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Lake Ontario Water Chemistry Atlas

H.F.H. Dobson

SCIENTIFIC SERIES NO. 139

INLAND WATERS DIRECTORATE
NATIONAL WATER RESEARCH INSTITUTE
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BURLINGTON, ONTARIO, 1984

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We are on the threshold of a very major success story in environmental control, the rehabilitation of Lakes Erie and Ontario.—James P. Bruce, 1972

For my dear wife, Carmelita, and my
daughters, Laura and Susan.

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Abstract

This atlas contains a broad assessment of the results of phosphorus loading reduction in Lake Ontario in the 1970s, including the in-lake phosphorus concentration reduction. It also describes trends of other indicators of recovery from eutrophication. The summer Secchi depths and summer oxygen depletion rates were fairly stable in the 1970s, whereas they would have worsened without phosphorus control. Particulate organic carbon in offshore surface waters during August/September declined steadily by 20% from 1975 to 1981.

Also illustrated are the chemical/biological aspects of the springtime thermal bar, and lakewide upwelling/downwelling in response to winds in summer. In July 1972, there was a prominent lakewide chlorophyll maximum at a depth of about 10 m. The springtime diatom crop was located near the lake bottom in summer, as indicated by abundant particulate organic matter and near-bottom release of soluble reactive silica. March/April nitrate + nitrite had steadily increasing values, from 215 μg N/L in 1968 to 340 μg N/L in 1981. There was a residual level of nitrate + nitrite in surface waters during late summer in the later years, amounting to about 100 μg N/L, which, along with decreased phosphorus and increased N:P ratios, means that troublesome blue-green algal blooms and scums will not occur.

In summary, the phosphorus control program and a fortuitous increase of soluble reactive nitrogen have resulted in very good metabolic conditions in Lake Ontario, with moderate phosphorus and plankton content, prevention of troublesome plankton blooms, and excellent oxygen conditions. It is strongly recommended that the phosphorus loading control program for Lake Ontario and upstream Lake Erie be continued, to maintain the presently ideal trophic conditions in Lake Ontario.

Résumé

Cet atlas contient une évaluation fédérale des résultats de la réduction des apports de phosphore dans le lac Ontario au cours des années 1970, y compris la diminution de la concentration du phosphore dans le lac. Il décrit aussi les tendances relatives à d'autres indicateurs de la déseutrophisation. La transparence, mesurée par la profondeur au disque de Secchi, et le taux d'appauvrissement en oxygène en été sont demeurés assez stables au cours des années 1970; la situation aurait empiré si aucune mesure n'avait été prise pour lutter contre le phosphore. La concentration du carbone organique particulaire dans les eaux de surface au large en août et septembre a diminué de façon continue de 20 % de 1975 à 1981.

Sont également présentés les aspects chimiques et biologiques de la stratification thermique au printemps et des remontées et descentes d'eau à la grandeur du lac sous l'action des vents en été. En juillet 1972, un maximum notable de la concentration de la chlorophylle a été observé à une profondeur d'environ 10 m dans tout le lac. Les diatomées produites au printemps se trouvaient près du fond du lac en été, comme l'indiquaient l'abondance des matières organiques particulaires et la libération près du fond de silice réactive soluble. La concentration des nitrates et nitrites en mars et avril a augmenté de façon continue : elle est passée de 215 μg N/L en 1968 à 340 μg N/L en 1981. On a observé une concentration résiduelle des nitrates et nitrites dans les eaux de surface à la fin de l'été dans les dernières années (environ 100 μg N/L). Compte tenu d'une diminution du phosphore et d'une augmentation des rapports N:P, cela signifie qu'il n'y aura pas d'écumes ni de poussées de cyanophytes nuisibles.

En résumé, grâce au programme de lutte contre le phosphore et à une augmentation opportune de l'azote soluble réactif, le lac Ontario présente de très bonnes conditions métaboliques, et plus précisément des teneurs modérées en phosphore et en plancton, les poussées planctoniques ont été freinées, et les conditions en ce qui concerne l'oxygène ont été rendues excellentes. On recommande fortement la poursuite du programme dans le lac Ontario, ainsi que dans le lac Érié en amont, afin de maintenir des conditions trophiques idéales dans le lac Ontario.

Executive Summary

Lake Ontario has been observed by analytical chemistry methods since 1966. The resulting data are, in large part, illustrated and interpreted in this atlas. Three structural features, thermal bar (spring), intermittent upwelling (summer), and a sub-surface chlorophyll maximum (July), required a detailed sampling program for trophic assessment.

The lake's recent recovery from eutrophication is a major success story in environmental control. Phosphorus levels in the lake are now near the desired level for control. Among four trophic indicators, only particulate organic carbon showed a decline like phosphorus, perhaps because zooplankton biomass was significant. Increased nitrogen-to-phosphorus ratios, caused by excess nitrate and decreased phosphorus, will probably prevent the occurrence of noxious blue-green algal types in the lake. The governments and the public can be satisfied with their choice of controlling phosphorus loadings, and control should definitely continue while the human population is still increasing.

Lake Ontario Water Chemistry Atlas

H.F.H. Dobson

INTRODUCTION

Lake Ontario is located at the downstream end of the Great Lakes chain and receives the waters of Lake Erie as well as the runoff from its own basin. The increasing population (Fig. 1) uses Lake Ontario water for drinking water supply, industry, fishing and recreation. In recent decades the quality of the waters of Lake Ontario has deteriorated as a result of increased human usage. During the 1960s and 1970s, the main perceived and visible problem was an accelerated eutrophication, with an abundance of pelagic phytoplankton, and beaches fouled by the shore alga *Cladophora*. Eutrophication came under some control in the late 1970s. The continuing remedial measure of phosphorus loading reduction and adjustment to an ideal value was initiated by an early shift to household detergents low in phosphorus, followed by phosphorus removal at municipal sewage treatment facilities. As will be shown, these phosphorus loading control measures are producing the desired eutrophication status of Lake Ontario in the 1980s. The related scientific information on nutrients in the main basin of Lake Ontario forms the major part of this atlas.

Although phosphorus loading control has been successful with the ensuing adjustment of Lake Ontario's basic productivity, a new problem must now be faced: the contamination of fish, especially large fish, and perhaps also of drinking water, with trace chemical compounds, introduced by industries, agriculture, and even drinking water treatment. This contamination has recently been studied with the sensitive instruments of modern analytical chemistry (Allan *et al*., 1983). Except for some trace metal data, the trace poisons in Lake Ontario's waters and biota are not considered here.

This atlas is about nutrients. Similar atlases for Lake Ontario have been published, but with different, more limited data bases. The present atlas gives a broad graphical representation of the lake's structure (spatial and temporal features) and trends. An atlas of the Canadian nearshore waters in springtime was recently published by the Province of Ontario (Ontario Ministry of the Environment, 1980). The present atlas differs by dealing with the whole lake throughout several years. An atlas by E.R. Allen (1977) considered some of the scientific literature on the lake but did not attempt to display a new and large data base as does this publication.

Lake-wide measurements of water quality of Lake Ontario, with emphasis on plant nutrients, phytoplankton abundance and dissolved oxygen, have been conducted since 1966 by the Canada Centre for Inland Waters (CCIW), which is situated at the west end of Lake Ontario, inside Hamilton Harbour, at Burlington. Among many other functions, CCIW uses oceanographic ships to carry out water quality surveys of the main basin and the northeast outlet area of Lake Ontario, at approximately one-month intervals (Kwiatkowski and Neilson, 1983). The present atlas displays a large part of the data from those surveys, in various plots, and interprets the distributions in a descriptive text. Graphs and text together form a new chemical geography of Lake Ontario.

Data from the surveys are stored in vaults and in a computer system at CCIW in Burlington. Distinct methodologies for a measured parameter are given a special code number, and there is a manual listing the methods for all code numbers (CCIW, 1982). The analytical team has made an ongoing effort towards accuracy, precision and consistency of data. Data found to be inaccurate have been discarded and do not appear in the files. Occasional high outliers may appear, sometimes owing to a keypunching error. Cruise mean values for each Lake Ontario water mass, shown later in this atlas, have therefore been subjected to trimming of gross outliers.

The following papers describe the CCIW analytical methods: Chawla and Traversy (1968); Traversy (1971); Philbert (1973); Philbert and Traversy (1973); Strachan (1973); Carew and Williams (1975); Philbert *et al*. (1975); Environment Canada (1983). This laboratory performed well in the ongoing interlaboratory analytical quality control program of the Great Lakes region (Aspila *et al*., 1983).

For data development, the long-term set of observations of Lake Ontario's water quality was available in two forms: digital data listings by cruise, station and depth in "report" format, and the same information for all cruises in the main CCIW computer. The graphs containing individual values were plotted by hand; contouring was also done by hand. But to establish seasonal cycles and long-term trends, mostly the mean values on each cruise for particular shallow or deep offshore (soundings > 100 m) water masses were used. These were trimmed mean values, computed automatically and then plotted manually. The output of the averaging program lists several other factors, such as standard deviation, number of values, the effect of trimming outliers, associated mean temperature, and the mean date of the data subset. All this would be a valuable foundation for limnological modelling research which might be stimulated by the data-displays of this atlas.

Lake Ontario is large (Fig. 2), with a length of 309 km (192 statute miles), a mean width of 60 km (37 statute miles), and a mean depth of 86 m (280 ft). The ratio of its length to mean depth is 3600:1. Let us now plunge into this lake, or rather, small ocean, and find out its chemical distributions.

LAKE PRODUCTIVITY MANAGEMENT VIA PHOSPHORUS LOADING CONTROL

Spatial Features Plotted on Spatial Coordinates

Vertical Profiles

Vertical profiles of concentration versus depth indicate the stratification or vertical structure of the lake in a simple way. Biochemical stratification develops in a temperate lake in spring and summer in the presence of thermal stratification. Stratification disappears when there is strong vertical mixing to the lake bottom, which occurs in this lake in December/January and May/June.

Water Temperature Profiles

A thermocline, with continuous density change with depth, can be tilted by the wind stress and can develop wave action within itself. The waves have signatures in the form of fine structure in the vertical profile.

Samples collected at a few discrete depths through a thermocline tend to miss the fine structure of the water chemistry profiles. The investigator must often be satisfied with a modest sampling effort in order to have a sufficiently small number of chemical analyses on each survey.

Figure 3 contains data for Lake Ontario's temperatures at 32 stations and at different depths for September 1972. At depths from 10 to 40 m, the temperatures were variable at each depth across the lake. Above about 10 m, there was a mixed surface layer from wind or from cooling. Below 50 m, temperatures were near 4°C.

Soluble Reactive Phosphorus Profiles

Figures 4, 5 and 6 show the vertical profiles of soluble reactive phosphorus at a mid-lake station at different times during 1972 and 1973. This fraction of dissolved phosphorus is the one most readily used for algal growth. The most homogeneous profiles were those of May and June (Fig. 4), at a time of year when the entire water column, at this mid-lake station, was overturning or convecting while being warmed at the surface from 3°C to 4°C. Later, during summer, the surface mixed layer became depleted of this fraction of phosphorus (Figs. 4 and 5). In mid-winter, some deep stratification occurred (Fig. 6).

Total Chlorophyll *a* Profiles

There was a wide range of chlorophyll values in the upper 25 m of Lake Ontario in summer (Figs. 7 and 8). In July 1972, the highest values were at a depth of about 10 m (Fig. 7); in September 1972, the highest values were at the lake surface (Fig. 8). Such a large range of values requires that synoptic spatial distributions be shown for the upper waters, which is done later in this atlas. Due to this large variability, year-to-year changes and long-term trends of the phytoplankton abundance in Lake Ontario will be difficult to discern.

Nitrite Profiles

Nitrite can be produced by bacteria as an intermediate stage of nitrification or denitrification; nitrite can also be excreted by phytoplankton. Nitrite was measured on the earliest surveys of Lake Ontario. A nitrite maximum of about 15 µg N/L, at depths near 30 m below the lake surface, occurred in August 1966 and August 1967 (Figs. 9 and 10).

Particulate Nitrogen Profiles

Vertical profiles of particulate nitrogen in July 1972 and September 1972 (Figs. 11 and 12) are similar to the corresponding profiles of chlorophyll (Figs. 7 and 8).

Vertical Profile of Dissolved Oxygen in September

The solubility of oxygen in the water at the surface of Lake Ontario varies with the water temperature, as follows:

°C	mg O_2/L
0.0	14.4
5.0	12.6
10.0	11.2
15.0	10.0
20.0	9.0
25.0	8.2

Usually, the deviation from atmospheric equilibrium is quantified by the oxygen percent saturation value:

$$\frac{\text{Observed mg } O_2/L}{\text{Solubility (mg } O_2/L\text{) at same temperature}} \times 100\%$$

Another way to show departure from air-equilibrium values is to give the absolute deviations from those values: observed O_2 (mg/L) *minus* the solubility value (mg O_2/L) at the same temperature.

The vertical distribution of oxygen deviations at offshore stations in mid-September 1970 (Fig.13) shows small positive deviations at the surface, a minimum with negative deviations at about 30 m, a broad maximum with slightly negative deviations from 50 to 100 m, and below that, scattered deviations averaging about 2 mg O_2/L, or 11 mg/L oxygen concentration in 4°C water, the solubility value of which is 13 mg/L. Adverse effects on fishes occur below 6 or 4 mg O_2/L (Davis, 1975). Therefore Lake Ontario's main basin oxygen levels are satisfactory.

Vertical Profile of pH

In Lake Ontario during September 1966, the pH ranged from 7.8 to 8.6, deep values averaged 8.1, and surface values averaged about 8.4 (Fig.14). These are similar to oceanic values. In Central Lake Erie bottom waters, the pH goes down to about 7.2 in late summer, accompanying the increase in carbon dioxide when dissolved oxygen is nearly entirely depleted. Further study is required to ascertain whether pH values in the Great Lakes, for example in Lake Superior, are slightly depressed by "acid rain."

The Thermal Bar Phenomenon

Freshwater has maximum density at 4°C. In a very large lake this results in a special phenomenon during the springtime warming period. Water colder than 4°C, when warmed at the surface, circulates vertically because the warmed upper part is the heaviest. But water warmer than 4°C, warmed at the surface, develops stratification because the warmed upper part becomes more buoyant. In a very wide Great Lake in springtime, there is an offshore core of cold unstratified water convecting vertically, and a nearshore ring of warmer stratified water. At the lake surface the 4°C isotherm gradually contracts towards the deepest part of the lake, and when the entire lake surface becomes warmer than 4°C in late spring, a lake-wide thermocline forms rapidly. In Lake Ontario, the date of this transition is usually about June 20.

The thermal bar phenomenon influences nutrients and phytoplankton in the Great Lakes, mainly by affecting the light regime of the upper waters. In the nearshore stratified area, the mixing depth is small, light conditions are good, and plant production occurs. In the offshore part, the mixed surface layer has a thickness of 100 m or more, its average light conditions are poor, and the plant production per unit volume is minimal in the season preceding stratification.

The following sections contain observations made when there has been a thermal bar in Lake Ontario.

Temperature and Total Chlorophyll *a*

On May 1, 1968, the water warmer than 4°C was discontinuous along the shores of Lake Ontario, and most of the lake surface was still below 4°C (Fig. 15).

On June 21, 1972, the thermal bar was present well offshore, where the soundings were about 160 m (Fig. 16). Shoreward of the edge of the cold convecting core, the surface temperatures were in the range of 8°C to 16°C. In the cold core the surface temperatures were near 4°C and were about to begin a rapid warming trend.

In early April and early May of 1972, the surface chlorophyll levels were about 2 µg/L in the cold core, and much higher in irregular patches along the shore (Figs. 17 and 18).

About June 22, 1972, temperatures and chlorophyll in vertical north-south sections (Fig. 19) showed the profound influence of the thermal bar on phytoplankton abundances via the light regime. The chlorophyll level of about 3 µg/L at the lake surface marks the location of the thermal bar in the sections (Figs. 20 to 25). In the westernmost section, "A", the thermocline had already spread across the entire section, but in the other two sections, farther east where Lake Ontario is the deepest, there was still a core of very low chlorophyll levels, about 2 µg/L. The northern warm layer is wider than the southern one each year because Lake Ontario's deepest areas are closer to the south shore. The thermal bar tends to match a particular bottom-depth-contour, at any one time in spring, as the thermal bar migrates offshore.

Particulate Nitrogen: Inshore-Offshore Differences

Particulate nitrogen at 1-m depth versus the sounding (used as an indicator of distance from shore) is illustrated in Figures 26 and 27, for May 26 and June 21, 1972. In Figure 27, the lower values in the extreme nearshore locations may be the result of edge effects such as increased vertical mixing or upwelling.

Soluble Reactive Silica

Soluble reactive nutrients become depleted in spring in surface waters shoreward of the thermal bar, but remain abundant in the cold core offshore (e.g., Fig. 28, soluble reactive silica on June 21, 1972). This agrees logically with the knowledge that in springtime, only the nearshore part produces abundant phytoplankton.

The Phenomenon of Upwelling

Temperature Distributions During Upwelling

The thermocline of a lake in summer can be tilted by the wind stress. The thermocline is pushed down to leeward and up to windward. In an extreme case, the coldest hypolimnetic water mass can be exposed along the windward shore. In a lake as large as Lake Ontario, the cold area at the lake surface is somewhat to the left of the downstream wind direction due to the earth's rotation. Winds from the west are common over Lake Ontario, and upwelling is common in the vicinity of Toronto and Oshawa. An example is given in Figure 29.

Since in autumn the density differences associated with thermal stratification are quite small and winds are often stronger, the movements of isotherms can be large (e.g., Fig. 30).

The wind speeds and directions are, of course, highly variable. Furthermore, the stress on the water surface is proportional to the speed squared, and thus the stress is highly variable indeed. An example of summer winds during 11 days is given in Figure 31. Temperature distributions in the upper part of Lake Ontario near the end of this period are mapped in Figures 32, 33 and 34. The profound lakewide character of this upwelling/downwelling is apparent. The transient distributions of water masses and nutrients must have the effect of causing extreme variability in the growth of phytoplankton.

Although most of this atlas deals with the offshore part of Lake Ontario, in the context of upwelling it is appropriate to show the extreme effect at the shore. Variations of water temperatures at the Hamilton Water Intake in 1959 and 1960 (Fig. 35) showed that the upwelling episodes were different each year and could not be forecasted because the winds cannot be forecasted.

Soluble Reactive Nutrient Redistribution by Upwelling

Lake-wide distributions of soluble reactive nutrients in Lake Ontario are strongly influenced by the surface winds (Figs. 36 and 37). Therefore an extremum along the shore may be due either to a shore discharge (e.g., Fig. 36, low nitrate + nitrite values of the Niagara River plume) or to upwelling (Fig. 36, high nitrate + nitrite near Toronto, not due to discharges from the city).

Additional Vertical Sections

A Longitudinal Temperature Section in Summer

A typical vertical, longitudinal section showing temperatures in summer from August 9 to 13, 1971 (Fig. 38) indicates that the mixed surface layer and the thermocline are shallow features in Lake Ontario in summer. Each summer there is a large water mass with temperatures near 3.8°C below a depth of about 50 m.

Transverse Sections of Total Chlorophyll *a* in Summer

The subsurface vertical structure of chlorophyll in Lake Ontario was observed on the 1972 cruises only. Chlorophyll distributions in three vertical sections, about July 19, 1972, show irregular higher concentrations near a depth of about 10 m (Figs. 39 to 42).

By September 6, 1972, the chlorophyll distributions became simpler, with more uniform values in the mixed surface layer (Figs. 43, 44 and 45). In late summer (August and September), surface chlorophyll values alone became more representative of the upper waters. This will be considered later in the search for long-term trends, using surface values available from surveys of 1971 and earlier, together with integrated 0 to 20-m chlorophyll data available for the years 1973 and after.

Longitudinal Sections of Nitrate + Nitrite and Soluble Reactive Silica in November

A vertical, longitudinal section of nitrate + nitrite in November 1971, shows the strongest vertical gradients at a depth of about 30 to 50 m, with only slight vertical gradients near the bottom (Fig. 46). In contrast, a soluble reactive silica section for November 1971, shows the strongest vertical gradients near the bottom (Fig. 47). The seasonal cycles near the lake bottom, discussed later, give more insight into this puzzle and suggest that in the case of silica (but not nitrate + nitrite), the deep dissolution and recycling are important.

Water Chemistry Data for a Mid-lake Station Shown in Time/Depth Diagrams

Diagrams with time-of-year on the x-axis and depth within the lake on the y-axis are a powerful way to show conditions at a single location in a lake. In these diagrams, contours of concentration are vertical when there are changes with time, and horizontal when there is strong vertical stratification.

Time-series data are available for mid-Lake Ontario during 1972 and early 1973. The station is designated "P-19". The sounding there is about 180 m.

Soluble Reactive Phosphorus Time/Depth Diagram

In a time/depth diagram of soluble reactive phosphorus at station "P-19" (Fig. 48), the mixed surface layer shows as a phosphate-depleted layer in the upper 20 m in July, August and September. In the offshore area, only the upper layer of summer has phosphate-limited plankton content. At all other times and depths at this location there is excess phosphate and therefore potential for algal stocks to increase.

In summer at "P-19", there are sometimes extremely high soluble reactive phosphorus concentrations near the bottom. These transient events could be local releases in deep water or from the mud-water interface, or they could be intrusions of high phosphate water from the deeper area farther east, caused by horizontal currents in the deep water in response to surface wind stress.

Nitrite Time/Depth Diagram, Averages at Each Time and Depth for the Whole Offshore Area

In Lake Ontario during August 1966 and 1967, there was a nitrite maximum layer at depth of 30 m (Figs. 49 and 50). The phenomenon was widespread; the values on these particular diagrams are averages at each depth for the whole offshore area.

Particulate Nitrogen Time/Depth Diagram

The time/depth diagram for mid-Lake Ontario for particulate nitrogen (Fig. 51) shows plankton the most abundant in the near-surface waters in summer. Other times and other depths had low values of 20 to 30 μg N/L, except for some transient higher levels near the lake bottom, which was probably the spring growth of diatoms, settling out to the bottom in summer (see also Munawar and Nauwerck, 1971; Sandilands and Mudroch, 1983).

Particulate Organic Carbon Time/Depth Diagram

The time/depth plot of particulate organic carbon at station "P-19" (Fig. 52) shows the same principal features as particulate nitrogen, with the highest concentrations in surface waters in summer as well as accumulations near the bottom in summer.

Particulate Carbon-to-Nitrogen Ratios, Time/Depth Diagram

Low ratios of particulate carbon-to-nitrogen in lake waters indicate particulate matter with high nitrogen and protein content. High ratios indicate particulates that are aged or partially digested (Russell-Hunter, 1970). The particulate carbon to nitrogen ratios in a time/depth plane at "P-19" (Fig. 53) show high values near the bottom in September and October. Perhaps this is caused by the aging diatom crop of the preceding spring in the process of sedimentation.

Soluble Reactive Silica Time/Depth Diagram

The plot of soluble reactive silica at "P-19" in 1972 and 1973 (Fig. 54) shows depletion in the warm surface layer of summer. This depletion of silica could cause diatoms to be replaced by other algal groups in offshore surface waters in summer (see also Munawar and Nauwerck, 1971; Schelske and Stoermer, 1971). The highest values of soluble reactive silica occurred at the lake bottom in summer and early autumn. The high values may have been from dissolution of diatom frustules in the process of sedimentation (Sandilands and Mudroch, 1983).

Oxygen Percent Saturation, Time/Depth Diagram

Oxygen percent saturation values at "P-19" during 1972/73 (Fig. 55) indicate that mid-Lake Ontario had excellent and high dissolved oxygen values. Surface waters were supersaturated, especially during July. There was a slight minimum layer at thermocline depth during September, and values near 90% at the lake bottom in September. Other times and depths at this mid-lake station had values in the range of 90% to 105% saturation, which shows dominance of the process of physical equilibration with air at the lake surface.

Seasonal Cycles and Long-Term Trends of Nutrients and Related Factors

Seasonal cycles and long-term trends are best considered together. Trends must be studied in the context of seasonal cycles, the latter being strong oscillations which, if not considered, might hide the long-term trends.

The offshore part of Lake Ontario has been selected for the cycles-and-trends study. The nearshore part of the lake would be more influenced by upwelling episodes and variable plumes. Moreover, it was undersampled in the time-domain in the monthly CCIW surveys. The data resulting from such undersampling show apparent fluctuations that are erroneous. The problem, called aliasing, has been explained by Pickard (1963).

Temperatures: Seasonal Cycle

The seasonal cycle of surface temperatures (unweighted cruise mean surface temperatures for the area where the soundings are greater than 100 m; Fig. 56) indicates extremely delayed warming of the offshore area in springtime. The critical 4°C temperature level is reached near June 1, followed by rapid warming to 17°C during June. In this offshore zone, summer can be defined as the period of warmest surface temperatures: July, August and September. Limnological autumn can be taken to be the period of cooling down to 4°C: October, November and December. Winter can be considered as the period of further cooling: January, February and March. The coldest cruise mean temperature in this data set was 0.5°C; the offshore area of Lake Ontario is usually free from ice in winter. April and May may be called "early spring" or the slow warming period, and June, with rapid warming, may be called "late spring." Warming of the offshore part is slow in early spring because warming at the surface, still below 4°C, is accompanied by convection and warming at all the deeper depths too.

Soluble Reactive Phosphorus: Seasonal Cycles and Trends in Surface and Bottom Waters

This section deals with changes in soluble reactive phosphorus in Lake Ontario during the last decade. These changes were caused by reduction in the external loading of phosphorus to the lake in the same period.

The seasonal cycle of soluble reactive phosphorus in offshore near-surface waters (Fig. 57) indicates nearly complete depletion during the summer period only, owing to plankton growth. Phosphorus-limited plankton stocks would occur only in summer in this part of Lake Ontario. Long-term trends of soluble reactive phosphorus could best be studied by comparing winter or early spring concentrations in different years. Long-term trends of plankton stock indicators could best be studied only in the summer period in this part of the lake (but also in spring in the nearshore part where surface warming occurs earlier).

All cruise mean values of soluble reactive phosphorus from 1969 to 1982 in the offshore zone are plotted in Figure 58 (surface values) and Figure 60 (bottom values). March/April surface values (Fig. 59) peaked in 1973, followed by declining values to 1981-1983, when values were close to an appropriate goal of 6 μg P/L (0.6 times the total phosphorus goal of 10 μg P/L, based on the average ratio of soluble reactive phosphorus to total phosphorus in March/April in the early 1970s).

Total Phosphorus: Fluctuations and Trends in the Offshore Surface Waters, 1969 to 1982

Cruise mean values of total phosphorus in unfiltered samples and unweighted annual mean values of total phosphorus (Fig. 61) show considerable variability within each year. They declined after 1973 to values just above the goal of 10 μg P/L in March/April, which was proposed in the Great Lakes Research Advisory Board Annual Report (1978).

Remarks on External Phosphorus Loadings to Lake Ontario

Modern lake science holds that plankton populations in a lake respond to influxes of the nutrient that happens to be in shortest supply relative to the needs of the plankton. Often, the stock-limiting nutrient is phosphorus. Sometimes, it is nitrogen. Elsewhere, some new evidence confirming phosphorus limitation of plankton stocks in Lake Ontario will be presented (Dobson, 1984, in preparation).

The recent history of the external phosphorus loading gives a clue to likely trends in the lake's plankton abundance. Also, knowledge of the magnitudes of various components of the external loading at the onset of control programs provides insight into phosphorus-loading manageability.

Chapra (1977) published a reconstruction of external phosphorus loadings to Lake Ontario in the period 1800 to 1970. In 1970, about one half of the total loading was potentially controllable. The controllable fractions were those from detergents and from human wastes within the Lake Ontario basin, and some portion of the influx from Lake Erie if that lake were managed too.

Chapra (1980) showed that phosphorus loadings to Lake Ontario peaked in about 1972, declining thereafter by about 40% by 1978. (The external total phosphorus loading to Lake Ontario is difficult to measure, as indicated by disagreement between different estimates shown by Chapra [1980].)

The steady-state phosphorus "calibration curves" for Lake Ontario, according to a number of different workers, were published together in Chapra (1980). This is the within-lake concentration of total phosphorus versus the external phosphorus loading. The curve permits the estimation of the required external loading for any chosen concentration of total phosphorus within the lake. Theory to solve this relationship must account for sedimentation of planktonic phosphorus. The curves suggest that for Lake Ontario, a within-lake concentration of 10 μg P/L in March/April requires an external loading of about 6000 metric tons of phosphorus per year. The work of Chapra (1977) suggests that such a loading could be achieved at present population levels, given stringent controls of phosphorus in detergents and sewage outfalls, if such controls were applied in the Lake Erie basin as well as the Lake Ontario basin. Depending on future trends of population and technology, the phosphorus loading might rise again in future decades, despite control efforts.

Trend Analysis of Within-Lake Properties: Summer-Mean Secchi-Depth Transparencies, 1965 to 1982

The transparency of Lake Ontario's near-surface waters is probably influenced by the phytoplankton and, to an unknown extent, by suspensions of calcium carbonate precipitates induced by algal metabolism each spring and summer (Strong and Eadie, 1978). Recent limnological papers have emphasized that transparency is influenced by particle size (Lorenzen *et al.*, 1980) and zooplankton abundance (Edmondson and Litt, 1982).

In the offshore area of Lake Ontario, the summer mean Secchi depths were 3.8 m in 1965, 2.1 m in 1971 and 1972, 3.4 m in 1977, and 2.2 m in 1982 (Fig. 62). The conclusion must be drawn that transparency in summer has not followed the trend of March/April soluble reactive phosphorus (Fig. 59). However, the lake in summer would probably have been much less transparent than 2.2 m in 1982 without the phosphorus control program.

Fluctuations and Trends of Total Chlorophyll a in the Offshore Near-Surface Waters, 1967 to 1981

In the CCIW water quality surveys of Lake Ontario, the sampling scheme for particulate organic matter shifted from 1-m samples before 1972, to a number of discrete depths in 1972, and then to integrated 0 to 20-m samples in 1974 and thereafter. The changes in sampling strategy complicate the comparison of early and more recent chlorophyll values. Comparison of shallow and integrated chlorophyll data (presented later) is only possible with the data of 1972.

Cruise mean chlorophyll values over all the years of observation, for near-surface offshore waters (Fig. 63), had great seasonal variability with highest values in summer. Phaeopigments (degraded or inactive chlorophyll) were small fractions of the total chlorophyll.

For chlorophyll trend analysis, August and September in different years were compared (Fig. 64). July was avoided because of its extreme vertical stratification of chlorophyll, already shown (e.g., Fig. 41). The August/September mean values of 1967 to 1981 had only random fluctuations; thus there was no resolved trend. Chlorophyll values may have been too variable in the upper offshore waters each summer for any trend to be discerned.

Seasonal Cycles and Long-Term Trend of Nitrate + Nitrite in Surface and Bottom Waters

The sum nitrate + nitrite was measured, but nitrite was probably low. Nitrate + nitrite in Lake Ontario increased steadily from 1968 to 1981 (Figs. 65, 66 and 67). Values in surface waters in summer were very low, about 10 μg N/L, up to 1972, but in recent years there has been a residual nitrate + nitrite level of about 100 μg N/L. Nitrate + nitrite may have been co-limiting the plankton stocks in the earlier years, along with phosphorus, but in later years, excess nitrate + nitrite meant that phosphorus alone was the stock-limiting factor. Excess nitrate + nitrite in surface waters in summer will prevent the occurrence of troublesome nitrogen-fixing kinds of blue-green algae, and thus excess nitrogen together with phosphorus control measures may be considered beneficial. High phosphorus levels and medium or high nitrogen levels would make Lake Ontario over-productive of algae. Thus the phosphorus control measures should definitely be continued.

Nitrate + nitrite is increasing rapidly in the other Great Lakes, even in Lake Superior (Dobson, 1981; Bennett, 1982). Acid rain is probably a major source of nitrate to the Great Lakes (Bennett, 1982).

Near the bottom of Lake Ontario, seasonal fluctuations of nitrate + nitrite have been small (Fig. 67), whereas the fluctuations have been large in surface waters (Fig. 65).

Fluctuations and Trend of Ammonia

Ammonia data for offshore near-surface waters of Lake Ontario from 1969 to 1980 show a decline to extremely low values, below 5 μg N/L (Fig. 68). Explanations for the decline of ammonia seem to be speculative.

Summary of Trends of Total Inorganic Combined Nitrogen: Nitrate + Nitrite + Ammonia

The utilization of inorganic nitrogen (winter value minus summer value) remained fairly constant, whereas the values in winter and summer increased (Fig. 69).

Particulate Nitrogen: Seasonal Cycle and a Search for a Trend

Particulate nitrogen in offshore near-surface waters was the highest in summer (Fig.70). In recent years, the August/September mean values of particulate nitrogen in offshore near-surface waters remained fairly constant (Fig. 71). This is similar to summertime Secchi transparencies (Fig. 62) and chlorophyll in late summer (Fig. 64), but dissimilar to the declining values of soluble reactive phosphorus in March/April (Fig. 59). This enigma disturbs our belief that phosphorus might have controlled all of Lake Ontario's plankton stock indicators in a simple, direct manner.

Carbon Trends: Soluble Reactive Carbon Indicated by Alkalinity, and Particulate Organic Carbon

Alkalinity, mostly bicarbonate ion in Lake Ontario, was depleted only slightly in summer, relative to March/April (Fig. 72). In a measurement of alkalinity (a titration with strong acid), 1 mg $CaCO_3$/L is equivalent to 240 μg C/L as bicarbonate. Thus the levels of soluble reactive carbon in Lake Ontario are about 90 mg $CaCO_3$/L, which equals 90×240, or 22 000 μg C/L. With such an abundance of bicarbonate, the element carbon could not be limiting the plankton stocks in the lake.

Particulate organic carbon in the offshore upper waters in August/September declined steadily from 1975 to 1981, with a 20% reduction occurring (Fig. 73). Among the four plankton indicators—Secchi, chlorophyll, particulate nitrogen, particulate organic carbon—only carbon has responded like phosphorus. Perhaps zooplankton have contributed significantly to these particulate organic carbon values.

Soluble Reactive Silica: Seasonal Cycles and Trends in the Offshore Part of Lake Ontario

Soluble reactive silica values were low in near-surface waters in summer (Figs. 74 and 75). A silica shortage could be limiting the stocks of diatoms in summer, permitting other kinds of phytoplankton to replace diatoms in summer. Soluble reactive silica values increased in the bottom waters in summer (Fig. 76). This suggests that there was considerable internal loading, i.e., recycling, of silica: a cycle of uptake near the lake-surface, sedimentation of diatom frustules, and their dissolution near the bottom.

The March/April values in surface waters fluctuated in the years 1968 to 1982, but the August/September surface values were always low, near 100 μg SiO_2/L (Fig. 77). The external loadings of silica to Lake Ontario probably influence the species composition of the phytoplankton, but external silica loadings cannot be known except by more analytical study of tributary waters.

Dissolved Oxygen in the Main Basin of Lake Ontario: Seasonal Cycles and a Search for Long-Term Trends in the Deep Consumption

From 1966 to 1981, oxygen in the offshore upper waters followed a regular cycle in concentration values. Minimum values occurred in August and September, in the range of 9 to 11 mg/L (Fig. 78).

The seasonal cycle of oxygen concentrations, together with the cycle of surface temperatures (Fig. 56), produces a third, different cycle of the near-surface oxygen percent saturation values, with supersaturation of oxygen in June, July and August (Fig. 79)

Cruise mean values of oxygen percent saturation in offshore samples with temperatures from 10°C to 15°C, in many years, are plotted in Fig. 80. In late summer, these values were near 100% saturation, which suggests that the oxygen minimum layer found at a mid-lake station in September 1972 (Fig. 55) does not involve the whole thermocline, or might not occur every year. (See also Boyd [1980].)

"Deep water" is defined here as water colder than 4.0°C and not within 10 m of the lake bottom. The deep water in late summer from 1966 to 1978 had a mean depletion rate of about 1.0 mg/L every three months (Fig. 81).

Table 1. Dissolved Oxygen Depletion Rates in the Deep Water of Lake Ontario in Summer, 1966 to 1981

Year	Oxygen depletion rate (mg/L/3 months)
1966	0.7
1967	0.6
1968	1.3
1969	0.9
1970	0.9
1972	0.9
1974	1.0
1976	0.6
1977	0.9
1978	0.7
1979	1.4
1981	1.0
Range	0.6 to 1.4
Mean	0.9

Note: The temperature was $<4^\circ$C. The measurements were not taken within 10 m of the bottom. There was no apparent long-term trend.

The cold water within 10 m of the bottom often had lower oxygen values than the deep water above it (Fig. 82). Periods with the least hypolimnetic oxygen stratification were December/January and May/June, when temperatures very close to 4°C permitted overturning to the bottom. (Here oxygen is giving insight into a physical process.)

Oxygen depletion rates in the deep water in summer/autumn were derived graphically, as in Figure 83. From 1966 to 1981, there was no apparent long-term trend of the oxygen depletion rates (Table 1).

In summary, the main basin of Lake Ontario had excellent oxygen conditions throughout the first period of its cultural eutrophication.

Oxygen in the Bottom Water of Prince Edward Bay

Prince Edward Bay is located on the west side of Lake Ontario's Northeast Outlet Region (Fig. 2). Observations of dissolved oxygen near the bottom in Prince Edward Bay showed depletion in late summer down to 4 mg/L (Fig. 84). This region has some importance for commercial fishing, and the Bay's oxygen levels have approached critical levels for fish (Davis, 1975; Great Lakes Water Quality Board and Research Advisory Board, 1977). The sensitivity to seasonal oxygen depletion in this area is due to the narrowness of its bottom water layer, owing to the Bay's shallowness. This morphometric influence on oxygen is similar to that of central Lake Erie (Charlton, 1980; Chapra and Dobson, 1981).

VERTICALLY INTEGRATED SAMPLING

In the CCIW observational data sets for particulate organic matter in Lake Ontario, three observational strategies were used: 1967 to 1971, samples from 1-m depth; 1972 only, samples from many discrete depths; and 1974 to 1982, vertically integrated samples in the interval 0 to 20 m. The detailed sampling of 1972 permits a study comparing the earlier and later strategies.

Two chlorophyll values at each station are compared: a 1-m value and a numerically integrated 0 to 20-m value derived from contoured transverse vertical sections with observations from many discrete depths. The locations of the sections are shown in Figures 19 and 39.

In the three sections near June 21, 1972, the integrated values were most often slightly lower than the 1-m values in the nearshore, with one exception, the north end of section "B" (Figs. 85 to 87).

Near July 20, 1972, integrated chlorophyll values were much lower than the 1-m values at the southernmost stations, but integrated values were much higher than 1-m values at offshore stations (Figs. 88 to 90). Near July 20, 1972, at all stations on the three sections, the grand mean integrated value was 8.9 µg/L, and the grand mean 1-m value was 3.9 µg/L.

Near September 7, 1972, integrated values were lower than 1-m values at all the stations (Figs. 91 to 93). The grand mean values were the following: integrated, 4.9 µg/L; 1 m, 6.8 µg/L.

Clearly, the earlier and later data cannot easily be compared to derive long-term trends for particulate organic matter. The most adequate sampling strategy is the one used in 1972, which reveals the vertical structure of the population of plankton, and for which the values at any depth, and numerically integrated values, can all be known.

In the Annual Report of the International Joint Commission on Great Lakes Water Quality, 1974, the following was stated: "The ultimate assessment of the effectiveness of phosphorus reduction programs must be made in terms of the changes in algal biomass in the Great Lakes." With inadequate sampling of the plankton, such changes will be poorly detected.

SIGNIFICANCE AND TRENDS OF MAJOR IONS, 1906 TO 1981

At the concentrations found in Lake Ontario, the major ions probably have a negligible influence on the abundance and species composition of the plankton, which are more likely affected by the principal limiting nutrients P, N, and Si, and perhaps microconstituents (nutrients and contaminants), in addition to the influences of grazing and physical processes. Beeton (1965) used major ions to "indicate" eutrophication, but probably there is no causative relationship.

In Lake Ontario, the small spatial variability of major ions is difficult to measure. Surface waters in summer have slightly lowered values of calcium and alkalinity. Major ions data for the period 1906 to 1966 were published in detail earlier (Dobson, 1967). In Figure 94, the mean values in different early years are from Dobson (1967), and the more recent data are late-winter mean values in offshore waters, from the CCIW data files.

Bicarbonate, magnesium and potassium have remained constant over the years, within measurement resolution

(Fig. 94). The other four major ions have increased since 1906; calcium by 30%; sulphate by 110%; chloride by 250%; and sodium by 160%. Chloride, sulphate and perhaps calcium decreased slightly in the late 1970s.

The sum of the seven major ions in Lake Ontario in 1981 was 230 mg/L. Mean seawater has a salinity of 34.7 mg/g and a density of 1.026 g/mL, giving a total salt content of 35 600 mg/L. Thus Lake Ontario in 1981 had a salt content which was 230/35 600 = 0.0065 = 0.65% of the salt content of mean seawater.

TRACE CHEMICAL CONSTITUENTS

Median values for ten elements in the offshore part of Lake Ontario in the 1970s are compiled in Table 2, with percentages of the maximum values accepted for drinking by humans, the latter taken from Guidelines for Canadian Drinking Water Quality, published by the Department of National Health and Welfare (1978). Although the study of metals and organic contaminants in Lake Ontario waters, colloids and biota, and their biological effects may be very difficult, clearly more work could be done to learn their vertical distributions, seasonal cycles and levels in the biota.

CONCLUSIONS

Phosphorus levels in Lake Ontario are now (1982) almost at the target established for the Great Lakes Water Quality Agreement. This is the result of the phosphorus control program for the Lake Erie and Lake Ontario basins.

Excess nitrate + nitrite in surface waters of Lake Ontario in August and September, amounting to about 100 µg N/L, is judged to be beneficial and, along with control of phosphorus, serves to prevent noxious blue-green algal blooms.

Dissolved oxygen in the main basin of Lake Ontario remained abundant throughout the first period of the lake's cultural eutrophication during the 1970s, which indicates that future limited eutrophication of this lake, even if it occurs, will produce the problem of overabundant phytoplankton and shore-algae without endangering the oxygen regime.

Given the three points mentioned above, the open waters of Lake Ontario seem to be in healthy condition in their nutrient-related aspects. The governments and the public should be satisfied in their roles as the lake's users and caretakers, who deliberately and wisely chose to control phosphorus. However, there may be continuing growth of shore-algae (*Cladophora*) and some taste and odour problems with the drinking water which perhaps cannot be totally prevented.

Phosphorus loading controls should continue in the Lake Erie and Lake Ontario basins. The two control measures (use of household detergents low in phosphorus, and chemical precipitation of phosphorus at municipal sewage treatment plants) should continue to prevent catastrophic eutrophication from the still-rising human population. As Lake Ontario will have abundant nitrate from now on, eutrophication must definitely be suppressed via phosphorus controls.

Table 2. Median Values of Trace Constituents in the Offshore Part of Lake Ontario in the 1970s

Constituent	Median values (µg/L) Dissolved	Total	Percent of maximum value acceptable for drinking
Aluminum		5.0	
Arsenic		0.7	1.4
Boron		19.0	0.4
Copper	2.6		0.3
Fluoride (1968)	120.0		8.0
Iron	1.8	10.8	4.0
Iron (acid-digested)	4.2		
Lithium	1.6		
Manganese	0.5	1.2	2.4
Strontium	180.0		
Zinc	7.6		0.15

CCIW data.

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REFERENCES

Allan, R.J. *et al*. 1983. The Niagara River-Lake Ontario pollution problem. J. Great Lakes Res. 9(2): 109-340.

Allen, E.R. 1977. *Lake Ontario Atlas: Chemistry*. New York State Sea Grant Institute, State University of New York, Albany, 101 pp., 91 figs.

Aspila, K.I., R.E. White and J.L. Clark. 1983. Interlaboratory quality assurance aspects of the International Joint Commission's Great Lakes monitoring programs. Paper presented at the Conference on Quality Assurance for Environmental Measurements, Boulder, Colorado, August 8-12, 1983. To appear in an ASTM Special Technical Publication.

Beeton, A.M. 1965. Eutrophication of the St. Lawrence Great Lakes. Limnol. Oceanogr. 10(2): 240-254.

Bennett, E.B. 1982. The nitrifying of Lake Superior, 1880-2000. Canada Centre for Inland Waters, Bayfield Laboratory, Manuscript Rep. No. 13, 26 pp.

Boyd, J.D. 1980. Metalimnetic oxygen minima in Lake Ontario, 1972. J. Great Lake Res. 6(2): 95-100.

Carew, T.J. and D.J. Williams. 1975. Surveillance Methodology—1974. Tech. Bull. No. 92, Inland Waters Directorate, Environment Canada, Burlington, Ontario, 28 pp.

CCIW. 1982. STAR Dictionary of Parameter Codes and Methods. National Water Research Institute, Data Management Group, Burlington, Ontario.

Chapra, S.C. 1977. Total phosphorus model for the Great Lakes. Proc. Am. Soc. Civ. Eng., J. Environ. Eng. Div. 103(EE2): 147-161.

Chapra, S.C. 1980. Simulation of recent and projected total phosphorus trends in Lake Ontario. J. Great Lakes Res. 6(2): 101-112.

Chapra, S.C. and H.F.H. Dobson. 1981. Quantification of the lake trophic typologies of Naumann (surface quality) and Thienemann (oxygen) with special reference to the Great Lakes. J. Great Lakes Res., 7(2): 182-193.

Charlton, M.N. 1980. Hypolimnion oxygen consumption in lakes: discussion of productivity and morphometry effects. Can. J. Fish. Aquat. Sci. 37(10): 1531-1539.

Chawla, V.K. and W.J. Traversy. 1968. Methods of analyses on Great Lakes waters. Proc. 11th Conf. on Great Lakes Res., pp. 524-530.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Board Can. 32(12): 2295-2332.

Department of National Health and Welfare. 1978. Guidelines for Canadian Drinking Water Quality, with supporting documentation. Ottawa, 816 pp.

Dobson, H.F.H. 1967. Principal ions and dissolved oxygen in Lake Ontario. Proc. 10th Conf. on Great Lakes Res., pp. 337-356.

Dobson, H.F.H. 1981. Trophic conditions and trends in the Laurentian Great Lakes. W.H.O. Water Qual. Bull. 6(4): 146-151, 158, and 160.

Dobson, H.F.H. 1984. Diagnosis of nutrient limitation of plankton stocks: the "nutrient % utilization" index. In preparation.

Edmondson, W.T. and A.H. Litt. 1982. *Daphnia* in Lake Washington. Limnol. Oceanogr. 27(2): 272-293.

Environment Canada. 1983. Sampling for Water Quality. Water Quality Branch, Inland Waters Directorate, Ottawa, 55 pp.

Great Lakes Research Advisory Board. 1978. Annual Report to the International Joint Commission, July 1978. Contains proposed goals for the phosphorus concentration and related properties in each Great Lake.

Great Lakes Water Quality Board and Research Advisory Board. 1977. Annual Report of the Water Quality Objectives Subcommittee and the Task Force on the Scientific Basis for Water Quality Criteria, June 1977. Contains recommended objectives for dissolved oxygen in Great Lakes waters, pp. 11-27.

Kwiatkowski, R.E. and M.A.T. Neilson. 1983. Lake Ontario Surveillance Data, 1968-1980. Tech. Bull. No. 126, Inland Waters Directorate, Environment Canada, Ottawa, 69 pp.

Lorenzen, M.W., R.O. Megard, J.C. Settles, H.A. Boyer, W.S. Combs, W.T. Edmondson and R.E. Carlsen. 1980. Four related articles on Secchi transparency. Limnol. Oceanogr. 25(2): 371-382.

Munawar, M. and A. Nauwerck. 1971. The composition and horizontal distribution of phytoplankton in Lake Ontario during the year 1970. Proc. 14th Conf. Great Lakes Res., pp. 69-78.

Ontario Ministry of the Environment. 1980. Lake Ontario Nearshore Water Quality Atlas 1976 to 1979. Water Resources Branch.

Philbert, F.J. 1973. The effect of sample preservation by freezing prior to chemical analysis of Great Lakes waters. Proc. 16th Conf. Great Lakes Res., pp. 282-293.

Philbert, F.J., O. El-Kei, W.D. Blythe and T.M. Sheikh. 1975. Applicability of the Technicon AutoAnalyzer I and II systems for shipboard analysis of Great Lakes water samples. Tech. Bull. No. 93, Inland Waters Directorate, Environment Canada, Burlington, Ontario, 10 pp.

Philbert, F.J. and W.J. Traversy. 1973. Methods of sample treatment and analysis of Great Lakes water and precipitation samples. Proc. 16th Conf. Great Lakes Res., pp. 294-308.

Pickard, G.L. 1963. Some trends in physical oceanography. Proc. 6th Conf. Great Lakes Res., pp. 1-8.

Russell-Hunter, W.D. 1970. *Aquatic Productivity: An Introduction to Some Basic Aspects of Biological Oceanography and Limnology*. The Macmillan Company, New York, 306 pp.

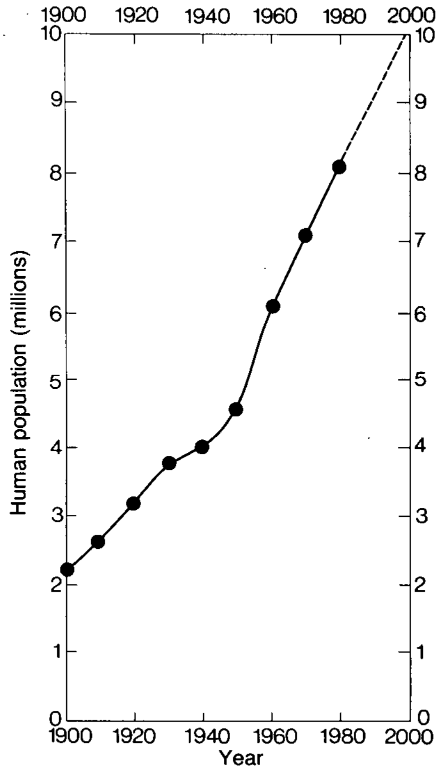
Sandilands, R.G. and A. Mudroch. 1983. Nepheloid layer in Lake Ontario. J. Great Lakes Res. 9(2): 190-200.

Schelske, C.L. and E.F. Stoermer. 1971. Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. Science, 173:423-424.

Strachan, W.M.J. 1973. A statistical examination of Great Lakes

chemical monitor data at Canada Centre for Inland Waters. Proc. 16th Conf. Great Lakes Res., pp. 949–957.
Strong, A.E. and B.J. Eadie. 1978. Satellite observations of calcium carbonate precipitations in the Great Lakes. Limnol. Oceanogr. 23(5): 877–887.
Traversy, W.J. 1971. Methods for Chemical Analysis of Waters and Wastewaters. Water Quality Division, Inland Waters Branch, Department of Fisheries and Forestry, Ottawa, 169 pp.

Figures 1 to 94



← **Figure 1. Lake Ontario, human population, 1900 to 2000 A.D. (Lake Ontario basin and city of Buffalo).**

Figure 2. Lake Ontario, depth contours in metres.
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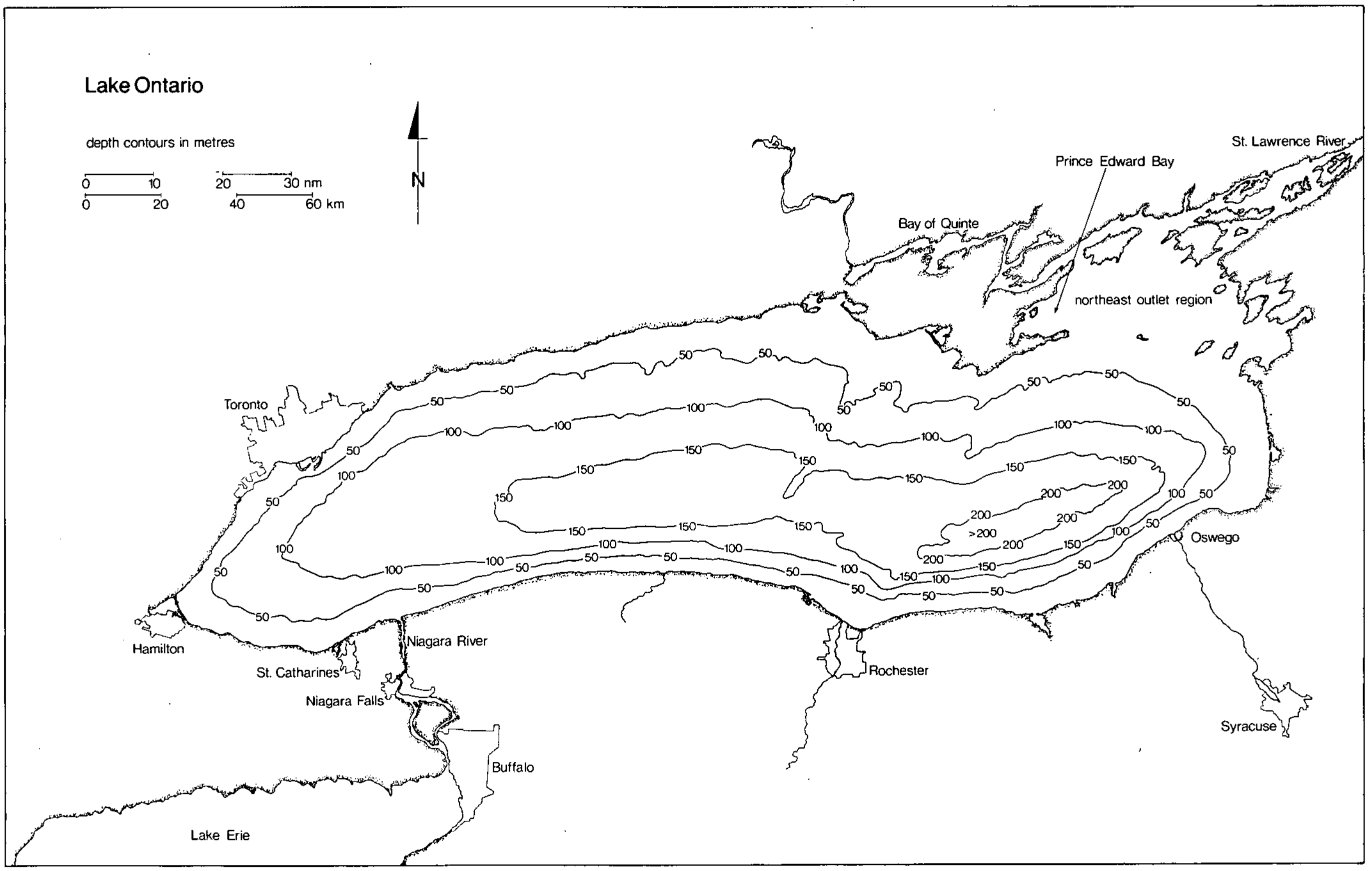
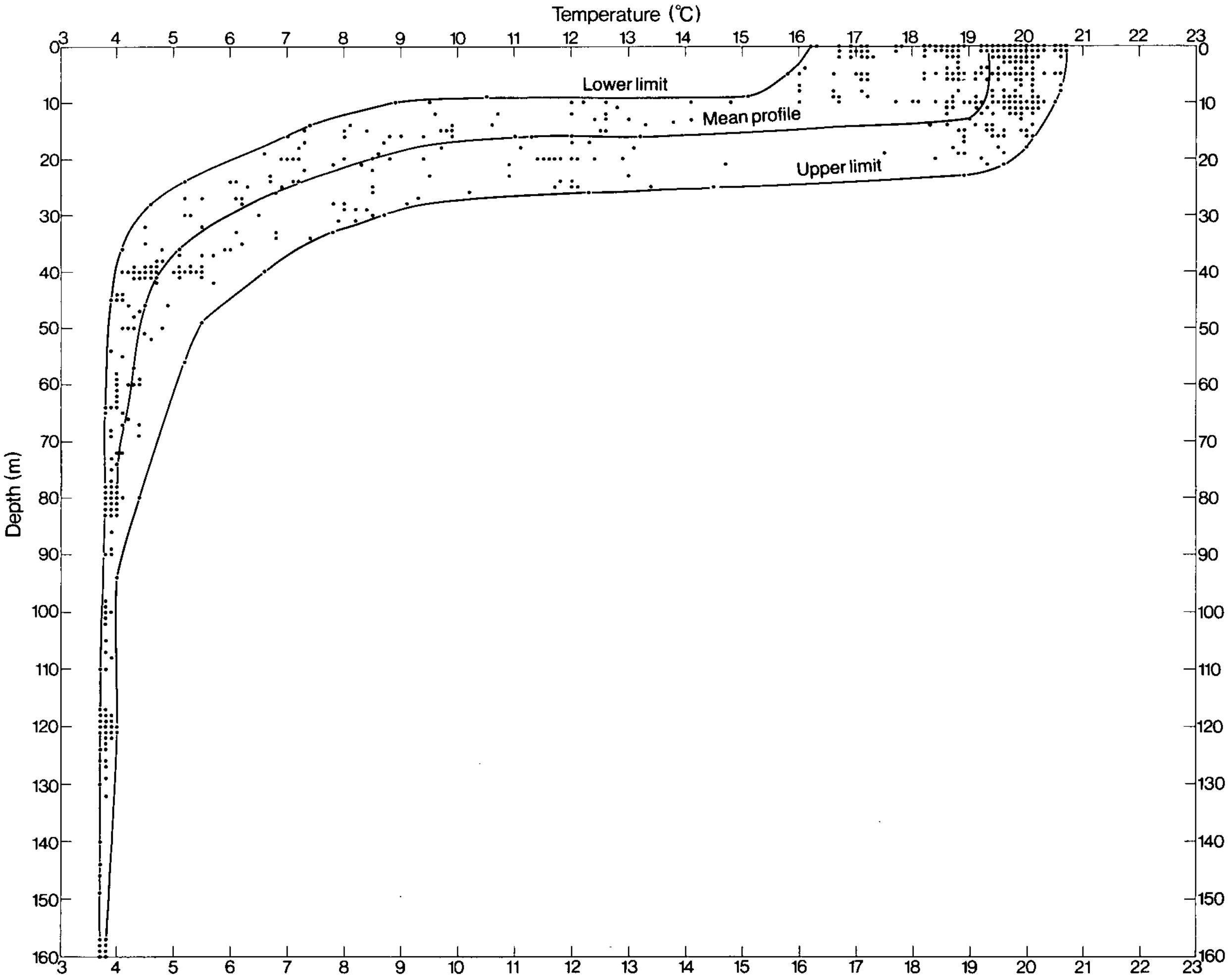




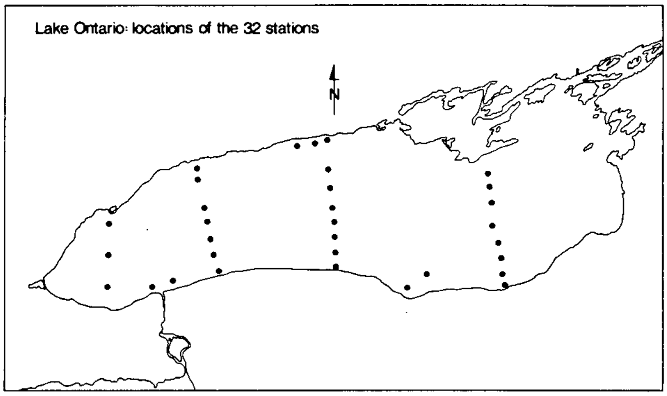


Figure 3. Temperatures versus depth at 32 stations, September 5 to 11, 1972. The *Martin Karlsen*.

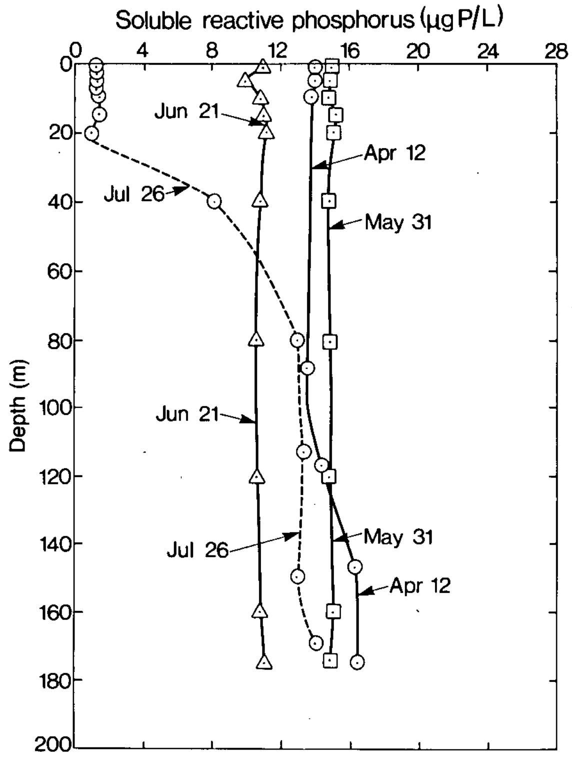


Figure 4. Soluble reactive phosphorus at a mid-lake station in 1972. The *Martin Karlsen*.

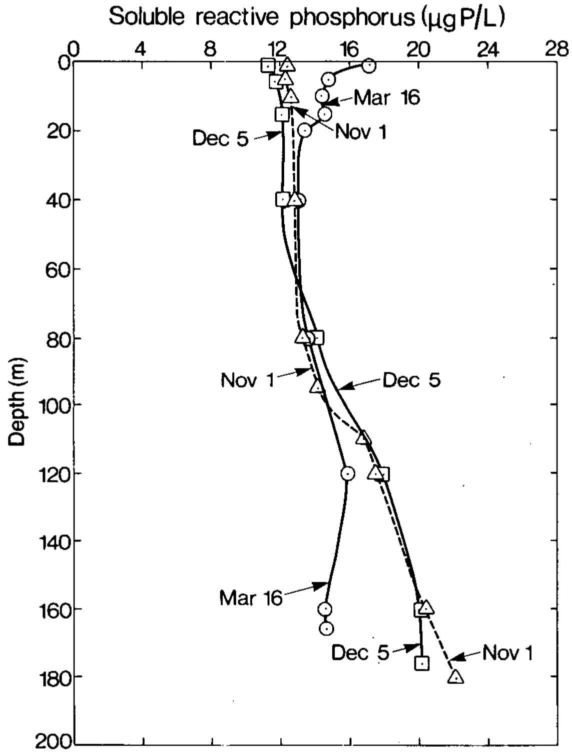


Figure 6. Soluble reactive phosphorus at a mid-lake station in 1973. The *Martin Karlsen*.

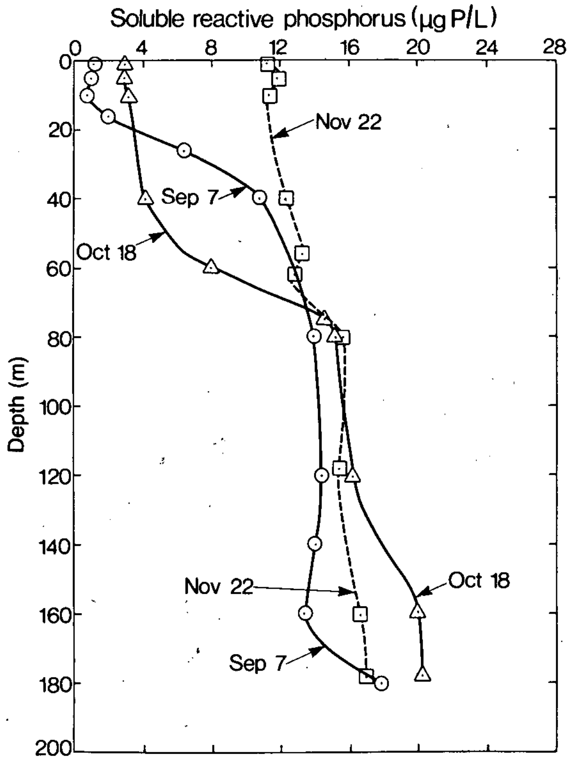


Figure 5. Soluble reactive phosphorus at a mid-lake station in late 1972. The *Martin Karlsen*.

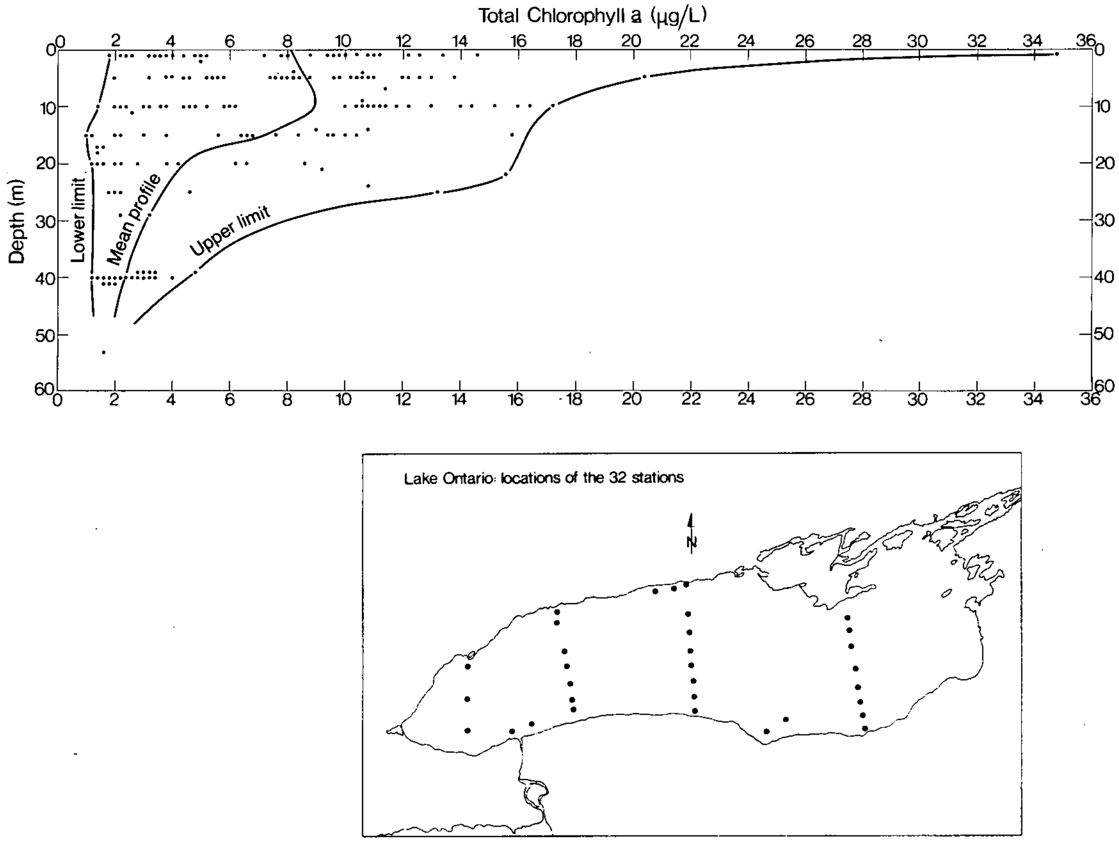


Figure 7. Total chlorophyll *a* versus depth at 32 stations, July 17 to 21, 1972. The *Martin Karlsen*.

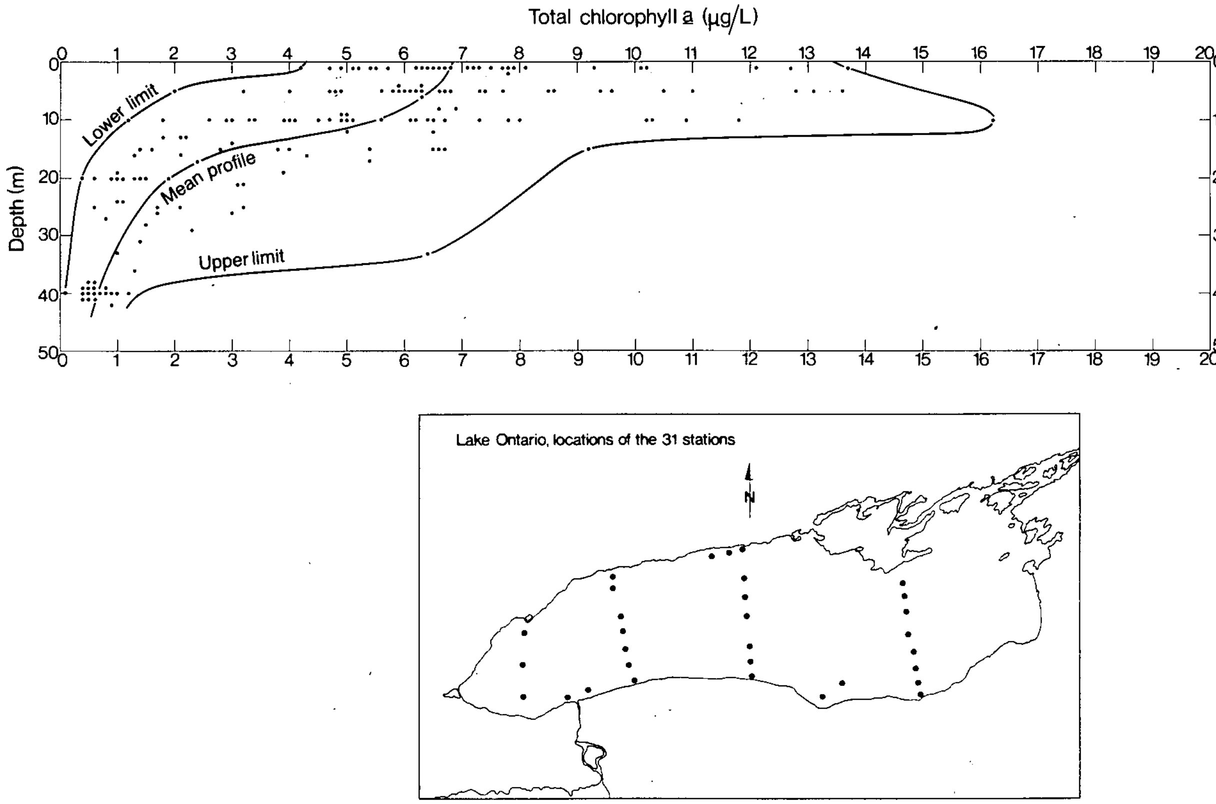


Figure 8. Total chlorophyll *a* versus depth at 31 stations, September 5 to 9, 1972. The *Martin Karlsen*.

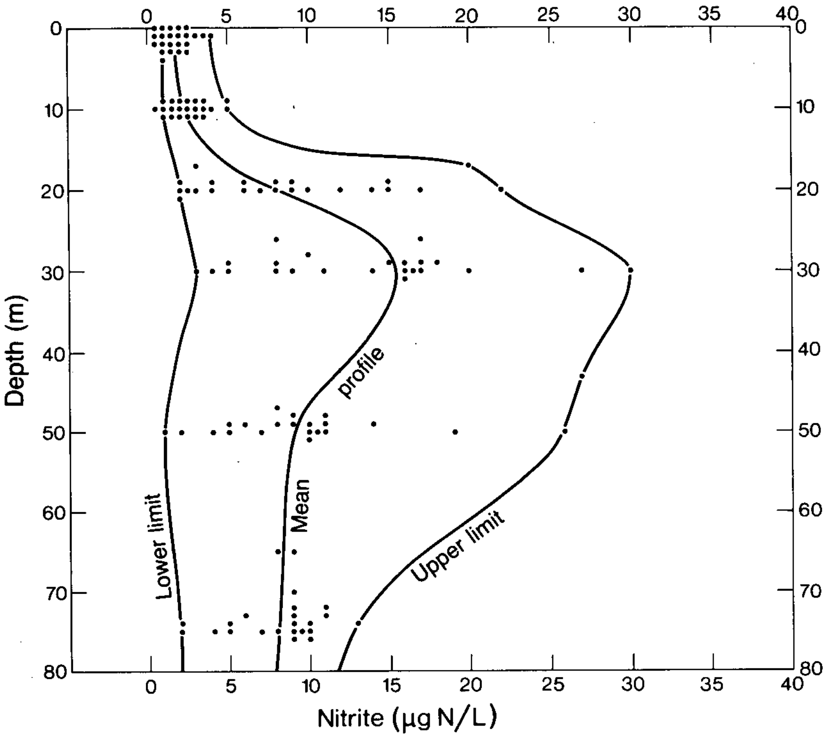


Figure 9. Nitrite versus depth at offshore stations with soundings >100 m, August 15 to 19, 1966. The *Brandal.*

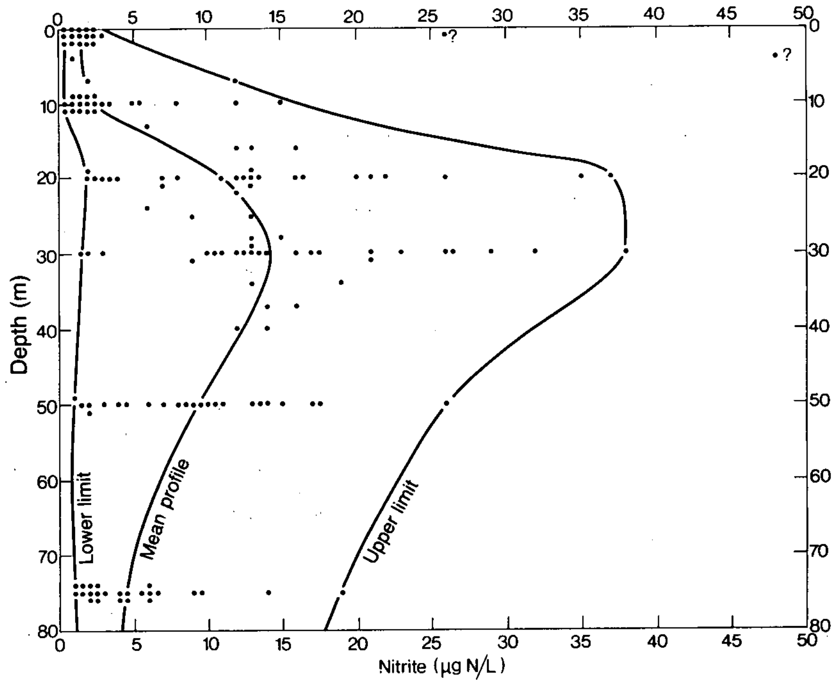


Figure 10. Nitrite versus depth at offshore stations with soundings >100 m, August 6 to 8, 1967. The *Theron.*

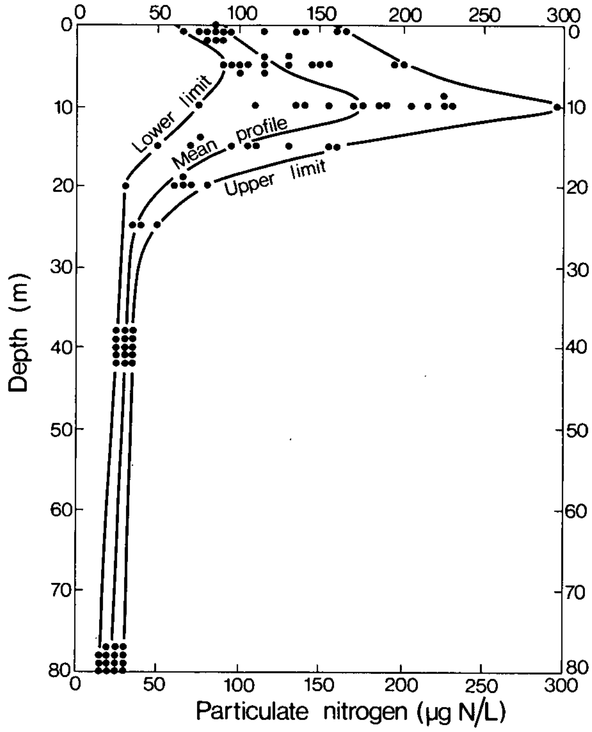


Figure 11. Particulate nitrogen at offshore stations with soundings >100 m, July 17 to 21, 1972. The *Martin Karlsen*.

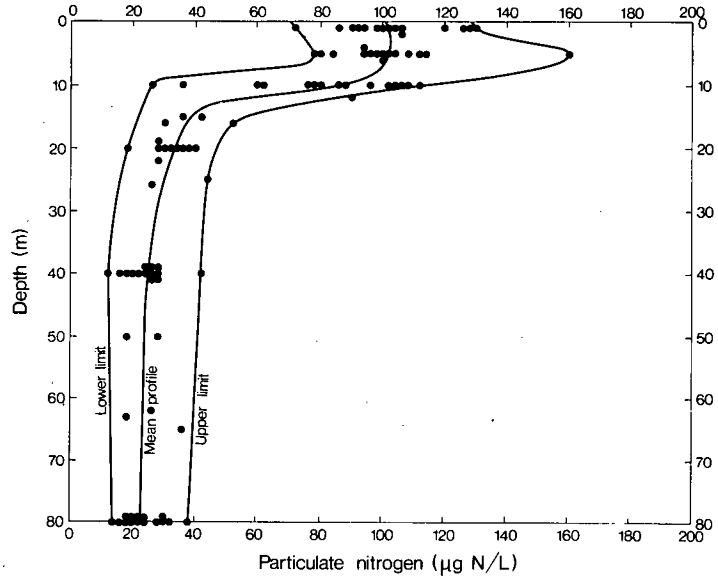


Figure 12. Particulate nitrogen at offshore stations with soundings > 100 m, September 5 to 9, 1972. The *Martin Karlsen*.

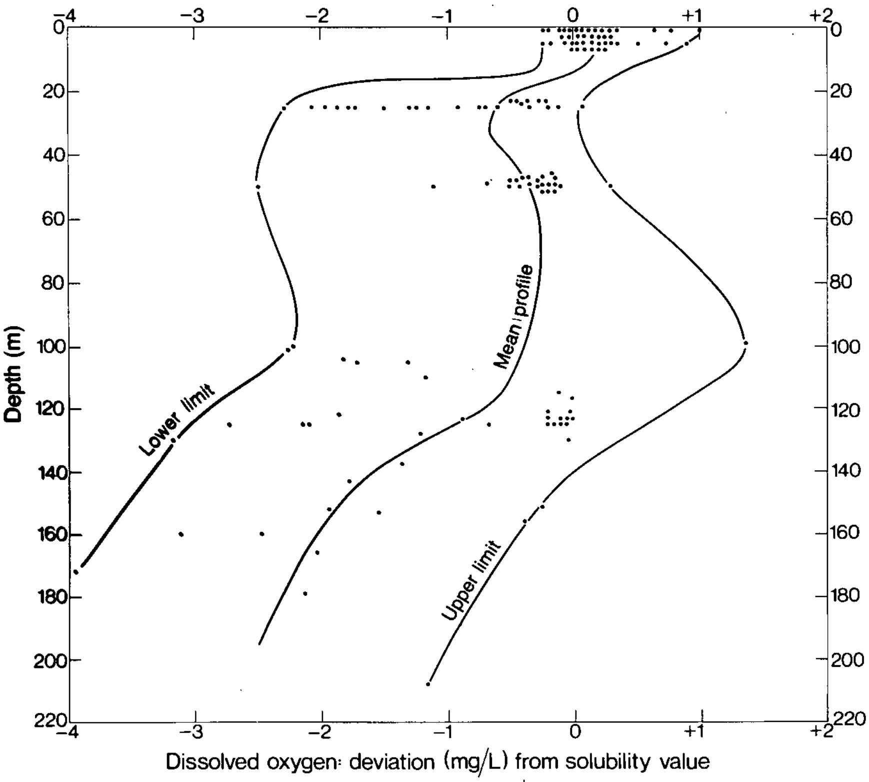


Figure 13. Dissolved oxygen deviations (mg/L) from solubility values versus depth at 24 offshore stations with soundings >100 m, September 15 to 19, 1970. The *Martin Karlsen.*

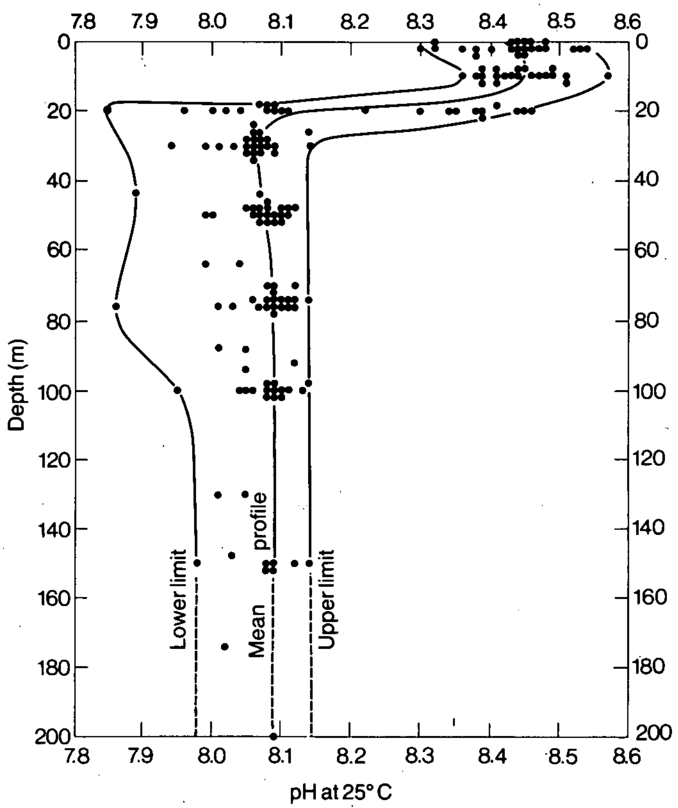


Figure 14. pH measured at 25°C versus depth at offshore stations with soundings >100 m, September 13 to 16, 1966. The *Brandal.*

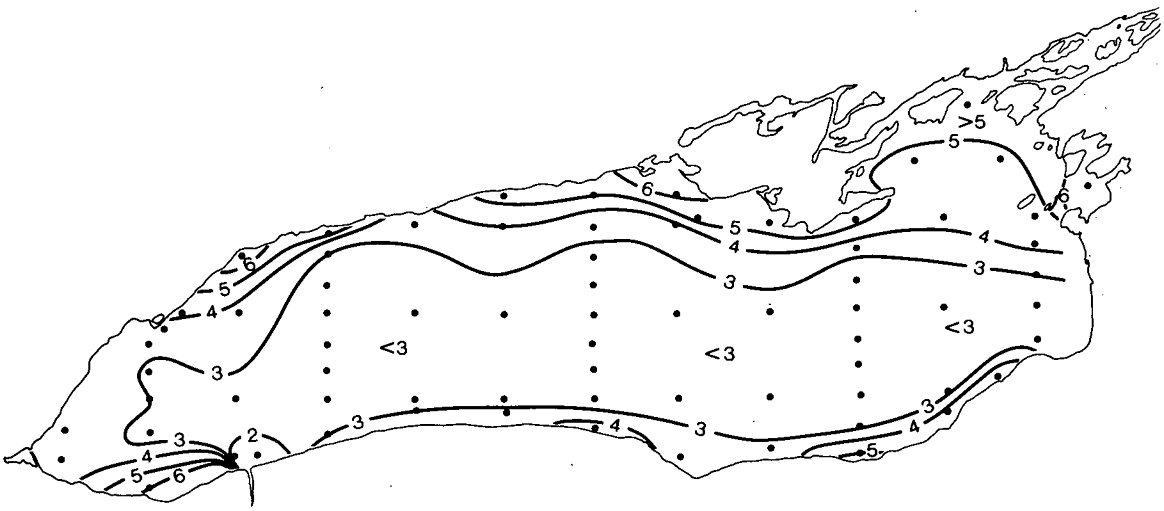
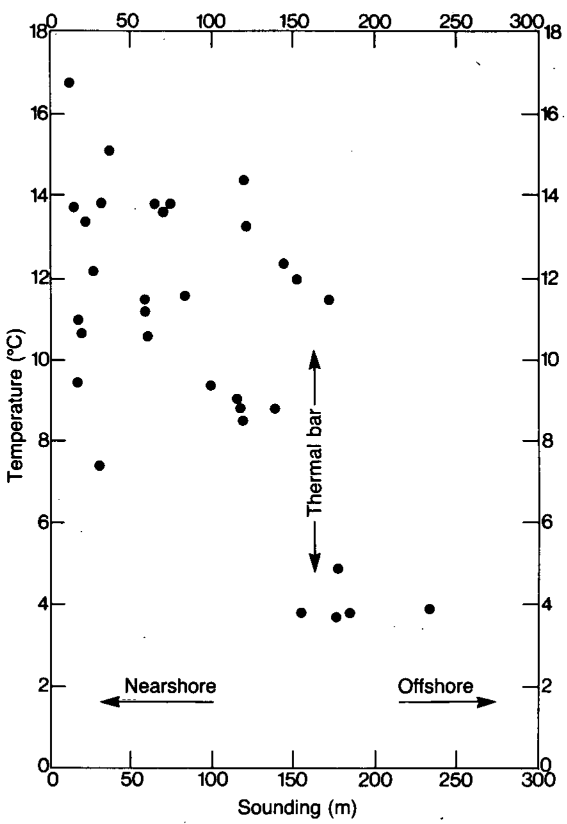


Figure 15. Temperatures (°C) at a depth of 1 m, April 29 to May 3, 1968. The *Theron.*



← Figure 16. Temperature at 1-m depth versus the sounding at the same station, June 19 to 23, 1972. The *Martin Karlsen.*

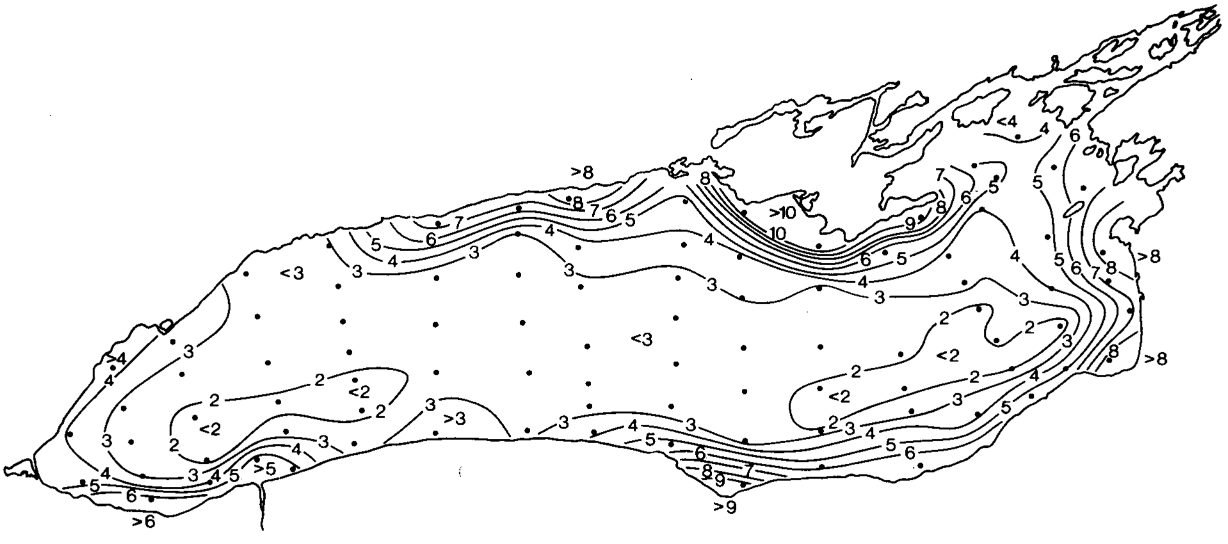


Figure 17. Total chlorophyll *a* (µg/L) at a depth of 0 m, April 4 to 8, 1972. The *Limnos* and *Porte Dauphine.*

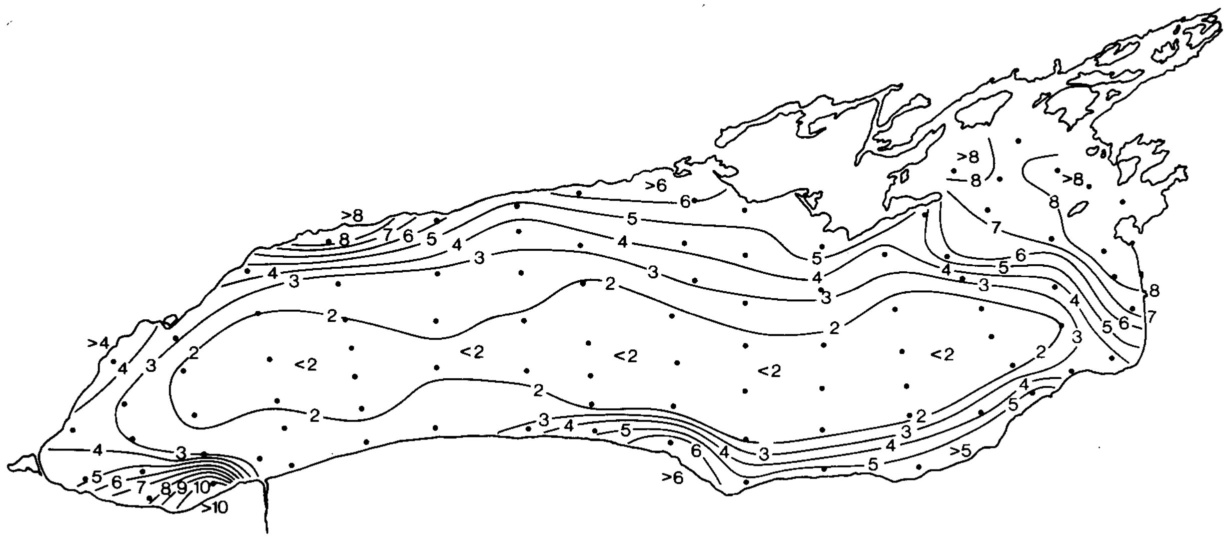


Figure 18. Total chlorophyll *a* (µg/L) at a depth of 0 m, May 1 to 3, 1972. The *Limnos* and *Porte Dauphine.*

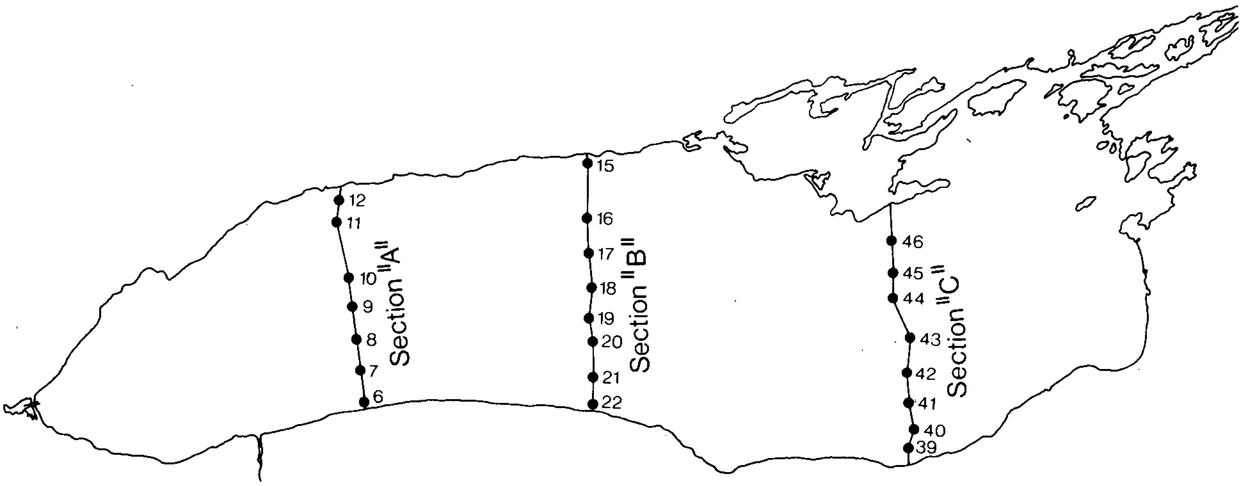


Figure 19. Locations of the three transverse sections and consecutive station numbers in Lake Ontario, June 20 to 23, 1972. The *Martin Karlsen.*

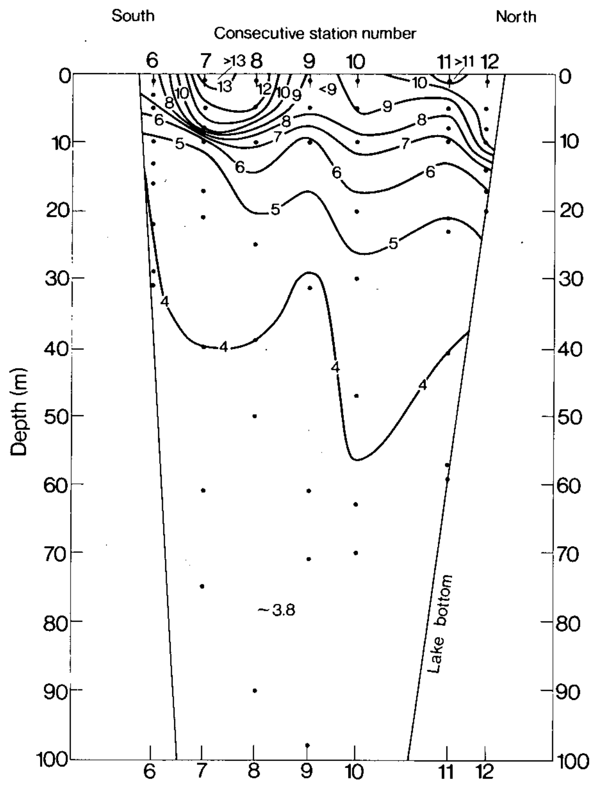


Figure 20. Temperatures (°C) in transverse section "A", June 20, 1972. The *Martin Karlsen*.

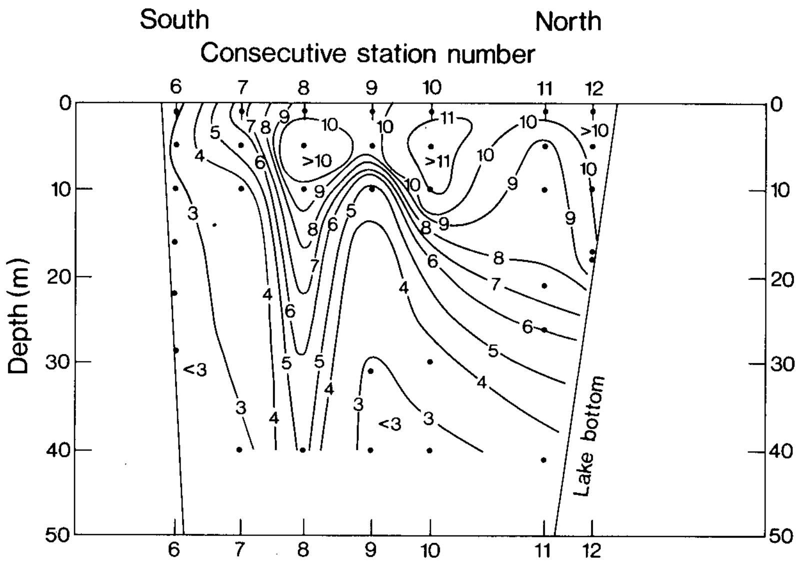


Figure 21. Total chlorophyll *a* (μg/L) in transverse section "A", June 20, 1972. The *Martin Karlsen*.

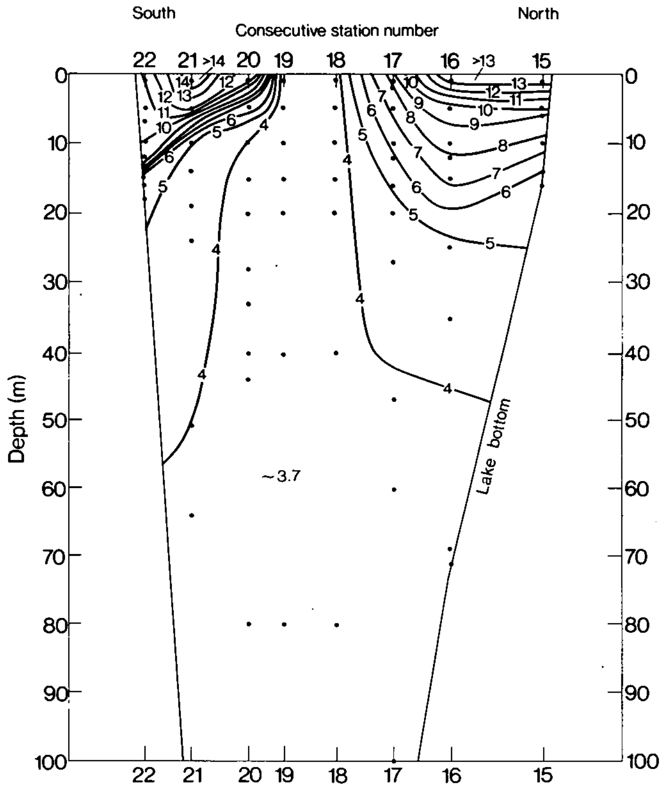


Figure 22. Temperatures (°C) in transverse section "B", June 20 and 21, 1972. The *Martin Karlsen.*

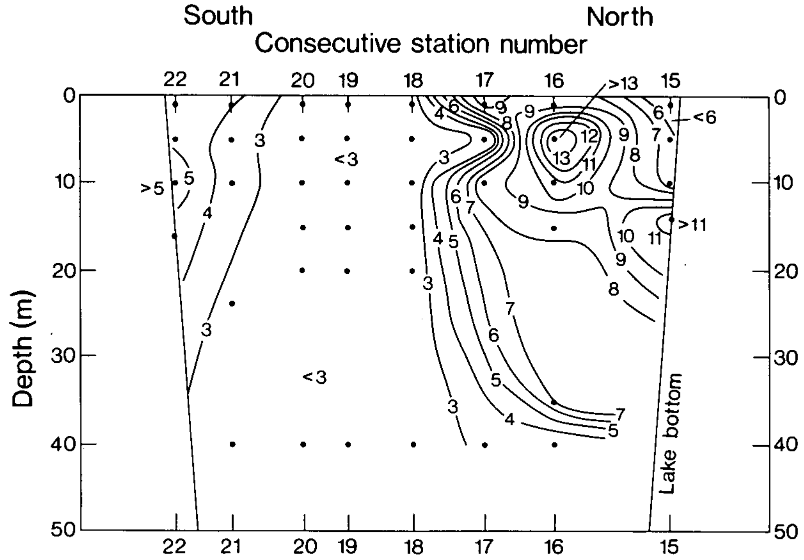


Figure 23. Total chlorophyll *a* (μg/L) in transverse section "B", June 20 and 21, 1972. The *Martin Karlsen.*

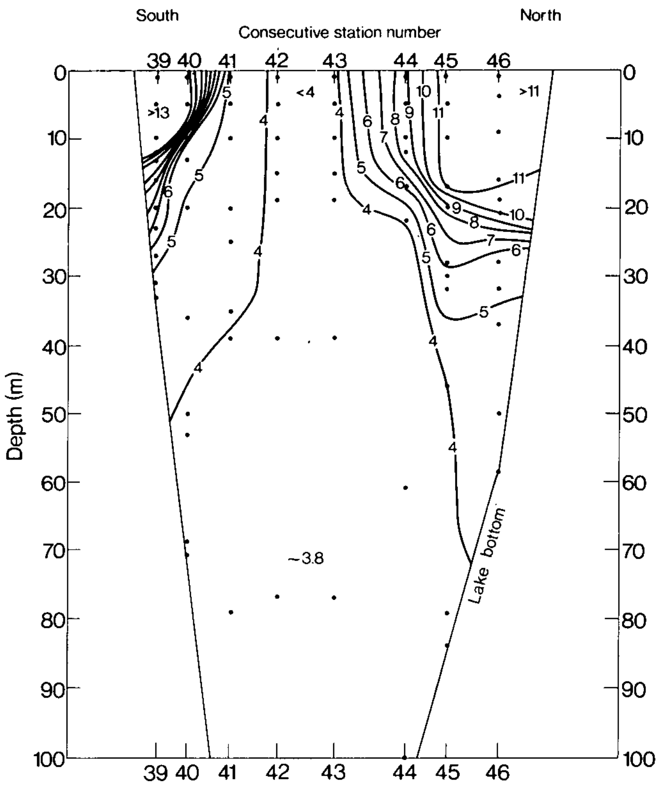


Figure 24. Temperatures (°C) in transverse section "C", June 22 and 23, 1972. The *Martin Karlsen.*

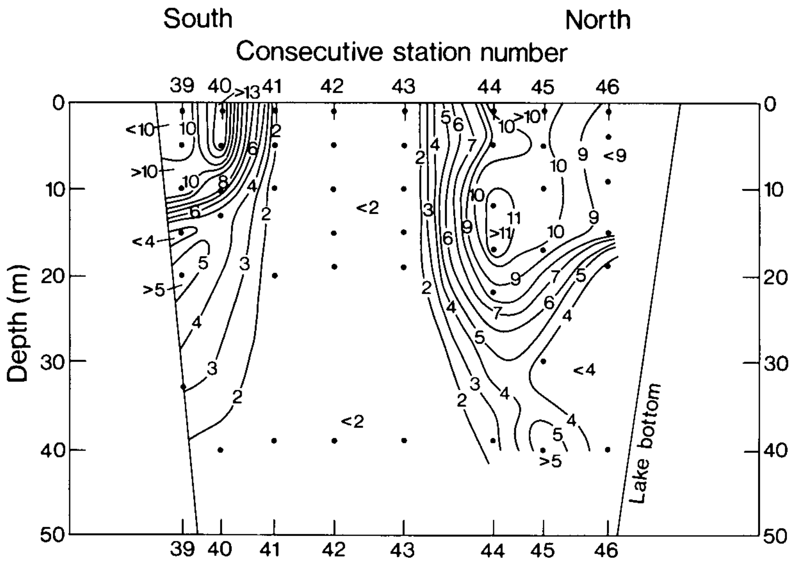


Figure 25. Total chlorophyll *a* (μg/L) in transverse section "C", June 22 and 23, 1972. The *Martin Karlsen.*

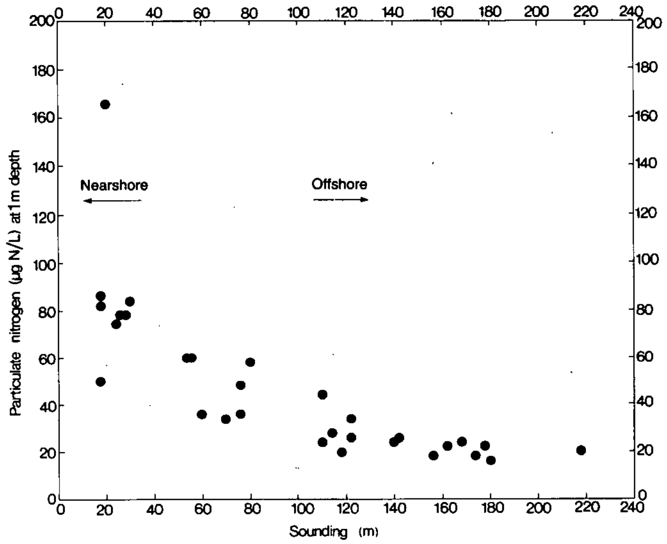


Figure 26. **Particulate nitrogen at 1-m depth versus the sounding at the same station, May 23 to 29, 1972. The *Martin Karlsen*.**

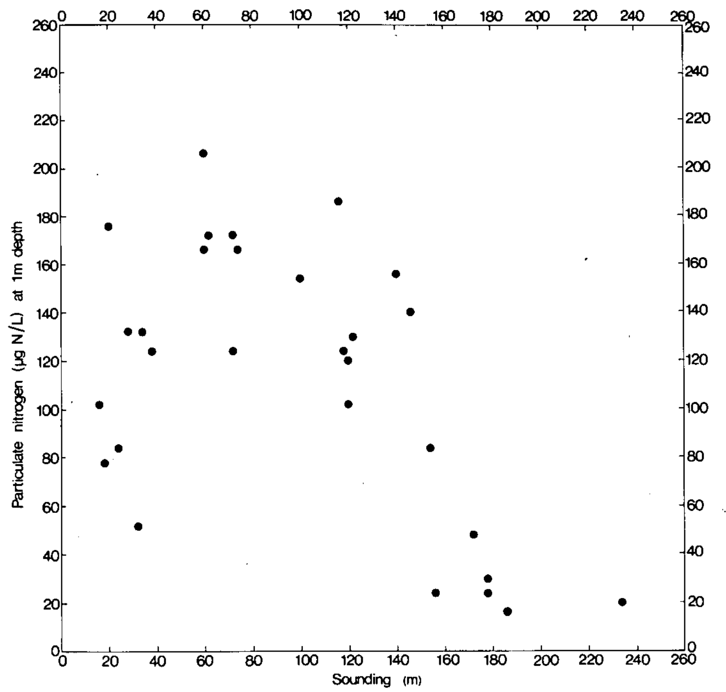


Figure 27. **Particulate nitrogen at 1-m depth versus the sounding at the same station, June 19 to 23, 1972. The *Martin Karlsen*.**

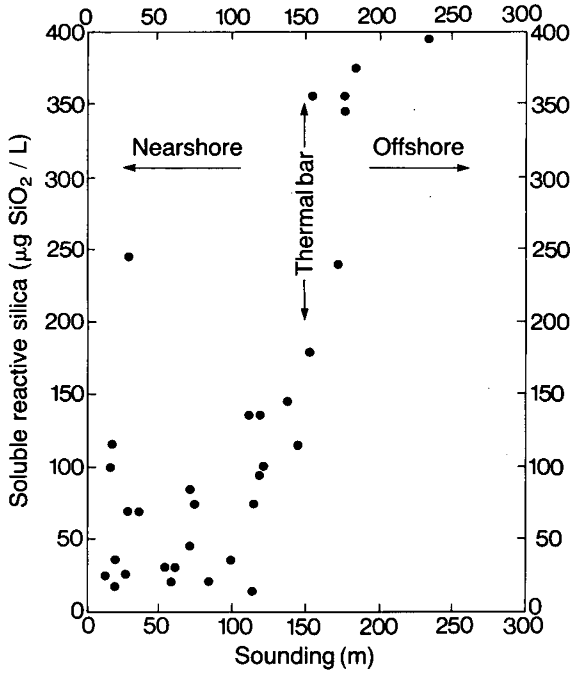


Figure 28. Soluble reactive silica at 1-m depth versus the sounding at the same station, June 19 to 23, 1972. The *Martin Karlsen.*

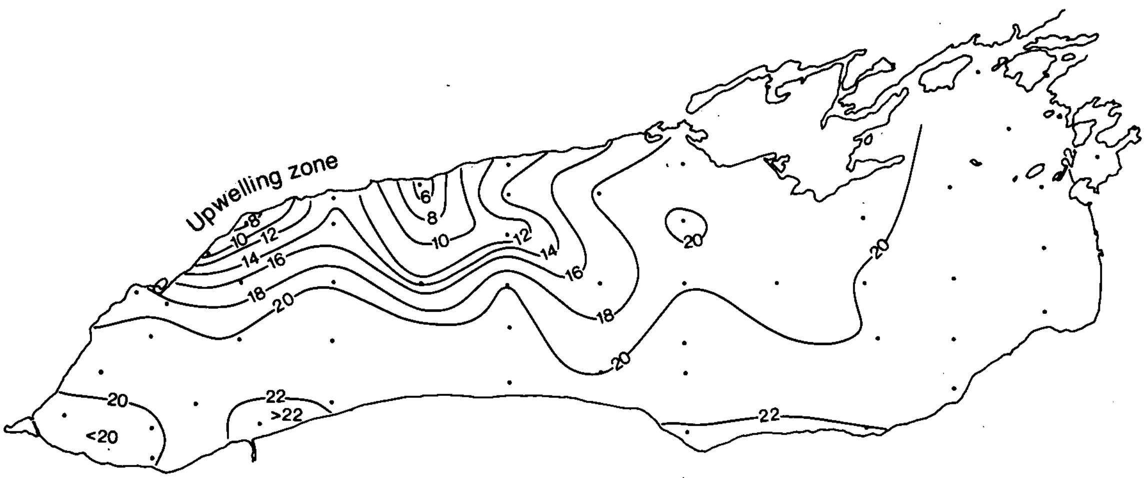


Figure 29. Temperatures (°C) at a depth of 1 m, August 9 to 13, 1971. The *Martin Karlsen.*

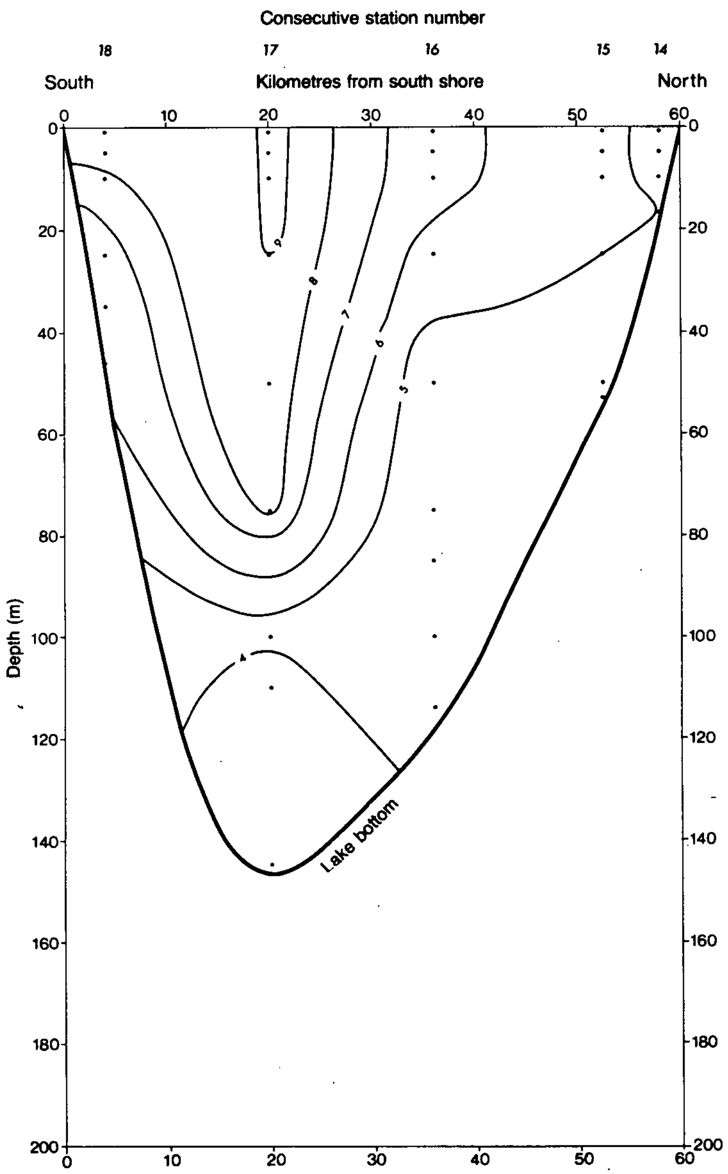


Figure 30. Temperatures (°C) in a transverse section from Oshawa, southward, November 16, 1971. The *Martin Karlsen*.

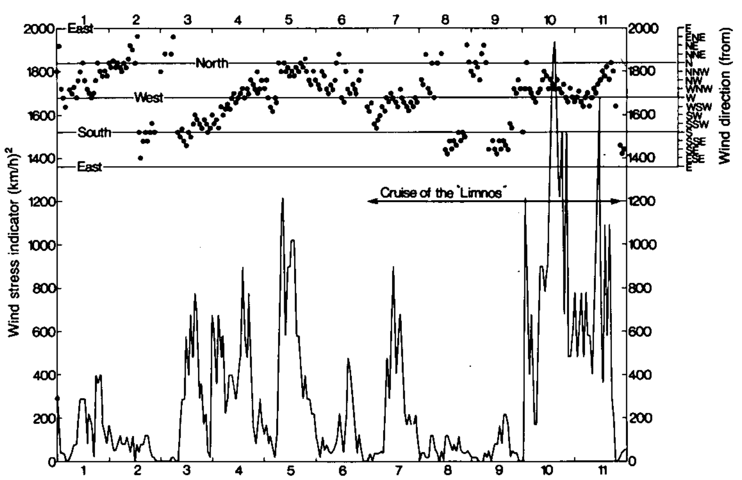


Figure 31. Winds at Toronto International Airport, September 1 to 11, 1976.

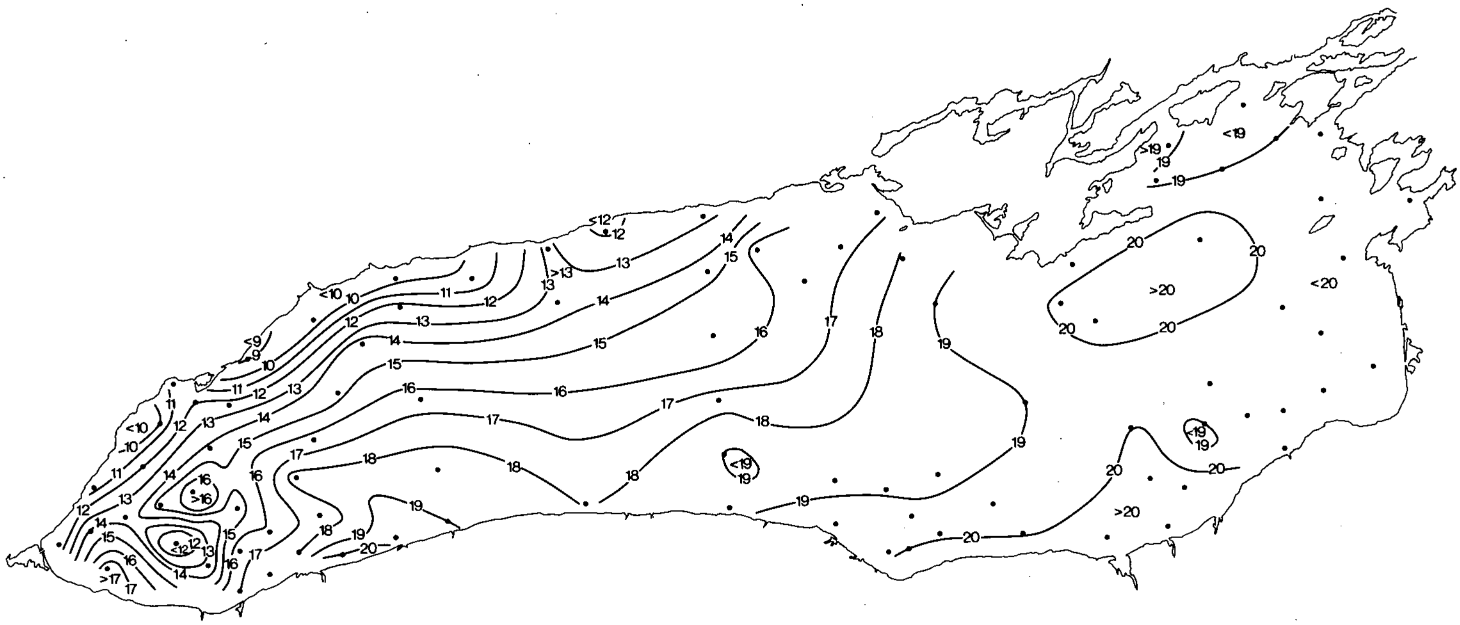


Figure 32. Temperatures (°C) at a depth of 0 m, September 7 to 11, 1976. The *Limnos.*

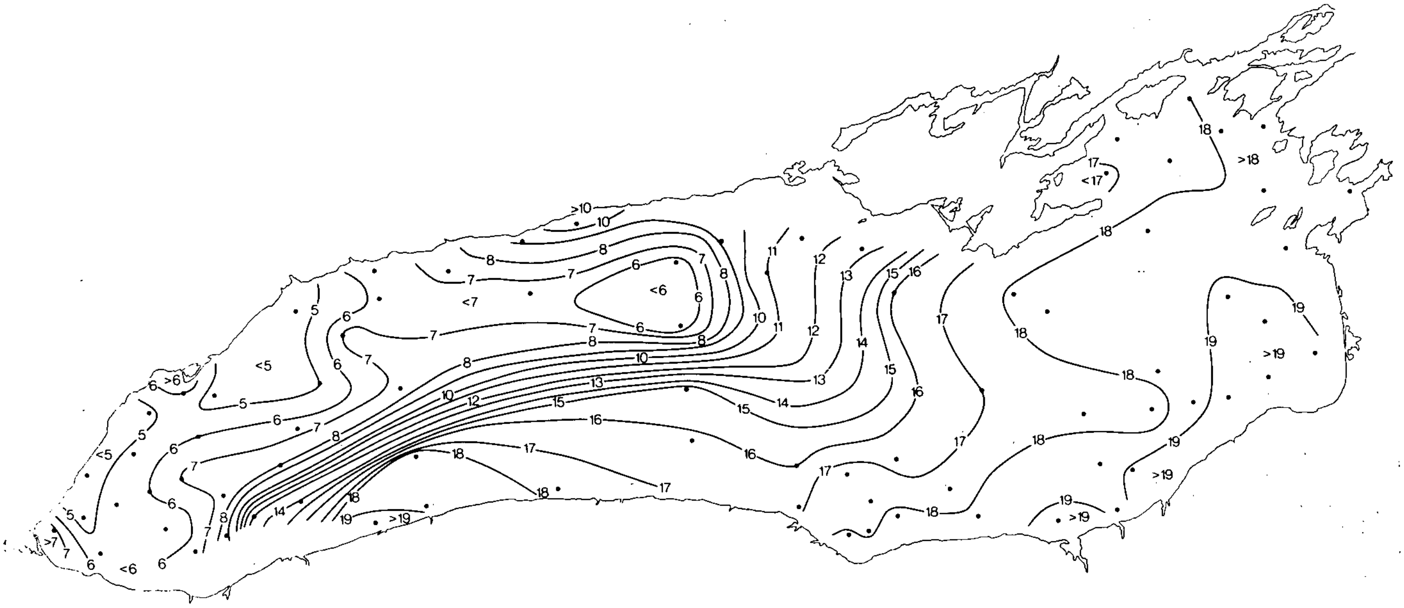


Figure 33. Temperatures (°C) at a depth of 20 m, September 7 to 11, 1976. The *Limnos.*

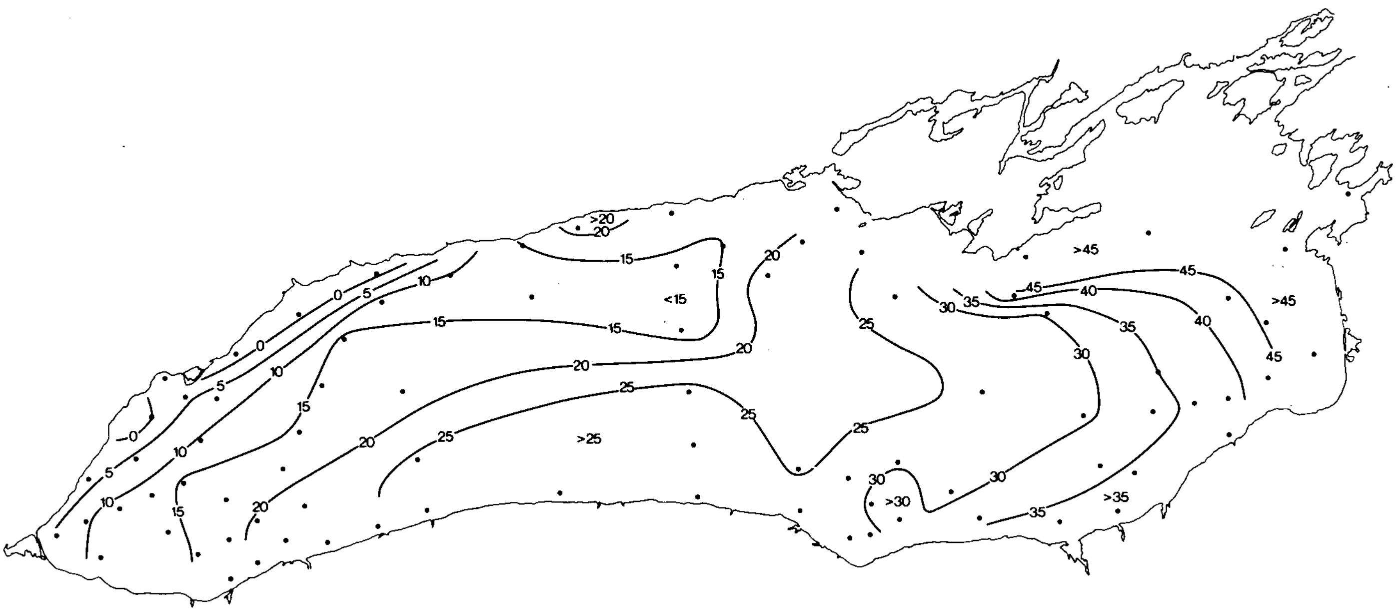


Figure 34. Depth (m) of the 10°C isothermal surface, September 7 to 11, 1976. The *Limnos.*

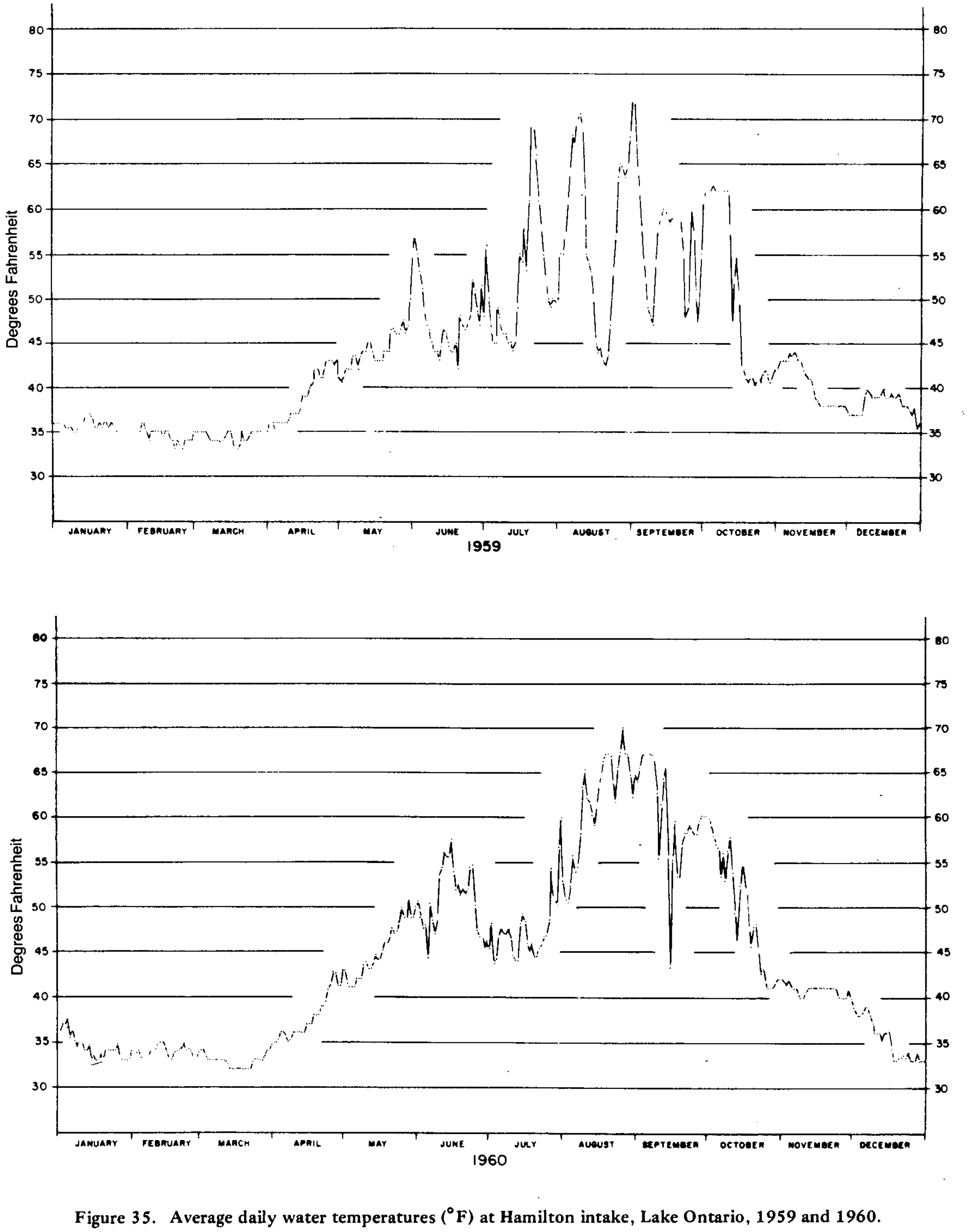


Figure 35. Average daily water temperatures (°F) at Hamilton intake, Lake Ontario, 1959 and 1960.

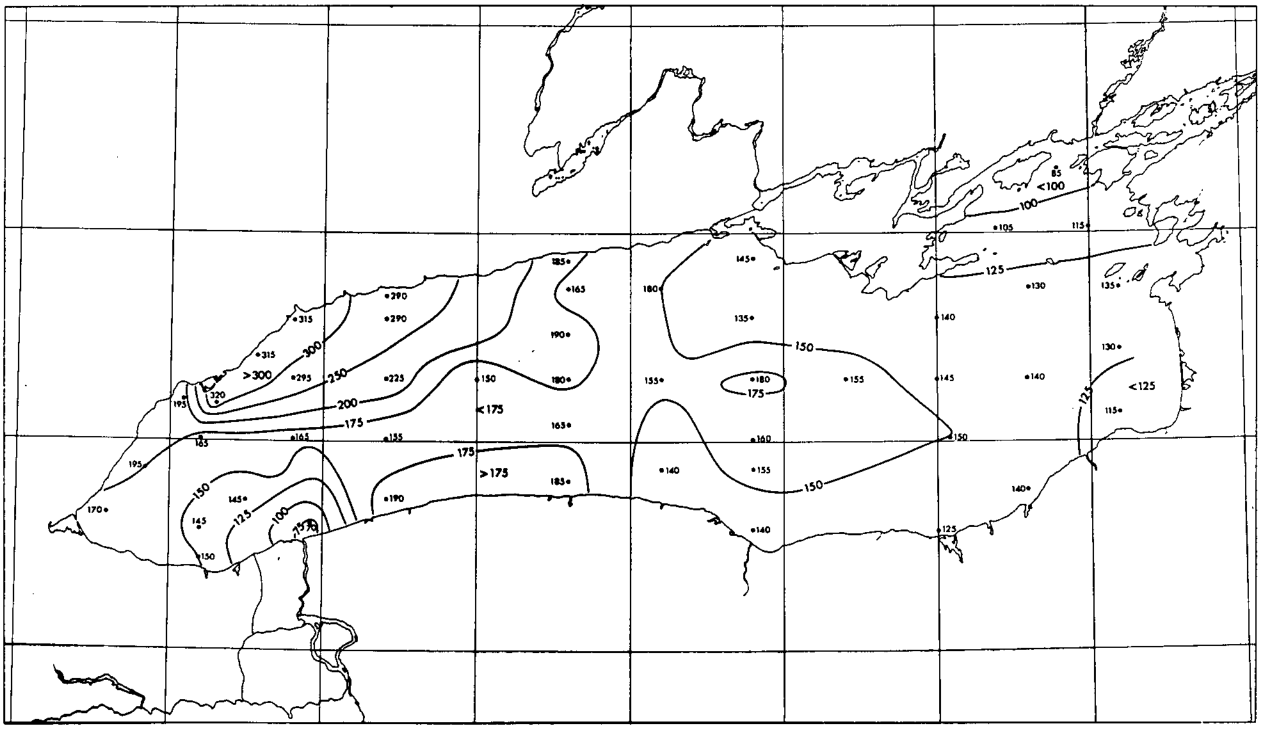
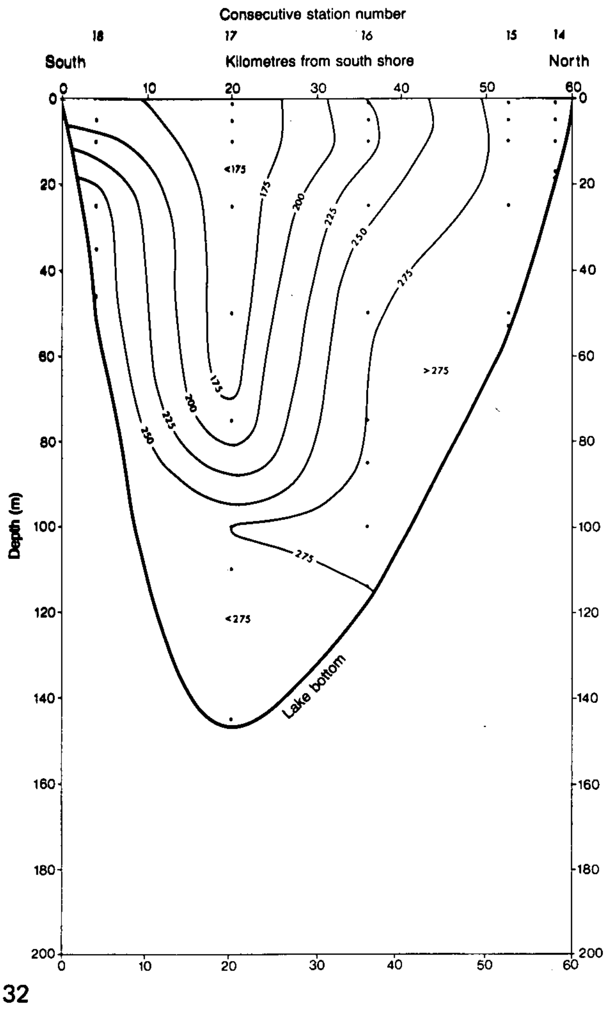


Figure 36. Nitrate + nitrite (μg N/L) at a depth of 1 m, November 15 to 19, 1971. The *Martin Karlsen*.



← Figure 37. Nitrate + nitrite (μg N/L) in a transverse section from Oshawa, southward, November 16, 1971. The *Martin Karlsen*.

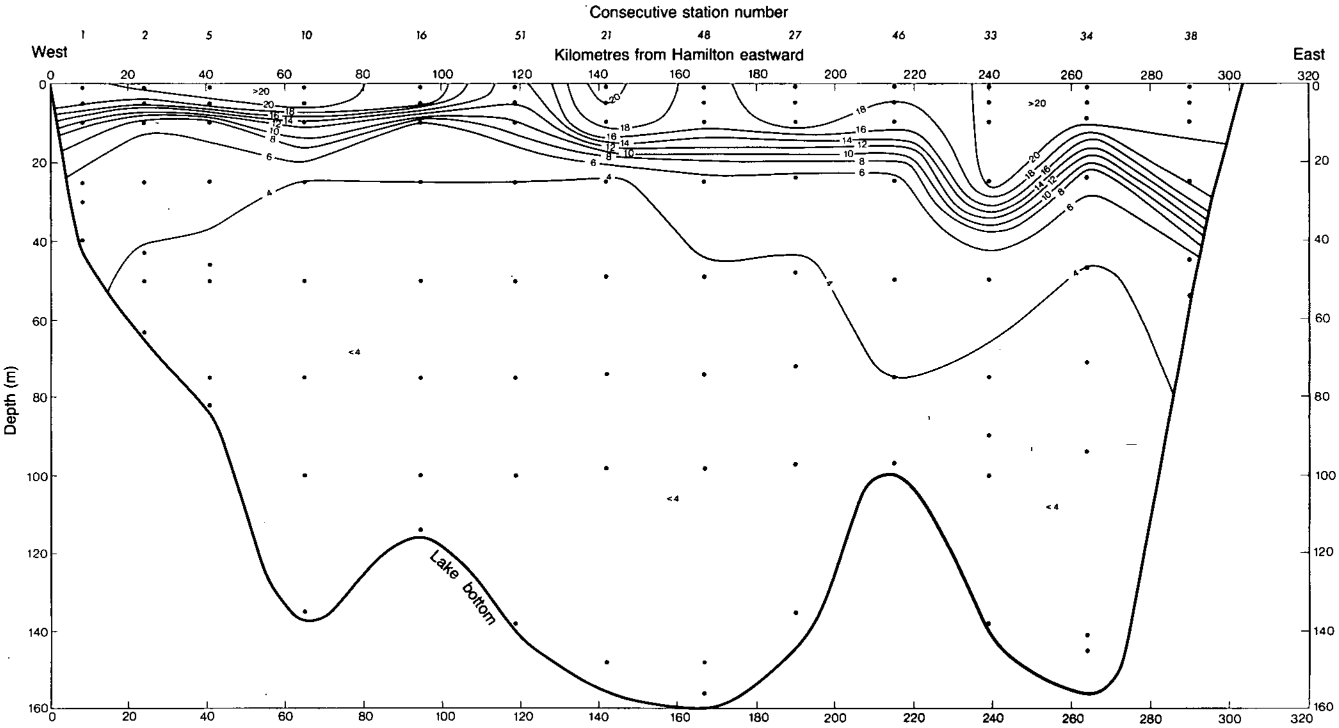


Figure 38. Temperatures (°C) in a longitudinal section from Hamilton, eastward, August 9 to 13, 1971. The *Martin Karlsen*.

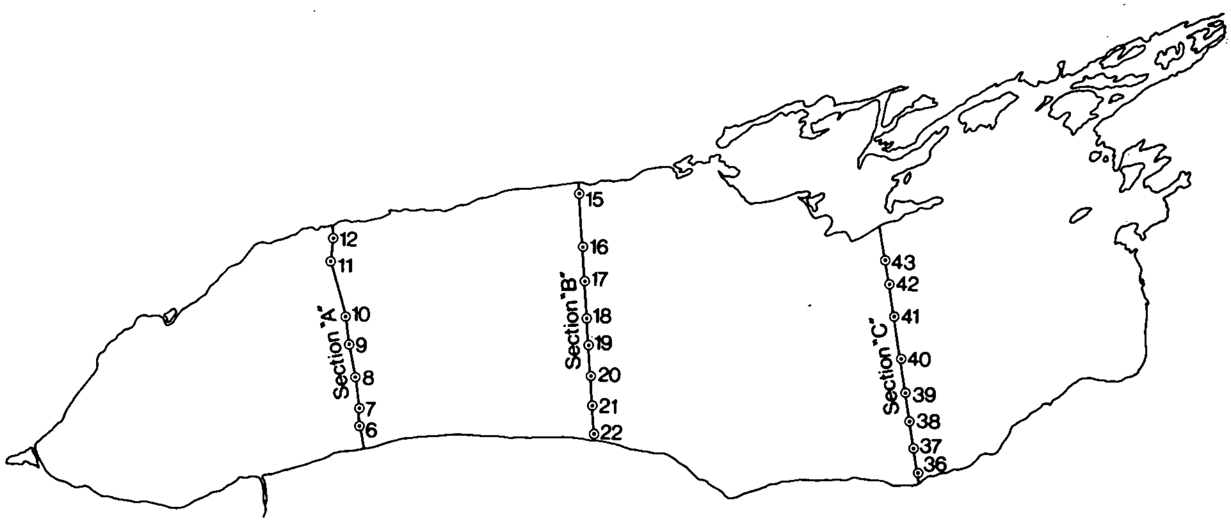


Figure 39. Locations of the three transverse sections and consecutive station numbers in Lake Ontario, July 18 to 21, 1972. The *Martin Karlsen*.

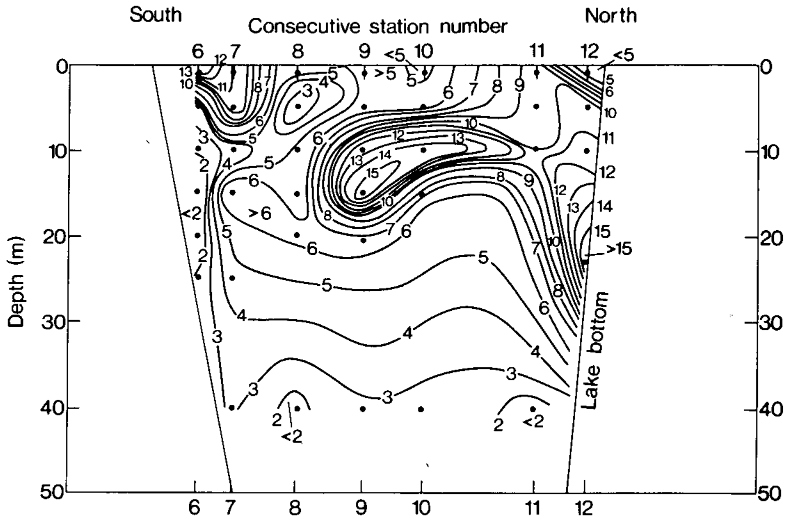


Figure 40. Total chlorophyll *a* (μg/L) in transverse section "A", July 18, 1972. The *Martin Karlsen*.

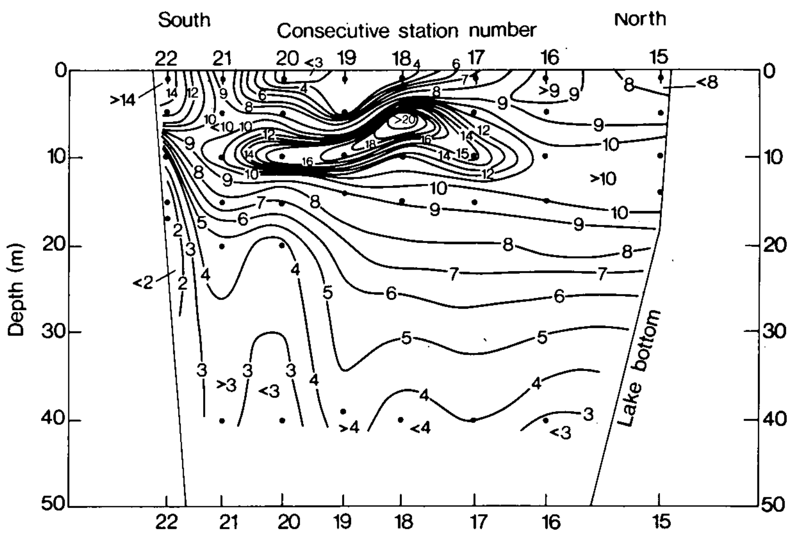


Figure 41. Total chlorophyll *a* (μg/L) in transverse section "B", July 18 and 19, 1972. The *Martin Karlsen*.

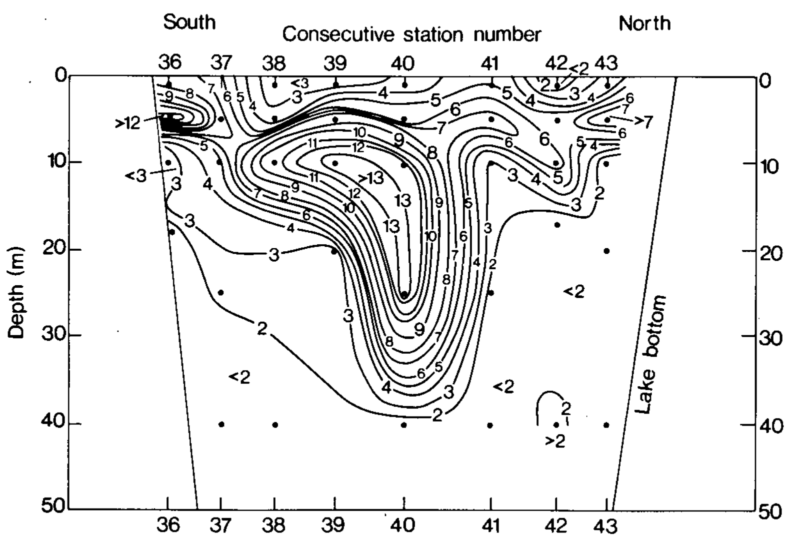


Figure 42. Total chlorophyll *a* (μg/L) in transverse section "C", July 20 and 21, 1972. The *Martin Karlsen*.

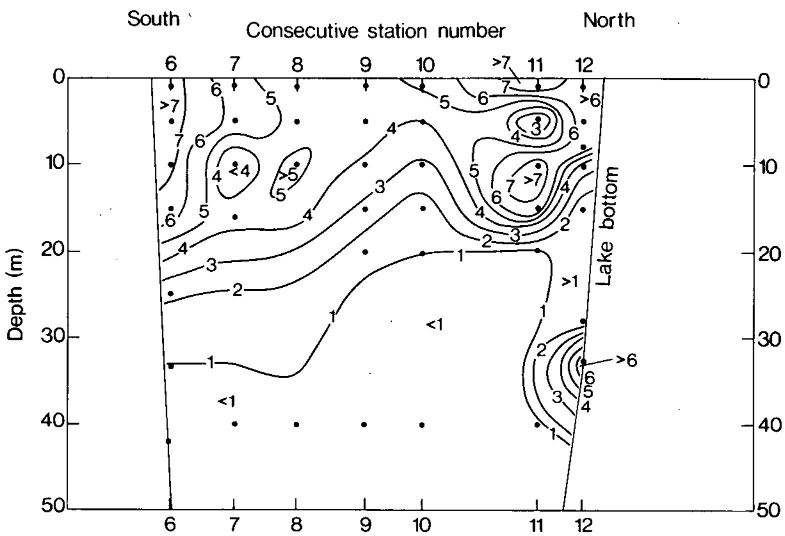


Figure 43. Total chlorophyll *a* (μg/L) in a transverse section "A", September 6, 1972. The *Martin Karlsen.*

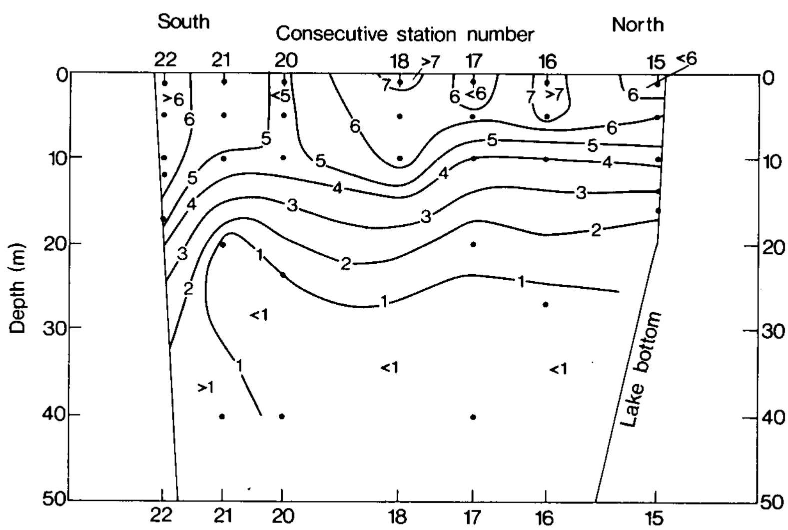


Figure 44. Total chlorophyll *a* (μg/L) in transverse section "B", September 6 and 7, 1972. The *Martin Karlsen.*

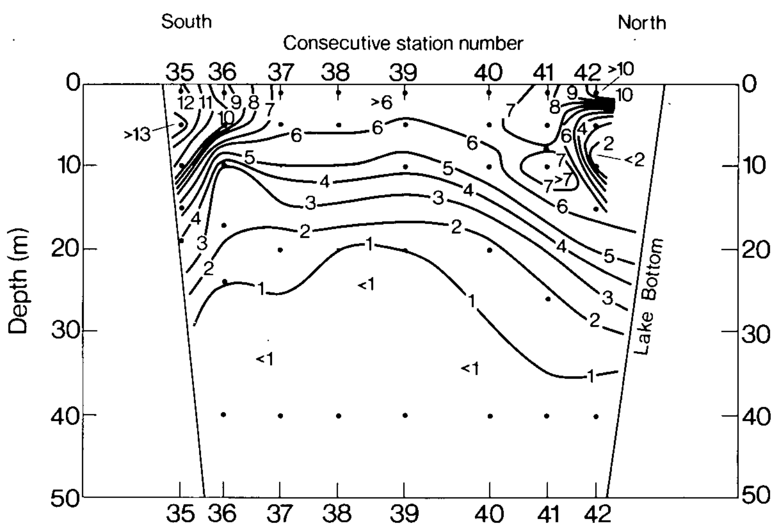


Figure 45. Total chlorophyll *a* (μg/L) in transverse section "C", September 8 and 9, 1972. The *Martin Karlsen.*

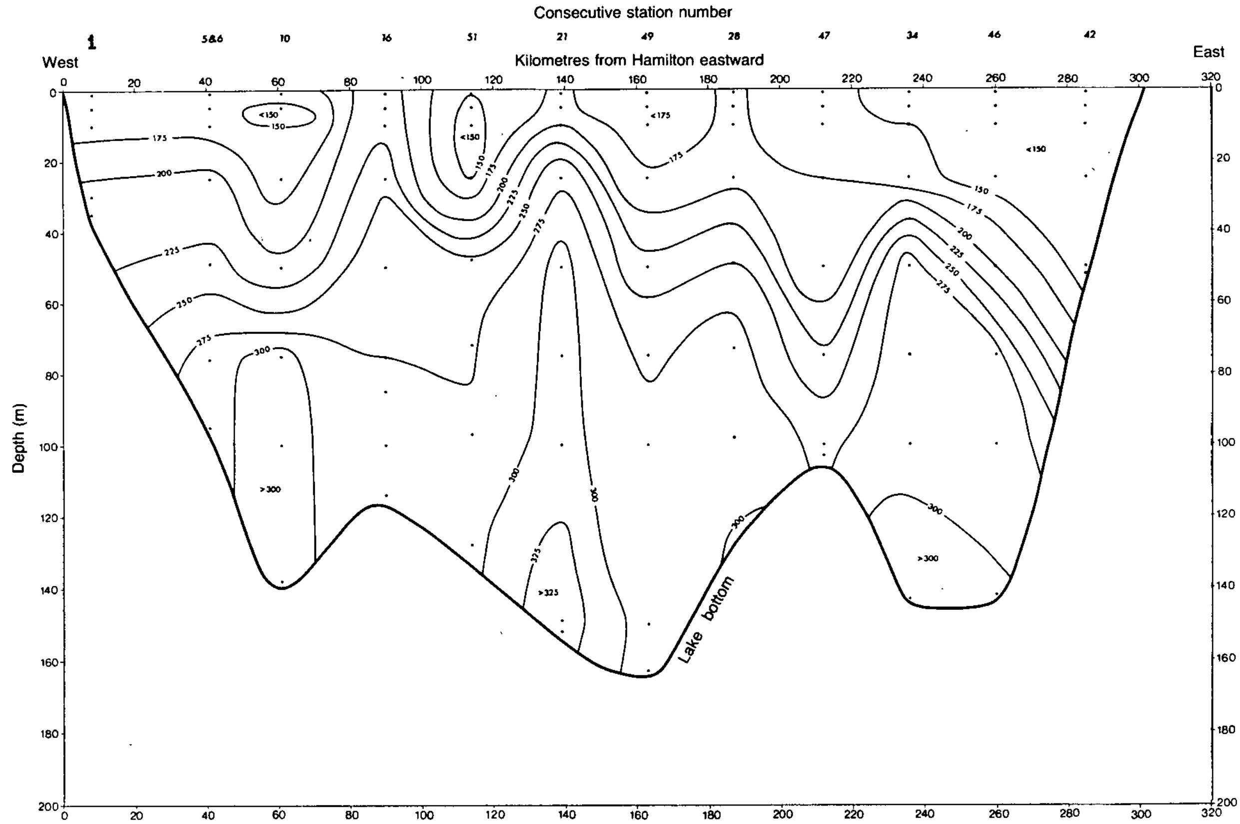


Figure 46. Nitrate + nitrite (μg N/L) in a longitudinal section from Hamilton, eastward, November 15 to 19, 1971. The *Martin Karlsen.*

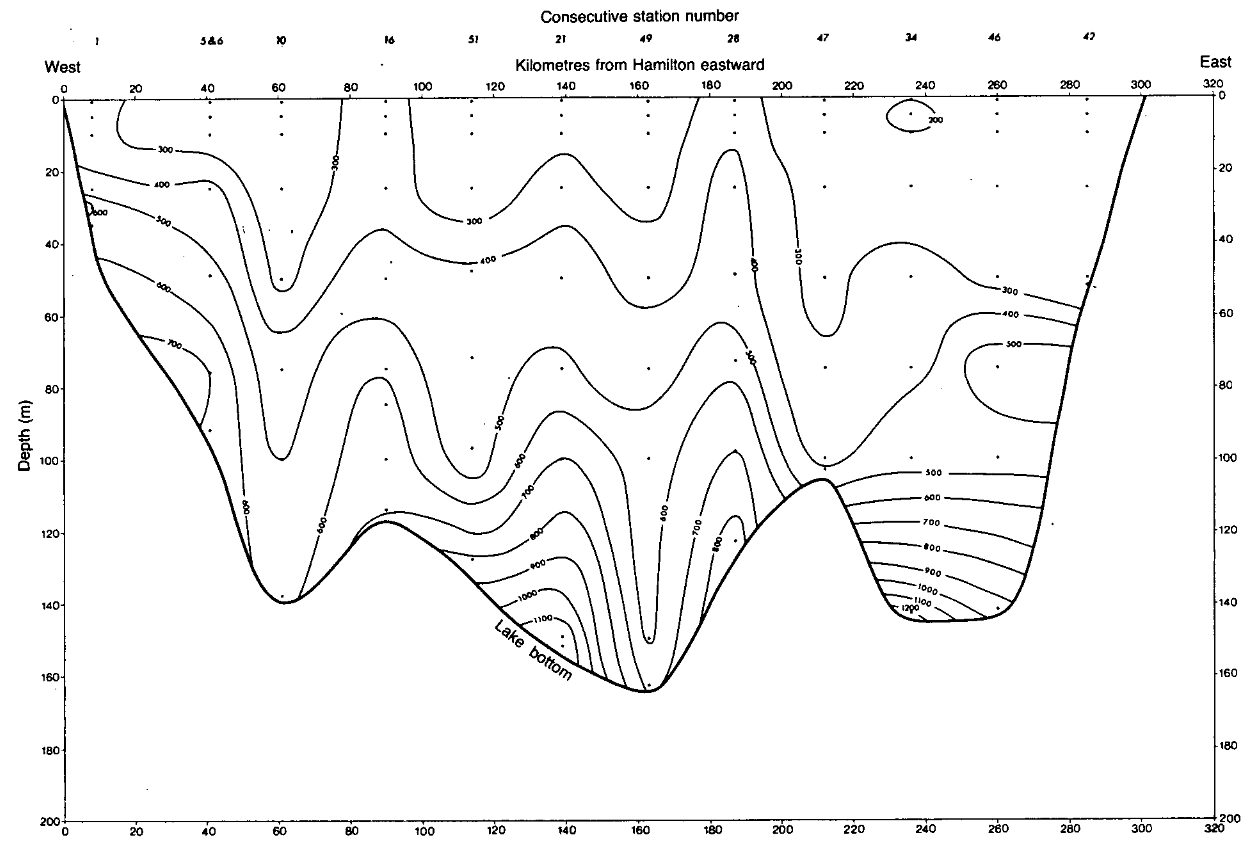


Figure 47. Soluble reactive silica (μg SiO_2/L) in a longitudinal section from Hamilton, eastward, November 15 to 19, 1971 (vertical exaggeration X 1000). The *Martin Karlsen.*

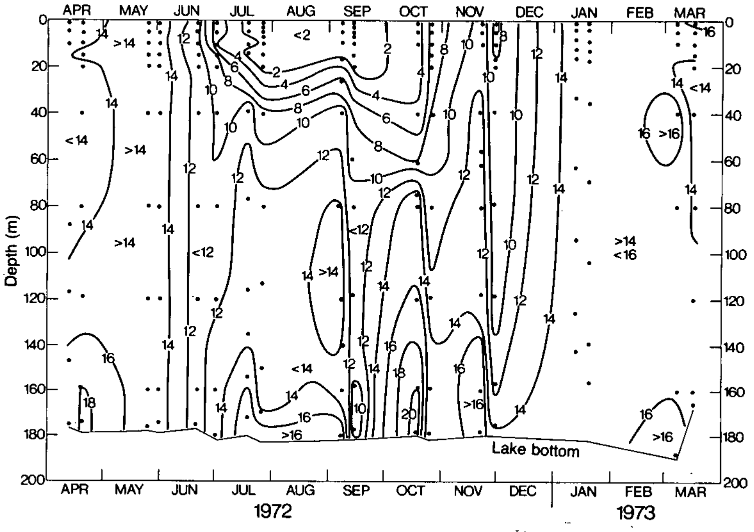


Figure 48. Soluble reactive phosphorus (μg P/L) versus time and depth at mid-lake station "P-19" during 1972 and early 1973. The *Martin Karlsen.*

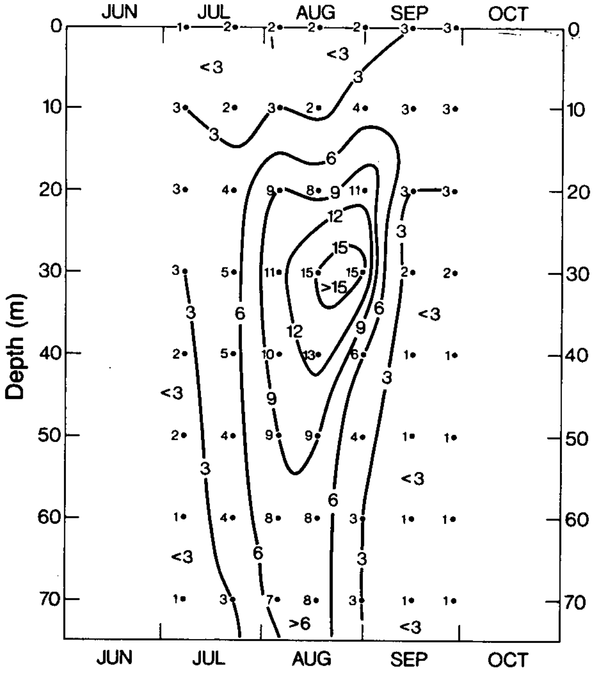


Figure 49. Nitrite (μg N/L) versus time and depth: mean values for the offshore area (soundings >100 m) during 1966. The *Brandal.*

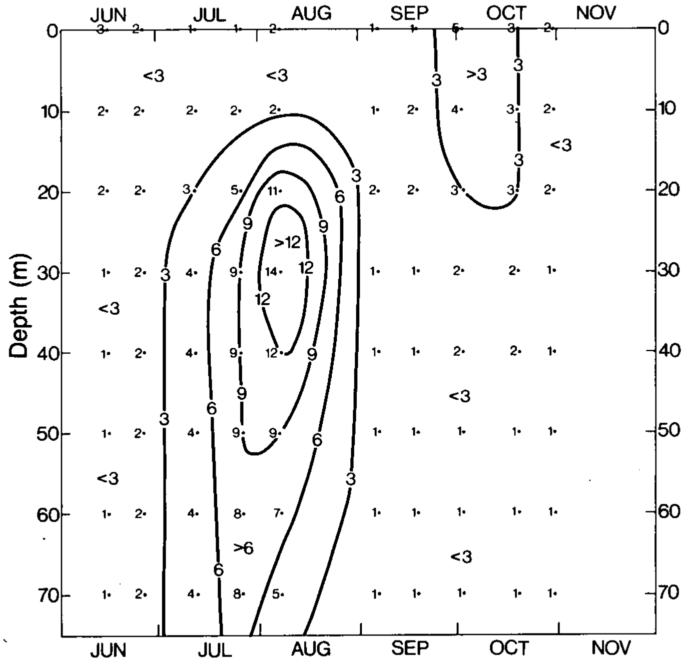


Figure 50. Nitrite (μg N/L) versus time and depth: mean values for the offshore area (soundings >100 m) during 1967. The *Theron.*

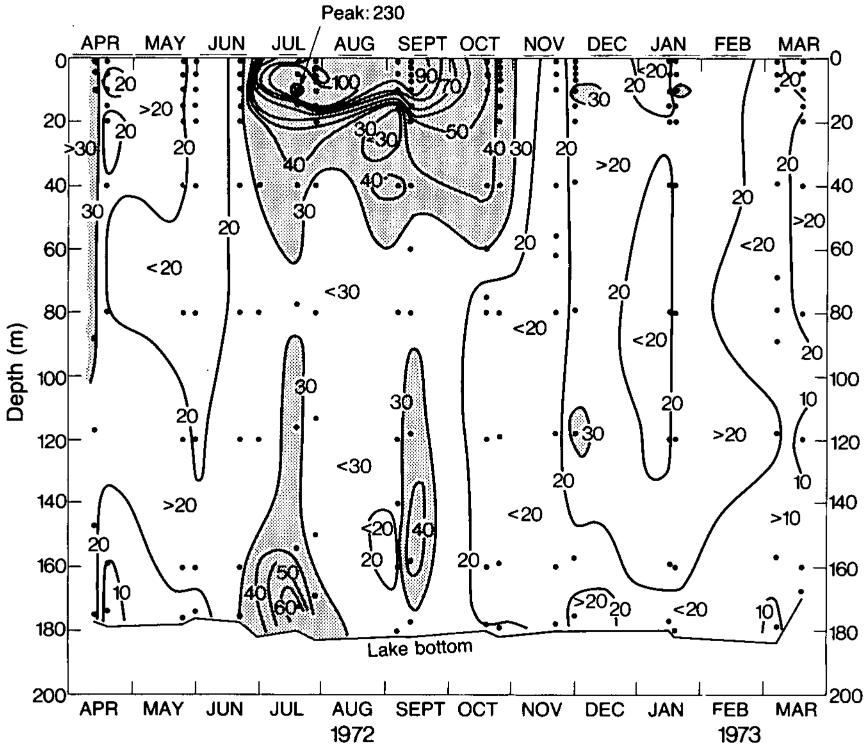


Figure 51. Particulate nitrogen (μg N/L) at mid-lake station "P-19" in 1972 and early 1973. The *Martin Karlsen.* Contour interval is 10 μg/L, except in the high patch. Areas > 30 are shaded.

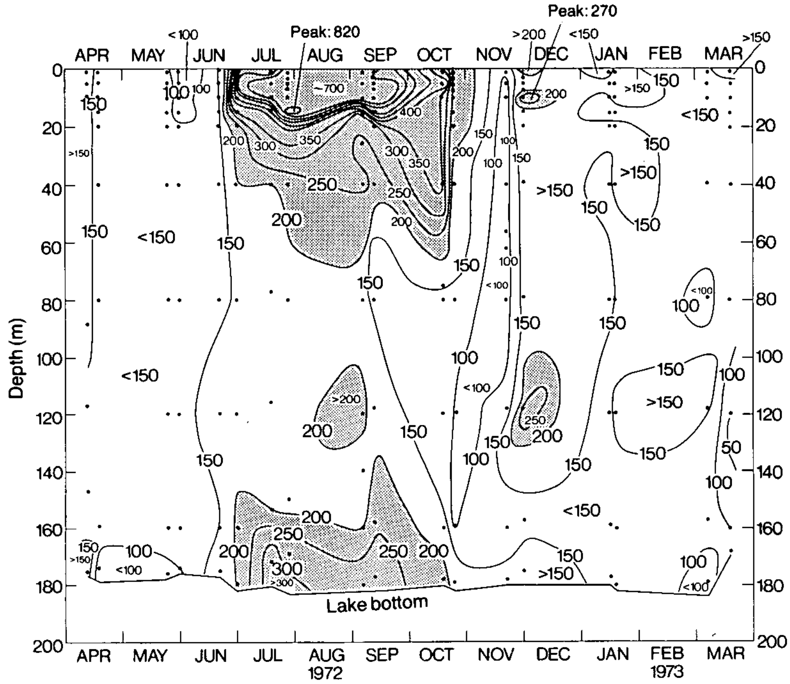


Figure 52. Particulate organic carbon (μg C/L) at mid-lake station "P-19" in 1972 and early 1973. The *Martin Karlsen*. Contour interval is 50 μg/L, except in high patch. Areas >200 are shaded.

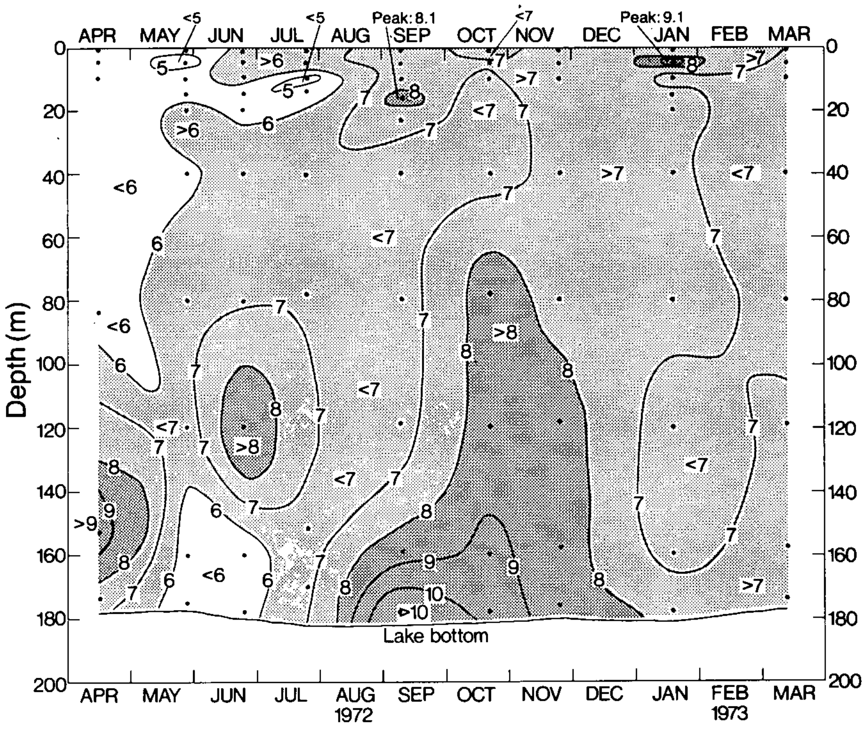
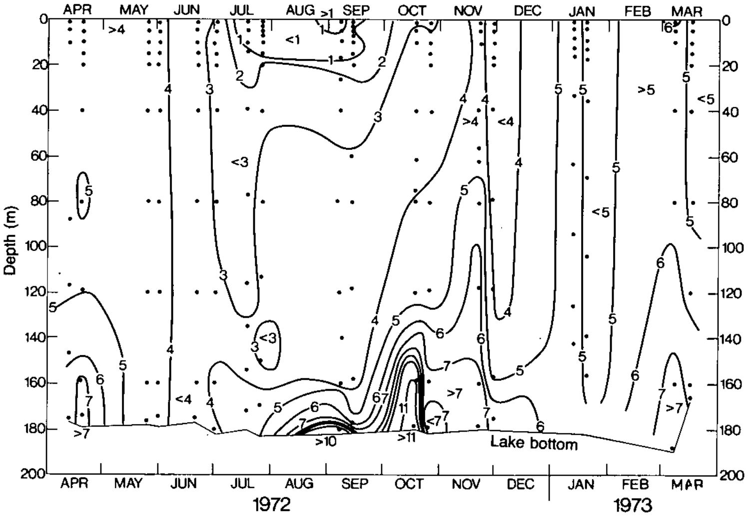


Figure 53. Particulate organic carbon/nitrogen ratio by weight at mid-lake station "P-19" in 1972 and early 1973. The *Martin Karlsen*.



← **Figure 54.** Soluble reactive silica versus time and depth at mid-lake station "P-19" during 1972 and early 1973. The *Martin Karlsen*. Units are hundreds of micrograms SiO_2 per litre. Contour interval is 100 $\mu g/L$.

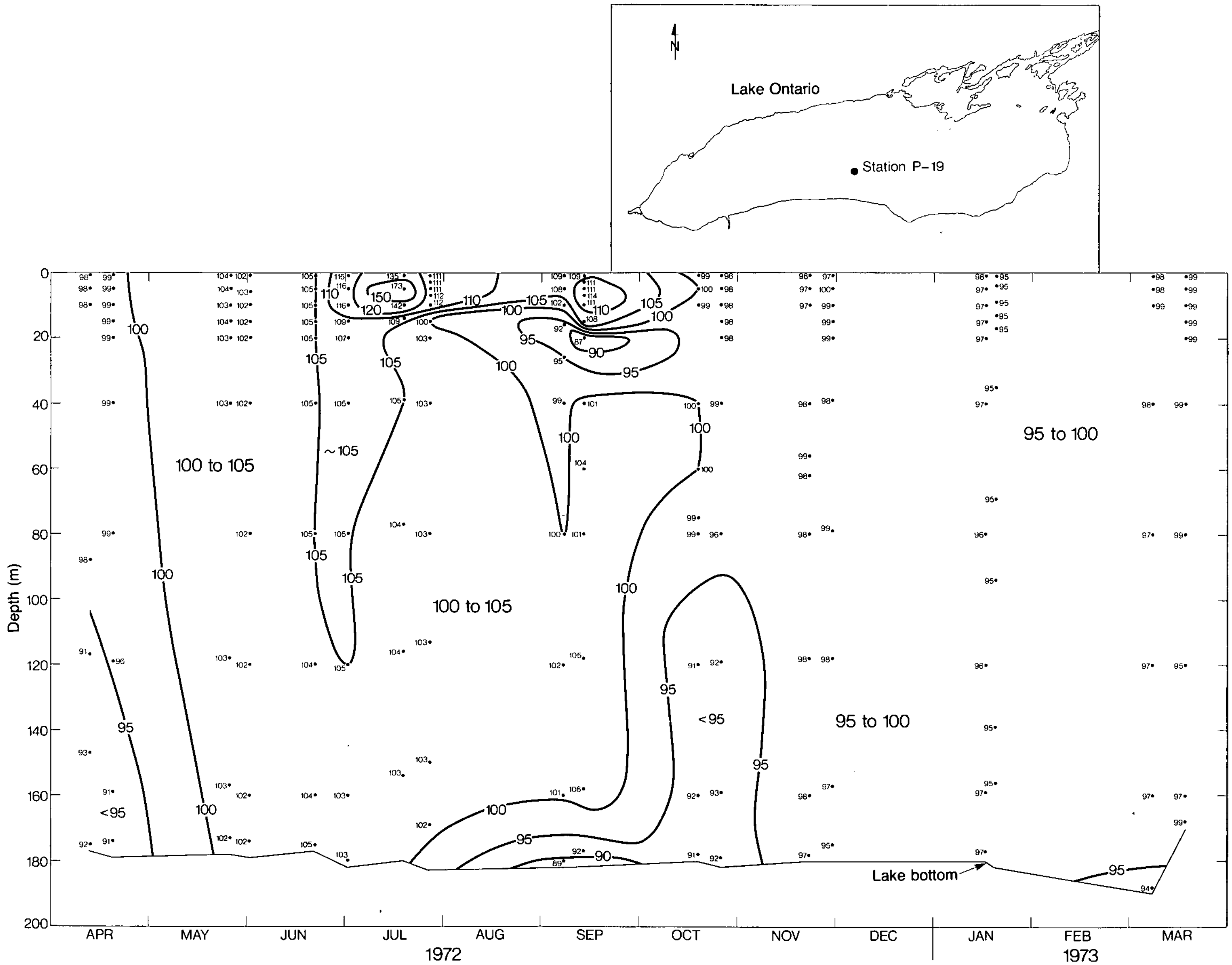


Figure 55. Dissolved oxygen versus time and depth at mid-lake station "P-19" during 1972 and early 1973. The *Martin Karlsen*. The values shown are percent saturation, or percent of the air-equilibrium value.

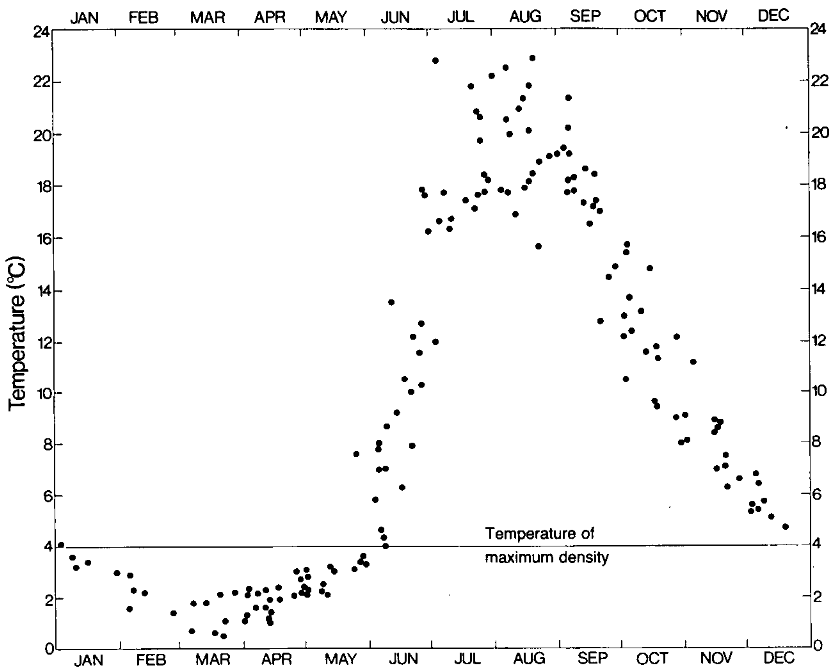


Figure 56. Seasonal cycle of cruise mean surface temperatures in the offshore part (soundings >100 m), 1966 to 1979. CCIW data.

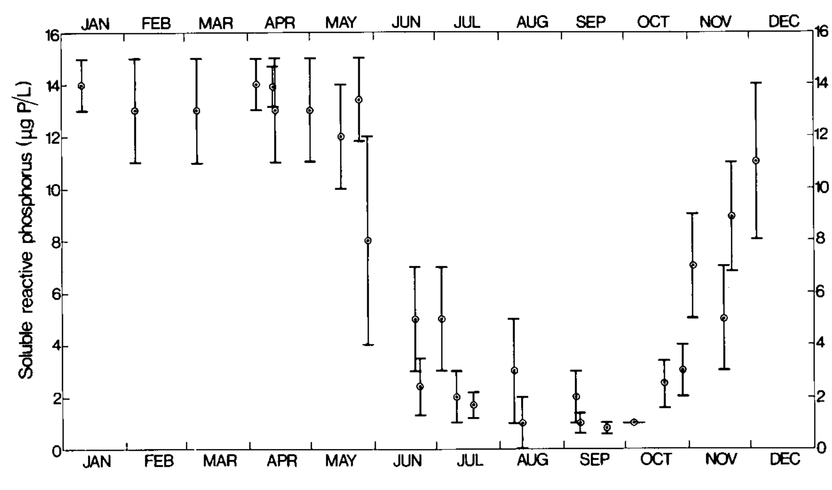


Figure 57. Soluble reactive phosphorus seasonal cycle in offshore surface waters, 1968 to 1972, observed on 27 cruises by CCIW vessels. Samples are from the upper 10 m at stations with soundings >100 m. For each cruise the mean value and one standard deviation are shown.

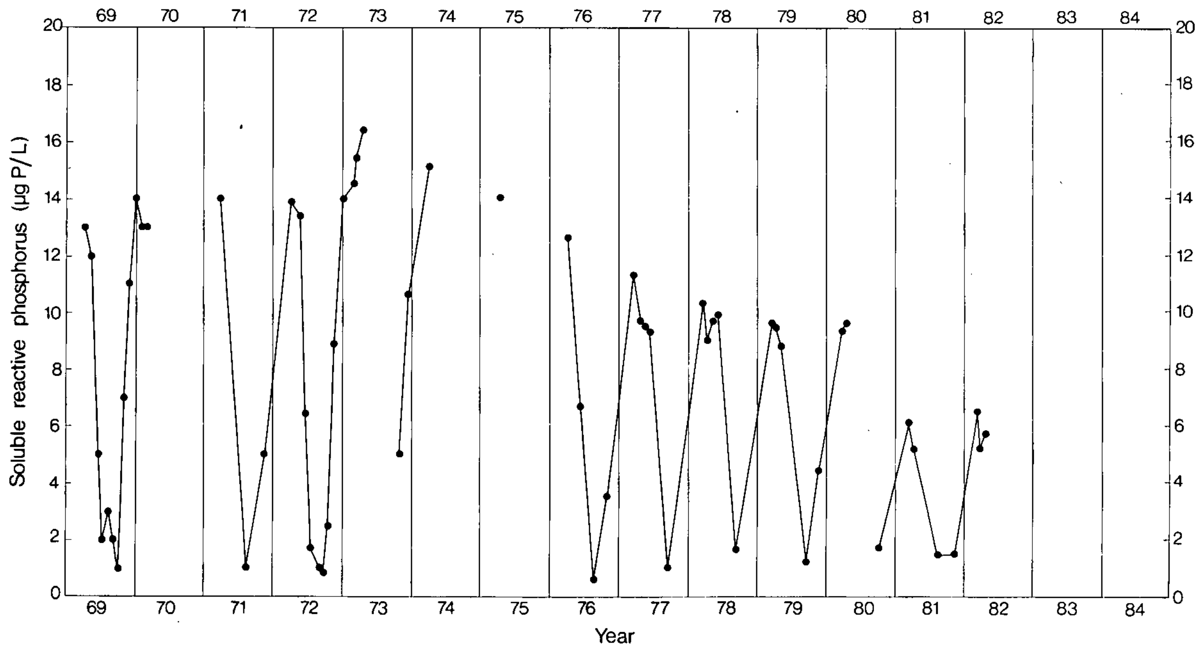


Figure 58. Soluble reactive phosphorus mean values in near-surface waters at offshore stations with soundings >100 m, on cruises of CCIW vessels, 1969 to 1982.

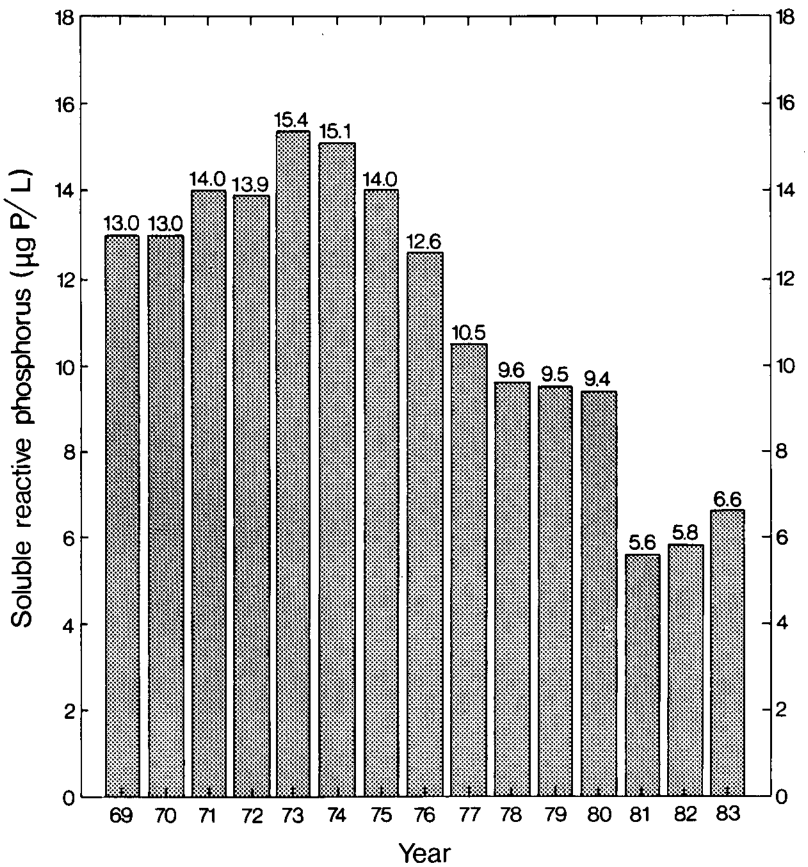


Figure 59. Soluble reactive phosphorus in offshore near-surface waters during March and April, 1969 to 1983. The goal is 6.0 μg P/L.

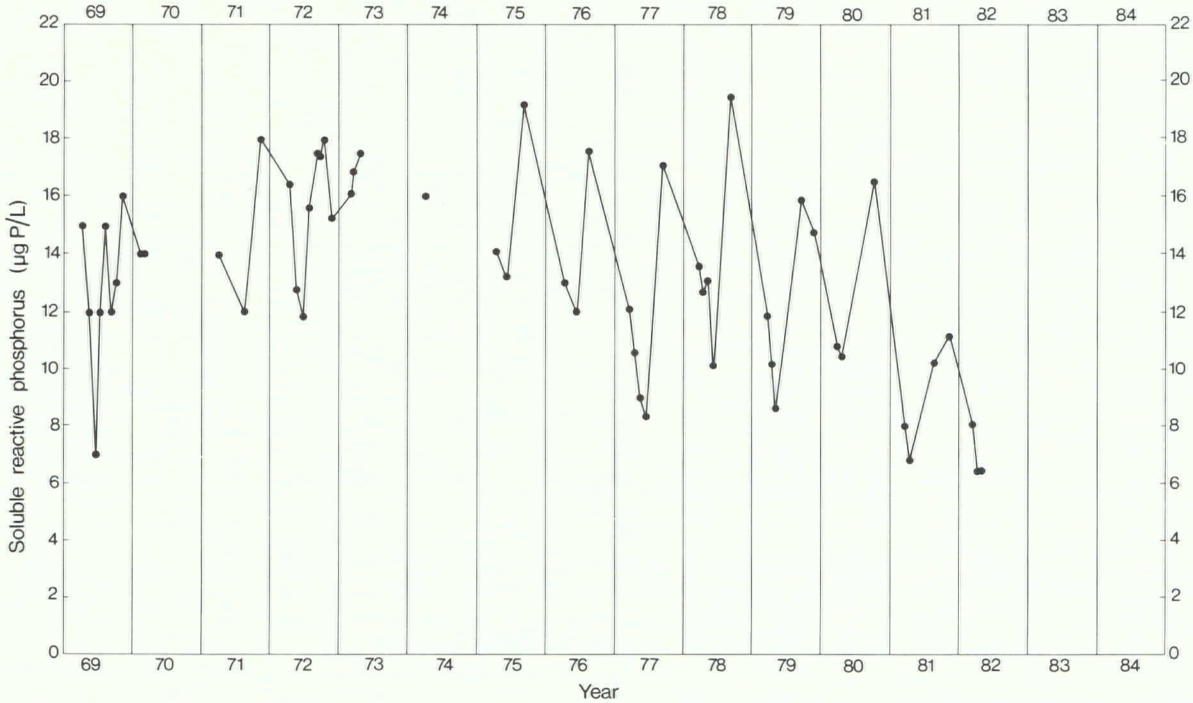


Figure 60. Soluble reactive phosphorus mean values in near-bottom waters at offshore stations with soundings >100 m, on cruises of CCIW vessels, 1969 to 1982.

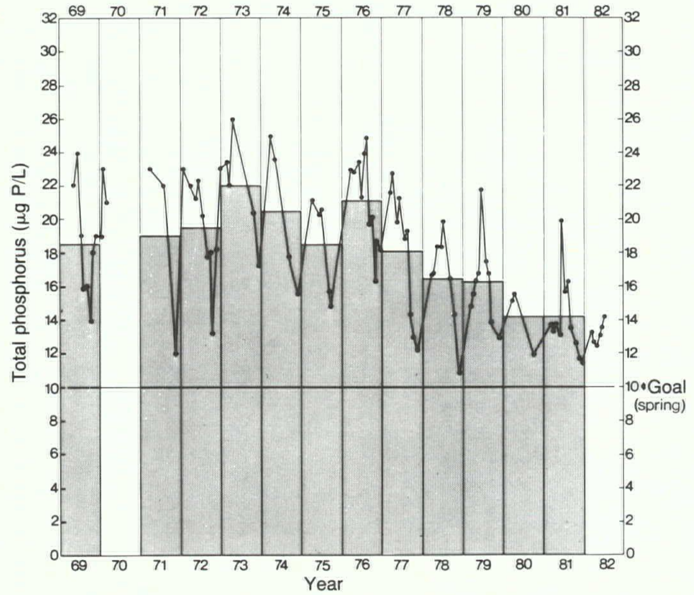


Figure 61. Total phosphorus in near-surface waters at offshore stations with soundings >100 m, 1969 to 1982. Dots indicate cruise mean values; bars represent unweighted annual mean values. CCIW data.

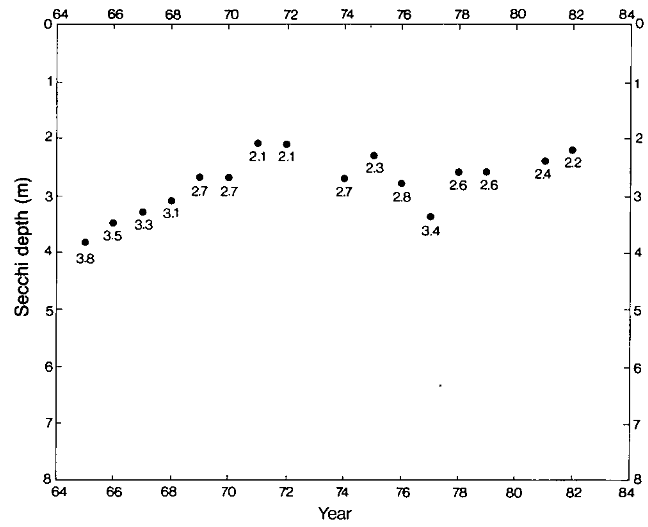


Figure 62. Secchi depth transparency mean values for summer (July, August and September), 1965 to 1982, in the offshore area with soundings >100 m. Reciprocal values were used in the calculations of summer means.

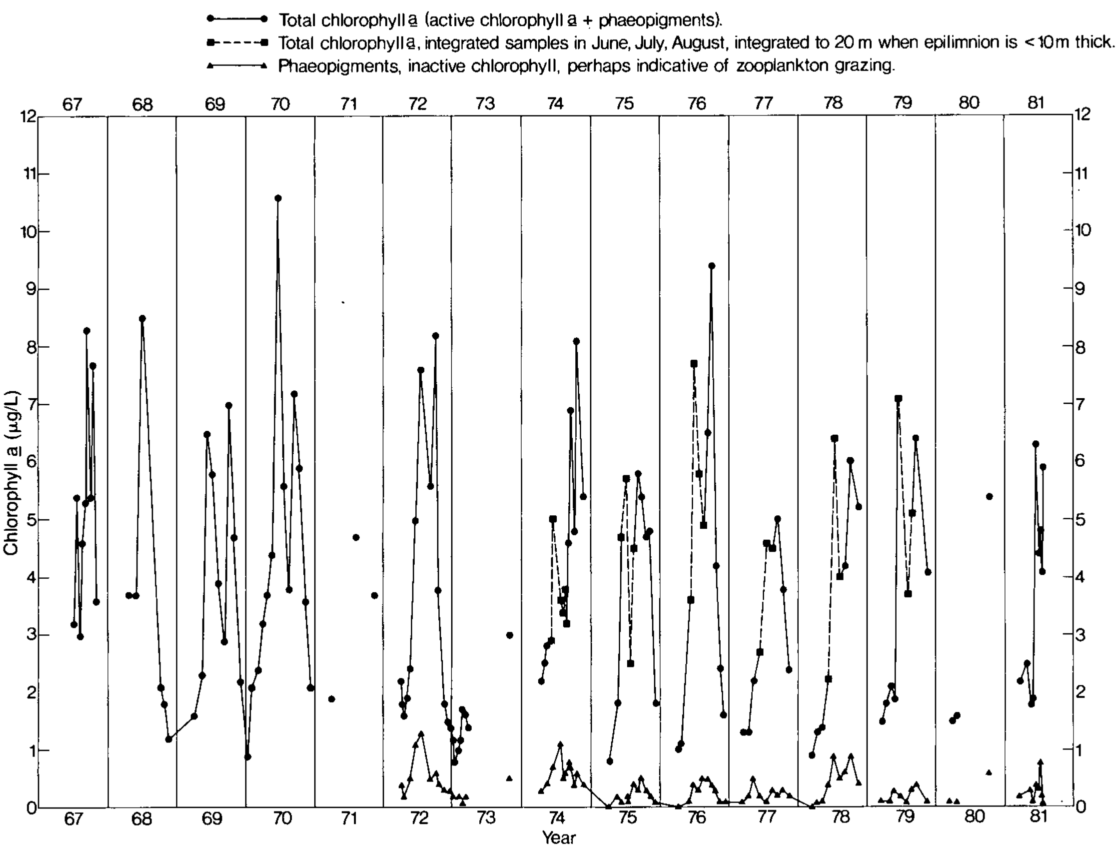


Figure 63. Chlorophyll *a* and phaeopigments in offshore near-surface waters, cruise mean values, 1967 to 1981.

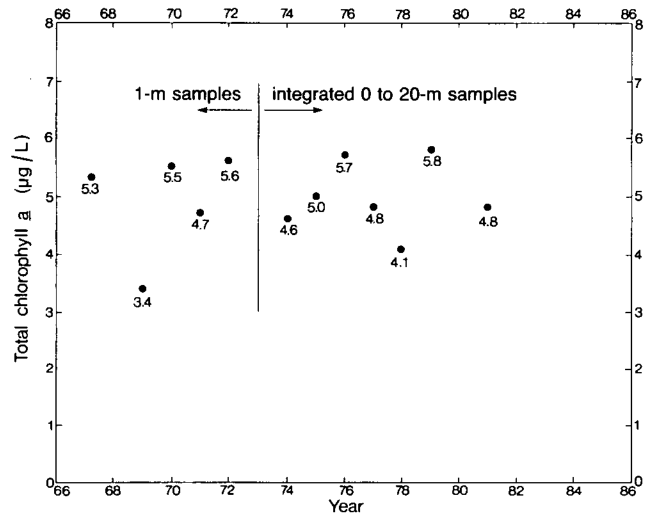


Figure 64. Total chlorophyll *a* mean values for August/September in offshore near-surface waters, 1967 to 1981. CCIW data.

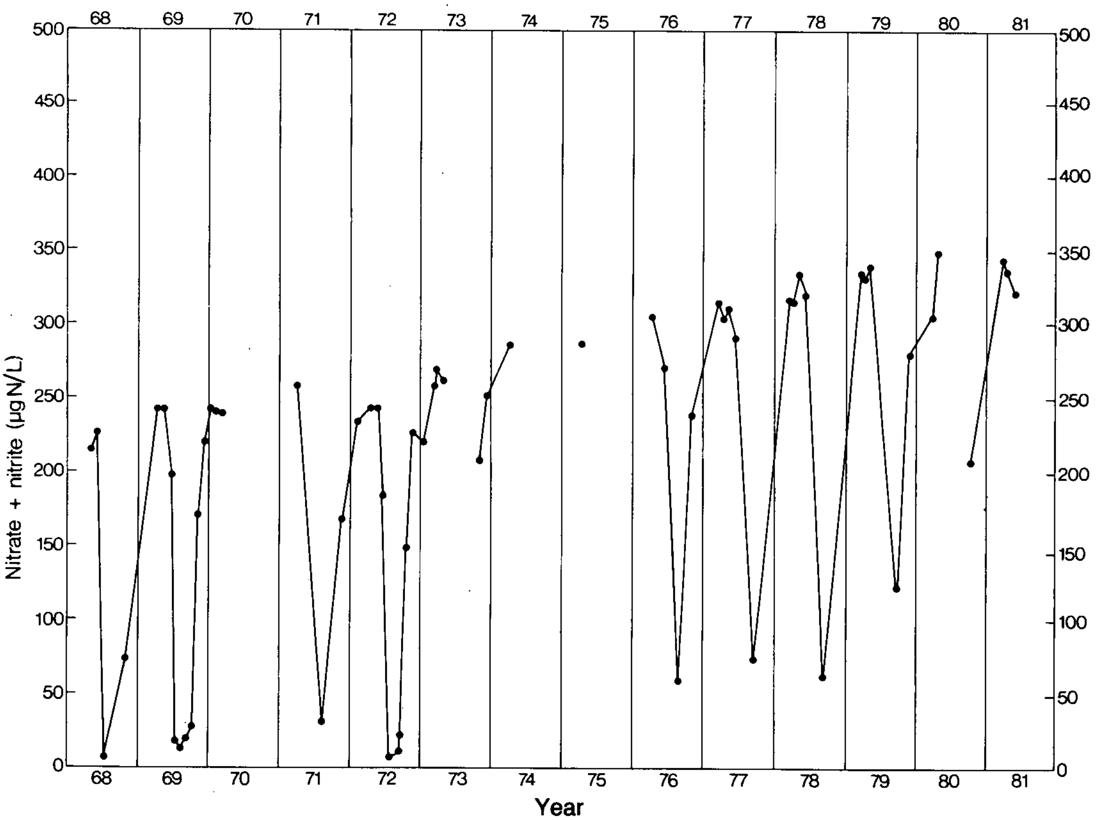


Figure 65. Nitrate + nitrite in offshore near-surface waters, cruise mean values, 1968 to 1981. The seasonal minimum was poorly defined for 1977 to 1980, which lacked data for August.

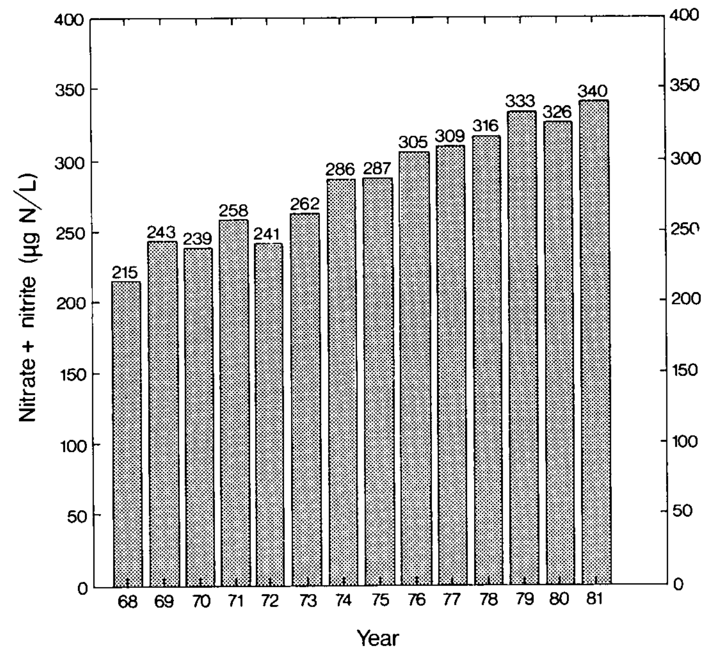


Figure 66. Nitrate + nitrite mean values in offshore near-surface waters during March and April, 1968 to 1981.

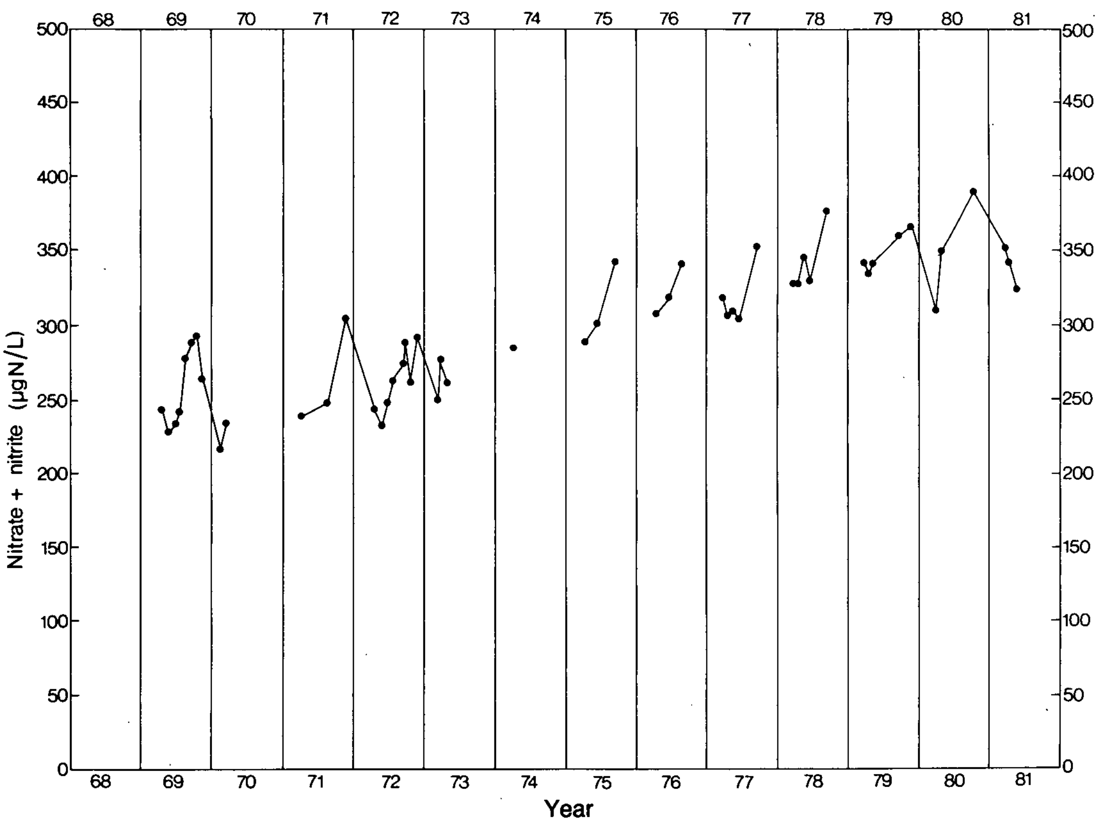


Figure 67. Nitrate + nitrite in offshore near-bottom waters, cruise mean values, 1969 to 1981.

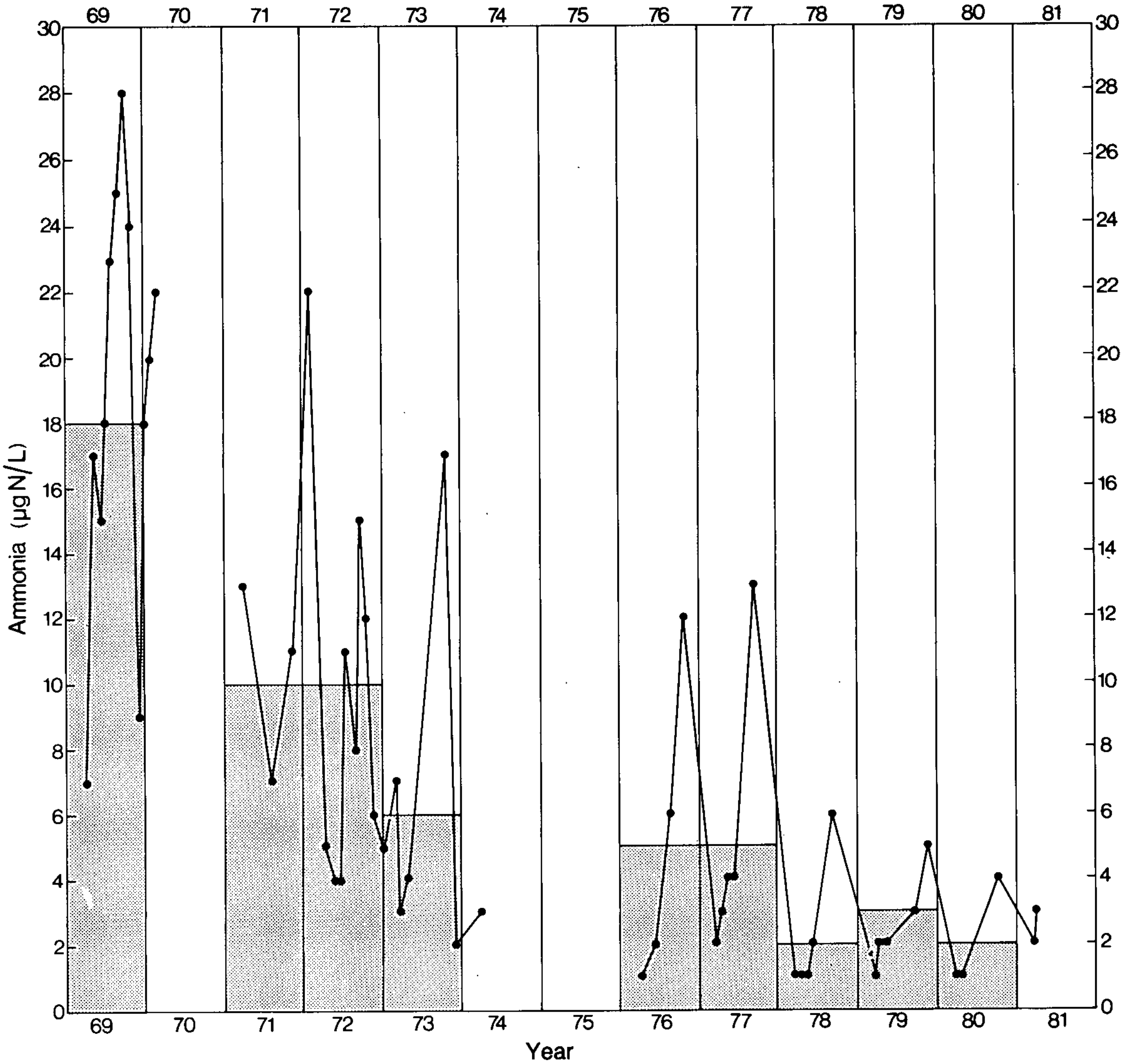


Figure 68. Ammonia in offshore near-surface waters, 1969 to 1981. Dots indicate cruise mean values; bars represent unweighted annual mean values.

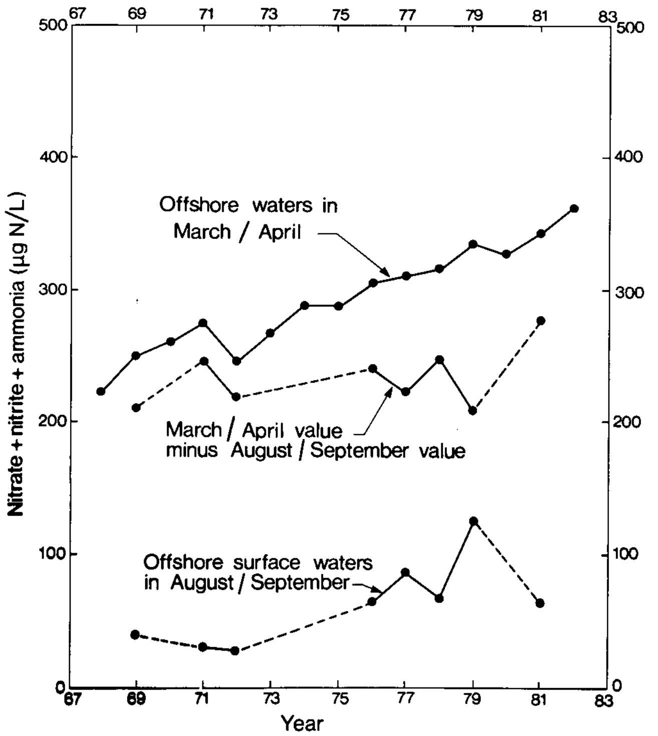


Figure 69. Nitrate + nitrite + ammonia, 1968 to 1982. CCIW data.

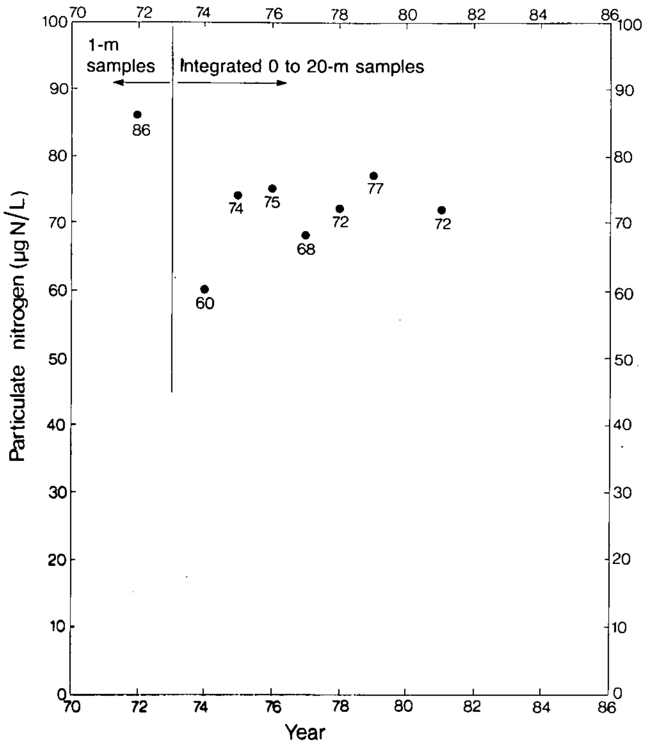


Figure 71. Particulate nitrogen mean values for August/September in offshore near-surface waters, 1972 to 1981. CCIW data.

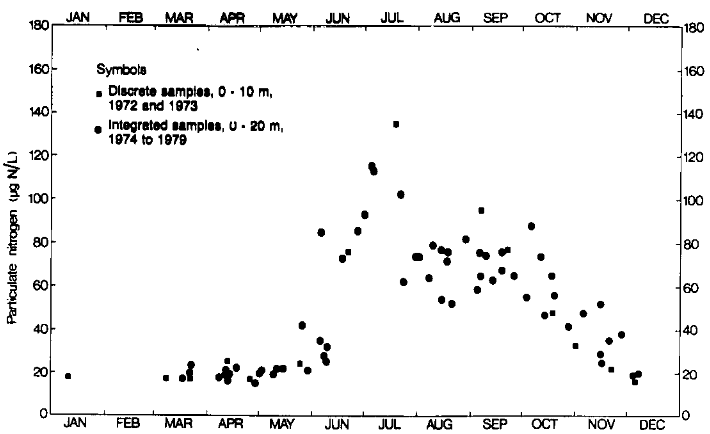


Figure 70. Particulate nitrogen in offshore near-surface waters, cruise mean values, 1972 to 1979.

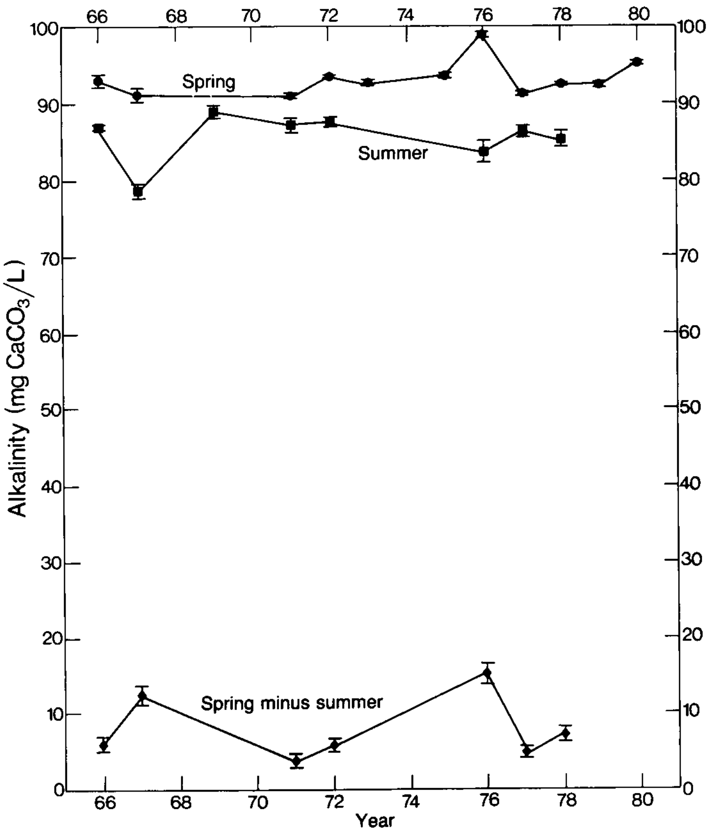


Figure 72. Alkalinity in offshore surface water: spring overturn period; summer (August 1 to September 15); and their difference. Error bars are 95% confidence intervals.

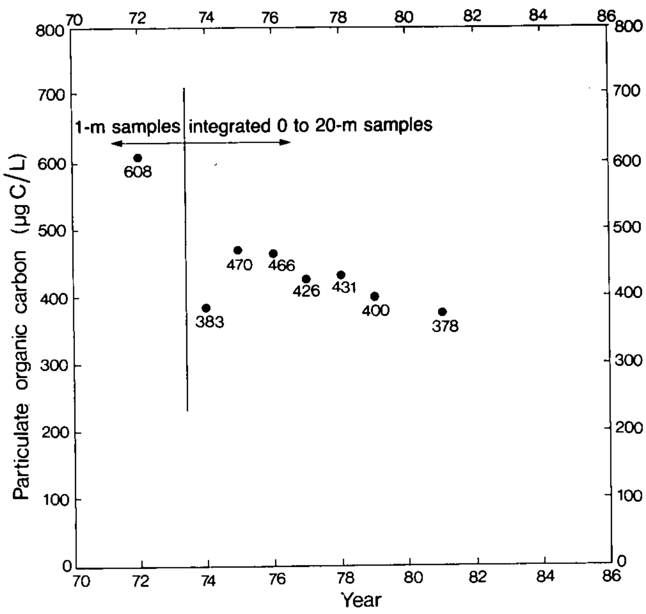


Figure 73. Particulate organic carbon mean values for August/ September in offshore near-surface waters, 1972 to 1981. CCIW data.

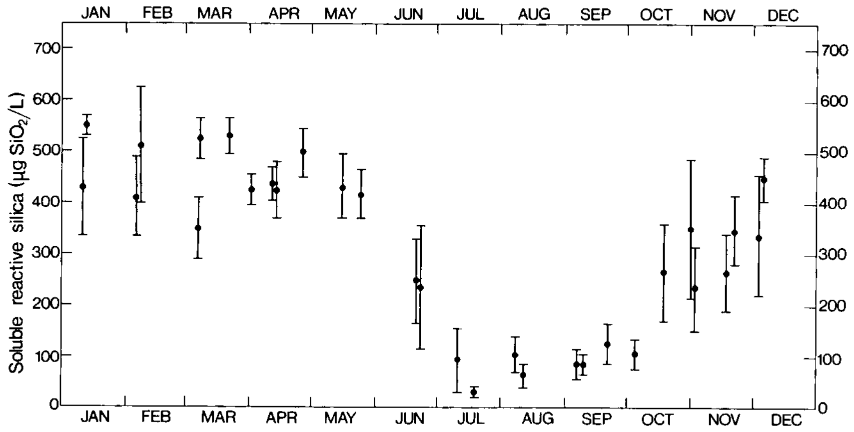


Figure 74. Soluble reactive silica seasonal cycle in offshore near-surface waters: cruise means and one standard deviation for 30 cruises, 1969 to 1973. Soundings >100 m; sample depths ≤10 m. CCIW data.

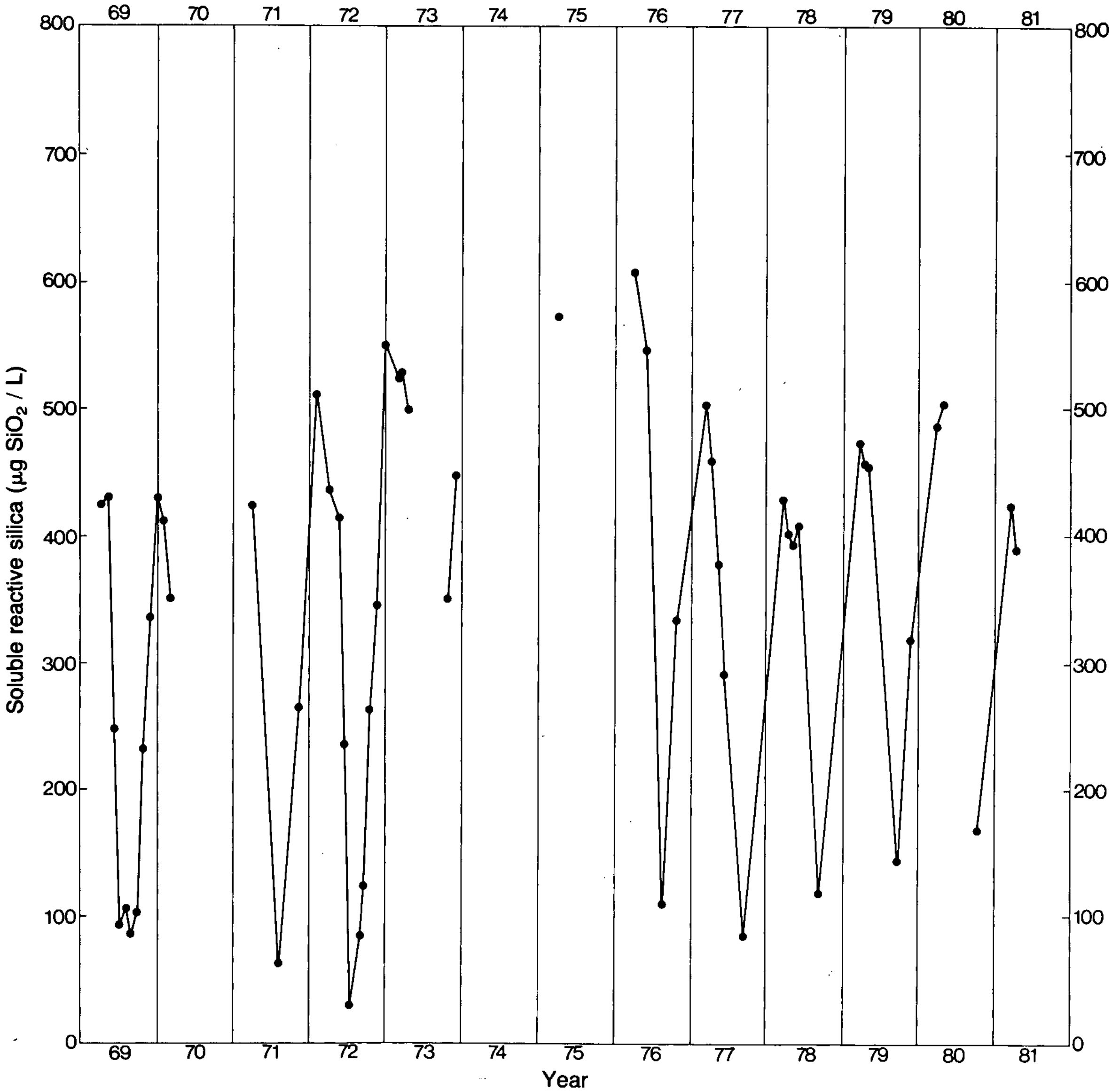


Figure 75. Soluble reactive silica in offshore near-surface waters, cruise mean values, 1969 to 1981.

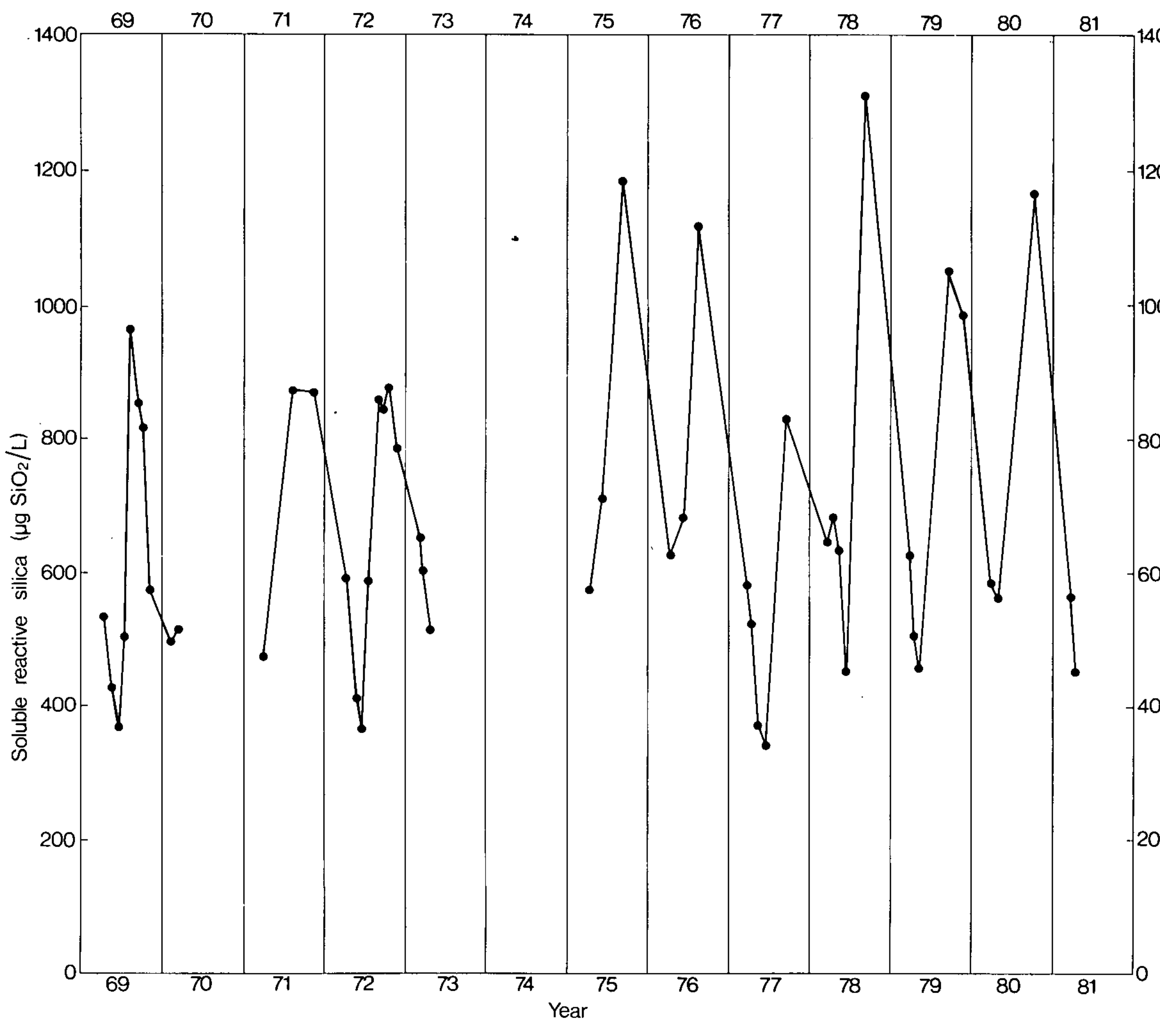


Figure 76. Soluble reactive silica in offshore near-bottom waters, cruise mean values, 1969 to 1981.

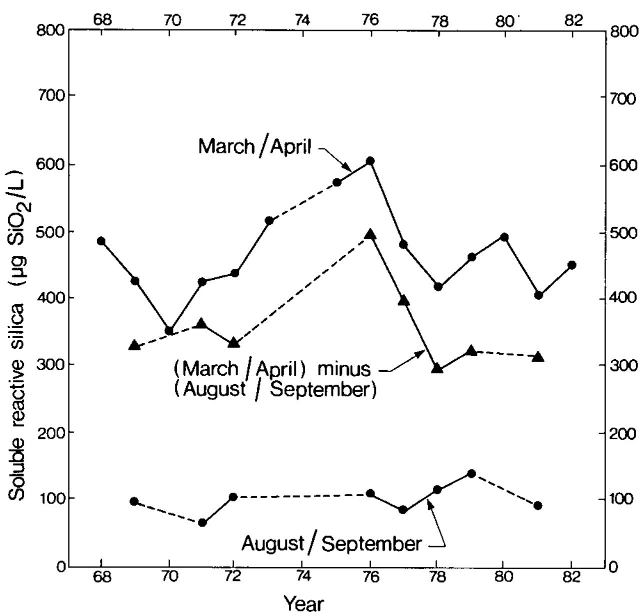


Figure 77. Mean values of soluble reactive silica in offshore near-surface waters, 1968 to 1982: winter values, summer values, and their difference. CCIW data.

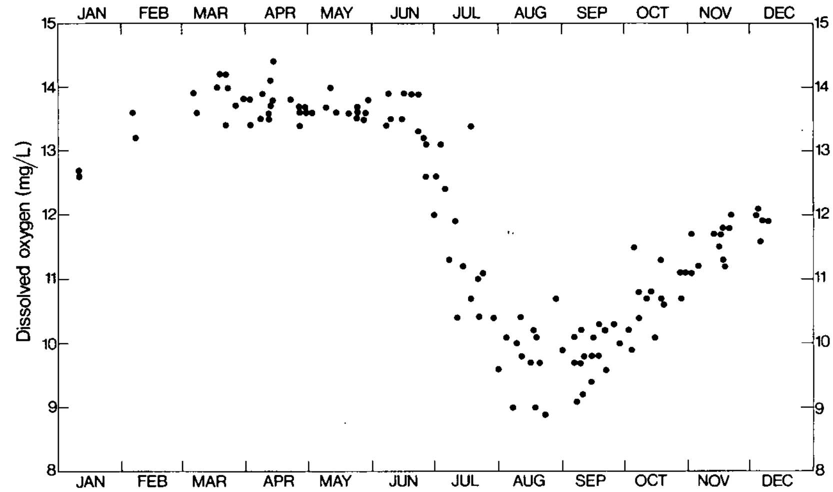


Figure 78. Dissolved oxygen (mg/L) in offshore near-surface waters, 124 cruise mean values, 1966 to 1981. Soundings >100 m; sample depths ≤ 10 m. CCIW data.

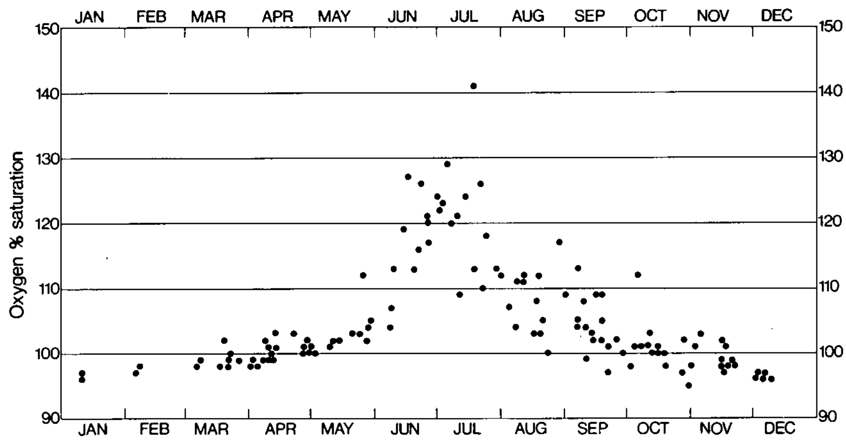


Figure 79. Oxygen percent saturation in offshore near-surface waters, 124 cruise mean values, 1966 to 1981. Soundings >100 m; sample depth ≤10 m. CCIW data.

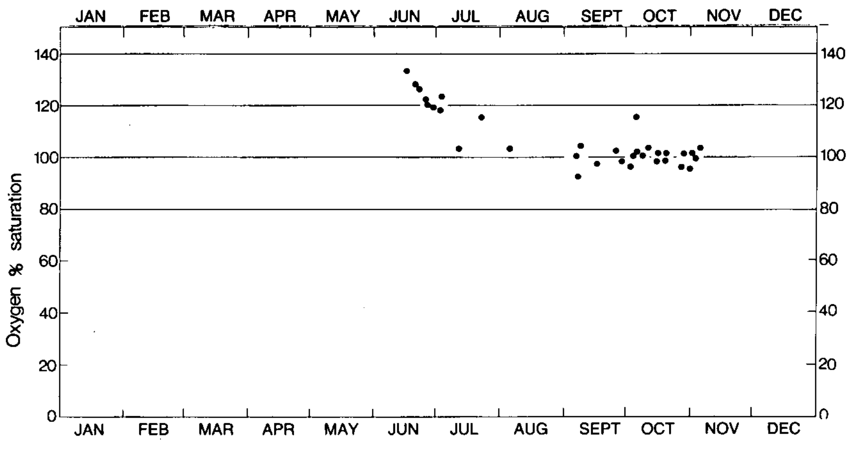


Figure 80. Oxygen percent saturation, cruise mean values at offshore stations (soundings >100 m), for samples with temperatures in the range 10°C to 15°C, from 33 cruises, 1966 to 1981. CCIW data.

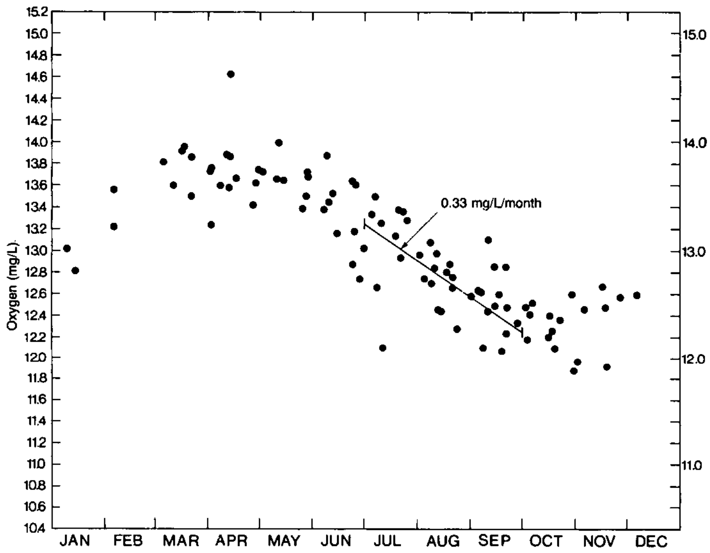


Figure 81. Dissolved oxygen (mg/L), mean values on each cruise, all years from 1966 to 1978, for samples colder than 4.00°C and not within 10 m of the lake bottom (offshore part where soundings >50 m).

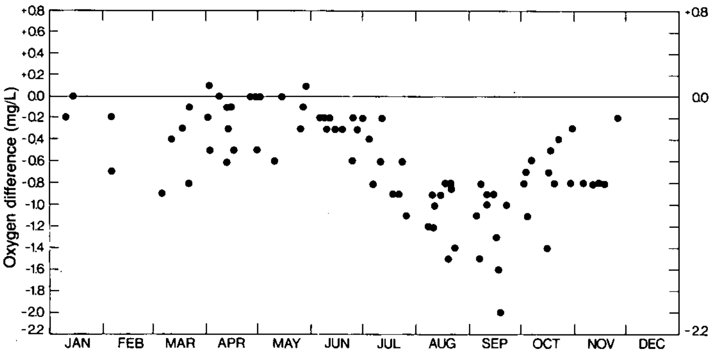


Figure 82. Dissolved oxygen (mg/L), mean values of near-bottom samples (within 10 m of bottom) minus mean values of other samples colder than 4.00°C, on each cruise, 1967 to 1978 (offshore part where soundings >50 m).

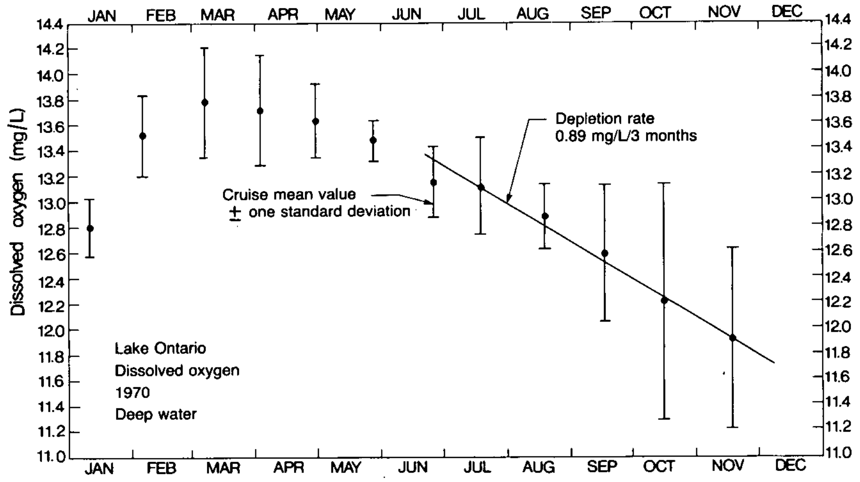


Figure 83. Dissolved oxygen (mg/L) in the deep water (samples with temperature <4°C and not within 10 m of the bottom), 1970. Data from 12 cruises of the *Martin Karlsen*.

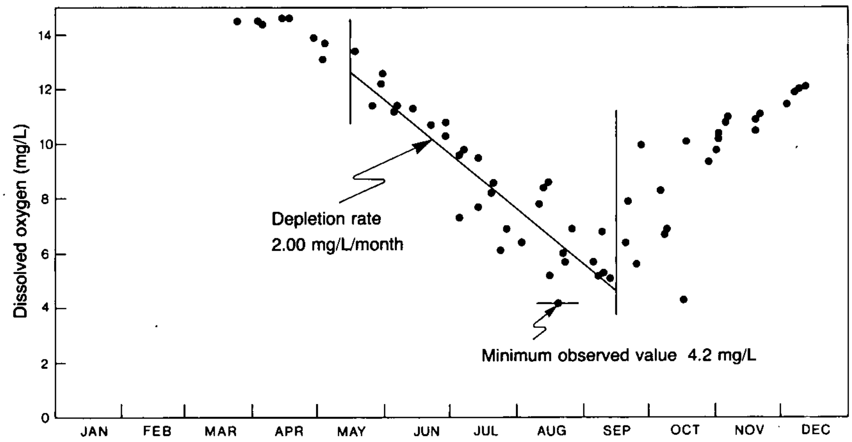


Figure 84. Seasonal cycle of dissolved oxygen in the bottom water of Prince Edward Bay (Lake Ontario), 1966 to 1975. CCIW data.

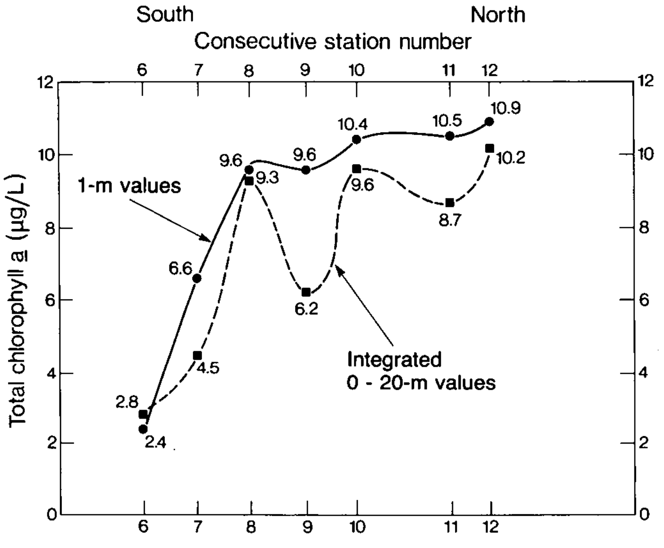


Figure 85. Total chlorophyll *a* in transverse section "A", June 20, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

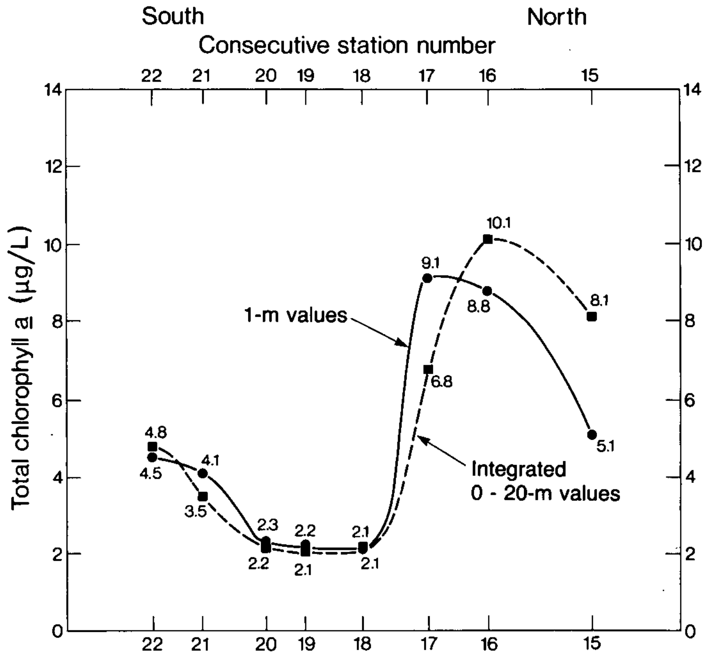


Figure 86. Total chlorophyll *a* in transverse section "B", June 20 and 21, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

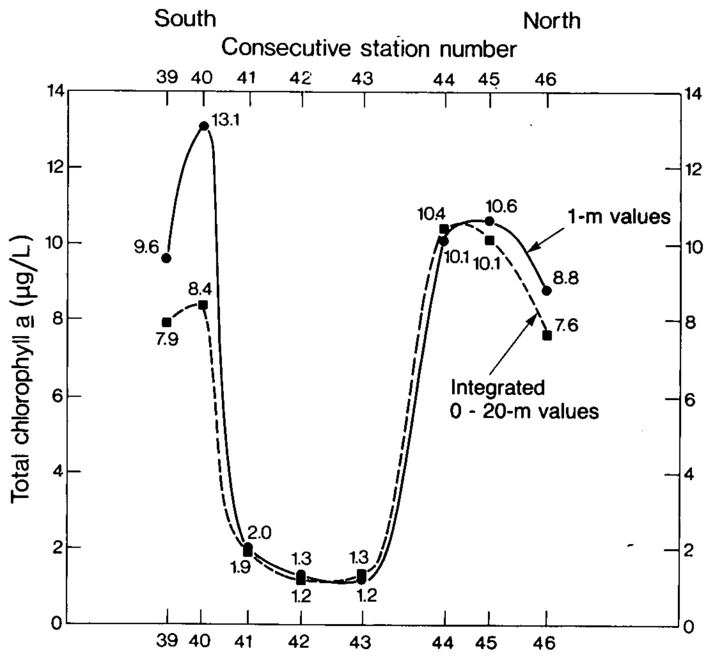


Figure 87. Total chlorophyll *a* in transverse section "C", June 22 and 23, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

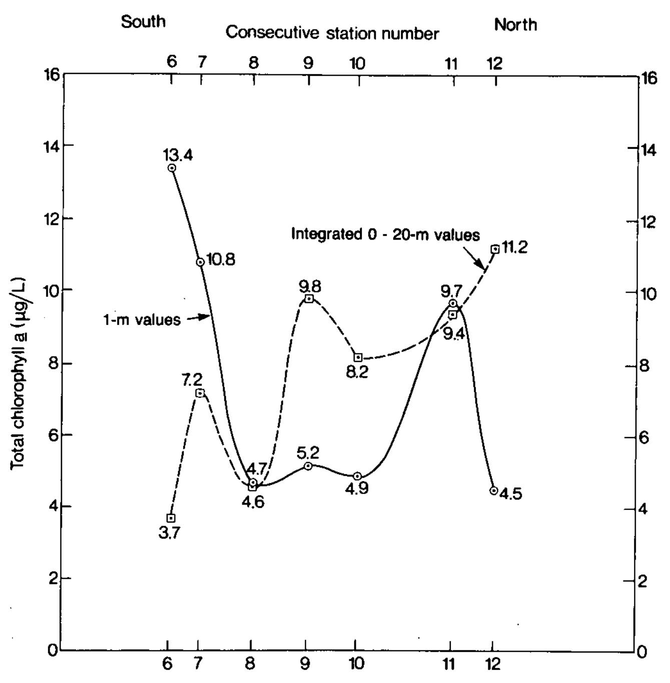


Figure 88. Total chlorophyll *a* in transverse section "A", July 18, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

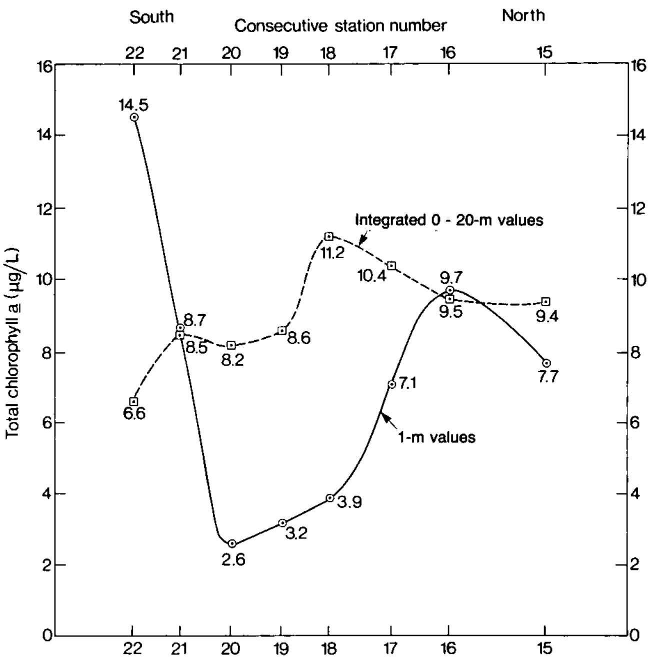


Figure 89. Total chlorophyll *a* in transverse section "B", July 18 and 19, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

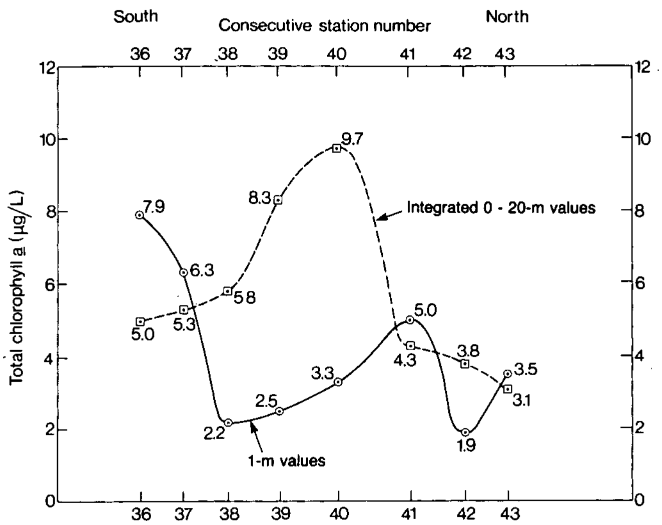


Figure 90. Total chlorophyll *a* in transverse section "C", July 20 and 21, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

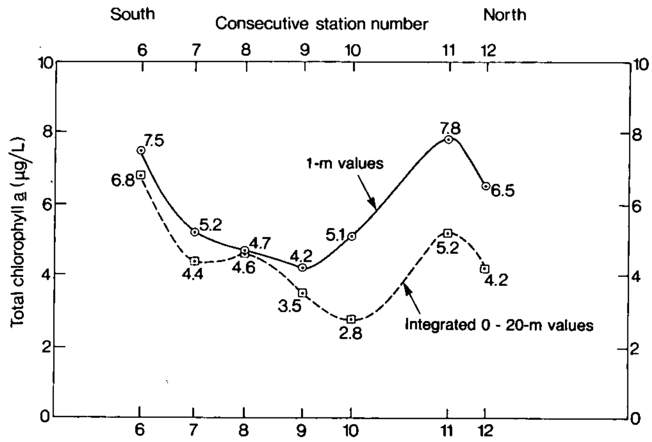


Figure 91. Total chlorophyll *a* in transverse section "A", September 6, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

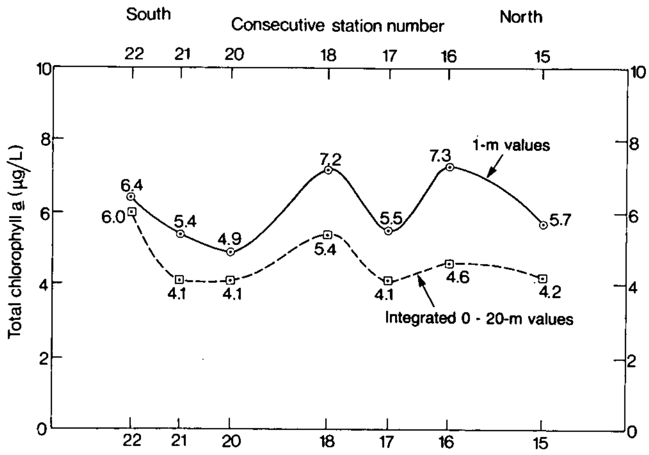


Figure 92. Total chlorophyll *a* in transverse section "B", September 6 and 7, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen.*

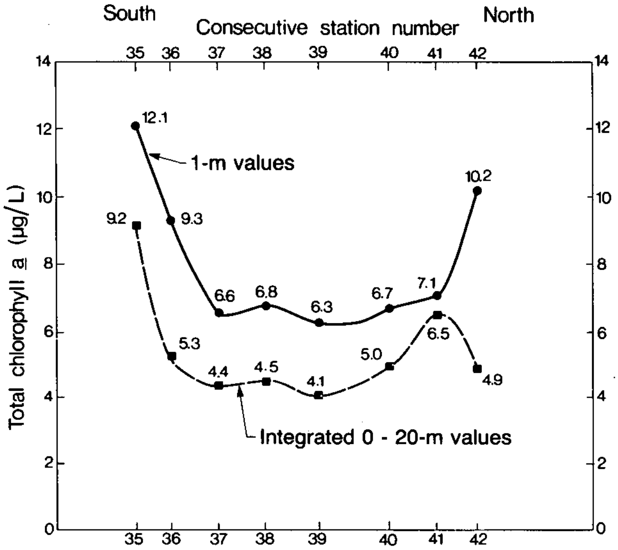


Figure 93. Total chlorophyll *a* in transverse section "C", September 8 and 9, 1972: comparison of 1-m values and integrated 0 to 20-m values. The *Martin Karlsen*.

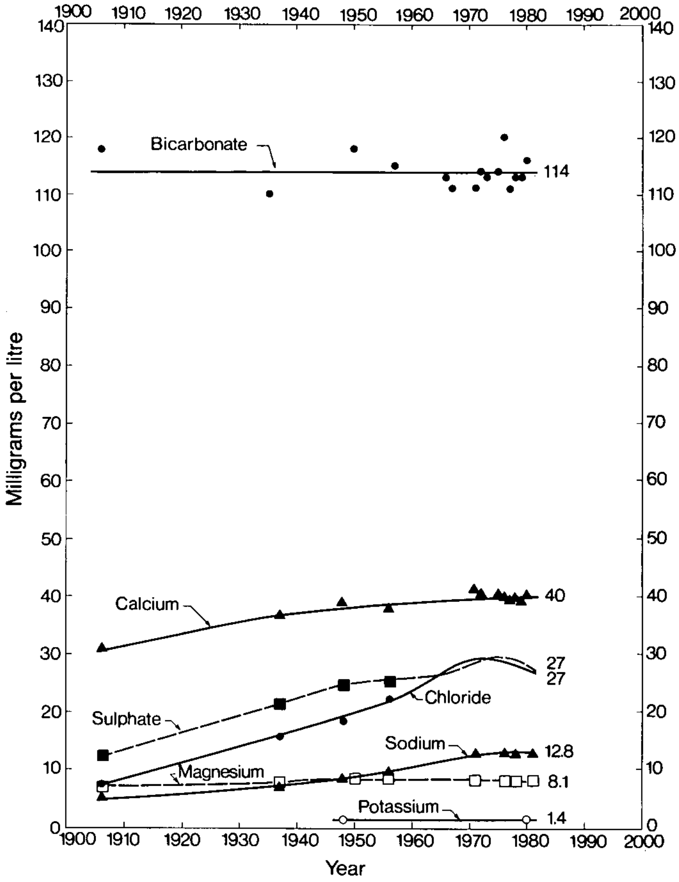


Figure 94. Trends in the concentrations of seven major ions, Lake Ontario, 1906 to 1981.