson River at Schuylerville. What is interesting in this case is that the main inlet and the outlet are located in the same quadrant of the lake. The area has a rich historical legacy.[16] Just east of the lake itself is the famous Saratoga Battlefield where the British Army under General Burgoyne surrendered to the American colonists under General Gates in 1777. This represented the southernmost penetration by the British in their attempt to separate New England from the rest of the colonies and was a turning point in the War of Independence.

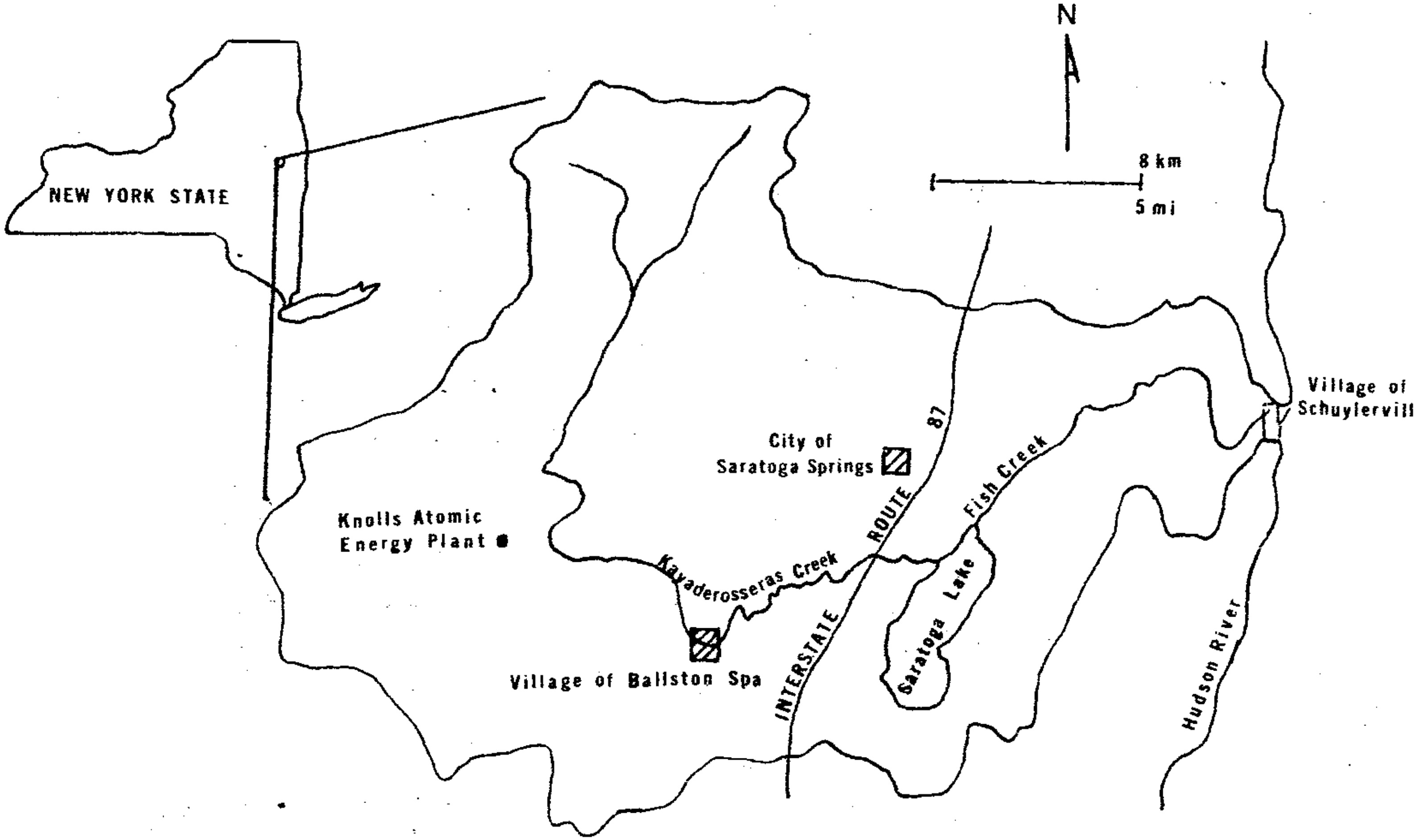


FIGURE 1

SARATOGA LAKE DRAINAGE BASIN

The morphological characteristics of Saratoga Lake are shown in Table 1. The lake is about 7 km (4.5 mi) long and 2.5 km (1.5 mi) wide. At its deepest point, it is 29 m (95 ft) deep in a rather broad well in the northeastern portion of the lake. A second shallower well of 15.5 m (51 ft) deep occurs at the southern portion of the lake just west of Snake Hill. The depth contours of the lake are shown in Figure 2. The long axis of the lake is situated approximately north-northeast with the outflow at the northern end. The major inflow, Kayaderosseras Creek, enters on the western shore about 1.5 km (1 mi) from the outlet into Fish Creek.

The major geological formations of consolidated bedrock underlying the Saratoga Lake basin were formed during the period 500 million to 350 million years ago. To the northwest of Saratoga Lake, the origins of the Kayaderosseras Creek are in the highly eroded and weathered Precambrian igneous rock of the Adirondack Mountains. The mountains, over a billion years old, are considered to be some of the oldest mountains of the world. Nearly all of the relief in the Saratoga Lake area is a result of the post-glacial erosion of thick deposits of glacial origin. As the most recent glacier receded approximately 11,000 years ago[12], Saratoga Lake was part of a much greater lake called Lake Albany. As this lake receded, what is now the present Mohawk River flowed through the present Kayaderosseras Creek and Saratoga Lake.

At the present time, Saratoga Lake may be considered highly eutrophic.[2] This conclusion is reached by observation of the many algal blooms, the proliferation of aquatic plants, the lack of dissolved oxygen in the hypolimnion during the summer, the large fish productivity, and

TABLE 1

MORPHOLOGICAL CHARACTERISTICS OF SARATOGA LAKE[4]

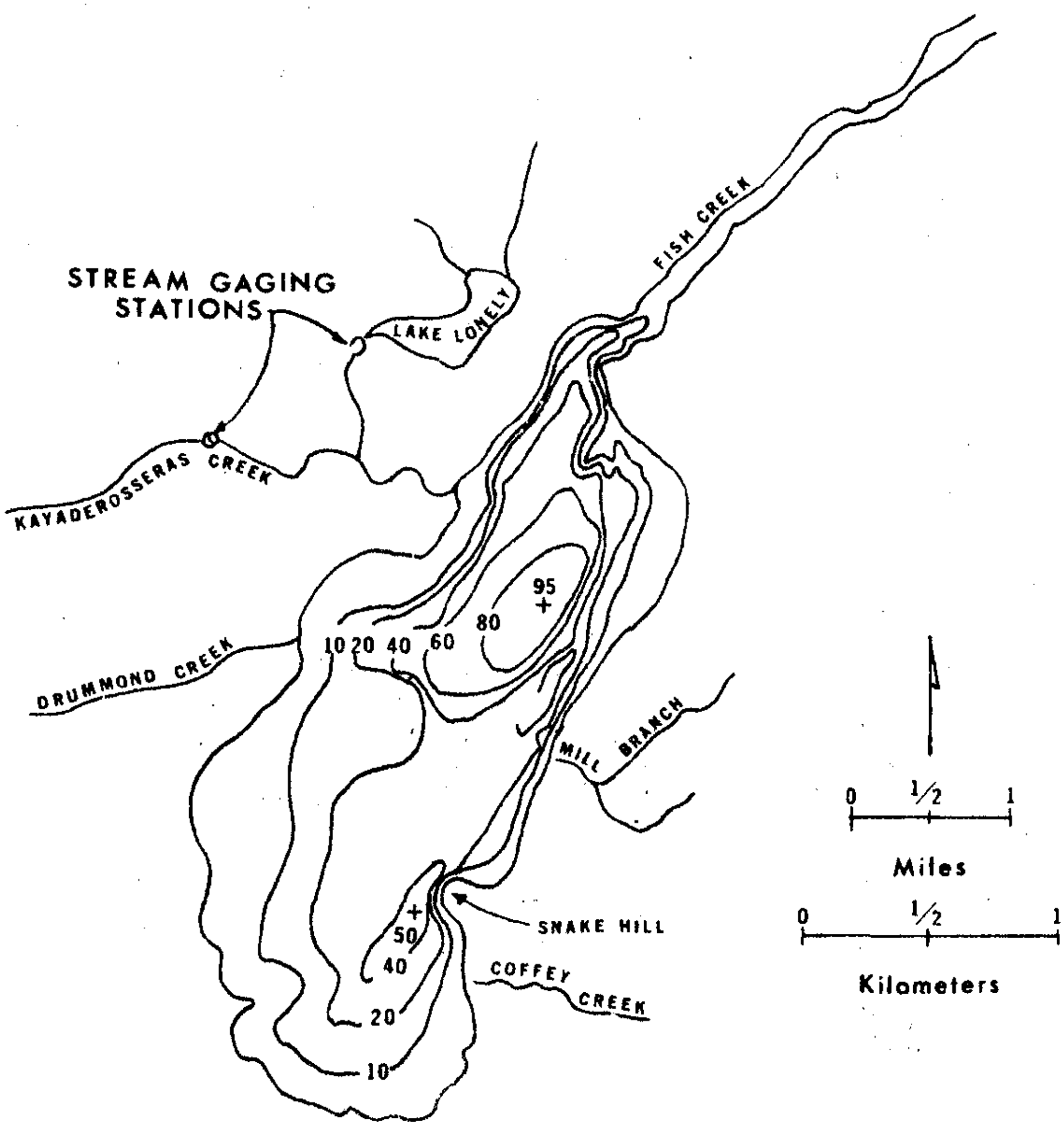
SURFACE AREA	15.6 km^2	(6.01 mi^2)
DRAINAGE AREA	544 km^2	(210.04 mi^2)
SURFACE AREA/DRAINAGE AREA		0.0286
MEAN LENGTH	7.2 km	(4.5 mi)
MEAN WIDTH	2.4 km	(1.5 mi)
LENGTH OF SHORELINE	37 km	(23 mi)
MEAN ELEVATION	62 m	(203 ft)
VOLUME AT MEAN ELEVATION	0.12 km^3	(4.3×10^9 ft^3)
MAXIMUM DEPTH	29 m	(95 ft)
AVERAGE DEPTH	8 m	(26 ft)
THEORETICAL HYDRAULIC DETENTION TIME		130 DAYS
PERCENT OF SURFACE AREA WITH DEPTH OF 3 m (10 ft) OR LESS		28.6%

FIGURE 2

SARATOGA LAKE

DEPTH CONTOURS IN FEET

10 FT = 3 M



numerous other parameters which are used to classify eutrophic conditions.[7] There are numerous factors which contribute to this eutrophication. Among them are (1) the large ratio of drainage basin to lake area, (2) the numerous farms and grazing of cattle in the watershed, (3) the effluent from two major sewage treatment plants and several minor ones as shown in Figure 3, (4) the relatively large areas of shallow water within the lake, and (5) the mineral springs in the Ballston Spa-Saratoga Springs area which are tributary to the lake. At present, a new sewage treatment plant is under construction which will divert all of the sewage effluents from the lake drainage basin sometime in 1977.

Although several studies have been conducted on Saratoga Lake, including one by the New York State Department of Conservation in 1932[1], one by Webster-Martin Engineers for the Saratoga Lake Property Owners in 1967[17], and a full year study by EPA in 1972-73[14], the most extensive studies were conducted by personnel at RPI over the period of October 1971 through August of 1973[3,4,5,10,11,13]. Samples were secured at various locations throughout the lake with particular emphasis on the two deep portions. Additional samples were taken of the various influent streams and the effluent from Saratoga Lake which is the start of Fish Creek. It is primarily these RPI studies which will be reported on here, although reference will be made to the other studies.

Although samples were secured throughout the lake and at various locations within the drainage basin area, the results here will be centered about the values found at the deepest portion of Saratoga Lake which is known as Station 7. The less deep well in the lake is designated as Station 13. Normally, measurements were made for dissolved oxygen (DO)

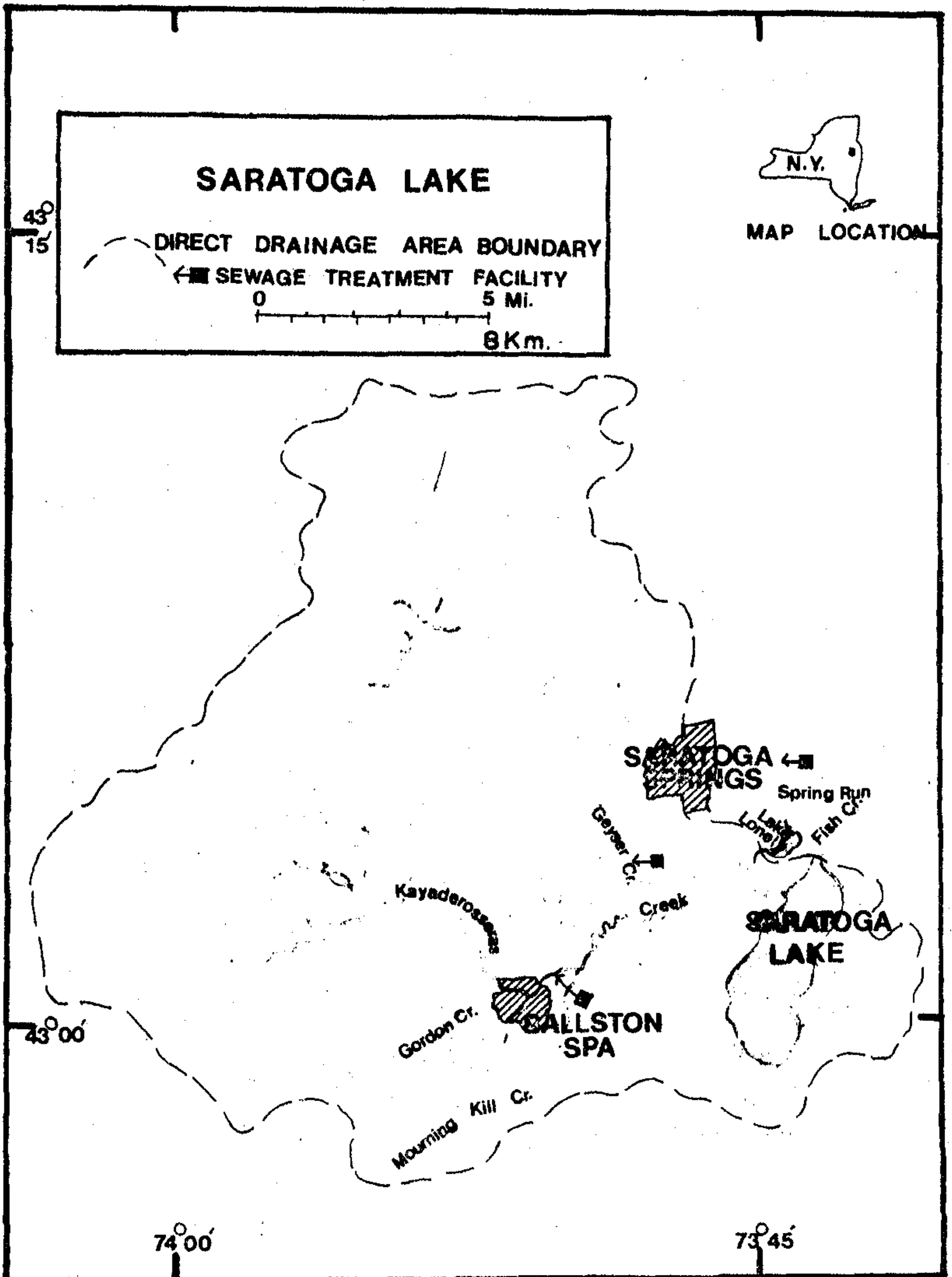

SARATOGA LAKE
DIRECT DRAINAGE AREA BOUNDARY
SEWAGE TREATMENT FACILITY
0
5 Mi.
8 Km.
N.Y.
MAP LOCATION
43° 15'
43° 00'
74° 00'
73° 45'
SARATOGA SPRINGS
Spring Run
Lake Lonely
Fish Cr.
Geyser Cr.
Kayaderosseras
Creek
SARATOGA LAKE
BALLSTON SPA
Gordon Cr.
Mourning Kill Cr.

FIGURE 3

and temperature at 1 meter intervals and samples were secured for chemical analysis at 3 meter intervals. However, for sake of clarity, only the values for the 3 meter depth and the 24 meter depth are recorded in this paper. The 3 meter depth represents conditions within the epilimnion which is normally mixed during the open water periods, whereas the 24 meter depth represents the deeper portion of the lake and becomes the hypolimnion during the period of summer stratification. Thus these two locations fairly well describe extreme conditions within the lake.

Results

Figure 4 shows that Saratoga Lake is primarily an alkaline lake. On only one occasion, Feb. 3, 1972, did the pH go below 7.0 and this was only to 6.95. At that time, there was ice cover on the lake. The pH in the hypolimnion is relatively constant, but the values in the epilimnion varied greatly, with the highest values occurring during the summer months. In general, the outlet of Kayaderosseras Creek had lower pH values throughout the year than did the surface of the lake. The highest pH value observed during all of these studies was 9.82 in the outlet of Lake Lonely on July 22, 1972. The pH in Fish Creek was essentially the same as that in the surface of Saratoga Lake.

Alkalinity data were secured only during 1973. The results shown in Figure 5 indicate that Saratoga Lake has a moderate alkalinity, generally varying between 55 and 70 mg/l although one low value of 31 mg/l was observed at the 3 meter depth on June 28. No value was obtained at the 24 meter depth on that date. During the period from February through May, there was no difference in the alkalinity between the 3 and the 24 meter depth samples. The average alkalinity at the mouth of the Kayaderosseras

FIGURE 4

PH IN SARATOGA LAKE

STATION 7

○ 3 METERS DEPTH

□ 24 METERS DEPTH

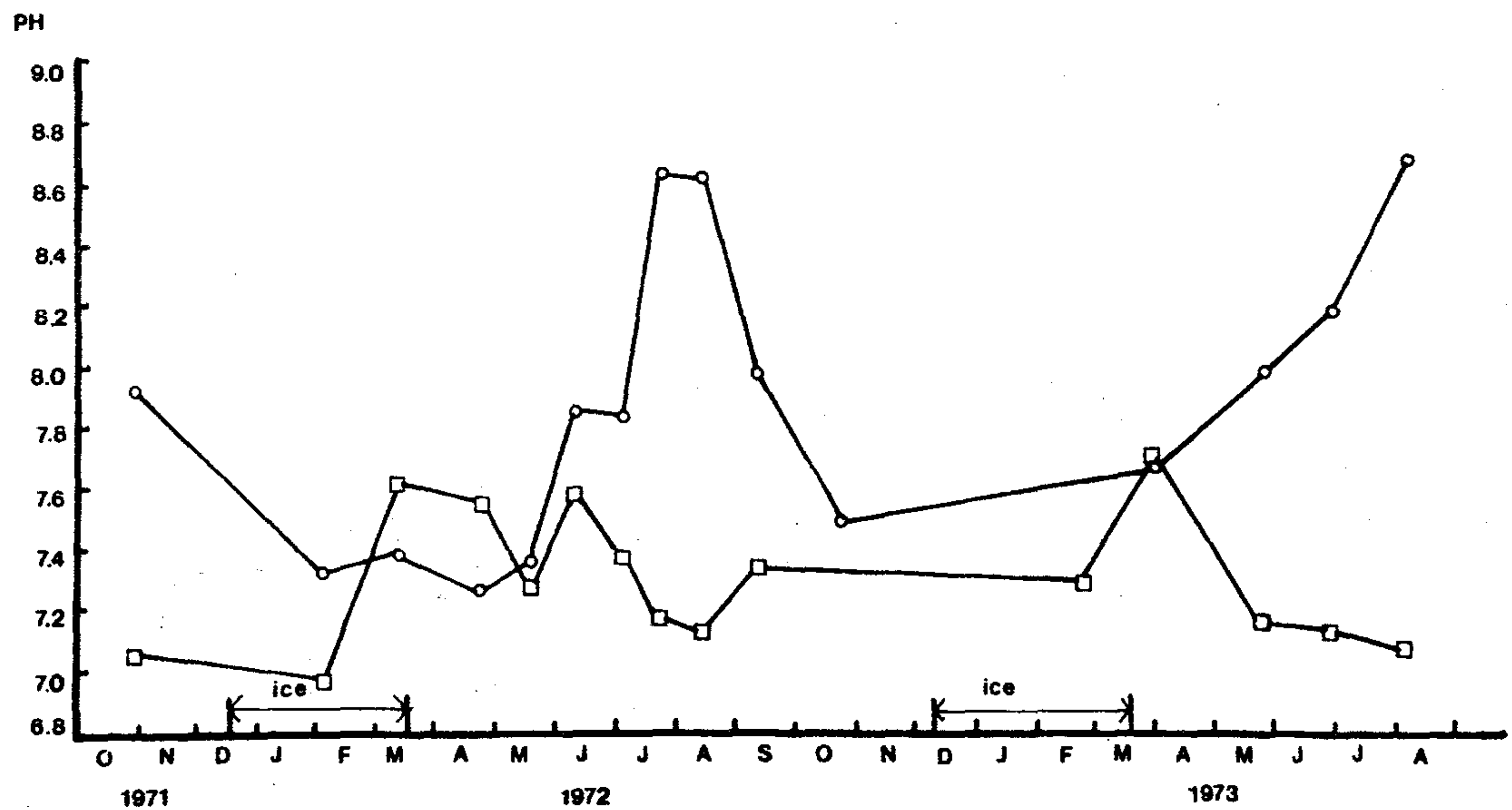


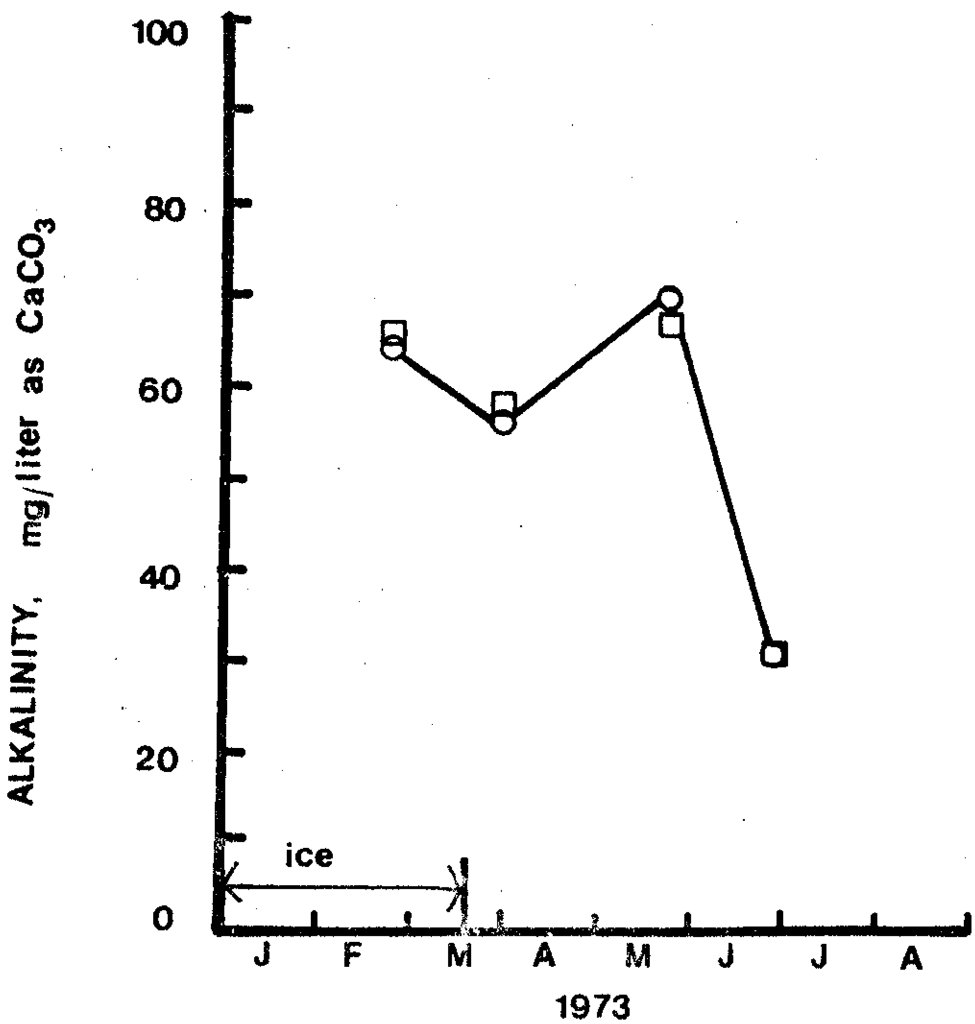
FIGURE 5

ALKALINITY IN SARATOGA LAKE

STATION 7

○ 3 METER DEPTH

□ 24 METER DEPTH



Creek was 108, indicating a contribution of alkalinity greater than that found in the lake itself. The highest alkalinity observed in the studies was in the outlet from Spring Run into Lake Lonely. This high alkalinity probably reflects the high alkalinity mineral waters which are the source of Spring Run and for which Saratoga Springs is famous.

An important factor in the trophic state of a lake is the amount of nitrogen and phosphorus in the lake. The nitrogen may be broken down into the ammonia, the organic, and the nitrate nitrogen. In addition, the total nitrogen is provided in these studies.

The ammonia nitrogen during the 2 year RPI studies is shown in Figure 6. The ammonia nitrogen content was generally low in the epilimnion with only one value observed greater than 0.1 mg/1, this occurring under the ice on Feb. 3, 1972. During the winter and times of turnover, the ammonia content of the hypolimnion was similar to that of the epilimnion. However, during summer stratification, the ammonia content of the hypolimnion was significantly greater than that of the epilimnion.

The total organic nitrogen, as shown in Figure 7, represents the organic nitrogen in both the decomposing material and the living material within the lake. With the exception of somewhat higher values in the epilimnion during August and September of 1972, there was generally no significant difference between the organic nitrogen content of the epilimnion and the hypolimnion. The actual values varied considerably with no particular trend between summer or winter, top or bottom. There did appear to be an overall trend of increasing organic nitrogen content during the two years of the study.

FIGURE 6

AMMONIA NITROGEN IN SARATOGA LAKE

STATION 7

○ 3 METER DEPTH

□ 24 METER DEPTH

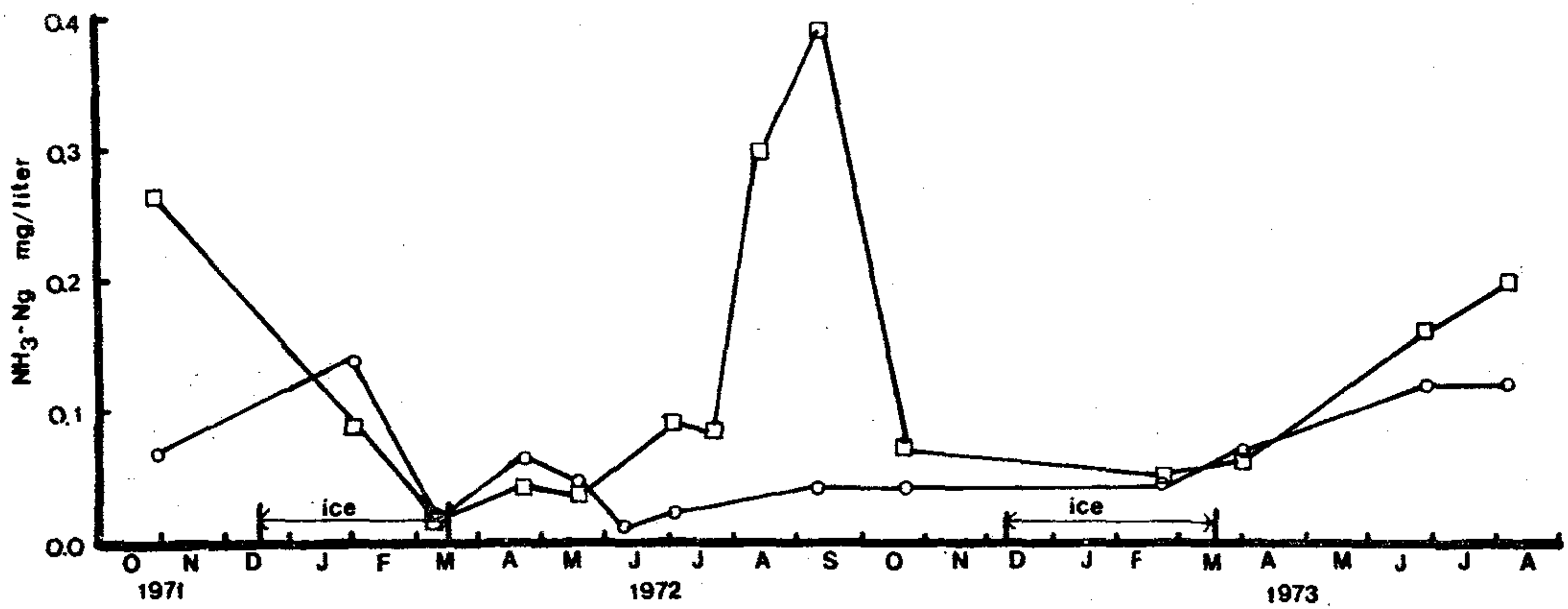
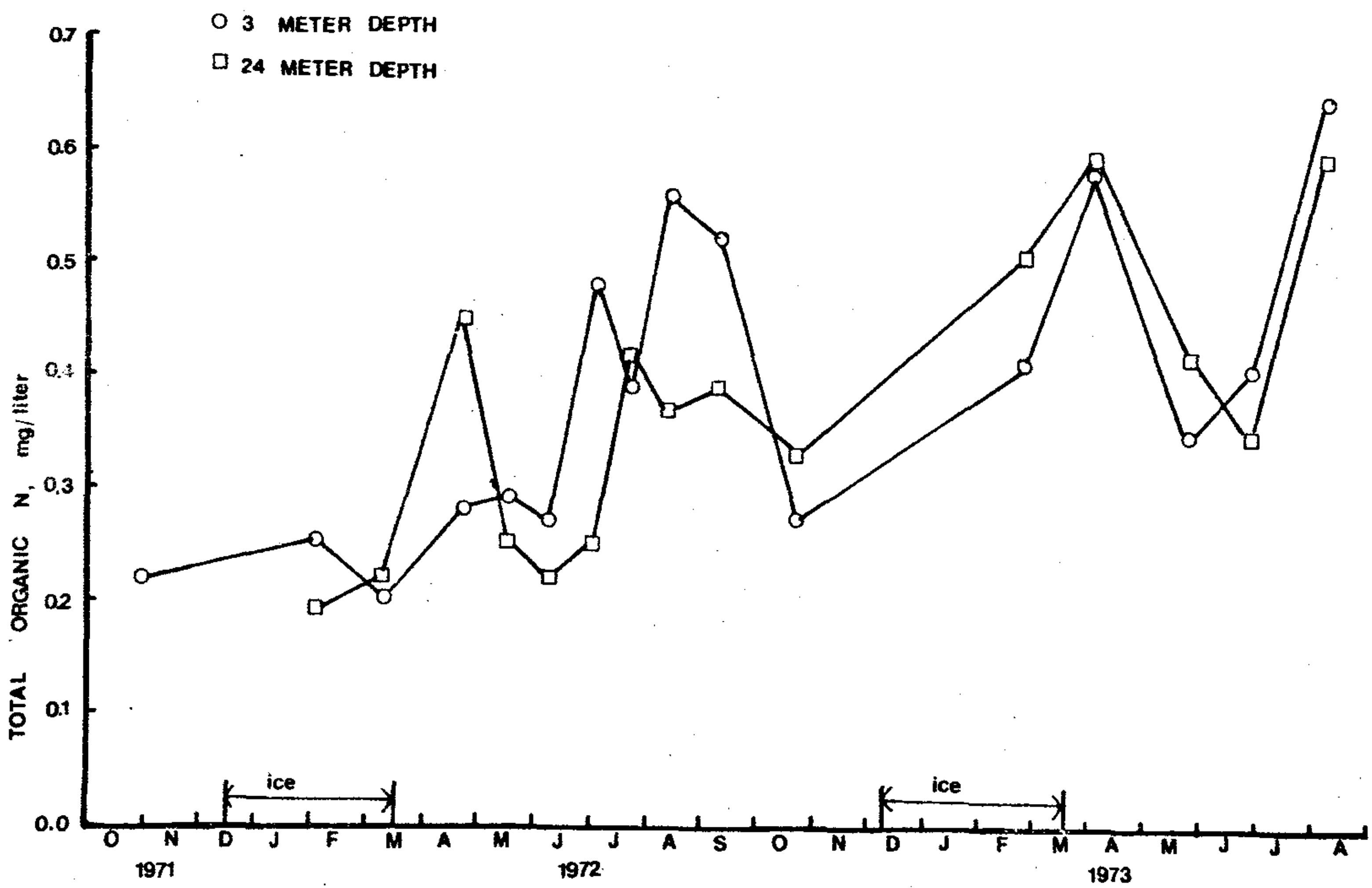


FIGURE 7

TOTAL ORGANIC NITROGEN IN SARATOGA LAKE

STATION 7



The nitrate represents the oxidized form of nitrogen. The results shown in Figure 8 indicate that the values at the two depths were similar except during the summer of 1972 when the concentration at the 24 meter depth increased significantly. During the summer of 1973, the concentration of nitrate decreased significantly in both the epilimnion and the hypolimnion.

The total nitrogen shown in Figure 9 is the sum of the individual values for the ammonia, organic, and nitrate. With the exception of the summer of 1972, the values at the two depths are rather similar. In addition, the overall values are relatively constant showing that the total amount of nitrogen present in the lake is quite constant; however, the individual components of the total nitrogen appear to vary significantly throughout the year. At no time during the period of the studies was the total nitrogen content of Saratoga Lake less than the 0.3 mg/l suggested by Vollenweider(15) as the maximum value to control excessive biological productivity in a lake.

Samples for nitrogen analysis taken in the drainage basin definitely show nitrogen in all forms is contributed in significant quantities by all of the sewage treatment plants in the basin. Immediately downstream from the sewage treatment plant discharges, high concentrations of ammonia and organic nitrogen were observed, but with passage downstream, these values decreased with an increase in the nitrate content of the stream. The outlet of the lake at Fish Creek had an average ammonia content of 0.089 mg/l, an average organic nitrogen content of 0.449 mg/l, and an average nitrage content of 0.632 mg/l.

FIGURE 8

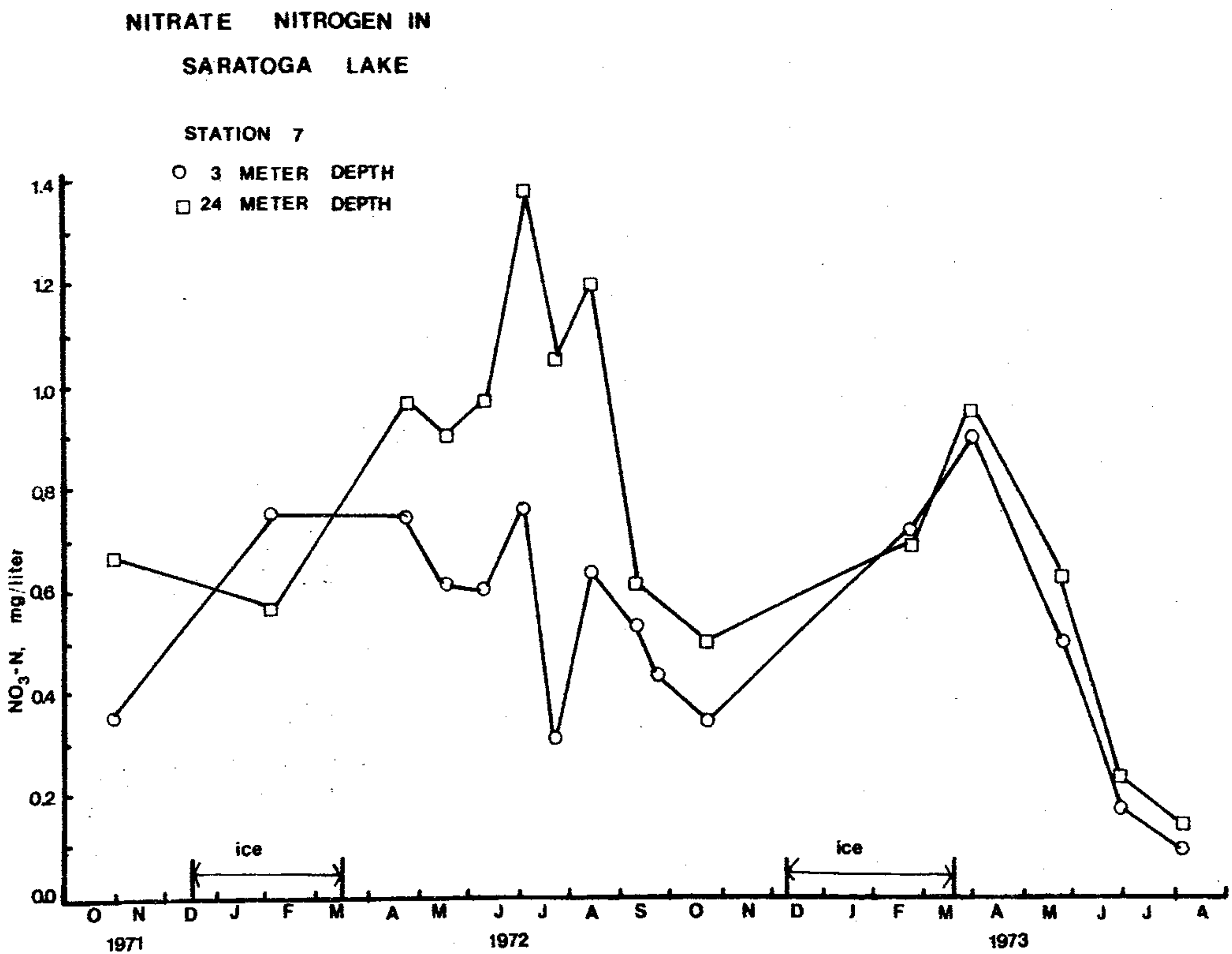
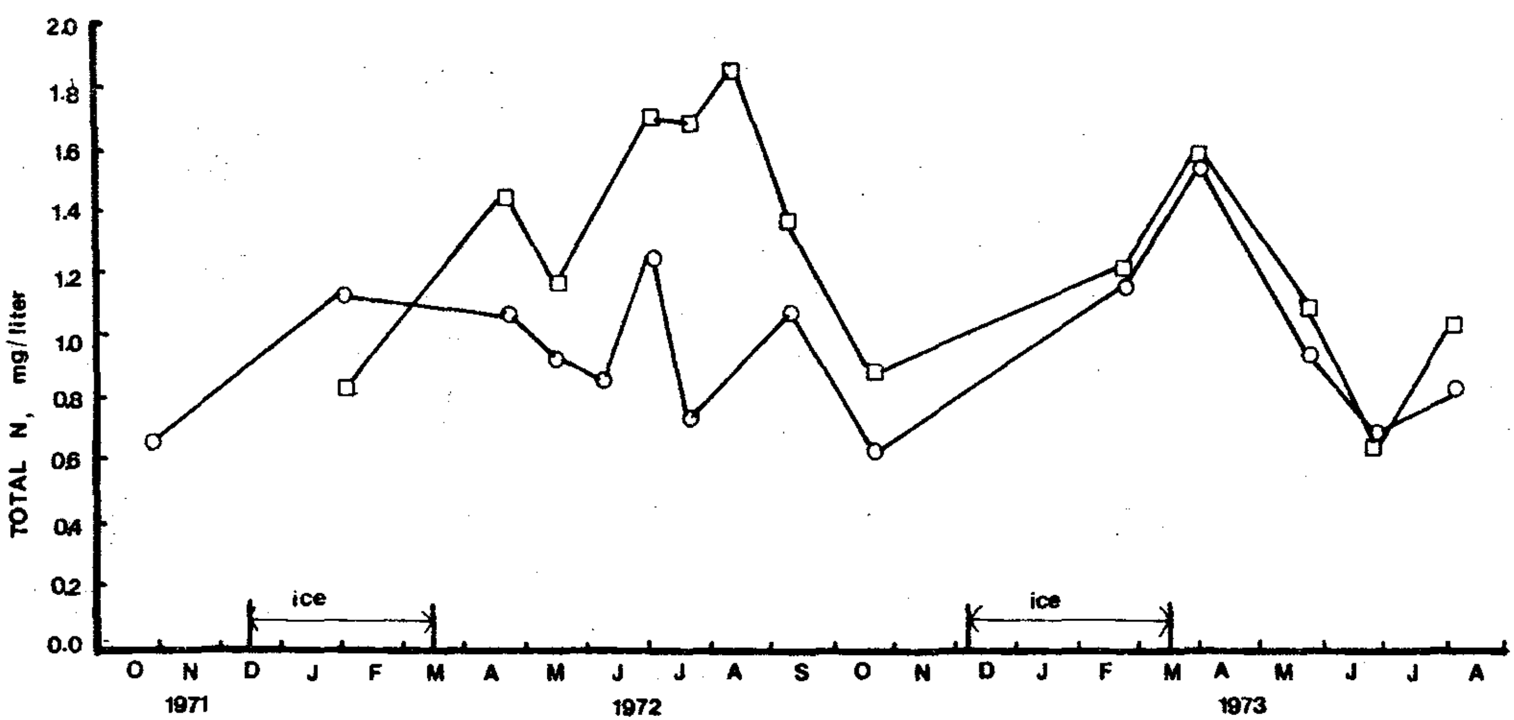

NITRATE NITROGEN IN
SARATOGA LAKE
STATION 7
○ 3 METER DEPTH
□ 24 METER DEPTH
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
NO_3-N, mg/liter
ice
ice
O N D J F M A M J J A S O N D J F M A M J J A
1971
1972
1973

FIGURE 9

TOTAL NITROGEN IN SARATOGA LAKE

STATION 7

○ 3 METER DEPTH
□ 24 METER DEPTH



The orthophosphate phosphorus content in Saratoga Lake is shown in Figure 10. The values were rather erratic; however, they do indicate higher values in the hypolimnion during the summer months. Abnormalities include a high value in the epilimnion in May of 1973, a high value in the hypolimnion in April of 1972, and a low value in the epilimnion on the same date. This was the only value less than the 0.01 mg/1 phosphorus which is recommended by Vollenweider[15] as the maximum to prevent undesirable biological growth. Again, as with nitrogen, it is evident from the stream sampling that a significant portion of phosphorus is contributed from the various sewage treatment plant effluents within the basin. Significant reduction in phosphorus was indicated as the stream flowed through Lake Lonely, although some of this apparent reduction may be due to dilution. The orthophosphate concentration at the outlet of Saratoga Lake to Fish Creek was similar to the concentration in the epilimnion of Saratoga Lake. The Kayaderosseras Creek is a major source of phosphate influent to Saratoga Lake. A ban on phosphate-containing detergents went into effect in New York State on June 1, 1973. However, no direct effects on either stream or lake phosphorus levels were observed in any of the samples secured after that date.

Iron is potentially a competitor for phosphate. Thus analyses were made for the presence of iron, but only during 1973 as shown in Figure 11. In general, the levels of iron were very low reaching the lower limits of detection. The highest iron content observed was 0.02 mg/1 under the ice at the 24 meter depth on Feb. 24, 1973.

The presence of silicon in the water is related to the diatoms which utilize silicon in their cell structure. Thus a limited number of

FIGURE 10

ORTHOPHOSPHATE PHOSPHORUS IN SARATOGA LAKE

STATION 7

○ 3 METER DEPTH

□ 24 METER DEPTH

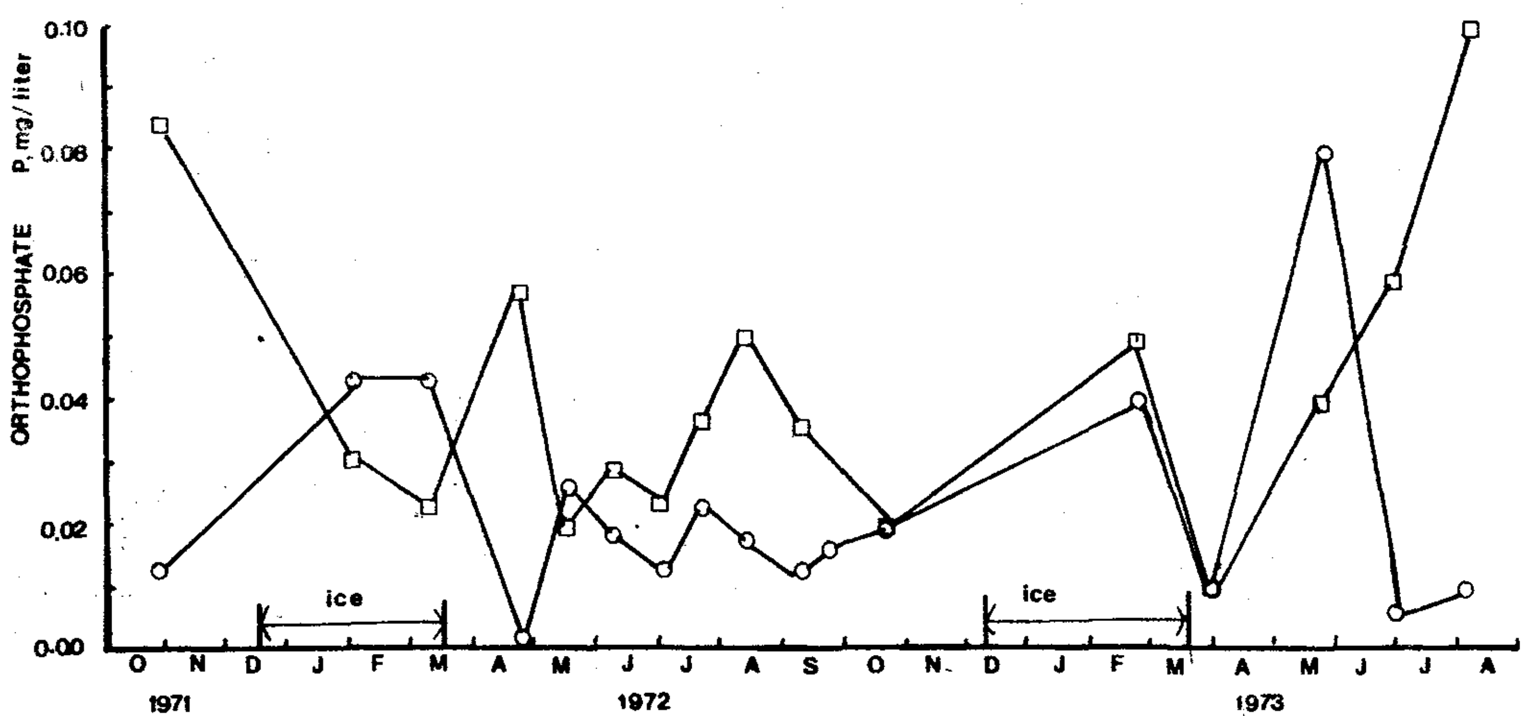


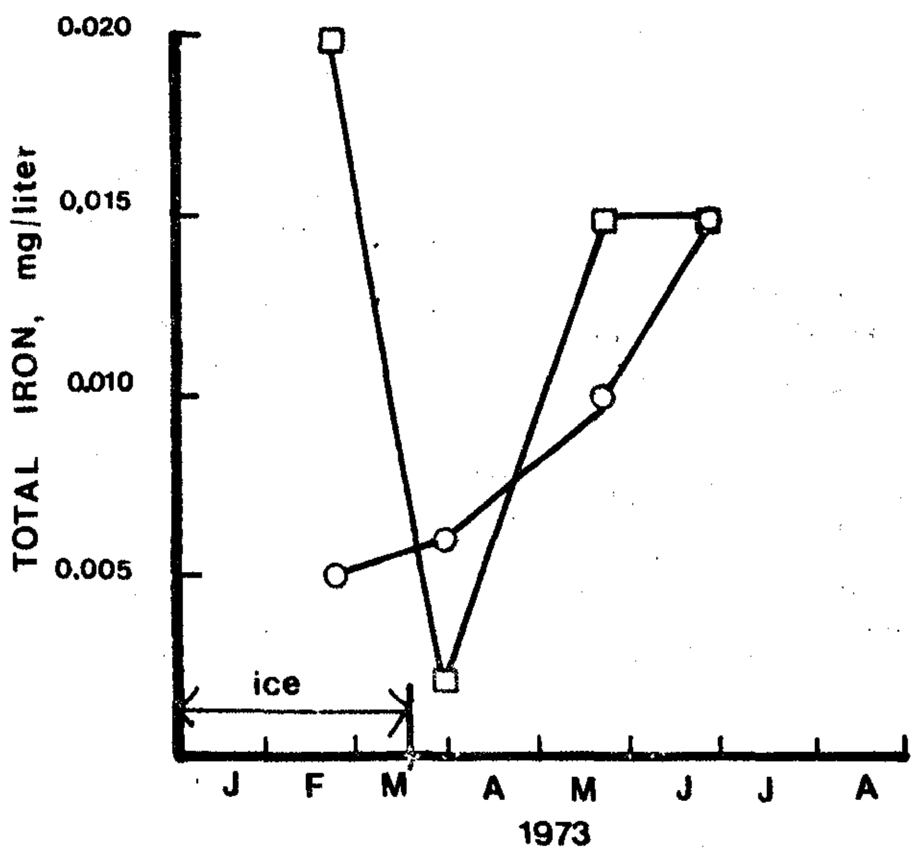
FIGURE 11

TOTAL IRON IN SARATOGA LAKE

STATION 7

○ 3 METER DEPTH

□ 24 METER DEPTH



analyses for this element were completed, as shown in Figure 12. The silicon content at the 3 meter depth was high in both years during the early summer but dropped dramatically in August of 1972 and in October of 1973. The levels at the 24 meter depth during 1973 were consistently high.

In order to interpret some of the various chemical data, information must be provided on temperature and dissolved oxygen in a lake. Complete temperature profiles over the 2 year period are shown in Figure 13. It may be seen that the Fall overturn occurs during the latter part of November and the beginning of December until ice cover occurs about the middle of December through approximately the middle of March. Isothermal conditions again occur during April and the thermocline begins to appear about the middle of May. In both 1972 and 1973 during June and the beginning of July, the temperature of the bottom of the lake increased somewhat above the traditional 4°C but during August and September, the temperature decreased again to approximately 5°C. It may be seen that the main portion of the thermocline occurred approximately at 12 meters in 1972, but at 6 to 9 meters in 1973, with stratification persisting from June until October.

The dissolved oxygen profile for Station 7 in Saratoga Lake is shown in Figure 14. Anaerobic conditions existed in the hypolimnion from approximately the middle of July to the middle of October during both years. In 1972, the anaerobic area extended from approximately 12 meters deep corresponding to the thermocline in that year, whereas in 1973 the low DO extended from the 6-9 meter depth, corresponding to the higher thermocline observed that year. During the winter of 1972, incomplete mixing was apparent in that the DO at the bottom was never raised to the

FIGURE 12

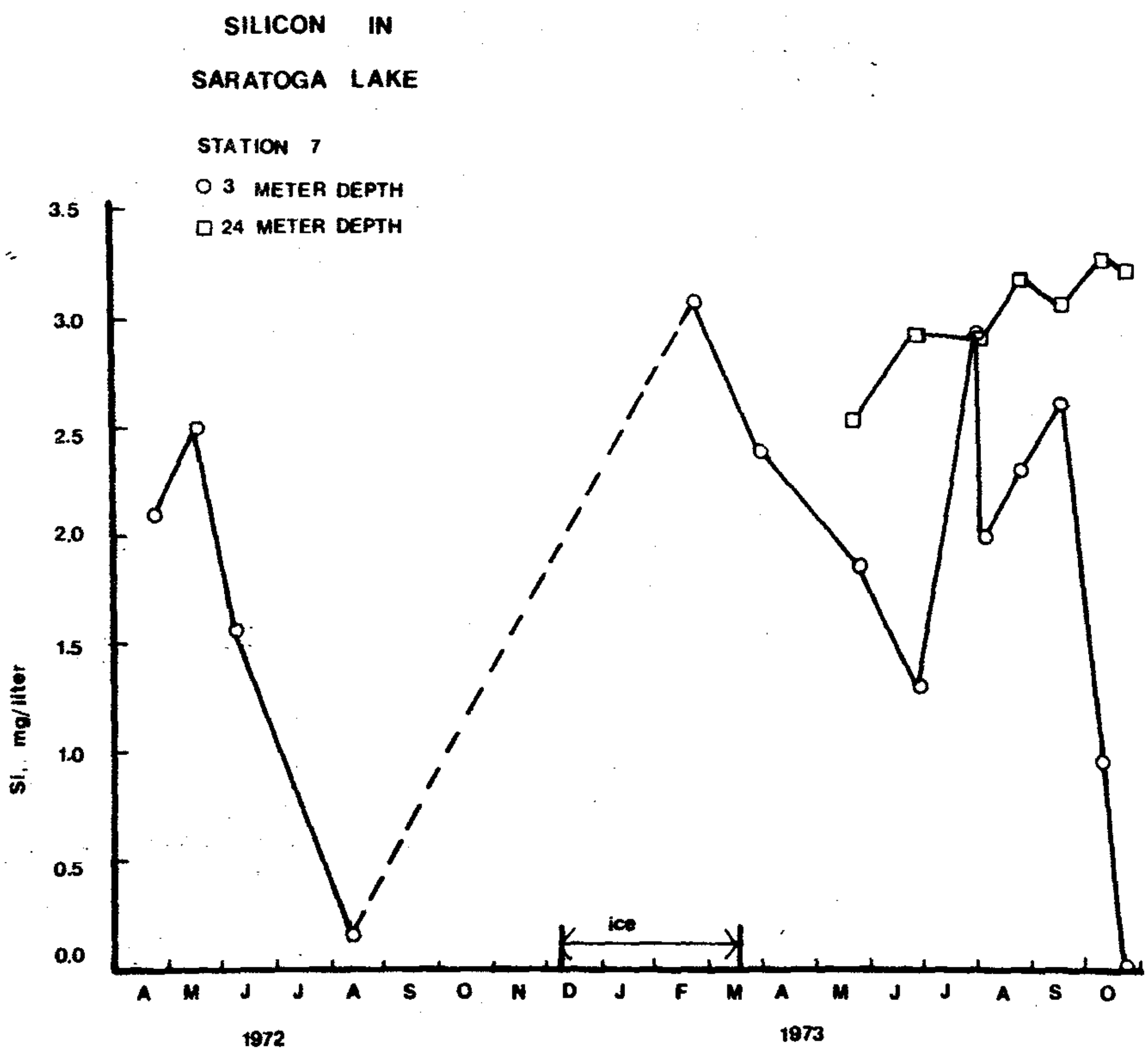

SILICON IN
SARATOGA LAKE
STATION 7
○ 3 METER DEPTH
□ 24 METER DEPTH
Si., mg/liter
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ice
A M J J A S O N D J F M A M J J A S O
1972
1973

FIGURE 13

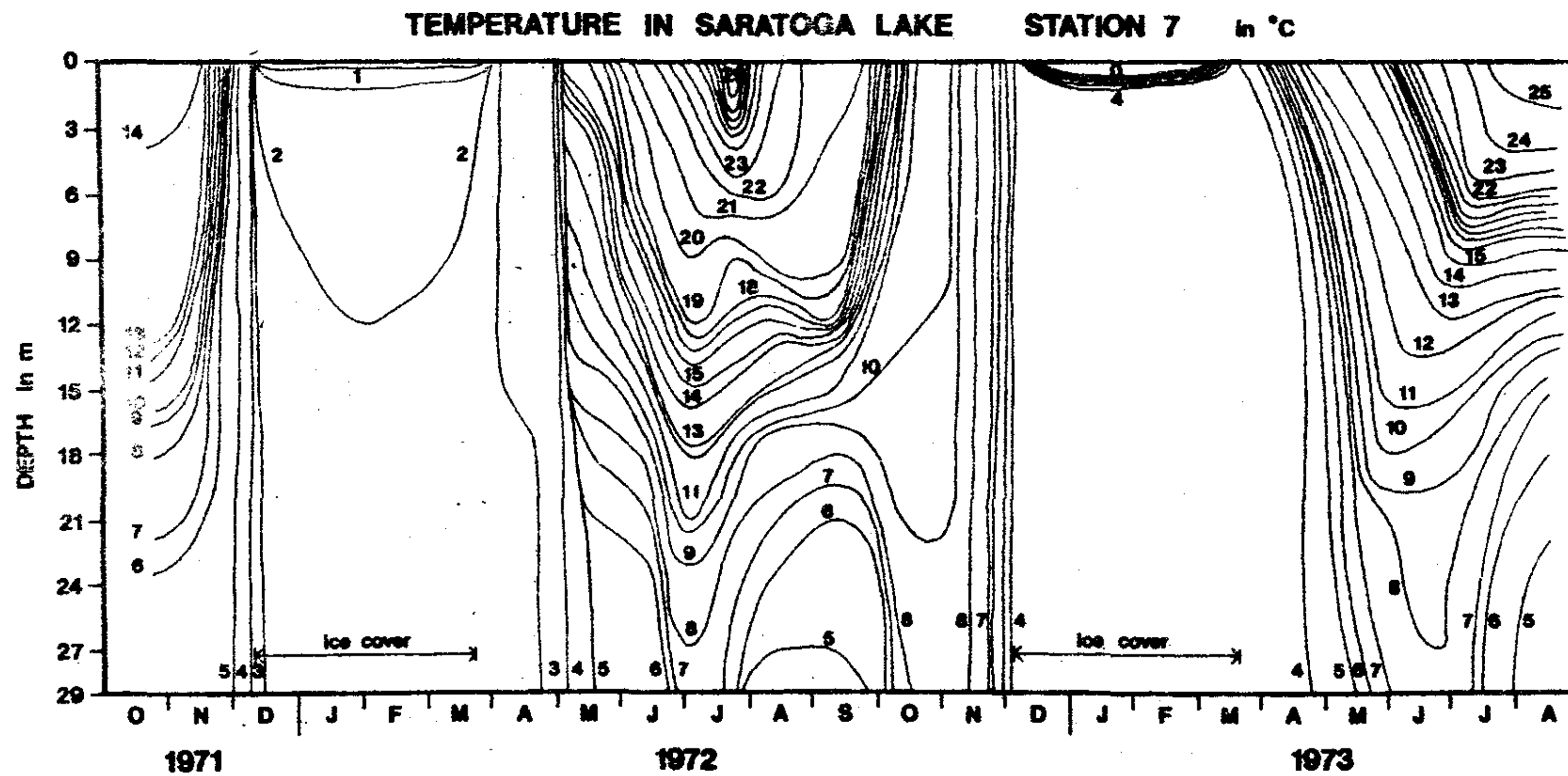
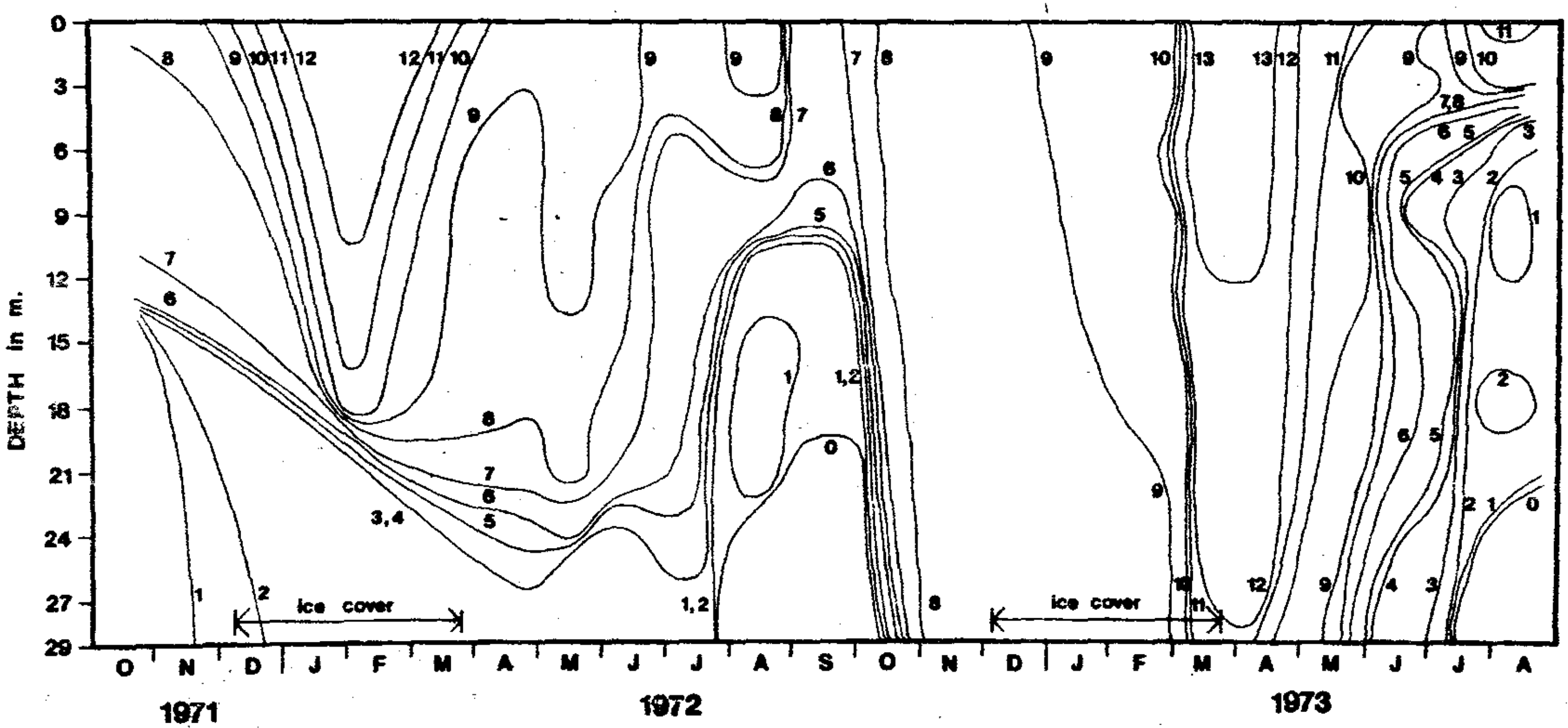

TEMPERATURE IN SARATOGA LAKE STATION 7 in °C
DEPTH in m
ice cover
ice cover
O N D J F M A M J J A S O N D J F M A M J J A
1971
1972
1973

FIGURE 14

DISSOLVED OXYGEN IN SARATOGA LAKE STATION 7 in mg/l



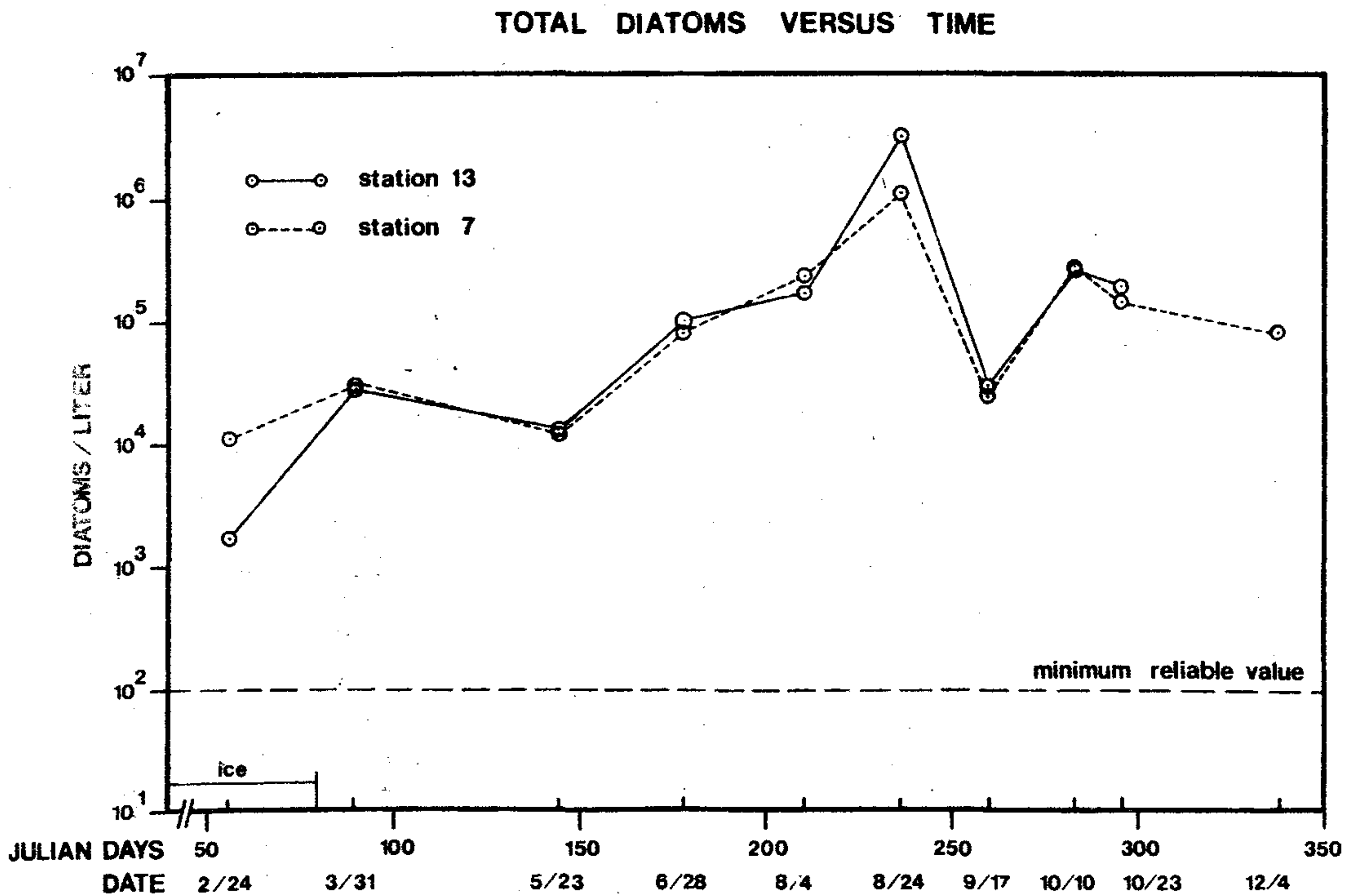
much higher levels which were observed at the shallower depths during the Spring turnover. The turnover in the Fall of 1972 appeared to be complete with high DO levels throughout the winter of 1973. One sample taken through the ice on Jan. 31, 1975[8] indicated a DO of 11.5 at the 24 meter depth indicating that adequate mixing had occurred with the Fall turnover of 1974.

As an indication of some of the biological productivity, the total diatom numbers during 1973 are shown in Figure 15. It may be seen that the greatest numbers occurred on Aug. 24 with a significant depletion on Sept. 17 and a secondary peak on Oct. 10. The initial increase immediately after ice-out was also indicated by the large increase on Mar. 31. Whereas the numbers do not truly represent the total biomass of silicon tied up in the diatoms (due to the fact that diatoms of larger size were observed during October), the numbers of diatoms will be useful in explaining the silicon concentration within the lake.

The total productivity per unit of surface area is shown in Figure 16 along with the incident solar radiation at Lake George, New York. The maximum productivity was observed in mid-August about six weeks after the maximum incident solar radiation. The values obtained definitely indicate that Saratoga Lake falls into the eutrophic range from the standpoint of productivity.

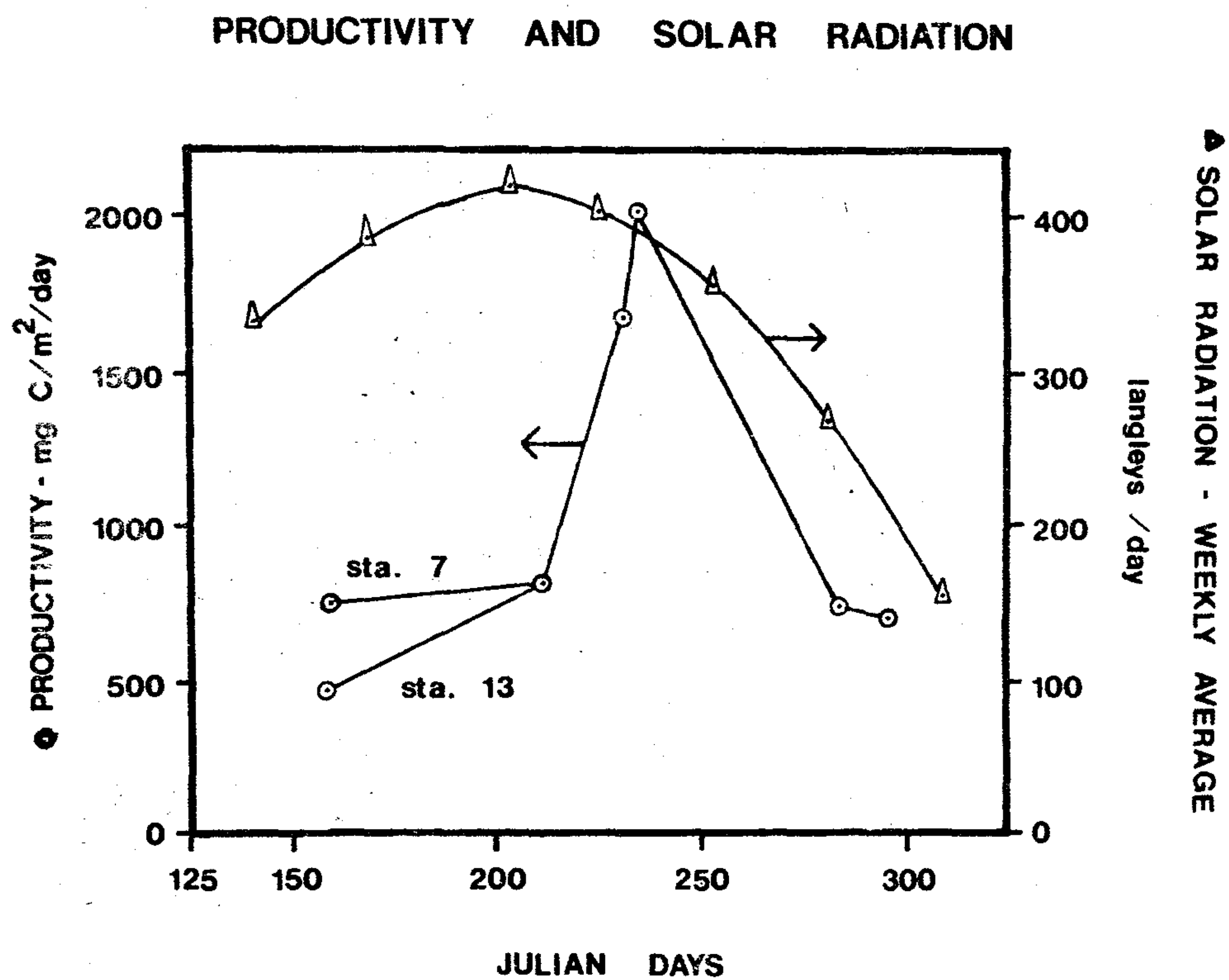
Many other parameters were measured in Saratoga Lake. However, space does not allow inclusion in this paper of all of the data which have been compiled into a larger report[2]. The data presented here are sufficient to make some interpretations as to the relationships of these parameters within the lake.

FIGURE 15



TOTAL DIATOMS VERSUS TIME
station 13
station 7
DIATOMS / LITER
10^7
10^6
10^5
10^4
10^3
10^2
10^1
minimum reliable value
ice
JULIAN DAYS 50 100 150 200 250 300 350
DATE 2/24 3/31 5/23 6/28 8/4 8/24 9/17 10/10 10/23 12/4

FIGURE 16



PRODUCTIVITY AND SOLAR RADIATION
PRODUCTIVITY - mg C/m²/day
SOLAR RADIATION - WEEKLY AVERAGE
langleys /day
2000
1500
1000
500
0
400
300
200
100
0
125
150
200
250
300
JULIAN DAYS
sta. 7
sta. 13

Interrelationships

The most common interrelationships are those between numerous chemical parameters and the dissolved oxygen level in the lake. A secondary relationship occurs with productivity. The high values of pH (Fig. 4) in the epilimnion during the summer definitely relate to the productivity and the production of oxygen (Fig. 14) by photosynthesis utilizing CO_2. The decrease in alkalinity (Fig. 5) also corresponds to the productivity and also reflects a total reduction of alkalinity within a lake as compared to the influent from the Kayaderosseras Creek. The ammonia nitrogen (Fig. 6), on the other hand, indicates the influence of reducing conditions in the hypolimnion during the summer stratification. The nitrogen is either reduced to ammonia in the hypolimnion or the influent ammonia is not oxidized in this area. The nitrate (Fig. 8) in the epilimnion shows higher values during the colder months and lower values during the summer. This, undoubtedly represents utilization of nitrogen by the biological productivity in the lake. This same trend is somewhat reflected in the total nitrogen (Fig. 9) indicating that all forms of nitrogen are converted to biomass during the periods of high productivity. The total inorganic nitrogen levels in Saratoga Lake were calculated during the spring and the summer. The inorganic nitrogen was used as a parameter since this is the normal source of nitrogen for biological productivity. It includes ammonia, nitrate and nitrite nitrogen. The results shown in Table 2 indicate that only 11 percent of the amount of the nitrogen which was in the lake at the time of spring turnover in 1973 was present in the hypolimnion during the late summer. Thus a large portion of the nitrogen in the lake is in the epilimnion and is available for biological productivity. The phosphate (Fig. 10) indicatesutilization of the orthophosphate in the epilimnion during

TABLE 2

INORGANIC NITROGEN LEVELS IN SARATOGA LAKE 1973[3]

	INORGANIC NITROGEN (AMMONIA AND NITRATE)
SPRING TURNOVER	
CONCENTRATION	1.07 MG/L
STANDING MASS	130,000 KG
LATE SUMMER HYPOLIMNION	
CONCENTRATION	0.75 MG/L
STANDING MASS	14,600 KG
PERCENT OF SPRING STANDING MASS	11.2

times of high productivity, but release of phosphate in the anaerobic hypolimnion during the periods of lack of oxygen during summer stratification. The total phosphorus levels in Saratoga Lake in 1973, as shown in Table 3, indicate that there is a greater amount of total phosphate in the hypolimnion during the summer than occurred in the entire lake in the spring. This indicates that there is dissolution of precipitated phosphorus in the anaerobic hypolimnion during the summer. This, therefore, shows that the lake bottom represents a significant source for phosphorus in the lake. Thus even if all the phosphorus were diverted due to the new sewage treatment plant, there would be a source of phosphorus which would continue for a significant period of time in Saratoga Lake. Another correlation with the phosphorus is the extremely low iron content of the lake (Fig. 11). It becomes apparent that either there is very little iron entering the lake system or more likely that all of the iron is tied up by the phosphate with significant amounts of phosphorus remaining unprecipitated by the iron. Unfortunately, data are not available as to the iron content of the Kayaderosseras Creek as it flows into Saratoga Lake nor are more extensive data on iron available in the hypolimnion of the lake during the summer.

Hardness measurements were not made in the RPI studies but some data are available from the 1967 study.(17) In general, the hardness of the surface of the lake was 140 mg/l as calcium carbonate, with the contribution from Kayaderosseras Creek in the order of 165 to 170 mg/l. Lake Lonely exhibited a hardness of 195 mg/l with 289 mg/l in the influent from Spring Run. This likely represents the effect of the highly mineralized water which is the source of Spring Run. Although there was a slight

TABLE 3

TOTAL PHOSPHORUS LEVELS IN SARATOGA LAKE[3]

	TOTAL PHOSPHORUS
SPRING TURNOVER	
CONCENTRATION	0.06 MG/L
STANDING MASS	7,000 KG
LATE SUMMER HYPOLIMNION	
CONCENTRATION	0.48 MG/L
STANDING MASS	9,350 KG
PERCENT OF SPRING STANDING MASS	133

reduction in the hardness in the lake as compared to the influent stream, apparently the hardness is not combining with the phosphate to cause a precipitate of all the calcium as phosphate.

Of particular interest is the correlation between the diatom content of the lake (Fig. 15) and the silicon concentration (Fig. 12). There is some correlation between the total diatoms and the silicon concentration. However, there is even a more striking relationship between the number of Stephanodiscus and the silicon content. Stephanodiscus is the largest diatom present in Saratoga Lake, therefore its presence indicates a large mass of silicon. On Aug. 24, the Stephanodiscus decreased to zero cells per liter while the silicon concentration increased even though other diatom genera were increasing. The Stephanodiscus were present in large numbers in the spring when there was a decrease in the silicon content and they were present in the largest numbers during October, at which time the silicon content in the lake dropped drastically to nearly zero.

Control

It may be seen from the complex interrelationships among the various parameters within the lake that control of the factors causing eutrophication of Saratoga Lake is not a simple matter. Diversion of the sewage effluent from the lake watershed will reduce the nitrogen and the phosphorus inputs to the lake; however, calculations[(2)] have shown that only 26 percent of the nitrogen and 17.5 percent of the phosphorus is contributed by the major sewage treatment effluents. The present concentration of total nitrogen at the mouth of Kayaderosseras Creek is 1.36 mg/l and the comparable value for phosphorus is 0.3 mg/l. After diversion of the treatment plant effluents, the expected values would be in the order of 1.0 mg N/l and 0.25 mg P/l. Thus diversion will not reduce the nitrogen and phosphorus levels to the values of 0.3 mg N/l and 0.01 mg P/l recommended for control of excessive algal growth in a lake[15] and therefore, will not be sufficient to change the trophic state of the lake significantly. Furthermore, the release of phosphorus in the hypolimnion during the summer will contribute large amounts of phosphorus to the lake for a significant period of years. Thus other methods of control were considered.

The methods of chemical control considered in this study may be divided into two basic types. The first is the addition of a chemical to remove the phosphorus by precipitation as an insoluble phosphate. The second is to add a chemical to change the basic chemical constituents of the lake to allow a different balance of biological productivity to occur. The three chemical precipitants considered were calcium, iron, and aluminum, since work has been done using these cations to precipitate phosphate[6]. For changing the chemical balance within a lake, the addition of silicon was considered under the premise that if sufficient silicon is present within the epilimnion, the diatoms will continue to thrive at the expense of the undesirable blue-green algae.

For the precipitation studies, the quantities of the chemical required to precipitate all of the phosphorus entering the lake from the Kayaderosseras Creek were calculated based upon the following molar ratios of the cation to phosphorus[6]:

Ca:P	3:1	at pH 9 or slightly less
Fe:P	2:1	at pH near neutral
Al:P	1.5:1	at pH near neutral

Peterson et.al.[9] working with sodium aluminate ($NaAlO_2$) found a molar ratio of 5.7:1 at neutral pH was needed for 90% phosphorus removal. Since such a high ratio would require much larger quantities of chemicals, no calculations were made on the basis of sodium aluminate. Cost estimates were made using the following chemicals at the estimated bulk costs listed below:

Alum	$Al_2(SO_4)_3$	$4.445/100 lbs dry weight
Lime (hydrated)	$Ca(OH)_2$	$54.20/ton
Ferric chloride	$FeCl_3$	$4.00/100 lbs dry weight, sewage grade
Sodium silicate	Na_2SiO_3	$7.95/100 lbs dry weight

All calculations were based upon the estimated input from the Kayaderosseras Creek at the present time of 116,000 kg P/yr and the projected loadings after the completion of the sewage treatment plant and the diversion of the effluent out of the basin of 95,300 kg P/yr. In all calculations, only the cost of the chemicals was considered. No estimate was made for the cost of storage facilities, mixing equipment and dosing equipment. Also, no consideration was made for the potential environmental impact of the large amount of sludge generated from the chemical addition.

The results of the calculations of the quantites and costs of the chemicals needed to remove the phosphorus are shown in Table 4. It may be seen that large quantities of all three chemicals are required and the annual cost is considerable. The lowest annual cost estimate is for addition of lime at an approximate cost of $50,000 per year. The highest cost was for the alum. Some savings in chemicals could be achieved by the

TABLE 4

QUANTITIES AND COSTS OF SEVERAL CHEMICALS TO REMOVE TOTAL ANNUAL PHOSPHORUS INPUT TO SARATOGA LAKE

CATION	RATIO CATION: P	COMPOUND ADDED	ANNUAL QUANTITY REQUIRED, kg PRESENT	ANNUAL QUANTITY REQUIRED, kg AFTER STP	ANNUAL COST, $ PRESENT	ANNUAL COST, $ AFTER STP
Ca	3:1	$Ca(OH)_2$	8.31×10^5	6.82×10^5	49,600	40,700
Fe	2:1	$FeCl_3$	12.2×10^5	10.0×10^5	107,200	88,200
Al	1.5:1	$Al_2(SO_4)_3$	19.2×10^5	15.8×10^5	188,000	155,000

diversion accomplished by the sewage treatment plant; however, the cost still is greater than could be afforded by the user of the lake.

Calculation of the amount of silicon needed to maintain an adequate concentration for the diatom population is more difficult. It is a simple matter to calculate the amount of silicon needed to raise the concentration by 1 mg/l, which is the concentration above which diatoms thrive. However, without information regarding the amount of silicon taken up by the diatoms, it is difficult to determine the amount of silicon needed to maintain this 1 mg/l concentration of the lake. Therefore, a calculation was made of the cost of adding 1 mg/l of silicon to the lake. On the other hand, the results showed that there was silicon depletion in only the epilimnion. Therefore, the volume to which the silicon would have to be added to maintain 1 mg/l was based on the volume of the epilimnion of the lake during summer stratification. The average depth of the thermocline was observed to be approximately 9 meters or 30 feet from the surface. By calculation from Connor's data[(4)], the volume of the epilimnion is approximately 8.8×10^{10} liters (3.1×10^{9} ft^{3}). Each additional mg/l of silicon would require 3.74×10^{5} kg of sodium silicate (8.25×10^{5} lbs, or 412 tons) which would cost approximately $65,600. Again it may be seen that this is a high cost.

An estimate was provided to the Saratoga Lake Property Owners, Inc. for an air mixing reaeration system. In 1972 dollars this was $130,000 for installation and $11,000/yr for operation. Thus from the cost standpoint, aeration is less costly than chemical addition. Maintaining aerobic conditions throughout the lake should reduce the phosphate concentration in the lake by stabilizing the naturally precipitated phosphates. The amount of this precipitation has not been determined in Saratoga Lake.

Conclusions

There are many complex chemical, physical, and biological relationships in a eutrophic lake. The high concentration of nutrients, particularly nitrogen and phosphorus, stimulates the biological growth under satisfactory conditions of light and temperature. This biological growth exerts a strain on the oxygen resources of the hypolimnion during summer stratification, depleting the oxygen from this zone of the lake. The anaerobic conditions in the hypolimnion in turn release additional phosphorus to the water. At the time of turnover, this then again becomes available for use by the biological systems. One way that was considered to control the excessive phosphorus concentration in the lake was precipitation with various chemicals. In all cases, the costs were extremely high with calcium being the least expensive, iron intermediate in cost and aluminum the most costly. Further consideration was made of maintaining a sufficiently high silicon content in the lake to allow the desirable diatoms to proliferate at the expense of the undesirable blue-green algae. Although the actual amount of silicon that would have to be added to maintain the desirable silicon level within the lake could not be calculated, the estimate for the cost of the sodium silicate was in the same range as the cost of chemical precipitation of the phosphorus. Aeration of the lake by mixing appears to be a less costly way of maintaining aerobic conditions in the hypolimnion and thus keeping the phosphates in an insoluble form. Control of eutrophication in Saratoga Lake by means of chemical additives cannot be recommended.

ACKNOWLEDGEMENT

The author would like to acknowledge the work done by students supervised by him. Much of their work is incorporated into this paper. Major contributions were made by James F. Roetzer, Joseph E. Coffey, Kenneth J. Connor, Dennis G. Tuttle, and John C. Rabai plus others. Some of the students who worked on this project were supported by EPA Training Grant No. T 900079.

References

1. Anonymous. "A Biological Survey of the Upper Hudson Watershed." New York State Dept. of Conservation; Supplement to 22nd Annual Report, Albany, N. Y. (1932).

2. Aulenbach, Donald B., Clesceri, Nicholas L., and Ferris, James J., "The Limnology of Saratoga Lake, New York," New York State Dept. of Environmental Conservation, Albany, N. Y. (July 1976)

3. Coffey, Joseph E., Jr., "Water Quality of Saratoga Lake, New York," Master of Eng. Thesis, Rensselaer Polytechnic Institute, Troy, N. Y. (1974).

4. Connor, Kenneth J., "Hydrology of Saratoga Lake," Master of Eng. Thesis, Rensselaer Polytechnic Institute, Troy, N. Y. (1974).

5. France, Roger A., "Sediment-Nutrient Relationships in Saratoga Lake, New York," Master of Eng. Thesis, Rensselaer Polytechnic Institute, N. Y. (1973).

6. Galonian, George E., and Aulenbach, Donald B., "Phosphate Removal from Laundry Wastewater," Jour. Water Pollution Control Fed. 45, 1708 (1973).

7. Kooyoomjian, K. Jack and Clesceri, Nicholas L., "Perception of Water Quality by Select Respondent Groupings in Inland Water-Based Recreational Environments," Fresh Water Inst. Report 73-7, Rensselaer Polytechnic Institute, Troy, N. Y. (1973).

8. Lewis, Edward N. and Porada, Sue E. Unpublished data (1975).

9. Peterson, Spencer A., Sanville, William D., Stay , Frank S., and Powers, Charles F., "Laboratory Evaluation of Nutrient Inactivation Compounds for Lake Restoration," J. Water Pollution Control Fed. 48, 817 (1976).

10. Rabai, John C. Raw data for Master's Thesis, Rensselaer Polytechnic Institute, Troy, N. Y. (1972).

11. Roetzer, James F., "Chemical Quality of Saratoga Lake," Master of Science Thesis, Rensselaer Polytechnic Institute, Troy, N. Y. (1973).

12. Rudemann, R., "Geology of the Capital District" New York State Museum Bulletin No. 285, Albany, N. Y. (1936).

13. Tuttle, Dennis G., "Phytoplankton Primary Productivity and the Diatom Population of Saratoga Lake, N. Y." Master of Eng. Thesis, Rensselaer Polytechnic Institute, Troy, N. Y. (1974).

14. U.S. Environmental Protection Agency, "Report on Saratoga Lake, Saratoga County, New York," EPA Region II, Working Paper No. 168, Pacific Northwest Environmental Research Laboratory, Corvallis, Oregon (1974).

15. Vollenweider, Richard A., "Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication," OECD, Directorate for Scientific Affairs, Paris (1968).

16. Waller, G., Saratoga, An Impious Era. Prentice-Hall, Inc. (1966).

17. Webster-Martin, Inc. "Saratoga Lake Survey" Prepared for Saratoga Lake Property Owners, Inc. Webster-Martin, Inc., South Burlington, Vermont (1967).

18. Williams, Sherman L. and Clesceri, Nicholas L., "Diatom Population Changes in Lake George, N. Y." Fresh Water Inst. Report 72-1 thru 72-8. Rensselaer Polytechnic Institute, Troy, N. Y. (1972).