NUTRIENTS IN LAKE SUPERIOR

by

Hugh Dobson

Canada Centre for Inland Waters

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ABSTRACT

A digest is given of the nutrient data for Lake Superior, along with supplementary information about the temperature regime, the Secchi depth transparency, and dissolved oxygen in the hypolimnion.

Nitrate and reactive silicate had measurable depletion rates in surface waters in summer, but their concentrations fell only slightly below winter-time and hypolimnion values. Soluble reactive phosphate was nearly undetectable at all depths, near 0.5 micrograms phosphorus per litre. Phosphorus is probably the growth-limiting element for phytoplankton in Lake Superior.

A mean particulate phosphorus value of 1.4 micrograms phosphorus per litre indicates that Lake Superior is oligotrophic. This classification is confirmed by Secchi depths, nitrate and reactive silicate depletion rates in the epilimnion during summer, and hypolimnetic oxygen depletion rates.

Nitrate is increasing over the years, perhaps due to a change in the composition of rainwater, but this probably has no effect on the plankton due to a continuing shortage of phosphorus.

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INTRODUCTION

This report brings together old and new data on the plant-nutrient conditions of the main offshore part of Lake Superior. The intention is two-fold: to provide a background for new intensive studies to be undertaken for the International Joint Commission, and second to allow a comparative study of nutrients in all of the St. Lawrence Great Lakes.

Another report has been prepared for Lake Huron (Dobson, 1971) and the two reports should be considered together.

Recent lake-wide cruises on Lake Superior by the vessels of the Canada Centre for Inland Waters have provided much new data on the nutrient status of the lake, so that an advance can be made beyond the level of the few earlier reports.

This report does not give special considerations to the regions very close to the cities of Thunder Bay and Duluth. That is a worthy subject for the International Joint Commission studies.

This report considers major plant nutrients and also supplementary material on Secchi depth transparency, dissolved oxygen in the hypolimnion, and the temperature regime. For summarizing the recent data, I have chosen to use lake-wide mean values at a depth of one metre, and mean values in the cold water-mass using the temperature criterion of colder than 5.0°C. These mean values were calculated for each cruise, and plotted against time of year. Complete monthly coverage is not yet available for any one year. Data from more than one year were combined to show the seasonal cycles.

The mean values for each recent cruise are unweighted mean values calculated from all data for a depth of one metre, and separately from all data for samples colder than 5.0°C. The station spacing was fairly even. The estimates of mean values would not be much improved if weighting factors were included to account for the slightly uneven spacing of stations and sample-depths. Secchi-depth observations were omitted during night-time on these cruises, resulting in a patchy distribution of Secchi-depth data. Only the unweighted lake-wide mean Secchi-depth values are considered here.

Horizontal distribution maps have been omitted. The errors of single nutrient values would probably indicate fictitious small horizontal gradients, except near the large cities.

Inventories of the data used in this report are presented in Tables 1 and 2.

DESCRIPTION

Surface temperature

Dissolved-nutrient depletion of near-surface waters in lakes occurs during the stratified summer period. Therefore I include some information about the seasonal cyle of surface temperatures in Lake Superior (Table 3 and Figure 1).

Surface temperatures on both sides of 4°C occur together from May to the end of July. This is the "thermal bar" regime, preceding

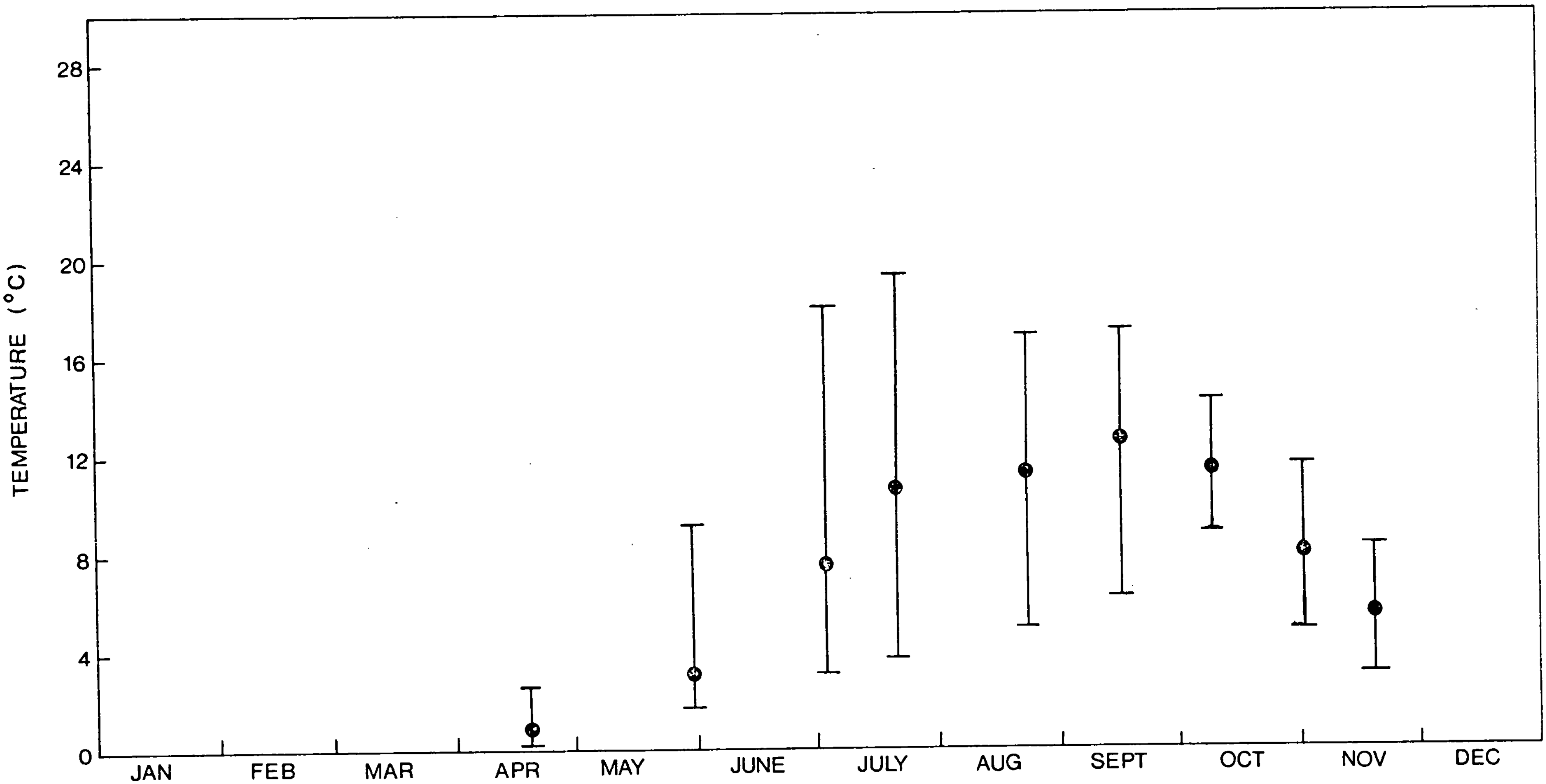

FIGURE 1. MEAN AND EXTREME TEMPERATURES AT A DEPTH OF ONE METRE IN LAKE SUPERIOR, FROM SYNOPTIC CRUISES, 1964 AND 1968 TO 1971.

the lake-wide thermocline of summer. For comparison, the thermal bar of Lake Huron disappears about July 1 and the thermal bar of Lake Ontario disappears about June 20.

In Lake Superior an early winter thermal bar regime occurs after November 10, earlier than in Lake Huron.

The lake-wide summer thermocline in Lake Superior lasts for only a little more than three months, from August to October.

Figure 2 illustrates the seasonal cycle of the lake-wide mean surface temperatures in Lakes Superior and Huron. In August Lake Superior has a mean surface temperature of only 11.°C, about 7.C degrees cooler than that of Lake Huron. In May and November Lake Superior has a mean surface temperature about 2.C degrees cooler than that of Lake Huron.

Secchi depth transparency

Secchi depth data for Lake Superior are summarized in Table 4. Only very recent data are available. A history of Secchi depth cannot be constructed. From 1968 onward the mean Secchi depth value for the entire period May to November was 8.6 metres.

Figure 3 illustrates the approximate seasonal cycle of lake-wide mean Secchi depth for Lakes Superior, Huron, and Ontario, and for the central basin of Lake Erie. The shape of the curve for Lake Superior is uncertain because it is based on few cruises. The comparison suggests that Lake Superior has the least standing stock of phytoplankton.

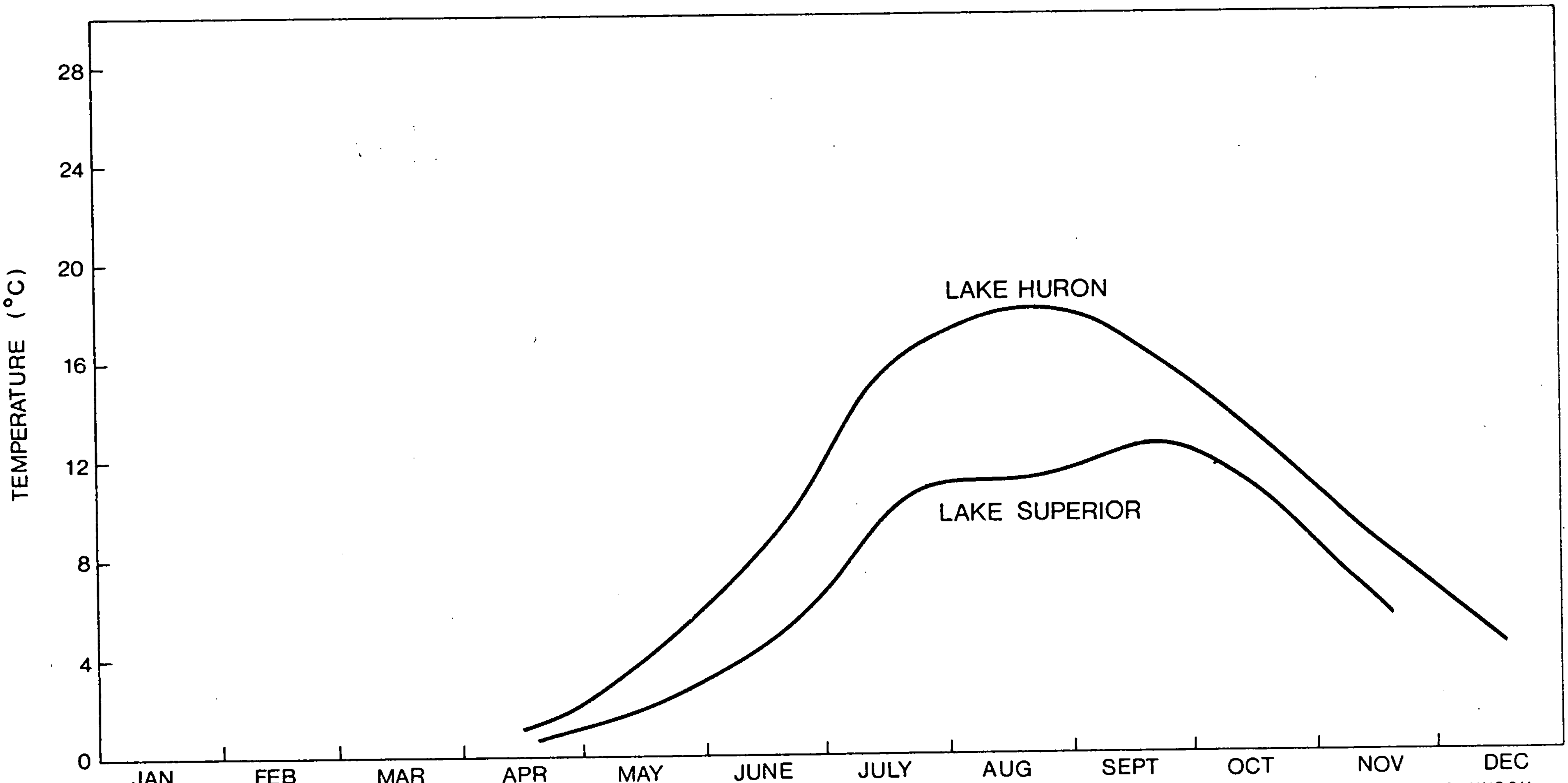

FIGURE 2. LAKE-WIDE MEAN TEMPERATURES AT A DEPTH OF ONE METRE, VERSUS TIME OF YEAR, FOR LAKES SUPERIOR AND HURON. THE LAKE HURON CURVE IS BASED ON 35 SYNOPTIC CRUISES, AND THE LAKE SUPERIOR CURVE IS BASED ON ONLY NINE CRUISES.

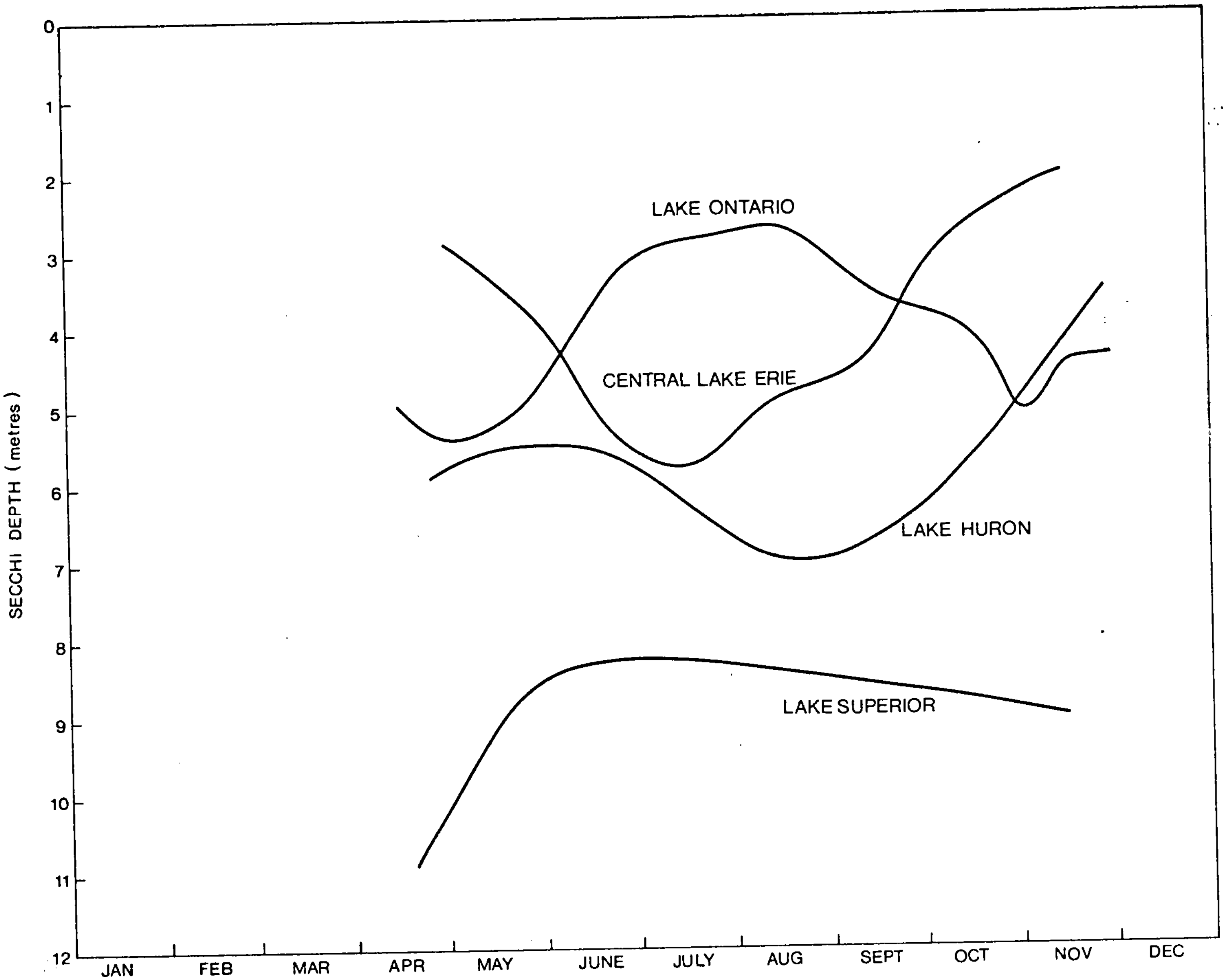

FIGURE 3. LAKE-WIDE MEAN SECCHI DEPTH VERSUS TIME OF YEAR, FOR LAKES SUPERIOR, HURON AND ONTARIO, AND FOR THE OFFSHORE PART OF CENTRAL LAKE ERIE. THE CURVES APPLY APPROXIMATELY TO THE YEARS 1967 TO 1971.

Table 5 also compares Secchi depths in this same group of lakes. Mean values are shown for the entire observational period May to November, and separately for the period July - August. The values are illustrated in Figures 4 and 5. The mean values for May to November place central Lake Erie close to Lake Ontario, but the mean values for July - August place central Lake Erie closer to Lake Huron.

Dissolved oxygen in the hypolimnion

Thermal stratification of a lake in summer prevents turbulent and molecular diffusive contact between the hypolimnion and the air above the lake. The light conditions of a deep lake prevent photosynthesis in the hypolimnion. Throughout the summer, oxygen concentrations decline in the hypolimnion due to biological consumption. The oxygen depletion rate in the hypolimnion measures respiration and decay of life in the hypolimnion.

The areal depletion rate, or the rate of oxygen depletion in a column of the hypolimnion having unit surface area, has been proposed as an indicator of the trophic status of the epilimnion, in part because of the fallout of phytoplankton. The reliability of this indicator is poor in the case of very deep lakes. It gives an unreasonably high value for Lake Huron (Dobson, 1971). Here I do not consider the areal oxygen depletion rate of Lake Superior.

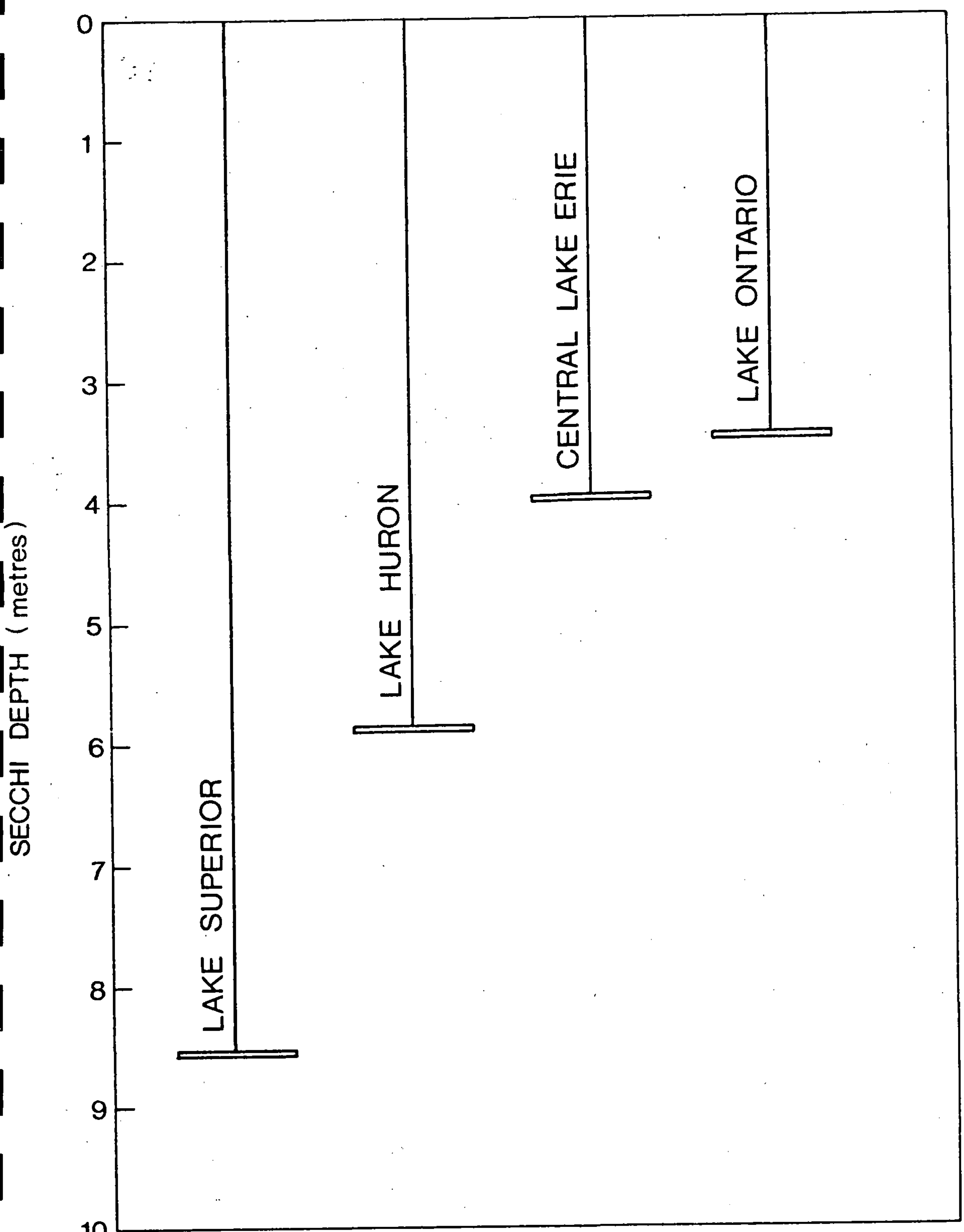

FIGURE 4. COMPARISON OF SECCHI DEPTHS IN THE GREAT LAKES: THE MEAN VALUES FOR THE ENTIRE PERIOD MAY TO NOVEMBER. THE VALUES APPLY APPROXIMATELY TO THE YEARS 1967 TO 1971.

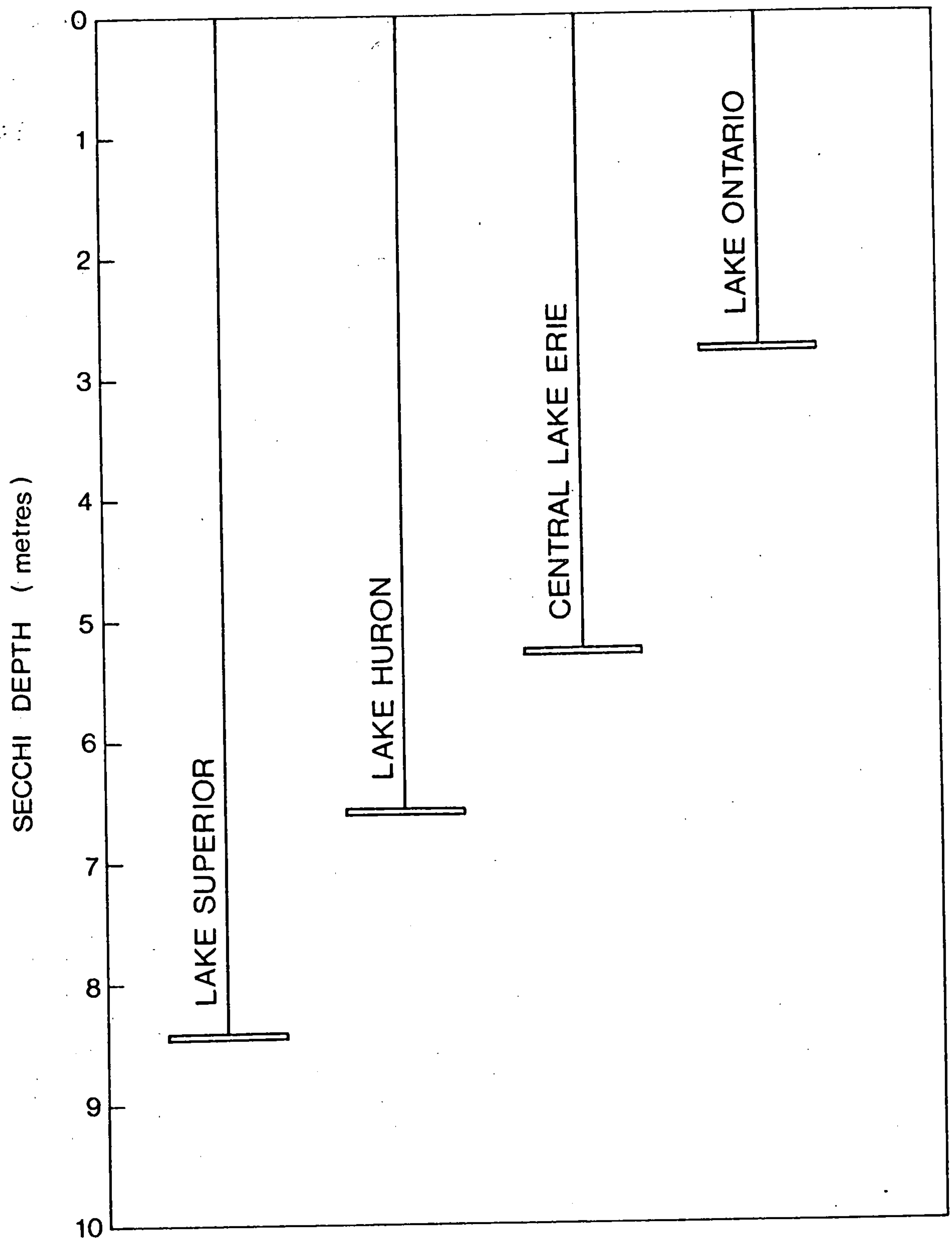

FIGURE 5. COMPARISON OF SECCHI DEPTHS IN THE GREAT LAKES: THE MEAN VALUES FOR THE MONTHS OF JULY AND AUGUST. THE VALUES APPLY APPROXIMATELY TO THE YEARS 1967 TO 1971.

Oxygen data for the cold water-mass (T <5°C) from recent cruises on Lake Superior are summarized in Table 6 and Figures 6 and 7. The mean temperatures of the cold water-mass are shown in Figure 8.

Oxygen percent saturation was calculated using recent determinations of oxygen solubility in water, as described in Dobson (1967).

The increase in oxygen percent saturation from April to July was caused by warming of the water, which reduces the solubility of oxygen. Although percent saturation increased during this period, oxygen concentrations were constant, near 13.4 mg/litre.

From July to November the percent saturation and oxygen concentration values declined steadily. The oxygen data are very consistent for this group of cruises from four different years. The depletion rate from July 3, 1971 to October 9, 1971 was 0.17 mg O_2/litre/month. For comparison, the oxygen depletion rate in the hypolimnion of Lake Huron during 1971 was 0.34 mg/litre/month, or 2.0 times as great as in Lake Superior (Dobson, 1971).

With such a small oxygen depletion rate in Lake Superior, very little regeneration of nutrients within the hypolimnion should be expected, when considered in terms of rate of change of concentration.

On the cruise of the "Martin Karlsen" of November 15-23, 1969, there was water colder than 5°C at the lake surface at some stations, whereas at other stations the cold water-mass was isolated by a thermocline from contact with the atmosphere. Oxygen values shown here are for all

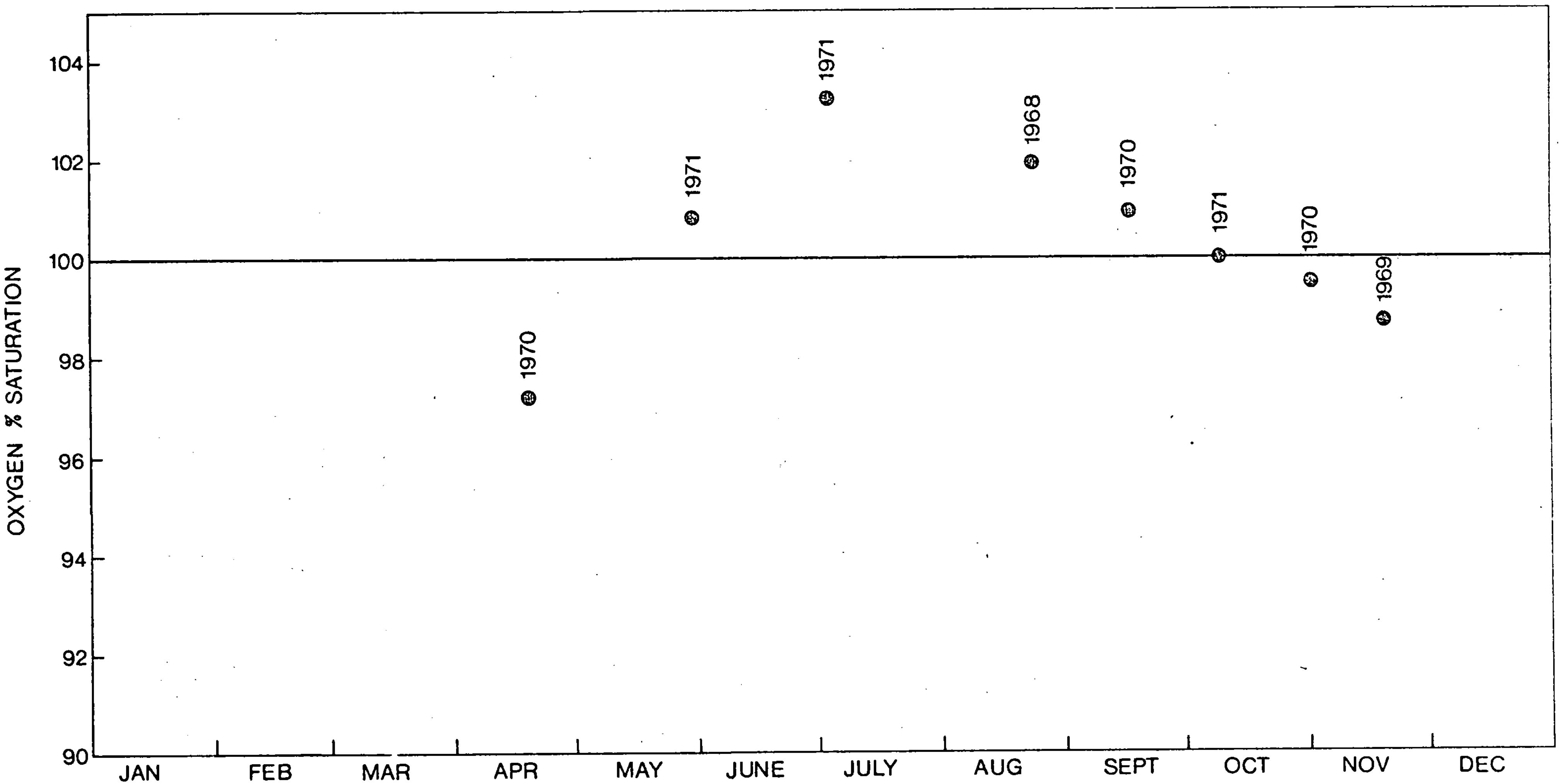

FIGURE 6. MEAN OXYGEN % SATURATION VALUES OF THE COLD WATER-MASS (T<5°C.) IN LAKE SUPERIOR, FOR CRUISES IN THE YEARS 1968 TO 1971.

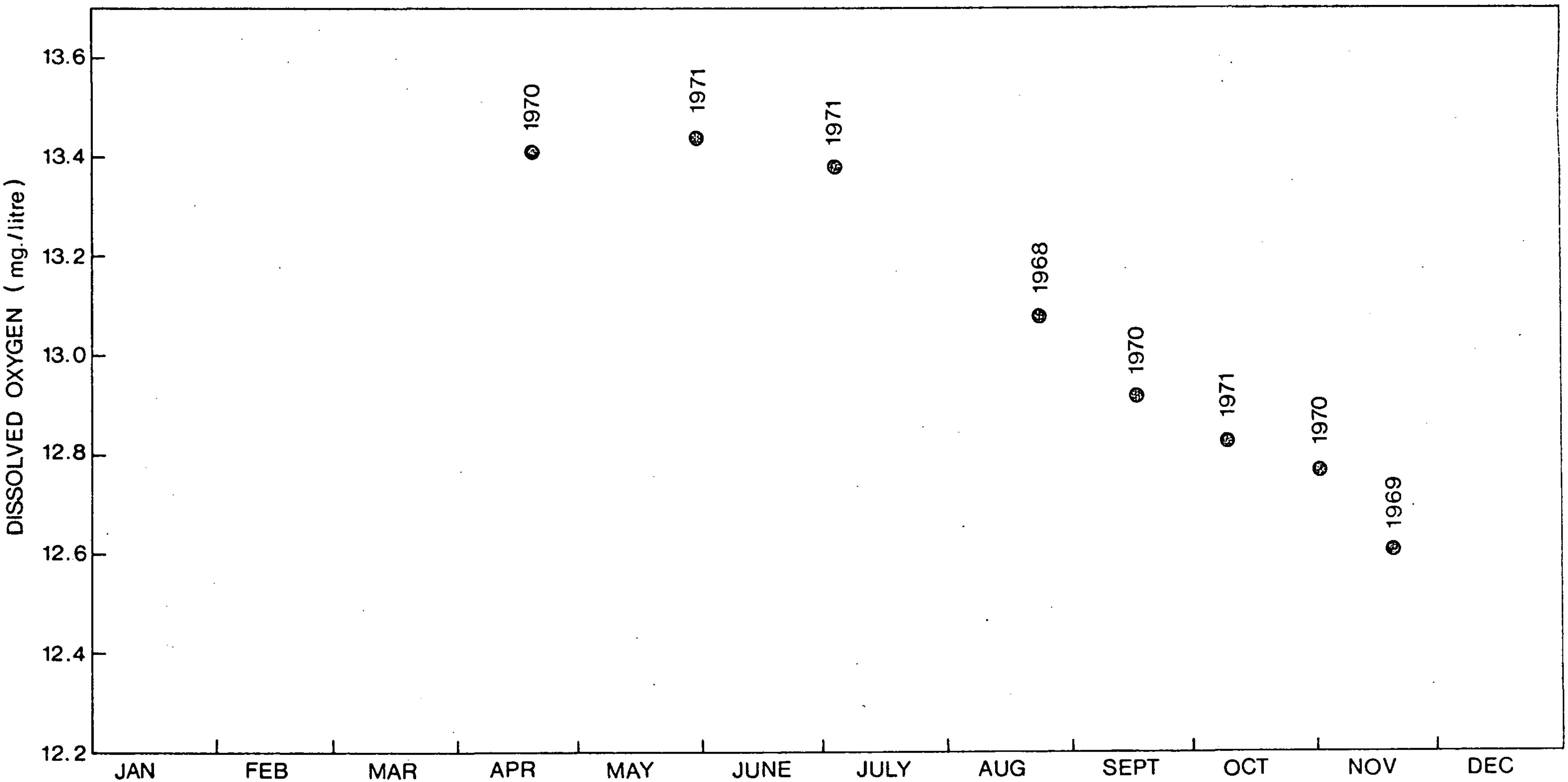

FIGURE 7. MEAN OXYGEN CONCENTRATIONS OF THE COLD WATER-MASS (T<5°C.) IN LAKE SUPERIOR, FOR CRUISES IN THE YEARS 1968 TO 1971. UNITS ARE MILLIGRAMS PER LITRE.

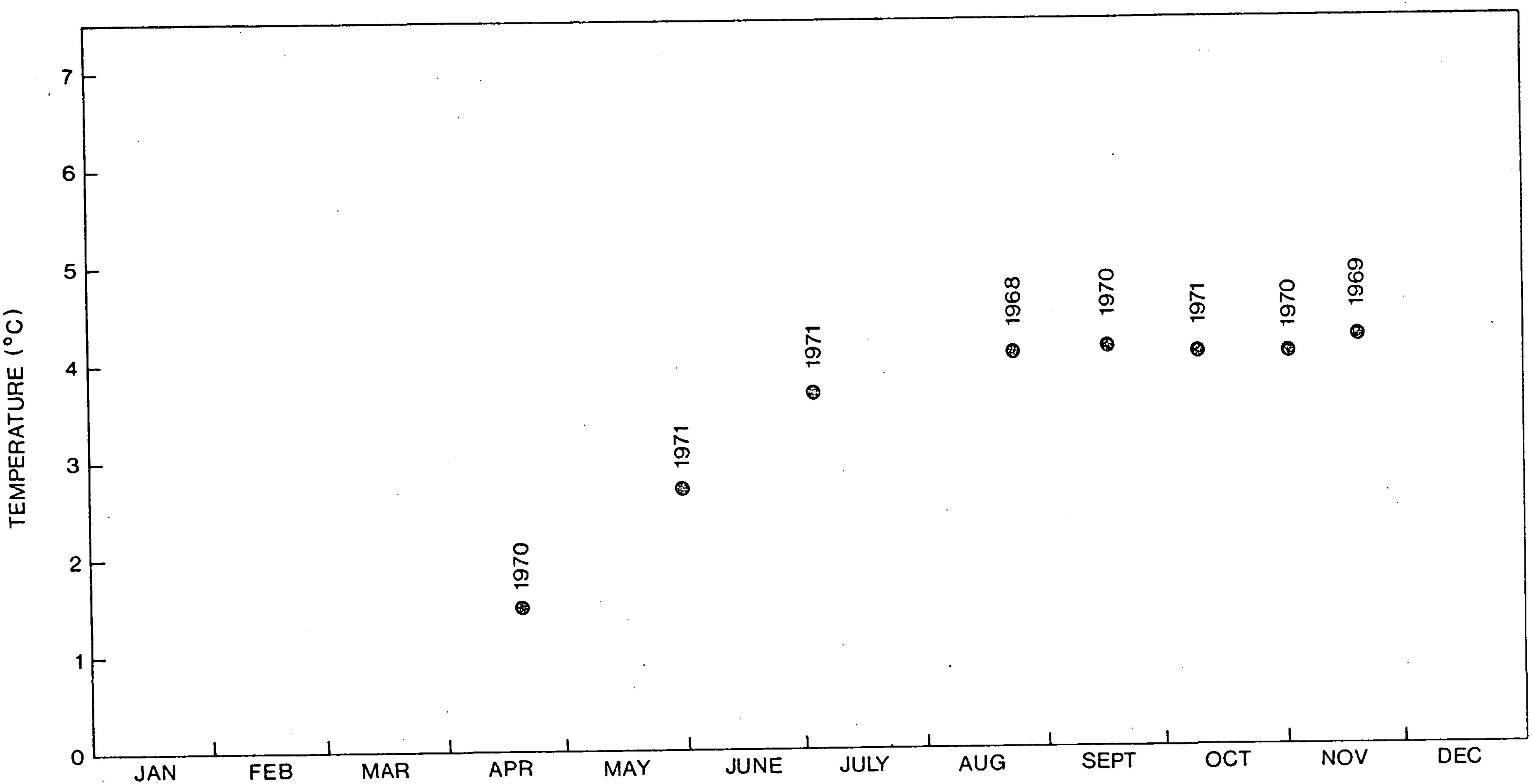

FIGURE 8. MEAN TEMPERATURES OF THE COLD WATER-MASS ($T<5°C.$) IN LAKE SUPERIOR, FOR CRUISES IN THE YEARS 1968 TO 1971.

waters colder than 5°C, which were in part exposed to the atmosphere. It was impractical to identify the remnant of the summer's hypolimnion separately.

Nitrate and ammonia

Data are available for constructing a history of nitrate in Lake Superior. The data show a surprising increase in nitrate concentration with time, for the period 1906 to 1971 (Table 7 and Figure 9). The rate of increase in recent decades was about 36. micrograms nitrogen per litre per 10. years. The nitrate concentration in 1971 was about 270. μg N/litre. A correct explanation is needed for the observed trend. Perhaps nitrate and ammonia concentrations in rainwater are increasing rapidly.

Some details are given here about the historical data.

The earliest data were those of Dole (1909). Eleven nitrate analyses of the St. Mary's River, the outlet of Lake Superior, for 1906 and 1907, averaged 75. μg N/litre.

Eleven analyses of nitrate in Lake Superior and the St. Mary's River in the years 1936 to 1943, reported by Leverin (1947), averaged 145. μg N/litre. The range, 18. to 280. μg N/litre, suggests that the mean value may be unreliable.

Thomas (1954) reported six analyses of nitrate in the St. Mary's River for 1948 and early 1949. Omitting one extremely high result of 1780. μg N/litre, the mean value was 194. μg N/litre.

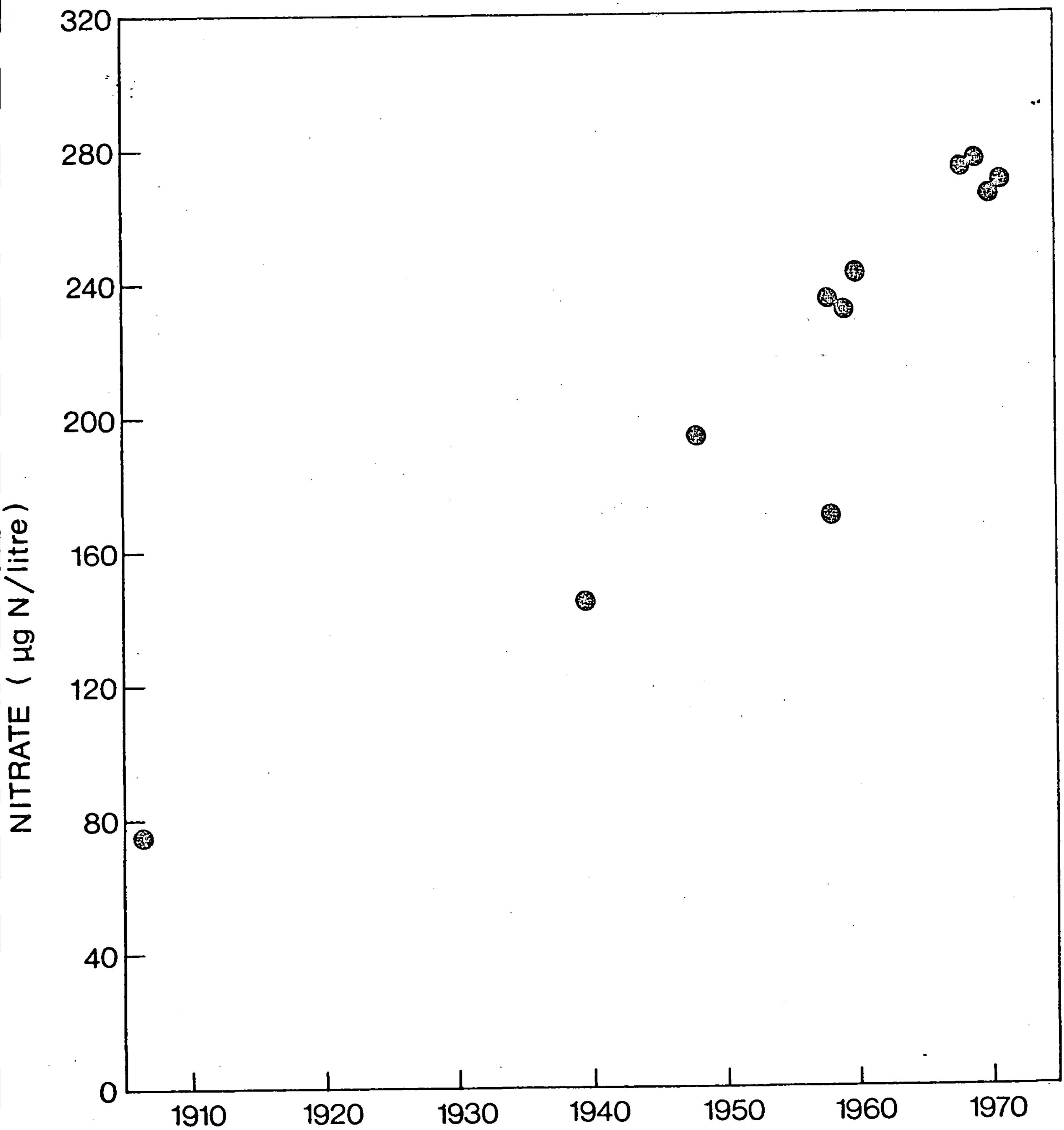

FIGURE 9. SUMMARY OF HISTORICAL DATA FOR NITRATE IN LAKE SUPERIOR. UNITS ARE MICROGRAMS NITROGEN PER LITRE.

The report of Thomas and Gale (1965) listed nitrate data for the St. Mary's River. Twelve monthly samples from October 1957 to September 1958 had a mean value of 170. μg N/litre.

Putnam and Olson (1959) reported nitrate values for western Lake Superior. For their station near Grand Marais, Minnesota, the mean nitrate value for the cold water-mass (temperature less than 5°C) in summer 1958, from only four analyses, was 234. μg N/litre.

Putnam and Olson (1960) reported further nitrate values for western Lake Superior in the summer of 1959. At their stations 16 and 17, near Knife River and Grand Marais, Minnesota, the mean value for the cold water-mass ($T < 5°C$) was reported to be 446. μg N/litre, based on seven analyses. However, judging from a note in their report about a conversion factor between μg NO_3/litre and μg N/litre which is given incorrectly, I believe there was a computational error by Putnam and Olson (1960) and that their mean value for the cold water-mass was actually 232. μg N/litre.

Putnam and Olson (1961) also reported nitrate values for western Lake Superior during 1960. The mean value at their station near Beaver Bay, Minnesota, from five analyses of the cold water-mass, was 484. μg N/litre. As in their preceding report, I believe there was a computational error and that the mean value was actually 242. μg N/litre.

The cruise of the "Theron" for the Canada Centre for Inland Waters in August 1968 showed a mean nitrate value in the cold water-mass ($T < 5°C$) of 274. μg N/litre.

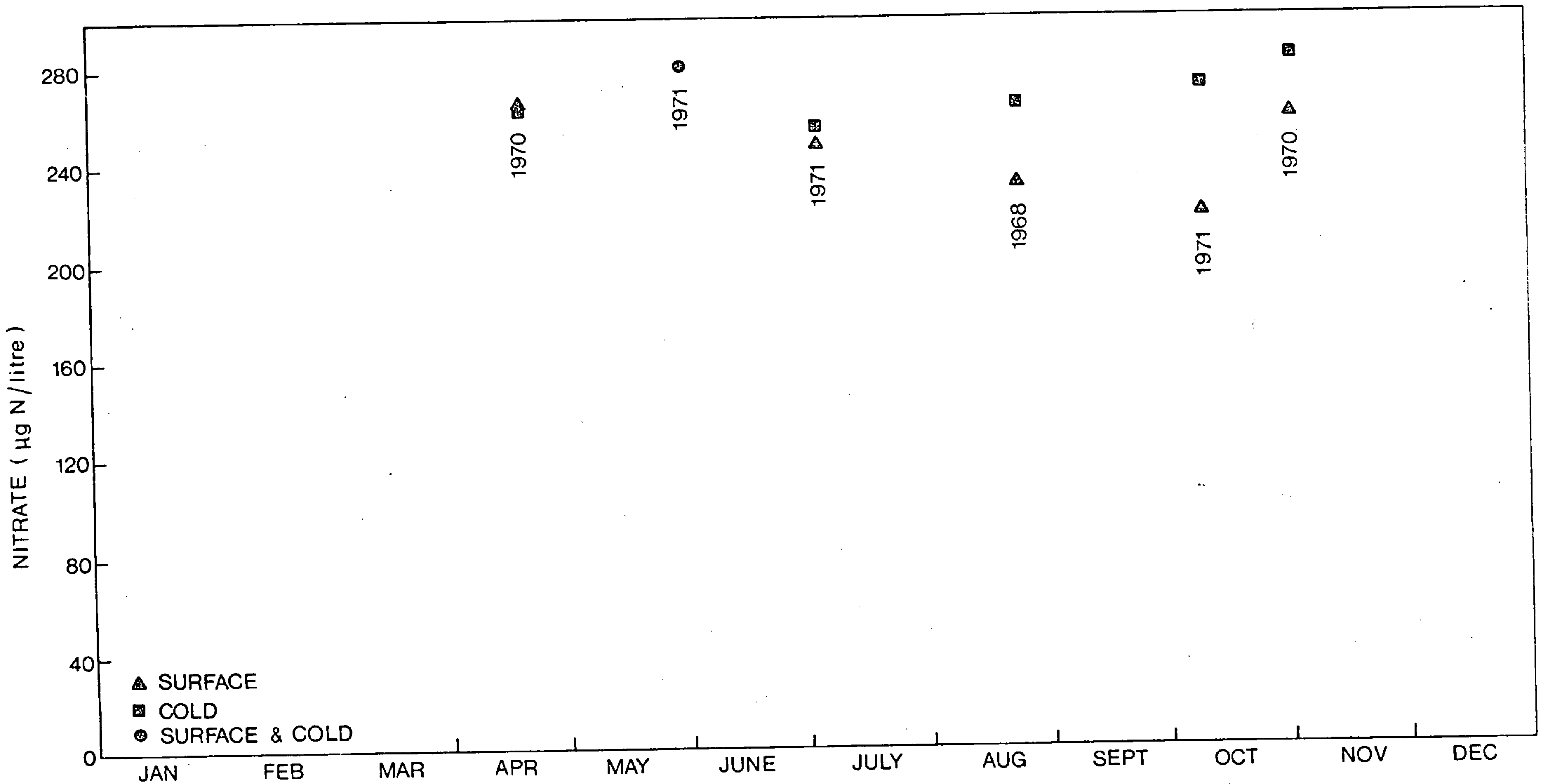

FIGURE 10. NITRATE IN LAKE SUPERIOR DURING 1968, 1970 AND 1971: MEAN VALUES IN THE COLD WATER-MASS (T<5°C.), AND MEAN VALUES AT A DEPTH OF ONE METRE, FOR EACH CRUISE OF THE "THERON" AND "MARTIN KARLSEN". UNITS ARE MICROGRAMS NITROGEN PER LITRE.

Schelske and Callender (1970) published nitrate data for the southern edge of Lake Superior. Sampling was done from July 2 to 9, 1969. Their 21 samples from near the lake bottom (temperature was not listed) had a mean value of 276. μg N/litre, in excellent agreement with recent results of the Canada Centre for Inland Waters.

Cruises of the vessel "Martin Karlsen" in 1970 and 1971 showed mean nitrate values in the cold water-mass (T <5°C) of Lake Superior to be 266. μg N/litre in 1970 and 270. μg N/litre in 1971.

Now I consider biological effects in the recent nitrate data.

Table 8 and Figure 10 summarize the recent observations of nitrate in Lake Superior, by mean values in the cold water-mass (T <5°C) and mean values at a depth of one metre, for each synoptic cruise. The mean value for the cold water-mass during 1971 was 270. μg N/litre. There was a slight depletion of nitrate in surface waters during summer.

The observed fluctuations from cruise to cruise in the mean values of the cold water-mass (Figure 10) are perhaps due to analytical rather than actual changes. Lake Superior has a large hypolimnion during summer, which probably has a very stable nitrate concentration. Seasonal cycles in the surface waters of Lake Superior can best be examined by comparing the surface values to the mean value in the cold water-mass on the same synoptic cruise. This approach leads to the definition of a "nitrate anomaly". The nitrate anomaly is defined as the lake-wide mean nitrate concentration at a depth of one metre on a particular synoptic cruise, minus the mean value in the cold water-mass (T<5°C) on the same cruise.

Lake-wide mean nitrate anomalies for six recent cruises are listed in Table 9 and illustrated in Figure 11. The extreme lake-wide mean nitrate anomaly was -53. μg N/litre, on October 9, 1971. The absolute concentration in the cold water-mass during 1971 was 270. μg N/litre. Thus the mean concentration at a depth of one metre was 217. μg N/litre on October 9, 1971, which is 80. % of 270. μg N/litre. Clearly nitrate is only slightly depleted during summer in Lake Superior. Nitrate is probably not a growth-limiting factor for phytoplankton in Lake Superior, but only an indicator of bioactivity.

From the mean nitrate anomalies on July 3, 1971 and October 9, 1971, I derive a nitrate depletion rate of 14. μg N/litre/month. For comparison, the nitrate depletion rate in Lake Huron in summer 1971 was about the same, 18. μg N/litre/month (Dobson, 1971).

The thermocline descends slowly during summer and more rapidly during autumn. The mixing of epilimnial and thermocline waters tends to offset biological nitrate depletion. During summer the biological effect is prominent, but the observed depletion is somewhat of an under-estimate of the biological rate of change. During autumn the mixing effect is prominent, nitrate concentrations in the epilmnion increase, and biological effects are obscured (see Figure 11).

To show the seasonal cycle of nitrate in warmer and cooler surface waters separately, the data for a depth of one metre were divided into two sets on either side of the mean surface temperature on each cruise,

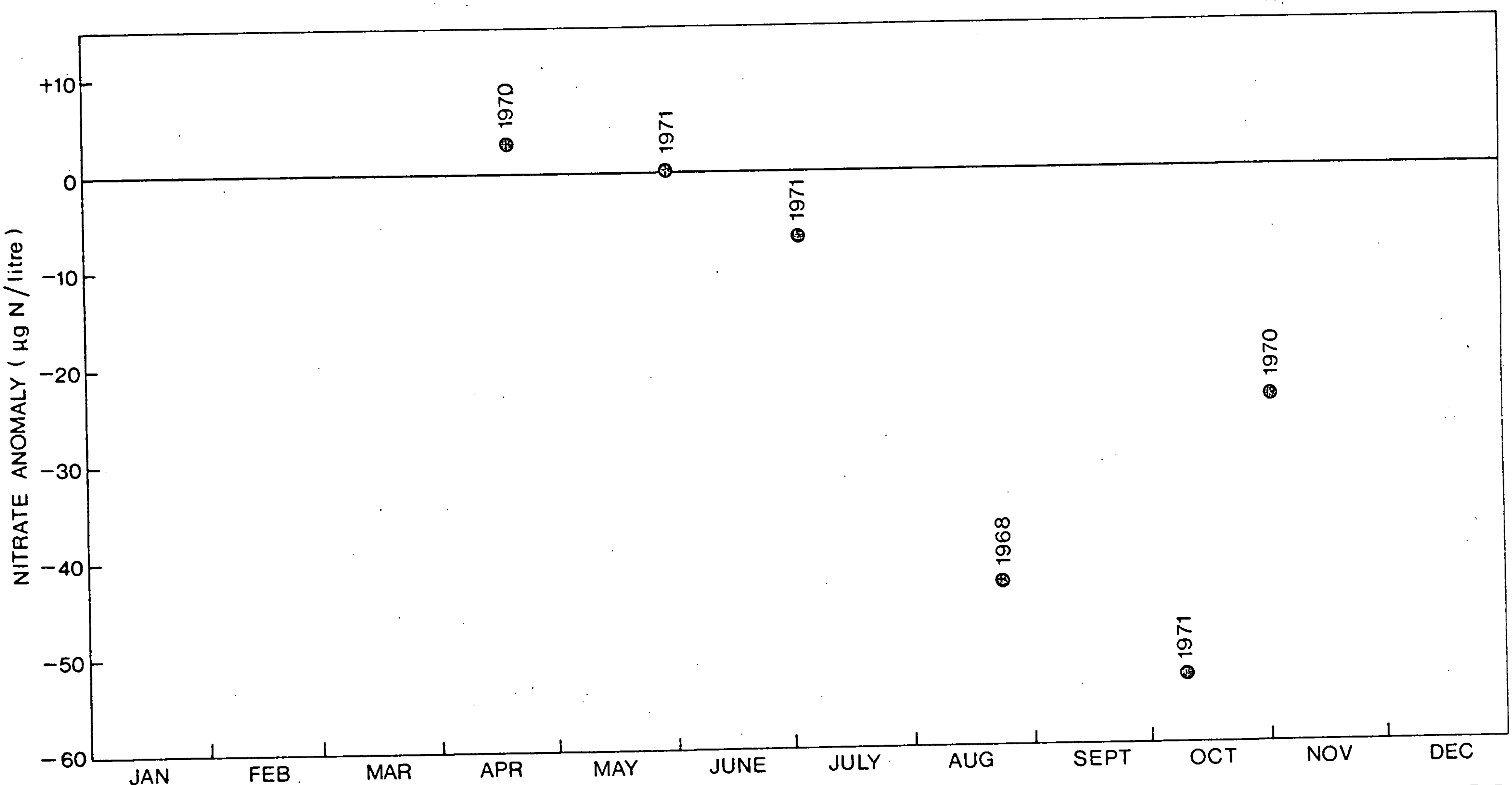

FIGURE 11. LAKE SUPERIOR: NITRATE ANOMALIES, DEFINED AS THE MEAN NITRATE VALUE AT A DEPTH OF ONE METRE, MINUS THE MEAN NITRATE VALUE IN THE COLD WATER-MASS (T<5°C.) ON THE SAME CRUISE, FOR CRUISES OF THE "THERON" AND "MARTIN KARLSEN" IN THE YEARS 1968, 1970 AND 1971.

and the mean nitrate anomalies were computed for the warm and cool groups of samples (Figure 12). This treatment was possible for only four cruises, for which the sampling was more complete. During August the warmer and cooler waters were depleted at the same rate, but the warmer waters had lower concentrations because their depletion commenced on an earlier date. The onset of nitrate depletion was probably associated with the offshore migration of the "thermal bar".

Ammonia was measured on cruises of the vessel "Cisco" in 1953 (Beeton, Johnson, and Smith, 1959). For the period July 3 to October 1, 1953, the mean value for 57. samples of the cold water-mass (T <5°C) was 110. μg N/litre. The ammonia results for 1953 are far greater than those of the Canada Centre for Inland Waters in 1970 and 1971. If both sets of data are correct, then ammonia has decreased over the years, while nitrate has been increasing. There is not overwhelming evidence for a long-term decrease in ammonia: the results of 1953 may have been incorrect. But the meagre evidence suggests a shift from ammonia to nitrate instead of a large change in the nitrogen loading to the lake, and this possibility should be considered.

Recent data for ammonia in Lake Superior, observed during 1970 and 1971, are summarized in Table 10 and Figure 13. The mean values for the five cruises are somewhat inconsistent, suggesting analytical difficulties. The mean ammonia concentration for 1971, taking one-metre data and cold-water data together, was 7. μg N/litre. These results were much lower than those for nitrate which averaged 270. μg N/litre in the cold water-mass.

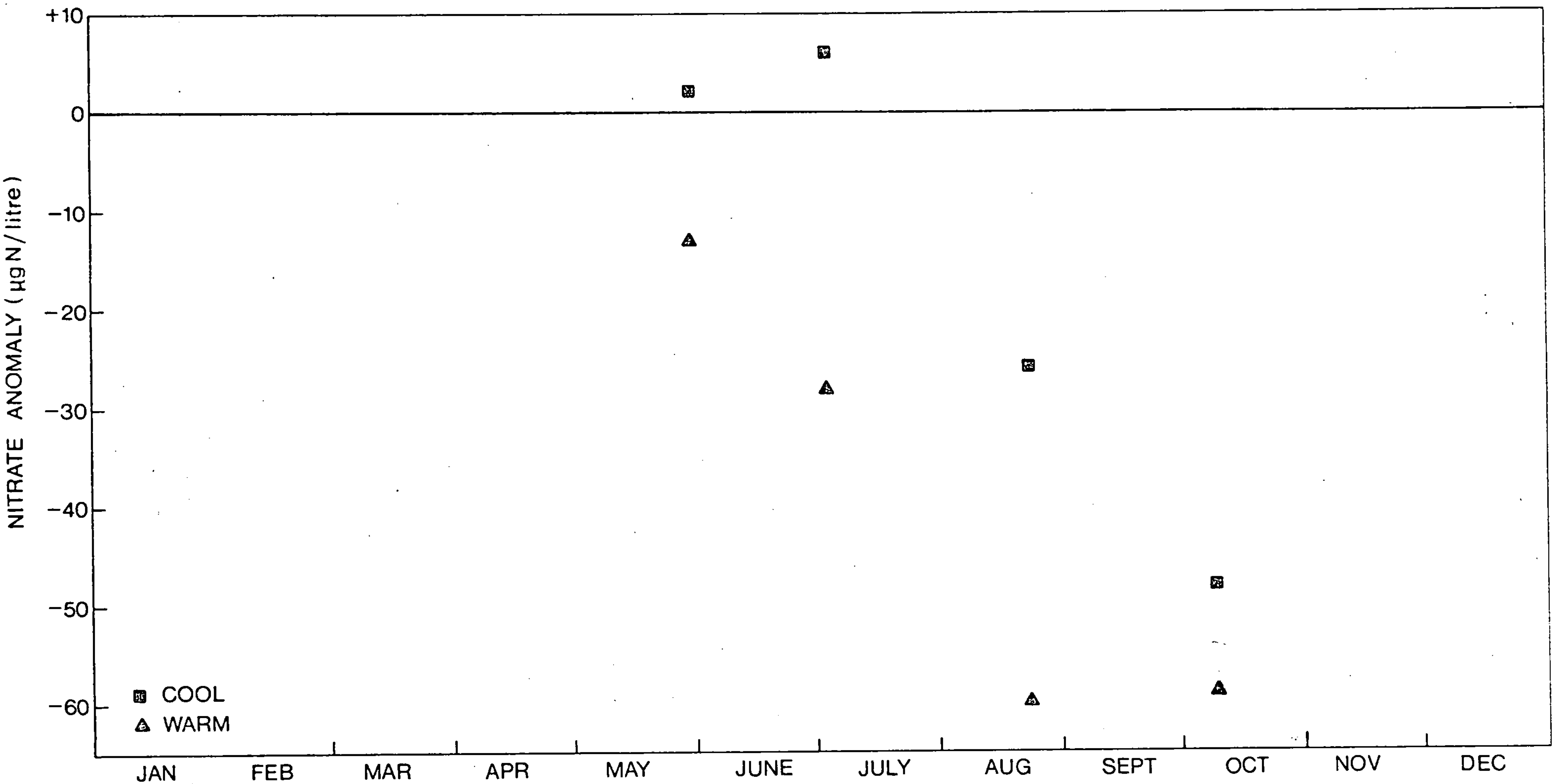

FIGURE 12. NITRATE ANOMALIES IN LAKE SUPERIOR DURING 1968 AND 1971: MEAN ANOMALIES FOR THE WARM ONE-METRE SAMPLES AND MEAN ANOMALIES FOR THE COOL ONE-METRE SAMPLES, FOR CRUISES OF THE "THERON" AND "MARTIN KARLSEN". UNITS ARE MICROGRAMS NITROGEN PER LITRE.

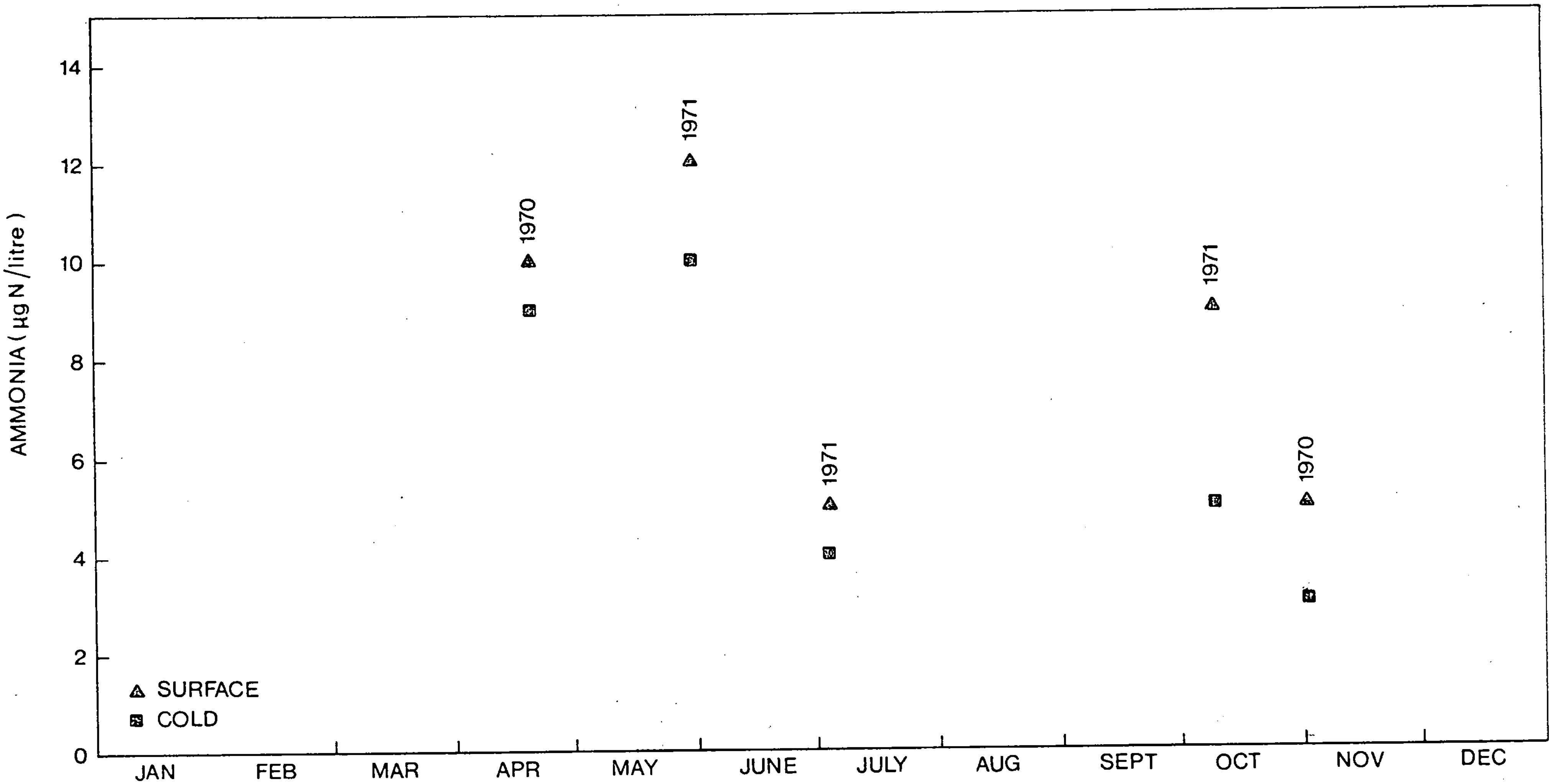

FIGURE 13. AMMONIA IN LAKE SUPERIOR DURING 1970 AND 1971: MEAN VALUES IN THE COLD WATER-MASS (T<5°C.), AND MEAN VALUES AT A DEPTH OF ONE METRE, FOR EACH CRUISE OF THE "MARTIN KARLSEN". UNITS ARE MICROGRAMS NITROGEN PER LITRE.

Ammonia data indicate similar concentrations in Lake Superior and Lake Huron. In 1971 Lake Huron had a mean ammonia value of 8. μg N/litre (Dobson, 1971).

Reactive silicate

The historical record of reactive silicate in Lake Superior begins with the data of Thomas (1954) for the year 1948. Summaries of the entire set of historical data are given in Table 11 and Figure 14. There is considerable inconsistency among the mean values of the earlier data, so that no clear trend is apparent. The data of Putnam and Olson for 1958 to 1960 agree closely with recent results for 1968 to 1971 obtained by the Canada Centre for Inland Waters, and also with the results of Schelske and Callender for 1969: this agreement suggests that reactive silicate in Lake Superior is not changing rapidly.

Some details are given here about the historical data for reactive silicate.

Thomas (1954) reported 11 analyses of reactive silicate in the St. Mary's River for 1948 and early 1949. The mean value was 3440. micrograms SiO_2 per litre

Reactive silicate was measured on cruises of the vessel "Cisco" on Lake Superior in 1953 (Beeton, Johnson, and Smith, 1959). For the period July 3 to October 1, 1953, the mean value for 79. samples of the cold water-mass ($T < 5°C$) was 5100. μg SiO_2/litre. The data were only reported to the nearest 1000. μg SiO_2/litre. The results are much higher than those of other years.

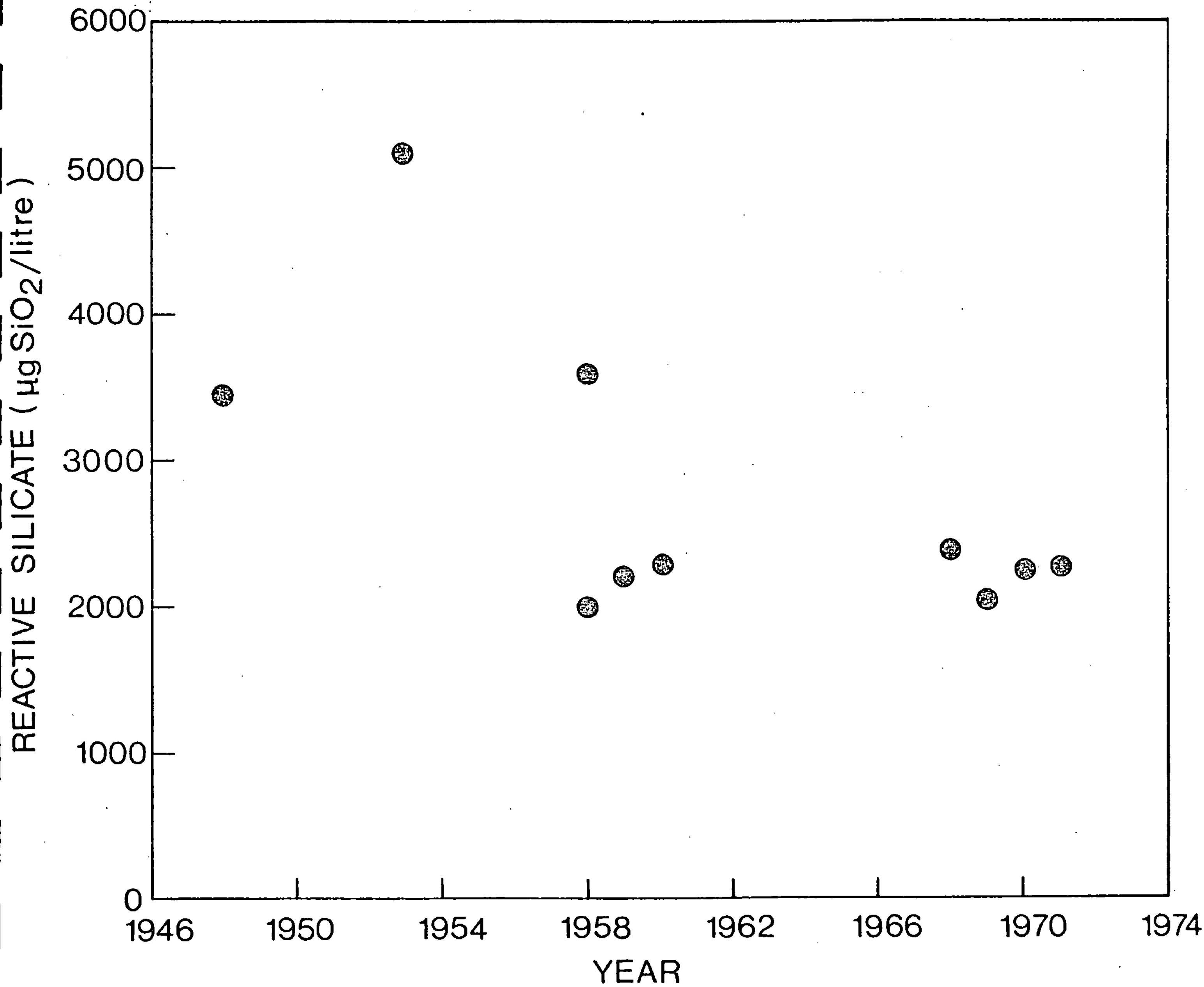

FIGURE 14. SUMMARY OF HISTORICAL DATA FOR REACTIVE SILICATE IN LAKE SUPERIOR.

The report of Thomas and Gale (1965) listed reactive silicate data for the St. Mary's River. Twelve monthly samples from October 1957 to September 1958 had a mean value of 3600. μg SiO_2/litre.

Putnam and Olson (1959) reported reactive silicate values for western Lake Superior. At their stations near Grand Marais, Minnesota, the mean reactive silicate value in the cold water-mass (T <5°C) in summer 1958, from only four analyses, was 2000. μg SiO_2/litre.

Putnam and Olson (1960) reported further reactive silicate values for western Lake Superior. At their stations 16 and 17 near Knife River and Grand Marais, Minnesota, the mean reactive silicate value for the cold water-mass (T <5°C) in summer 1959, from seven analyses, was 2,190. μg SiO_2/litre.

Putnam and Olson (1961) also reported reactive silicate values for western Lake Superior. At their station near Beaver Bay, the mean reactive silicate value for the cold water-mass in the summer of 1960, from five analyses, was 2,280. μg SiO_2/litre.

The cruise of the "Theron" for the Canada Centre for Inland Waters in August 1968 showed a mean reactive silicate value in the cold water-mass (T <5°C) of 2,380. μg SiO_2/litre. There were 66. analyses of the cold water-mass.

Schelske and Callender (1970) published reactive silicate data for the southern edge of Lake Superior. Sampling was done from July 2 to 9, 1969. Their 22. samples from near the lake bottom (temperature was not listed) had a mean value of 2,010. μg SiO_2/litre, slightly lower than recent results of the Canada Centre for Inland Waters.

Cruises of the vessel "Martin Karlsen" in 1970 and 1971 showed mean reactive silicate values in the cold water-mass (T <5°C) of Lake Superior to be 2,240. µg SiO_2/litre in 1970 and 2,260. µg SiO_2/litre in 1971. There were 63. analyses of the cold water-mass in 1970, and 779. in 1971.

Now biological effects in the recent reactive silicate data are considered.

Recent observations of reactive silicate in Lake Superior are summarized in Table 12 and Figure 15. Mean values are given for two regions: the cold water-mass (T <5°C), and the lake surface represented by samples from a depth of one metre.

Fluctuations from cruise to cruise in the mean values for the cold water-mass are probably due to analytical inconsistencies rather than actual changes.

In late summer some depletion of reactive silicate at a depth of one metre is evident. This small effect is best examined by use of the reactive-silicate "anomaly", already introduced for nitrate.

Reactive-silicate anomalies, defined as the mean value at a depth of one metre, minus the mean value for the cold water-mass (T <5°C) on the same cruise, are listed in Table 13 and illustrated in Figure 16. Depletion due to diatom production was evident after July. In November the reactive silicate concentration at one metre began to increase due to mixing with undepleted thermocline waters.

The extreme value for the mean reactive-silicate anomaly was -210. µg SiO_2/litre, on October 9, 1971. The mean concentration of reactive silicate in the cold water-mass in 1971 was 2,261. µg SiO_2/litre.

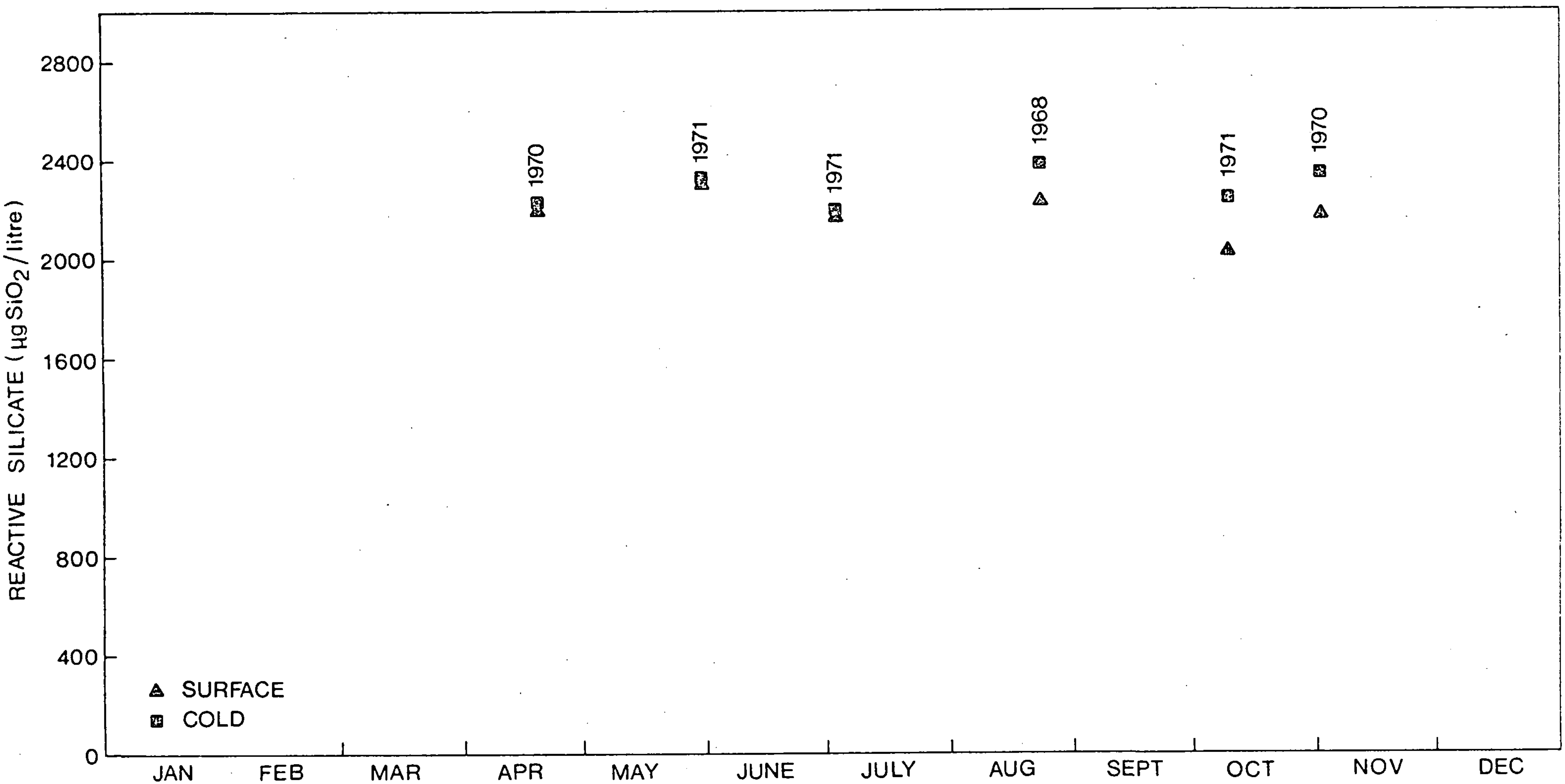

FIGURE 15. REACTIVE SILICATE IN LAKE SUPERIOR DURING 1968, 1970 AND 1971: MEAN VALUES IN THE COLD WATER-MASS (T<5°C.), AND MEAN VALUES AT A DEPTH OF ONE METRE, FOR EACH CRUISE OF THE "THERON" AND "MARTIN KARLSEN". UNITS ARE MICROGRAMS SiO_2 PER LITRE.

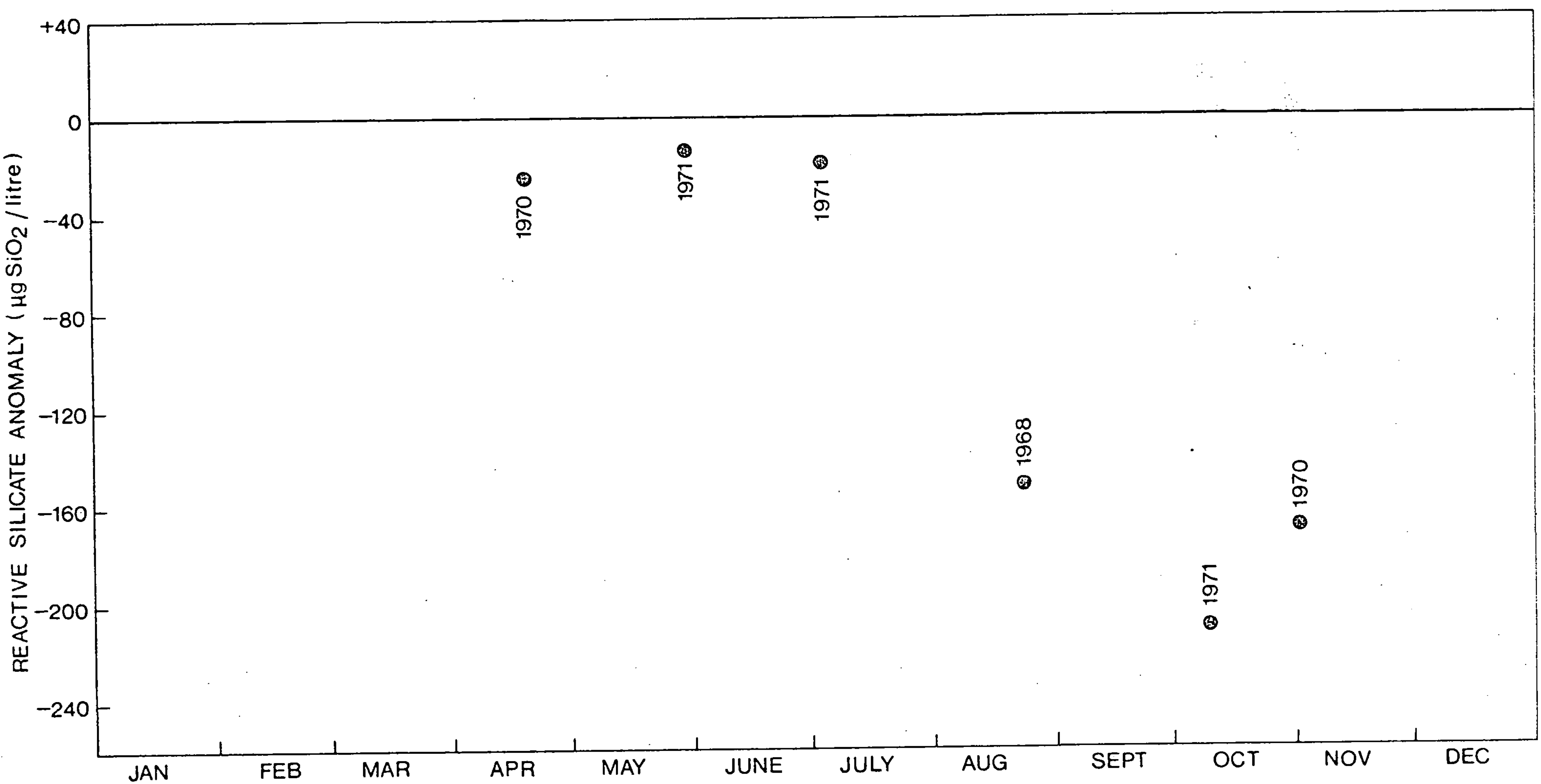

FIGURE 16. LAKE SUPERIOR: REACTIVE SILICATE ANOMALIES, DEFINED AS THE MEAN REACTIVE SILICATE VALUE AT A DEPTH OF ONE METRE, MINUS THE MEAN REACTIVE SILICATE VALUE IN THE COLD WATER-MASS (T<5°C.) ON THE SAME CRUISE, FOR CRUISES OF THE "THERON" AND "MARTIN KARLSEN" IN THE YEARS 1968, 1970 AND 1971.

Thus the absolute mean concentration at one metre on October 9, 1971 was probably 2,051. μg SiO_2/litre or 91.% of 2,261. μg SiO_2/litre. Reactive silicate (and also nitrate) is not much depleted in the surface waters of Lake Superior during summer, and reactive silicate concentrations do not limit diatom production.

The depletion rate for reactive silicate at a depth of one metre in Lake Superior during the summer of 1971, computed from the mean anomalies -19. μg SiO_2/litre on July 3 and -210. μg SiO_2/litre on October 9, was 59. μg SiO_2/litre/month. For comparison Lake Huron surface waters had a mean depletion rate of 61. μg SiO_2/litre/month between June 22 and October 1, 1971 (from Dobson, 1971). This agreement suggests that there is a similar production of diatoms in the two lakes. Note that the nitrate depletion rates in the two lakes were also in close agreement.

As already discussed for nitrate, the mean reactive-silicate anomalies for the warm and cool groups of samples indicate their seasonal cycles separately, and these anomalies have been computed for four of the cruises which had more complete sets of observations (Figure 17). By late summer the warm stations had less reactive silicate than the cool stations, suggesting that depletion may have started earlier at the warmer stations. But separation of the two types is not apparent in the data for early summer, probably because only very small effects are being sought.

Phosphorus in various forms

There is a small amount of historical data on total phosphorus concentrations in Lake Superior. The early data, for the years 1953 and

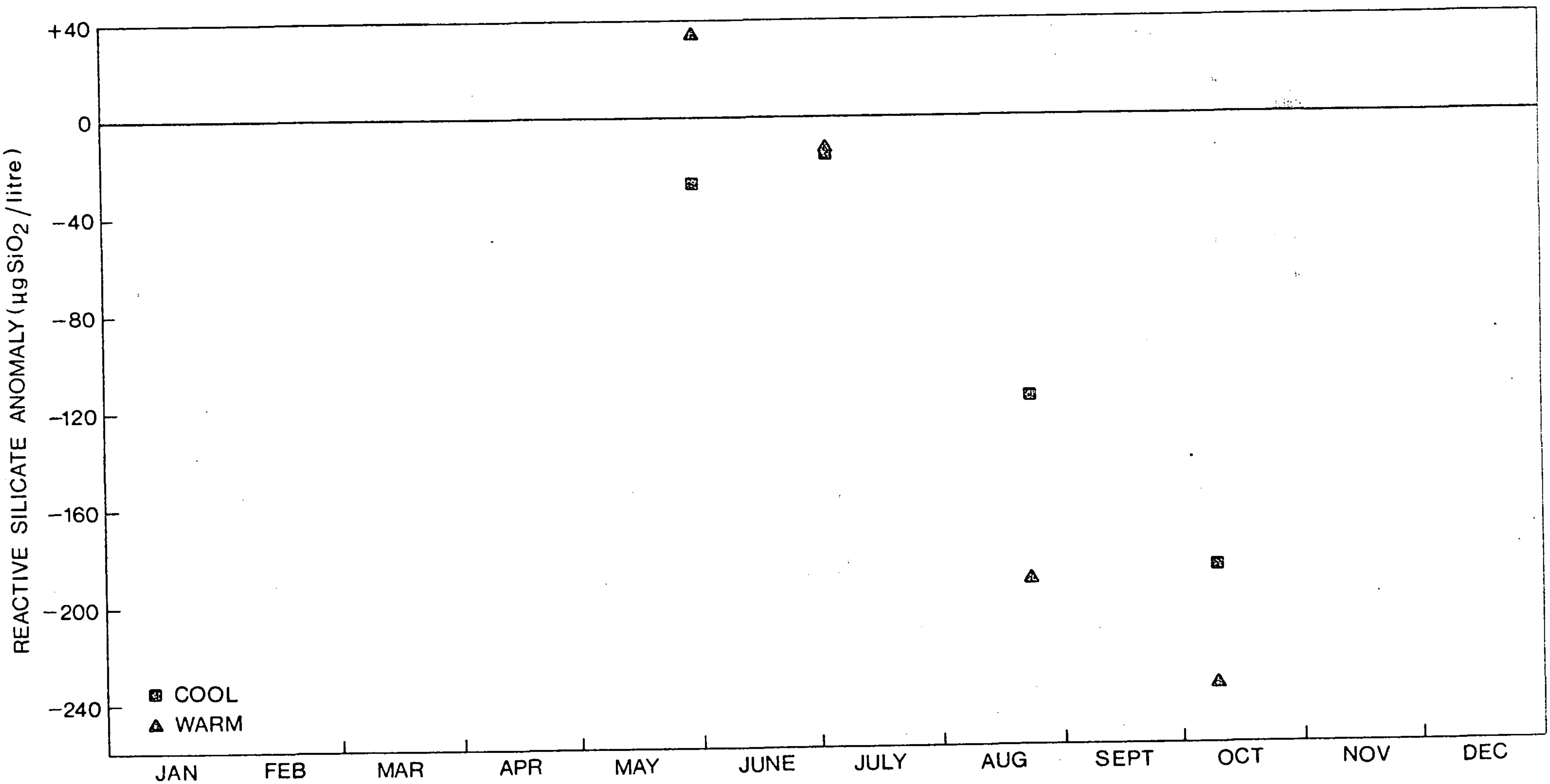

FIGURE 17. REACTIVE SILICATE ANOMALIES IN LAKE SUPERIOR DURING 1968 AND 1971: MEAN ANOMALIES FOR THE WARM ONE-METRE SAMPLES AND MEAN ANOMALIES FOR THE COOL ONE-METRE SAMPLES, FOR CRUISES OF THE "THERON" AND "MARTIN KARLSEN". UNITS ARE MICROGRAMS SiO_2 PER LITRE.

1958-1960, were about three times the concentrations measured by the Canada Centre for Inland Waters in recent years. An actual decrease seems very unlikely, and the discrepancy between the early and recent data cannot be explained.

Total phosphorus was measured on cruises of the vessel "Cisco" on Lake Superior in 1953 (Beeton, Johnson, and Smith, 1959). For the period July 3 to October 1, 1953, the mean value for 43 samples of the cold water-mass (T <5°C) was 9.3 micrograms phosphorus per litre.

Putnam and Olson (1959) reported total phosphorus concentrations for western Lake Superior. At their stations near Grand Marais, Minnesota, the mean total phosphorus value in the summer of 1958, from 27 analyses at numerous depths, was 8.7 μg P/litre.

Putnam and Olson (1960) reported further total phosphorus data for western Lake Superior. At their stations 16 and 17 near Knife River and Grand Marais, Minnesota, the mean total phosphorus value in the summer of 1959, from 32 analyses at numerous depths, was 10.2 μg P/litre.

Putnam and Olson (1960) also reported some results for soluble reactive phosphate, called by them "inorganic phosphorus", for the summer of 1959. At their stations 16 and 17, about half of the results were below their detection limit. Therefore a mean value cannot be calculated.

Putnam and Olson (1961) reported total phosphorus data for western Lake Superior. At their two stations near Larsmont and

Beaver Bay, Minnesota, the mean total phosphorus value in the summer of 1960, from 11 analyses, was 7.2 μg P/litre.

Recent measurements of phosphorus in Lake Superior in the years 1968, 1970 and 1971, by the Canada Centre for Inland Waters, have included three fractions: soluble reactive phosphate, total filterable phosphorus, and total phosphorus. The samples analysed for total filterable phosphorus and for soluble reactive phosphate were filtered before analysis, through membrane filters having pore diameters of 0.45 microns (equal 0.45×10^{-3} millimeters). The procedure does not distinguish a colloidal fraction from dissolved and particulate fractions.

The recent data, from lake-wide cruises, are summarized in Tables 14 to 16 and Figures 18 to 20. There were no obvious seasonal cycles in the data for the various fractions of phosphorus. There was no obvious difference between the concentrations of surface and deeper waters. The three measured fractions and two calculated fractions can be summarized further by grand mean values for the years 1970 and 1971. About 1000 observations of each kind were used for this computation. Results are:

Soluble reactive phosphate	0.5 μg P/litre
Total filterable phosphorus	1.8 μg P/litre
Total phosphorus	3.2 μg P/litre
Particulate phosphorus (total minus total filterable)	1.4 μg P/litre
Dissolved organic phosphorus (total filterable minus soluble reactive)	1.3 μg P/litre

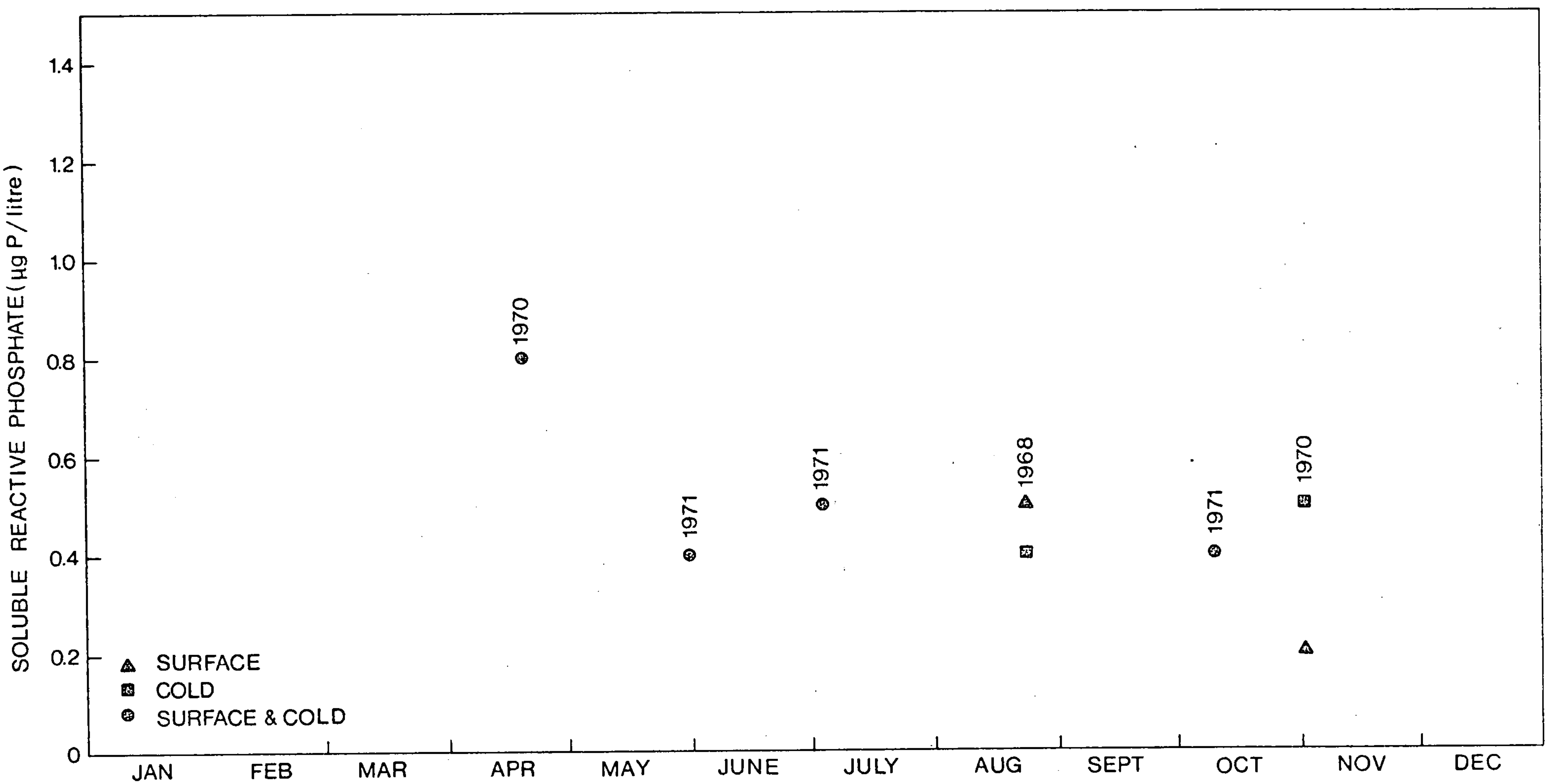

FIGURE 18. SOLUBLE REACTIVE PHOSPHATE IN LAKE SUPERIOR DURING 1968, 1970 AND 1971: MEAN VALUES IN THE COLD WATER-MASS (T<5°C.), AND MEAN VALUES AT A DEPTH OF ONE METRE, FOR EACH CRUISE OF THE "THERON" AND "MARTIN KARLSEN". UNITS ARE MICROGRAMS PHOSPHORUS PER LITRE.

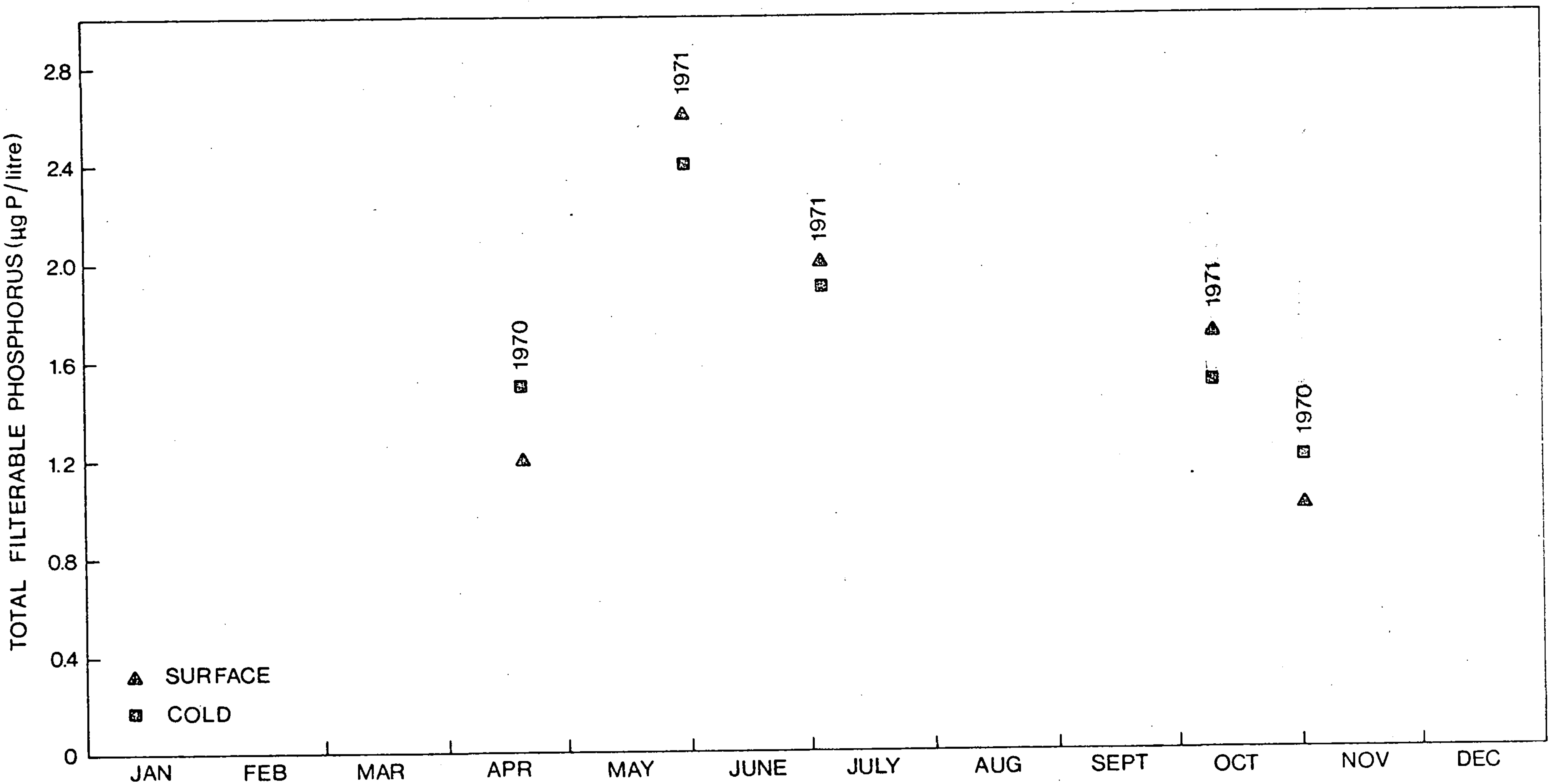

FIGURE 19. TOTAL FILTERABLE PHOSPHORUS IN LAKE SUPERIOR DURING 1970 AND 1971: MEAN VALUES IN THE COLD WATER-MASS ($T<5°C.$), AND MEAN VALUES AT A DEPTH OF ONE METRE, FOR EACH CRUISE OF THE "MARTIN KARLSEN". UNITS ARE MICROGRAMS PHOSPHORUS PER LITRE.

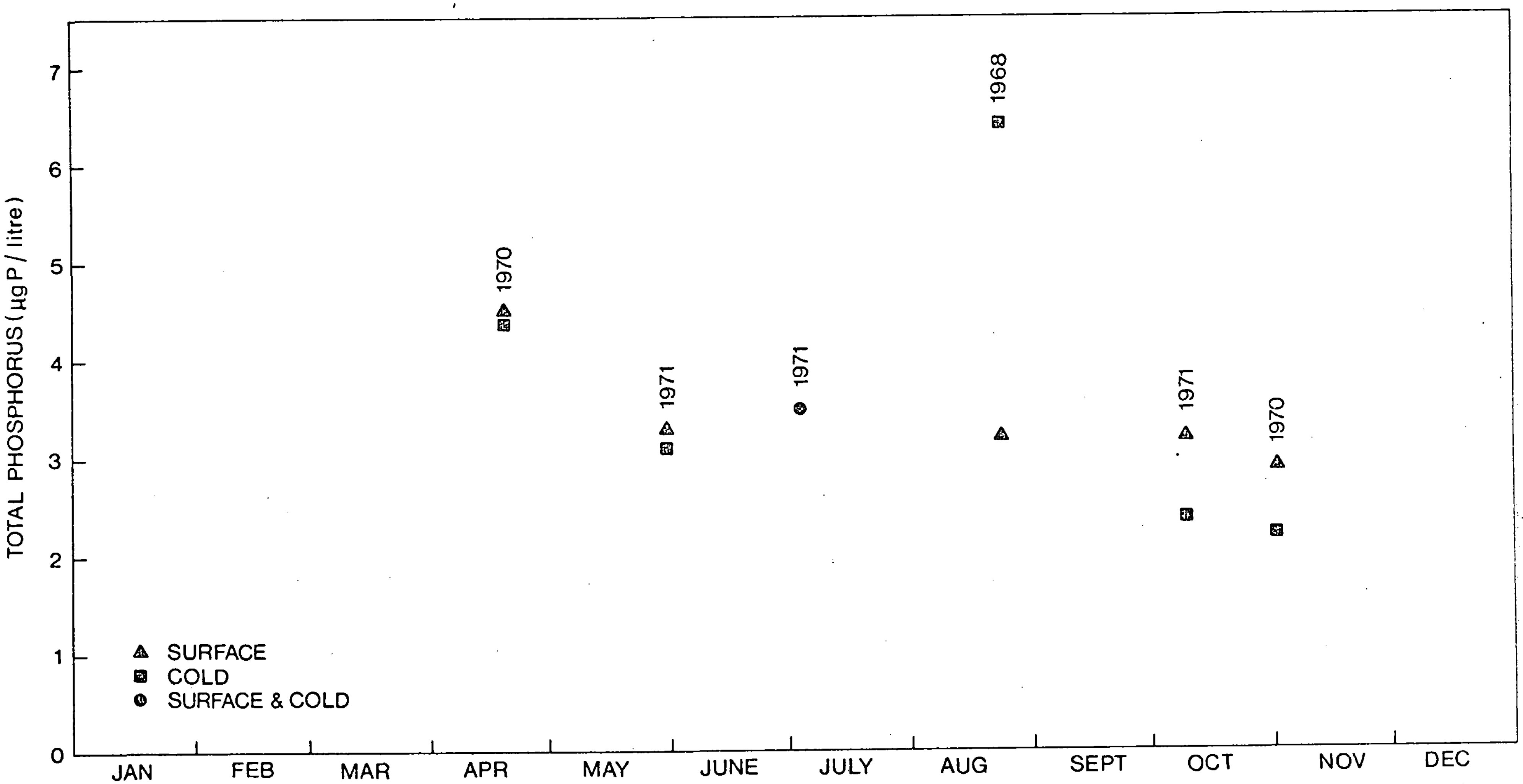

FIGURE 20. TOTAL PHOSPHORUS IN LAKE SUPERIOR DURING 1968, 1970 AND 1971: MEAN VALUES IN THE COLD WATER-MASS (T<5°C.), AND MEAN VALUES AT A DEPTH OF ONE METRE, FOR EACH CRUISE OF THE "THERON" AND "MARTIN KARLSEN". UNITS ARE MICROGRAMS PHOSPHORUS PER LITRE.

The mean concentrations of phosphorus in various fractions in Lakes Huron and Superior are compared in Figure 21. The Lake Huron values are taken from the report of Dobson (1971). The particulate phosphorus values can be used as trophic scale indicators. Based on suggestions in the limnological literature, a value for particulate phosphorus of 10. μg P/litre may be taken as the lower level for eutrophy. The mean concentration of particulate phosphorus in Lake Superior, 1.4 μg P/litre, and that of Lake Huron, 2.4 μg P/litre, give clues to the trophic status of these lakes. They are both oligotrophic in their offshore parts, but Lake Huron probably has a greater standing stock of plankton than Lake Superior.

Carbon

The bicarbonate concentration in Lake Superior is about 50. milligrams HCO_3 per litre, equals about 10. milligrams carbon per litre. In the presence of so much dissolved inorganic carbon, probably carbon is not a growth-limiting factor in Lake Superior. Schindler (1971) provides an account of the unimportance of carbon as a limiting factor in freshwater lakes.

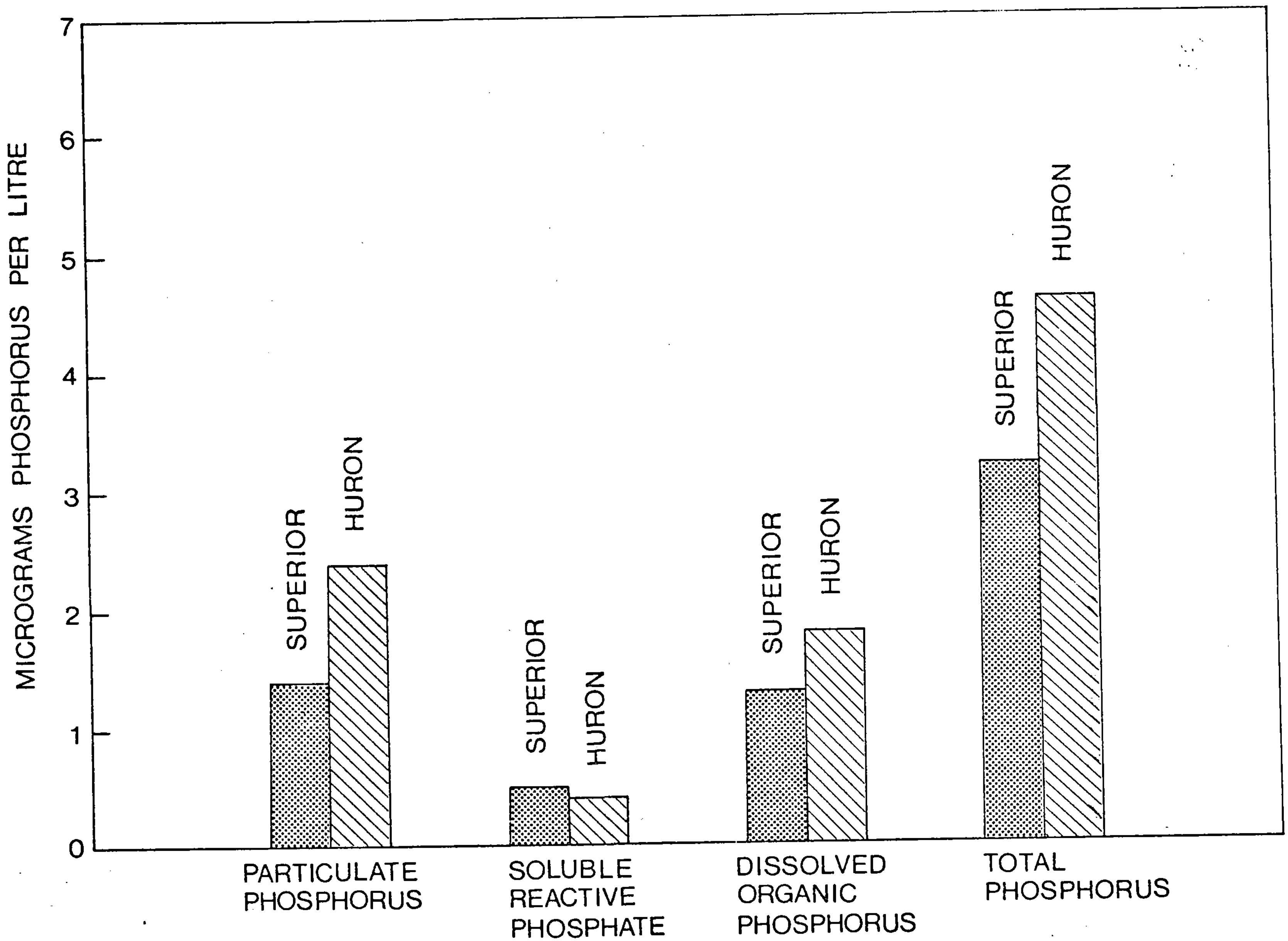

FIGURE 21. COMPARISON OF THE PHOSPHORUS CONCENTRATIONS IN LAKE SUPERIOR (1970 AND 1971) AND LAKE HURON(1971)

NOTE: A PARTICULATE PHOSPHORUS VALUE OF 10 μgP/LITRE CORRESPONDS TO THE LOWER LEVEL FOR EUTROPHY.

DISCUSSION

A note on standing stock parameters and trophic scales.

The standing stock of planktonic plants and animals is an important aspect of lakes and the key to trophic classification. Unfortunately the subject of consistent trophic scales among the various standing stock parameters is quite undeveloped. Limnologists have been satisfied with a two-fold oligotrophic/eutrophic classification instead of continuous trophic scales.

The concentrations of particulate (= sestonic) carbon, nitrogen, and phosphorus give an indication of the standing stock of phytoplankton plus zooplankton plus detritus. Following suggestions by Sawyer (1947, 1966) and Vollenweider (1968), a particulate phosphorus value of 10. micrograms P per litre is here proposed as the lower limit for eutrophy.

Schindler (1971) reported carbon/nitrogen/phosphorus ratios in the seston of his fertilized "Lake 227" to be 130/13/1 by weight. Thus a trophic scale using particulate carbon is suggested as follows:

$$\frac{\text{Particulate carbon} \ (\mu g \ \text{C/litre})}{130.}$$

gives a trophic value on a scale where 1300. μg C/litre is the lower level for eutrophy. Also, for particulate nitrogen,

$$\frac{\text{Particulate nitrogen} \ (\mu g \ \text{N/litre})}{13.}$$

gives a trophic value on a scale where 130. μg N/litre is the lower level for eutrophy. These trophic scales using carbon and nitrogen will have values of 10. as the lower limit for eutrophy.

The usefulness of chlorophyll a as a trophic indicator needs critical evaluation. A tentative suggestion is given here: a chlorophyll a value of approximately 10. micrograms per litre is the lower limit for eutrophy.

In real samples the chlorophyll a value need not be consistent with the trophic values indicated by particulate carbon, nitrogen or phosphorus, because of the presence of zooplankton and detritus together with the phytoplankton.

For the elements C, N and P a potential trophic status is indicated by the sum of the particulate fraction plus the dissolved inorganic fraction. Perhaps the dissolved organic fraction is not readily available for phytoplankton growth. Thus we have a potential standing stock indicated by each element as follows:

Particulate C + bicarbonate C,

Particulate N + nitrate N + ammonia N,

Particulate P + soluble reactive P.

Now the lowest potential trophic value among these three elements will indicate which of the three elements is or will become the growth-limiting factor.

The concentrations of the various major nutrients in Lakes Huron and Superior are as follows:

	Huron	Superior
Particulate phosphorus	2.4 μg P/ℓ	1.4 μg P/ℓ
Nitrate (winter)	247. μg N/ℓ	270. μg N/ℓ
Bicarbonate	18.0 mg C/ℓ	10. mg C/ℓ
Reactive silicate (winter)	1367. μg SiO_2/ℓ	2261. μg SiO_2/ℓ

Now we use an assumed ratio of the elements in the particulate matter to convert these nutrients values to standing stock values all having the units μg P/ℓ, by dividing each of the above concentrations by the ratio of one element to phosphorus. The elemental ratios assumed are

SiO_2/ C / N / P

130? / 130 / 13 / 1 by weight.

The SiO_2/P ratio is only a guess.

Then the possible trophic values, in units of μg P/litre, are:

	Huron	Superior
Particulate phosphorus (actual trophic value)	2.4	1.4
Nitrate	19.0	21.
Bicarbonate	138.	77.
Reactive silicate	10?	17?

This indicates that among these elements phosphorus is clearly the one likely to be limiting, and it indicates that nitrate and silicate are in adequate supply to support somewhat eutrophic conditions, and it indicates that carbon is present in quantities to support extreme eutrophy.

Conclusion

It is concluded in the present study that phosphorus, rather than carbon or nitrogen or silicate, is probably the element is short supply which limits production of phytoplankton in Lake Superior.

Secchi depth, dissolved oxygen and nutrient data indicate that the lake is oligotrophic. Particulate phosphorus data suggest a trophic value of 1.4 on a scale where 10. is the lower limit for eutrophy.

Evidence was found for an increasing nitrate concentration, which probably has little influence on the plankton due to a continuing shortage of phosphorus.

The conclusions of this report need confirmation by direct studies of the phytoplankton and zooplankton.

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Table 1. Inventory of historical data related to the nutrient conditions in Lake Superior.

Year of observations	Relevant parameters measured	Data source
1906, 1907	Nitrate.	Dole, 1909.
1936 - 1943	Nitrate.	Leverin, 1947
1948, 1949	Nitrate, reactive silicate.	Thomas, 1954.
1953	Ammonia, reactive silicate, total phosphorus.	Beeton, Johnson, and Smith, 1959.
1957, 1958	Nitrate, reactive silicate.	Thomas and Gale, 1965.
1958	Nitrate, reactive silicate, total phosphorus.	Putnam and Olson, 1959.
1959	Nitrate, reactive silicate, total phosphorus, soluble reactive phosphate.	Putnam and Olson, 1960.
1960	Nitrate, reactive silicate, total phosphorus.	Putnam and Olson, 1961.

Table 1 (continued)

Year of observations	Relevant parameters measured	Data source
1964	Secchi depth	Great Lakes Institute, University of Toronto, 1971.
1969	Nitrate, reactive silicate.	Schelske and Callender, 1970.

Table 2. Inventory of recent data related to the nutrient conditions in Lake Superior.

Cruise dates	Vessel	temperature	secchi depth	dissolved oxygen	soluble reactive phosphate	total filterable phosphorus	total phosphorus	nitrate	ammonia	reactive silicate
Aug. 18 - 28, 1968	THERON	X	X	X	X		X	X		X
Nov. 15 - 23, 1969	MARTIN KARLSEN	X	X	X						
Apr. 15 - 23, 1970	MARTIN KARLSEN	X	X	X	X	X	X	X	X	X
Sept. 12 - 21, 1970	PORTE DAUPHINE	X	X	X						
Oct. 28 - Nov. 6, 1970	MARTIN KARLSEN	X	X	X	X	X	X	X	X	X
May 26 - June 2, 1971	MARTIN KARLSEN	X	X	X	X	X	X	X	X	X
June 30 - July 7, 1971	MARTIN KARLSEN	X	X	X	X	X	X	X	X	X
Oct. 5 - 13, 1971	MARTIN KARLSEN	X	X	X	X	X	X	X	X	X

Table 3. Lake-wide mean and extreme surface temperatures of Lake Superior, from synoptic cruises.

Mean date of cruise	Vessel	Minimum temp. (°C)	Mean temp. (°C)	Maximum temp. (°C)	Number of stations
April 19, 1970	MARTIN KARLSEN	0.2	0.9	2.6	65.
May 30, 1971	MARTIN KARLSEN	1.7	3.1	9.2	68.
July 3, 1971	MARTIN KARLSEN	3.1	7.5	18.1	72.
July 21, 1964	PORTE DAUPHINE	3.7	10.6	19.4	86.
Aug. 23, 1968	THERON	4.9	11.3	16.9	86.
Sept. 16, 1970	PORTE DAUPHINE	6.2	12.6	17.1	82.
Oct. 9, 1971	MARTIN KARLSEN	8.8	11.4	14.2	72.
Nov. 1, 1970	MARTIN KARLSEN	4.8	8.0	11.6	86.
Nov. 19, 1969	MARTIN KARLSEN	3.0	5.5	8.3	86.

Table 4. Lake-wide mean Secchi depth transparency values for Lake Superior, from synoptic cruises.

Mean date of cruise	Vessel	Lake-wide mean Secchi depth (metres)	Number of observations
July 21, 1964	PORTE DAUPHINE	11.2	44.
Aug. 23, 1968	THERON	7.9	48.
Nov. 19, 1969	MARTIN KARLSEN	8.7	33.
Apr. 19, 1970	MARTIN KARLSEN	10.9	36.
Sept.16, 1970	PORTE DAUPHINE	9.6	20.
Nov. 1, 1970	MARTIN KARLSEN	9.8	29.
May 30, 1971	MARTIN KARLSEN	8.5	42.
July 3, 1971	MARTIN KARLSEN	8.3	43.
Oct. 9, 1971	MARTIN KARLSEN	7.9	30.

Table 5. Comparison of Secchi depths in the Great Lakes. The values apply approximately to the years 1967 to 1971.

	Mean value for the entire period May to November (metres)	Mean value for the months of July and August (metres)
Lake Ontario	3.5	2.8
Central Lake Erie	4.0	5.3
Lake Huron	5.9	6.6
Lake Superior	8.6	8.4

Table 6. Recent observations of dissolved oxygen in the cold water-mass of Lake Superior. The "cold water-mass" includes samples having temperatures colder than 5.0^{o}C. During summer stratification this corresponds to the hypolimnion.

Mean date of cruise	Vessel	Mean oxygen concentration (mg/ℓ)	Mean temperature (^{o}C)	Mean oxygen percent saturation	Number of samples in the cold water-mass
Apr. 19, 1970	MARTIN KARLSEN	13.41	1.48	97.2	282.
May 30, 1971	MARTIN KARLSEN	13.44	2.70	100.8	402.
July 3, 1971	MARTIN KARLSEN	13.38	3.68	103.2	308.
Aug. 23, 1968	THERON	13.08	4.07	101.9	276.
Sept. 16, 1970	PORTE DAUPHINE	12.92	4.13	100.9	83.
Oct. 9, 1971	MARTIN KARLSEN	12.83	4.06	100.0	151.
Nov. 1, 1970	MARTIN KARLSEN	12.77	4.06	99.5	96.
Nov. 19, 1969	MARTIN KARLSEN	12.61	4.23	98.7	182.

Table 7. Summary of historical data for nitrate in Lake Superior.

Year	Mean nitrate concentration (micrograms nitrogen per litre)	Reference
1906, 1907	75.	Dole, 1909.
1936 to 1943	145.	Leverin, 1947
1948	194.	Thomas, 1954.
1958	170.	Thomas and Gale, 1965.
1958	234.	Putnam and Olson, 1959.
1959	232?	Putnam and Olson, 1960.
1960	242?	Putnam and Olson, 1961.
1968	274.	unpublished data, Canada Centre for Inland Waters.
1969	276.	Schelske and Callender, 1970.
1970	266.	unpublished data, Canada Centre for Inland Waters.
1971	270.	unpublished data, Canada Centre for Inland Waters.

Table 8. Recent observations of nitrate in Lake Superior. Data for the cold water-mass (temperature less than 5.0°C) and data for a depth of 1 metre are considered separately. Units are micrograms nitrogen per litre.

Mean date of cruise	Vessel	Cold water-mass		Depth of 1 metre	
		Mean Nitrate Value (μg N/ℓ)	Number of Observations	Mean Nitrate Value (μg N/ℓ)	Number of Observations
Apr. 19, 1970	MARTIN KARLSEN	263.	55.	266.	19.
May 30, 1971	MARTIN KARLSEN	281.	361.	281.	56.
July 3, 1971	MARTIN KARLSEN	255.	283.	248.	57.
Aug. 23, 1968	THERON	274.	66.	231.	86.
Oct. 9, 1971	MARTIN KARLSEN	272.	135.	219.	57.
Nov. 1, 1970	MARTIN KARLSEN	283.	8.	259.	20.

Table 9. Nitrate anomalies at a depth of 1 metre in Lake Superior. The nitrate anomaly is defined as the mean value at a depth of 1 metre on a particular synoptic cruise, minus the mean value in the cold water-mass ($T < 5^{o}C$) on the same cruise. Units are micrograms nitrogen per litre.

Mean date of cruise	Vessel	Nitrate anomaly at a depth of 1 metre ($\mu g\ N/\ell$)
Apr. 19, 1970	MARTIN KARLSEN	+ 3.
May 30, 1971	MARTIN KARLSEN	0.
July 3, 1971	MARTIN KARLSEN	- 7.
Aug. 23, 1968	THERON	-43.
Oct. 9, 1971	MARTIN KARLSEN	-53.
Nov. 1, 1970	MARTIN KARLSEN	-24.

Table 10. Recent observations of ammonia in Lake Superior. Data for the cold water-mass (temperature less than 5.0°C) and data for a depth of 1 metre are considered separately. Units are micrograms nitrogen per litre.

Mean date of cruise	Vessel	Cold water-mass		Depth of 1 metre	
		Mean Ammonia value (μg N/ℓ)	Number of Observations	Mean Ammonia value (μg N/ℓ)	Number of Observations
Apr. 19, 1970	MARTIN KARLSEN	9.	53.	10.	17.
Nov. 1, 1970	MARTIN KARLSEN	3.	8.	5.	20.
May 30, 1971	MARTIN KARLSEN	10.	360.	12.	56.
July 3, 1971	MARTIN KARLSEN	4.	283.	5.	57.
Oct. 9, 1971	MARTIN KARLSEN	5.	135.	9.	56.

Table 11. Summary of historical data for reactive silicate in Lake Superior.

Year	Mean reactive silicate concentration (micrograms SiO_2/ℓ)	Reference
1948	3440.	Thomas, 1954.
1953	5100.	Beeton, Johnson and Smith, 1959.
1958	3600.	Thomas and Gale, 1965.
1958	2000.	Putnam and Olson, 1959.
1959	2190.	Putnam and Olson, 1960.
1960	2280.	Putnam and Olson, 1961.
1968	2380.	unpublished data, Canada Centre for Inland Waters.
1969	2010.	Schelske and Callender, 1970.
1970	2240.	unpublished data, Canada Centre for Inland Waters.
1971	2260.	unpublished data, Canada Centre for Inland Waters.

Table 12. Recent observations of reactive silicate in Lake Superior. Data for the cold water-mass (temperature less than 5.0°C) and data for a depth of 1 metre are considered separately. Units are micrograms SiO_2 per litre.

Mean date of cruise	Vessel	Cold water-mass		Depth of 1 metre	
		Mean Silicate value ($\mu g\ SiO_2/\ell$)	Number of Observations	Mean Silicate value ($\mu g\ SiO_2/\ell$)	Number of Observations
Apr. 19, 1970	MARTIN KARLSEN	2228.	55.	2203.	19.
May 30, 1971	MARTIN KARLSEN	2321.	361.	2308.	55.
July 3, 1971	MARTIN KARLSEN	2194.	283.	2175.	57.
Aug. 23, 1968	THERON	2378.	66.	2226.	86.
Oct. 9, 1971	MARTIN KARLSEN	2239.	135.	2029.	57.
Nov. 1, 1970	MARTIN KARLSEN	2344.	8.	2175.	20.

Table 13. Reactive silicate anomalies at a depth of 1 metre in Lake Superior. The silicate anomaly is defined as the mean value at a depth of 1 metre on a particular synoptic cruise, minus the mean value in the cold water-mass ($T < 5^{o}C$) on the same cruise. Units are micrograms SiO_2 per litre.

Mean date of cruise	Vessel	Reactive silicate anomaly at a depth of 1 metre ($\mu g\ SiO_2/\ell$)
Apr. 19, 1970	MARTIN KARLSEN	- 25.
May 30, 1971	MARTIN KARLSEN	- 13.
July 3, 1971	MARTIN KARLSEN	- 19.
Aug. 23, 1968	THERON	-152.
Oct. 9, 1971	MARTIN KARLSEN	-210.
Nov. 1, 1970	MARTIN KARLSEN	-169.

Table 14. Recent observations of soluble reactive phosphate in Lake Superior. Data for the cold water-mass (temperature less than 5.0°C) and data for a depth of 1 metre are considered separately. Units are micrograms phosphorus per litre.

Mean date of cruise	Vessel	Cold water-mass		Depth of 1 metre	
		Mean SR-phosphate value (μg P/ℓ)	Number of observations	Mean SR-phosphate value (μg P/ℓ)	Number of observations
Apr. 19, 1970	MARTIN KARLSEN	0.8	54.	0.8	18.
May 30, 1971	MARTIN KARLSEN	0.4	361.	0.4	56.
July 3, 1971	MARTIN KARLSEN	0.5	283.	0.5	57.
Aug. 23, 1968	THERON	0.4	66.	0.5	86.
Oct. 9, 1971	MARTIN KARLSEN	0.4	135.	0.4	57.
Nov. 1, 1970	MARTIN KARLSEN	0.5	8.	0.2	20.

Table 15. Recent observations of total filterable phosphorus in Lake Superior. Data for the cold water-mass (temperature less than 5.0 ^{o}C) and data for a depth of 1 metre are considered separately. Units are micrograms phosphorus per litre.

Mean date of cruise	Vessel	Cold water-mass		Depth of 1 metre	
		Mean TF-phosphorus value (μg P/ℓ)	Number of Observations	Mean TF-phosphorus value (μg P/ℓ)	Number of observations
April 19, 1970	MARTIN KARLSEN	1.5	55.	1.2	19.
May 30, 1971	MARTIN KARLSEN	2.4	111.	2.6	19.
July 3, 1971	MARTIN KARLSEN	1.9	234.	2.0	56.
Oct. 9, 1971	MARTIN KARLSEN	1.5	131.	1.7	57.
Nov. 1, 1970	MARTIN KARLSEN	1.2	8.	1.0	20.

Table 16. Recent observations of total phosphorus in Lake Superior. Data for the cold water-mass (temperature less than 5.0^{o}C) and data for a depth of 1 metre are considered separately. Units are micrograms phosphorus per litre.

Mean date of cruise	Vessel	Cold water-mass		Depth of 1 metre	
		Mean total phosphorus value (μg P/ℓ)	Number of observa-tions	Mean total phosphorus value (μg P/ℓ)	Number of observa-tions
Apr. 19, 1970	MARTIN KARLSEN	4.4	55.	4.5	19.
May 30, 1971	MARTIN KARLSEN	3.1	322.	3.3	50.
July 3, 1971	MARTIN KARLSEN	3.5	239.	3.5	56.
Aug. 23, 1968	THERON	6.4	12.	3.2	17.
Oct. 9, 1971	MARTIN KARLSEN	2.4	133.	3.2	57.
Nov. 1, 1970	MARTIN KARLSEN	2.2	8.	2.9	20.