# LAKE ONTARIO ATLAS:
## Chemistry

Eric R. Allen

1977

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# LAKE ONTARIO ATLAS MONOGRAPHS

THE LAKE ONTARIO ATLAS consolidates much of the available data on Lake Ontario into a series of monographs intended to be useful to industry and government. The eight monographs use graphics to aid interpretation of large amounts of data and to present information in summary form. The final product, a meld of the monographs, will be a nontechnical, graphic atlas for Lake Ontario.

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# ABSTRACT

*THE CHEMISTRY MONOGRAPH provides an analysis of long and short-term variations in chemical and water quality characteristics of Lake Ontario. The loading of nutrients, major ions, trace elements and synthetic organic compounds is given special attention. The environmental influences of tributary rivers, waste discharges and atmospheric precipitation are assessed. This monograph will be useful for limnology, water pollution control, water treatment and use and land use planning.*

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# LAKE ONTARIO ATLAS: Chemistry

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# Abstract

The chemical and water quality characteristics of Lake Ontario reported prior to the International Field Year for the Great Lakes (IFYGL, 1972-1973) study have been reviewed and summarized. The low surface-to-volume ratio of this lake has allowed it to retain oligotrophic characteristics based upon biological parameters. However, some of the chemical parameters, including the nutrient inputs and concentrations, suggest that eutrophication is imminent. In general, the water quality of Lake Ontario is good and projected increases in the loadings of major ions do not pose a threat to the use of this natural water resource during the rest of this century. The input of trace materials, such as the heavy metals and refractory organic compounds, is cause for concern since a significant contribution is made by an uncontrollable source, namely atmospheric precipitation. More stringent controls on the discharge of phosphorus, trace elements and synthetic organic compounds is recommended to preserve the integrity of Lake Ontario for the continued benefit of all users of its waters.

## Introduction

The effect of man's increasing industriousness and desire for higher living standards has had a noticeable effect on the water quality of the Great Lakes as on other water bodies across the nation. Concern over environmental changes and their consequent effects on the Great Lakes dates back to the last quarter of the nineteenth century, when depletion in size and quantity of certain varieties of fish was noted. More recently the impact of man's activities upon localized areas of the Lake Ontario environment, such as the pollution of bays, harbors and tributaries, has been reported. Much less is known, however, about the lakewide deterioration in water quality or the accelerated eutrophication as proposed by Beeton (1961). Information on environmental quality and chemical changes is, therefore, sorely needed in order to assess the influence of man's activities on the lake waters. An assessment of changing chemical characteristics should not only enable a determination of the cause of the change to be made, but also should suggest the means of combatting future deterioration.

Surprisingly little information exists on the chemical state of Lake Ontario prior to the mid 1950s. Before the surge in chemical measurement activity some 20 years ago, most of the available information came from the required routine monitoring of water quality properties at municipal water intakes and from a few isolated limnological studies. Even now problems arise in assessing the early data due to discontinuities in water quality records; and the frequent changes in analytical methods and instrumentation that have occurred in recent years. Thus, as a result of improvement in techniques it is difficult, if not impossible, to compare and correlate early data with recent measurements. Nevertheless, extensive limnological studies of Lake Ontario have been undertaken during the last thirty years that warrant collation and review of this wealth of information in a summarized form in one document.

Lake Ontario is unique among the Great Lakes in as much as the water quality of the lake is determined not only by its immediate environment but also by the water quality of the four upper Great Lakes, and particularly by Lake Erie. The combined effluents of the upper lakes flow into Lake Ontario via the Niagara River. Thus, the pollution abatement controls necessary to preserve the environmental quality of Lake Ontario must be much more widespread than for the other Great Lakes and the overall changes or effects must be assessed much more carefully to determine cause. In reviewing and assessing changes in chemical characteristics which affect water quality it is necessary to classify the changes in properties into appropriate environmental categories. Beeton (1969) has suggested the following classification: (1) pollution of inshore areas, including harbors and tributaries; (2) long-term changes in open waters of the lake; and (3) long-term changes in the sediments. Note that immediate improvement in the management and control of municipal and industrial waste discharges will have an effect only on the first category (1). These short and long-term environmental influences will be borne in mind as the review progresses.

In preparing this report extensive use was made of the "Annotated Bibliography of Lake Ontario Limnological and Related Studies", Vol. I - Chemistry by Proto and Sweeney (1973). In addition, two recently published reports, "Lake Ontario Environmental Summary, 1965" by Casey, Fisher and Kleveno (1973) and "Report to the International Joint Commission on the Pollution of Lake Erie, Lake Ontario and the International Section of the St. Lawrence River", Vol. 3, (1969), served as major sources of reference material and reliable data.

## 1. Purpose

The purpose of this review is to summarize and make available in one document the chemical, physicochemical and water quality characteristics of Lake Ontario. Subsequently, this information will be condensed and incorporated into an Environmental Atlas of Lake Ontario. It is to be hoped that the data presented here will provide investigators in the future with a suitable basis for estimating "background" levels and predicting trends in individual chemical constituents and collective water quality parameters of Lake Ontario. Such information is not only useful for planning future research, but is a requirement for the preparation of environmental impact statements. In addition, areas where information is sparse, contradictory or non-existent will be identified which should help investigators determine whether or not additional measurements or monitoring of the lakes' chemical properties are either necessary or desirable.

## 2. Scope

Some of the data incorporated into this review extend back into the latter part of the nineteenth century, whereas other more specific parameters have been measured only recently, in the last decade or so. Nevertheless, in most cases a sufficient number of determinations have been made to warrant collecting and presenting this information here. This summary may then be used to obtain an estimate of the previous measurement activity for the properties considered, as well as for estimating present and future levels, seasonal variations and annual trends in the chemical constituents of Lake Ontario's waters. Also, it is expected that the information contained in this review will be useful to those planning future studies of the lakes' chemistry by identifying gaps in our knowledge and inconsistencies in available data.

It was not intended that this review be a complete and exhaustive treatise, which could be a monumental task for anyone to undertake, but rather it is meant to be a reasonably detailed summary containing what is believed to be the most representative and consistent data on chemical parameters presently available. Wherever possible, trends in chemical characteristics of the lake are quantitatively estimated and present levels of chemical constituents and water quality parameters suggested. In addition data is presented concerning concentration distributions at the surface and variations with depth for lakewide, mid-lake and certain off-shore stations. In some cases, such as for the chemical nutrients, the magnitude of seasonal variations is identified together with annual trends. Also, relevant chemical data pertaining to lake sediments and estimates of chemical inputs from tributaries, waste discharges and precipitation are presented. A complete listing of reference sources used in compiling the data for the figures and tables presented is given in an Appendix to this review.

Although it is recognized that many factors govern the viability of the lake's ecosystems, of which the chemistry is just one contributor, neither the physical nor biological characteristics of the lake nor their interdependence and interactions have been considered here, except where they may affect chemical measurements. These related topics will be described in detail elsewhere, in an accompanying series of monographs. Chemical data obtained during the International Field Year for the Great Lakes (IFYGL 1972-1973) is not included in this review, unless published prior to September 1975. It is expected that a summary of the results from this most recent series of closely coordinated and concerted international efforts to study the Great Lakes will be made available through a publication by the National Oceanic and Atmospheric Administration, US Department of Commerce, in the near future.

### 3. Acknowledgements

The author is greatly indebted to Ms. Bonnie Friedman, Ms. Daria Barsigian and Mr. Brian Biittner of the State University of New York at Albany, for their dedicated effort and painstaking care taken in literature searching, collecting, tabulating and plotting much of the chemical data contained in this report. To accomplish this task within a reasonable period of time would have been impossible without their assistance. The continual advice and encouragement given by Ronald Stewart, Project Director, throughout this undertaking was deeply appreciated. Support for this work through the Office of Sea Grant, National Oceanic and Atmospheric Administration, US Department of Commerce is gratefully acknowledged.

## Physical Features of Lake Ontario and its Environment

### 1. Morphometry

Lake Ontario is the last and most easterly of the west-to-east progression in the Great Lakes chain system. This lake is fed mainly by the Niagara River and discharges into the St. Lawrence River. It straddles the international boundary between New York State, United States of America, situated on the south and east shores, and the Province of Ontario, Canada, situated on the north and west shores of the lake. This water body is located between 43° and 44°N latitude, 76° and 80°W longitude.

It is a relatively narrow lake, approximately 305 kilometers (km) (190 miles [mi]) long by 85 km (53 mi) wide, with its long axis aligned in an east-west direction, see Figure 1. In surface area it is the smallest of the Great Lakes, having been variously estimated to be in the range 19,000 to 19,700 square kilometers ($km^2$) (7,340 and 7,600 square miles [$mi^2$]). In this report we shall use a mean lake surface area of 19,400 $km^2$ (7,500 $mi^2$). Due to its large mean depth, reported to lie between 84 and 91 meters (m) (276 and 300 ft), the lake contains a volume of water corresponding to about 1630 cubic kilometers ($km^3$) (391 cubic miles [$mi^3$]), using the more preferred, lesser mean depth value. This is more than three times the volume of water in the larger, but much shallower, Lake Erie. The drainage basin serving Lake Ontario, the Niagara and St. Lawrence Rivers is estimated to cover from 76,500 to 90,100 $km^2$ (29,500 to 34,800 $mi^2$). In this review the larger latter basinal area is preferred. The elevation of the lake's surface is 75 m (246 ft) above sea level, whereas, at its deepest-point it is approximately 175 m (574 ft) below sea level.

It is apparent in Figure 1 that Lake Ontario consists of two longitudinal basins. A western basin encompassing almost two thirds of the lake with a maximum depth of 192 m (630 ft) and a smaller, more sharply defined eastern basin with a maximum depth about 244 m (800 ft.) A ridge, apparently geologically controlled, with a maximum sill depth of 165 m (540 ft) separates these basins. The more gradual bathymetry of the western basin as well as the difference in depths are attributed to different sedimentation rates in the two basins. The greater part of the shallow waters is at the northeastern end of the lake. Differentiated glacial scour during the Pleistocene era accounts for the south side of the lake being steeper than the north side.

A hypsometric curve, relating fractional surface area with depth, for the main part of Lake Ontario is shown in Figure 2. For the most part this curve is almost linear and, thus, the fractional surface area can be equated to the fractional volume of the water mass. This curve also indicates a very important physical characteristic of Lake Ontario, namely, the large volume of water mass available per unit surface area. Taking an average depth for the epilimnion (the upper layer of a thermally stratified lake) of 20 m (66 ft), then it is seen that about 85 percent of the lake's water mass resides below this level. This property has a marked influence on the chemical and biological systems existing in the lake. For example, a large reserve of oxygen is stored in the hypolimnion (the lower layer of a thermally stratified lake), which makes it unlikely that a serious overall depletion of available oxygen will occur, except possibly in very localized areas. Similarly, a large nutrient reserve may be built up in the hypolimnion due to the small surface growing area available to biota relative to the volume of this reservoir.

## 2. Hydrology

The major hydrological influences on Lake Ontario are quantitatively identified in Table I. It is seen that the greatest factor influencing the lake environment is the Niagara River accounting for about 80 percent of the total inflow. Estimates of the Niagara River mean annual discharge rate range from 5,490 to 5,750 $m^3/sec$ (194,000 to 203,000 $cu \cdot ft \cdot sec^{-1}$[cfs]). Both of these values are correct for specific circumstances. The former value refers to the mean annual flow at the head of the Niagara River draining Lake Erie; whereas the latter value is the total outflow from the Niagara River Basin into Lake Ontario, which includes municipal and industrial discharges into the upper Niagara River and the outflows from Twelve Mile Creek and the Welland Canal in Ontario, Canada.

TABLE I

The Water Budget of Lake Ontario

| | INPUT | |
|---|---|---|
| WATER SOURCE | $m^3/sec$ | (cfs) |
| Niagara River Basin (US and CAN) | 5,750 | (203,000) |
| Oswego River (US) | 176 | ( 6,200) |
| Trent River (CAN) | 118 | ( 4,200) |
| Black River (US) | 108 | ( 3,800) |
| Genesee River (US) | 77 | ( 2,700) |
| Other tributaries, waste discharges (US and CAN) | 208 | ( 7,300) |
| Atmospheric Precipitation | 516 | ( 18,200) |
| Total, all sources | 6,950 | (245,400) |
| WATER SINK | OUTPUT | |
| St. Lawrence River | 6,420 | (226,600) |
| Evaporation* | 530 | ( 18,800) |

*Bruce and Rodgers (1962)

The Niagara River flow is steady throughout the year due to the upstream damping influences of the upper lakes and power plants. The uniform discharge of the Niagara River into Lake Ontario imposes a virtually steady state gradient flow from the southwestern inlet to the lake to the northeastern outlet at the St. Lawrence River. The latter, being the natural outlet for the entire Great Lakes system, has a mean annual outflow to the Atlantic Ocean estimated to be 6,600 $m^3/sec$ (233,000 cfs). This flow, however, includes a contribution of 180 $m^3/sec$ (6,400 cfs) by tributary rivers flowing into the St. Lawrence River basin. There are only four other major rivers serving the Lake Ontario drainage basin. These are, the Oswego River, which drains the Finger Lakes Region; the Black River, which drains the western Adirondack Mountains; the Trent River, which drains part of Central Ontario, Canada; and the Genesee River, which drains the Appalachian Front. However, rainfall over the lake and runoff via small rivers and streams draining the sedimentary rocks surrounding the lake accounts for substantially more inflow than the major rivers combined, excluding the Niagara River.

The mean annual precipitation in the lake basin is approximately 79 cm (31 in), but varies considerably from year to year. In general, the west-central part of the basin has the lowest precipitation values whereas the Adirondack Mountains and the Appalachian Front show the highest values. According to Brunk (1964), about one-half of the drainage basin rainfall becomes streamflow. Over the lake itself the average annual precipitation is about 84 cm (33 in). Losses by evaporation have been estimated to be approximately equal to precipitation rates. A simplified residence or retention time, defined as the time required to displace all the water in the lake, may be calculated by dividing the lakes' volume by the average discharge rate. Thus, assuming the volume of Lake Ontario is 1630 $km^3$ and the net drainage rate is 6,420 $m^3/sec$, then

$$\text{Average residence time} = \frac{1630 \times 10^9}{6420 \times 3.15 \times 10^7} \text{ years} = 8.1 \text{ years}$$

However, this estimate assumes displacement of lake water with no mixing or loss of fresh water from the lake during this period. In practice this is not the case as mixing with existing water does occur and some of the inflow will be discharged at the St. Lawrence River before it reaches the same composition as the lake water. Also during summer stratification the inflowing water is mainly confined to the upper, epilimnion layer and little mixing will occur with the deeper water. The latter would, thus, be retained for much longer periods than predicted above. Models taking some of these factors into account predict longer residence times of the order 20 years for a 90 percent depletion in lake concentrations. However, considering the effects of stratification and net circulation the actual retention time for a parcel of water must be at least 15 years. This suggests that even if the discharge of polluted waters into the lake ceased it would still take many years before the lake approached natural levels.

The level of Lake Ontario has been routinely and systematically measured since the mid-nineteenth century. The range in monthly mean values is 2 m (6.5 ft). Annual cycles display low monthly mean levels in winter and high values in summer. The annual mean values have shown variations up to 1 m (3 ft).

## 3. Thermal Structure

Lake Ontario is a dimictic lake. It has a surface temperature above 13°C (55°F) in summer and below 4°C (39°F) in winter, a large thermal gradient and two seasonal top-to-bottom overturns or vertical circulation periods, one in the spring and the other late in the fall.

During the summer the lake water is stratified into three distinct and definable layers, as shown in Figure 3. The upper surface layer called the epilimnion, is uniformly warm and well-mixed and aerated by wind-induced circulation and turbulence. The mean thickness of the epilimnion is sometimes defined by the depth of the 10°C isotherm.

During the fall cooling period the epilimnetic waters cool to 4°C (the maximum density of water), sink and displace and mix with the deep waters of the lake, creating an overturn. The lower bottom layer called the hypolimnion consists of cold, dense, relatively stable undisturbed water. In this layer the temperature is fairly constant from the lake bottom almost to the thermocline. The hypolimnion is largely insensible to wind and sun action due to the intervening epilimnion and thermocline. During summer stratification the water mass of the hypolimnion (about 85% of the total in Lake Ontario) is physically and chemically isolated from the surface waters. The intermediate layer, separating the epilimnion and hypolimnion, is a region of high temperature gradient called the thermocline. By definition the temperature gradient in the thermocline is 1°C per meter or larger. In Lake Ontario the average temperature gradient in the strongly developed summer thermocline is between 1 and 2.5°C per meter and extends over a temperature interval of 6 to 8°C. The average depth of the thermocline under these conditions is approximately 17 meters. However, the mean depth and thickness of this transitory layer varies during the summer stratification period.

A typical annual cycle of Lake Ontario temperatures near the surface and in bottom waters is shown also in Figure 3. A large temperature difference ($\sim$ 20°C) in the summer indicates a strong stratification is occurring. It can also be seen that in winter, after the fall overturn, a weaker, reverse gradient, thermal stratification takes place when surface temperatures drop below 4°C. However, for practical purposes the lake is considered to be isothermal during winter. Although the surface water may occasionally cool to 0°C in winter, Lake Ontario does not usually freeze over, except in localized areas.

Typically, the lake begins to stratify in late May and reaches its maximum heat content in August. By September, the epilimnion begins to cool and continues cooling until the temperature gradient becomes unstable. The fall "overturn" occurs late in November and is usually induced by a lake storm. Similarly, in May, when surface waters warm up to 4°C the spring "overturn" occurs. It should also be pointed out here that during the winter and early spring, when the epilimnetic surface waters are below 4°C, a vertical thermal barrier or bar will be set up in the vicinity of warmer inflowing waters (Rodgers 1965 1966; Casey, Fisher and Kleveno 1973). Thus, the warmer inflowing water will be cooled by mixing with the cooler lake water until the temperature of the inflow is reduced to 4°C, at this point the inflow water will sink and create a strong vertical circulation which effectively separates the warmer inflowing water from the main body of the colder lake water. This situation can occur locally or lakewide and may persist for many weeks as the bar moves towards the center of the lake. The condition prevents the circulation and mixing of the pollution-laden inflowing waters to the detriment of near-shore communities and activities. A similar, but weaker, reverse thermal bar situation is apparent in the fall when inflowing waters are below 4°C and epilimnion temperatures are above this level.

### 4. Climate

The climatology of the Great Lakes Basin has recently been reviewed by Phillips and McCulloch (1972). Specifically, the Lake Ontario basin is generally considered to have a continental climate. The presence of the lake, however, has a moderating effect consisting of the influences of a marine climate as evidenced by its temperature, humidity and air circulation. In the summer months heat is stored up in the lake, which reaches a maximum thermal content after the maximum surface temperatures are observed (Rodgers and Anderson 1961 1963). This heat is then released to the atmosphere during the late fall and early winter as the lake cools. The annual cycle of heating (March to September) and cooling (September to March) phases delays both the onset of cold weather in the fall and of warm weather in the spring. Upper and lower extremes of air temperatures are modified by this "lake effect" so that the daily as well as the long-term ranges of temperatures are less than expected for a continental climate at this latitude. The average range is between 21°C (70°F) in July and -4°C (25°F) in February. In the summer months rarely do temperatures reach 38°C (100°F), whereas, in winter seldom do temperatures drop to -18°C (10°F). The "lake effect" also causes increased cloudiness during cold weather, which accounts for the enhanced frequency and severity of snowfall in this region in winter. A principal source of rainfall in the basin is due to cyclonic systems, which follow the St. Lawrence storm track and transport moisture from the Gulf of Mexico.

The average wind speeds on the lake vary from 11 to 16 km per hour (7 to 10 mph) in summer and from 16 to 19 km per hour (10 to 12 mph) in winter. These winds in winter are predominantly from the southwest and west with a high frequency of northerly components along the north shore and southerly components along the south shore. In summer, the wind direction frequency pattern is similar to that in winter although high frequencies of northwesterly and northerly winds predominate over the northwestern part of the lake and southwesterly winds are dominant in the northwestern section of the lake. The wind speed and direction over the lake play a major role in determining the circulation patterns and mixing of surface waters, which in turn affects the movement and distribution of pollutants and other materials either being discharged into or residing in the lake. The net circulation pattern during summer stratification is apparently counterclockwise around the lake (Casey, Fisher and Kleveno 1973) according to long-term lakewide current and wind metering data obtained between August 1964 and November 1965. During isothermal conditions, however, the net surface flow is eastward with a bottom return flow westward, that is, a vertical circulation develops.

### 5. Geology

The Lake Ontario basin is entirely of erosional origin, with the lake preferentially situated along an outcrop seam of soft Ordovician (400 million years) shale bedrock of the Paleozoic era. The long axis of the lake is oriented parallel to the strike of the rocks, which dips southward.

Excavation of the lake bed along the axis of a former valley of glaciers occurred in Pleistocene time (2 million years). Retreat of the last glacier from this valley about 13,000 years ago initiated the known history of the present lake basin. In all probability the basin first drained via its present route when the St. Lawrence River valley became ice-free some 10,000 years ago. Niagara dolomite around the southern edge of the lake, as evident at Niagara Falls, forms a rim that gradually declines eastward. The superficial geology or present sediment distribution on the lakebed is the result of marine, glacial and lake deposition as well as erosion since the lake was formed.

### 6. Population

Although much of the watershed use in the Lake Ontario basin is agricultural, several large metropolitan areas border the lake. Toronto and Hamilton are situated in the western part of the basin and Rochester lies on the south shore.

This area was settled earlier than the other Great Lakes basins and boasted a population of more than one million by the 1830s. The rate of increase in population, however, was not as great as that for the more heavily industrialized basins of Lakes Erie and Michigan. Nevertheless, the Lake Ontario basin has experienced steady population growth during the last century, as shown in Figure 4. Projections suggest that there will be a doubling in population on the US side of the basin (1.3%/year) and a tripling on the Canadian side (3.8%/year) in the 60 years between 1960 and 2020. Population estimates for the Buffalo metropolitan area prior to 1950 are not included in Figure 4. According to Beeton (1969) these numbers should be included in the demographic figures for the Lake Ontario basin, as most of Buffalo's municipal and industrial wastes enter the Niagara River and, thus, they will have a greater impact on Lake Ontario than on Lake Erie.

The greatest Canadian population pressure extends around the western side of the lake from the Niagara frontier to the east of Oshawa, Ontario. This highly populated arc includes the two major centers of urbanization, Hamilton and Toronto. Similar pressures are expected on the south side of the lake as the metropolitan areas of Rochester and Oswego-Syracuse grow. A megalopolis stretching from Rochester to Oshawa may be a reality by the turn of the century as the basin population climbs over the 10 million mark. This growth could have serious and far reaching consequences on the water resources of the Lake Ontario region.

## Chemical Characteristics of Lake Ontario Water

### 1. Introduction

The chemistry of the inflowing and lake waters determines the various uses for this water as well as the types of life it can support. In fact, the most significant properties of natural waters are usually determined by the quantity of dissolved materials, such as minerals, which they contain.

This, in turn, can affect the overall natural, agricultural and technological productivity of the region.

Lake Ontario, being last in the chain of Great Lakes, receives large quantities of pollutants not only from the upper lakes but also from its own drainage basin. Although it has a large volume and diluting capacity, higher concentrations of conservative elements are found here relative to the upper lakes. Non-conservative elements, including nitrogen, phosphorus and carbon, are removed from the lake water by sedimentation. Thus, despite large polluting inputs from the Niagara River and the Toronto, Rochester, Hamilton metropolitan areas, the chemical characteristics are changing only slowly.

The chemistry of materials in lake waters is part of an overall dynamic ecological system, where all interdependent species are continually varying and adjusting to biological, physical and chemical constraints. For example, many of the chemical elements and compounds are involved in a complex biogeochemical system, where they are constantly interacting and being transformed. Thus, the measurement of any particular specie represents only that portion that is existing in a specific phase of the system at that time and under those particular conditions. Such measurements do not completely describe the quantities or speeds of elements or compounds as they are transported through the various parts of the biogeochemical system. For this reason, chemical parameters alone are less useful than is desired for the critical evaluation of the water quality of a large lake. The concept of availability of elements or compounds, rather than the concentration of dissolved substances, appears to be more important in a lake as opposed to a stream or river. This is because of the long residence times experienced by materials in large lakes.

The common unit used to express the content of dissolved substance is the part-per-million (ppm), which is a measure of the number of parts, by weight, of material in one million parts, by mass or volume of water. This unit is used interchangeably with the concentration unit, milligrams per liter (mg/ℓ), as the density of water is unity ($1 gm/cm^3$) at 15°C (59°F). Similarly, the parts-per-billion (ppb) unit corresponds to micrograms per liter (μg/ℓ), with negligible error involved in the conversion. It should be pointed out here that a statistical analysis of water chemistry data (Strachan 1973) has shown that the greatest errors in measurements of chemical constituents result from sampling of the water rather than from analytical methods.

With regard to water quality certain general characteristics are apparent in the Lake Ontario basin. During the summer, when the lake is stratified, the chemical characteristics of the surface (epilimnetic) and bottom (hypolimnetic) waters differ markedly. However, in the spring and fall the difference in chemical properties is less apparent because of the rapid vertical circulation and mixing occurring during the overturns. This feature is common to many deep lakes situated in temperate climatic regions. In addition, the near-shore and the interior waters of the lake constitute quite different water quality zones. The former zone is strongly influenced by local pollution sources, tributary inflows and relatively higher temperatures. These influences contribute to high biological activity and varying water quality around the perimeter of the lake. The main body of the lake, however, appears to be impervious to inflow except for that due to the Niagara River. There is little variation in water quality across the lake, from the western to the eastern basin, suggesting that lake constituents are homogeneously mixed. Indeed, the outflowing St. Lawrence River generally reflects the quality of water found in Lake Ontario.

## 2. Eutrophication

The overall process of enrichment of plant nutrients in natural waters, resulting in increased biological populations and productivity, is called eutrophication. Thus, an increase in the rate of addition of essential nutrients such as nitrogen, phosphorus, silicon and carbon, in their various dissolved forms, can accelerate plant and algal growth and reproduction. The extent of eutrophication is usually determined by the least available of the necessary elements, called the "limiting" nutrient. The concentration of the latter determining the extent of biological activity. For this reason nitrogen and phosphorus are considered to be the most significant nutrient elements and their concentration ratio is used to indicate their relative importance.

Eutrophication may occur naturally or as a result of man's influence, through waste disposal and agricultural practices. Although natural eutrophication is considerably slower than that induced by man, sediment build-up in lakes and sedimentary rock drainage will enhance their eutrophic nature. Lakes may be classified according to the trophic system, depending upon the degree of plant nutrient enrichment and biological productivity. Lakes poorly supplied with nutrients and supporting little plant growth are described as being oligotrophic. They are characterized by clear waters, low biological productivity and consistently show high values (near saturation) for dissolved oxygen at depth throughout the year. Consistent with the latter property, populations of salmonid and coregonid fish are found in the bottom waters. On the other hand, lakes rich in plant nutrients and supporting a heavy aquatic plant growth are termed eutrophic. These lakes are characterized by a high biological productivity, turbid waters due to excessive growth of suspended algae (phytoplankton) and, during periods of restricted vertical circulation, show a depleted level of dissolved oxygen as a result of decomposition of the large amounts of organic material produced. Because of the oxygen deficiency at depth, during summer stratification fish fauna are restricted to warm-water species. In extreme cases of inshore eutrophication algae are so abundant that offensive odors are emitted, the water quality reduced and water intake lines clogged. Lakes with a moderate supply of nutrients, plant abundance and biological productivity, being intermediate between eutrophic and oligotrophic, are designated as being mesotrophic.

According to Beeton (1965) Lake Ontario exhibits some of the characteristics of a eutrophic lake, namely in water quality properties such as relatively low transparency, high total dissolved solids and high specific conductance. However, the biota and the high dissolved oxygen concentrations (90 to 100% saturation) at depth indicate oligotrophic characteristics. He has recently concluded (Beeton 1969) therefore, that Lake Ontario is best described as morphometrically oligotrophic (Rawson 1960).

### 3. Nutrient Chemistry

This class of substances, the aquatic plant nutrients includes nitrogen, phosphorus, silicon and carbon compounds, All of these elements are essential constituents of living organisms and their availability will determine biological productivity and, hence, the water quality of the lake.

#### a. Nitrogen

The element nitrogen is a component of all major classes of biochemical compounds, being a particularly important constituent in the structure of proteins and enzymes. As such it is a fundamental element in the metabolism of organisms, which involves the synthesis and maintenance of protoplasm. Apparently nitrogen chemistry is controlled largely by biochemical reactions in natural waters. For example, in the aquatic nitrogen cycle the oxidation and reduction of nitrogenous substances occurs primarily through enzymatic processes.

In addition to the aquatic forms of nitrogen, two external sources constitute important inputs of nitrogeneous materials to the lake. Atmospheric precipitation provides mainly ammonia and nitrate, and biological processes, such as nitrogen fixation and denitrification, provide mechanisms for the significant transport of potential nutrient materials across the air-water interface. However, it should also be noted that significant amounts of material can be transferred from the lake water to the atmosphere by the bursting of bubbles at the surface and separation of water droplets from the surface during periods of strong turbulence (Blanchard 1975).

Nitrogen exists in Lake Ontario water in five major forms: ammonia ($NH_3$) or ammonium ion ($NH_4^+$), atmospheric nitrogen ($N_2$), nitrite ion ($NO_2^-$), nitrate ion ($NO_3^-$) and organic nitrogen compounds. Thus, the nitrogen in the lake organisms and waters is present in several interconvertible oxidation states ranging from minus three (ammonia and amino compounds) to plus five (nitrate). For consistency all analytical data concerning nitrogenous compounds in the aquatic environment are usually presented in terms of the equivalent content of the element N. Thus, lake water analyses are usually confined to the measurement of ammonia nitrogen ($NH_3$-N), nitrite nitrogen ($NO_2$-N), nitrate nitrogen ($NO_3$-N) and total Kjeldahl nitrogen, TKN ($NH_3$-N plus organic N). Total N usually refers to the sum of $NO_2$-N, $NO_3$-N and total Kjeldahl-N.

The cyclic seasonal interrelationships between nitrate, ammonia and organic nitrogen in both surface waters and at depth for Lake Ontario during 1965 have been reported by Casey, Fisher and Kleveno (1973). They observed that in the spring (57%-$NO_3$, 33%-organic N, 10%-$NH_3$) the surface layer is rich in nitrate, carried over from winter. By July (55%-$NO_3$, 38%-organic N, 7%-$NH_3$) an increase in organic nitrogen is apparent due to photosynthetic conversion of nitrate, with a corresponding decrease in nitrate and ammonia. In the fall (60%-$NO_3$, 30%-organic N, 10%-$NH_3$) the fraction of organic nitrogen in the surface layers decreases accompanied by an increase in nitrate and ammonia.

Vertical profiles during the spring of 1965 showed no specific trends in nitrate, organic nitrogen or ammonia. However, an inverse relationship between organic nitrogen and nitrate was suggested. In the summer, maxima in organic nitrogen and ammonia were observed just above the thermocline but nitrate concentrations were found to increase with depth to a maximum at approximately 150 meters (492 ft). Similar relative profiles were observed in the fall but nitrate concentrations had increased overall with a corresponding decrease in organic nitrogen. Nitrogen data reported by the Federal Water Pollution Control Administration (FWPCA) (Casey, Fisher and Kleveno 1973) consisted of weighted (in relation to total water mass) averages for samples taken at various depths. The seasonal values for the late spring, summer and early fall cruises in 1965 are shown graphically in Figure 5, together with estimates of the annual mean values for nitrogenous species.

### 1) Ammonia-Nitrogen

Free ammonia ($NH_3$) and the ammonium ion ($NH_4^+$) constitute ammonia-nitrogen ($NH_3$-N). They are produced primarily by the bacterial decomposition of organic waste matter originating in plants and animals. Bacterial counts show a direct seasonal correlation with $NH_3$-N concentrations which indicates the bacterial conversion of organic nitrogen to ammonia. Ammonia-nitrogen is mainly removed by aqueous oxidation, via the nitrite, to nitrate by microorganisms under aerobic conditions. The latter process accounts for the relative instability of ammonia in the water of Lake Ontario.

Prior to the late 1950s the only data available concerning surface $NH_3$-N concentrations in Lake Ontario originated from the routine monitoring of municipal water and waste treatment facilities. Data obtained at the City of Toronto, Island Filtration Plant during the period 1923-1964, has been reported by Schenck and Thompson (1965). These values for inshore surface $NH_3$-N (filled-circles), together with more recent lakewide (open circles) surface data are shown graphically in Figure 6 and as a bar graph of annual mean surface concentrations in Figure 7. It is seen that inshore surface $NH_3$-N values approximately doubled during the thirty-year period between 1925 and 1955, whereas prior to 1930 values averaged about 16 μg $NH_3$-N/l in the Toronto region. Since 1955 both inshore and lakewide $NH_3$-N values have been increasing exponentially, which should be a cause for concern, except that the concentrations observed are still well below the water quality criteria level of 0.40 mg $NH_3$-N/l set by the World Health Organization (1963). However, as pointed out elsewhere, this data is greatly influenced by localized pollution from the rapidly expanding urban and metropolitan areas of Toronto and may not be indicative of the state of the lake as a whole. In 1967, the Canada Department of National Health and Welfare (CDNHW) confirmed high concentrations of $NH_3$-N (> 50 μg $NH_3$-N/l) in surface waters near Toronto, Oswego and near the mouth of the Niagara River. Similar conditions have been reported to exist in the vicinity of Rochester and at the mouths of all tributary streams by FWPCA and in Canadian nearshore waters by the Ontario Water Resources Commission (OWRC). All of these observations appear to confirm the greatly increased influx and production of ammonia-nitrogen in 1965-66. Lakewide distributions, obtained by FWPCA, for $NH_3$-N during the period of anomalously high activity in the spring, summer and fall of 1965 are presented in Figures 8, 9 and 10, respectively. The distribution of median $NH_3$-N values for 1967 are shown in Figure 11.

Representative mid-lake surface values for $NH_3$-N have been obtained only since 1957. All available data are displayed graphically (open circles) in Figure 6 and as a bar graph of annual mean values (shaded bars) in Figure 7. Matheson (1962) has reported that uncontaminated water samples from Lake Ontario in general contained less than 50 μg $NH_3$-N/l. This is apparent from Figures 6 and 7, prior to 1960. However, since that time, mid-lake values for surface $NH_3$-N have apparently oscillated through two maxima. In 1961, a maximum of about 20 μg $NH_3$-N/l is observed followed by a much larger maximum of about 60 μg $NH_3$-N/l in 1965-66. Since 1966 offshore surface $NH_3$-N values have been steadily declining to a low of 8 μg $NH_3$-N/l in 1972. Thus, a 90 percent recovery from the large perturbation of 1965-66 in $NH_3$-N concentrations has taken about six to seven years. The reason for the large influx in 1965-66 is not clear at this time, except for the increasingly excessive discharge of sewage and industrial wastes into the lake prior to 1966. In which case, the decreasing trend in $NH_3$-N values since that time could be due possibly to the required incorporation of governmentally mandated pollution control equipment and practices at sewage and waste-water treatment facilities since the mid 1960s. Alternatively, if the 1965-66 phenomenon was an isolated incident then the return to normally observed levels could be due to natural cleansing and gradual displacement of pollutants in a time comparable to the estimated residence time for Lake Ontario. Studies of the St. Lawrence River in 1965 by FWPCA (10 to 420 μg $NH_3$-N/l) and in 1967 by CDNHW (0 to 275 μg $NH_3$-N/l, median 23 μg $NH_3$-N/l) showed that outflowing waters contained similar amounts of ammonia-nitrogen as the main body of lake water.

Ammonia and Kjeldahl-nitrogen values show opposite seasonal trends and peaks. In general, $NH_3$-N accounts for only 10 to 20 percent of Kjeldahl-nitrogen, which results in the much stronger influence of organic-nitrogen on seasonal Kjeldahl-nitrogen values.

### 2) Kjeldahl-Nitrogen and Organic Nitrogen

Total Kjeldahl-nitrogen (TKN) refers to the procedure for extraction of nitrogeneous materials and is a measure of organic-nitrogen plus ammonia-nitrogen. In most cases unfiltered samples of water are subjected to measurement, in which case the organic nitrogen component consists of soluble and particulate (insoluble) organic nitrogen. Organic nitrogen is that nitrogen which is chemically bound up in organic materials, ranging from simple chemical compounds such as urea to complex proteins. Organic nitrogen is made up of two fractions, the dissolved and the particulate phases. The latter component consists of both living and inanimate solids in suspension. Organic nitrogen in Lake Ontario is mainly of biological origin with lesser contributions from the discharge of municipal and industrial wastes. Thus, the concentration of organic nitrogen compounds as organic-N can be used as an indicator of the lake's primary production. Consequently, high organic-N values are usually found in nearshore areas where the greatest biological activity occurs and the highest values occur in the vicinity of intense urban and industrial developments and major stream estuaries. Like ammonia-nitrogen, most of the organic-nitrogen is found in the epilimnion. Oxidative decomposition of organic nitrogen compounds leads to the production of inorganic nitrate nitrogen.

Little information exists concerning Kjeldahl nitrogen values for Lake Ontario prior to 1965. Even since that time, few studies have been made. In 1965, FWPCA found total Kjeldahl nitrogen to vary between 0 and 0.80 mg N/l, with a mean of 0.23 mg N/l. Subsequently, CDNHW in 1967 observed values in the range 0.10 to 0.80 mg N/l, with a median of 0.295 mg N/l at the surface and 0.225 mg N/l in the hypolimnion. The values, shown graphically in Figure 12 and as a bar graph of annual means in Figure 13, are too few to suggest a trend but they do indicate a possible increase during the period 1965 through 1968. In general, values of total Kjeldahl-nitrogen are higher in nearshore waters than in mid-lake for the reasons presented above (see Figure 14). Also high turbidity values for inshore waters suggest that these higher values could at least in part be due to particulate organic material. The somewhat higher total Kjeldahl-N values for the epilimnion as opposed to the hypolimnion suggests that the algae make a large contribution to the organic nitrogen (Report to the International Joint Commission [RIJC] 1969). In support of this conclusion Kjeldahl-N and $NH_3$-N values showed two maxima, corresponding to peak periods of algal activity, in June and September 1967. The seasonal peaks were observed in the hypolimnion as well as in the epilimnion.

Measurements of Kjeldahl-N in the St. Lawrence River showed essentially the same values as found within Lake Ontario. The median values for total Kjeldahl nitrogen (ca. 300 µg N/l) reported to date fall in the same concentration range as the nitrate nitrogen, thus, accounting for approximately half of the total nitrogen measured. This range, however, is lower than that characteristic of eutrophic lakes reported by Stewart and Rohlick (1967).

Organic nitrogen data are usually obtained by subtracting $NH_3$-N values from total Kjeldahl-N values obtained from the same water sample and they usually account for 80 to 90 percent of the Kjeldahl nitrogen. FWPCA reported weighted averages 0.20 mg N/l, 0.21 mg N/l and 0.20 mg N/l for organic-N during the spring, summer and early fall cruises in 1965. However, they point out, that much of the organic nitrogen is situated in the epilimnion, and, thus, the use of weighted averages gives greater statistical weight to those samples taken from greater depths, that is, greater water mass and lower concentrations. Although these values do represent the amount of organic nitrogen residing in the water mass the corresponding unweighted arithmetic averages are somewhat higher at 0.26, 0.25 and 0.23 mg organic-N/l, respectively, reflecting the higher concentrations in surface water. Insufficient data exist in order to establish reliable current values and trends for organic-nitrogen. Reported values are shown graphically in Figure 15 and as a bar graph of annual mean values in Figure 16. Both representations suggest values averaging about 0.28 mg organic-N/l for the period 1965-1968; decreasing to approximately 0.08 mg organic-N/l in 1972. This observation correlates well with the decline in $NH_3$-N values since 1967. Typical distributions of organic nitrogen in surface waters of Lake Ontario during the spring, summer and fall of 1965 (Casey, Fisher and Kleveno 1973) are shown in Figures 17, 18 and 19, respectively.

### 3) Nitrite nitrogen

The inorganic nitrite ion ($NO_2^-$) is a transitory intermediate in the bacterial oxidation of organic nitrogen and ammonia to nitrate. It is of particular environmental importance as its presence in large amounts indicates substantial pollution from bacterial and organic sources. Nitrite nitrogen ($NO_2$-N) is seldom found, except at extremely low concentrations, in northern freshwater lakes. Apparently, the oxidative conversion proceeds sufficiently rapidly to completion under such conditions, that the resulting product nitrate ion is the principal form of inorganic nitrogen found in lakes. A median value of 2 µg $NO_2$-N/l in Lake Ontario water was determined by CDNHW in 1967. The highest concentrations (10 µg $NO_2$-N/l) being observed at the thermocline in August of that year. In nearshore areas, particularly off the western shoreline between Toronto and the Niagara River, values in excess of 4 µg $NO_2$-N/l were found, see Figure 20. Nitrite-nitrogen values in the St. Lawrence River corresponded closely to offshore Lake Ontario values, except near local pollution sources.

### 4) Nitrate nitrogen

The inorganic nitrate ion ($NO_3^-$) is the end product of the aqueous oxidation of nitrogenous materials. It is the most important state of nitrogen being the form most required and readily used by growing suspended algae (phytoplankton).

Studies performed near the beginning of this century, as reported by Clarke (1924), suggest that pre-1925 values for nitrate-nitrogen concentrations were about 300 µg $NO_3$-N/l. However, it was not until 1960 that additional reliable data became available. During the period 1960 to 1965 annual mean surface concentrations rose from 120 to 350 µg $NO_3$-N/l but since that time they have averaged about 140 µg $NO_3$-N/l. In 1965 FWPCA found high values for surface nitrate-nitrogen ranging from 30 to 870 µg $NO_3$-N/l with a median value of 350 µg $NO_3$-N/l, which corresponds to the enhanced ammonia and organic nitrogen concentrations found at that time. Subsequently, CDNHW in 1967 determined generally lower values in the range 0 to 285 µg $NO_3$-N/l with a median surface concentration of 165 µg $NO_3$-N/l; and in 1970 Chiomi and Chawla (1970) reported a similar median value of 149 µg $NO_3$-N/l for 1969-1970. The annual trend in surface nitrate-nitrogen values for the period 1960-1970 is shown graphically in Figure 21 and as a bar graph of annual means in Figure 22. All studies of Lake Ontario to date have shown a large (100-150 µg $NO_3$-N/l) depletion in nitrate-nitrogen concentrations in surface waters during summer stratification, see Figure 23. Depending upon the early spring content of $NO_3$-N, this component may be almost completely depleted throughout the epilimnion during the summer; and it apparently does not increase again until the thermal barrier to vertical circulation breaks down in the fall. Nitrate-nitrogen exists in the hypolimnion at generally higher concentrations than in the epilimnion and has been found to remain relatively constant throughout the summer with median values falling in the range 150 to 250 µg $NO_3$-N/l (CDNWH 1967). Recently, Shiomi and Chawla (1970) have reported a mean value of 207 µg $NO_3$-N/l in hypolimnetic waters for 1969-1970. In addition they reported a lake water maximum value of approximately 250 µg $NO_3$-N/l, obtained at a time when soluble nutrients are uniformly distributed vertically throughout the lake. Absolute concentrations of nitrate nitrogen as well as variations with depth, similar to those found in Lake Ontario, have been observed at the mouth of the St. Lawrence River (CDNHW 1967). Lakewide surface distributions of $NO_3$-N for the summer and fall of 1965, showing overall depletion in the former case and nearshore accumulation for the latter, are presented in Figures 24 and 25, respectively.

#### 5) Total nitrogen

Total inorganic nitrogen is the sum of the soluble nitrogenous constituents; ammonia, nitrite and nitrate-nitrogen concentrations, whereas total nitrogen usually refers to the sum of total inorganic and organic nitrogen, the latter containing an insoluble (particulate) component. According to Sawyer (1947), lakes with total inorganic nitrogen content less than 300 µg N/l (and inorganic phosphorus less than 45 µg $PO_4$/l) at the time of the spring overturn are not generally subject to excessive algal growth during the summer. In one respect these limiting values were exceeded in 1965-1966 for Lake Ontario, that is, inorganic-N was 400-480 µg N/l and inorganic-P was 39 µg $PO_4$/l. However, as noted later by Shiomi and Chawla (1970), the pre-overturn concentrations of these nutrients remained close to these limits in 1969-1970 (273 ± 10 µg N/l and 45 µg $PO_4$/l). Values for total nitrogen in Lake Ontario appear to be decreasing, however, from about 0.6 mg N/l in 1965 to 0.4 mg N/l in 1972, as shown in Figures 26 and 27.

### b. Phosphorus

Phosphorus, like nitrogen, is an essential constituent of all living organisms and plays an important role in the complex biogeochemical cycle of the lake. The various forms of phosphorus in the lake environment are not well known. In living organisms, however, the element exists mainly as a constituent of DNA (deoxyribonucleic acid). As such it is involved in cellular reproduction and protein synthesis as well as being an intermediary in the necessary energy transfer processes of respiration and photosynthesis. Phosphorus mainly occurs naturally in its fully oxidized state as the phosphate ion ($PO_4^{3-}$), although in a few cases organic phosphorus compounds and biologically reduced forms of phosphorus have been discovered. The majority of lake water analyses have been confined to the relatively simple measurement of soluble reactive phosphate as orthophosphate ($PO_4^{3-}$), with the insoluble component removed by filtration; and of total phosphorus (P) or phosphate ($PO_4$), which contains both dissolved and particulate components. The former measurement, usually written as $PO_4$-P, generally refers to the soluble phosphate in terms of the element P that occurs in aqueous solution in the inorganic forms $H_2PO_4^-$, $HPO_4^{2-}$, $PO_4^{3-}$, as well as sodium and calcium hydrogen phosphates. Total phosphorus, usually written as total-P, describes the phosphorus present as orthophosphate ions following acid digestion of unfiltered lakewater samples. The latter includes, therefore, both dissolved inorganic orthophosphate-phosphorus as well as polyphosphates and organically-bound phosphorus in particulate matter. It should be noted that in some cases phosphorus concentrations have been reported as phosphate in µg $PO_4$/l, these values may conveniently be converted to µg P/l by dividing by three.

The residual annual input of phosphorus to Lake Ontario is estimated to be $9.6 \times 10^6$ kg P/year for 1967, which amounts to about 25 percent of the total phosphorus present in Lake Ontario ($39.2 \times 10^6$ kg P), using an average lakewide concentration of 24 µg P/l. Although this fraction is large enough to cause an increase in total phosphorus content during the year, in general, total phosphorus concentrations have remained fairly constant throughout. This fact suggests that efficient processes are removing phosphorus at about the same rate as it is being acquired from tributary rivers, municipal and industrial discharges and precipitation.

Several mechanisms account for the removal of phosphate, as well as other materials, from the water mass but with a resultant enhancement in the overall chemical content of the total lake environment. These sinks for phosphorus include materials stored in biota and sediments as well as the soluble and suspended fractions. Thus, the biota may ingest soluble phosphate at the inflow from rivers and deposit bound phosphorus as sedimentary particles at the end of their life cycle. It has also been suggested that colloidal and larger clay particles may remove substantial quantities of phosphate ions from aqueous solution by chemical and physical adsorption, interstitial absorption and ion-exchange processes. In addition, other factors play important roles in the phosphorus cycle. For example, the element iron generally exists in surface waters as an organically stabilized ferric hydroxide hydrosol, but the oxidation-reduction potential ($E_h$), and to a lesser extent the proton activity (pH), will determine the form of the iron to be precipitated. When iron is precipitated under the highly oxidizing conditions existing in Lake Ontario, both ferric hydroxide and phosphate are formed, and the ferric hydroxide precipitate carries the phosphate ions with it as it settles to the bottom. Sutherland (1966) has shown that phosphate in Lake Ontario is in equilibrium with respect to the hydroxyapatite system [$Ca_{10} (PO_4)_6 (OH)_2$], in which case excess phosphate ions are removed by combination with metallic ions and subsequent precipitation to conserve the equilibrium in the water mass. It is fortunate that these processes as well as the complex overall equilibrium established in lake waters has been able to cope with man's polluting activities. The danger remains, however, that if any of the important controlling natural factors are subject to a major change then the overall equilibrium may shift with drastic consequences.

A major cause for concern regarding Lake Ontario is the possibility of eutrophication, where the accumulation of nutrients progressively increases the capacity of the lake to sustain a larger biomass. One way to control or abate the eutrophication process is to determine which of the necessary nutrients is deficient relative to the others and then to impose strict controls over the discharge of this limiting nutrient into the lake.

Measurements of the ratio of nitrogen to phosphorus in the protoplasm of algae suggest an ideal ratio of 15:1 for N:P. Based upon this result, Sawyer (1947) suggests that in lakes with N:P ratios less than 15:1, algae production would be limited by available nitrogen, whereas in those cases where N:P ratios exceed 15:1 phosphorus would be the limiting nutrient. Despite the usefulness of N:P ratios as indicators of limiting nutrients they should be interpreted with caution, as the biota can alter their relative demand for these nutrients in response to the relative supply. From measurements of soluble inorganic nitrogen and inorganic phosphorus during major lake studies in 1965, 1967 and 1969-1970, a mean ratio of N:P of about 22:1 is obtained, suggesting that phosphorus rather than nitrogen is the limiting nutrient in Lake Ontario.

As soluble phosphate in Lake Ontario is transitory in nature due to its involvement in the biogeochemical phosphorus cycle and its input to the lake from point sources is variable; then it appears that soluble phosphate levels determined at major lake input locations would make considerably better water quality indicators of the amount of available phosphate than lakewide phosphate criteria.

### 1) Inorganic Orthophosphate Phosphorus

Historical data on this component (inorganic $PO_4$-P) in Lake Ontario is limited to the last decade. FWPCA reported values ranging from 3 to 33 μg $PO_4$-P/l with a weighted average of 15 μg $PO_4$-P/l in 1965. Measurements in 1967 by CDNHW yielded values in a similar range, 0 to 37 μg $PO_4$-P/l but with a much lower median value of 2 μg $PO_4$-P/l in surface water and 12 μg $PO_4$-P/l in the hypolimnion. Shiomi and Chawla (1970) have reported values of about 15 μg $PO_4$-P/l in late winter under isothermal conditions, with values in the epilimnion falling to 1-2 μg $PO_4$-P/l during summer stratification to give an annual median surface concentration of 8 μg $PO_4$-P/l. Similar seasonal variations in soluble phosphate were observed in 1969-1970 but giving a larger median value of 11 μg $PO_4$-P/l. Thus, although soluble phosphate concentrations are uniform with depth during the spring overturn and achieve a maximum value in surface waters during the winter; they show a definite concentration gradient during summer stratification which is an inverse function of the thermal gradient. A typical seasonal variation in soluble phosphate phosphorus in surface and bottom waters is shown in Figure 28. Trends in measurements of soluble phosphate at the surface since 1965 are shown graphically in Figure 29 and as a bar graph of annual mean values in Figure 30.

Studies of the surface distribution of soluble phosphate indicate significantly higher values in near shore areas than in mid-lake, a typical distribution of reactive phosphate in 1965 is shown in Figure 31. Values as high as 20 μg $PO_4$-P/l were observed along the south shore in 1965 and reaching 30 μg $PO_4$-P/l at the mouth of the Niagara River in 1967. Similarly, along the north shore, in the vicinity of Toronto, values in the range 15 to 30 μg $PO_4$-P/l were observed in 1966-1967. In 1967, the St. Lawrence River values were found to fall in the range 0 to 10 μg reactive $PO_4$-P/l with a median concentration of 7 μg $PO_4$-P/l, except near local sources of pollution; which is identical to the overall median mid-lake value of 7 μg $PO_4$-P/l.

### 2) Total Phosphorus

The concentration range of total phosphorus measured in 1965 by FWPCA was 3 to 50 μg total-P/l with a depth-weighted average value of 18 μg total-P/l. Studies by CDNHW in 1967 showed values in the range 9 to 24 μg total-P/l with a median value of 15 μg total-P/l. More recently Shiomi and Chawla (1970) have reported concentrations averaging 25 μg total-P/l in both surface and bottom waters with a winter maximum of 26 μg total-P/l during 1969-1970. Thus, unlike soluble phosphate-phosphorus, total phosphorus remains at a reasonably constant concentration throughout the year and is uniformly distributed with depth at all times. In surface waters, soluble phosphate accounts for only about 10 percent total-P in early fall but reaches a maximum level of more than 60 percent total-P in mid-winter. Similarly, for bottom waters, soluble phosphate shows a maximum of 25 percent total-P in summer and rises to a maximum of 66 percent total-P in mid-winter. From these observations, it has been suggested (RIJC 1969; Shiomi and Chawla 1970) that the depletion in soluble phosphate during summer stratification corresponds to biological transformation into particulate organic phosphorus compounds. Total phosphorus concentrations determined since 1965 in offshore waters of Lake Ontario are shown graphically in Figure 32 and as a bar graph of annual mean concentrations in Figure 33. It can be seen that during the last decade total phosphorus concentrations are slowly increasing at a rate of 1 to 1.5 μg P/l or five percent annually.

The horizontal distribution of total phosphorus in Lake Ontario averages about 25 μg total P/l in offshore waters but nearshore values average about two to three times larger, falling in the range 30 to 150 μg total-P/l. In much the same manner as soluble phosphate, total phosphorus is enhanced near the shoreline by metropolitan, industrial and tributary discharges, as may be seen in Figure 34.

### c. Silicon

Silicon (Si) is one of the most abundant and widespread of the chemical elements found in the earth's crust but exists only in the combined state in nature. In natural waters it is found in the oxidized state as partially soluble silicate ($SiO_4^{3-}$), colloidal silica ($SiO_2$) and sestonic mineral particles. The solubility of the silicates, however, increases with the pH of the aqueous solution. Soluble or reactive silica ($SiO_2$), as determined in lake waters, is that form of silica which is available as a nutrient for algal growth in the dissolved or colloidal state and is usually reported as μg $SiO_2$/l. In Lake Ontario the primary natural sources of silica appear to be clay minerals (aluminosilicates) and dead diatom skeletons (Casey, Fisher and Kleveno 1973). Limiting concentrations of reactive silica for several diatom species have been determined by Lund (1965) to be in the range 20 to 40 μg $SiO_2$/l. However, attempting to control the input of silica into the lake is not a feasible approach to preventing eutrophication because natural processes, such as the dissolution of siliceous rocks, constitute a major inflowing source.

### 1) Soluble Silica

In 1965, FWPCA measured soluble silica values in Lake Ontario and found that depth-weighted mean values were highest in the spring (1.6 mg $SiO_2$/l) and progressively decreased through the summer and fall to 1.2 and 0.85 mg $SiO_2$/l, respectively. The high spring value correlated with the highest diatom populations observed and it was suggested that during this period silica was recirculated from bottom waters probably as diatom skeletal material. Reactive silica concentrations in the range from 0.02 to more than 2.0 mg $SiO_2$/l have been found in Lake Ontario since 1965. Mean soluble silica concentrations in the epilimnion vary from 100 to 400 μg $SiO_2$/l during the year with a minimum in late summer as shown in Figure 35. Median surface reactive silica concentrations range from 365 μg $SiO_2$/l in 1967 to 260 μg $SiO_2$/l in 1969-1970. In the hypolimnion, soluble silica concentrations are minimal in spring, correlating with good vertical circulation and uniform mixing, and rise to a maximum in the fall due to the sedimentation of dead organisms from the photic zone. During summer stratification soluble silica concentrations increase markedly with depth below the thermocline. Shiomi and Chawla (1970) have determined a median value of 415 μg $SiO_2$/l for bottom waters in 1969-1970. Trends in surface concentrations of soluble silica are shown in Figures 36 and 37.

The seasonal variations in horizontal surface distributions of soluble silica are similar to those found for the other available reactive nutrients, nitrate and soluble phosphate. In the winter and early spring when soluble silica concentrations are at a maximum, a general lakewide west-to-east decrease in values is observed. It has been suggested (Shiomi and Chawla 1970) that the higher values in the western region of the lake could be due to up-welling supplementing the replenishment of surface concentrations by vertical circulation in the fall overturn. In the late spring, depletion of reactive silica commences in nearshore waters relative to mid-lake, see Figure 38. This effect could be caused by increased biological activity in inshore regions, as a result of the thermal bar limiting vertical and horizontal circulation to shallow waters, and due to the higher temperatures and the greater relative photic zone available around the edge of the lake. As the summer progresses a continual lakewide depletion and a progressively more uniform distribution in soluble silica concentrations is observed, as shown in Figures 39 and 40.

### 4. Major Ion Chemistry

The observed concentrations of conservative elements, such as ionic species, are higher in Lake Ontario than in any of the other Great Lakes. This is not unexpected as the former, being last in the chain of lakes, receives the accumulated large amounts of pollutants discharged into the upper lakes via the Niagara River, its principal inflow, in addition to that from its own drainage basin. Concentrations of the major ions are, however, only a few percent greater in Lake Ontario than in Lake Erie, the excess being attributed to significant local sources such as the Toronto, Hamilton and Rochester metropolitan areas. The principal cations found in Lake Ontario are calcium ($Ca^{++}$), sodium ($Na^+$), magnesium ($Mg^{++}$) and potassium ($K^+$), which are associated with the following major anions, bicarbonate ($HCO_3^-$), chloride ($Cl^-$), sulfate ($SO_4^=$) and carbonate ($CO_3^=$), both sets of ions being listed in decreasing order of abundance. These ions almost completely account for the total soluble material and ionic content of the lake water as indicated by measurements of specific conductance and total dissolved solids. The latter properties, however, which are related to the total ionic content, will be discussed in detail in a later section which describes water quality measurements.

The earliest measurements of minerals in Lake Ontario (Beeton 1965) and in the St. Lawrence River (Hunt 1857) were made in the 1850s. Despite advances in analytical techniques and instrumentation during the last one hundred years, these early data are sufficiently reliable to indicate a stable ion content prior to 1910. Mean concentrations of the major ions in Lake Ontario in 1970 and their rates of change are summarized in Table II. It should be noted here that in order to gain insight into the overall material balance of cations with anions it is necessary to convert the mass concentrations of the ions into their ionic equivalent concentrations. This is accomplished by dividing a specific ion concentration in mg/l by the atomic (molecular) weight of the element(s) comprising the ion and multiplying by the ion valence (number of positive or negative charges on the ion) to obtain the equivalent concentration in milliequivalents per liter (meq/ℓ). As can be seen in Table II, within the experimental error of the individual ion measurements, all of the cations are accounted for by the anions observed, on an equivalent basis. However, the total mass concentration of principal ions is about 20 percent larger than that of dissolved solids. This discrepancy will be discussed later in the section describing dissolved solids measurements.

The most comprehensive historical survey of major ion concentrations in Lake Ontario is that compiled by Beeton (1965). Apparently from this review of early measurements there was little or no change in the content of major ionic species or dissolved solids concentrations in Lake Ontario from 1850 to 1910. However, since that time several ionic constituents of the lake water have increased markedly in concentration as a result

### TABLE II

Estimated Concentrations and Rates of Change
of the Principal Ions in Lake Ontario for 1970

| Ionic species | Concentration in 1970 | | Rate of change in 1970 | | |
|---|---|---|---|---|---|
| | mg/l | meq/ℓ | mg/l/10yrs (ppm/decade) | meq/ℓ/ 10 yrs | percent/ 10 yrs |
| $Na^+$ | 13.0 | 0.57 | +2.6 | +0.11 | +20 |
| $K^+$ | 1.4 | 0.04 | 0 | 0 | 0 |
| $Ca^{++}$ | 42.2 | 2.11 | +1.6 | +0.08 | +4 |
| $Mg^{++}$ | 8.0 | 0.66 | 0 | 0 | 0 |
| Total cations: | (64.6) | 3.38 | (+4.2) | +0.19 | +6 |
| $HCO_3^-$ | 114 | 1.87 | 0 | 0 | 0 |
| $Cl^-$ | 28.1 | 0.79 | +6.2 | +0.17 | +22 |
| $SO_4^=$ | 28.9 | 0.60 | +2.5 | +0.05 | +8 |
| $CO_3^=$ | 2.9 | 0.10 | 0 | 0 | 0 |
| Total anions: | (174) | 3.36 | (+8.7) | +0.22 | +7 |
| Total ionic content: | (239) | 6.74 | (+12.9) | +0.41 | +6 |
| Total dissolved solids: | 195 | -- | +9.3 | -- | +5 |
| Conductance at 25°C: | 328 micromho/ cm | -- | +13 micromho/ cm/decade | -- | +4 |

of the proliferating use of the Great Lakes as a repository for municipal, industrial and agricultural wastes. For example, the rate of increase in sodium and chloride ion concentrations has been climbing steadily since 1910 with an exponential accumulation rate of about 20 percent per decade, which corresponds to a doubling in their concentrations approximately every forty years. Calcium and sulfate concentrations, however, appear to have been increasing at a constant rate during the same period, corresponding to 1·6 ppm/decade and 2·5 ppm/decade, respectively. Magnesium, potassium, carbonate and bicarbonate ions, on the other hand, have remained fairly constant in their respective concentrations during the last sixty years. Consequently, the overall principal ion concentration in Lake Ontario is increasing at a rate of about five percent per decade, which corresponds to a doubling in the total ionic content every 140 years, if present discharge practices persist. These variations in ion concentrations, as expected, closely parallel the increases in ion concentrations found in Lake Erie, which drains into and provides the main inflow to Lake Ontario. The greatest contribution to the observed increase in total ion concentration is clearly from the sodium and chloride ions, which could be in part a result of road deicing operations in the Lake Ontario Basin (Bubeck et al. 1971).

Although the steady accumulation of these major ions in Lake Ontario is not an immediate cause for concern they do, because of their conservative nature, provide a good indicator of the magnitude of the associated discharge of the more harmful organic and nutrient pollutants into the Great Lakes. A comparison of the estimated total ion content(6.7 meq/ℓ) for Lake Ontario in 1970 with the average for rivers worldwide (2.8 meq/ℓ) as reported by Dobson (1967) shows this lake to have an above average salinity. The lake's total ion content, however, is still adequately low for municipal, industrial and agricultural consumption, being only 0.5 percent of that in sea water.

The principal ions in Lake Ontario are distributed uniformly both horizontally and vertically throughout the lake, except in certain localized near-shore areas in the proximity of outflows and tributary streams (Palmer 1972). Thus, Lake Ontario may be considered to be homogeneously mixed with respect to its ionic constituents.

### a. Principal Cations

#### 1) Sodium and Potassium

Sodium and potassium are reactive alkali metals, consequently they never exist in a free state in nature. These monovalent cations are abundant in lake waters because the majority of their compounds are soluble. Their solubility and the absence of important aquatic chemical or biological systems capable of significant removal of these elements from solution accounts for their even distribution throughout the lake. The primary natural source of the alkali metals is probably the sedimentary rocks in the Great Lakes Basin. This view is supported by the fact that calcium is the dominant cation, exceeding sodium by a factor of four, based upon equivalent concentrations.

Until the early 1940s sodium and potassium were measured together and reported as the sum of these alkali metal ions. However, the subsequent development of flame photometric methods has enabled these ions to be determined separately since the late 1940s. Thus, it was found that the exponential increase in sodium plus potassium concentrations observed prior to 1950 was solely due to increasing sodium ion concentrations, see Figure 41.

Trends in concentration measurements during the period 1900 to 1970 for sodium plus potassium, sodium and potassium ions are shown in Figure 41. Bar graphs of annual mean potassium and sodium ion concentrations from 1947 to 1969 are displayed in Figure 42. According to Beeton (1965), prior to 1900 the concentrations of sodium plus potassium in Lake Ontario were constant at 6 mg/l, but from 1900 to the early 1940s sodium plus potassium concentrations were increasing exponentially at a rate of 13 percent per decade. However, since 1950, when $[Na^+] = 9$ mg/l, sodium ion concentrations have been increasing exponentially at a rate of about

20 percent per decade. This accelerating rate of accumulation correlates well with the mean values of 11.5 mg Na/l determined by CDNHW in 1965 and 12.2 mg Na/l reported for 1967 by RIJC (1969), and extrapolates to a concentration of 13 mg Na/l for 1970. Unlike sodium, potassium has remained reasonably constant at 1.4 mg K/l over the twenty year period from 1950 to 1970.

Both sodium and potassium are homogeneously distributed at the surface as well as with depth, throughout the lake as shown in Figures 43 and 44, respectively.

Similarities between the exponential accumulation of both sodium and chloride ions support the conclusion that man's activities influence the water quality of Lake Ontario by the discharge of municipal and industrial wastes and the use of salt in seasonal road deicing operations (Bubeck et al. 1971).

2) Calcium

Although calcium can be leached from nearly all rocks it is usually prevalent in water originating from regions with deposits of limestone, dolomite and gypsum. Areas where granite or siliceous sand are dominant tend to have very low calcium levels in the waters. In limestone regions, such as that found in the Lake Ontario Basin, calcium concentrations may range from 30 to 100 mg Ca/l. Most calcite ($CaCO_3$) minerals, however, contain varying amounts of the phosphate-containing mineral apatite ($Ca_5(PO_4)_3F$) and as the $CaCO_3$-$CO_2$-$H_2O$ equilibrium imposes a pH near eight on the aqueous solution, this explains why natural solutions of calcite create highly-productive alkaline lakes. Thus, the presence of calcium is important to the biological productivity of lake waters, also it is important in the trophic classification of lakes. Usually waters with less than 10 mg Ca/l are oligotrophic whilst those with more than 25 mg Ca/l are distinctly eutrophic. Although Lake Ontario is definitely in the latter category with respect to calcium ion concentrations other factors, as discussed previously, also have an important bearing on the overall classification of this uniquely deep lake.

Beeton (1965) has reported that prior to 1900 calcium ion concentrations in Lake Ontario were constant at 31 mg Ca/l. Trends in calcium concentrations from 1900 to 1970 are shown in Figure 45 and the same data are displayed as a bar graph of annual mean concentrations for the period from 1906 to 1968 in Figure 46. The data suggest that since 1900 calcium ion concentrations have been increasing linearly at a rate of 1.6 ppm Ca/decade, which compares favorably with a value of 1.5 ppm Ca/decade reported by RIJC (1969) for the period from 1910 to 1960. Interpolated values from the curve in Figure 45 indicate mean values averaging seven percent less than those reported by CDNHW (45 mg Ca/l) for 1965 and RIJC (43 mg Ca/l) in 1966. Extrapolation of the curve provides a mean value of 42.2 mg Ca/l for 1970.

The constant values for calcium concentrations prior to 1900 are probably a good measure of the natural calcium contribution to the lake water or the natural "background" level, whereas the increases observed since that time reflect man's increasing industriousness and activities in the Great Lakes region which have markedly influenced the water quality of Lake Ontario.

Calcium is evenly distributed throughout the lake as shown in Figure 47 for the fall of 1964. There is a minor seasonal variation in calcium content with depth during the summer stratification period. This effect is attributed to the increased solubility of calcium carbonate as the water temperature rises and subsequent precipitation of the calcium, to maintain the $CaCO_3$-$CO_2$-$H_2O$ equilibrium. Similarly, hardness, alkalinity and specific conductivity values simultaneously indicate reduced calcium concentrations in the warmer epilimnion layer.

### 3) Magnesium

Magnesium in natural waters originates from the leaching of igneous and carbonate rocks, in much the same way as calcium. Indeed in hardness measurements magnesium is measured along with calcium unless special precautions are taken. In regions where the natural sources mentioned above are common, the magnesium concentrations in natural water are found in the range 5 to 50 mg Mg/l. Magnesium is an essential element in plant growth and development and is particularly important in its function as the nucleus of the chlorophyll molecule.

Measurements of magnesium ion concentrations from 1900 to 1970 are shown in Figure 48 and the same data are displayed as a bar graph of annual mean concentrations for the same period in Figure 49. It is readily apparent that during the last forty years or so magnesium ion concentrations in Lake Ontario have remained reasonably constant at a mean level of 8 mg Mg/l. Because of the large variations (>20%) in reported measurements this value does not seriously conflict with reported mean values of 9.2 mg Mg/l by FWPCA for 1965 and 6.4 mg Mg/l by RIJC for 1966. The lack of any significant increase in magnesium concentrations during the period of observation suggests that it mainly originates from natural sources.

## b. Principal Anions

### 1) Chloride

The element chlorine is present in the waters of rivers and lakes as the chloride ($Cl^-$) monovalent anion. The primary natural source of chloride is the leaching of this element from soil and rocks by precipitation run-off. However, during the last fifty years man-made sources, such as municipal and industrial waste discharges and deicing operations, have overshadowed natural sources in the Great Lakes region. Chloride salts are in general very soluble in water and are not known to be controlled by any naturally occurring chemical or biological systems. Thus, concentration variations may arise only through evaporation or by dilution and for these reasons the chloride ion is considered to be a good pollution tracer element.

It is to be expected that Lake Ontario has the highest chloride concentrations of all the Great Lakes as a result of the conservative nature of the ion and the fact that the accumulated pollution discharged into the Great Lakes system eventually reaches Lake Ontario. Just as in the case of the other major ions, Beeton (1965) has reported that chloride concentrations remained relatively constant at 7 mg Cl/l until about 1900. Since that time, however, chloride concentrations have been increasing exponentially at a rate of 22 percent per decade. This trend is shown graphically in Figure 50 for the period 1900 to 1973 and as a bar graph of annual mean concentrations for the same period in Figure 51. Interpolation from the curve in Figure 50 provides a mean value of 26.1 mg Cl/l for 1966 which agrees remarkably well with the extensive lakewide chloride analyses conducted by FWPCA in 1965 and CDNHW in 1966 and 1967. In these studies median values of 25, 26 and 26.8 mg Cl/l were determined for 1965, 1966 and 1967, respectively. The interpolated mean value for lakewide surface chloride concentration for 1970 is 28.1 mg Cl/l.

Chloride is evenly distributed throughout the lake at the surface and with depth. A typical surface distribution is shown in Figure 52 for the summer of 1965. It can be seen that minor enhancements in chloride occur near shore due to the influence to metropolitan area discharges and tributary stream outflows. Although chloride is usually mixed homogeneously with depth, higher concentrations have been found occasionally at the surface of the lake.

Despite the fact that chloride concentrations are increasing at an accelerating rate the levels are still well below the maximum permissible criteria levels (250 mg Cl/l) for public water supplies. This trend suggests that there is little cause for concern in the immediate future with regard to increasing chloride levels in Lake Ontario. Nevertheless, the recent chloride increases do indicate an excessive associated dumping of the more hazardous and potentially reactive organic and nutrient pollutants into the Great Lakes system. A water quality model describing the build-up of chloride in the Great Lakes as a result of anthropogenic discharges has been developed recently by O'Connor and Mueller (1970).

### 2) Bicarbonate and Carbonate

Bicarbonates in aqueous solutions are mainly responsible for the alkalinity of natural waters. Bicarbonate ions ($HCO_3^-$), as well as carbonate ions ($CO_3^=$), are found in rivers and lakes because of the prevalent natural abundance of carbonate minerals and the ubiquitous presence of atmospheric carbon dioxide. In this section we are mainly concerned with the concentration of the bicarbonate ion measured as mg $HCO_3$/l. In lakes such as Lake Ontario the alkalinity is mainly due to the abundant bicarbonate ion. However, alkalinity measurements, which will be discussed later, are usually expressed in terms of the equivalent mass concentration of calcium carbonate in mg $CaCO_3/\ell$. Measurements of bicarbonate concentrations from

1906 through 1968 are plotted in Figure 53 and the same data are represented by a bar graph of annual mean concentrations in Figure 54. It is apparent that bicarbonate levels in Lake Ontario have remained unchanged at a mean value of 114 mg $HCO_3$/l for about 60 years. This observation suggests that bicarbonate concentrations are controlled mainly by natural sources. Carbonate concentrations have been measured in a few instances and found to occur at an average concentration of 2.9 mg $CO_3$/l. There is little reason to believe that this value will vary significantly on an annual basis.

### 3) Sulfate

In most natural waters the sulfate anion ($SO_4^=$) is usually the next most abundant anion to the bicarbonate ion. Natural sources of sulfate include the dissolution of sulfur-bearing sedimentary rocks, the oxidative degradation of organic sulfur compounds and the aqueous oxidation of hydrogen sulfide. In addition to the natural loading, in recent years increasing quantities of sulfate have been discharged into the lakes in the form of municipal, industrial and agricultural wastes and by the precipitational scavenging of atmospheric sulfur dioxide and particulate sulfates. The element sulfur is cyclic in the natural lake environment involving interchange between the various oxidation states ranging from organically-bound reduced forms on the one hand to the highest oxidation state, the sulfate ion. The latter is the common form of sulfur taken up by higher plants and is probably of equal importance to algae. However, although sulfate may be reduced to hydrogen sulfide by certain anaerobic bacteria or it may precipitate out with calcium in concentrated solutions, neither of these removal mechanisms appear to be significant in Lake Ontario.

Beeton (1965) has reported that the sulfate content of Lake Ontario was relatively constant at 13 mg $SO_4$/l between 1850 and 1900, but since 1900 it appears that the concentration of this anion has been increasing steadily at a rate of 2.5 ppm/decade. This trend is clear from the observational data plotted in Figure 55 for the period from 1906 to 1968. This conclusion, however, is in conflict with the suggestion by Dobson (1967) that the rate of increase of sulfate has declined since 1930. Interpolation of the curve in Figure 55 yields a mean value of 28.2 mg $SO_4$/l for 1967 which is in good agreement with the median value of 27.5 mg $SO_4$/l reported by RIJC (1969) for the same year. Extrapolation of the curve gives a mean value of 28.9 mg $SO_4$/l for 1970. The same data are reduced to a bar graph of annual mean sulfate concentrations for the same sixty year period in Figure 56.

Sulfur-34 isotope studies by Nriagu (1973) indicate an enrichment of this isotope in certain lakes of the Great Lake system but the increases do not correlate with the progression in sulfate abundances from Lake Superior to Lake Ontario.

Although few investigations have been made of either the horizontal or vertical distributions of sulfate in Lake Ontario, it is reasonable to assume that this constituent is uniformly mixed throughout. The levels of sulfate in the lake, despite their steady increase over the years are still well below the maximum permissible limit (250 mg $SO_4$/l) for drinking water. Thus, there does not appear to be any cause for concern regarding the accumulation of this specie in the near future.

### 5. Trace Elements

Compilations of the concentrations of trace metals and elements measured in the Lake Ontario region have been reported by the US Public Health Service for 1962-1963, CDNHW in 1967, Kopp and Kroner (1969), Chau et al. (1970), Meloon et al. (1970 1971) and Jenne (1972). The data collected by the US Public Health Service was obtained by sampling at Massena, New York on the St. Lawrence River. In most cases the concentrations of trace elements were higher than the lakewide measurements made subsequently by other investigators. It would appear, therefore that these early measurements might be in error due to the contaminating influence of local sources. The best available data have been summarized in Table III, which lists for each trace element measured an estimate of the mean concentration at the surface, the standard deviation from the mean and the number of reports used in obtaining the estimate. The latter quantities provide a measure of the significance and reliability of the tabulated data. In their most extensive and detailed investigation of the trace elements in Lake Ontario, Chau et al. (1970) have found that the majority of these minor constituents are fairly evenly distributed at the surface of the lake and they are homogeneously mixed with depth, thus, only surface values are presented in Table III.

#### a. Iron

Iron is a trace metal in rivers and lakes which plays an important role in several aquatic biogeochemical systems. It occurs in natural waters as a result of bacterial action, in the presence of organic matter, upon iron-containing rocks and soil. In the reduced form, as the ferrous ion ($Fe^{++}$), iron is quite soluble in water. However, this form of dissolved iron is readily oxidized to the insoluble ferric state ($Fe^{+++}$) and precipitates out of solution. Thus, in oxygen-rich waters such as those of Lake Ontario, the oxidation and sedimentation processes occur readily and little iron is usually present in solution. Iron can also exist in surface waters as ferric oxide hydrosol stabilized by organic colloids. The compound of iron that is precipitated in natural waters depends principally upon the oxidation-reduction potential (Eh) of the solution (Garrels 1950) and to a lesser extent upon the pH (hydrogen ion activity). Under the highly oxidizing conditions found in Lake Ontario, ferric hydroxide and ferric phosphate are formed. The ferric hydroxide precipitates out and carries phosphate ions with it by coprecipitation as it settles to the bottom of the lake. In this way the iron cycle has an influence on the phosphate cycle.

Total iron has been measured routinely at water treatment plants on Lake Ontario for many years, as well as in infrequent isolated lakewide investigations. Available data for total iron concentrations are summarized as a bar graph of annual mean total iron concentrations for the period

## TABLE III

Estimated Mean Trace Element Concentrations in Micrograms per Liter, at the Surface in Lake Ontario, 1967-1970

| Element | Symbol | Mean Concentration μg/l (ppb) | Standard Deviation | Number of Reports |
|---|---|---|---|---|
| Aluminum | Al | 84 | 4 | 1 |
| Arsenic | As | < 17 | ---- | 1 |
| Barium | Ba | 24 | 4 | 1 |
| Beryllium | Be | <0.05 | ---- | 1 |
| Boron | B | 23 | ---- | 1 |
| Bromine | Br | 0.05 | 0.01 | 1 |
| Cadmium | Cd | 0.09 | 0.03 | 7 |
| Chromium | Cr | 0.74 | 0.29 | 6 |
| Cobalt | Co | 0.11 | 0.14 | 6 |
| Copper | Cu | 6.4 | 4.3 | 6 |
| Fluorine | F | 120 | 5 | 4 |
| Iodine | I | 2.9 | 1.1 | 2 |
| Iron | Fe | 50 | 7 | 10 |
| Lead | Pb | 4.8 | 5.3 | 6 |
| Lithium | Li | 2 | 1 | 4 |
| Manganese | Mn | 0.47 | 0.15 | 6 |
| Mercury | Hg | 0.13 | 0.07 | 1 |
| Molybdenum | Mo | 1.08 | 0.13 | 1 |
| Nickel | Ni | 2.9 | 1.4 | 6 |
| Silver | Ag | <0.4 | ---- | 1 |
| Strontium | Sr | 182 | 7 | 6 |
| Vanadium | V | 0.03 | 0.02 | 1 |
| Zinc | Zn | 11 | 6 | 6 |

1906 to 1964 in Figure 57. Prior to 1943 the total iron concentration averaged 50 μg Fe/l. However, in 1960 a much higher concentration of 400 μg Fe/l was reported which has steadily declined to a mean value of 60 μg Fe/l in 1964. The earlier mean values probably reflect the concentration of total iron in 1970 (ca. 50 μg Fe/l).

The two values shown for 1967 and 1969 in Figure 57 refer to biologically-available iron and not to total iron. Biologically-available iron has been determined by CDNHW in 1967 to vary from 4 to 25 μg Fe/l with a mean value of 7 μg Fe/l (RIJC 1969). The distribution of biologically-available iron determined in the spring, 1967 is shown in Figure 58. High iron concentrations are associated with the high population density and industrial activity at the western end of the lake. Otherwise the biologically-available iron is fairly evenly distributed throughout Lake Ontario.

### b. Fluoride

Fluoride is a typical trace element ion found in rivers and lakes. In much the same manner as chloride, it may be leached from rocks and soil. The measured concentrations of this halogen anion in Lake Ontario, however, are considerably lower than for the chloride ion. A bar graph of annual mean concentrations measured from 1961 to 1969 is presented in Figure 59. The measurements suggest that fluoride concentrations have remained constant during the observation period with a mean value of 0.12 mg F/l. It must be concluded, therefore, that the fluoride found originates mainly from natural sources.

### c. Mercury

Mercury is a typical toxic heavy metal trace element found in rivers and lakes receiving waste discharges. It has attracted considerable attention in the recent past because of its accumulation in the aquatic fauna via the food chain and the subsequent transfer to animals, birds, and man (Bligh 1971; Jenne 1972). The distribution of trace quantities of this element in Lake Ontario during 1970-1971 is shown in Figure 60, where it is seen that the influence of anthropogenic sources is widespread.

It is important to note here that in general the concentrations of trace elements in Lake Ontario are substantially below the maximum permissible limits for those elements where potable water quality criteria have been established by such bodies as the US Public Health Service (1962), the World Health Organization (1963) and the Committee on Water Quality Criteria, Federal Water Pollution Control Administration (1968).

## 6. Organic Compounds

The term organic compounds encompasses a wide variety of industrial, commercial, and domestic products, by-products and wastes including insecticides, herbicides, detergents, agricultural chemicals, fats, waxes, oils and petrochemicals. Some of these organic materials that are discharged into the aquatic environment are chemically or biologically degraded, but the majority of these compounds are refractory, that is, they are resistant to biochemical conversion, and thus persist and accumulate in natural waters.

During the last thirty years there has been a rapid expansion in industrial productivity as a result of the invention of new synthetic organic products and product applications as well as the development of more economical and efficient processes for existing products. These innovations have been accompanied by a steadily increasing demand in both the quantity and type of synthetic organic materials required for industrial, commercial and agricultural applications. It is not surprising, therefore, that these compounds as well as the manufacturing by-products and wastes are finding their way into the aquatic environment in ever increasing amounts through industrial and municipal waste discharges and agricultural land drainage. Since many of these synthetic organic compounds are resistant to both conventional water and waste treatment practices and natural water purification processes their persistence and accumulation constitutes a real threat to the health of human and aquatic communities. Some of these organic chemicals have shown toxic effects at very low concentrations and because of the variety of compounds found and their persistence the possibility of synergistic effects becomes important. In addition, even at fairly low concentration levels (200 μg/l) organic chemicals impart an unpleasant taste and odor to public water supplies which will become an important factor as water reuse must increase to meet the new demands for potable water by expanding communities. Thus, it is desirable to minimize, if not eliminate, the discharge of organic-pollutants into natural water supplies, such as rivers and lakes. This can be accomplished only by the imposition of more stringent controls at the pollutant sources, if we are to prevent the build-up of refractory organic compounds and the accompanying deterioration in water quality (Weaver et al. 1965; Breidenback et al. 1967).

In general there is a lack of information concerning the nature and amounts of the individual organic contaminants in the Great Lakes. This is in part due to the time-consuming, elaborate and sophisticated techniques required for the unequivocal identification and quantification of organic contaminants present at low concentrations in water. Since it would be an extremely difficult, if not impossible, task to define and assess the chemical and toxicological nature of all organic pollutants present in Lake Ontario, the usual procedure is to measure organic contaminants in bulk by extraction with chloroform. In this case the results are expressed in terms of the bulk amount of organic material extracted from one liter of water as carbon chloroform extract (CCE). These results, however, should be regarded as minimum values as the recovery efficiency for chloroform is low for certain organic constituents. Individual organic contaminants in water have been concentrated, separated and analyzed by different techniques. One of these involves adsorption on a low-flow carbon filter which extracts and concentrates the organics from the water. Recovery of these adsorbed compounds is by elution from the carbon filter by appropriate organic solvents, such as chloroform or ethyl alcohol. Fractions of the eluate are then examined by infrared spectrophotometry or chromatography for the identification of specific compounds.

Sparse data are available on bulk organic pollutants in the Lake Ontario region measured by CCE. The Federal Water Pollution Control Administration has determined a maximum concentration of 54 μg/l at Massena on the St. Lawrence River in 1962-1963. More recently much higher maximum (156 μg/l) and mean (91 μg/l) values have been reported in the vicinity of Toronto for 1967-1968. Although these values are somewhat higher than have been found in clean surface and ground waters (25 to 50 μg/l) they are still within the permissible limit (200 μg/l) set by the US Public Health Service Drinking Water Standards (1962). The total organic material in Lake Ontario, however, is greater than that found in the other Great Lakes (Robertson and Powers 1967).

Unlike the organic pollutants discussed previously, suspended organic matter (organic seston) consists mainly of phytoplankton. Organic seston is collected on Millipore filters, dried and determined gravimetrically by the weight difference before and after ignition. In 1965 FWPCA found "dry" organic seston values near the surface of Lake Ontario in the range 0 to 8 mg/l with a mean value of 1.1 mg/l. Particulate organic material averages 3 to 10 times lower concentrations than soluble organic material (Robertson and Powers 1967).

Certain types of organic contaminants, such as pesticides, herbicides, and phenols have received special attention because of their accumulation and resultant deleterious effects on the aquatic food chain and animal life (Henderson et al. 1969; Reinert 1970; Bligh 1971; Veith et al. 1974; Haile 1974). These classes of organic contaminants are discussed in greater detail below.

### a. Pesticides and Herbicides

This group of organic materials has proliferated both in number and quantity during the last thirty years. Many commercial pesticide preparations, particularly the chlorinated hydrocarbons, are highly resistant to biochemical degradation. Herbicidal and pesticidal compounds are usually applied to foliage and the soil, but in some instances they are applied also to water masses or courses. Contamination of water resources results from application by aerial spraying, agricultural run-off from eroded areas, percolation through the soil into aquifers and industrial and municipal waste discharges. Most surface waters in the United States during the period 1958 to 1965 contained chlorinated hydrocarbon insecticides, particularly DDT and dieldrin and certain herbicides, such as 2,4-D (Breidenbach et al. 1967). Although concentrations were generally below 1 µg/l these compounds have been used in amounts sufficient to assure their trace presence in water bodies for many years after their use has been terminated.

Pesticides in the Lake Ontario basin have been observed routinely since 1962 by the US Public Health Service at Massena, NY on the St. Lawrence River. In 1962 dieldrin, endrin and DDT or its derivatives (DDD and DDE) were observed. However, since that time only DDT has been measured with any consistency. In 1965 DDD, Heptachlor and Heptachlorepoxide were determined at 0.010, 0.031 and 0.017 µg/l, respectively.

Although pesticide levels in the waters of Lake Ontario have received little attention (Weaver et al. 1965; Breidenbach et al. 1967; Haile 1974), both detailed and comprehensive investigations of pesticide levels in Lake Ontario fish have been performed (Henderson et al. 1969; Reinert 1970; Bligh 1971; Haile 1974; Veith et al. 1974). Since DDT is not only resistant to chemical and biological degradation (Mckee and Wolfe 1963; Woodwell 1967) but is also very soluble in fats and oils, it is rapidly and selectively absorbed and concentrated by certain organisms (plankton) even when present at very low concentration levels

(Premdas and Anderson 1963; Mack et al. 1964). Thus, the concentration of pesticide residues is magnified at each stage in the aquatic food chain and can produce harmful effects on fish and wildfowl. For this reason the examination of fish for pesticide residues is considered to be a more sensitive and meaningful indicator of the presence and level of pesticides in the lake waters. The combined DDT and DDE concentration levels found in fish samples taken from Lake Ontario in 1966-1967 were generally low, the majority of samples had residue levels less than 2 mg/kg (RIJC 1969). In general the pesticide and PCBs in fish taken from Lake Ontario are present at intermediate levels in comparison to samples taken from the other Great Lakes. The highest concentrations were observed in fish taken from Lake Michigan (Veith et al. 1974). In general pesticide concentrations in the waters of Lake Ontario do not exceed maximum permissible criteria levels for chlorinated hydrocarbon insecticides (FWPCA 1968).

### b. Phenols

Phenol ($C_6H_5OH$) and phenolic compounds occur in lake waters as a result of natural processes and anthropogenic sources. Natural phenols are present in the oils secreted by algae whereas pollutant phenols originate from waste discharges associated with the oil, coal and plastics industries. Phenol and phenolic compounds are usually measured by the color development produced by their specific reaction with 4-amino-antipyrene.

As early as 1948-1949 phenol values averaging 1.4 ppb were reported for the west end of Lake Ontario (Black and Devendorf 1954). In 1960 phenol concentrations found in the open lake were in the range 0 to 3 µg $C_6H_5OH$/l, and in 1967 the Canada Center for Inland Waters reported values in the range 0 to 8 µg $C_6H_5OH$/l with a median value of 3 µg $C_6H_5OH$/l, whereas, for the same observation period CDNHW reported concentrations in the range 0 to 15 µg $C_6H_5OH$/l with a median value near 2 µg $C_6H_5OH$/l. In general phenol values decrease with distance from the shoreline in Lake Ontario; however, median values in the range 1.2 to 2.4 µg $C_6H_5OH$/l have been measured in the St. Lawrence River in 1967 (RIJC 1969). Thus it appears that phenol concentrations in Lake Ontario generally exceed the maximum permissible criteria limit of 1 µg $C_6H_5OH$/l set by the Committee on Water Quality Criteria, Federal Water Pollution Control Administration (1968).

Little information is available on fats, waxes and oils in Lake Ontario except in nearshore industrialized areas (Zweig et al. 1967). In the future, as our knowledge of environmental deterioration improves, it is clear that other exotic organic chemicals will be identified which have marked ecological impacts. For example, at this time insecticide chemicals, such as Mirex and Kepone, and industrial chemicals such as the polychlorinated biphenyls (PCB) are receiving considerable attention because of their potential toxicity and concentration in aquatic animal life (Kaiser 1974; Haile 1974; Veith et al. 1974). Also, it is now realized that the chlorination process used widely in disinfecting municipal waste water is an important source of chlorinated hydrocarbon materials, through the reaction of chlorine with organic compounds.

## Water Quality Characteristics of Lake Ontario

In defining and assessing the environmental impact of man's activities on aquatic systems it is necessary to determine at least the relative importance of various anthropogenic sources of water pollution. Such a determination, however, is complicated by the fact that seldom are individual, traceable pollutants discharged as wastes at one particular location. Usually polluting discharges are composed of highly variable, complex mixtures of a variety of substances that are disposed of sporadically at widespread locations and whose chemical nature and concentration are largely unknown. Thus, it would be an extremely difficult, if not impossible, task to individually identify and continuously monitor all of the pollutants in the waters, particularly at the low concentrations found in rivers and lakes. To overcome this difficulty it has been necessary, for practical purposes, to describe waste water and natural waters in terms of collective or bulk characteristics, without necessarily specifying the individual chemical contaminants involved. These collective analyses, which encompass a broad range of relatively simple, rapid and standardized physical and chemical measurements, group together the effects of similar or related contaminants into an overall property of the aqueous solution. These collective parameters are used to define the "maximum permissible" as well as "desirable" water quality criteria for the various uses of natural water resources. Thus, it is possible to describe the environmental quality of water bodies in terms of these bulk characteristics. In addition they may be used to assess any deterioration or improvement in the water environment and to support the recommendation of appropriate controls on the discharge of selected pollutants as required. Standard procedures to be followed in making water quality measurements have been published by the American Public Health Association (1971) and the Environmental Protection Agency (1971). These water quality characteristics will be reviewed and discussed in detail in this section as they apply to Lake Ontario.

### 1. Dissolved Oxygen

The dissolved oxygen (DO) in water bodies originates from dissolution of atmospheric oxygen and from aquatic plant photosynthesis. It is an essential constituent for the support of life in water bodies and is required in the purification process of natural waters involving the bacterial oxidation of organic matter (aerobic degradation) and for stabilizing the sediment-water equilibrium. The DO content of a water mass is dependent upon the gaseous diffusion gradient and wind-driven turbulence and mixing at the air-water interface, as well as on the photosynthetic and respiratory activities of the biota and benthos. Concentrations less than 3 mg DO/l are believed to impose severe stress on most aquatic vertebrates and concentrations below 5 mg DO/l are deemed undesirable. In addition, the DO content is an important factor in the regulation of the aqueous iron cycle and consequently it affects indirectly the quantity of phosphate that is precipitated from or assimilated into solution. Because the solubility and, thus, the saturation concentration of oxygen in water varies inversely with temperature the DO content is usually expressed in both units of percent saturation and in milligrams per liter. In the latter case, however, the water temperature must be specified. To readily convert from one unit to the other an oxygen solubility table of the type shown below (Table IV) is used. At water temperatures below 25°C the solubility of DO is also directly proportional to the atmospheric pressure.

TABLE IV

Solubility of Oxygen in Pure Water in Equilibrium with Water-Saturated Air at Mean Sea Level Pressure of 1 Atmosphere (760 Torr)

| Temperature (°C) | DO (mg/liter) | Temperature (°C) | DO (mg/liter) |
|---|---|---|---|
| 0 | 14.16 | 18 | 9.18 |
| 1 | 13.77 | 19 | 9.01 |
| 2 | 13.40 | 20 | 8.84 |
| 3 | 13.05 | 21 | 8.68 |
| 4 | 12.70 | 22 | 8.53 |
| 5 | 12.37 | 23 | 8.38 |
| 6 | 12.06 | 24 | 8.25 |
| 7 | 11.76 | 25 | 8.11 |
| 8 | 11.47 | 26 | 7.99 |
| 9 | 11.19 | 27 | 7.86 |
| 10 | 10.92 | 28 | 7.75 |
| 11 | 10.67 | 29 | 7.64 |
| 12 | 10.43 | 30 | 7.53 |
| 13 | 10.20 | 31 | 7.42 |
| 14 | 9.98 | 32 | 7.32 |
| 15 | 9.76 | 33 | 7.22 |
| 16 | 9.56 | 34 | 7.13 |
| 17 | 9.37 | 35 | 7.04 |

The dissolved oxygen concentration in most natural waters is readily determined with an estimated accuracy of ± 0.1 mg DO/l by the azide-modified Winkler method (Rodgers 1972). This technique depends upon the formation of a loose precipitate (floc) of manganous hydroxide which rapidly and irreversibly scavenges dissolved oxygen from the solution as it settles, forming a higher hydroxide. Acidification in the presence of iodide releases iodine in quantity equivalent to the DO originally present. The liberated iodine is titrated with a standard solution of either sodium thiosulfate, using starch as an indicator, or with phenylarsine oxide. The Winkler method suffers from interferences in the presence of readily oxidizable or reducible compounds. For example, in the presence of easily reduced materials such as nitrites or ferric iron, additional iodine is liberated from the iodide causing the results to be too high. However, these interferences may be eliminated by the addition of sodium azide and potassium fluoride, respectively, in the initial stages of the analyses. Easily oxidized materials on the other hand, such as ferrous iron, sulfites, sulfur compounds, and organic materials cause low DO results by removing some of the iodine liberated prior to titration. In general, if interferences are suspected then specific tests are recommended to demonstrate the presence of readily oxidized or reduced materials (Ellis et al. 1948).

Leverin (1947) has reported dissolved oxygen concentrations in Lake Ontario for the period 1934 to 1938, the range in values was from 11.8 to 13.3 mg $O_2$/l with a five year mean concentration of 12.5 mg $O_2$/l. These determinations, however, were made using the Millar method, which involves reaction with alkaline tartrate and titration with ferrous sulfate solution using methylene blue indicator. Extensive DO data were collected in the early 1960s by the Great Lakes Institute, University of Toronto (Rodgers 1963, 1964 and 1965). Recently, however, the validity of data collected in 1960 and 1961 has been questioned (Rodgers 1972) and is thought to be quantitatively unreliable because the observations were consistently 20 to 40 percent lower than all subsequent values obtained using a modified DO reagent formulation. Thus, it appears that reliable dissolved oxygen measurements for Lake Ontario are available only for recent years, from 1962 to the present. Individual lakewide dissolved oxygen concentrations measured at the surface of Lake Ontario are shown in Figure 61, and displayed as a bar graph of annual mean values in Figure 62, for the period 1934 to 1968. The apparent decrease in mean concentration from a value of 12.5 mg $O_2$/l in the 1930s to 10.0 mg $O_2$/l in the late 1960s may not be real because of the inadequacies of analytical methods used prior to 1962. A typical surface distribution of dissolved oxygen in mg $O_2$/l for September 1964 is shown in Figure 63.

Dissolved oxygen levels as well as vertical and horizontal distributions in Lake Ontario during the spring, summer and fall months of 1965, 1966 and 1969 have been reported in detail by Casey et al. (1973), Dobson (1967), Sweers (1969) and Dobson (1972), respectively. In all cases during the stratification period the surface concentrations exceeded 100 percent saturation and a moderate depletion, by 10 to 20 percent of surface values, was found in bottom waters. Although an initial increase in absolute oxygen concentration (in mg $O_2$/l) was found with increasing depth from the surface, this was more than offset by the temperature lapse rate, which determines the saturation concentration. The lowest median lakewide value for DO in bottom waters determined during these cruises was 82 percent saturation found in early fall 1967. This should be compared with DO levels in the range 50 to 60 percent saturation in deep waters during the winter of 1962 reported by Beeton (1965). Typical distributions of dissolved oxygen as percent saturation in surface waters during the spring, summer and fall months of 1965 are shown in Figures 64, 65 and 66, respectively. Figure 67 shows a typical lakewide seasonal variation in dissolved oxygen in surface and deep waters as measured in 1969 (Dobson 1972).

To explain the seasonal as well as the vertical and horizontal distributions of dissolved oxygen during the summer stratification period it is necessary to consider the different dominating factors operating in four distinct vertical zones: the epilimnion, the thermocline, the hypolimnion and the near bottom waters. Immediately following the spring overturn the lake water is saturated with oxygen. Supersaturation with oxygen occurs in the epilimnion layer during May and June due to the increase in surface water temperature and photosynthetic oxygen production associated with the algal bloom, see Figures 64 and 67. In July the surface waters become less supersaturated as equilibrium conditions with atmospheric oxygen are established, see Figures 65 and 67. In late August and September the oxygen levels rise again slightly above saturation as a result of the fall algal bloom, see Figures 66 and 67. Cooling of the epilimnion in October causes the near surface waters to become undersaturated with oxygen with respect to the lower lake temperatures until such time as equilibrium with the atmospheric component is reestablished.

Algae and algal debris tend to concentrate in the thermocline region. As a result oxygen levels in this zone are primarily influenced by photosynthetic production and removal by oxidation of organic material. In the spring photosynthesis accompanying algal bloom raises DO levels well above saturation but as the algae die and accumulate at the thermocline the increased bacterial oxidation can lower oxygen levels considerably. A similar though less marked cycle occurs during the fall algal bloom.

Dissolved oxygen in the hypolimnion and bottom waters is replenished only during the spring and fall overturns when the lake water is vertically mixed. Oxygen consumption in both of these zones is primarily by the bacterial oxidation of sestonic material. The greatest oxygen demand and depletion occurs in near bottom waters due to the presence of sedimented organic material.

Oligotrophic Lake Ontario is capable of maintaining adequate dissolved oxygen levels during stratification because of the large reserve of oxygen stored in its voluminous hypolimnion. Minimum oxygen levels approaching 60 percent saturation have been found in shallow near-bottom waters at the northeastern end of the lake. Maximum oxygen levels as high as 140 percent saturation have been observed in the late spring of 1966 for surface waters in the vicinity of Toronto and Hamilton, which is probably due to enhanced nutrient levels causing increased algal bloom and photosynthetic activity in the warmer shallower waters. The levels of dissolved oxygen found in the St. Lawrence River are consistently at or near saturation with a median concentration of 8.7 mg $O_2$/l reported for 1967. Apparently local polluting discharges do not affect the oxygen levels in the river and any oxygen deficiency must be rapidly overcome by the atmosphere-water exchange enhanced by turbulence and mixing.

## 2. Oxygen Demand

The biochemical oxygen demand (BOD) of waste or polluted water is a measure of the concentration of aerobically biodegradable organic material in the sample. This measurement involves not only the amount of organic matter present but also the rate at which it is decomposed by bacterial oxidation. In the standard test ($BOD_5$) the concentration of dissolved oxygen in mg $O_2$/l is measured which is required by microorganisms as they degrade or transform the carbon and nitrogen containing compounds in organic matter over a five day incubation period at 20°C. In deep lakes such as Lake Ontario the BOD test is considered to be of limited value in terms of being a measure of the effect of biodegradable organic matter on the lake environment. The oxygen deficit in bottom waters, as discussed previously, is a much more reliable parameter in this regard.

In addition to a few isolated measurements, $BOD_5$ determinations on Lake Ontario waters have been made by FWPCA in 1965 and CDNHW in 1967. In all cases individual surface values were less than 3 mg $O_2$/l and mean values were well below 2 mg $O_2$/l, which is approaching the accuracy limit of the BOD test. Similar values were obtained in the St. Lawrence River where an average $BOD_5$ of about 1 mg $O_2$/l was determined.

Chemical oxygen demand (COD) is based upon the fact that most organic compounds can be oxidized to carbon dioxide and water by strong oxidizing agents. This analysis is, therefore, a measure of the equivalent gross oxygen demand of inorganic (ferrous iron, sulfite, sulfide, etc.) and organic (carbonaceous and nitrogenous) compounds that are chemically oxidizable by strong agents such as potassium permanganate or dichromate.

Measurements of COD in Lake Ontario have been made by the New York State Department of Health (1965) in the vicinity of Oswego. During the period 1960 to 1964 the range of values found was from 4.2 to 2.0 mg $O_2$/l, with a mean value of 2.7 mg $O_2$/l for the five year duration. As in the case of BOD measurements, COD values for Lake Ontario are of little value in describing the state of the lake waters.

## 3. Hydrogen-Ion Concentration (pH)

The hydrogen-ion concentration of natural and waste waters is usually expressed in terms of the more convenient pH units. pH is defined as the logarithm of the reciprocal hydrogen-ion concentration in moles/liter. Deaerated and deionized distilled water at 20°C has a pH of 7, corresponding to neutrality. pH values less than 7 indicate an acidic solution and values greater than 7 indicate a basic or alkaline solution. The greater the divergence of pH from 7 the stronger the acid or basic solution. Thus, the pH of a water sample provides a measure of the hydrogen-ion activity. This property is of great importance in defining lake water characteristics, being a function of both the nature and quantity of dissolved solids. However, pH represents the overall dynamic balance of a number of interrelated chemical and biological equilibria, which determines the bulk hydrogen-ion concentration, as a result it reflects the state of the total lake environment. pH is measured by the potential generated by a specific hydrogen-ion electrode at a known temperature. The accuracy of the method is generally ± 0.2 pH units.

The pH of most natural waters lies in the range from 5 to 8 pH units and is mainly controlled by the buffer system $CaCO_3$-$CO_2$-$H_2O$, involving solution of naturally occurring calcite (calcium carbonate, $CaCO_3$) and atmospheric carbon dioxide ($CO_2$). A saturated solution in pure water of carbon dioxide in equilibrium with its partial pressure in air has a pH of 5.2 whilst a saturated solution of calcium carbonate in air-saturated water has a pH near eight (Mason 1958). Soluble phosphates, silicates, borates and fluorides can also affect the pH of natural waters but to a lesser extent than the calcite-carbon dioxide system. The fact that calcite-bearing rocks contain varying amounts of the phosphate mineral, apatite [$Ca_5(PO_4)_3F$] may also partially explain why alkaline lake waters are usually much more productive than acidic lakes. For this reason pH has been used to classify the trophic nature of lakes and on this basis alone Lake Ontario, which is alkaline (pH $\gtrsim$ 8), should be eutrophic (Bass-Becking 1960). However, as mentioned previously, other factors should be taken into account in the trophic classification of this uniquely deep lake. In addition the pH of lake water regulates the iron cycle and, consequently, it is also important in determining the availability of soluble (reactive) phosphate ions. pH values greater than eight have been attributed to lake warming causing a shift in the $CaCO_3$-$CO_2$-$H_2O$ equilibrium and to biological activity, which suggests that these low hydrogen-ion concentrations are at least partially related to the availability of nutrients.

Lake Ontario is located in a predominantly limestone basin and its waters are moderately hard and basic. All measurements of pH have shown it to be an alkaline, biologically productive lake, with its surface waters near saturation levels in calcium carbonate and with very low free carbon dioxide levels. The pH of Lake Ontario has been measured by a large number of investigators since the mid-1930s. Early measurements from 1934 to 1938 were in the range 7.5 to 7.8 pH units with a mean value of 7.7 (Leverin 1947). Individual lakewide measurements of pH at the surface are plotted in Figure 68 and displayed as a bar graph of annual mean values for the same period (1934-1970) in Figure 69. If there is an increasing trend in pH values, from 7.7 in 1936 to 8.2 in 1970, then it is only very slight, amounting to ± 0.15 pH units per decade, which hardly exceeds experimental error. The mean lakewide value of pH at the surface of Lake Ontario from 1960 to 1970 is 8.0 ± 0.2 pH units.

The surface distribution of pH is similar to the patterns observed for dissolved oxygen, soluble phosphate, water temperature and circulation. Localized surface measurements have been found to vary from 7.1 to 9.3 pH units. Also in most cases pH has been found to decrease slightly with increasing depth, which has been attributed to removal of carbonic acid by algal activity near the surface. Typical surface distributions of pH in Lake Ontario in the spring, summer and fall of 1965 determined by FWPCA are shown in Figures 70, 71 and 72, respectively.

Since the generally high pH values at the surface are attributed to biological activity it seems reasonable that wind direction and velocity must play a role in the observed distribution through transport and mixing. In Figure 70 measurements at the western end of the lake were made when the wind was blowing from the southwest, causing the higher pH values found nearshore to decrease towards mid-lake. Investigations made at the east end of the lake, however, were influenced by a northeasterly wind which created pools of high pH water by pushing near shore (high pH) waters into mid-lake and causing mixing with lower pH water. Inshore surface waters at the east end of the lake had lower pH values due to loss of integrity of the high pH waters by wind-induced turbulence and mixing.

The distribution of pH in the summer during a quiescent period is shown in Figure 71. In this case pH increases from nearshore to mid-lake, with values as high as 9.0 being commonly found. In the early fall pH values are lower than in summer and correlate well with the observed circulation and surface temperatures of the lake, see Figure 72.

A similar situation exists in the St. Lawrence River as in Lake Ontario, where the US Public Health Service (1963) has reported pH values in the range 7.4 to 9.3 and an overall median value of 8.4 ± 0.1 pH units.

4. Alkalinity

The total alkalinity of water is a measure of its hydrogen-ion affinity or its capacity to accept protons. It is dependent upon the nature and quantity of soluble compounds which collectively shift the pH to the alkaline side of neutrality. Three ionic species contribute to the total alkalinity, they are hydroxide ($OH^-$), carbonate ($CO_3^=$) and bicarbonate ($HCO_3^-$). Since hydroxide and bicarbonate are mutually exclusive in solution then there are five possible combinations of these species which may account for the observed alkalinity. In river and lake waters soluble bicarbonates are mainly responsible for the total alkalinity observed because of the natural abundance of carbonate minerals. In some cases carbonates and the salts of weak acids may also make a minor contribution. The total alkalinity, however, is usually expressed in terms of an equivalent amount of calcium carbonate, mg $CaCO_3$/l, although in some instances the total alkalinity has been reported in terms of an equivalent amount of bicarbonate ion, mg $HCO_3$/l. Seldom do hydroxides contribute to natural alkalinity, except during periods of algal activity, when carbonate and hydroxide have been proposed as being mainly responsible for the alkalinity observed in surface waters. Generally, the presence of hydroxide is attributable to water treatment or contamination. Natural total alkalinities may vary from 45 to 200 mg $CaCO_3$/l.

Total alkalinity is determined by titrating a water sample with a standard solution of a strong acid, such as sulfuric acid using an indicator (methyl orange or bromocresol green-methyl red) or a pH meter to monitor the end-point at pH = 4.5. In addition the carbonate alkalinity can be determined on another sample of the same water by titrating to an endpoint of pH = 8.3 (phenolphthalein indicator). The difference between total alkalinity and carbonate alkalinity for natural waters is the bicarbonate alkalinity. In these titrations care must be taken not to agitate the solution otherwise interference by atmospheric $CO_2$ will occur. The accuracy of these measurements is estimated to be ± 4 mg $CaCO_3$/l.

The total alkalinity of Lake Ontario, which is mainly due to the bicarbonate ion (see Table III) has been measured by a large number of investigators since the beginning of this century. The lakewide surface water data on total alkalinity expressed as bicarbonate concentration and obtained during the period 1906 to 1966 is plotted in Figure 73. Similar measurements of total alkalinity expressed as calcium carbonate concentrations obtained from 1936 to 1972 are plotted in Figure 74 and displayed as a bar graph of annual mean values in Figure 75. The data in all of these Figures suggests that the total alkalinity in surface waters of Lake Ontario has remained reasonably constant over the extensive measurement period, at estimated mean values of 114 mg $HCO_3$/l and 93.5 mg $CaCO_3$/l from the data in Figures 73 and 74, respectively. A lower overall mean value of 90 mg $CaCO_3$/l and a standard deviation of ± 7 mg $CaCO_3$ (± 1 σ corresponding to 80% confidence limits) is obtained from the average annual mean values shown in Figure 75. A slightly higher median value (93 mg $CaCO_3$/l) for the total alkalinity in the hypolimnion was determined by CDNHW in 1966 and 1967.

The surface distribution of total alkalinity measured in September 1964 is shown in Figure 76. The values are higher than the mean probably because of the fall algal bloom. It is seen that this water quality parameter is relatively uniform throughout the central region of the lake whereas nearshore areas show higher alkalinity levels suggestive of increased algal activity in these shallower waters. Lowest values in total alkalinity occur during the summer corresponding to the period of least algal activity.

As is to be expected the alkalinity values found in the St. Lawrence River fall in the range 74 to 95 mg $CaCO_3$/l (US Public Health Service 1963) with a median value of 89 mg $CaCO_3$/l (CDNHW 1967).

## 5. Hardness

Hard water is that which requires either large amounts of soap to produce a lather or which, upon evaporation, forms a scum or deposit on the container. The hardness is mainly due to dissolved salts of calcium and magnesium and to a lesser extent on the polyvalent metals iron, aluminum and manganese. Early determinations of hardness involved measuring the capacity of water to precipitate soap when a water sample and liquid soap solution was shaken to produce a lather persisting for five minutes. More recently this collective property has been redefined as that characteristic of water represented by the total concentration of calcium and magnesium ions expressed in terms of an equivalent amount of calcium carbonate, mg $CaCO_3$/l. When other ions are present in insignificant amounts the hardness will be equal to or less than the total alkalinity and is termed the carbonate hardness. However, if the hardness exceeds the total alkalinity then the presence of other ions is indicated and the excess hardness is expressed as non-carbonate hardness. Thus, total hardness determinations may be used to corroborate total alkalinity measurements and when determined in conjunction with the calcium ion content of water samples from the same source, they may be used to estimate magnesium concentrations by the difference in equivalent concentrations.

Hardness in natural waters is a result of the chemical and biological dissolution of calcium and magnesium carbonates from sedimentary rocks. Hard water is not necessarily harmful to man since within reasonable limits the ions causing hardness are necessary for normal plant and animal survival. There is, however, some evidence to suggest that hardness in waters may affect the tolerance of fish to toxic metals. Hardness is usually measured by buffering a water sample to a pH of 10 and titrating to a blue endpoint with a standard solution of disodium ethylenediamine-tetracetate using an indicator of Eriochrome Black T dye in sodium chloride. The accuracy of this method is probably no better than ± 5 mg $CaCO_3$/l. Waters are also commonly classified in terms of the degree of hardness.

Lake Ontario exhibits a slightly higher hardness than Lake Erie as a result of its being last in the chain of the Great Lakes system. Measurements of hardness in this lake fall in the range 75 to 150 mg $CaCO_3$/l, suggesting a moderately hard classification. Data obtained from 1934 to 1968 for the total hardness in surface waters of Lake Ontario are plotted in figure 77 and displayed as a bar graph of annual mean values in Figure 78. The data suggest that the total hardness has remained relatively unchanged during the observation period with an overall mean value of 131 mg $CaCO_3$/l. This value is almost identical with the median value (132 mg $CaCO_3$/l) reported by CDNHW for 1966 and 1967. No significant variations in hardness have been found in different regions of the lake although this water quality parameter does appear to increase slightly with depth. The fact that total hardness exceeds total alkalinity in Lake Ontario suggests that in the late 1960s Lake Ontario waters consisted of 90 mg $CaCO_3$/l carbonate hardness and 41 mg $CaCO_3$/l non-carbonate hardness. These values should be compared with very similar mean values found in the late 1930s of 94 mg $CaCO_3$/l carbonate hardness and 35 mg $CaCO_3$/l non-carbonate hardness (Leverin 1947).

Total hardness values found in the St. Lawrence River confirm the levels found in Lake Ontario. The values have remained fairly constant since 1961 falling in the range 126 to 130 mg $CaCO_3$/l (USPHS 1963; CDNHW 1965, 1966 and 1967).

### 6. Dissolved Solids

The total dissolved solids content of water is determined gravimetrically by measuring the weight of filterable residue after evaporation and drying at 103°C. In those waters having a low soluble organic matter content the dissolved solids (filterable residue) determination may be used as a check on the completeness of the analysis for soluble mineral content. Thus, a good correlation between the total mass concentration of the major cations and anions, that is, $Na^+$, $Ca^{++}$, $HCO_3^-$, $SO_4^=$, etc., and the total dissolved solids content is indicative that no major ionic constituent has been omitted from the analyses. Other related measurements include total residue, which is the material remaining after evaporation and drying at 103°C of an unfiltered raw water sample and consists of organic and inorganic material, each being subcategorized as particulate or dissolved matter. Volatile matter is the difference between the weight obtained in either of the above specified procedures for filterable or total residue and the residue after ignition at 600°C. Determination of volatile matter provides only a crude estimate of the organic matter content because some inorganic compounds decompose at the ignition temperature employed.

In Lake Ontario the equivalent concentrations of cations and anions balance very well yet the concentrations of dissolved solids found are substantially less than the sum of anion and cation concentrations, by about 20 percent, see Table II. This discrepancy suggests that partial decomposition of inorganic species, such as bicarbonate and carbonate, must occur during the dissolved solids determination. Nevertheless, the dissolved solids concentrations in Lake Ontario are the highest found in all of the Great Lakes for the same reasons that concentrations of major ions, hardness and specific conductance are also highest in this lake.

The dissolved solids content of Lake Ontario water has been measured infrequently since 1850 and frequently since the early 1930s (Beeton 1965). Prior to 1910 total dissolved solids concentrations remained constant at 140 mg/l. Available data since that time on lakewide surface concentrations of dissolved solids have been plotted in Figure 79 for the period 1906 to 1968 and displayed as a bar graph of annual mean values in Figure 80. It appears that the concentration of dissolved solids in the lake has been increasing linearly at a rate of 9.3 mg/l/decade since the turn of the century. This rate of increase extrapolates to a mean value of 195 mg/l dissolved solids in 1970 and a rate of increase about 5 percent per decade. These values correspond closely with the 10 ppm/decade rate of increase reported by Beeton (1965), and with the median surface water value of 196 mg/l dissolved solids content determined by DCNHW in 1966 and 1967. Slightly higher dissolved solids concentrations are found with increasing depth, the highest values being observed in bottom water samples.

A relatively uniform concentration of dissolved solids exists in the St. Lawrence River consistent with the values found for Lake Ontario (RIJC 1969). Median values, however, determined in the early 1960s (USPHS 1963) and falling in the range 142 to 212 mg/l were somewhat lower than those found by CDNHW during the period 1965 to 1967.

Dissolved solids concentrations in Lake Ontario are still well below the maximum permissible level (500 mg/l) for public water supplies specified by the US Public Health Service (1962) and the Canadian Drinking Water Standards (1968). The present levels, however, are at the point of exceeding the desirable level (< 200 mg/l) for drinking water as proposed by the Committee on Water Quality Criteria, Federal Water Pollution Control Administration (1968).

### 7. Specific Conductance

The specific conductance of an aqueous solution is a measure of its ability to conduct an electric current. Thus, conductance in water is dependent upon the total concentration of ionized substances in solution and the temperature, which affects the mobility of the ions. More specifically, the overall specific conductance is a function of the nature of the various dissolved ions, their absolute and relative concentrations as well as the ionic strength. As this water quality measurement is the inverse of resistance to flow of current, which is measured in ohms, then the corresponding unit of conductance is the mho.

In naturally occurring waters the conductance is low and a more appropriate unit of measurement is used, the micromho ($10^{-6}$ mho). Measurements of specific conductance are usually made by determining the current flow in amps across electrodes spaced 1 cm apart at a known potential difference in volts when immersed in an aqueous solution at a known temperature. The precision of these measurements is about two percent. Specific conductances are reported in units of micromhos/cm at a standard temperature, usually 25°C, which normally requires the application of a temperature correction factor of about 2.5 percent per °C difference between the sample and standard temperatures. Limnologists have preferred to report specific conductance at 18°C because this temperature is closer to the average natural water temperature found in the United States. As a result of this preference, measurements of this property in 1966 and prior years were corrected to this lower standard temperature. Since 1967, however, the higher standard temperature (25°C) has been generally accepted as the International standard temperature for reporting specific conductance measurements. A correction factor of 1.16 is recommended for correcting the earlier values reported at 18°C to the present standard of 25°C (Rodgers 1972).

Measurement of specific conductance in natural waters is most useful in determining the total dissolved solids (total ionic) content in solution. At the low concentrations occurring naturally the individual ions move and behave independently of each other and there is a direct relationship between specific conductance and concentration. Thus, an empirical factor may be used to convert specific conductance, in micromho/cm at 25°C, into total dissolved solids or total ionic content in mg/l. However, as mentioned previously there is a large discrepancy (20%) between the sum of the concentrations of major ions and the total dissolved solids content in Lake Ontario waters. As a result of this marked difference, although a multiplication factor of 0.59 is suitable for estimating the total dissolved solids from specific conductance measurements, a factor of 0.73 is required for estimating the total ionic content of Lake Ontario, see Table II.

Specific conductance measurements on the waters of Lake Ontario have been made since the late 1940s. Data from lakewide measurements of surface waters in the lake from 1947 to 1968 are plotted in Figure 81 and the same data are shown as a bar graph of annual mean values of specific conductance at 25°C for the same observation period in Figure 82. The data suggests that the specific conductance of Lake Ontario waters has been increasing linearly at a rate of 13 micromho/cm/decade over the thirty year observation period. This trend extrapolates to an average value of 328 micromho/cm at 25°C for 1970 and a corresponding +4 percent/decade rate of increase for that year. This rate of increase correlates well with the estimated rates of increase for total dissolved solids (+5% decade) and total ionic content (+6%/decade) described previously, see Table II. A minor increase (about 2%) in specific conductance with depth has been found in Lake Ontario during the summer months, which also correlates well with vertical distributions of ions and total dissolved solids.

The surface distribution of specific conductance at 18°C for Lake Ontario, as measured in September 1964, is shown in Figure 83. In addition, we have shown the isopleths multiplied by a factor of 1.16 to convert these specific conductance values to the corresponding currently accepted standard temperature, 25°C. In this case the typical distribution does confirm that the major portion of the lake, particularly the central region, is homogeneously mixed with respect to major dissolved ions. The higher conductance values observed around the edge of the lake are a result of enhanced ion concentrations caused by local inputs.

Specific conductance measurements in the St. Lawrence River have been made by CDNHW in 1966 and 1967. They found a median value of 316 micromho/cm at 25°C which agrees quite well with the average value for Lake Ontario at that time, 323 µmhos/cm at 25°C. Thus, in the case of specific conductance, as for many other water quality properties, measurements in the St. Lawrence River follow the lakewide values very closely.

### 8. Suspended Solids

This property of natural waters describes the non-filterable residue present or the total weight of dried suspended material in mg/l. Its importance in determining water quality depends upon the fact that suspended matter can hinder the use of natural water for a variety of purposes.

A comprehensive set of measurements of suspended solids in Lake Ontario waters for 1967 has been reported by CDNHW. Values reported for surface waters were in the range 0.5 to 5 mg/l. Median concentrations given for suspended solids found in the epilimnion and hypolimnion were 2.6 ± 1.7 mg/l and 1.7 ± 1.3 mg/l, respectively. The slightly higher values obtained near the surface being attributed to algal activity in the photic zone. In addition, a seasonal variation in suspended solids was observed as an increase during the summer months and a decrease in the fall.

The highest median values for suspended solids were found in near shore areas of the western and central regions of the lake. In general the distribution patterns for suspended solids are similar to those found for total Kjeldahl-nitrogen and turbidity (RIJC 1969).

The concentrations of suspended solids in the St. Lawrence River are variable but the median values of 2.5 ± 0.5 mg/l are similar to those found in the surface waters of Lake Ontario.

### 9. Turbidity, Visibility and Color

Turbidity is a measure of the hindrance to transmission of visible light by suspended solids. Attenuation of the light is by absorption and scattering. Thus, although this water quality property is related to the concentration of suspended solids, it is primarily a function of the size and number of particles rather than their mass. Turbidity measurements are usually expressed in terms of Jackson Turbidity Units (JTU). Determinations are made by placing a water sample in a one inch (2.5 cm) path cell and measuring the percentage of the monochromatic incident light at 450 nm transmitted. A standard conversion table is used to convert percent transmission into JTUs.

Visibility is a measure of the depth of penetration of visible light in meters. It is important since the visibility is directly related to the depth of the photic zone and may be used in estimating the latter both rapidly and accurately with experience. The photic zone is the depth at which the intensity of incident light at the surface of the lake is attenuated by a factor of 100 to 1 percent and defines the depth at which photosynthetic activity ceases. Visibility is measured by lowering a 10 inch circular disc painted black and white in opposite quarters (Secchi disc) into the water and taking the average of the depths at which it disappears from view on lowering and reappears when raised. Secchi disc visibility measurements, however, require an experienced observer as they depend upon several factors including the type of sky light, the position of the sun and its relation to the observer, and the roughness of the water. In order for these measurements to be meaningful the observer must make an effort to standardize his observational procedures whenever possible. Secchi disc measurements of visibility are either reported as the depth in meters or in reciprocal Secchi units defined as the reciprocal of depth in meters multiplied by 30, or the average photic depth in meters.

Turbidity and reduced visibility in natural waters are caused by suspended material such as phytoplankton, clay, silt and organic debris. In Lake Ontario turbidity is mainly due to the phytoplankton and, with the exception of spring run-off, only minor contributions result from suspended clay and silt. Thus, the turbidity of Lake Ontario waters is a good indicator of the phytoplankton standing crop and the corresponding state of eutrophication.

Nearshore turbidity measurements have been made routinely at municipal water intakes for many years although few have been made on a lakewide basis. Secchi disc measurements have been made on a regular basis since the early 1960s (Rodgers 1963, 1964 and 1965).

Simultaneous lakewide measurements of turbidity and visibility in Lake Ontario were made by EMR and CDNHW in 1967. The former were found to lie in the range 0.2 to 2.5 JTU and the latter readings were in the range 1.5 to 7.5 meters with a seasonal median of 3.5 meters.

Nearshore data on turbidity of Lake Ontario are plotted in Figure 84 and displayed as a bar graph of annual mean values from 1906 to 1963 in Figure 85. It appears from these data that inshore turbidity, at least, in Lake Ontario has been increasing at a rate of 3.2 JTU per decade since the 1920s. However, the possibility of a decline in turbidity levels since the late 1950s cannot be ruled out.

A typical surface distribution of turbidity in Lake Ontario found in 1967 is shown in Figure 86. It can be seen that in the mid-lake deep waters and at the eastern end of the lake the turbidity levels are low and fairly uniform whereas, at the western end of the lake turbidity levels are the highest, undoubtedly due to the influence of the major metropolitan areas and industrial concentration in that region. The distribution of turbidity is similar to the patterns observed for total Kjeldahl-nitrogen and suspended solids. This relation supports the contention that turbidity results mainly from phytoplankton activity. Similarly turbidity values follow a seasonal pattern with maxima occurring in late spring and early fall corresponding to phytoplankton blooms at those times. The low turbidities in deep waters indicate a lower phytoplankton productivity, whereas the higher turbidities in nearshore areas suggest a larger phytoplankton population, although the influences of debris from waste discharges and tributary streams could be significant. On the basis of turbidity measurements the water of Lake Ontario may be classified as being of good quality.

Simultaneous turbidity and visibility measurements have been made in the St. Lawrence River in 1966 and 1967. In general the values obtained were in the ranges 1.5 to 3.0 JTU and one to seven meters, respectively, and reflect the state of Lake Ontario at that time (RIJC 1969).

Natural waters acquire color mainly through algae and extraction from decaying leaves and vegetable matter. Polluted waters may be colored by inorganic salts and compounds such as those of the transition metals and by organic compounds, such as dyes. Color in water is usually reported on an empirical scale in Hazen units.

Color readings on Lake Ontario waters have been obtained by CDNHW in 1966-1967. The values were consistently less than five Hazen units. Measurements in the St. Lawrence River have been reported for the early 1960s by the US Public Health Service (1963), the values were in the range 0 to 30 Hazen units, with the majority being less than five units. In 1967 CDNHW reported a value of five Hazen units for the river which substantiates the values found in Lake Ontario at that time (RIJC 1969). High color readings (up to 70 Hazen units) have been found at the mouths of inflowing tributary rivers but these do not appear to significantly affect the main lake body. In terms of color measurements Lake Ontario exhibits good water quality, the maximum permissible level for public water supplies being 75 Hazen units and the desirable level being less than 10 Hazen units (Committee on Water Quality Criteria, FWPCA 1968).

## 10. Radioactivity

Alpha and beta activity are the two important types of radioactivity found in water. Alpha activity, associated with ejection of helium nuclei, is mainly attributed to natural sources whereas beta activity involving loss of electrons, is associated with anthropogenic activities. Thus, the latter form of radioactivity is a good indicator of contamination from nuclear weapon testing as well as from nuclear power stations, nuclear material and waste processing and from other uses including industrial, medical and research facilities. In all except the first of these sources the amounts of radioactive wastes discharged in these operations are strictly prescribed and enforced by government agencies and are subject to critical surveillance to ensure the levels do not exceed the limits set. The beta activity in water is usually expressed in picoCurie/liter (pCi/l).

Nuclear weapon testing has lead to the injection into and long term fallout of radionuclides from the upper atmosphere. Important fallout products are strontium (Sr-90), cesium (Cs-137) and iodine (I-131). These airborne radionuclides can enter water bodies directly from the atmosphere by precipitation scavenging (rain-out and wash-out) and by dry deposition, or indirectly by run-off and leaching of radioactive debris deposited on the ground. Assimilation of radioactive materials by water bodies may also occur through discharges resulting from nuclear applications, development and research by industrial, medical and research facilities.

Radioactivity in water bodies may be assimilated by humans either by direct ingestion or through the consumption of contaminated fish or other aquatic products. Because of the potential health hazard to users of water supplies by exposure to radiation from radioactive materials various government agencies have undertaken monitoring programs lasting a number of years. These studies have included radioactivity measurements of raw water supplies in rivers and lakes, the biota, bottom sediments and beach sands in recreational areas.

Measurements of total beta radioactivity in Lake Ontario waters have been made near Hamilton from 1958 to 1965. These data are shown plotted in Figure 87. Examination of the individual data points shows that the greatest fraction of atmospheric fallout occurs during the spring precipitation period of each year. The smoothed curve shows the cumulative effects of nuclear weapon testing in the 1950s and the brief resumption of testing in the early 1960s.

Concentrations of specific radionuclides (Sr-90 and Cs-137) have been measured in Toronto drinking water from 1964 through 1968. The average values found during this observation period were 1.02 pCi/l for Sr-90 and 0.17 pCi/l for Cs-137, see Figure 88. The data points for Sr-90 in Figure 88 show the buildup in Sr-90 as computed by a model developed by Lerman (1972). The observed values were the lowest found in a national survey of radioactivity in lake-derived water sources by the Canadian government, which provided nationwide averages of 2.20 pCi/l and 0.25 pCi/l for Sr-90 and Cs-137, respectively. These concentrations of radioactive materials are well below the maximum permissible levels (1000 pCi/l for beta radioactivity, 10 pCi/l for Sr-90) recommended for drinking water supplies by the International Commission for Radiological Protection and the Committee on Water Quality Criteria, Federal Water Pollution Control Administration (1968).

## Environmental Characteristics Influencing Lake Ontario Chemistry

Several important factors contributing to the overall chemical state and the water quality of Lake Ontario waters have been mentioned briefly in passing but have not been reviewed in detail in previous sections. These influential characteristics play either a dominant or significant role in determining the concentrations and trends in the loading of species found in the lake for materials such as the nutrient elements, dissolved (major ions) and suspended (particles) solids and trace elements and compounds, including heavy metals and organic chemicals. Specific environmental influences characteristic of Lake Ontario to be reviewed and discussed here include the roles of sediments, tributaries, waste discharges and atmospheric precipitation in determining the bulk chemistry and quality of the lake water.

### 1. Sediments

The sequential sedimentary processes occurring in a lake include erosion from the drainage basin and shore, dispersion of suspended material by lake currents, sedimentation and genetic transformations in the lake bed. In geologic time these continuous processes can cause an expansion of the lake perimeter and siltation of its basin, characteristic of natural lake aging. Thus, the lake sediments can hold information concerning its evolution and nature. Analysis of lake bed core samples enables the sequential deposition of fossils and other debris in sedimentary strata to be studied and has provided useful information on past and present trends in the lake's environmental characteristics such as its trophic state, water level, climatology, aquatic biota and water chemistry. In fact, a detailed knowledge of these sedimentary processes is essential to the reliable prediction of the transport and fate of particulate pollutants discharged into the lake.

The chemical and biological effects of sedimentation are not as obvious as the visual physical manifestation. For example, phosphates in fertilizers unlike other constituents are not easily leached out of soil but tend to adhere to soil particles. As a result stream bank and soil erosion transports these phosphate-enriched particles into the rivers and lakes providing an additional supply of nutrients. Many types of pesticides, such as DDT and dieldrin are translocated into natural waters in a similar fashion. These pollutant materials may thus accumulate in the river and lake bottom sediments where, as a result of ingestion by lower forms of aquatic life, they may enter the food chain. Sedimentary mechanisms are important also in removing the translocated or transformed non-conservative nutrient elements such as phosphorous, nitrogen and carbon as part of the natural self-purification process occurring in lake waters. Conversely, decomposition of organic material and chemical reduction in the surficial sediments can release nutrients and chemical compounds to the overlying bottom waters, which may cause a delayed detrimental effect on the water quality.

The shoreline of Lake Ontario is of recent submergence and has the character of an eroded shore bluff. In areas where the bluffs are cut through by tributary streams the flooding of stream valleys is a common occurrence causing separation of the bluffs from the lake by a sandy barrier beach. This type of feature is particularly apparent along the southern edge of the lake. Detailed descriptions of the Lake Ontario shoreline have been reported by Coleman (1937), Langford (1952), the US Army Corps of Engineers (1943, 1954, 1955a 1955b) and the New York-New England Interagency Committee (1954). Eroded shore materials consist mainly of silt and clay grain sizes (< 0.06 mm diameter), which also accounts for a significant fraction of the sediment found in the lake.

Stream and river bank erosion appears to be the major source of the sediment in Lake Ontario. Estimates of the large sediment loads carried into Lake Ontario by the major tributary rivers are given in the next section dealing with tributary inputs of suspended solids. In some areas the problem of sediment inflow and deposition at the river mouth is sufficiently acute that frequent dredging is necessary, as is the case for the Toronto and Rochester harbors at the mouths of the Don and Genesee Rivers, respectively. The major source of suspended solids carried into Lake Ontario is the Niagara River. Because of its large discharge volume it introduces about 80 percent of the total suspended solids load annually. Other important sediment-carrying tributaries are the Black, Oswego and Genesee Rivers in New York State and Twelve Mile Creek in Ontaria, Canada.

A number of studies have been made of the sediments in Lake Ontario. The earliest description of the regional distribution of sediments was reported by Kindle (1925) following a detailed lakewide bottom sampling program. More recently extensive investigations have been carried out by FWPCA in 1965 and CDNHW in 1966 and 1967. The distribution and nature of bottom sediments has been reported by Lewis and McNeely (1967), RIJC (1969), Williams and Moyer (1972), Thomas (1969, 1972a 1972b) and Casey et al. (1973). The surficial bottom sediments have been classified into three types: the complex nearshore sediments, glaciolacustrine clays and post-glacial muds. The approximate distribution of these specific sediment types in Lake Ontario is shown in Figure 89.

The complex nearshore sediments consist mainly of modern and glacial sands mixed with gravel (pebbles), and bedrock (boulders) and interspersed with mollusc shells and shell fragments. They extend completely around the periphery of the lake in a belt varying from 5 km (3 mi) wide on the southern side to 19 km (12 mi) wide along the northern edge and out to a depth of at least 40 meters (122 ft). Most of this material originates from the extensive glacial and bedrock (shale) deposits observed along the shoreline, which are much more predominant in the Canadian side of the lake. The grain sizes of the complex nearshore sediments vary from that of silty fine sand to gravel (< 0.05 mm diameter). The sediments grade laterally from sand to silt to clay beyond this band of nearshore sediments.

Glaciolacustrine clays, consisting of clay sediments deposited earlier in geologic time during the existence of glacial lakes, are found exposed in two areas of the lake. A large area of the lake bed in the western basin approximately due east of Toronto contains these clays as does a smaller area in the eastern basin approximately due north of Rochester, see Figure 89. The lacustrine clays are mainly fine-grained (< 0.002 mm diameter), calcareous and grey or grey-brown in color.

Post-glacial muds cover the greatest area of the lake bottom. These muds are composed of soft or silty clay with a mean particle diameter in the range 1-4 μm diameter and are medium grey in color. An orange-colored clay has been observed near the top of the mud column in core samples taken from the central region of the lake which presumably contains iron oxide deposited during the last 200 years. The rate of deposition of mud in the deeper eastern basin has been estimated at 1 mm per year by Lewis and McNeely (1967). Fresh-looking sand found mixed with clay and silt in the eastern basin suggests that sediments in this deep water region consist not only of particles from stream and shore erosion but also a wind-driven airborne fraction (Casey et al. 1973).

The mineralogic composition of offshore sediments has been reported by Kramer (1962). Illite, montmorillonite, kaolinite and traces of corrensite were identified in the "black" and "brown" bottom sediments, and a small amount of an iron sulfide mineral similar to troilite was found in the muds. Approximately two-thirds of the mud deposits consist of clay minerals (Kemp and Lewis 1968).

The chemical composition of the individual and lakewide sediments found in Lake Ontario have been discussed in a series of publications by Kemp and his colleagues (1968, 1969, 1970, 1971a, 1971b, 1973a, 1973b 1974a). Their extensive and detailed investigation of Lake Ontario sediment core samples have provided information on sedimentation rates and a knowledge of recent sedimentary chemical history. The latter is summarized and depicted graphically in Figure 90, which shows the estimated trends in the sediment content of total sulfur, carbonate and organic carbon, total nitrogen and total phosphorous since 1800. Note that the content of these constituents are reported as a percentage of the sediment mass. It is seen that, whereas the total sulfur in sediments has remained fairly constant over the observation period, carbonate and organic carbon and total phosphorous have been increasing exponentially since the middle of the last century. Total nitrogen, on the other hand, has noticeably increased only since a time early in this century (ca 1910) which corresponds closely to the observed onset of lakewide pollution due to increasing anthropogenic activity in the Lake Ontario basin, as suggested by other water quality indicators. Other properties of the three types of sediments found in Lake Ontario as well as a lakewide average are given in Table V, which summarizes data obtained in 1969 (Kemp 1971a). Sediments have also been analyzed for phosphorus (Armstrong 1973), phosphate and total iron (Casey et al. 1973), mercury (Thomas 1972a), sodium and chloride (Lerman and Weiler 1970) and strontium-90 (Lerman and Taniguchi 1972). Whereas the individual values of total phosphate and total iron varied the ratio was constant, confirming that the iron and phosphorus cycles are directly related through a coprecipitation mechanism. The chemistry of interstitial water in the sediments has been studied by Weiler (1970 1973) and Casey et al. (1973). It accounted for about 60 percent of the mass of sample but depended directly upon the depth at which sediment samples were obtained. Concentrations of total phosphate and total iron in the interstitial water were approximately 200 and 40 μg/l, respectively.

Analysis of lake bottom sediments for oxidizable organic matter has been reported by Lewis and McNeely (1967). They found that high levels of organic material existed in the sediments near the center of the basins of mud accumulation and also near the mouth of the Niagara River. Low concentrations of organic material were associated with the coarser sediments and the areas of the glaciolacustrine clays. In general, the highest organic content was found in the finest-grained deposits. Values for organic carbon content in lakewide sediments obtained in 1971 and 1972 averaged 4.8 percent by mass, which was noticeably higher than the 1969 values given in Table V. Kemp and Lewis (1968) have studied the relation between organic carbon, chlorophyll pigments and the depth of burial in sediments. They have shown that most of the chlorophyll, which presumably originates from phytoplankton in the surface waters, is partially decomposed by the time it reaches lake bottom. Additional decomposition is indicated within the sediments by a rapid decrease in concentration in organic carbon and chlorophyll degradation products with depth of burial. Thus, a marked change in the composition of the sedimentary organic fraction must occur in the surficial muds.

TABLE V

Summary of the Properties of Sediments in Lake Ontario
During 1969

| | Sediment type | | | |
|---|---|---|---|---|
| Property | Mud | Silt | Sand | Lakewide |
| % Sand (0.06 - 2.0 mm diam) | 1 | 9 | 82 | 1 ± 0.5 |
| % Silt (0.004 - 0.06 mm diam) | 27 | 61 | 8 | 29 ± 9 |
| % Clay (< 0.004 mm diam) | 72 | 30 | 10 | 70 ± 9 |
| % Fine Clay (< 0.002 mm diam) | 65 | -- | -- | 65 |
| $E_h$, volts | + 0.03 | + 0.12 | + 0.34 | 0.00 ± 0.03 |
| pH | 7.7 | 7.6 | 7.6 | 7.6 |
| % Carbonate C ($10^{-2}$ g/g) | 0.8 | 1.2 | 0.3 | 0.8 ± 0.5 |
| % Organic C ($10^{-2}$ g/g) | 3.5 | -- | -- | 3.5 ± 0.5 |
| % Total N ($10^{-2}$ g/g) | 0.55 | -- | -- | 0.55 ± 0.03 |
| % Total P ($10^{-2}$ g/g) | 0.18 | -- | -- | 0.18 ± 0.02 |
| % Total S ($10^{-2}$ g/g) | 0.10 | -- | -- | 0.10 |

The redox potential ($E_h$) of sediments has been studied by Kemp and Lewis (1968). This property is a measure of the oxidizing or reducing ability, involving electron transfer, relative to the interconversion of protons ($H^+$) and molecular hydrogen ($H_2$), which is defined as $E_h = 0.00$ volts. These investigators found values for $E_h$ in the range +0.16 to -0.03 volts in the surficial sediments and a decreasing $E_h$ with depth of burial. The values suggest that the uppermost layer of sediment (to 1 cm depth), which is colored light grey or brown, is oxidizing in nature, whereas the sediments below this layer are reducing and are colored black. Their studies indicated that the mud sediments are topped by a thin oxidized microzone presumed to be rich in ferric hydroxide and phosphate. This microzone constitutes a chemical barrier preventing bound phosphate in the underlying reducing sedimentary layer from returning into solution. Material precipitating to the bottom of the lake is assimilated in an oxidized state into the surficial microzone and trapped there. Thus, a natural self-regulating mechanism exists between the phosphate cycle and lake muds. Should this oxidizing microzone be destroyed, however, then phosphate can be recycled into the water mass from the reducing sediments below. It appears that the oxidized microzone in Lake Ontario may exist year round. If this is the case then a reduction in the phosphate discharged into the lake by the imposition of controls on municipal and industrial wastes could result in an immediate improvement in water quality and its trophic state (Vallentyne et al. 1970). Note that such action would not produce such a marked result in shallower lakes, where an oxidized microzone may disappear in early summer. So long as this microzone exists the phosphorus in the various biogeochemical systems which is precipitated out will remain bound up, and the longer the microzone exists the more phosphorus will be irreversibly removed from the water mass.

Sediments have been studied in the Niagara River and at its inflow into Lake Ontario. The sediments in the river consisted of sandy silt with an organic carbon content of 0.5 to 2.7 percent by mass. Sedimentary nitrate-nitrogen concentrations varied from 0 to 2 ppmm (parts per million on a mass basis), phosphate-phosphorus was in the range 0 to 0.5 ppmm and ammonia-nitrogen values found were from 0 to 145 ppmm. These concentrations were determined for the readily extractable forms of the species, which included the fraction present in interstitial water as well as that bound to the solid particles. The sediments in the sand bar in Lake Ontario, beyond the mouth of the Niagara River, have been studied and were found to contain much lower concentrations of organic carbon, nitrate, ammonia and phosphate. However, beyond the sand bar in the deep region of the lake the sediments were reduced and consisted of 60 percent clay. In this regime the organic carbon in surface sediments was 3.8 percent by mass and higher values were found for nitrate and phosphate. The latter constituent being an order of magnitude greater in concentration than was found in the sand bar and river sediments (RIJC 1969).

## 2. Tributary Rivers and Waste Discharges

Major tributaries of lakes transport residual wastes and materials from upstream municipal, industrial and land drainage sources into the lake environment, in addition to the direct discharge of wastes into the lake from anthropogenic activities around the lakes perimeter. However, oxygen-consuming wastes carried by tributaries are usually subject to degradation before entering the lake or being completely assimilated by the lake waters, but nutrient elements acquired in this manner will have a wide and long-term influence on the water quality of the lake. Lake tributaries can contribute dissolved and suspended solids, synthetic chemical compounds, pesticide residues and heavy metals to the lake waters in addition to nutrients. In some cases the silt loading alone can cause a serious problem as mentioned previously in the case of the Toronto and Rochester harbors.

The Niagara River is the largest single source of material input to Lake Ontario when compared with all other tributaries and sources. This can readily be seen in Table VI where the loadings of certain pollutant materials are listed, that were carried annually by major tributaries into Lake Ontario in 1966-1967. The relative influence of the materials carried initially by the Niagara River originating at the Lake Erie outflow and the additional wastes acquired through anthropogenic activities in the Niagara River drainage basin are presented also in Table VI. These local sources contributing to the Niagara River loading include municipal and industrial wastes resulting from development along the upper river banks extending from Buffalo and Fort Erie at Lake Erie to Niagara Falls. As a result of these significant local inputs the total nitrogen and total phosphorous content of Niagara River water increases by 20 and 70 percent, respectively, as it flows from Lake Erie to Lake Ontario. In terms of total annual tributary material loadings the Niagara River inflow supplies Lake Ontario with about 81 percent of the suspended solids, 83 percent of the dissolved solids, 73 percent

## TABLE VI

### Material Loadings (metric kilotons/yr)* of Major Tributaries Supplying Lake Ontario in 1966-1967 (RIJC 1969)

| Tributary | Flow $m^3$/sec | (cfs) | Solids* metric kilotons/yr Total | Solids* metric kilotons/yr Suspended | Total Nitrogen* metric kilotons/yr | Total Phosphorus* metric kilotons/yr | Chlorides* metric kilotons/yr |
|---|---|---|---|---|---|---|---|
| Lake Erie to Niagara River | 5,493 | (194,000) | -- | -- | 72.0[a] | 4.1[a] | 4,540[a] |
| Niagara River Basin | | | | | | | |
| State of New York | 21 | (745) | -- | -- | 8.8 | 2.0 | 156 |
| Province of Ontario | 16 | (555) | -- | -- | 5.6 | 0.9 | 25 |
| Niagara River to Lake Ontario | 5,530 | (195,300) | 38,830 | 4,563 | 86.4[b] | 7.0[b] | 4,720[b] |
| Oswego R. (US) | 176 | (6,200) | 3,211 | 303 | 5.8 | 0.57 | 980 |
| Genesee R. (US) | 77 | (2,730) | 952 | 289 | 6.0 | 0.29 | 70 |
| Black R. (US) | 108 | (3,830) | 387 | 82 | 2.7 | 0.16 | 11 |
| Other tribs (US) | 68 | (2,410) | 384 | 51 | 2.7 | 0.24 | 34 |
| Total US tribs to Lake Ontario | 430 | (15,170) | 4,935 | 725 | 17.2 | 1.26 | 1,095 |
| Twelve Mile Cr (CAN) | 181 | (6,400) | 1,642 | 197 | 7.0 | 0.53 | 163 |
| Trent R. (CAN) | 118 | (4,170) | 492 | 35 | 2.4 | 0.14 | 25 |
| Welland Canal (CAN) | 35 | (1,230) | 318 | 51 | 1.0 | 0.11 | 38 |
| Other tribs (CAN) | 100 | (3,520) | 615 | 73 | 4.0 | 0.57 | 46 |
| Total CAN tribs to Lake Ontario | 434 | (15,320) | 3,067 | 356 | 14.4 | 1.35 | 272 |
| Total trib input to Lake Ontario | 6,394 | (225,800) | 46,500 | 5,640 | 118 | 9.6 | 6,090 |

*To convert to US short kilotons multiply by 1.1

[a] Based upon 0.42 mg N/1, 0.024 mg P/1 and 26.2 mg Cl/1

[b] Equivalent to 0.50 mg N/1, 0.040 mg P/1 and 27.1 mg Cl/1

of the total phosphorus and 77 percent of the chloride input. Thus, it accounts for approximately three quarters of the total pollutant material input to Lake Ontario. Twelve Mile Creek, the Oswego, Genesee and Black Rivers together carry in excess of 60 percent of the nutrient input, 80 percent of the suspended solids and 90 percent of the chloride in the remaining quarter of the total annual tributary loading supplying the lake. Thus, the combined inputs of all Lake Ontario tributaries, except the Niagara River, supply 27 percent of the total annual nutrient load or 38 percent of the nutrient load supplied by the Niagara River. The industrial, municipal and agricultural waste components of these specified tributary loads represent an annual nitrogen and phosphorus contribution of 370 kg (815 lb) and 21 kg (40 lb) per square kilometer (0.39 mi$^2$), respectively, when averaged over the entire Lake Ontario drainage basin (RIJC 1969).

Tributaries flowing into the St. Lawrence River on both the Canadian and American sides, which are not included in Table VI contributed a flow of 182 m$^3$/sec (6,400 cfs) and carried a total annual burden of 562 metric kilotons ($10^6$ kg) total solids, 127 metric kilotons suspended solids, 22 metric kilotons chloride, 2.4 metric kilotons total nitrogen and 0.17 metric kilotons total phosphorus in 1966-1967 (RIJC 1969) [Conversion to US short tons (2000 lb) from metric tons (1000 kg) is achieved by multiplying by a factor of 1.1].

The earliest detailed investigations of the chemistry of tributary rivers flowing into Lake Ontario were made by Wagner (1926, 1927 1929) in the 1920s. Since that time the waters near the mouths of several major tributaries feeding Lake Ontario have been subjected to numerous chemical and water quality measurements, particularly in recent years. The data obtained from a number of independent investigations is summarized for the Niagara, Genesee, Oswego and Black Rivers in Table VII. From a knowledge of the mean flow of these tributaries and the concentrations of constituents it is possible to estimate the relative importance of these tributaries with regard to their contributions of specific pollutants to Lake Ontario. In terms of the nutrient elements and solids (dissolved and suspended) the major contributing tributaries are the Niagara, Oswego Rivers, Twelve Mile Creek (CAN), Genesee, Trent (CAN), Black Rivers and the Welland Canal (CAN) in decreasing order of importance. In general, the estimated contribution by all tributaries located on the United States side of Lake Ontario is slightly greater than that of the combined Canadian tributaries.

Direct inputs of municipal and industrial waste discharges in 1966-1967 have been reported by the International Joint Commission on Pollution of Lake Erie, Lake Ontario and the International Section of the St. Lawrence River (RIJC 1969). These data on major pollutants are summarized in Table VIII for both American and Canadian activities. From this summary it appears that municipal and industrial wastes discharged from point sources in Canada (> 85% of total for all pollutants except phosphorus) greatly exceeds that discharged on the US side of the lake from similar sources. From Tables VI and VIII, it is seen that almost half of the total phosphorus input is associated with municipal and industrial wastes

## TABLE VII

### Summary of Chemical and Water Quality Characteristics of Four Major US Tributaries Flowing into Lake Ontario, 1967-1973*

| | SOURCE | | | |
|---|---|---|---|---|
| Characteristic | Niagara River | Genesee River | Oswego River | Black River |
| $NH_3$-N (mg/l) | - | 0.32 (0.20) | - | 0.15 |
| $NO_2$-N (mg/l) | - | 0.07 (0.01) | - | 0.007 |
| $NO_3$-N (mg/l) | 0.38 (0.9) | 0.70 (0.25) | - | 0.35 (1.2) |
| Soluble organic N (mg/l) | 0.28 | 0.28 | 0.33 | 0.31 |
| Particulate organic N (mg/l) | 0.14 | 0.56 | 0.28 | 0.20 |
| Total organic N (mg/l) | 0.42 | 0.77 ± 0.07 | 0.60 | 0.48 ± 0.05 |
| Total N (mg/l) | 0.8 | 1.85 ± 0.5 | 1.4 | 0.89 ± 0.02 |
| Sol. Phosphate - P (mg/l) | - | - | - | - |
| Total Phosphate - P (mg/l) | - | 0.17 (0.20) | - | 24 |
| $SiO_2$ (mg/l) | (6.2) | 3.9 (2.0) | - | 5.9 (5.3) |
| Na (mg/l) | 14 (10) | 30 (28.7) | - | 2.5 (3.1) |
| K (mg/l) | 1.8 (1.2) | 2.7 (4.2) | - | 0.8 (0.9) |
| Ca (mg/l) | 38.6 (39) | 52 (60) | - | 13.5 (11) |
| Mg (mg/l) | 9.1 (8.3) | 10.5 | - | 1.5 (1.5) |
| Fe (mg/l) | (0.04) | 0.5 (0.7) | - | 0.25 (0.17) |
| $HCO_3$ (mg/l) | (120) | - | - | (26) |
| Cl (mg/l) | 26.3 (22) | 45 (66) | - | 2.1 (2.7) |
| F (mg/l) | (0.2) | 1.5 (0.15) | - | 0.07 (0.2) |
| $SO_4$ (mg/l) | (24) | 65 (77) | - | 10.3 (15) |
| Dissolved solids (mg/l) | 190 | - | - | (80) |
| Total residue (mg/l at 103°C) | - | (352) | - | - |
| Spec. Cond at 25°C (μmho/cm) | 330 (308) | 471 (407) | - | 93 (93) |
| Total hardness ($CaCO_3$ mg/l) | 128 (133) | 175 (188) | - | 39 (34) |
| Non-carb. hardness ($CaCO_3$ mg/l) | (35) | - | - | (12) |
| Turbidity (JTU) | - | (13) | - | - |
| Diss. $O_2$ (mg/l) | - | (7.8) | - | - |
| Total alkalinity ($CaCO_3$ mg/l) | 89.2 | 97 (96) | - | 31 |
| pH | 8.0 ±0.4 (7.6) | 7.7 (7.5) | - | 7.2 (6.3) |
| COD (mg $O_2$/l) | - | 7 (4.8) | - | 15 |

*Note that figures in parentheses are 1959-1964 data.

TABLE VIII

Summary of Municipal and Industrial Wastes Discharged (metric kilotons/yr)
Directly into Lake Ontario 1966-1967 (RIJC 1969)

| Source | Flow $m^3$/sec | (cfs) | Solids* metric kilotons/yr Total | Solids* metric kilotons/yr Suspended | Total Nitrogen* metric kilotons/yr | Total Phosphorus* metric kilotons/yr | Chloride* metric kilotons/yr |
|---|---|---|---|---|---|---|---|
| Municipal Wastes | | | | | | | |
| Canadian | 14.6 | (514) | 348 | 28.7 | 9.3 | 1.82 | 114 |
| US | 3.7 | (131) | 100 | 40.9 | 2.7 | 0.86 | 19 |
| Total Municipal | 18.3 | (645) | 448 | 69.6 | 12.0 | 2.7 | 133 |
| Industrial Wastes | | | | | | | |
| Canadian | 21.4 | (754) | 359 | 62 | 16.1 | 0.2 | 8.3 |
| US | 0.1 | (4) | 3 | 2 | -- | -- | 0.1 |
| Total Industrial | 21.5 | (760) | 362 | 64 | 16.1 | 0.2 | 8.4 |
| Total Municipal and Industrial | 40 | (1,400) | 810 | 134 | 28.1 | 2.9 | 141 |
| Total mun, ind, and trib input to Lake Ontario | 6,430 | (227,200) | 47,300 | 5,770 | 146 | 12.5 | 6,230 |

*Multiply by 1.1 to convert to US short kilotons

and only about one third of the annual phosphorus load originates in the inflow from Lake Erie. Municipal and industrial point sources, on the other hand, account for less than one third of the annual total nitrogen input, approximately half of which originates in the Lake Erie inflow. These basic relationships are of importance in models describing nutrient loading effects (Thon 1969) and in the planning and assessment of water quality control programs designed to improve the lake environment with regard to the nutrient elements.

In addition to the major pollutants listed in Table VIII, industry in the Lake Ontario basin discharges a wide variety of inorganic and organic pollutant chemicals and by-products which eventually reach the lake waters. An indication of the annual quantities of materials discharged directly into Lake Ontario by industry in 1966-1967 is given in Table IX. As can be seen this is a non-exhaustive listing which does not include important pollutants that have recently been shown to have harmful ecological effects even in trace quantities, such as Mirex (Kaiser 1974), heavy metals, pesticide residues, polychlorinated biphenyls (PCB), etc. Although the annual inputs of the latter materials may be small their effects are widespread and possibly of a long-term nature due to their concentration in the aquatic food chain. Also not included in Table IX are those chemical materials which are specific to certain industries, such as asbestos, fluorides, sulfides, fats, waxes and oils, etc. but which could be present in trace amounts in the lake waters.

TABLE IX

Estimated Annual Inputs (metric tons/yr) of Some Chemical Pollutants to Lake Ontario by Major Industrial Point Sources in the US and Canada 1966-1967 (RIJC 1969)

| Pollutant | Discharge Rate (metric tons/yr)* |
|---|---|
| Total Iron | 22,270 |
| Dissolved Iron | 1,082 |
| Sulfate | 9,804 |
| Sulfite | 278 |
| Ether Solubles | 11,680 |
| Cyanide | 256 |
| Phenols | 465 |
| COD | 73,320 |
| $BOD_5$, industrial | 21,680 |
| $BOD_5$, municipal | 38,240 |

*Multiply by 1.1 to convert to US short tons

Other contributing sources of pollutants include the wastes and spills associated with the operation of commercial and recreational vessels, reentrainment of materials from dredging operations and a direct input from atomspheric precipitation on the lake surface. The latter source will be reviewed and discussed in more detail in the next section of this report.

In order to assess the overall impact of the various pollutional inputs on the water quality of Lake Ontario it is instructive to calculate the material balance between contaminants entering the lake and those leaving via the St. Lawrence River. Estimates of the input and output of four categories of pollutants: dissolved solids, total nitrogen, total phosphorus and chloride, in Lake Ontario during 1966-1967 are given in Table X. This calculation assumes that precipitation data obtained in 1970 is valid for the mid-1960s. The input data used is based upon the tributary, municipal, industrial and atmospheric precipitation source annual loadings, whereas the outputs are estimated from a knowledge of the flow and concentrations of these materials at the head of the St. Lawrence River, the latter being similar to the lakewide levels found in Lake Ontario.

The data presented in Table X provide an overall picture of the origin and fate of pollutants in Lake Ontario in addition to a knowledge of the relative importance of contaminants from various sources. Considering the large input of dissolved solids annually (42 metric megatons), the total input and output of this water quality indicator are in reasonable agreement. The difference gives a residue of total dissolved solids retained in the lake, corresponding to about eight percent of the total annual input. Such an accumulation corresponds to a one percent per year increase in the lake loading, which is approximately double that determined experimentally. This discrepancy may be resolved partly by the fact that the error in estimating the material balance for dissolved solids is very large and that a fraction of the dissolved solids may be removed from solution by chemical and biological processes involving fixation and precipitation.

The total annual loadings of the nutrients nitrogen and phosphorus per unit surface area of the lake, 8.7 and 0.7 gm/m$^2$/yr, respectively, are approaching the dangerous level with regard to eutrophication as prescribed by Vollenweider (1968), for lakes of similar surface area and volume. Tentative estimates of the admissible and dangerous annual loadings for a lake of 100 meters mean depth (Lake Ontario mean depth = 84 meters) are 6 and 12 gm/m$^2$/yr for total nitrogen and 0.4 and 0.8 gm/m$^2$/yr for total phosphorus, respectively. The large imbalances observed for the nutrient elements, nitrogen and phosphorus, indicates a high retention and rapid transformation of these non-conservative materials during their residence period in the lake. If about 40 percent of the input nitrogen and almost 70 percent of the input phosphorus are retained by the lake each year then these accumulations would correspond to lakewide concentration increases of 8 percent per year and 24 percent per year, respectively. Such is not the case in practice, however, since most of

TABLE X

Material Balance of Important Pollutant Materials Entering and Leaving Lake Ontario in 1966-1967

| Input sources | Water Flow $m^3$/sec | (cfs) | Dissolved Solids* metric kilotons/yr | Total Nitrogen* metric kilotons/yr | Total Phosphorus* metric kilotons/yr | Chloride* metric kilotons/yr |
|---|---|---|---|---|---|---|
| Tributaries | 6,394 | (225,800) | 40,860 | 118 | 9.6 | 6,090 |
| Municipal Waste | 18 | (645) | 380 | 12 | 2.7 | 133 |
| Industrial Waste | 33 | (760) | 300 | 16 | 0.2 | 8 |
| Atmospheric Precip. | 516 | (18,200) | 200 | 24 | 1.9 | 10 |
| Total Input | 6,950 | (245,500) | 41,740 | 170 | 14.4 | 6,240 |
| Total Output via St. Lawrence R. | 6,420 | (226,600) | 38,500 | 101 | 4.8 | 5,450 |
| Difference | 530 | (18,800) | 3,200 | 69 | 9.6 | 790 |
| Percent of input transformed or retained in lake | Loss by Evaporation | | 8 | 40 | 66 | 13 |
| Lake Ontario content (metric Kilotons) | ($1,630\ km^3$) | | 310,000 | 816 | 39.2 | 44,000 |
| Accumulation rate, %/yr | 0 | | 1 | 8 | 24 | 2 |

*Multiply by 1.1 to convert to US short kilotons

the available nutrient materials in the lake are ultimately transformed and translocated to the bottom sediments, where they are irreversibly bound by the oxidized microzone.

The chloride material balance is not as good as that for the dissolved solids. Being a conservative element, that chloride which is retained must contribute to an increased lake loading. If 13 percent of the annual chloride input is retained in the lake this would amount to an accumulation rate of 20 percent per decade, which is in good agreement with observed increases in chloride concentrations in Lake Ontario's waters (22%/decade) during recent years.

### 3. Atmospheric Precipitation

Most of the influx of atmospheric materials into Lake Ontario is a direct result of the scavenging of atmospheric particles and gases by rain and snow and of the dry fallout of airborne particles. (Kellog et al. 1972, Shaw and Whelpdale 1973 1974). Small contributions have been attributed to the transport and dissolution of atmospheric gases at the air-water interface (Whelpdale and Shaw 1974) and to the fixation of dissolved nitrogen by certain blue-green algae. Rainout (in cloud) and washout (below cloud) are particularly effective in cleansing the atmosphere of particles and pollutant gases, thus, converting an air pollution problem into one of water pollution. However, because of the finite amounts of airborne pollutants available during precipitation periods the concentrations of constituents in precipitation are inversely dependent upon the amount of precipitation collected per event and the frequency of precipitation events. Thus, it is necessary to adjust individual concentration measurements (volume weighting) in order to obtain a meaningful annual average concentration loading. In the absence of precipitation, material is transported from the atmosphere as dustfall. By nature these atmospheric particles large enough (> 10 μm diameter) to settle out of the atmosphere are agglomerates of smaller particles of varying chemical nature and composition. In addition, varying amounts of gaseous and liquid materials are associated with these particles by adsorption and absorption. As a consequence it is not surprising that all of the recognized water pollutant compounds are found to some extent in precipitation samples. It should be noted, however, that both the nature and composition of atmospheric particles can be greatly influenced on a local scale by the type and extent of industrial and commercial operations and transportation activities, as well as the meteorology of the area.

In Table X it is seen that of the four pollutant materials chosen, only the nutrient elements, nitrogen (14% total) and phosphorus (13% total), in bulk precipitation constitute a significant fraction of the total supply to Lake Ontario. Here bulk precipitation refers to the annual amount transferred from the atmosphere by rainfall, snowfall and dustfall. In the case of nutrient analysis in precipitation, however, much more emphasis has been placed upon nitrogeneous materials than on phosphorus compounds. As a result our knowledge of the phosphorus compounds in precipitation samples is sparse.

The two most important nitrogenous species in precipitation are nitrate ($NO_3^-$) and ammonium ($NH_4^+$). Some nitrate may originate from nitrogen fixation in electrical discharges associated with thunderstorms, but the direct oxidation of atmospheric nitrogen in the atmosphere is unimportant (Hutchinson 1954). Oxidation of atmospheric ammonia (Feth 1966) in aqueous solution or by adsorption on catalytic surfaces, and the generation and release of nitrogen oxides and nitric acid vapor to the atmosphere by mobile and point sources seem to be much more plausible sources of atmospheric nitrate. Since the early studies of atmospheric particles by Junge (1963) there has been overwhelming evidence to confirm the abundance of airborne ammonium-containing particles, the ammonia presumably originating mainly from natural sources. Analyses of samples from individual precipitation events in the US have shown that the ammonium and nitrate in rain originated from gaseous components of the atmosphere, that is, ammonia and nitrogen oxides (Gambell and Fisher 1964). It should be noted that industrial processes, combustion sources and vehicles emit substantial quantities of atmospheric contaminants including particles, ammonia and nitrogen oxides.

A number of studies of the nitrogenous components in atmospheric precipitation have been made in the vicinity of Lake Ontario as well as elsewhere. Early studies during the first quarter of this century by Schutt and Hedley (1925) near Ottawa, Ontario showed that the nitrite plus nitrate nitrogen constituted about one third of the total nitrogen in rain or snow. They found also that rain accounted for 83 percent and snow for 17 percent of the total nitrogen in precipitation. From their data they estimated that the total nitrogen contributed to the land by precipitation was about 8 kg/hectare/year (7 lb/acre/yr) during a 17 year observation period. Studies of the inorganic nitrogen content of precipitation and atmospheric particulate matter at Hamilton, Ontario have been reported by Matheson (1951). The average annual deposition of total nitrogen recorded was in the range 6-9 kg/hectare (5-8 lb/acre). In addition he found that 61 percent of the total nitrogen was collected over 25 percent of the days, corresponding to the frequency of precipitation events. The balance of the total nitrogen was obtained during times of no precipitation and was attributed to the sedimentation of particulate material. The ammonia nitrogen in the samples accounted for slightly more than half of the total nitrogen found. Similar studies by McKee (1962) in Europe have indicated a rate of nitrogen deposition from the atmosphere by precipitation and dustfall in the range 2-10 kg/hectare/yr (2-9 lbs/acre/yr).

Recently, detailed analyses of precipitation samples in the vicinity of Lake Ontario (Shaw and Whelpdale 1973, Shiomi and Kuntz 1973) and in the Northeastern United States (Pearson and Fisher 1971) have been reported which indicate the extent to which atmospheric precipitation influences the chemistry of Lake Ontario. Shiomi and Kuntz (1973) collected and analyzed bulk precipitation samples at stations around the perimeter of Lake Ontario as well as at a station on Duck Island in the eastern basin of the lake. Because of the perturbing influence of local sources on the atmospheric concentrations of several atmospheric contaminants at the perimeter stations near centers of population, it would seem that the samples obtained at Duck Island would be the most representative of the bulk precipitation falling on the lake. It is these volume-weighted mean concentrations of nutrients, major ions and trace elements which are tabulated in Table XI. Estimates of the annual precipitation loading of Lake Ontario based upon an average annual total precipitation of 84 cm (33 in) over the lake surface (19,400 $Km^2$) are presented also in this table. In addition, for purposes of comparison, the mean concentrations of the same constituents in the surface waters of Lake Ontario in 1970 and the corresponding bulk content of the lake, based upon a volume of 1,630 $km^3$, are given in Table XI. These data allow the reader to obtain an estimate of the magnitude of atmospheric precipitation as a non-controllable pollutional source of input to the lake for each specie. It is important to note that precipitation over the rest of the Lake Ontario Basin could account for for an additional loading equal to almost twice that by direct precipitation, shown in Table XI. This indirect contribution, however, is manifested as part of the tributary input in Table VI.

In general, the nutrients are more highly concentrated in precipitation than in the lakewater and the result would be an enhancement in total nutrients by this source. In fact, as pointed out previously, the nutrient input by direct precipitation over the lake is almost 15 percent of the total input from all sources. In the case of the major ions, the concentrations in precipitation are much lower than are present in lake waters. Thus, it is to be expected that precipitation would have a diluting effect on the major ion levels present in the lake. The annual addition of trace elements by precipitation, however, represents a significant fraction (1-15%/yr) of the total amounts of the individual potentially hazardous heavy metals found in the lake. It would appear, therefore, that in this case atmospheric precipitation could be a major, if not the most important, source of the majority of the heavy metal trace elements observed in the lake waters. This view is supported by the fact that atmospheric particles which are liable to be scavenged by precipitation processes contain a wide variety and significant quantities of environmentally hazardous trace elements. In addition synthetic organic chemicals such as PCBs, organic carcinogens and pesticides are frequently found to be associated with atmospheric particles, therefore it would not be surprising if atmospheric precipitation were a significant source of these hazardous trace materials as well, for the same reasons as are given above.

In conclusion, the radioactivity in precipitation samples has been routinely monitored since 1954, and the data reported by the Health and Safety Laboratory (1970). The semi-annual rates of deposition of $^{90}Sr$ by precipitation in milliCurie per square kilometer per year ($mCi/km^2/yr$) are plotted for the period 1954 to 1970 in Figure 91. Although the input from this source went through a maximum of about 20 $mCi/km^2/yr$ in 1963 the deposition rate has since declined to about 1.2 $mCi/km^2/yr$ in 1968, and has presumably remained constant thereafter. This value corresponds to a total annual loading of $^{90}Sr$ by direct precipitation and run-off (50% of total) in the drainage basin of about

## TABLE XI

Comparison of Bulk Precipitation Concentrations, Bulk Precipitation Loading, Lakewide Concentrations and Total Lake Contents for Lake Ontario in 1970

| Constituent | Volume-weighted mean concentration in bulk precip. (mg/l) | Bulk Precipitation Loading (metric kilotons/yr)* | Mean lakewide concentration (mg/l) | Lake Content in 1970 (metric kilotons)* |
|---|---|---|---|---|
| NUTRIENTS | | | | |
| Reactive orthophosphate as P | 0.066 | 1.0 | 0.012 | 19.6 |
| Total phosphorus as P | 0.114 | 1.9 | 0.024 | 39.2 |
| (Nitrite + Nitrate) as N | 0.770 | 12.6 | 0.2 | 327 |
| Ammonia as N | 0.712 | 11.5 | 0.1 | 163 |
| Total Nitrogen as N | 1.48 | 24.1 | 0.5 | 816 |
| MAJOR IONS | | | | |
| Calcium | 3.34 | 54.2 | 42.2 | 69,000 |
| Sodium | 1.66 | 27.0 | 13.0 | 21,230 |
| Potassium | 0.61 | 9.9 | 1.4 | 2,270 |
| Magnesium | 0.44 | 7.2 | 8.0 | 13,060 |
| Sulfate | 5.74 | 93.5 | 28.9 | 47,200 |
| Chloride | 0.63 | 10.3 | 28.1 | 45,900 |
| TRACE ELEMENTS | | | | |
| Zinc | 0.096 | 1.6 | 0.011 | 18.0 |
| Iron | 0.028 | 0.46 | 0.050 | 82 |
| Copper | 0.008 | 0.13 | 0.006 | 10.4 |
| Lead | 0.007 | 0.11 | 0.005 | 7.8 |
| Nickel | 0.004 | 0.06 | 0.003 | 4.7 |
| Cadmium | 0.002 | 0.03 | 0.0001 | 0.2 |

*Multiply by 1.1 to convert to US short kilotons

65 Ci per year. This rate of input should be compared with an average $^{90}Sr$ content of 1,660 Ci in Lake Ontario from 1964 to 1968, which suggests that atmospheric precipitation is the principal source of this radionuclide in Lake Ontario, replenishing it at a rate of four percent per year.

## Summary and Conclusions

The physical, chemical and environmental characteristics which determine the chemistry and water quality of Lake Ontario's waters have been reviewed and discussed in detail in the preceding chapters. Important properties and environmental influences are summarized briefly below and conclusions are drawn concerning future trends in contamination and the necessity for control of specific pollutants.

Lake Ontario is situated completely in Paleozoic rock of the Ordovician Age, which was exposed along the axis of a former valley by glacial action in Pleistocene time. This rock consists mainly of shales and limestone.

The lake contains a large volume of water with respect to its surface area. From late spring until early fall the lake water is thermally stratified, approximately 85 percent of the water mass residing below the epilimnion. This important physical characteristic greatly influences the aquatic biological and geochemical processes occurring in the lake by providing a large reserve of available nutrients and oxygen in the hypolimnion. When stratified the volume of lake water capable of mixing with the inflowing pollutants is greatly reduced, since at times of maximum stratification the thermocline is only 20 meters below the surface. In early spring and late fall a vertical stratification develops which effectively separates inshore waters from the main water body offshore.

The Niagara River is the main tributary into Lake Ontario providing about 80 percent of the total annual inflow. It exerts a constant, as well as the greatest, hydrological influence on Lake Ontario, imposing an essentially steady gradient flow across the lake eastward from its mouth to the St. Lawrence River. Other tributary streams and rivers serving Lake Ontario have high flows in the spring and very low flows in summer, characteristic of the limestone terrain.

The temperature structure of the lake indicates an overall counterclockwise circulation of lake water from the spring to the fall. Two distinct patterns in surface circulation emerge during the year. In the summer months, when the lake water is stratified, the net surface circulation is counterclockwise. The main current flows eastward along the southern shore with a lesser return flow westward along the northern shore. In the winter months, when the water mass is isothermal, the net surface flow is eastward. Wind action can markedly affect the currents in the lake. For example, winds from the north around to the southeast produce a surface gyre in the western basin which has the tendency to trap materials discharged by the Niagara River and the Toronto-Hamilton-St. Catherines' region in the western part of the lake. Generally, the prevailing winds in the summer and fall are from the southwest with an average velocity of about 16 km/hr (10 mph). Under westerly wind conditions pollutant materials entering the western basin are dispersed along the southern shoreline of New York State.

The average net water transport velocity is approximately 2 cm/sec in the summer and 5 cm/sec in the winter. Inflowing water has a mean retention time of at least 15 years as a result of the circulation patterns and thermal stratification in summer. The general circulation patterns from spring through fall are such that the pollutants in nearshore areas from inflowing tributaries and waste discharges will tend to be confined to the inshore zone. In this way the most productive region of the lake is kept well supplied with nutrients during periods of algal activity.

Sedimentation mainly occurs at the western end of the lake and beyond the mouth of the Niagara River. Lakewide, from the shore to mid-lake, the sediments are graded laterally from sand through silt to clay. An oxidized sedimentary microzone exists at the mud-water interface in Lake Ontario, which plays an important role in the natural self-regulation of nutrient phosphorus.

Although the Lake Ontario Basin is considered to have a continental climate, the lake does have a moderating influence on the region by superimposing the features of a marine climate. The average range of air temperatures is from 21°C (70°F) in July to 4°C (25°F) in February. Precipitation over the lake averages 84 cm (33 in) annually, and 79 cm (31 in) over the Lake Ontario Basin as a whole.

The long residence time of chemical species in Lake Ontario waters suggests that the concept of a chemical elements availability is probably more meaningful than its concentration in determining its influence on the aquatic biogeochemical systems. The ratio of the nutrient elements, nitrogen to phosphorus in the lake suggest that the latter is the limiting nutrient. However, phosphate-phosphorus is part of a complex biogeochemical cycle that is not well understood. High concentrations of phosphate and nitrate are found in nearshore areas in the vicinity of cities and tributary rivers. Coprecipitation of phosphate occurs with ferric hydroxide, in this way the iron cycle and pH both affect the phosphate cycle. Phosphorus is removed by sedimentation on to the oxidized sedimentary microzone layer, where it is irreversibly bound and prevented from returning into solution. Dissolved silica concentrations are directly related to diatom populations. In the spring the diatoms take up silica but in the fall the silica is recycled in the form of dead diatom skeletal material.

The major ions found in Lake Ontario are bicarbonate ($HCO_3^-$), calcium ($Ca^{++}$), sulfate ($SO_4^=$), chloride ($Cl^-$), sodium ($Na^+$), magnesium ($Mg^{++}$), carbonate ($CO_3^=$) and potassium ($K^+$), in decreasing order of abundance. The concentrations of the cations, sodium and calcium, and the anions, chloride and sulfate, have been increasing steadily since about 1910. The rates of increase of these ions suggests a close association between sodium and chloride and between calcium and sulfate. The other major ions have remained at constant levels in Lake Ontario since observations were initiated. Many other chemical elements and compounds have been observed and measured in trace amounts in the lake. These include transition metals, heavy metals, halogens, pesticides and synthetic organic chemicals.

Studies of Lake Ontario waters in terms of water quality measurements have shown that the pH, total alkalinity and hardness have remained fairly constant since measurements were started. Dissolved solids, specific conductance and turbidity on the other hand have been steadily increasing since about 1910, which correlates well with trends observed in major ion concentrations. Dissolved oxygen in surface waters is at or above saturation. Lower concentrations are found in the hypolimnion ranging from about 60 percent saturation in winter, to about 85 percent saturation in summer. Measurements of $BOD_5$ in Lake Ontario are too low to be meaningful. Studies of total beta activity and strontium-90 radioactivity in Lake Ontario have shown levels at least one order of magnitude less than the maximum permissible levels set for potable water.

The most important source of pollutants in Lake Ontario is the Niagara River which supplies annually a loading of about 50 percent of the nutrients, 80 percent of the dissolved solids and 75 percent of the chloride total input. Other tributary rivers account for most of the remaining annual input of dissolved solids and chloride. Direct discharge of municipal and industrial wastes provides about 20 percent of the annual nutrient loading. Atmospheric precipitation is responsible for about 13 percent of the nutrient loading and also it can make a significant contribution to the total lake loading of trace chemical elements and compounds, including the highly toxic heavy metals, pesticide residues, polychlorinated biphenyls and other synthetic inorganic and organic chemicals associated with atmospheric particles. Estimates of the increasing lake loading of dissolved solids and chloride by material balance of the total input and outputs of the lake agree reasonably well with the observed trends in these pollutional parameters. Despite the fact that measurements of several chemical constituents and water quality parameters indicate a steadily increasing loading of certain pollutant materials, the concentrations of individual species found and the water quality measurement levels are still well below the maximum permissible limits for drinking water in most cases. The most serious problem appears to be the likelihood of the lake becoming eutrophic in the future as a result of phosphorus in municipal and industrial discharges. A secondary, but nevertheless important, problem is the build up of trace amounts of potentially harmful heavy metals and chlorinated hydrocarbon residues in the aquatic food chain with the eventual possibility of transference to man.

If the present average population (2.5%/yr) and economic (4%/yr) growth rates in the Lake Ontario basin continue through the end of this century then it would be expected that the annual nutrient loading by the discharge of municipal and industrial wastes will approximately double every 20 years, if additional controls are not applied. As a result the forecasted input of nutrients in the mid-1980s could lead to a serious deterioration in water quality by significantly advancing the degree of eutrophication of Lake Ontario. Since phosphorus appears to be the limiting nutrient element in this lake, the control of this specific pollutant in municipal and industrial waste discharges has been recommended. This has been achieved in part by the conversion to low phosphorus or phosphorus-free detergents which accounted for a major fraction of municipal inputs of phosphates (Heinke 1969) by hydrolysis and degradation. The major source of phosphate in tributaries, however, is the use of phosphorus-based fertilizers in agriculture. Several other factors lend support to phosphorus regulation, they are:

- Algal growth appears to be more dependent upon phosphorus availability than on the presence of nitrogen compounds.
- Almost complete removal (80-95%) of phosphorus can be achieved efficiently and inexpensively during sewage treatment; this is not the case for nitrogen compounds.
- Less phosphorus in contributed by uncontrollable sources, such as agricultural drainage, bottom sediments, atmospheric precipitation and exchange, than is nitrogen.

In addition to concern for the increased loading of nutrient materials we should also be aware of the effect of future industrial and economic expansion on the variety and quantity of industrial waste materials including acids and alkalies, phenolic and synthetic organic chemicals, pesticidal and herbicidal preparations, oils, heavy metals, asbestos, etc. that will be discharged directly or indirectly into Lake Ontario. Recent experience has shown that organic contaminants including persistent or biochemically resistant compounds are being increasingly observed in tributary rivers and in municipal and industrial waste discharges as a result of new commercial product formulations and the continued need for effective insecticides, herbicides and other agricultural chemicals. In view of the refractory and highly toxic nature of these preparations, even in low concentrations, and the fact that they can be incorporated and concentrated in the food chain, they must be considered as a growing contemporary threat to the water quality of the lake, the aquatic fauna and flora and the use of the lake environment as a whole.

Additional studies of lake waters are required to monitor the overall effect of controls on the discharge of specified pollutants such as phosphorus, to provide additional information on seasonal and annual trends of species where data are sparse and to indicate the nature and quantity of trace organic chemicals and other materials resulting from new products and processes.

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# APPENDIX 1

Due to the voluminous amount of literature available concerning the chemical and water quality characteristics of Lake Ontario and its tributaries, it was not possible to refer to all sources of information in the text in the interest of conciseness. However, in order to acknowledge these numerous investigations, which were used as reference material, a bibliographic listing (by reference number) has been compiled below in the subject categories as they appear in the text. It should be noted that sources of quantitative data are underlined which were used in developing the figures and tables displayed in this report. It is hoped that the interested reader will find this listing to be a useful guide to additional, more detailed information.

## 1. Nutrients

Ammonia-Nitrogen: 9, 10, 12, 19, 23, 24, 25, 26, 27, 28, 29, 34, 37, 39, 40, 43, 50, 51, 60, 75, 77, 98, 101, 107, 108, 110, 115, 129, 130, 138, 151, 155, 156, 160, 162, 165, 166, 181, 197, 201, 202, 203, 207

Kjeldahl and Organic-Nitrogen: 5, 12, 19, 23, 24, 25, 26, 29, 34 37, 51, 60, 75, 101, 108, 138, 160, 165, 166, 181, 197, 200, 201, 202, 203

Nitrite and Nitrate-Nitrogen: 4, 5, 9, 12, 19, 22, 23, 24, 25, 26, 28, 29, 34, 37, 39, 40, 43, 44, 50, 60, 75, 77, 93, 98, 107, 108, 115, 129, 130, 138, 155, 156, 159, 160, 162, 165, 166, 169, 181, 192, 193, 195, 197, 198, 199, 200, 201, 202, 203, 207, 219

Total-Nitrogen: 9, 11, 12, 29, 34, 37, 58, 69, 71, 74, 77, 79, 85, 107, 115, 130, 159, 160, 162, 165, 166, 200, 201, 202, 203, 207

Soluble Reactive-Phosphorus: 3, 19, 22, 23, 24, 25, 26, 27, 28, 29, 34, 37, 39, 40, 43, 50, 54, 58, 60, 130, 138, 155, 156, 160, 162, 165, 166, 181, 219, 229

Particulate Organic-Phosphorus: 5, 37, 39, 40, 138, 224, 228, 229

Total Phosphorus: 3, 5, 9, 10, 11, 12, 19, 21, 25, 26, 28, 29, 30, 34, 37, 39, 40, 41, 42, 43, 50, 51, 54, 60, 74, 79, 83, 85, 86, 101, 107, 115, 129, 130, 138, 155, 156, 158, 159, 162, 165, 166, 172, 174, 181, 197, 198, 201, 202, 203, 207, 224, 228, 229

Soluble Reactive-Silica: 1, 4, 12, 23, 24, 25, 26, 27, 28, 29, 30, 39, 40, 43, 44, 50, 60, 61, 80, 83, 85, 86, 93, 107, 115, 130, 138, 155, 162, 164, 165, 169, 181, 192, 193, 195, 197, 198, 199, 201, 202, 203, 219

Total and Organic Carbon: 12, 21, 40, 41, 42, 51, 60, 68, 69, 71, 74, 75, 76, 77, 78, 79, 80, 94, 158, 162, 165, 171, 172, 173, 210, 224, 229

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Sodium and Potassium: 1, 4, 7, 9, 10, 11, 12, 23, 24, 25, 26, 27, 28, 29, 30, 34, 38, 44, 60, 78, 83, 85, 86, 90, 104, 105, 107, 115, 125, 129, 138, 156, 157, 164, 165, 169, 170, 172, 192, 193, 195, 197, 198, 199, 201, 202, 203, 216, 219

Calcium: 1, 4, 8, 9, 10, 11, 12, 23, 24, 25, 26, 27, 28, 30, 34, 38, 44, 60, 83, 85, 86, 93, 104, 105, 107, 115, 125, 129, 138, 156, 157, 164, 165, 169, 170, 172, 192, 193, 195, 197, 198, 199, 201, 202, 203, 216, 219

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Bicarbonate and Carbonate: 4, 68, 69, 71, 74, 75, 77, 85, 93, 125, 129, 138, 171, 173, 192, 193, 195, 197, 198, 199, 201, 202, 203, 216

Sulfate: 4, 10, 11, 12, 23, 24, 25, 26, 27, 28, 30, 34, 38, 44, 60, 83, 86, 93, 107, 115, 116, 125, 129, 138, 154, 156, 169, 192, 193, 195, 197, 198, 199, 201, 202, 203, 216, 220

## 3. Trace Elements

Iron: 3, 4, 23, 24, 25, 26, 31, 34, 44, 60, 61, 80, 81, 93, 101, 107, 115, 138, 156, 158, 165, 169, 172, 192, 193, 195, 198, 201, 202, 203, 216, 219, 221, 229

Fluoride: 12, 28, 60, 83, 86, 107, 115, 169, 192, 193, 195, 197, 198, 199, 200, 201, 202, 203, 216, 219

| | |
|---|---|
| Mercury: | 15, 32, 33, 60, 64, 78, 79, 165, 172, 201, 202, 203 |
| Aluminum: | 60, 61, 80, 81, 172, 198 |
| Arsenic: | 201, 202, 203 |
| Barium: | 12, 81 |
| Boron: | 81 |
| Bromine: | 175 |
| Cadmium: | 23, 24, 25, 26, 31, 93, 125, 192, 193, 195, 197, 198, 199, 201, 202, 203 |
| Chromium: | 12, 23, 24, 25, 26, 31, 60, 78, 81, 138, 165, 216 |
| Cobalt: | 12, 23, 24, 25, 26, 31, 138 |
| Copper: | 12, 23, 24, 25, 26, 31, 34, 60, 78, 81, 156, 165, 201, 202, 216 |
| Iodine: | 175, 225 |
| Lead: | 12, 23, 24, 25, 26, 31, 34, 78, 156, 165, 201, 202, 203, 216, 221 |
| Lithium: | 12, 23, 24, 25, 26, 34, 138 |
| Manganese: | 12, 23, 24, 25, 26, 31, 34, 60, 78, 81, 107, 115, 138, 165, 172, 198, 201, 202, 203, 216, 219 |
| Molybdenum: | 31 |
| Nickel: | 12, 23, 24, 25, 26, 31, 34, 60, 78, 138, 156, 165, 216 |
| Radium: | 198 |
| Selenium: | 165 |
| Strontium: | 12, 23, 24, 25, 26, 31, 34, 57, 81, 91, 92, 138, 216 |
| Uranium: | 198 |
| Vanadium: | 31 |
| Zinc: | 12, 23, 24, 25, 26, 31, 34, 68, 78, 138, 156, 165, 216 |

### 4. Organic Compounds

Pesticides and Herbicides: 12, 15, 56, 59, 66, 96, 107, 114, 115, 136, 138, 165, 201, 202, 203, 208, 214

Phenols: 12, 13, 19, 23, 24, 25, 26, 101, 107, 115, 138, 165, 198

Detergents: 31, 114, 166, 201, 202, 203, 208

Greases, Oils, Solvents, etc.: 32, 41, 69, 76, 77, 114, 129, 166, 230

### 5. Water Quality Properties

Dissolved Oxygen: 1, 9, 12, 22, 23, 24, 25, 26, 27, 28, 29, 34, 38, 39, 40, 42, 43, 53, 54, 55, 93, 108, 110, 112, 114, 115, 127, 138, 155, 157, 162, 166, 168, 181, 201, 202, 203

Oxygen Demand: 22, 23, 24, 25, 26, 29, 51, 108, 110, 112, 115, 138, 166, 181, 193, 200, 201, 202, 203

Hydrogen-Ion Concentration (pH): 1, 9, 12, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30, 50, 54, 55, 60, 68, 71, 74, 75, 76, 83, 85, 86, 93, 101, 107, 108, 110, 115, 127, 129, 138, 149, 151, 154, 157, 162, 164, 165, 168, 169, 173, 181, 192, 193, 195, 197, 198, 199, 200, 201, 202, 203, 216, 219

Alkalinity: 1, 4, 12, 22, 23, 24, 25, 26, 27, 28, 30, 34, 38, 44, 50, 53, 54, 60, 83, 85, 86, 93, 101, 107, 108, 110, 115, 130, 138, 149, 151, 157, 162, 164, 168, 169, 181, 192, 193, 195, 197, 200, 201, 202, 203, 216, 219

Hardness: 12, 22, 23, 24, 25, 28, 54, 93, 107, 110, 112, 115, 138, 151, 157, 168, 169, 173, 192, 193, 195, 197, 199, 200, 201, 202, 203

Dissolved Solids: 4, 9, 10, 11, 23, 24, 25, 26, 28, 29, 34, 44, 54, 93, 107, 108, 112, 115, 125, 138, 157, 166, 181, 192, 193, 197, 198, 199, 200, 201, 202, 203, 216, 220

Specific Conductance: 1, 12, 19, 22, 23, 25, 26, 27, 28, 30, 38, 50, 53, 54, 55, 86, 101, 107, 115, 127, 138, 149, 154, 155, 157, 162, 167, 168, 169, 181, 192, 195, 197, 198, 199, 200, 201, 202, 203

Suspended Solids: 93, 110, 138, 181

Volatile Solids: 157, 165, 181

Total Solids: 115, 157

Turbidity, Visibility and Color: 4, 10, 12, 19, 22, 23, 24, 25, 26, 27, 28, 40, 41, 42, 43, 44, 53, 54, 55, 93, 107, 108, 110, 112, 113, 115, 127, 149, 151, 155, 162, 169, 181, 192, 193, 195, 197, 199, 200, 201, 202, 203

Radioactivity: 12, 57, 91, 92, 138, 198, 201, 202, 203

Temperature: 22, 23, 24, 25, 26, 27, 28, 38, 50, 53, 54, 55, 93, 101, 107, 108, 110, 113, 115, 116, 127, 131, 138, 145, 146, 155, 157, 164, 168, 192, 193, 197, 200, 201, 202, 203, 215, 218

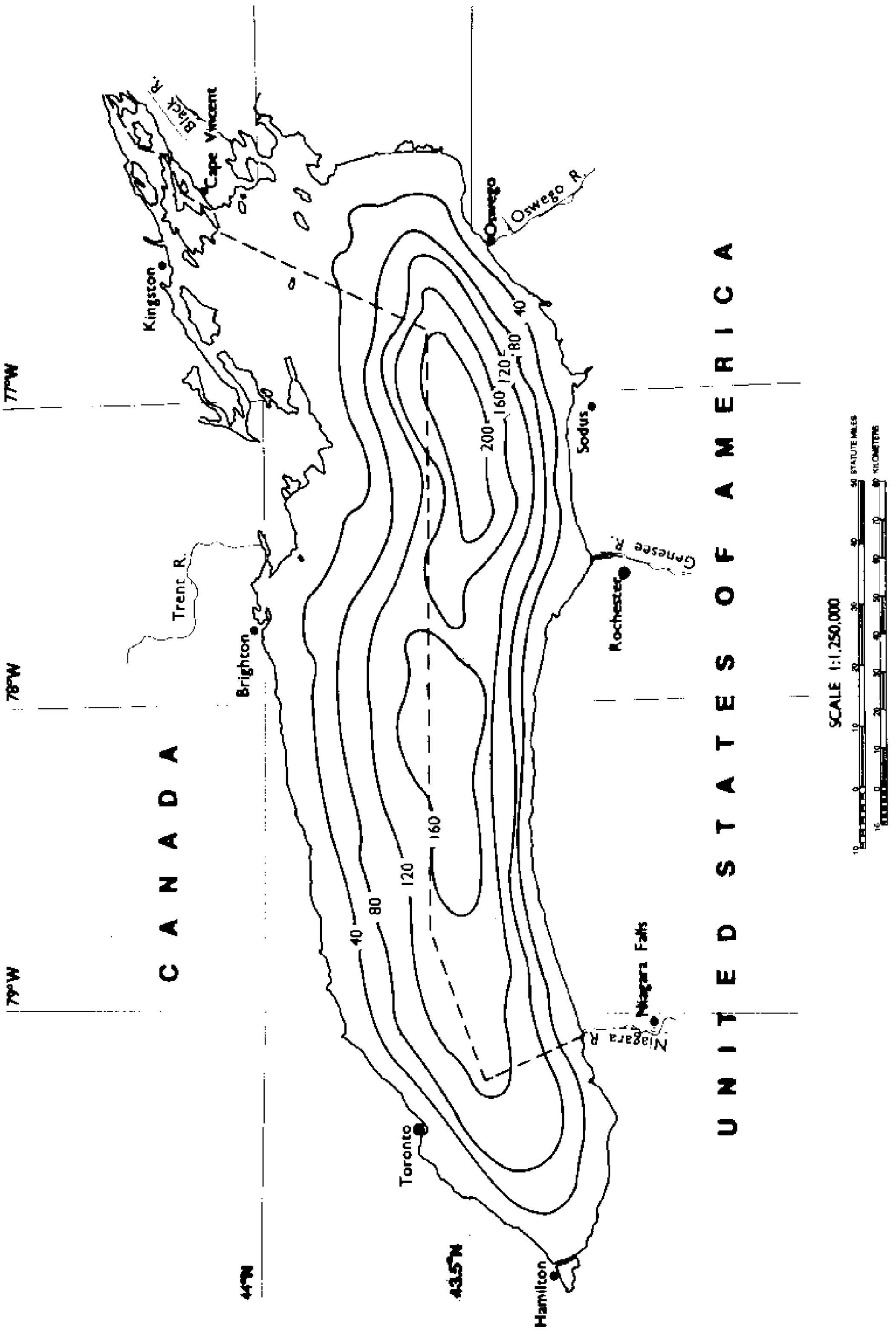
## 6. Environmental Characteristics

Sediments: 3, 5, 51, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 89, 90, 91, 94, 138, 158, 170, 171, 172, 173, 181, 217, 219, 224, 228, 229

Tributary Rivers and Waste Discharges: 11, 13, 30, 35, 37, 60, 61, 87, 88, 93, 100, 101, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 119, 120, 121, 122, 123, 124, 125, 128, 134, 138, 157, 165, 169, 193, 200, 203, 211, 212, 213, 214

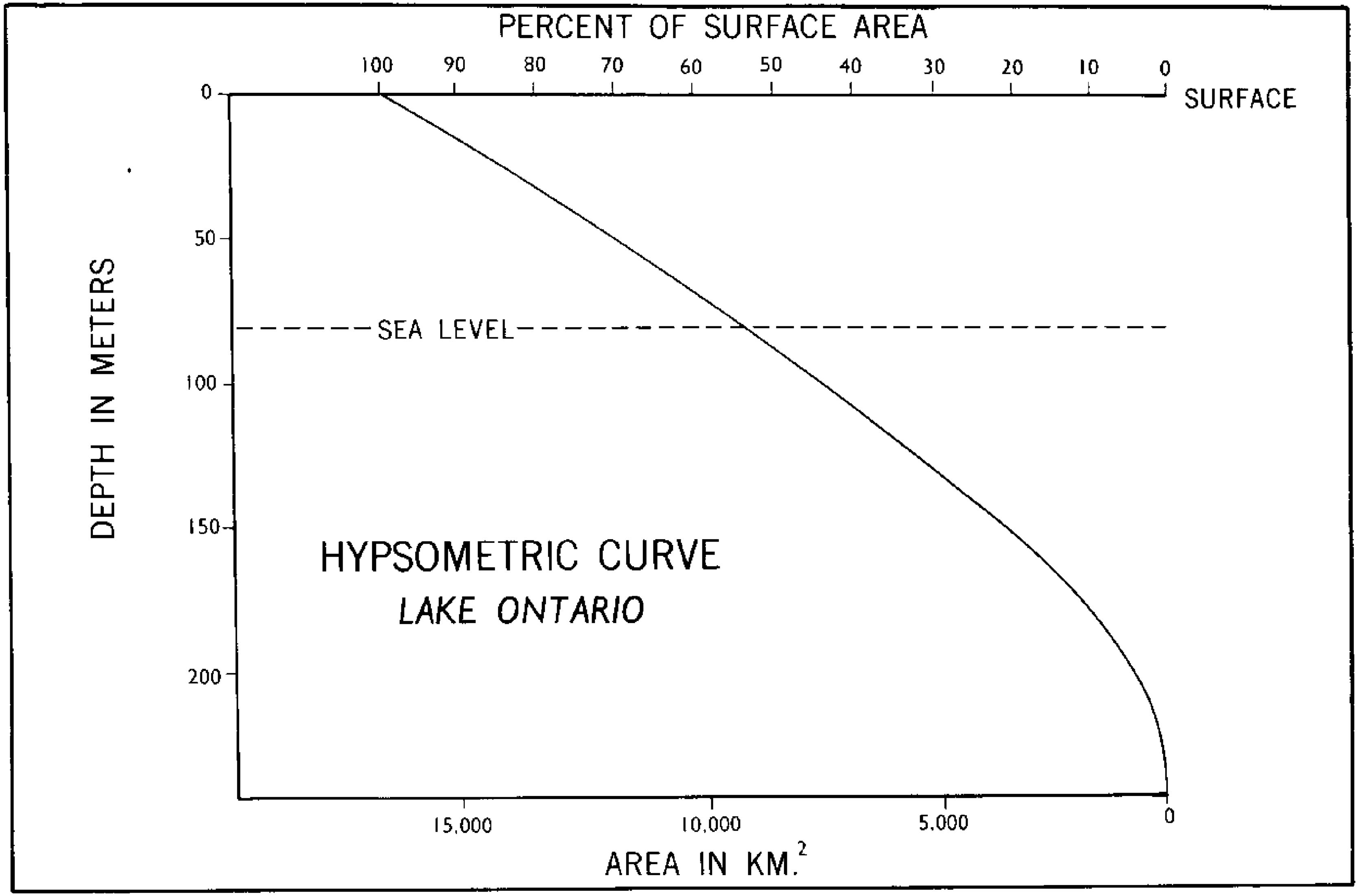
Atmospheric Precipitation: 17, 57, 65, 92, 98, 110, 129, 131, 138, 149, 152, 154, 156, 175, 221, 222

FIGURE 1



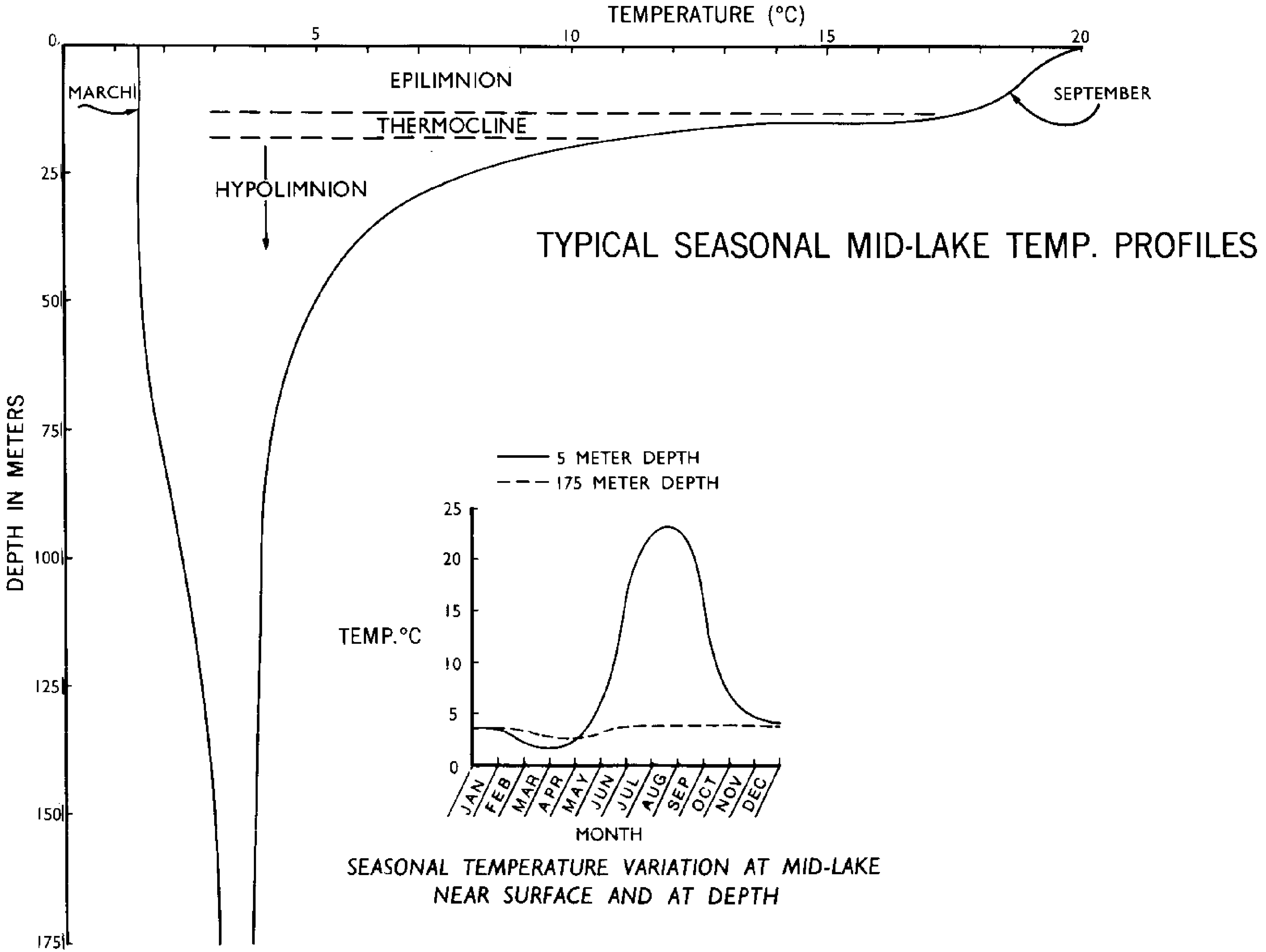
Bathymetric chart of Lake Ontario (depth in meters)

FIGURE 2



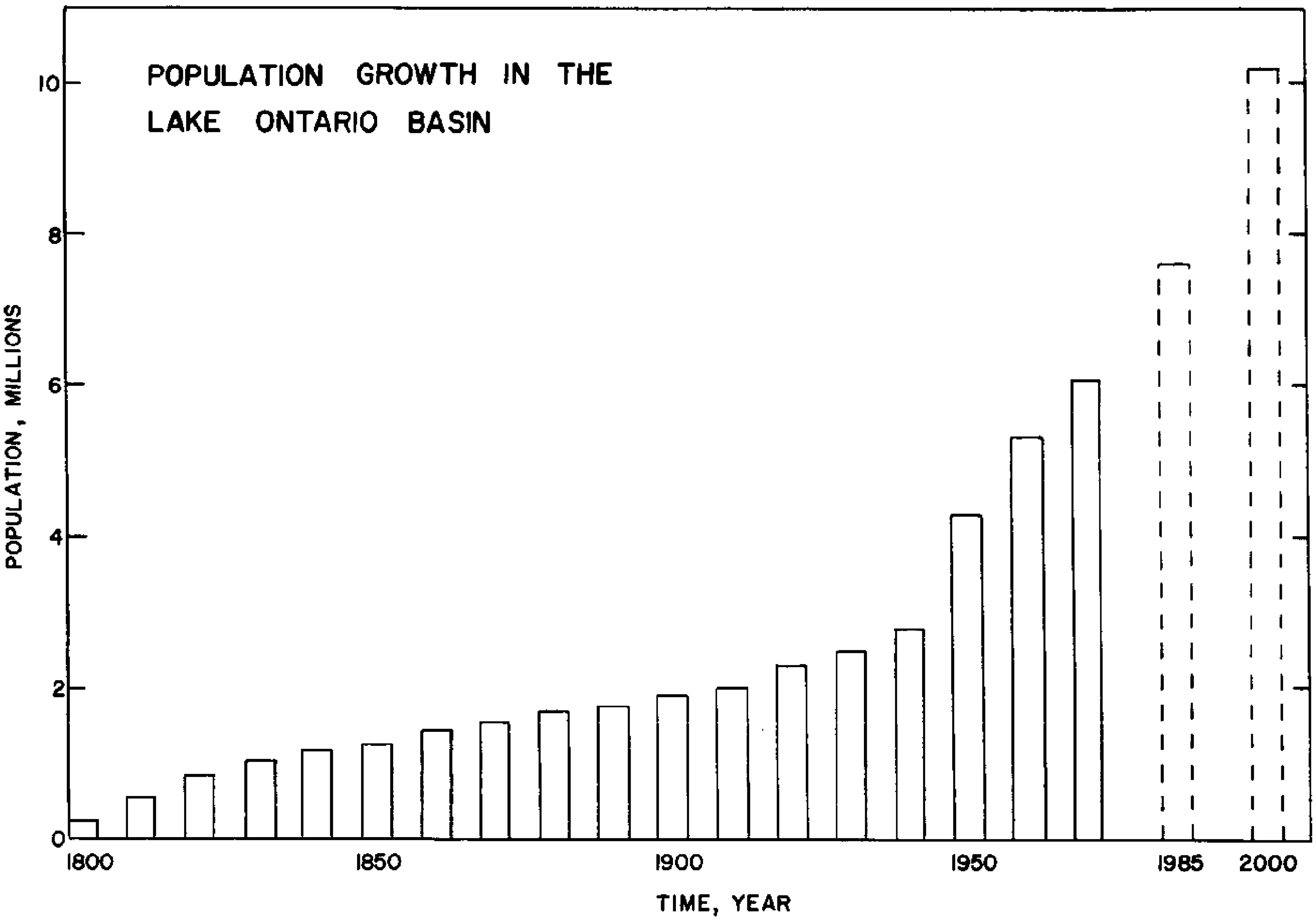
Hypsometric curve for Lake Onatrio

FIGURE 3



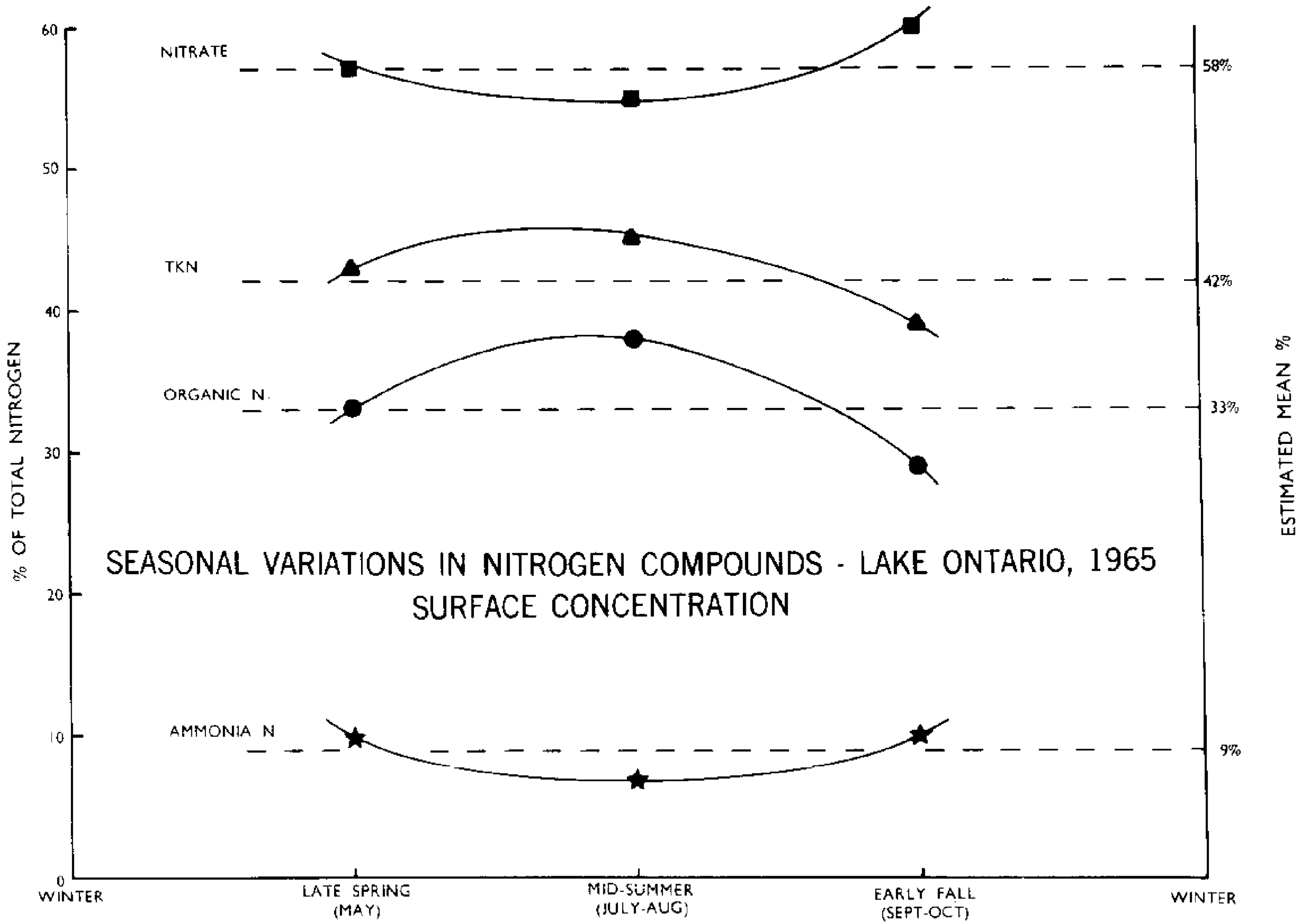
Thermal structure and seasonal temperature variation in Lake Ontario

FIGURE 4



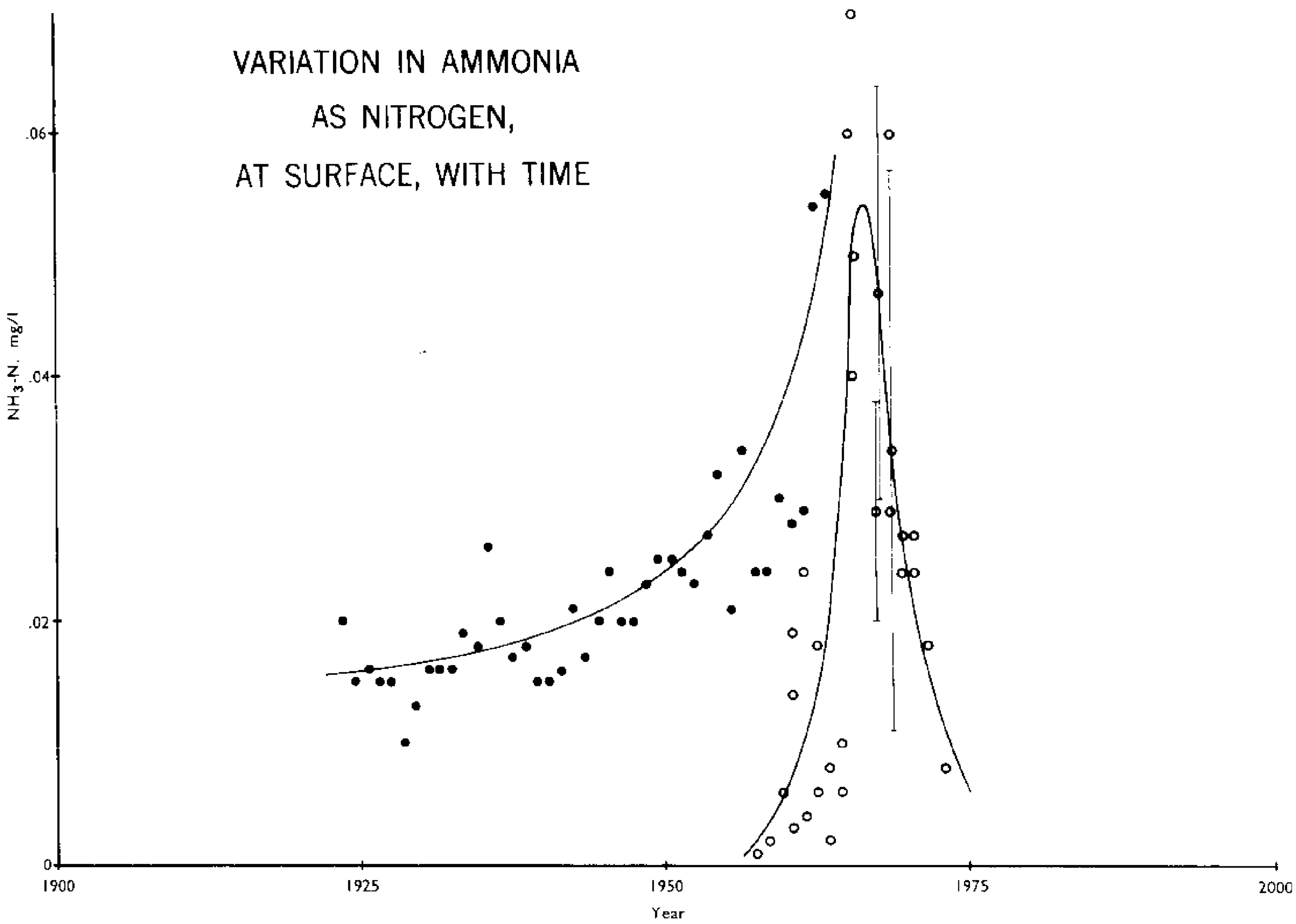
Actual and projected population growth estimates for the Lake Ontario basin, 1800-2000. Prior to 1950 estimates of the contribution by the metropolitan Buffalo area have not been included.

FIGURE 5



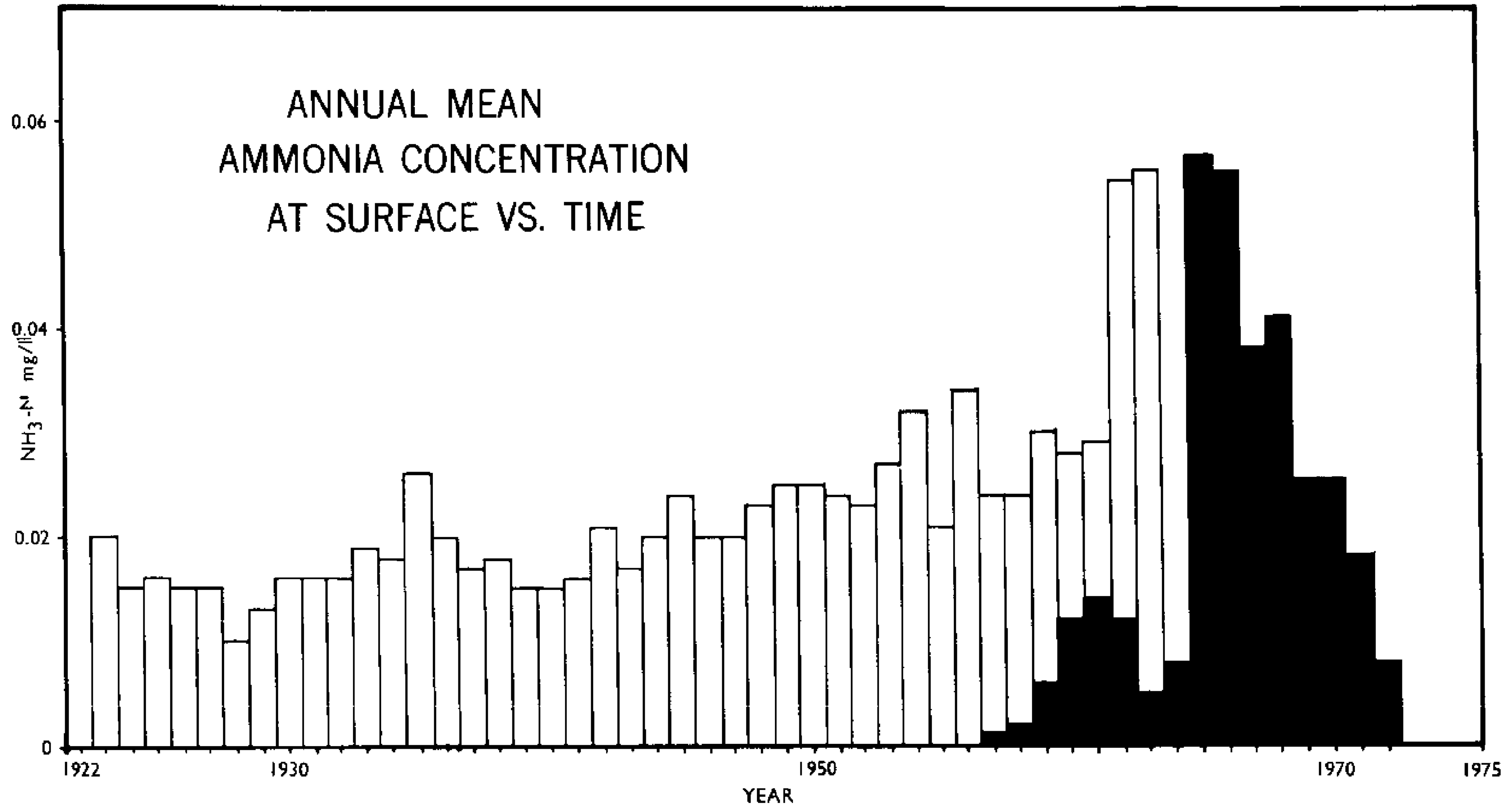
Seasonal variations in aquatic nitrogenous materials at surface, as percent of total nitrogen, 1965

FIGURE 6



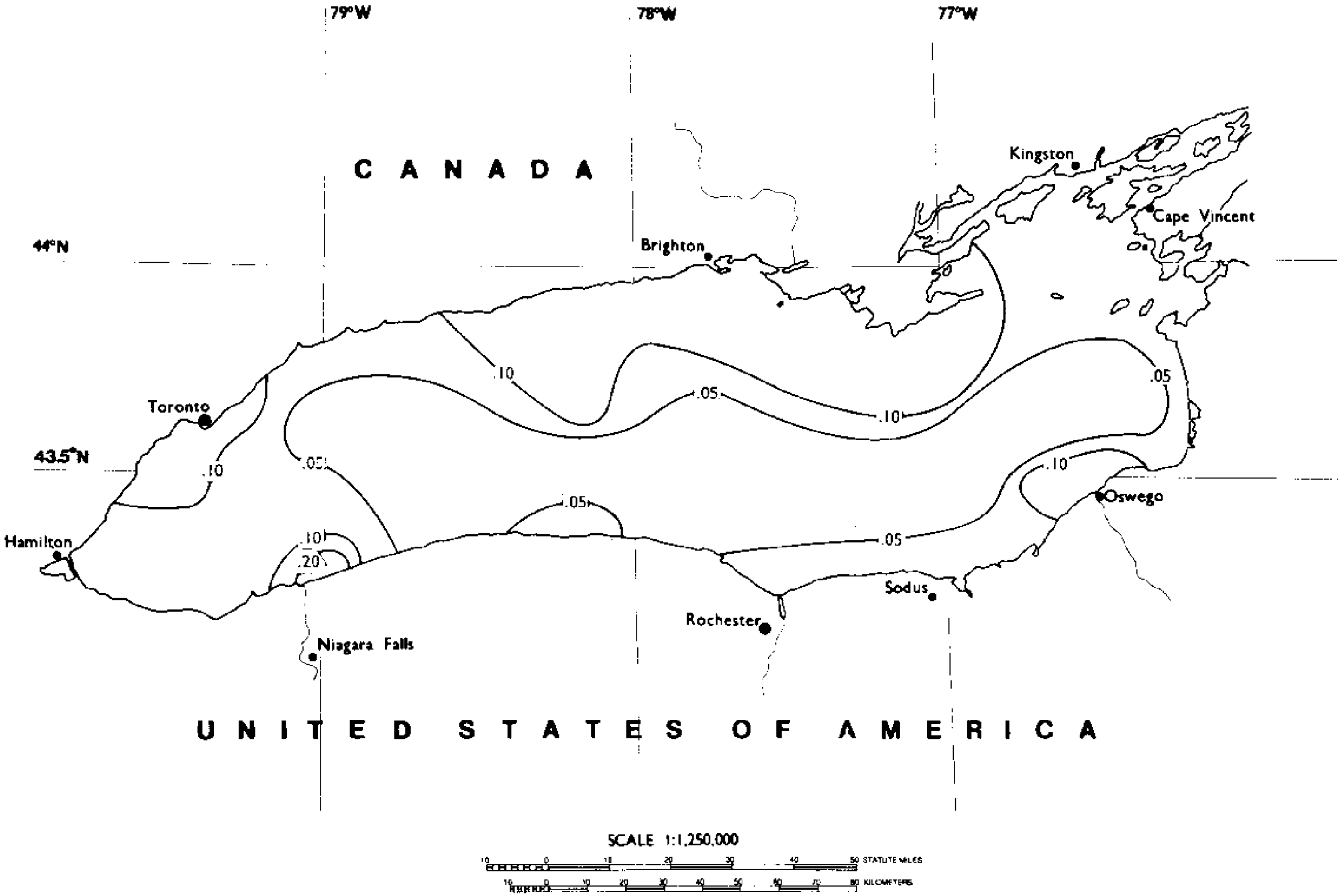
Variation in inshore (filled circles) and lakewide (open circles) ammonia-nitrogen concentrations (mg N/ℓ) at surface with time, 1923-1972

FIGURE 7



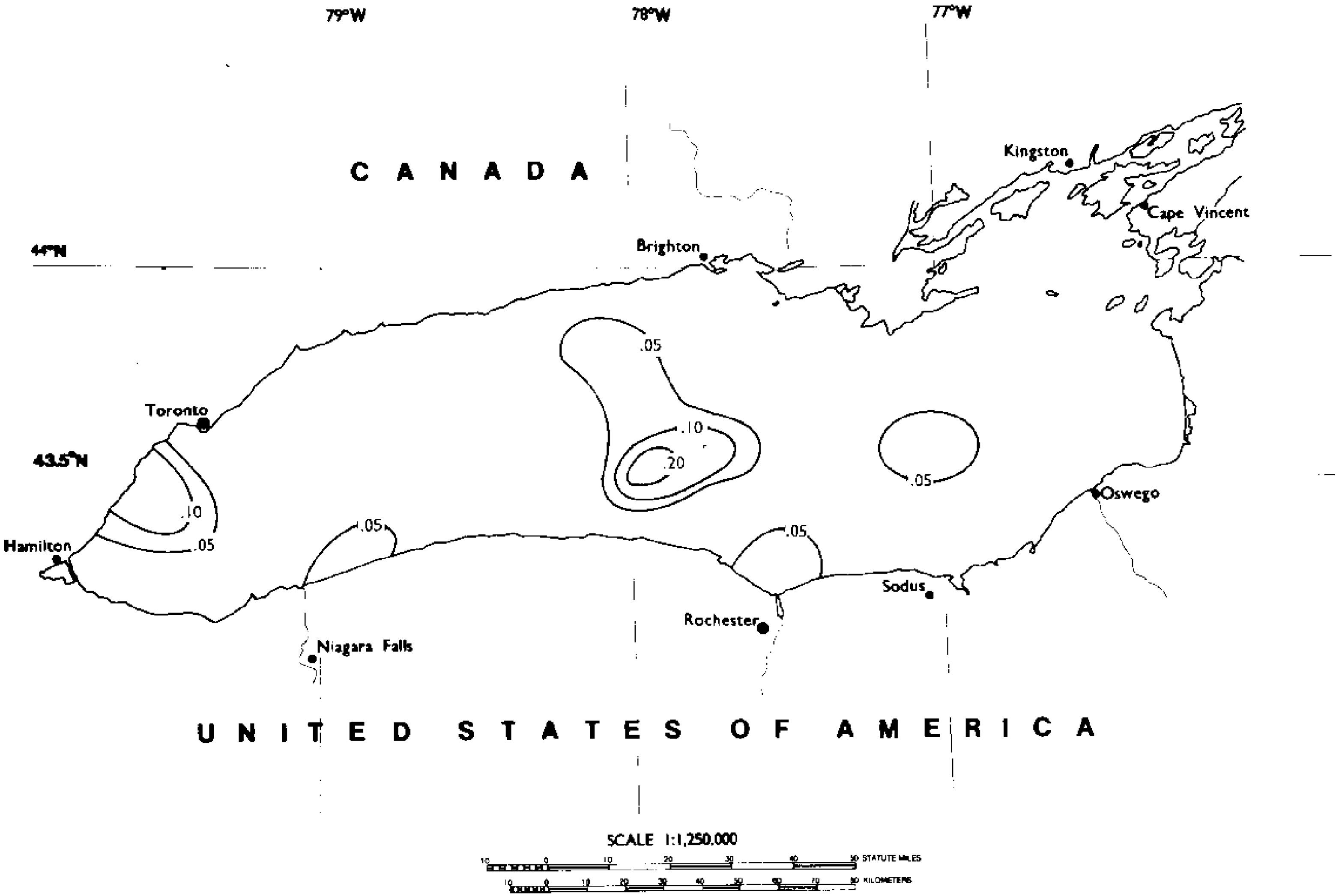
Bar graph of inshore (open bars) and lakewide (filled bars) annual mean ammonia-nitrogen concentrations (mg N/ℓ) at surface, 1923-1972

FIGURE 8



Surface distribution of ammonia-nitrogen (mg N/ℓ), Spring 1965

FIGURE 9

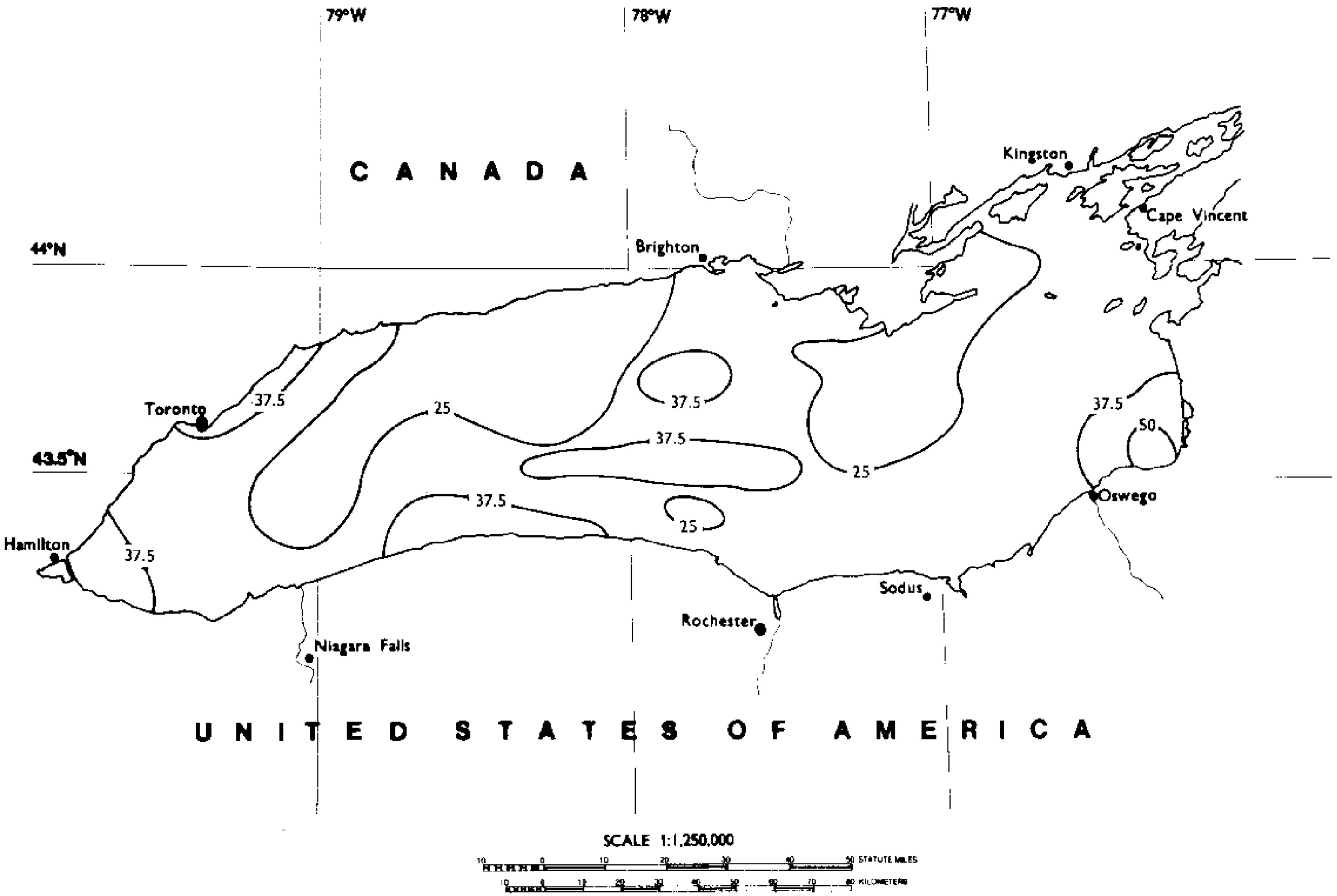


Surface distribution of ammonia-nitrogen (mg N/ℓ), Summer 1965

FIGURE 10

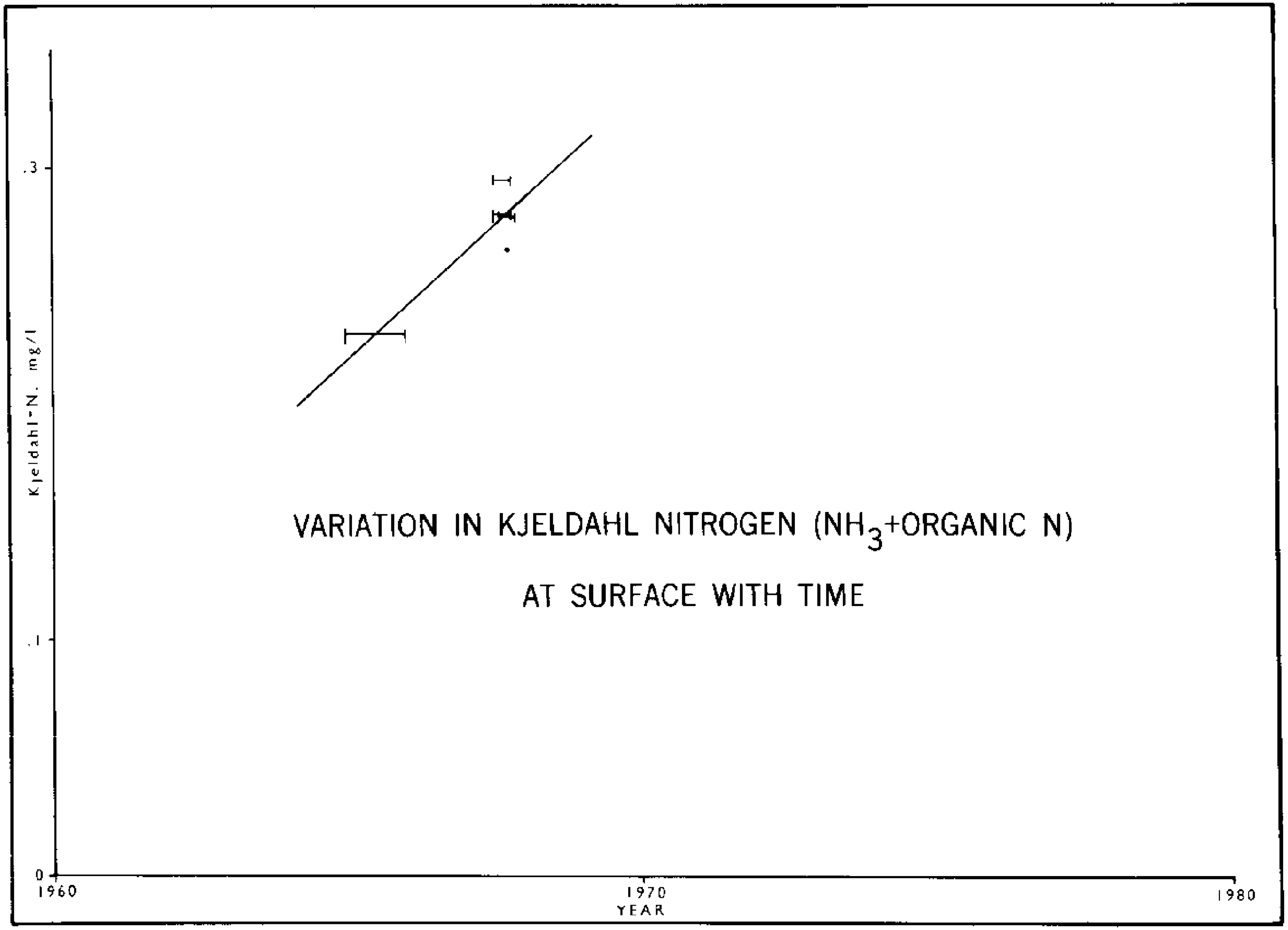
Surface distribution of ammonia-nitrogen (mg N/ℓ), Fall 1965

FIGURE 11



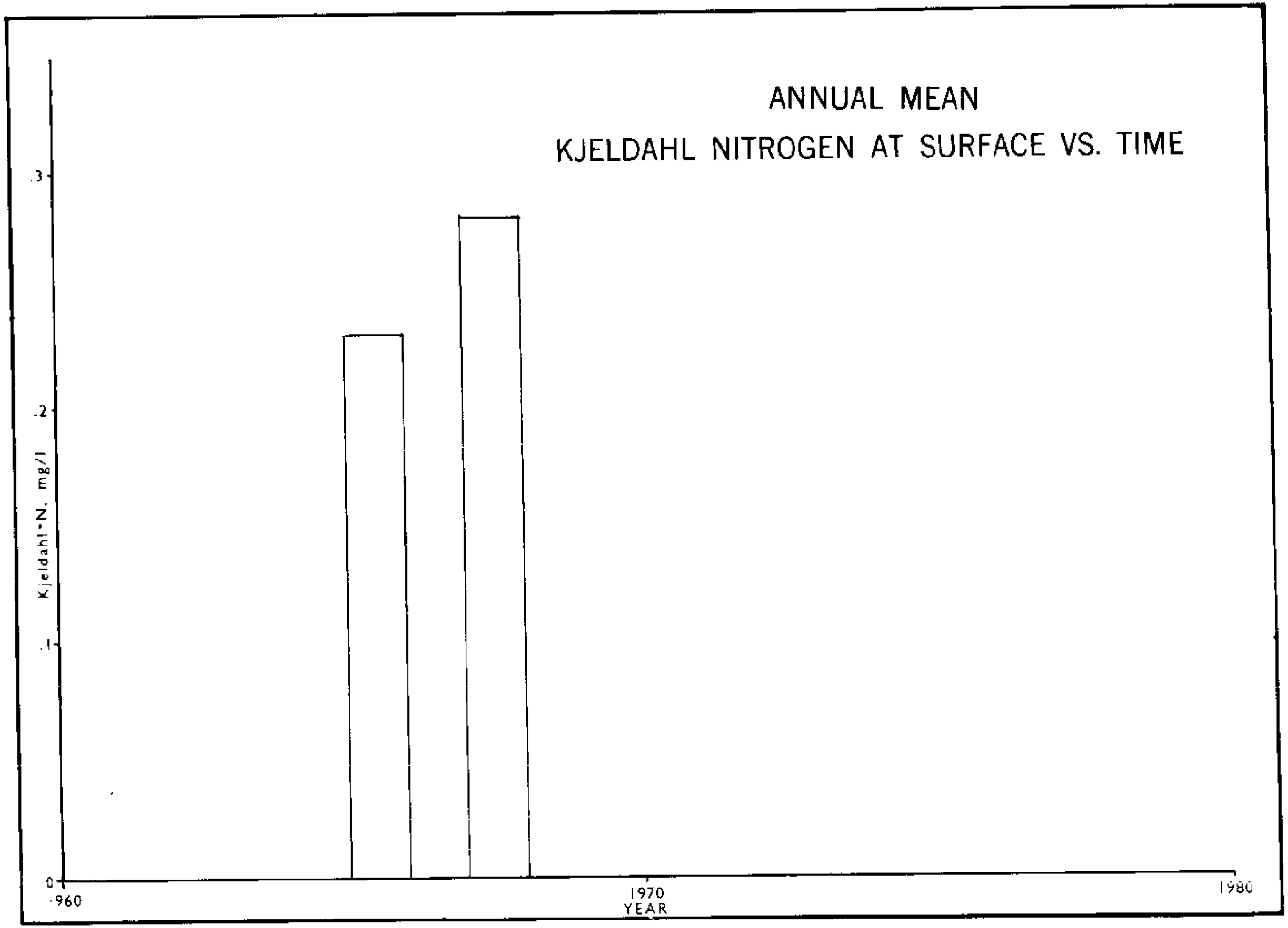
Surface distribution of ammonia-nitrogen (mg N/ℓ), annual median values. 1967

FIGURE 12



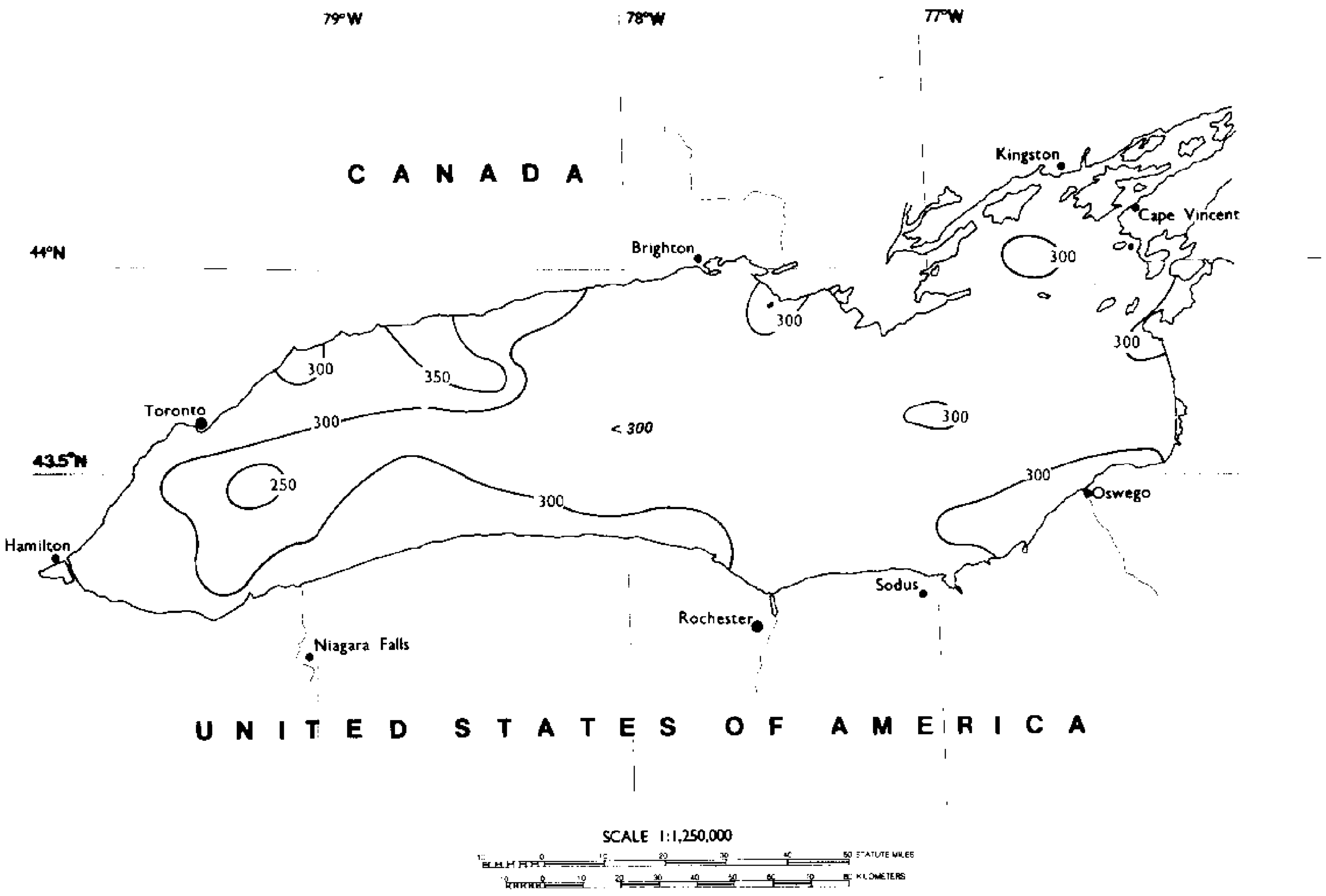
Variation in Kjeldahl-nitrogen concentrations (mg N/ℓ) at surface with time, 1965-1968

FIGURE 13



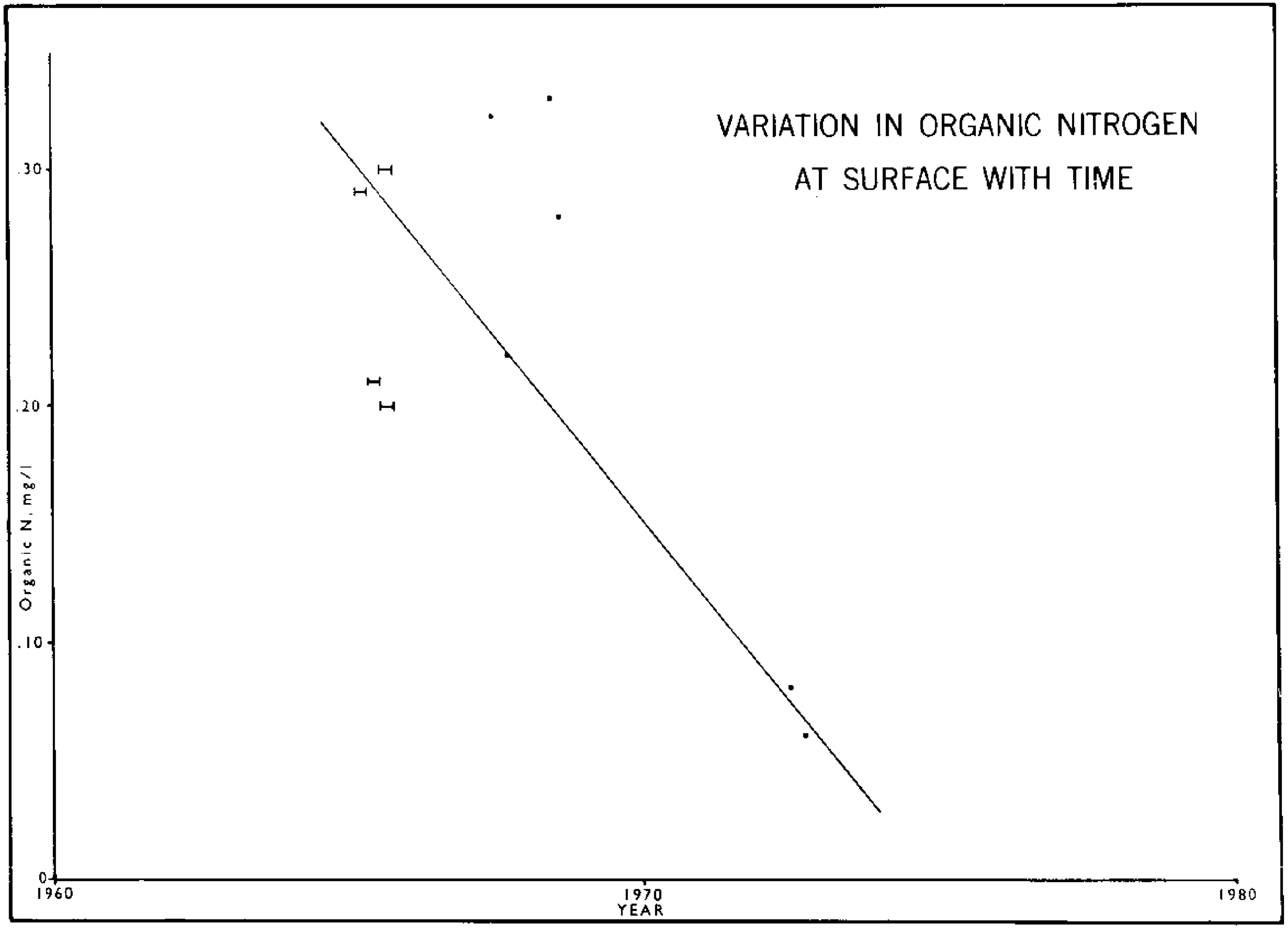
Bar graph of annual mean Kjeldahl-nitrogen concentrations (mg N/ℓ) at surface, 1965-1968

FIGURE 14



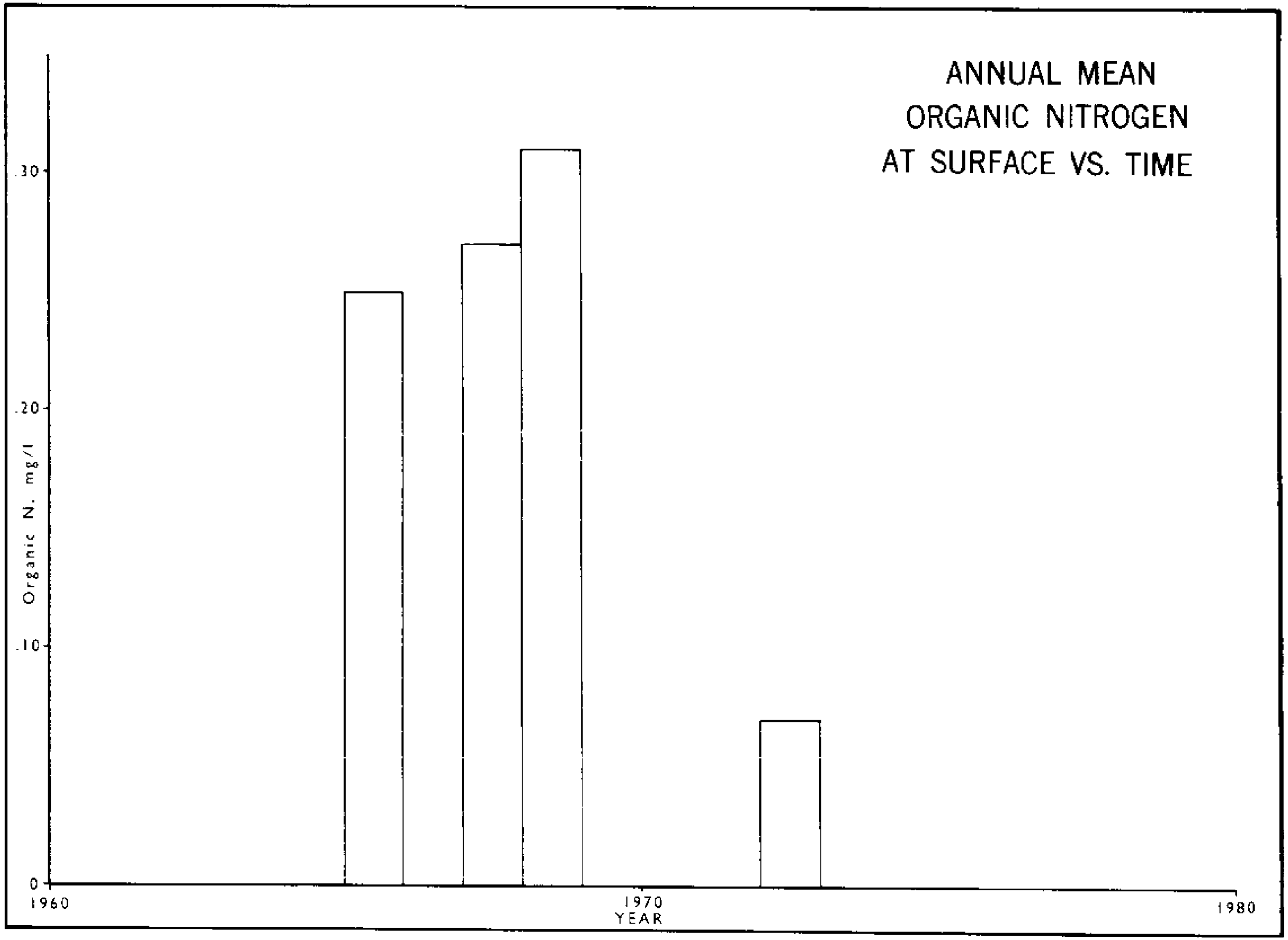
Surface distribution of Kjeldahl-nitrogen (μg N/ℓ), annual median values, 1967

FIGURE 15



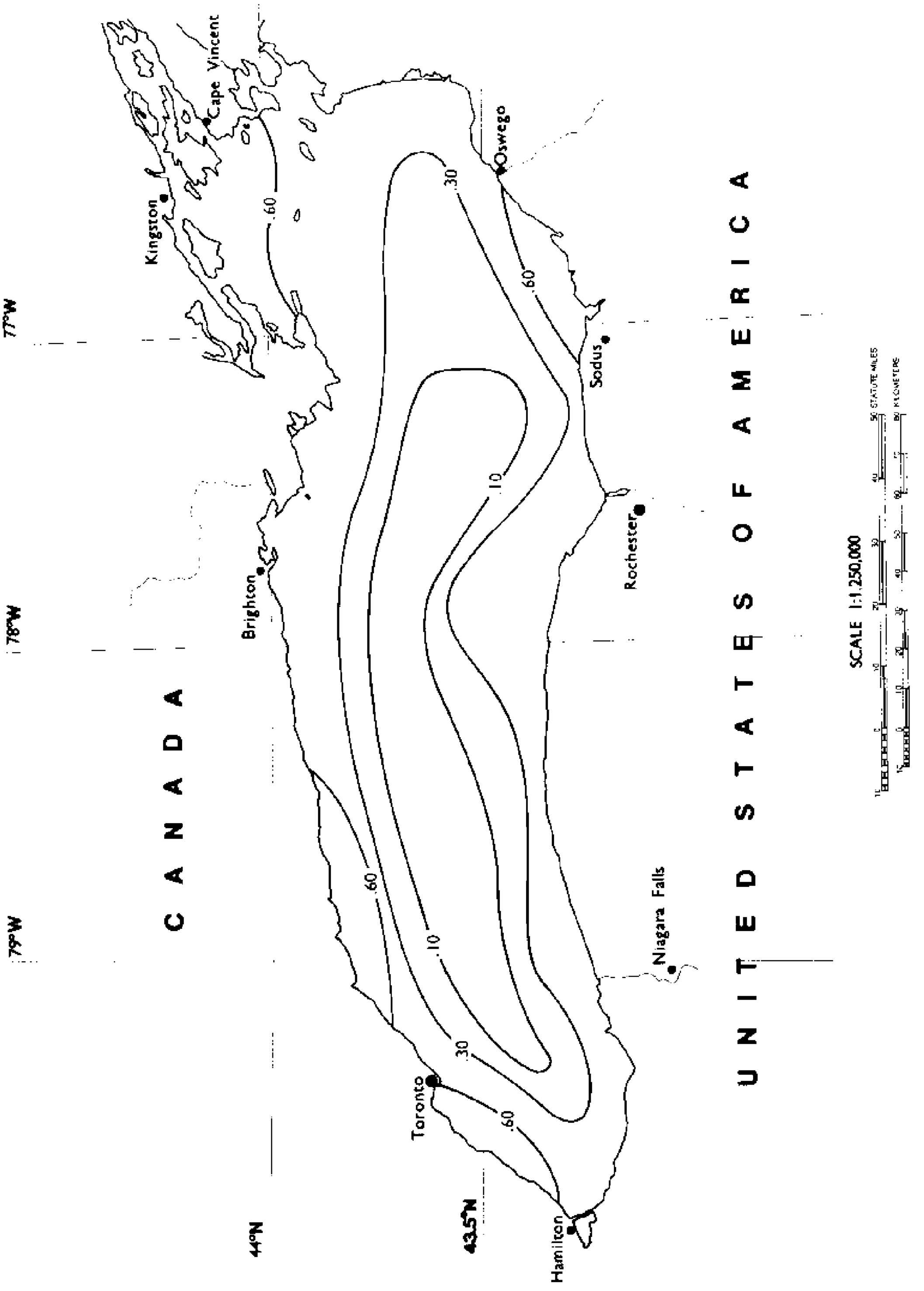
Variation in organic-nitrogen concentrations (mg N/ℓ) at surface with time, 1965-1972

FIGURE 16



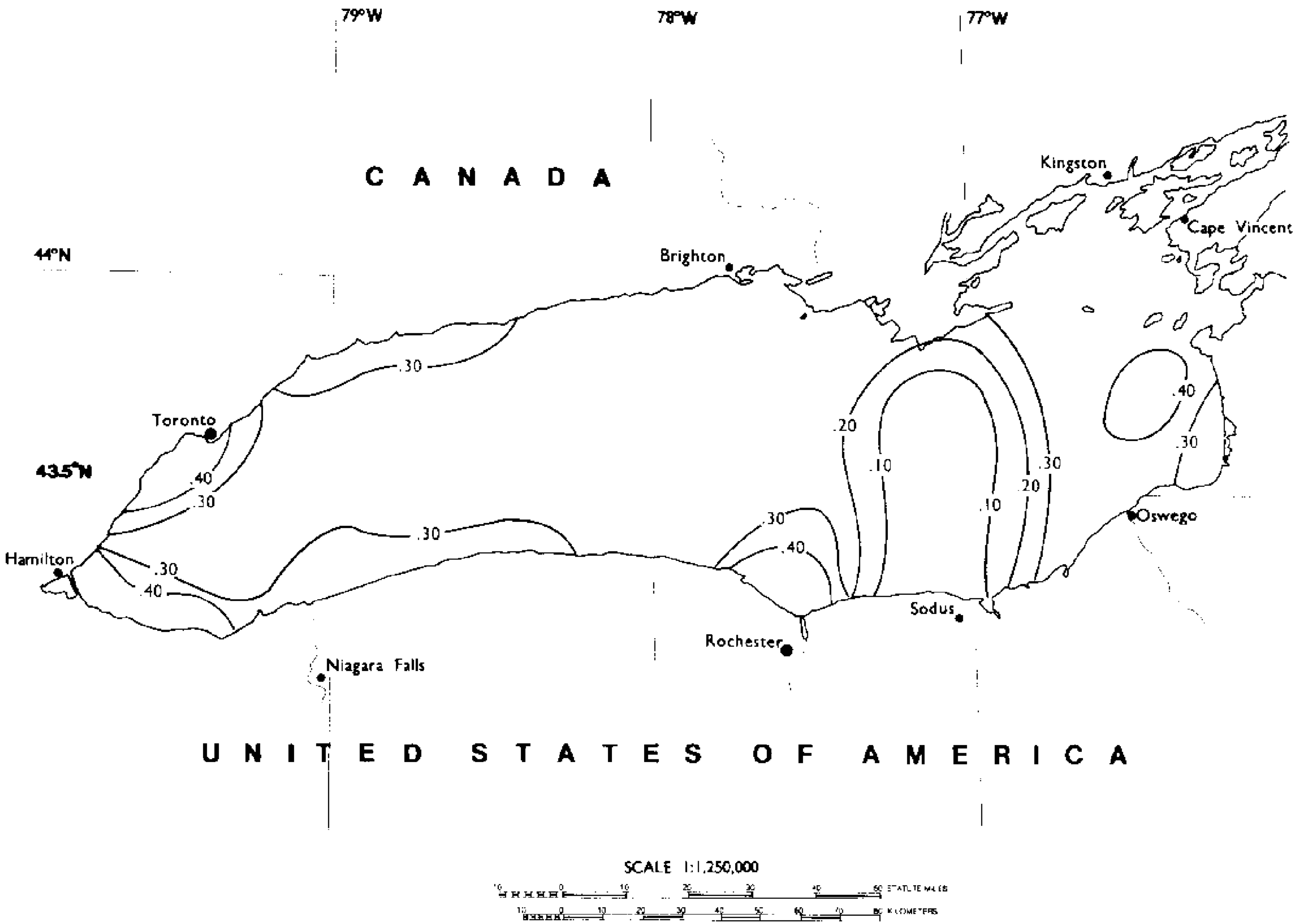
Bar graph of annual mean organic-nitrogen concentrations (mg N/ℓ) at surface, 1965-1972

FIGURE 17



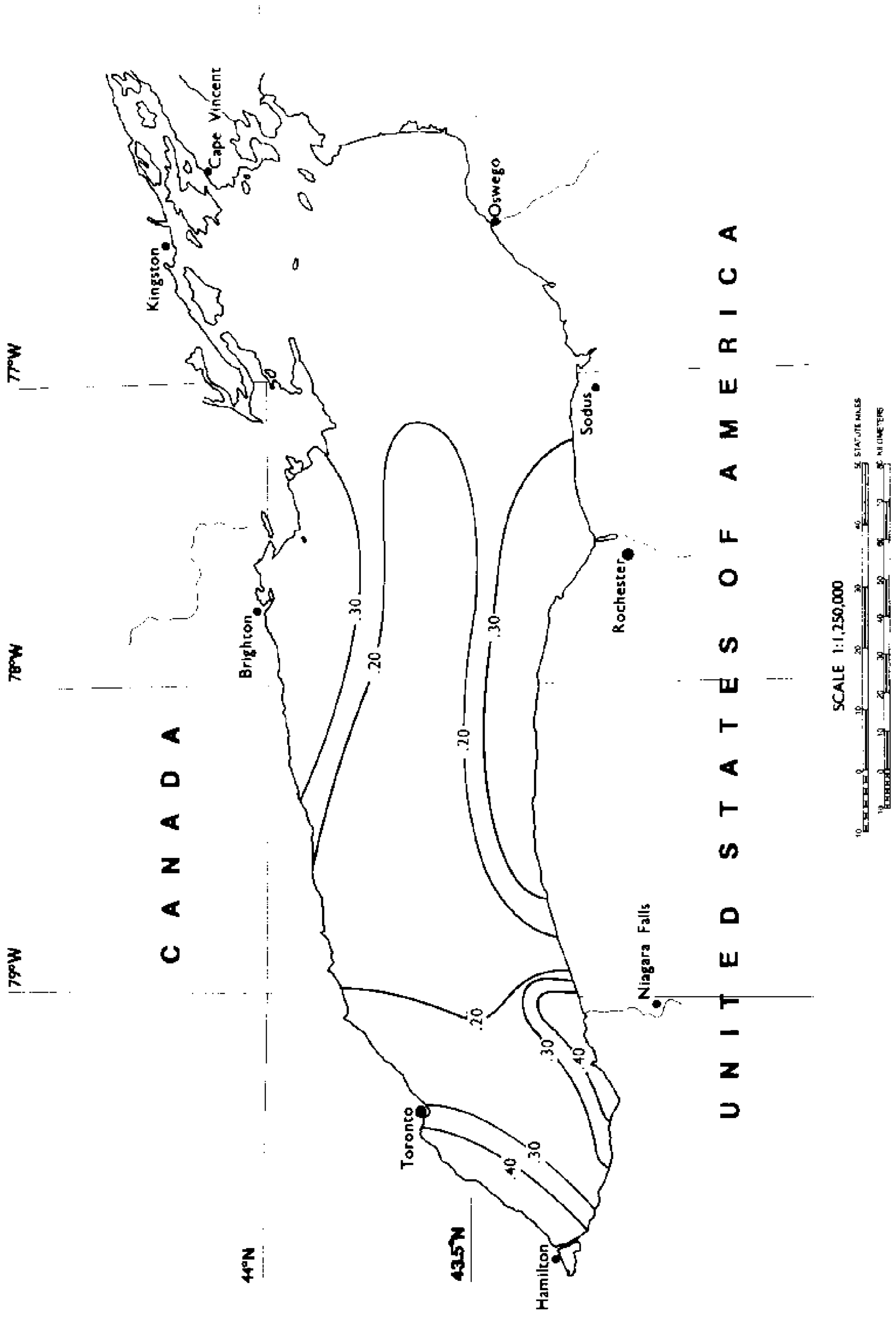
Surface distribution of organic-nitrogen (mg N/ℓ), Spring 1965

FIGURE 18



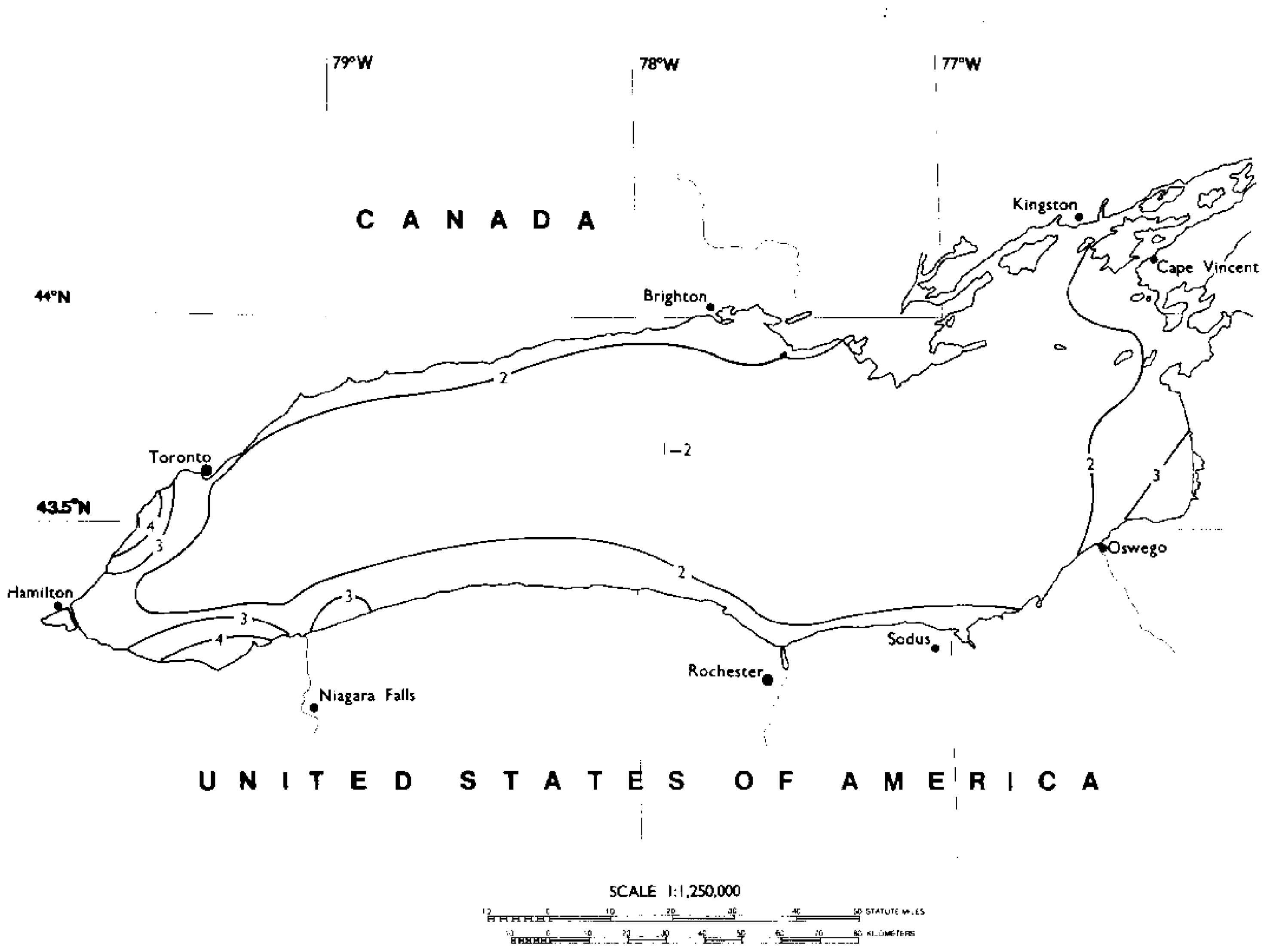
Surface distribution of organic-nitrogen (mg N/ℓ), Summer 1965

FIGURE 19



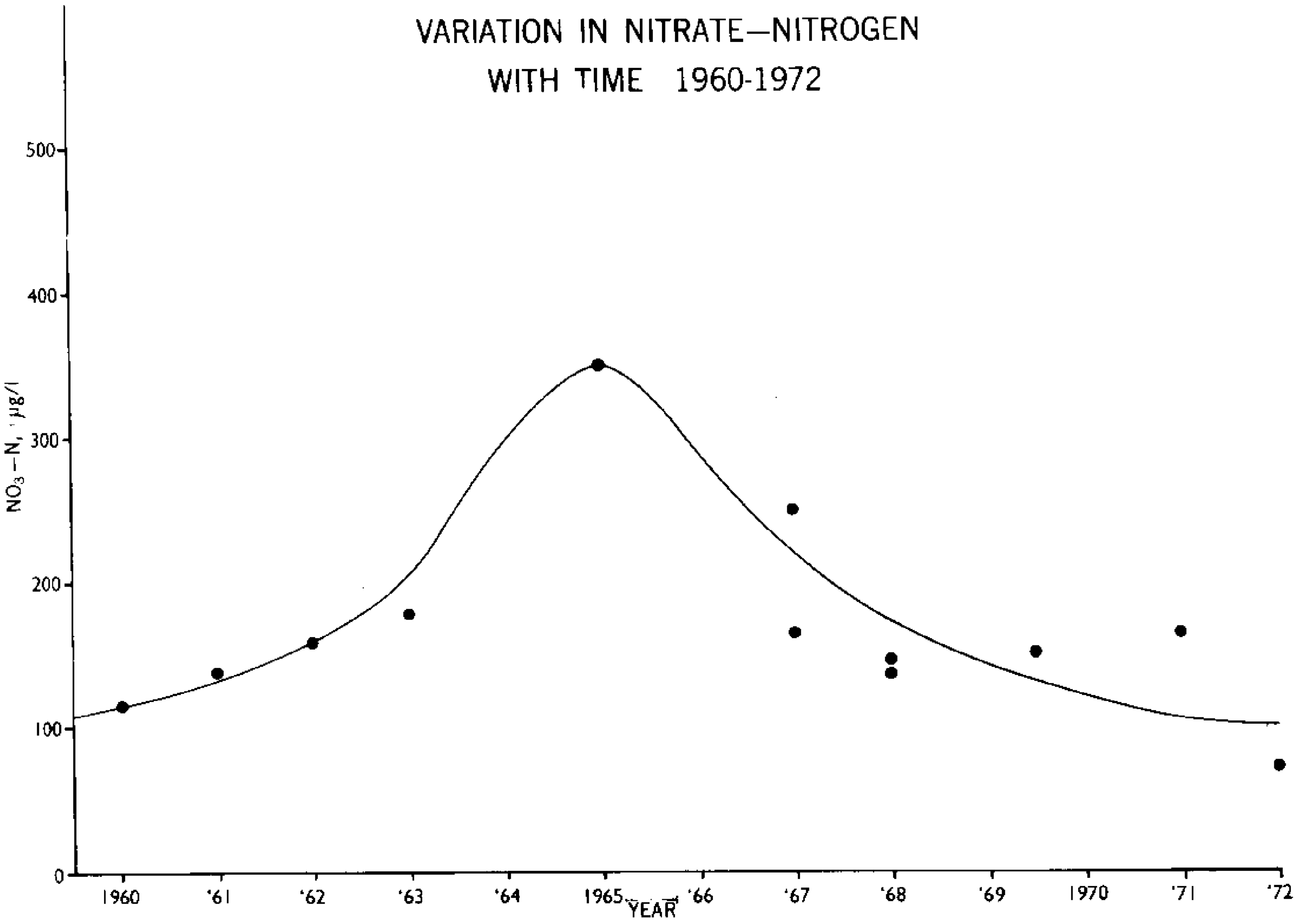
Surface distribution of organic-nitrogen (mg N/ℓ), Fall 1965

FIGURE 20



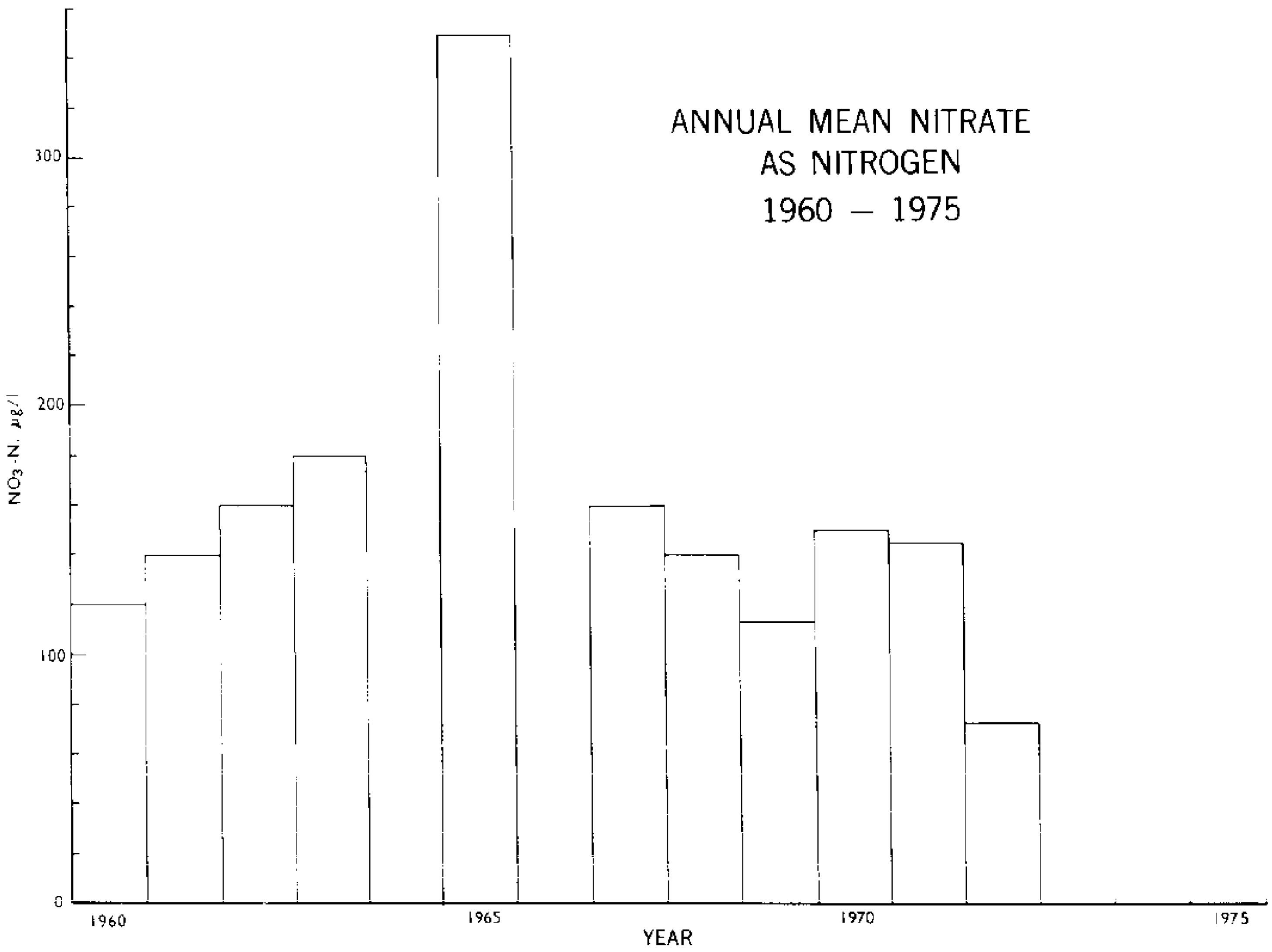
Surface distribution of nitrite-nitrogen (µg N/ℓ), annual median values, 1967

FIGURE 21



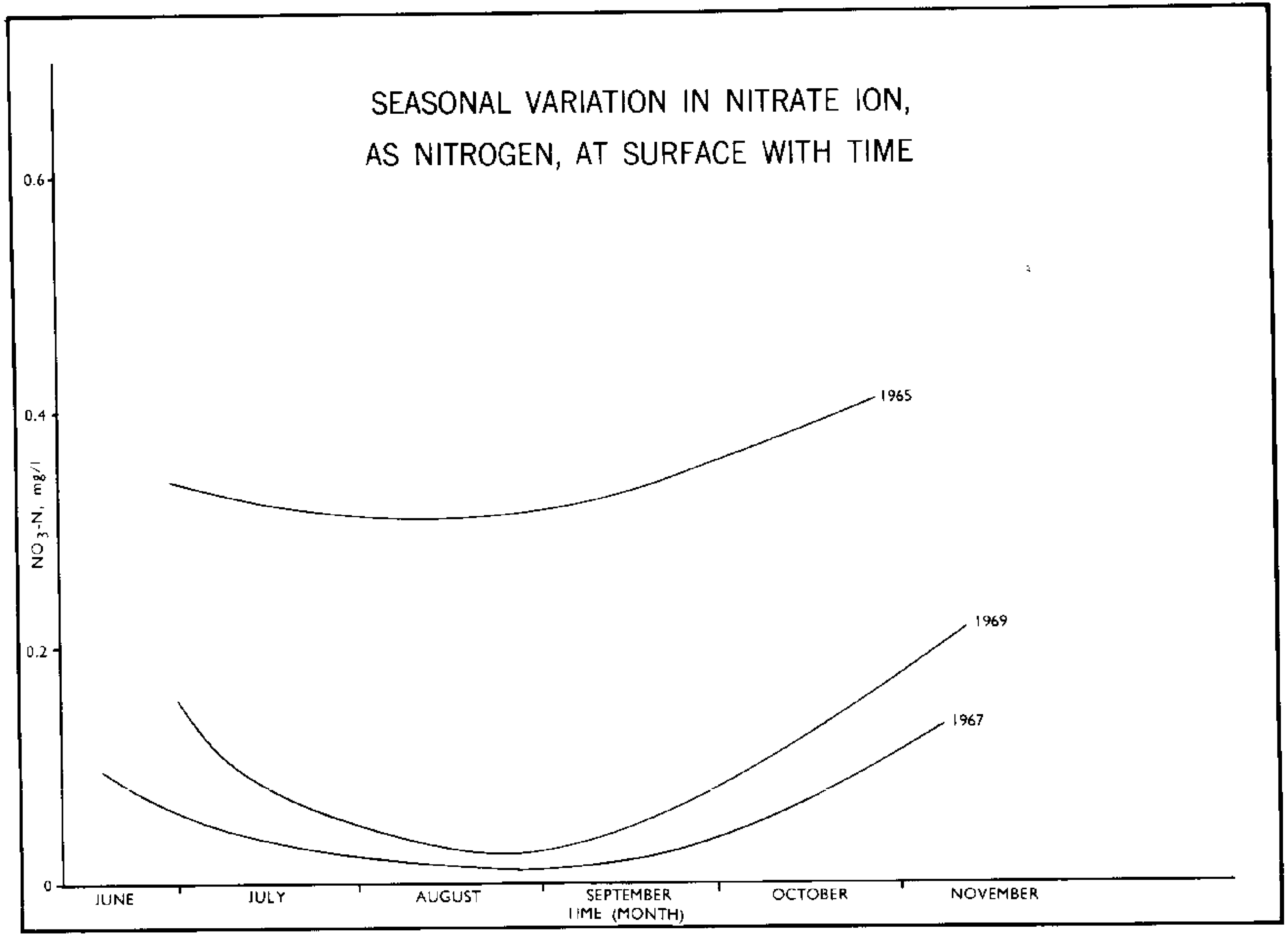
Variation in annual mean nitrate-nitrogen concentrations (μg N/ℓ) at surface with time, 1960-1972

FIGURE 22



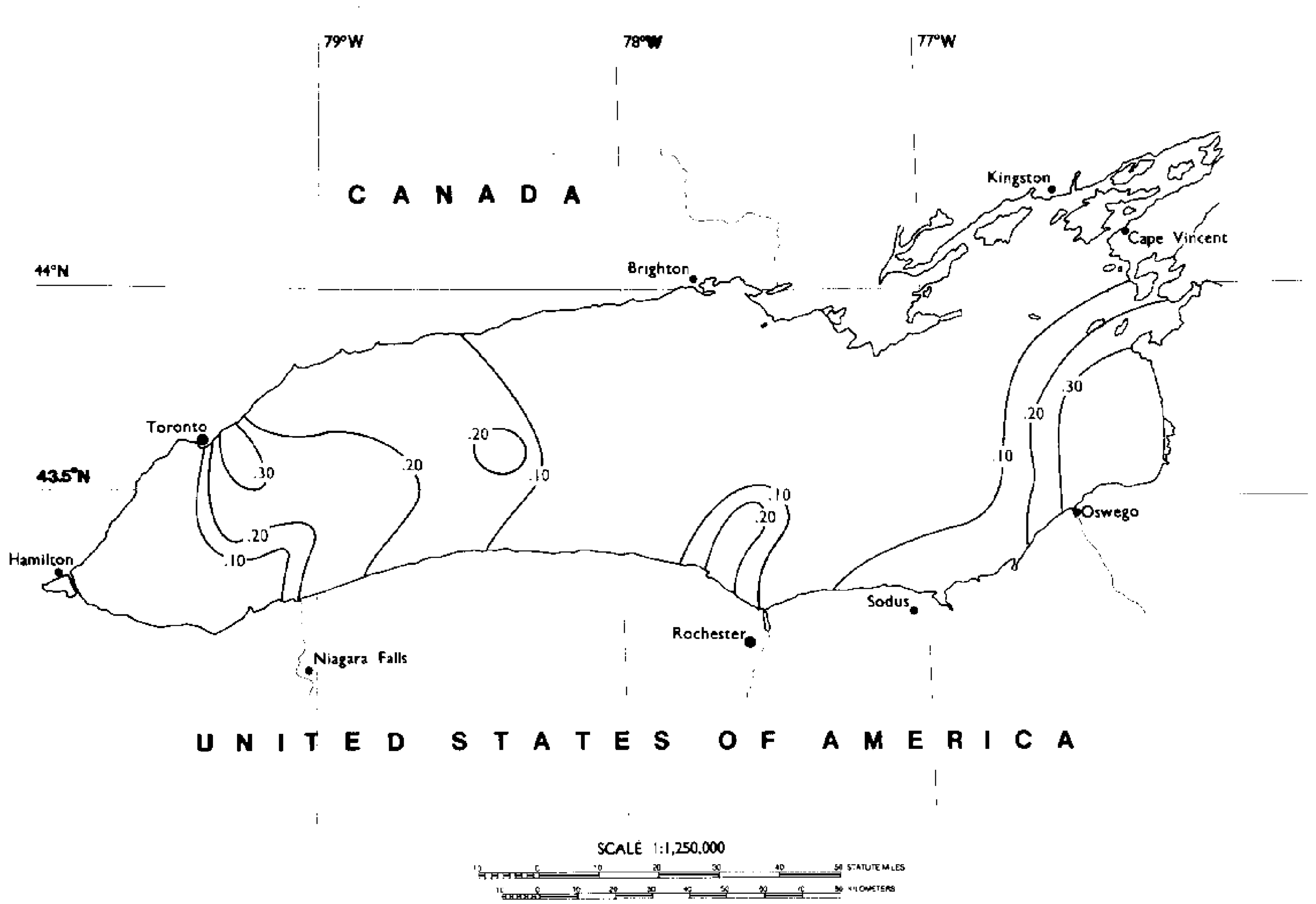
Bar graph of annual mean nitrate-nitrogen concentrations (µg N/ℓ) at surface, 1960-1972

FIGURE 23



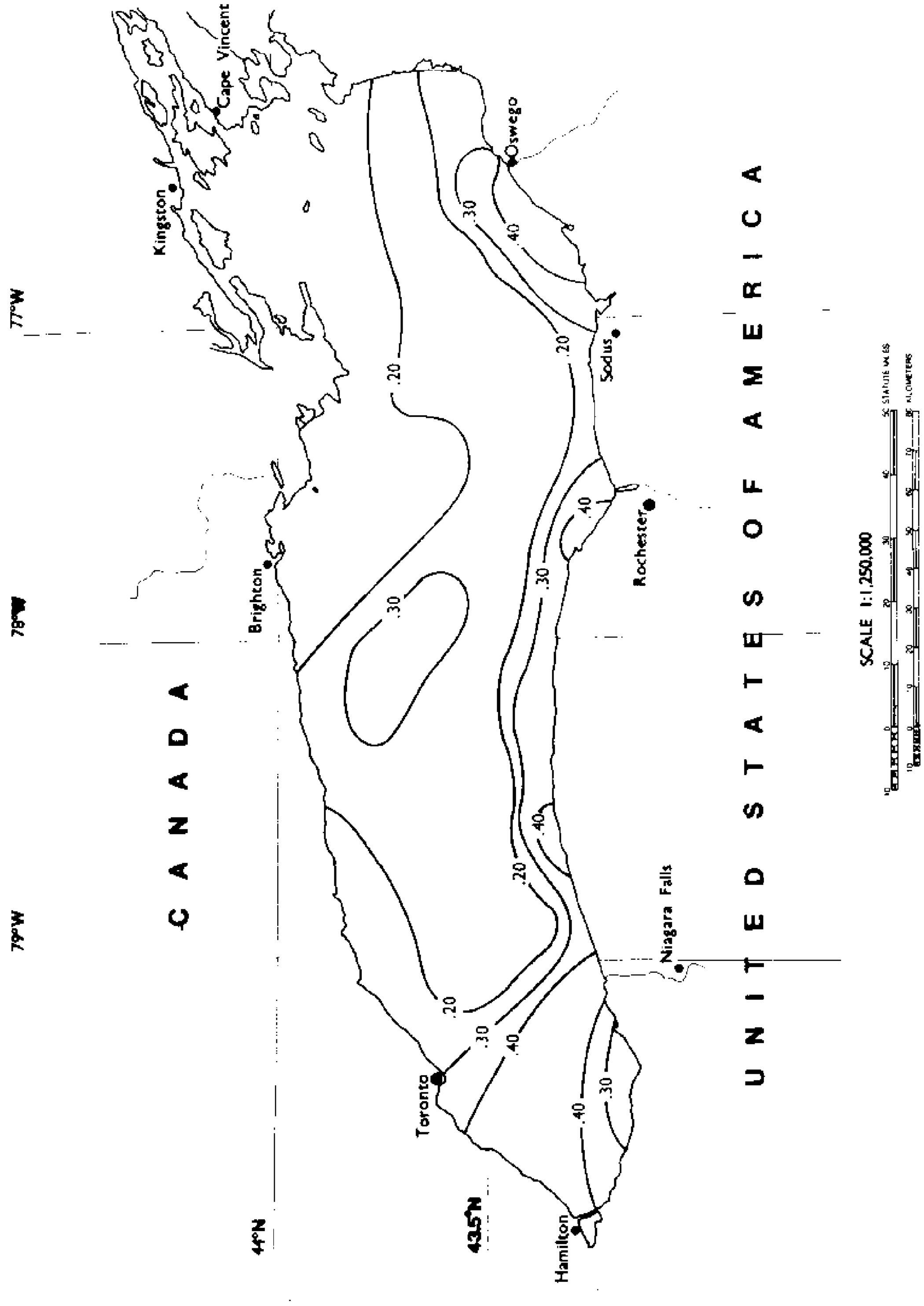
Seasonal variations in nitrate-nitrogen concentrations (mg N/ℓ) at surface in 1965, 1967 and 1969

FIGURE 24



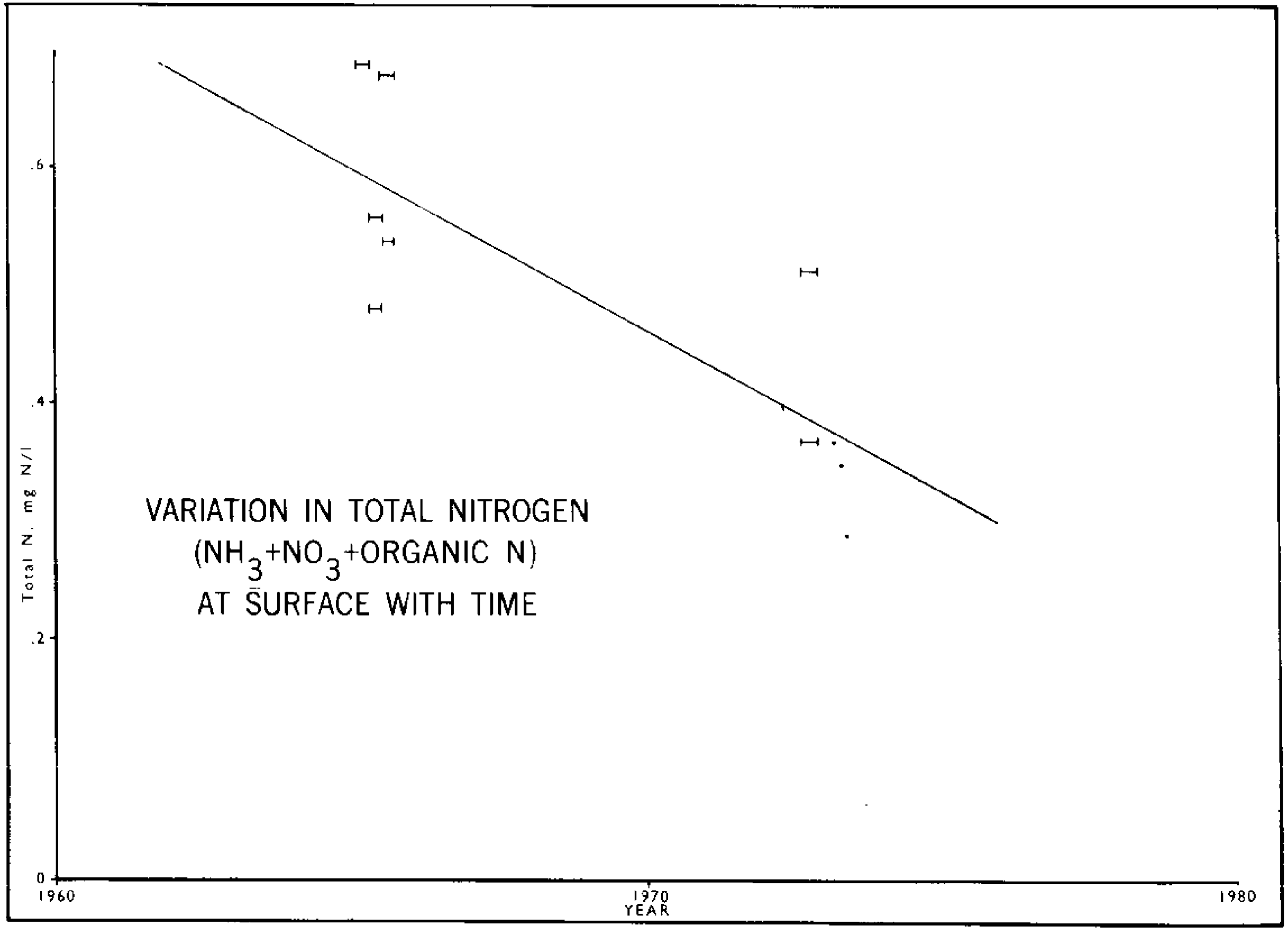
Surface distribution of nitrate-nitrogen (mg N/ℓ), Summer 1965

FIGURE 25



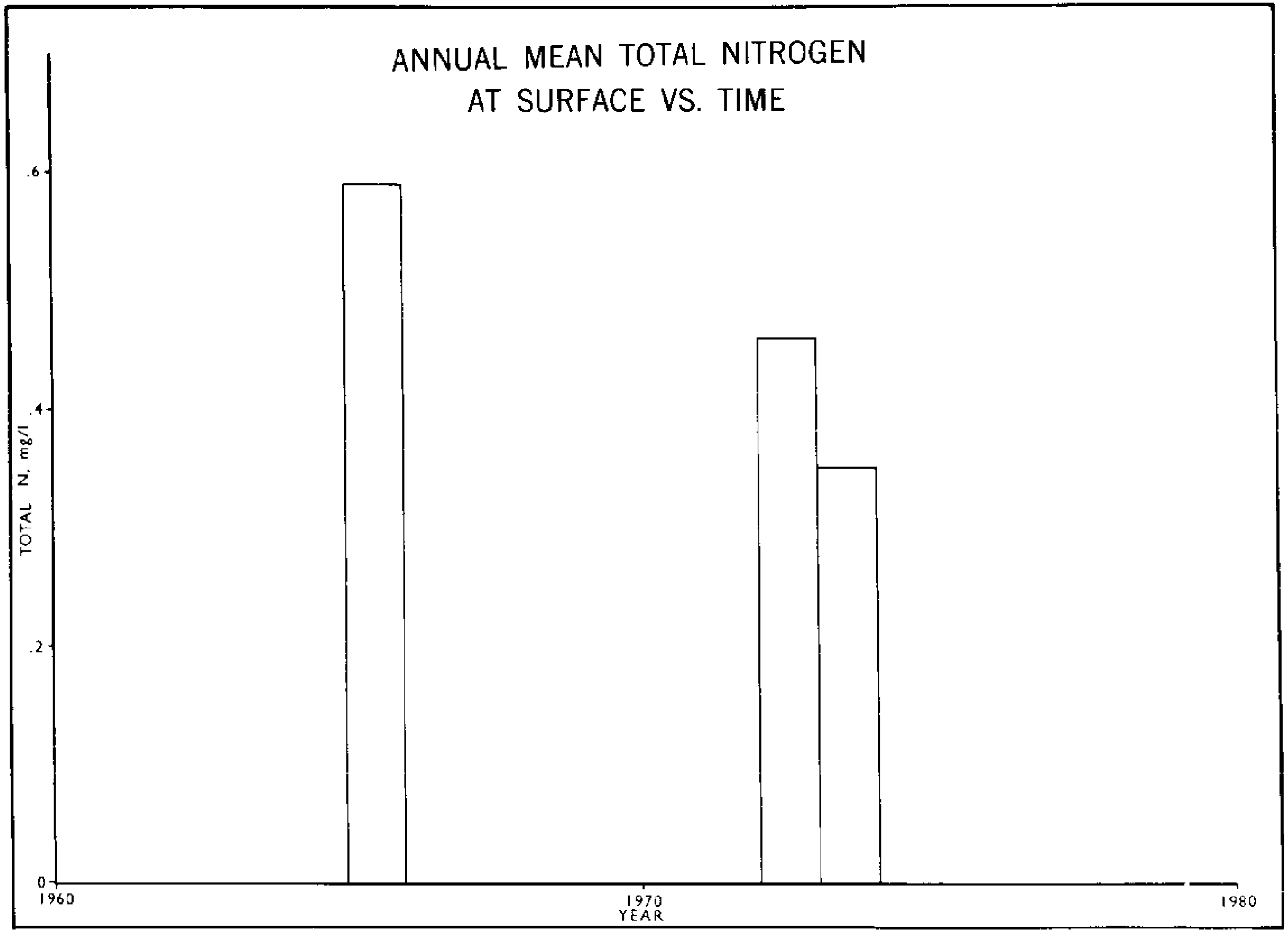
Surface distribution of nitrate-nitrogen (mg N/ℓ), Fall 1965

FIGURE 26



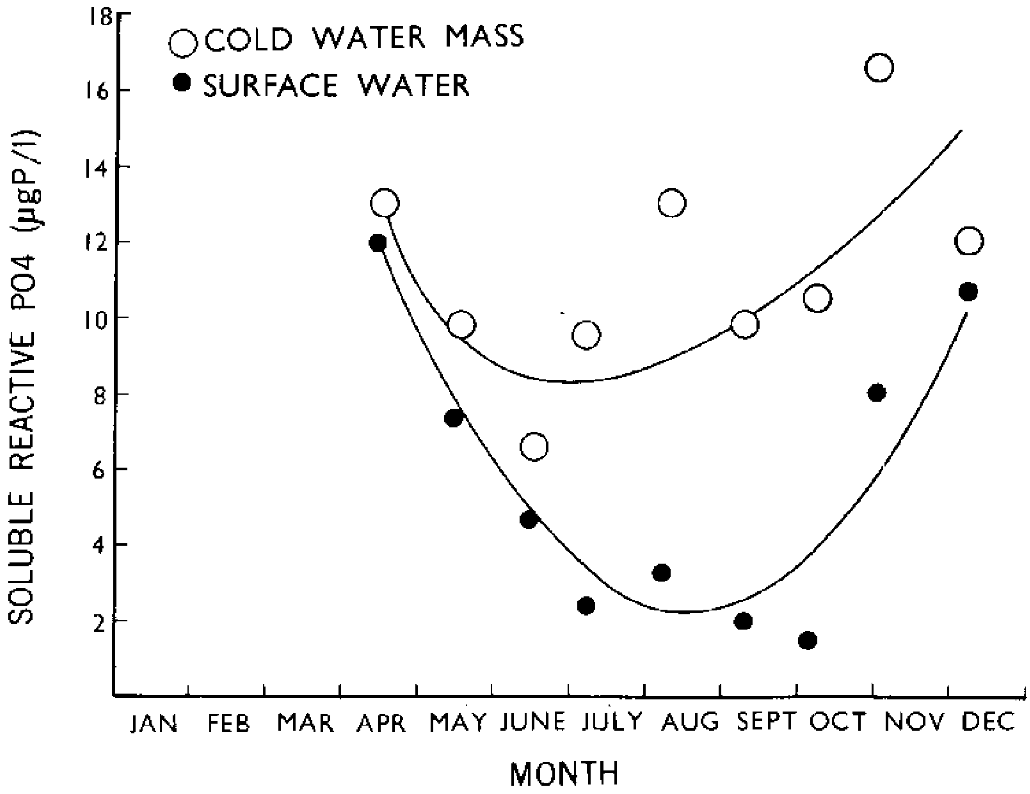
Variation in total-nitrogen concentrations (mg N/ℓ) at surface with time, 1965-1973

FIGURE 27



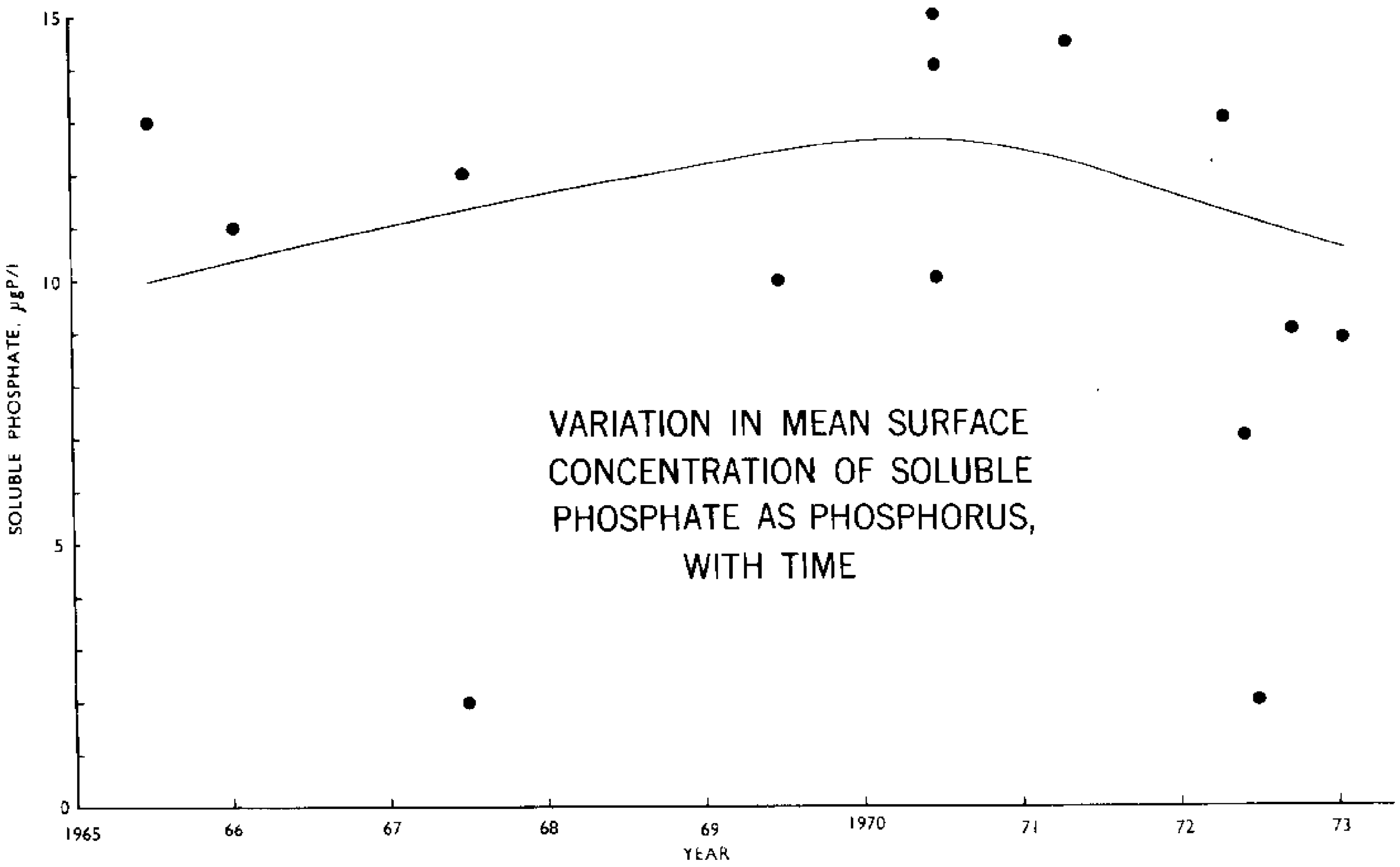
Bar graph of annual mean total-nitrogen concentrations (mg N/ℓ) at surface, 1965-1973

FIGURE 28



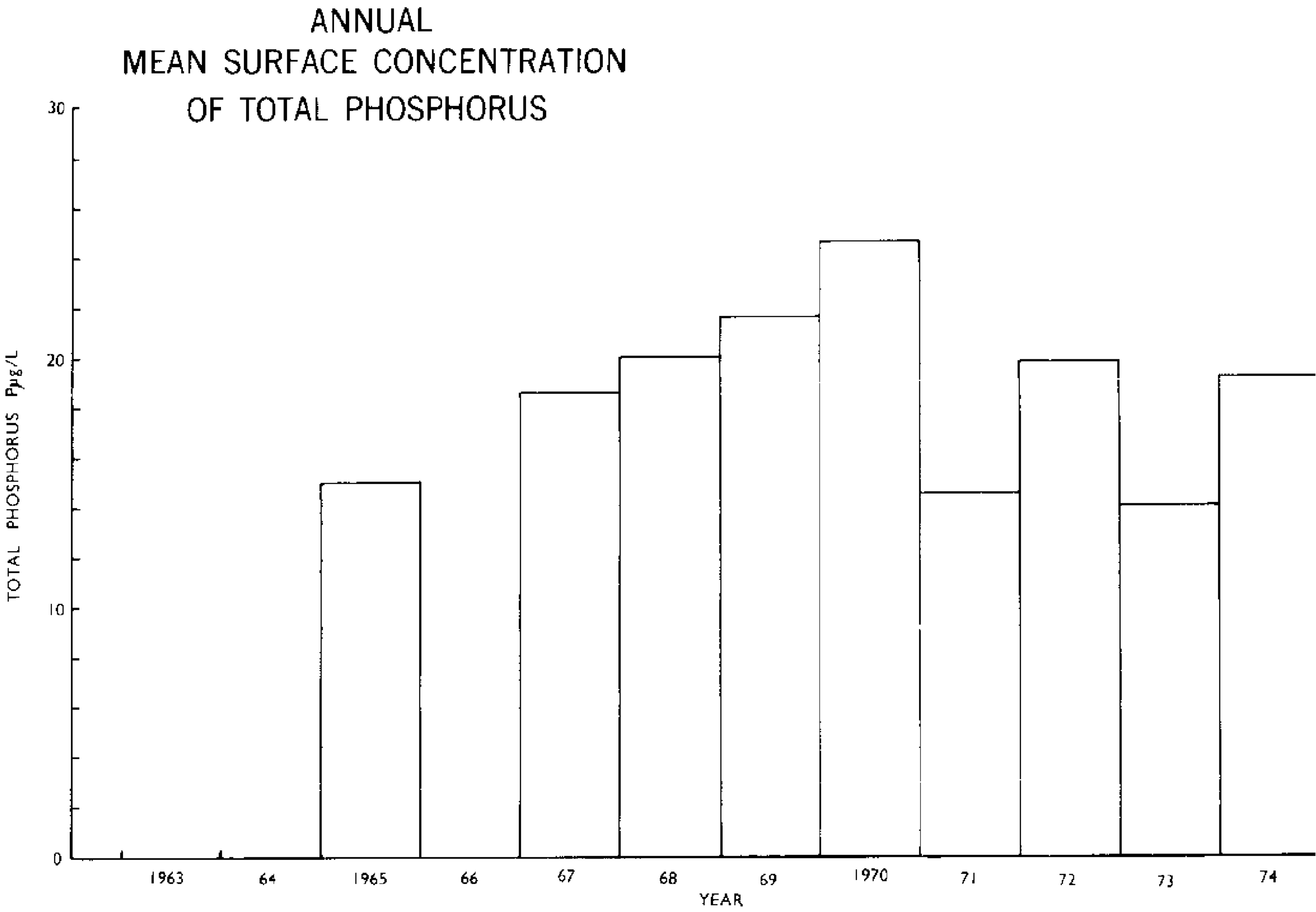
Seasonal variations of soluble reactive-phosphate concentrations (µg P/ℓ) in the epilimnion (filled circles) and the hypolimnion (open circles)

FIGURE 29



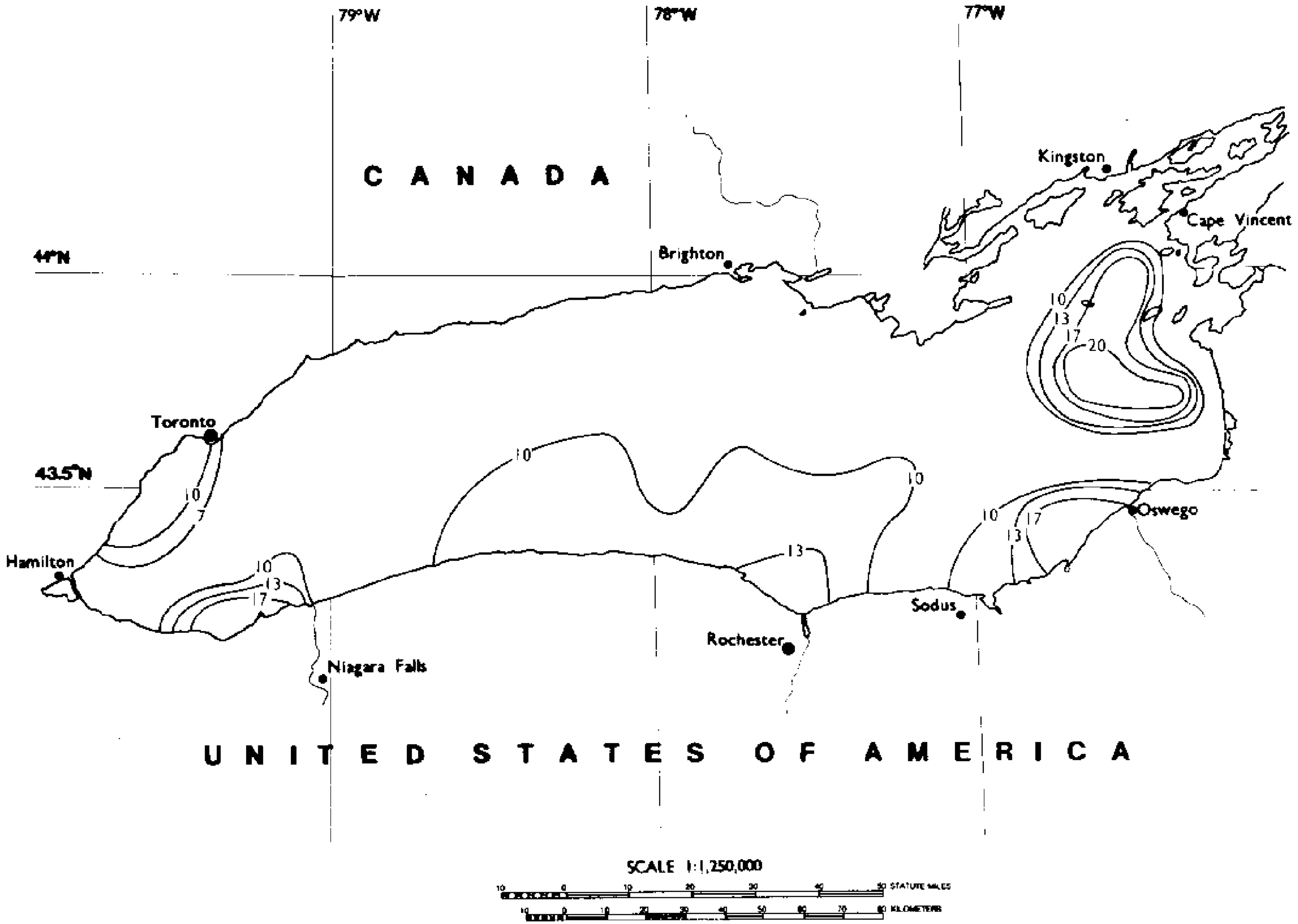
Variation in mean soluble reactive-phosphate concentrations (µg P/ℓ) at surface with time, 1965-1973

FIGURE 30



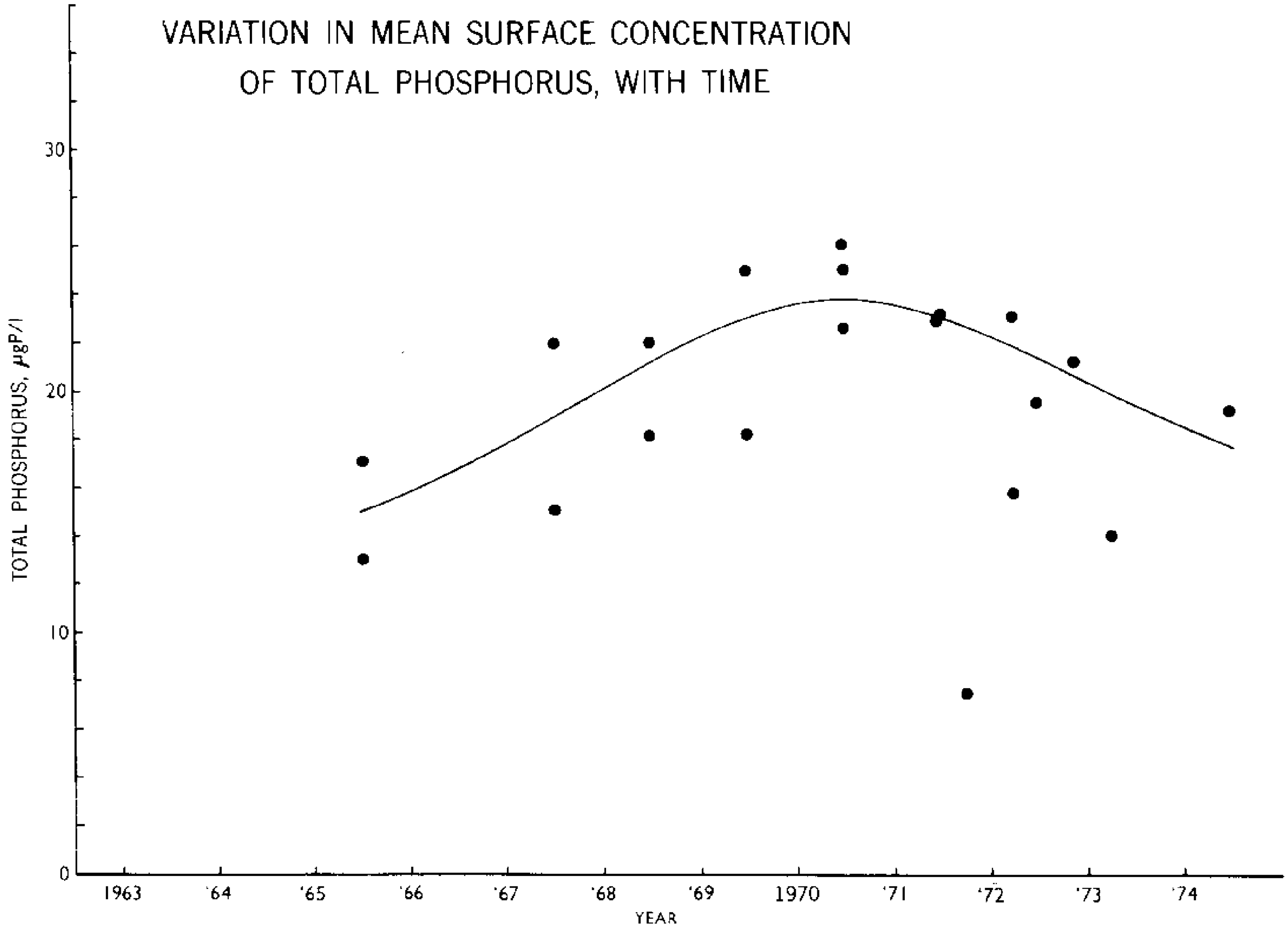
Bar graph of annual mean soluble reactive-phosphate concentrations (µg P/ℓ) at surface, 1965-1973

FIGURE 31



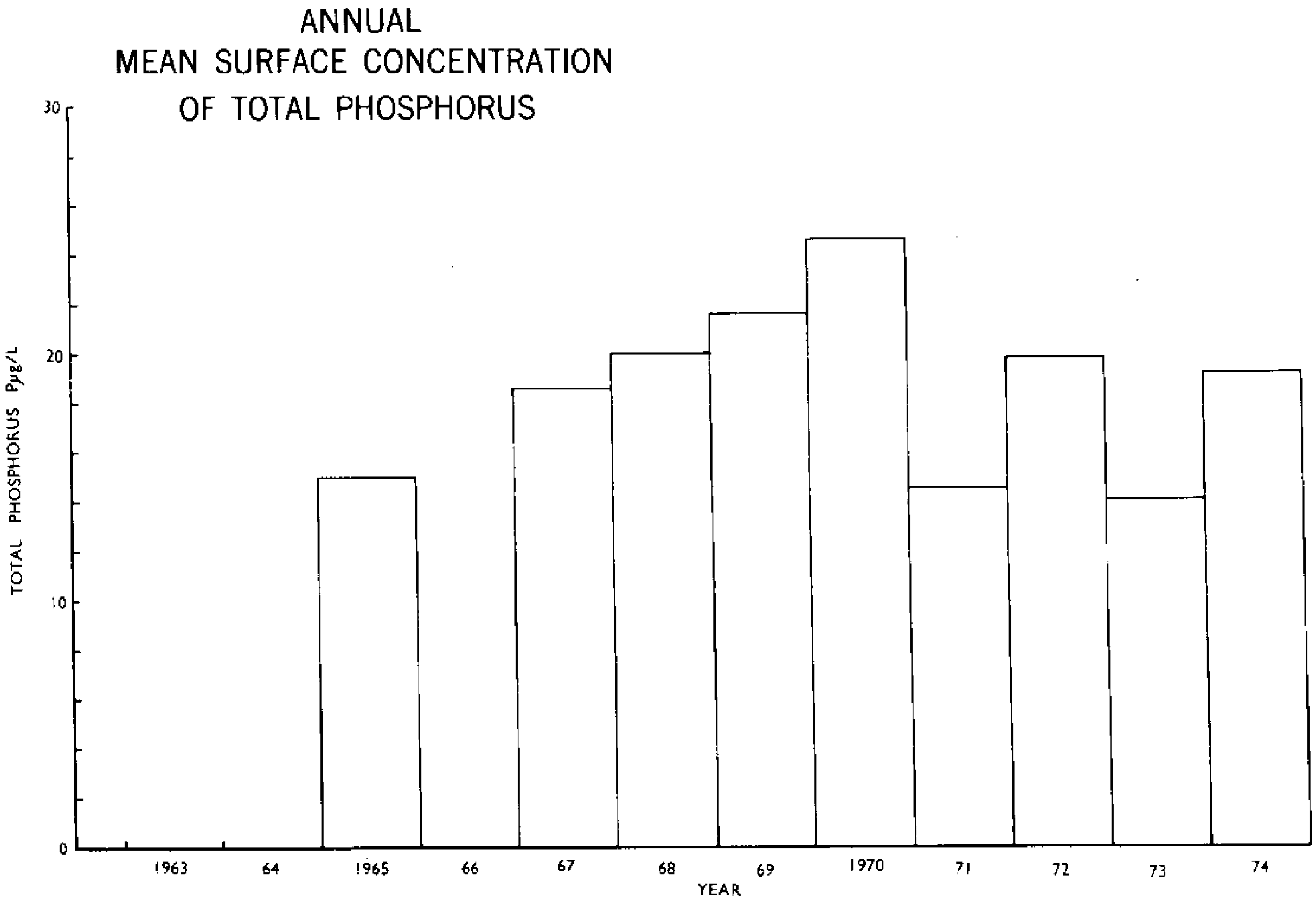
Surface distribution of soluble reactive-phosphate (µg P/ℓ),
Summer 1965

FIGURE 32



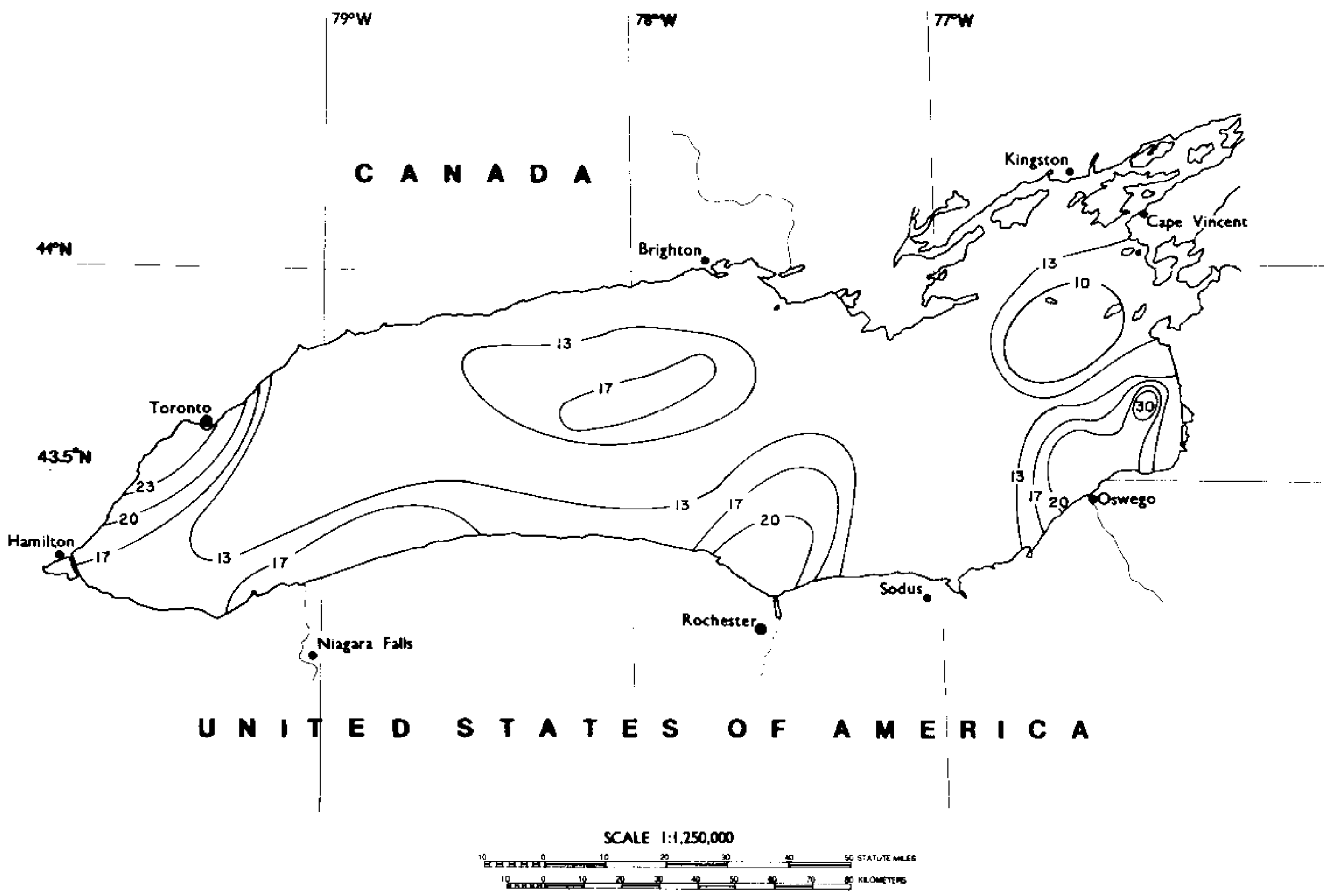
Variation in total-phosphorus concentrations (µg P/ℓ) at surface with time, 1965-1974

FIGURE 33



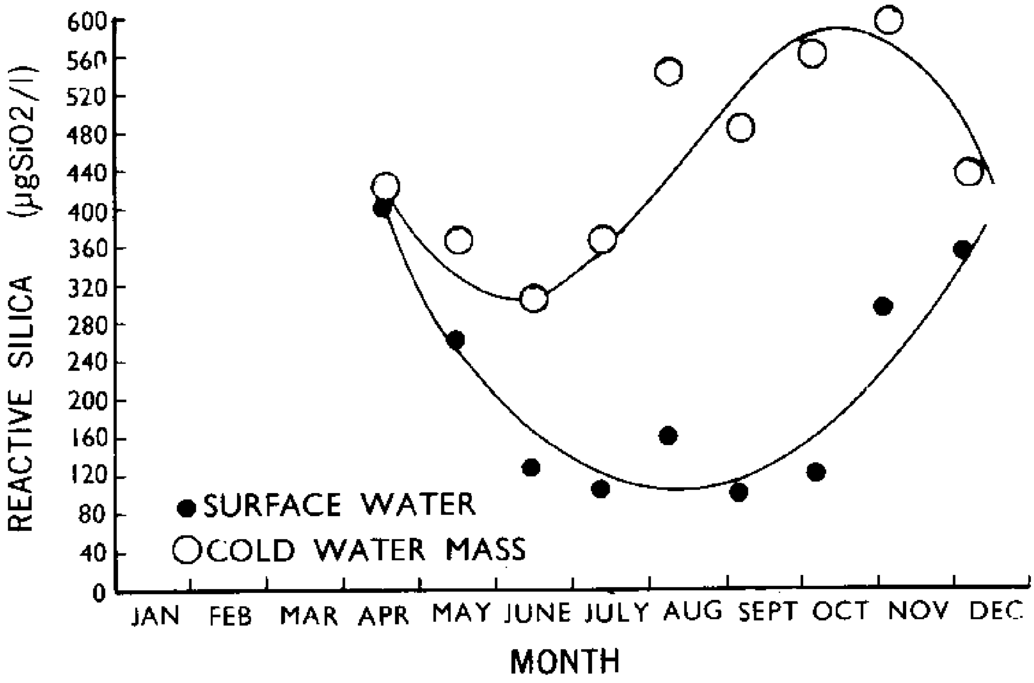
Bar graph of annual mean total-phosphorus concentrations (μg P/ℓ) at surface, 1965-1974

FIGURE 34



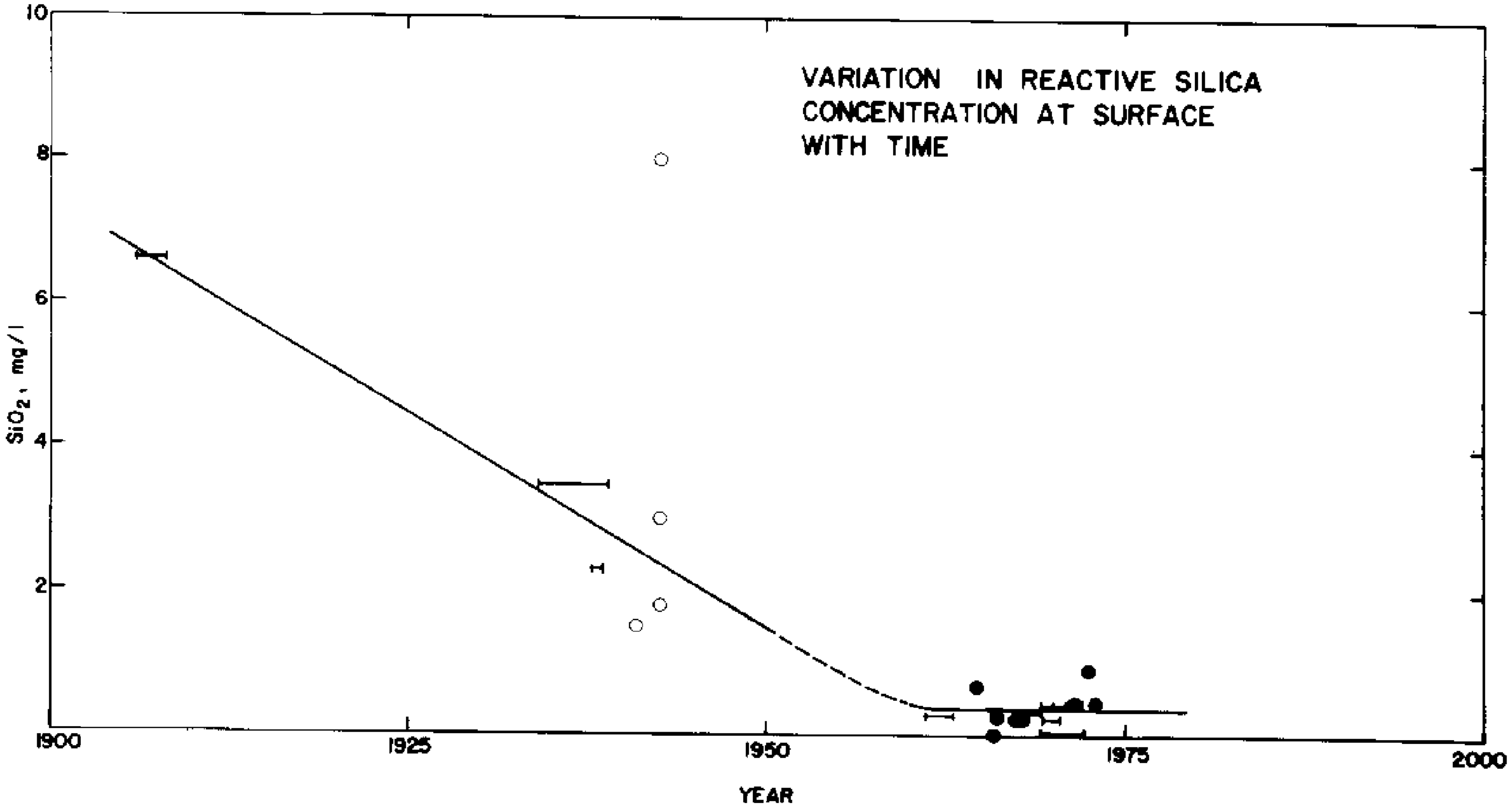
Surface distribution of total-phosphorus (µg P/ℓ), Summer 1965

FIGURE 35



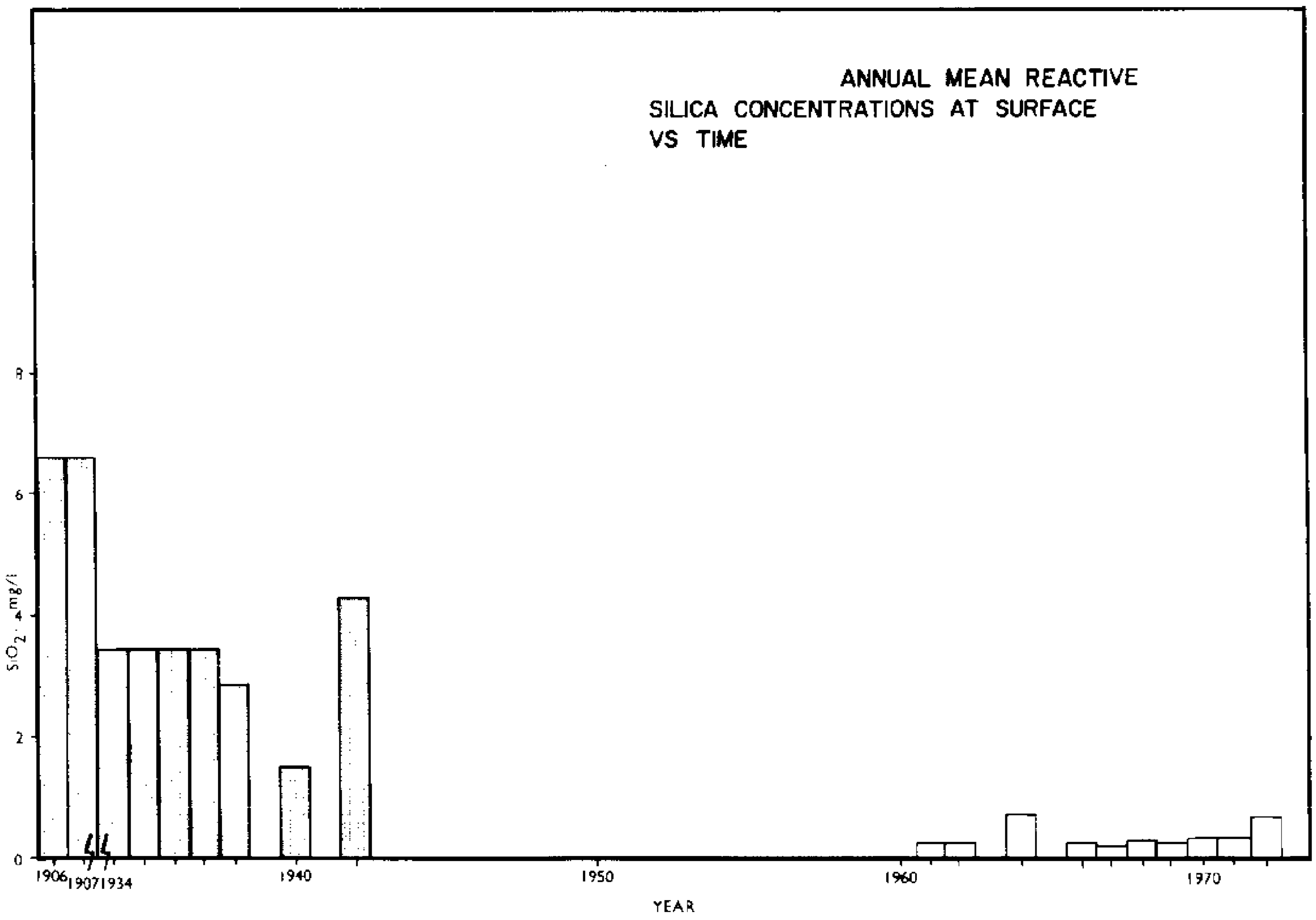
Seasonal variations of reactive-silica concentrations (µg $SiO_2$/ℓ) in the epilimnion (filled circles) and the hypolimnion (open circles)

FIGURE 36



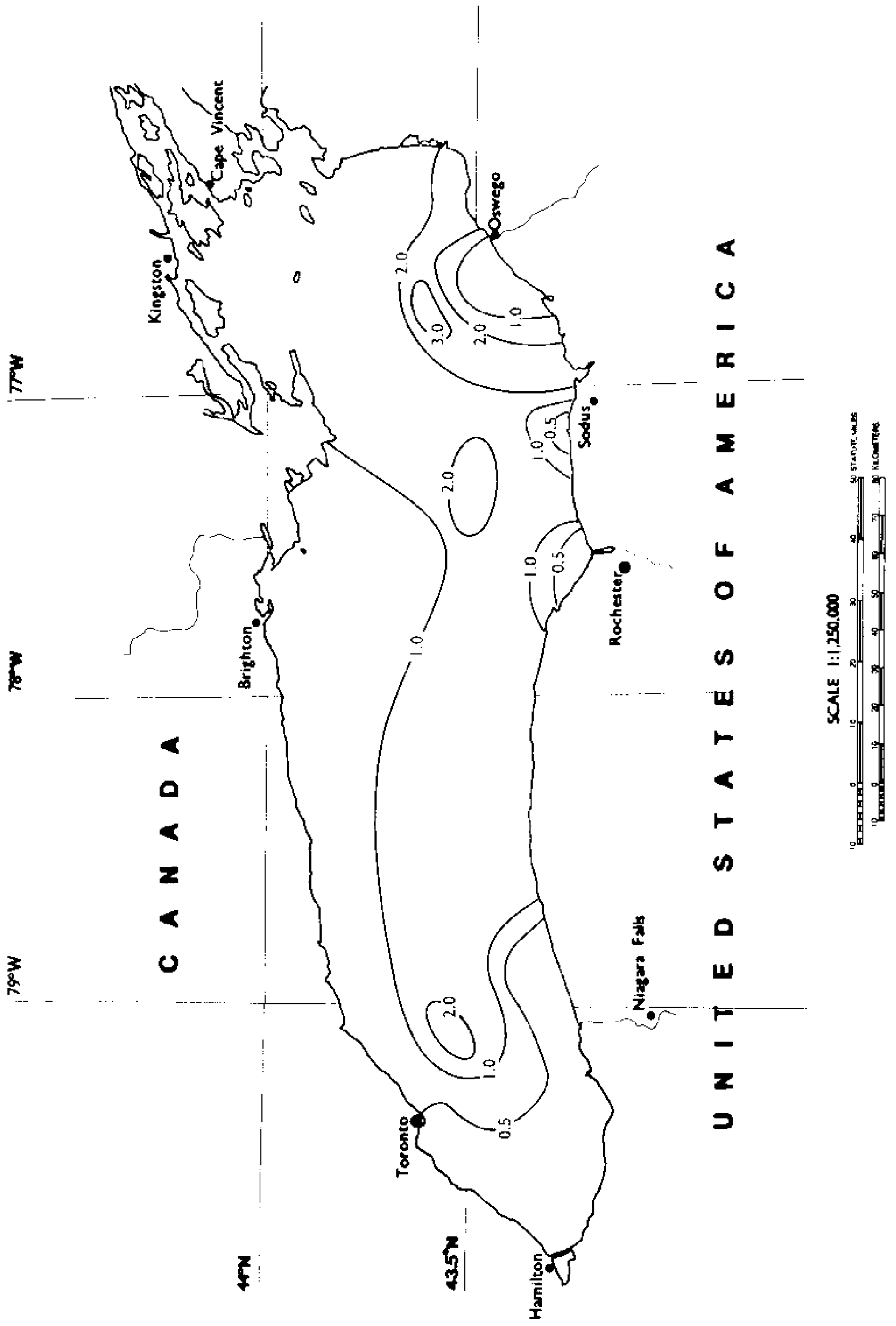
Variation of inshore (open circles) and lakewide (filled circles) reactive-silica concentrations (mg $SiO_2/\ell$) at surface with time, 1906-1972

FIGURE 37



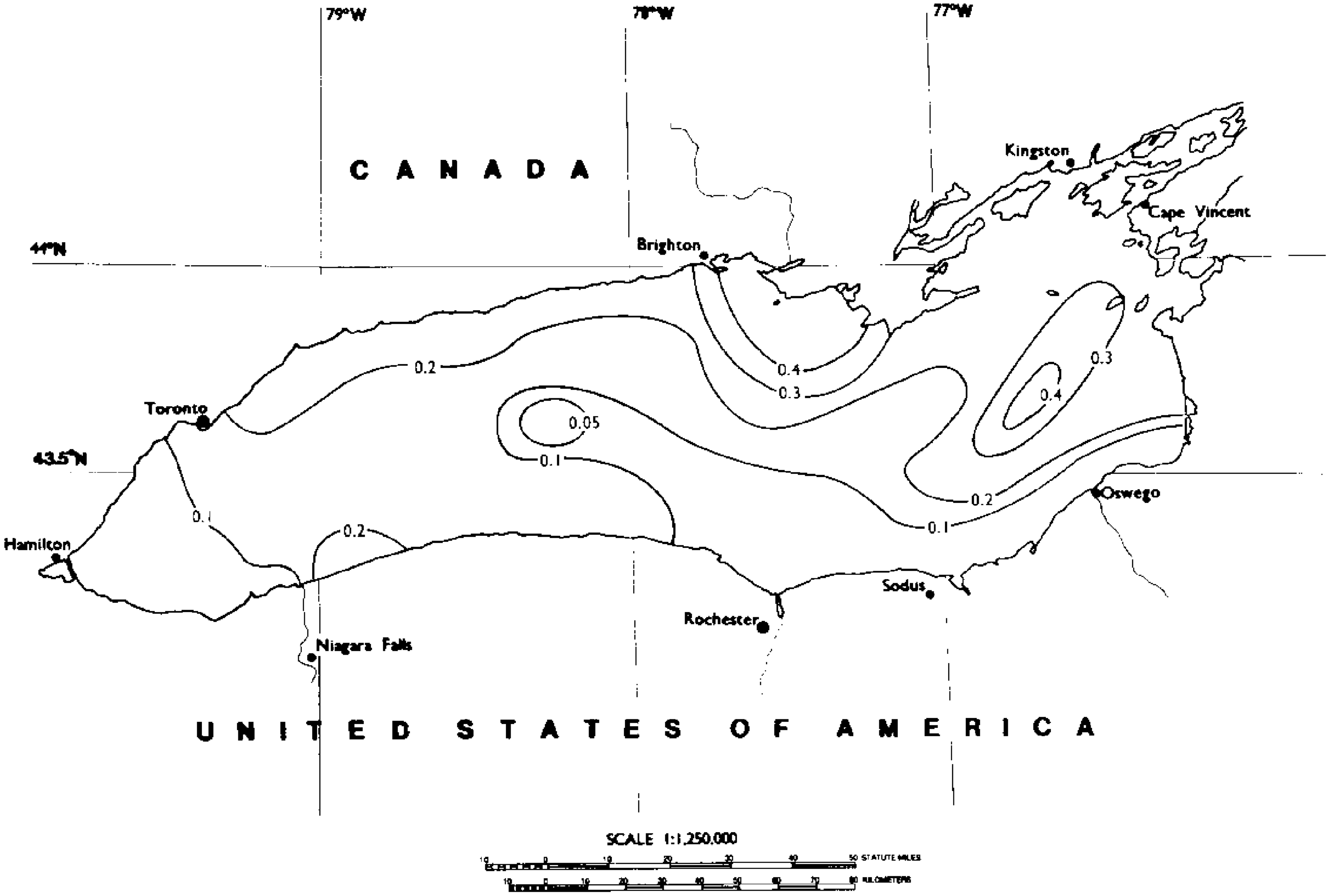
Bar graph of inshore (filled bars) and lakewide (open bars) annual mean reactive-silica concentrations (mg $SiO_2$/ℓ) at surface, 1906–1972

FIGURE 38



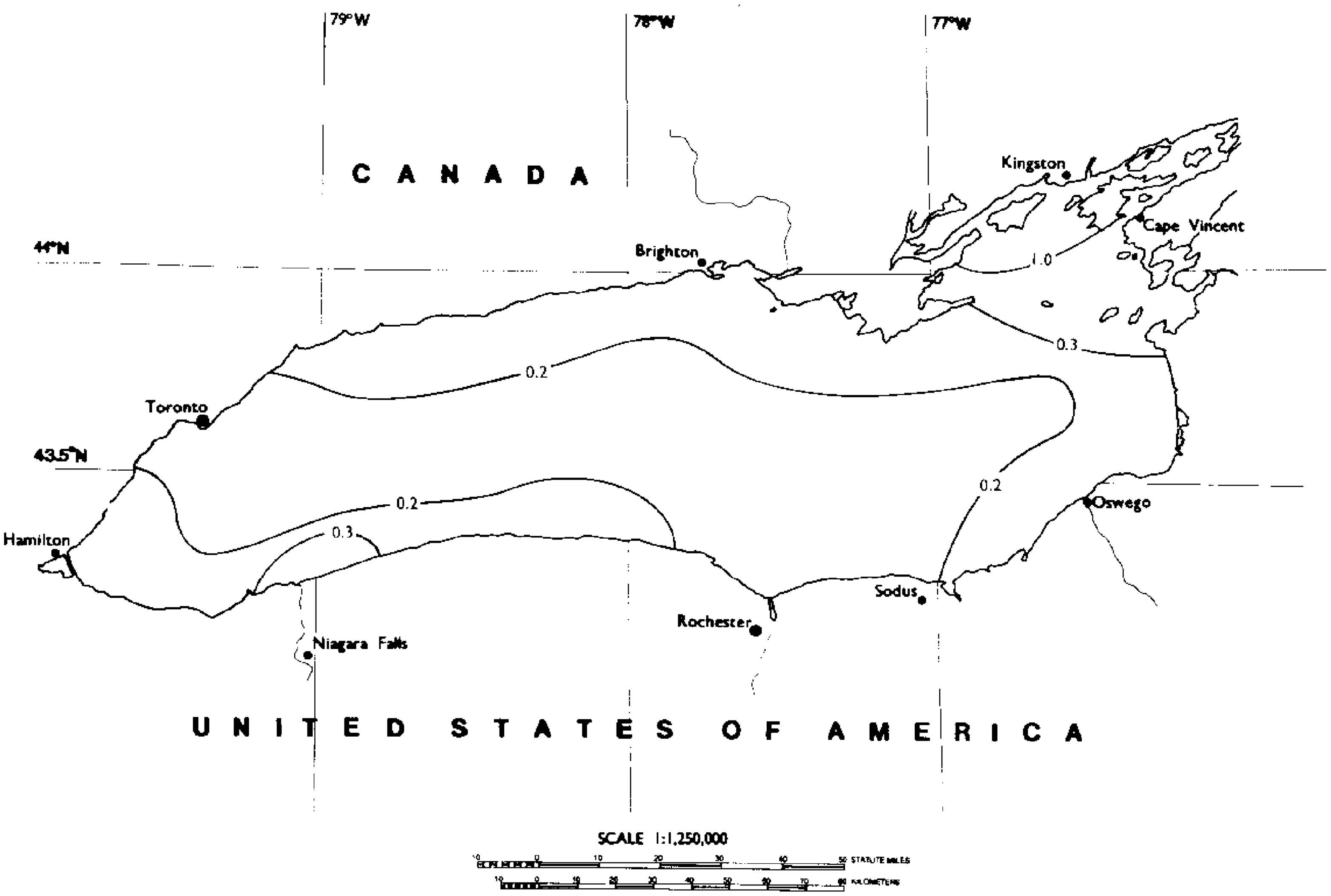
Surface distribution of reactive-silica (mg $SiO_2/\ell$), Spring 1965

FIGURE 39



Surface distribution of reactive-silica (mg $SiO_2/\ell$), Summer 1965

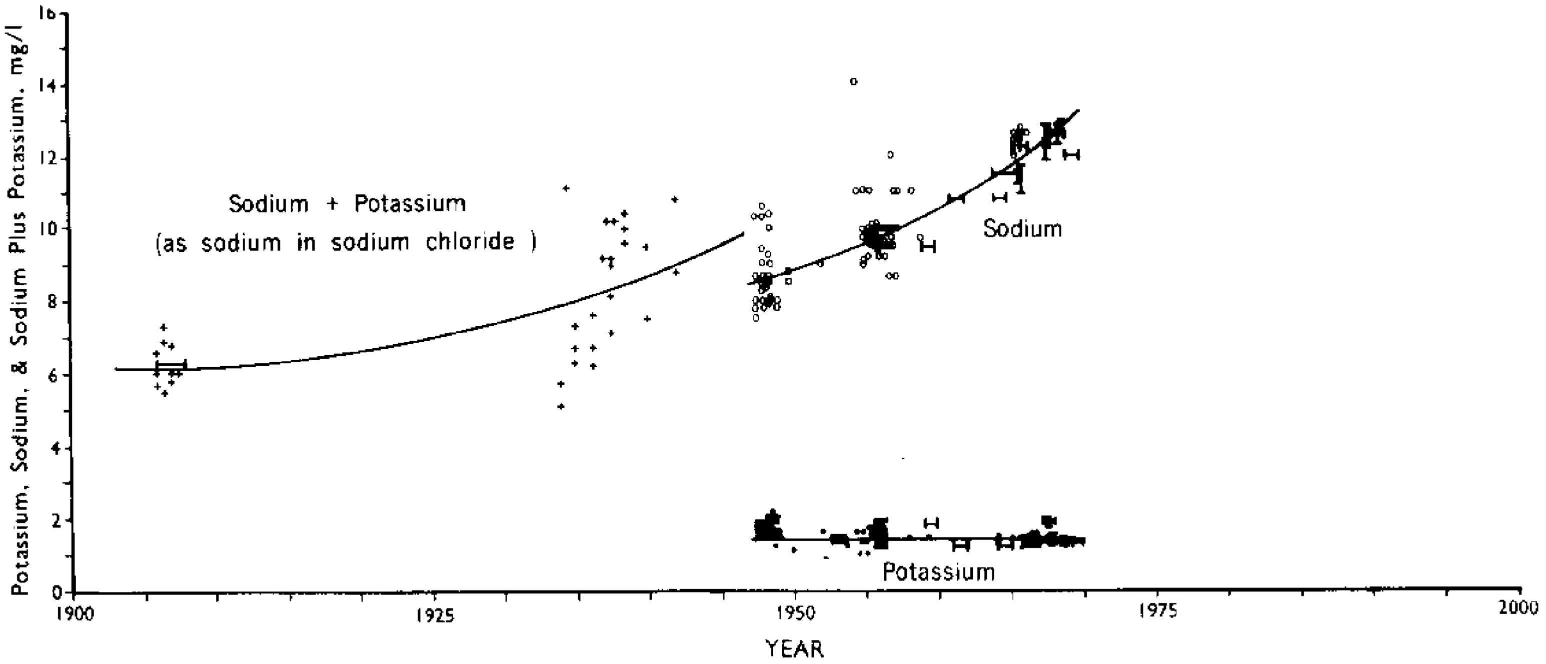
FIGURE 40



Surface distribution of reactive-silica (mg $SiO_2/\ell$), Fall 1965

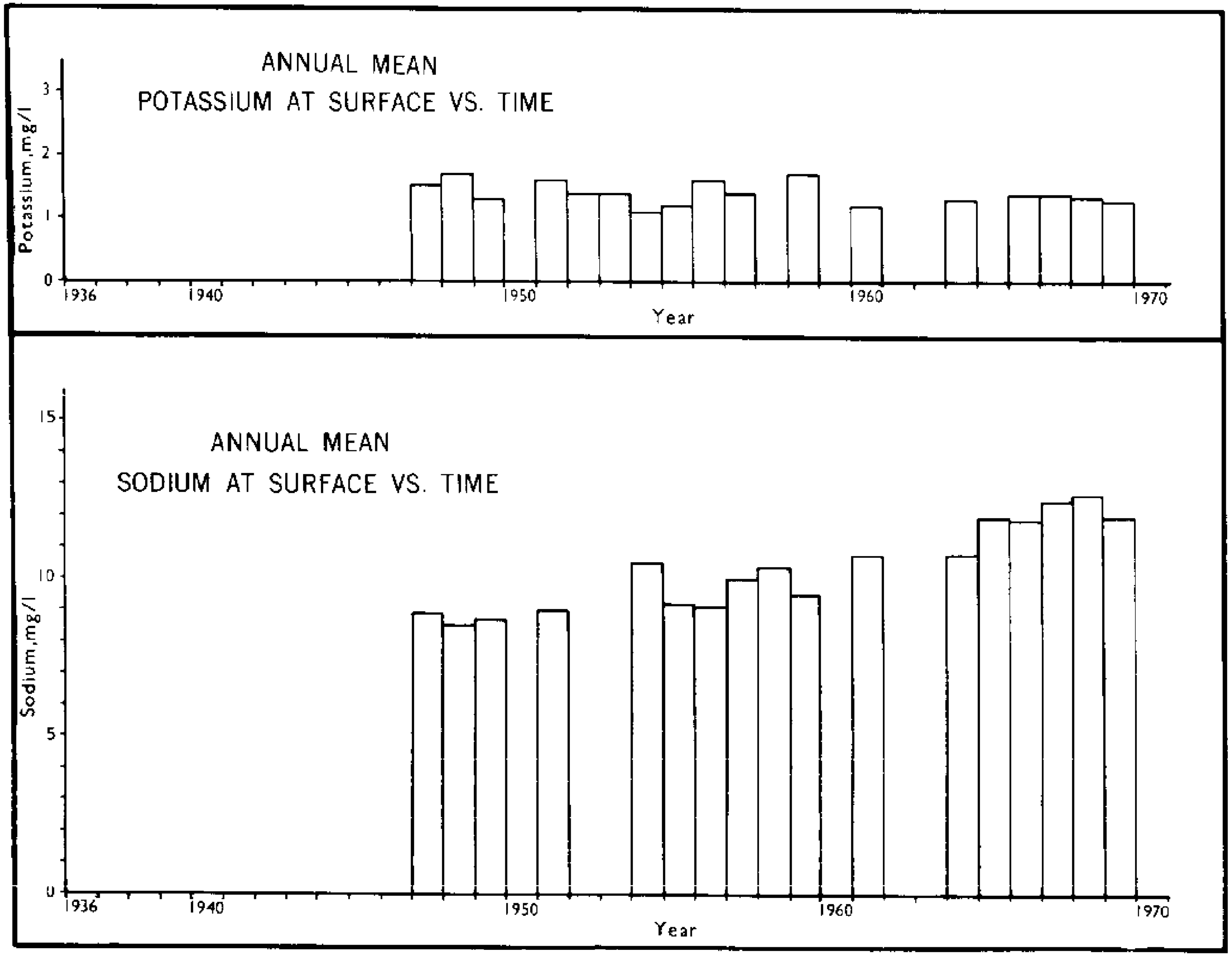
FIGURE 41

VARIATION OF SODIUM, POTASSIUM,
& SODIUM + POTASSIUM
AT THE SURFACE VS. TIME



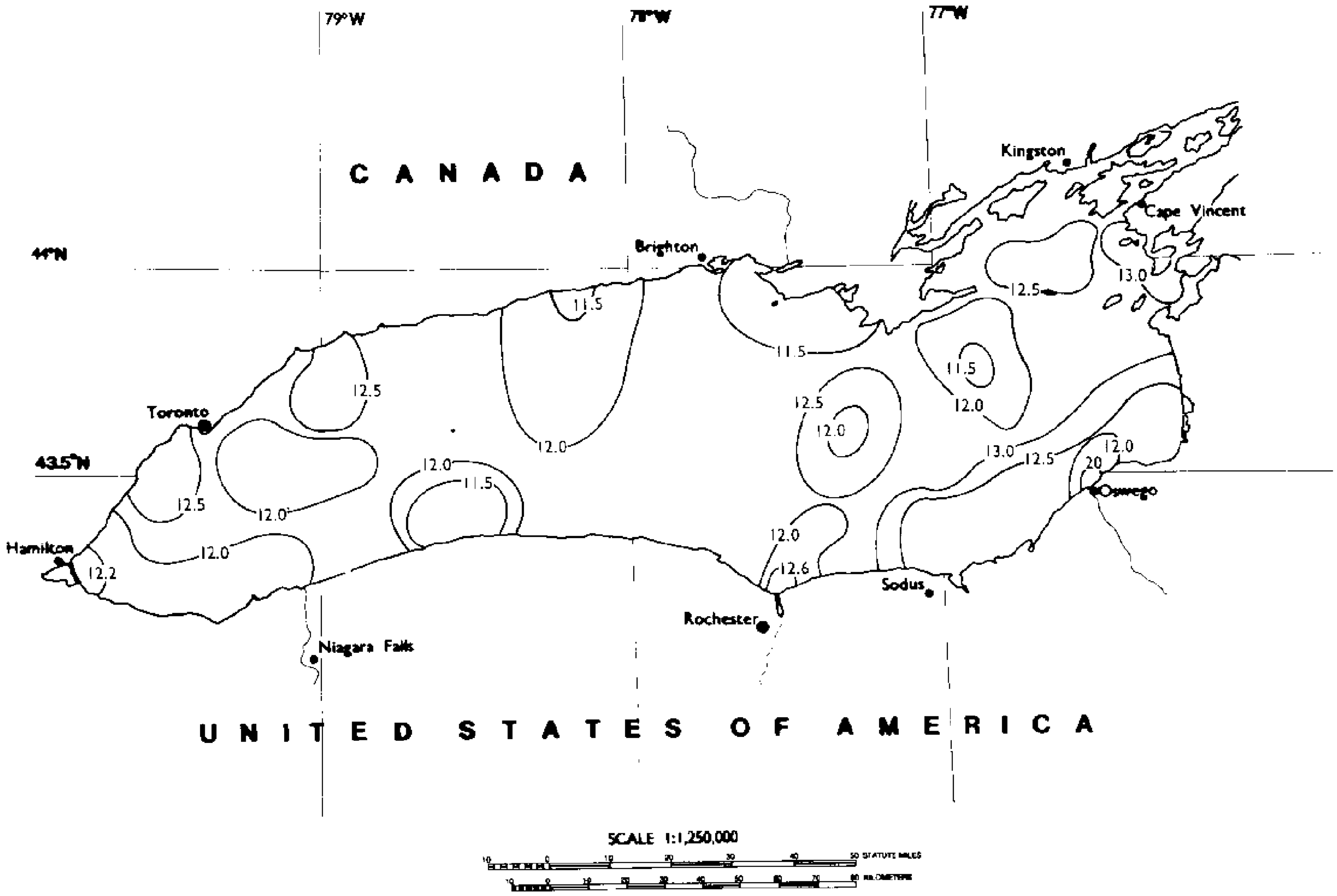
Variation in sodium plus potassium as sodium in equivalents of sodium chloride (crosses), sodium (open circles) and potassium (filled circles) ion concentrations (mg/ℓ) at surface with time, 1900–1970

FIGURE 42



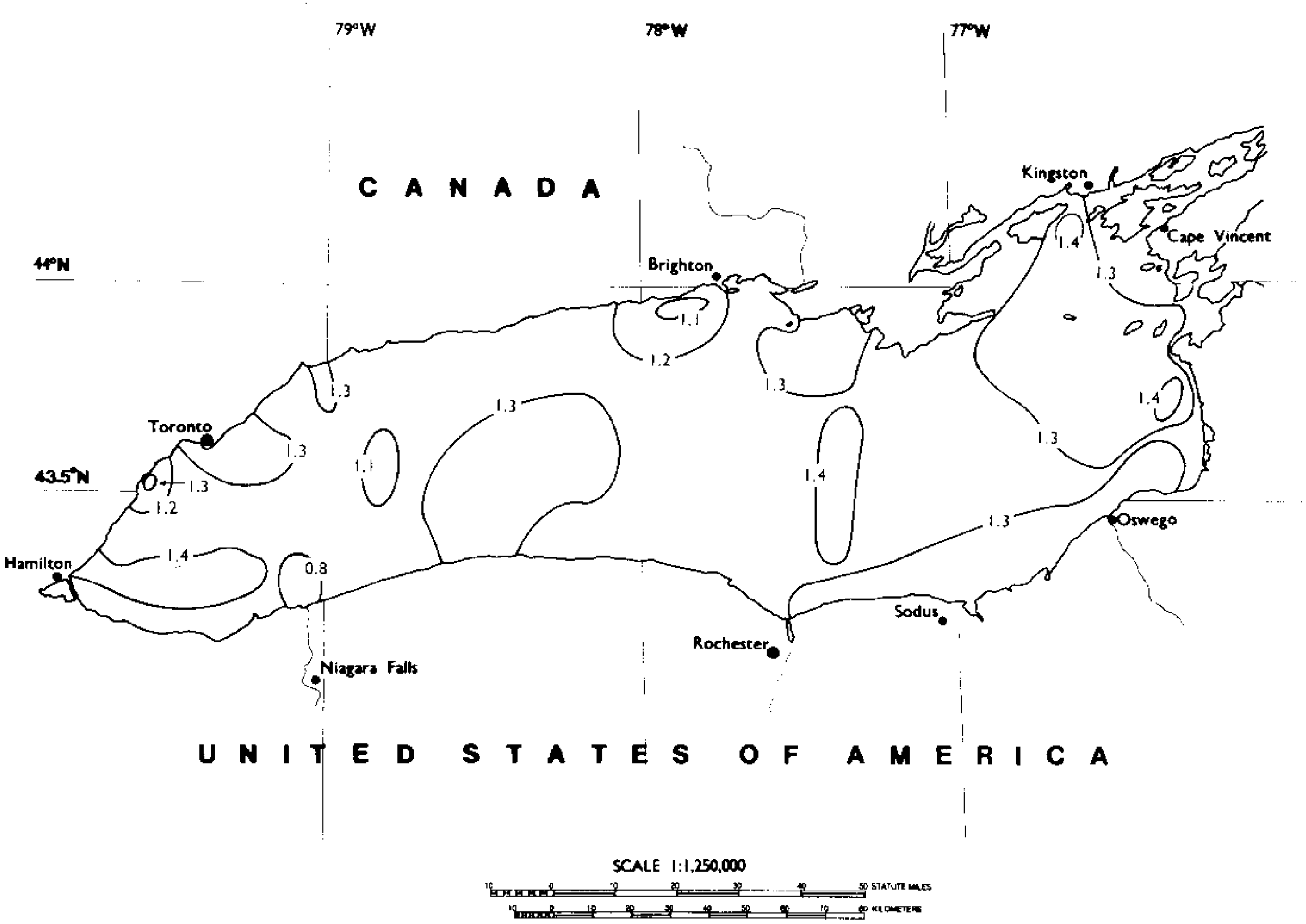
Bar graphs of annual mean potassium and sodium ion concentrations (mg/ℓ) at surface, 1947-1969

FIGURE 43



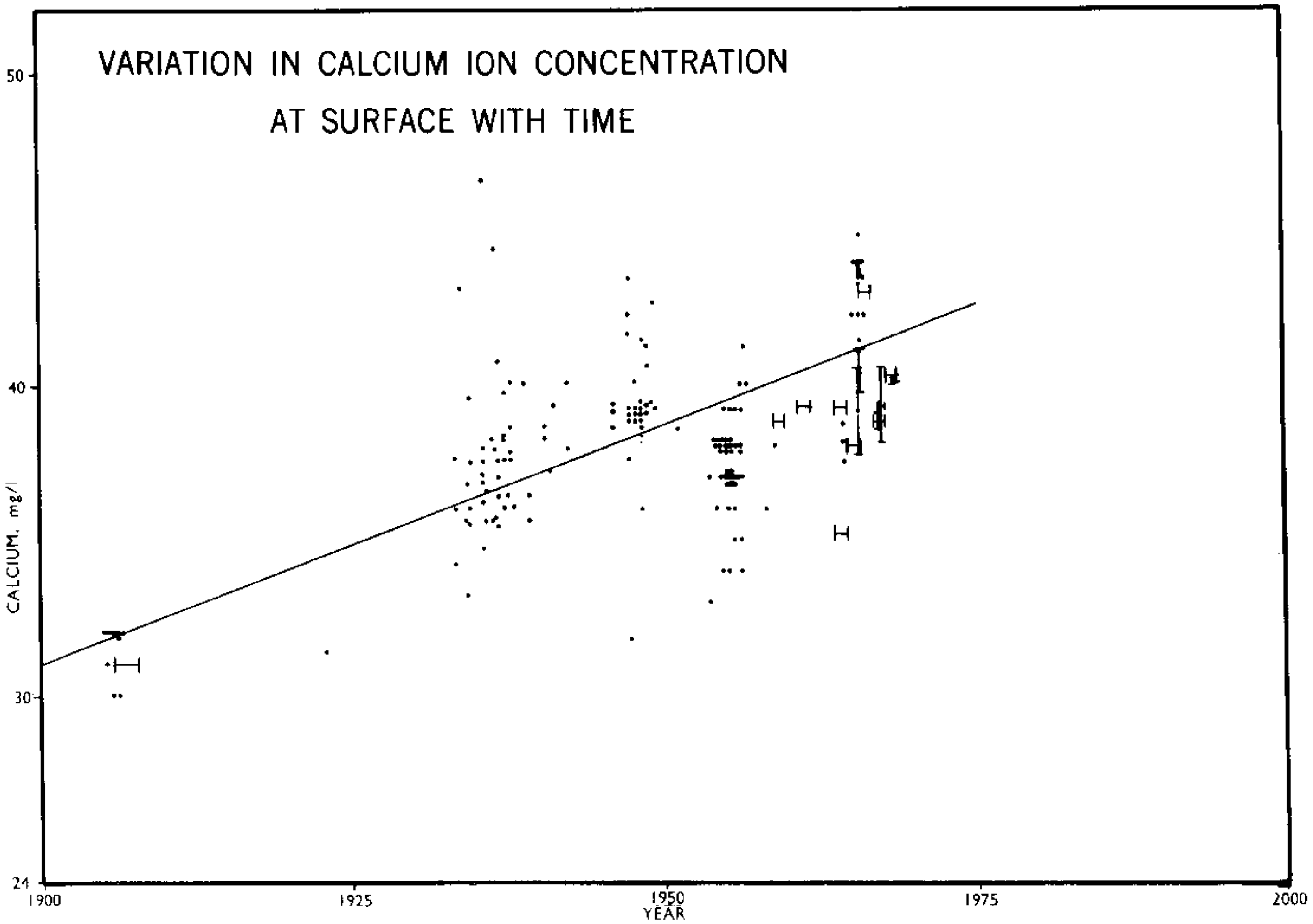
Surface distribution of sodium ions (mg Na/ℓ), Fall 1964. Note, area inside isopleths are of lesser concentration, except at the mouths of tributary rivers.

FIGURE 44



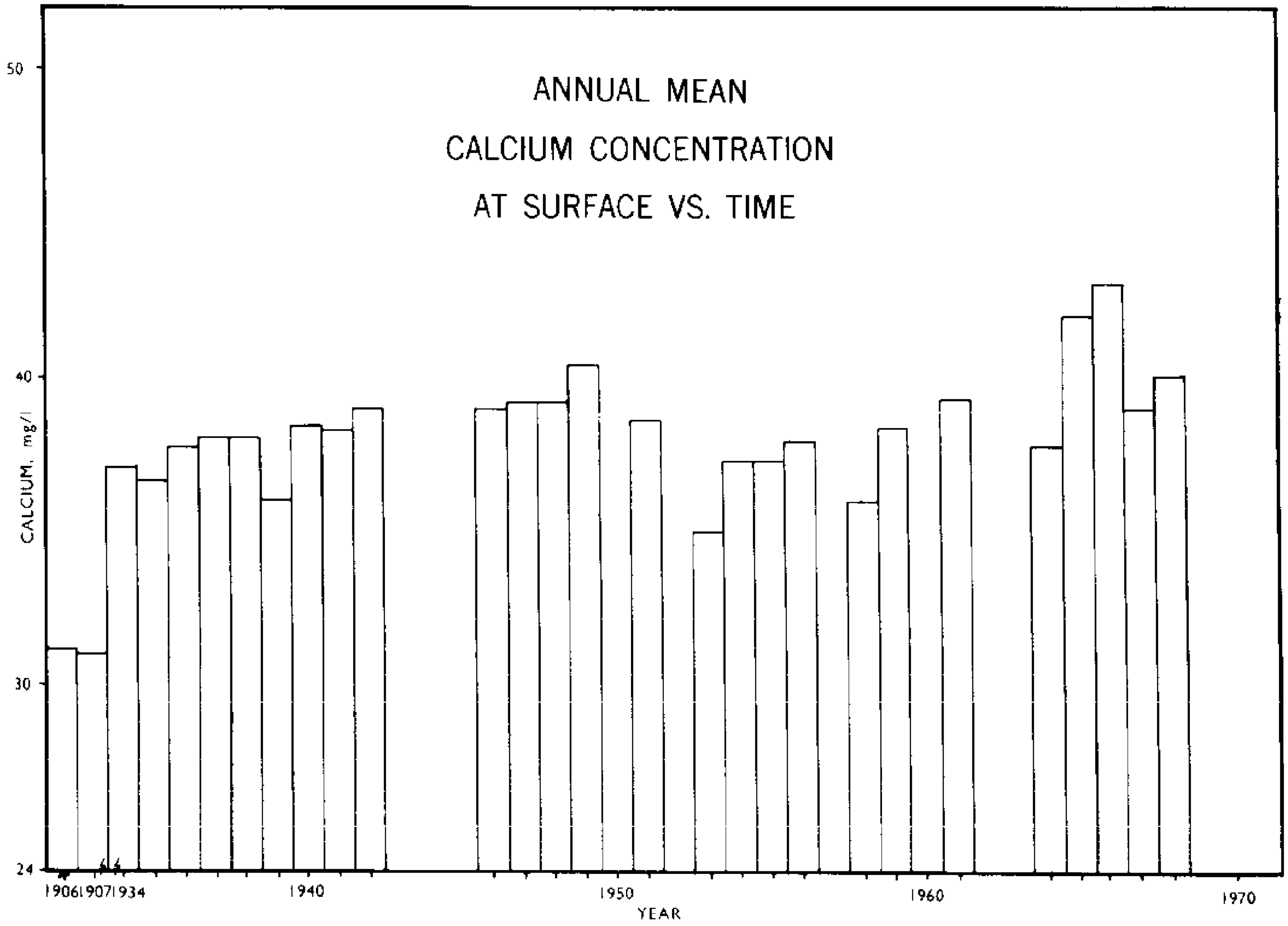
Surface distribution of potassium ions (mg K/ℓ), Fall 1964

FIGURE 45



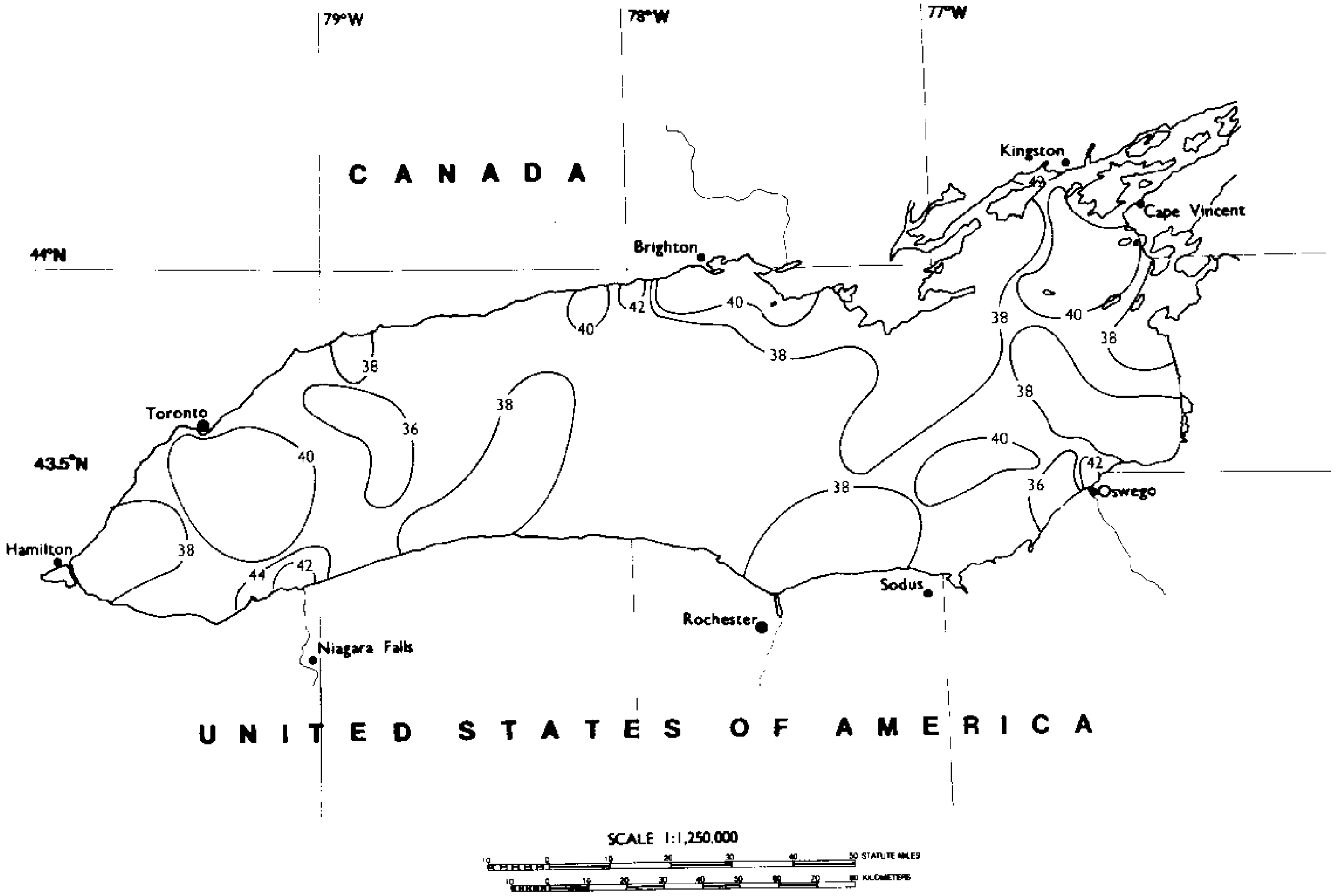
Variation in calcium ion concentrations (mg Ca/ℓ) at surface with time, 1906-1968

FIGURE 46



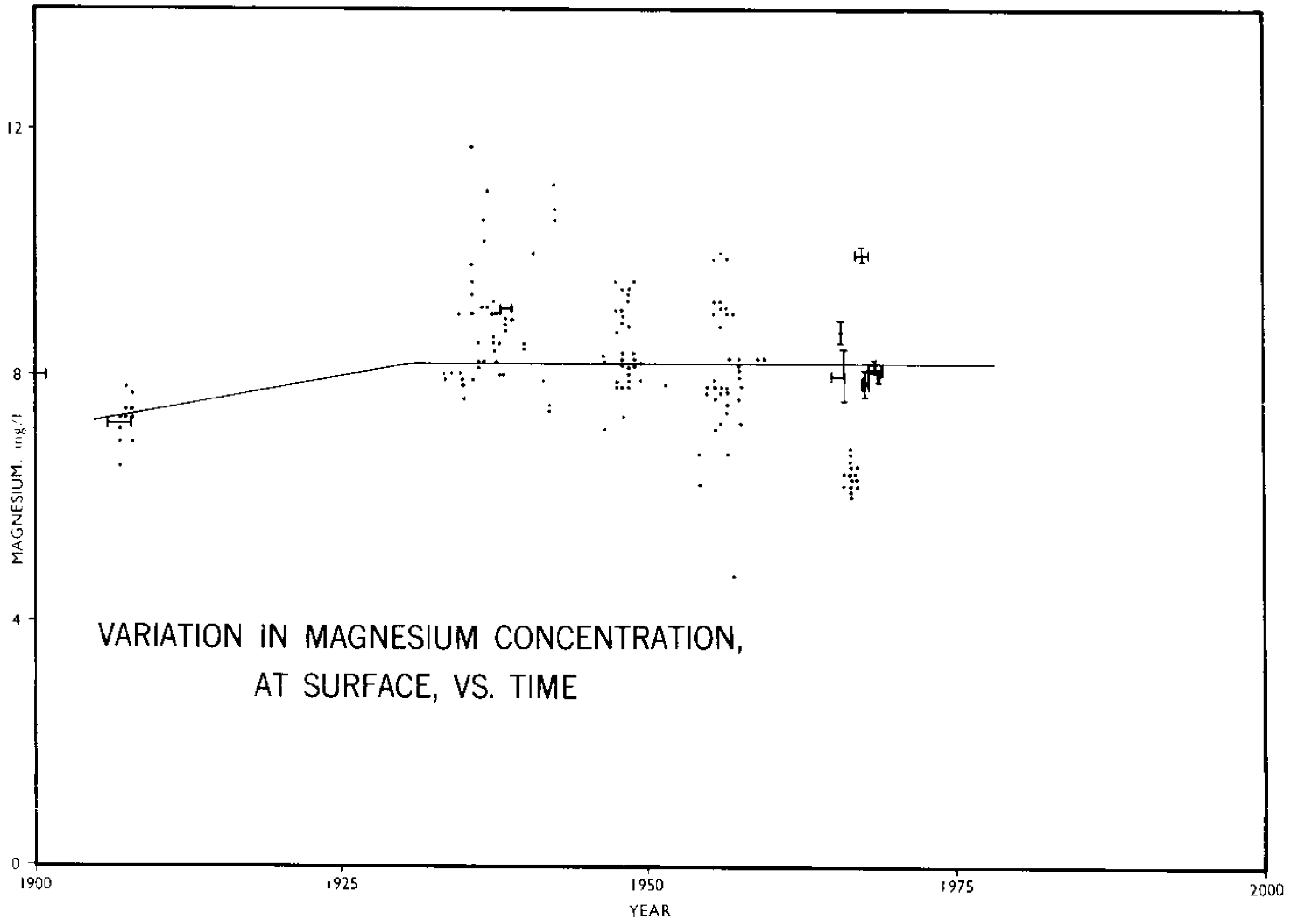
Bar graph of annual mean calcium ion concentrations (mg Ca/ℓ) at surface, 1906-1968

FIGURE 47



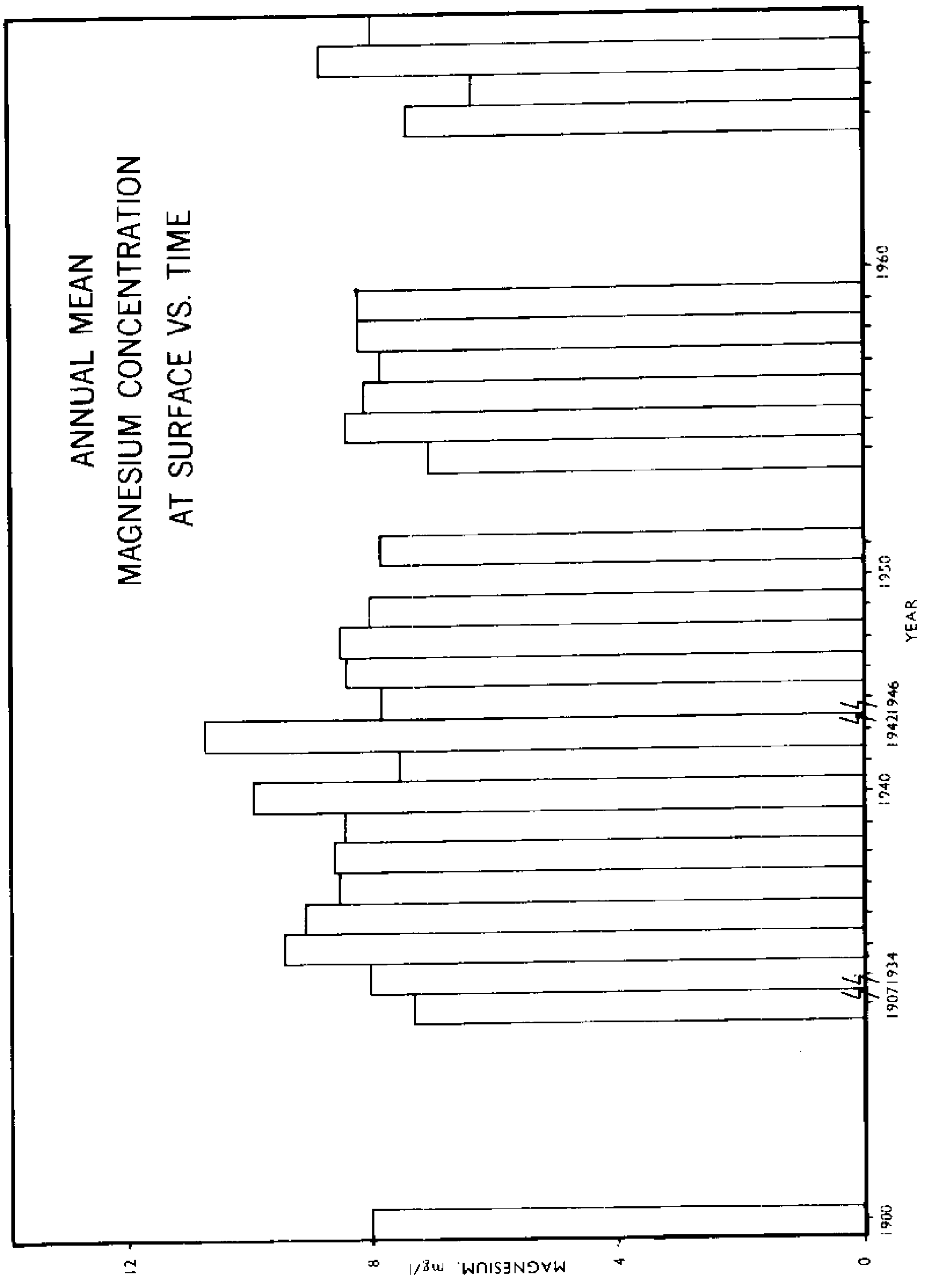
Surface distribution of calcium ions (mg Ca/ℓ), Fall 1964

FIGURE 48



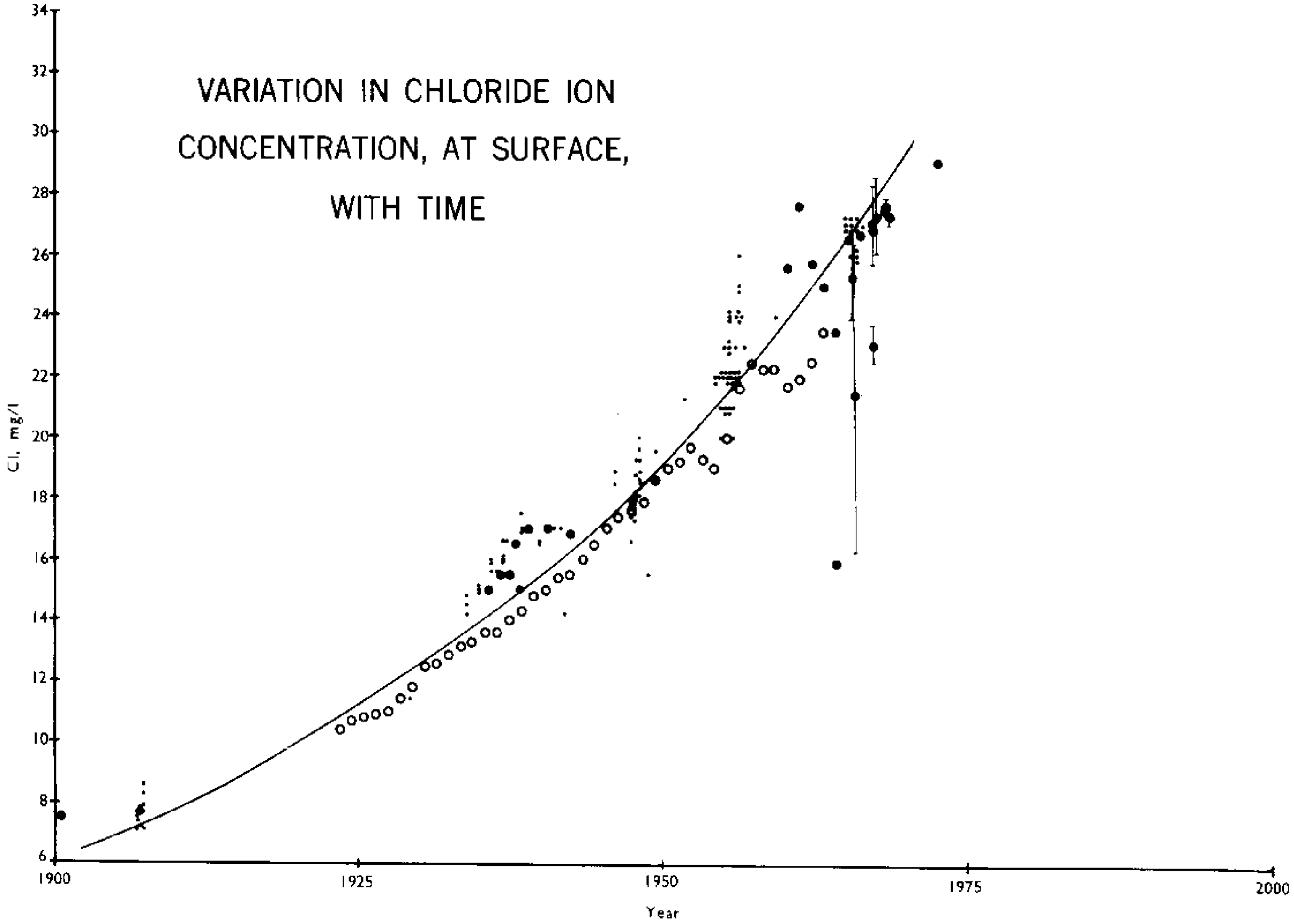
Variation in magnesium ion concentrations (mg Mg/ℓ) at surface with time, 1900-1968

FIGURE 49



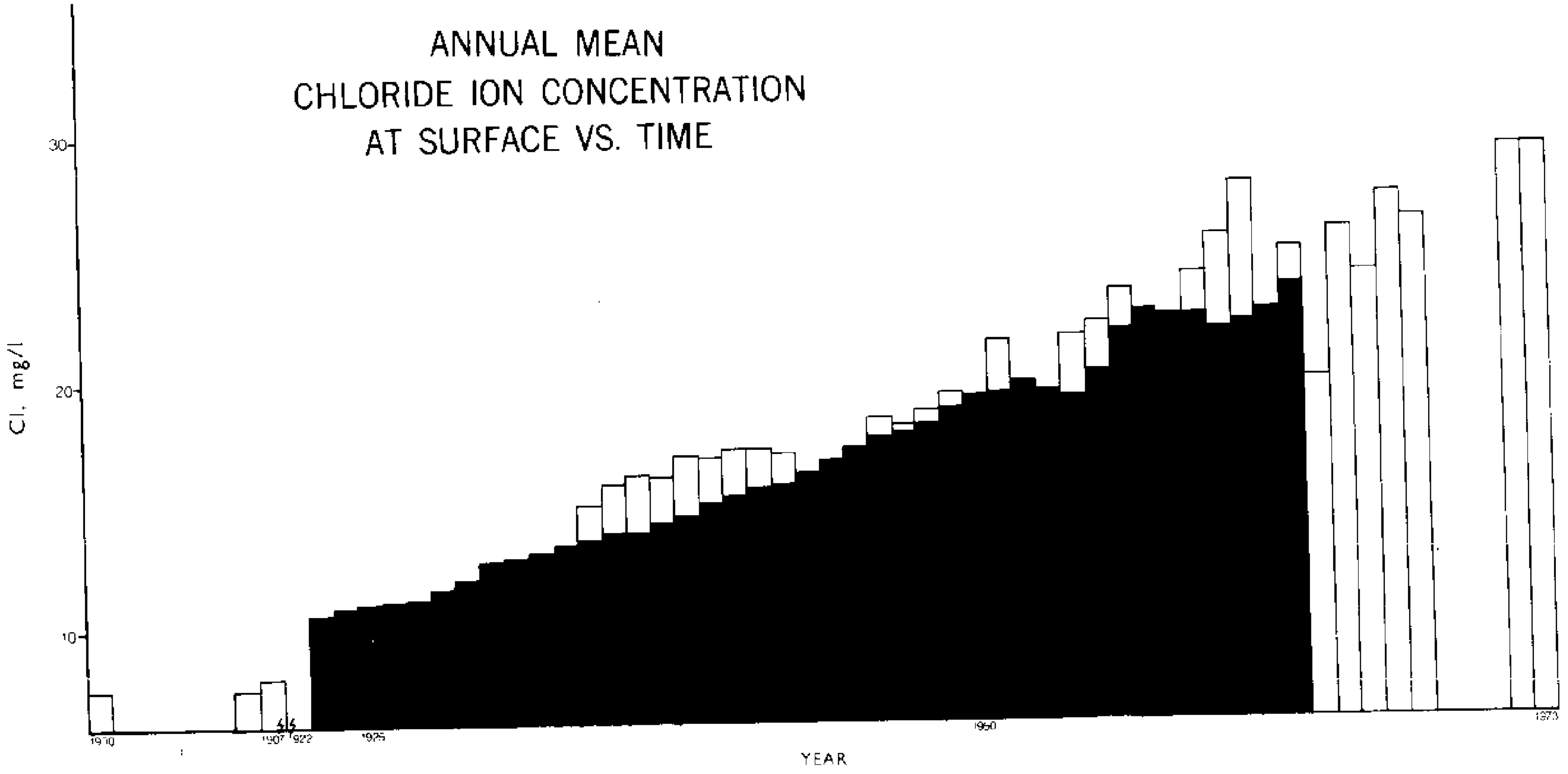
Bar graph of annual mean magnesium ion concentrations (mg Mg/ℓ) at surface, 1900-1968

FIGURE 50



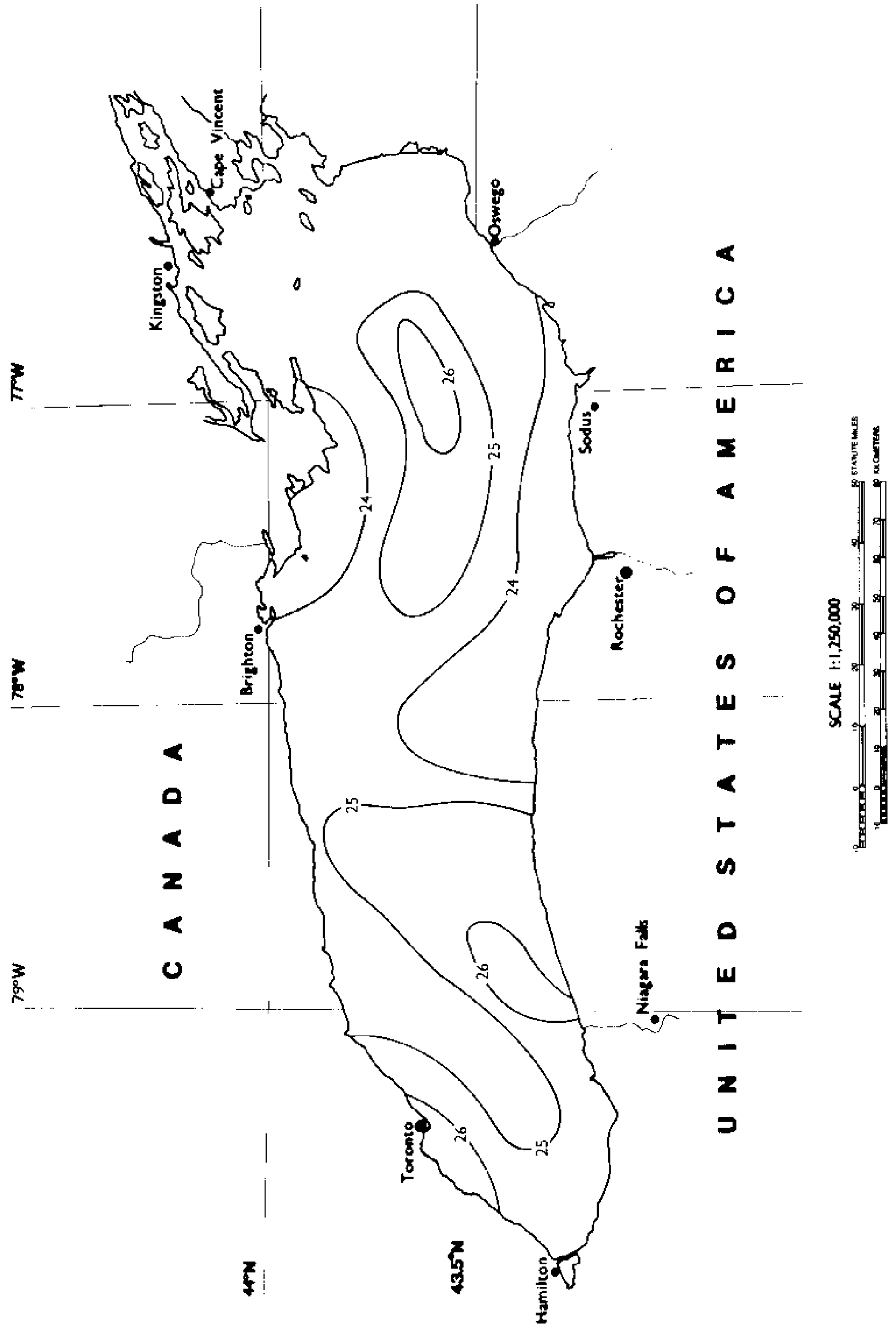
Variation in nearshore (open circles) and lakewide (filled circles) chloride ion concentrations (mg Cl/ℓ) at surface with time, 1900-1973

FIGURE 51



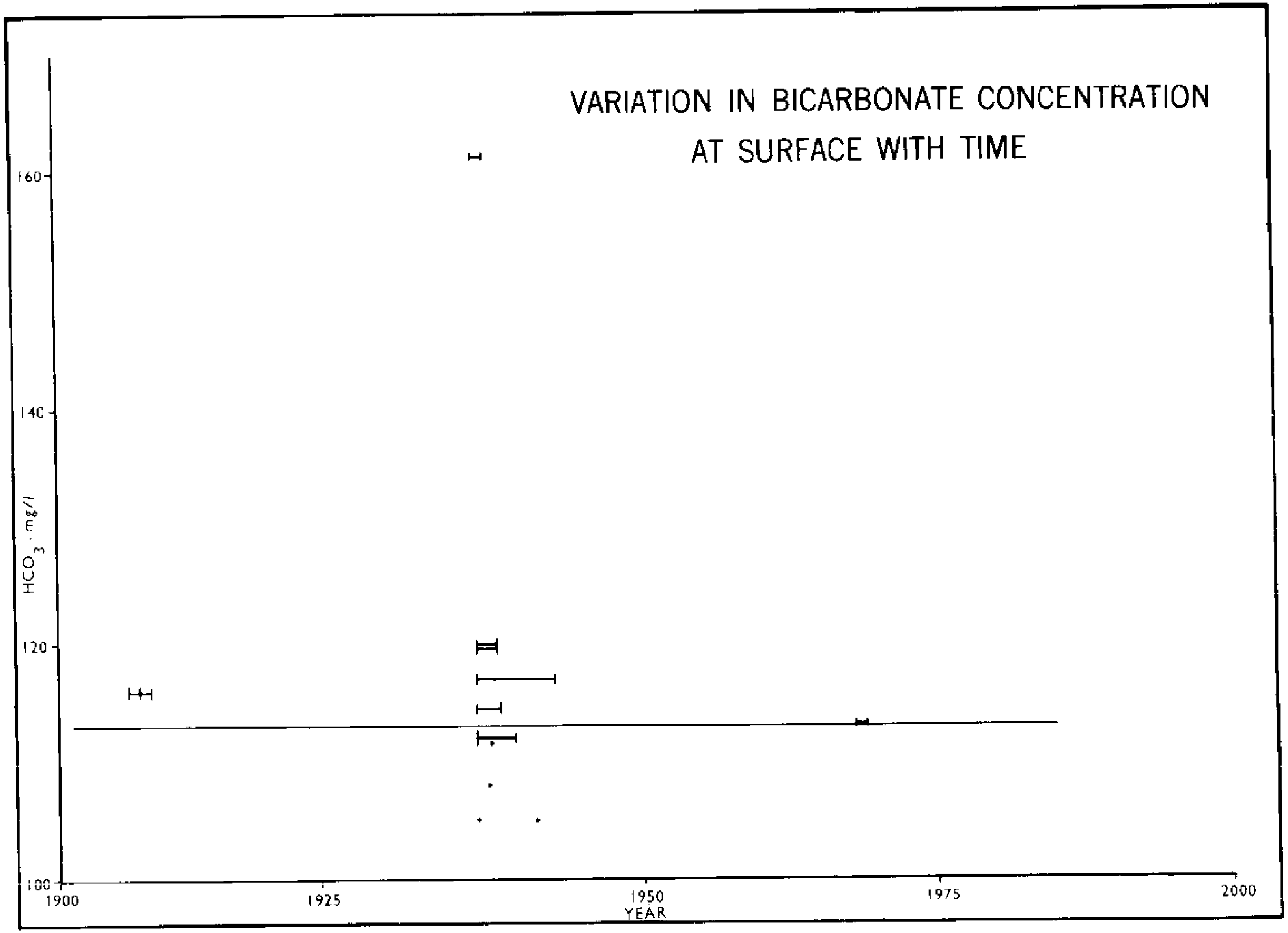
Bar graph of nearshore (filled bars) and lakewide (open bars) annual mean chloride ion concentrations (mg Cl/ℓ) at surface, 1900-1973

FIGURE 52



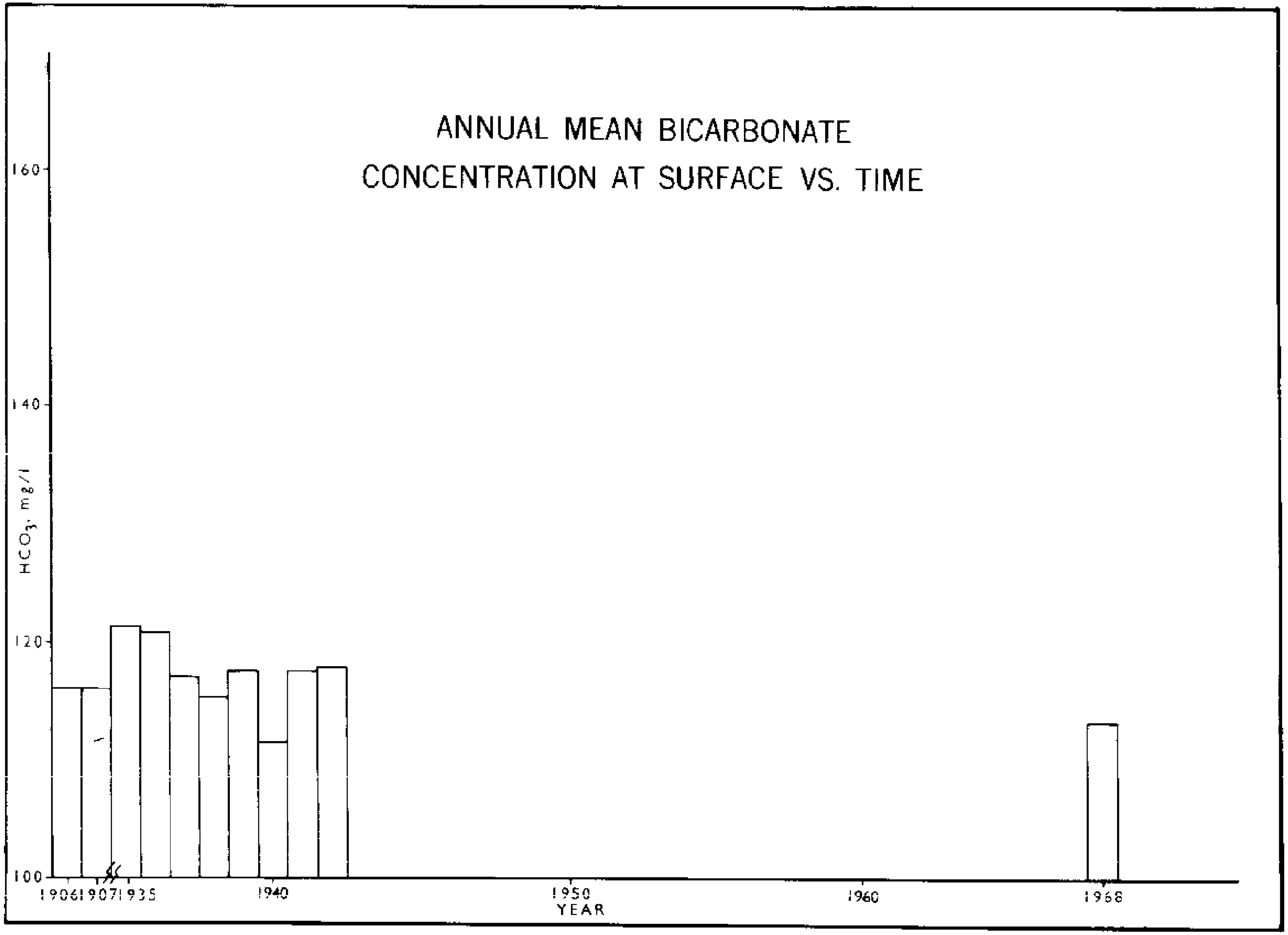
Surface distribution of chloride ions (mg Cl/ℓ), Summer 1965

FIGURE 53



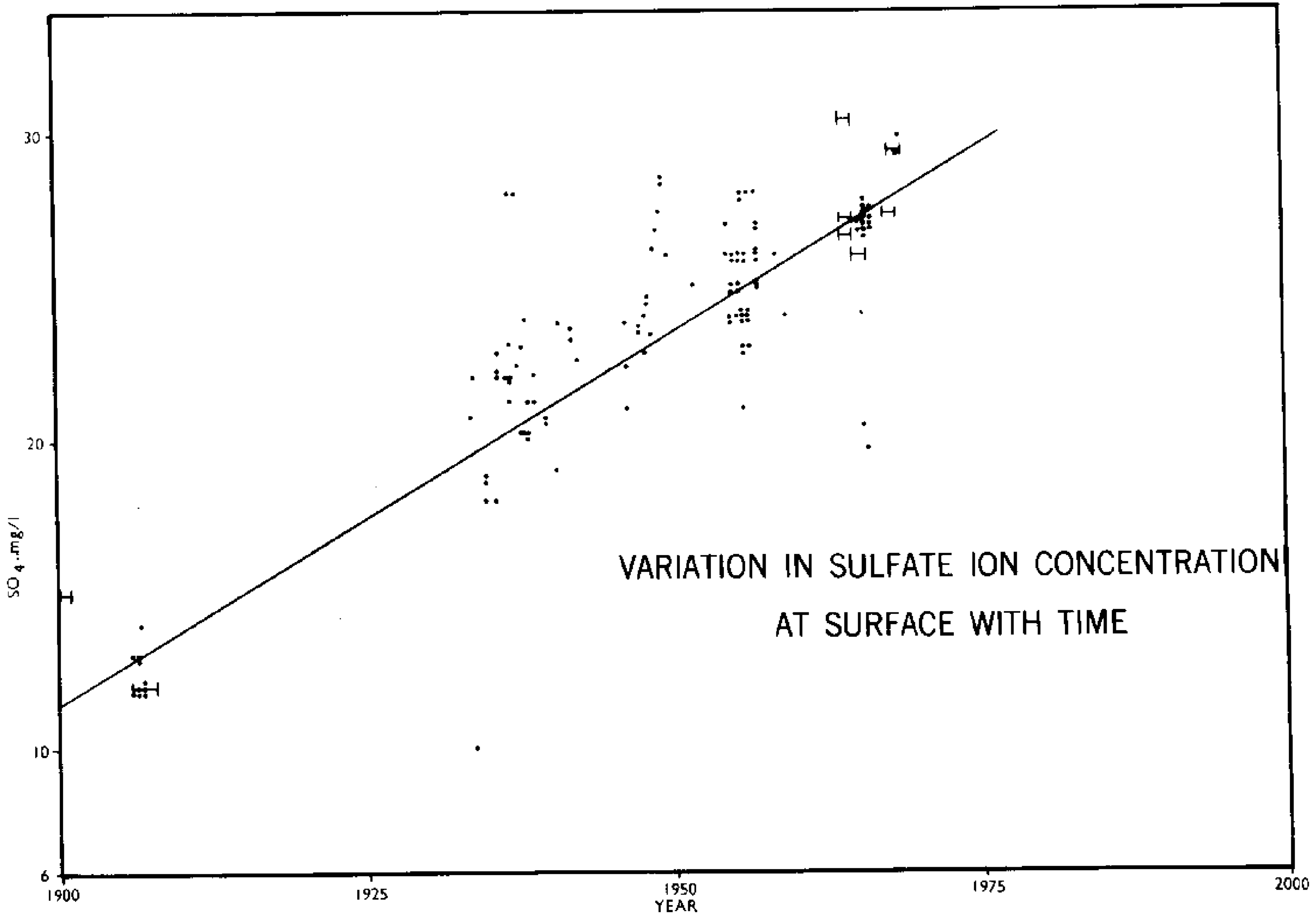
Variation in bicarbonate ion concentrations (mg $HCO_3/\ell$) at surface with time, 1906-1968

FIGURE 54



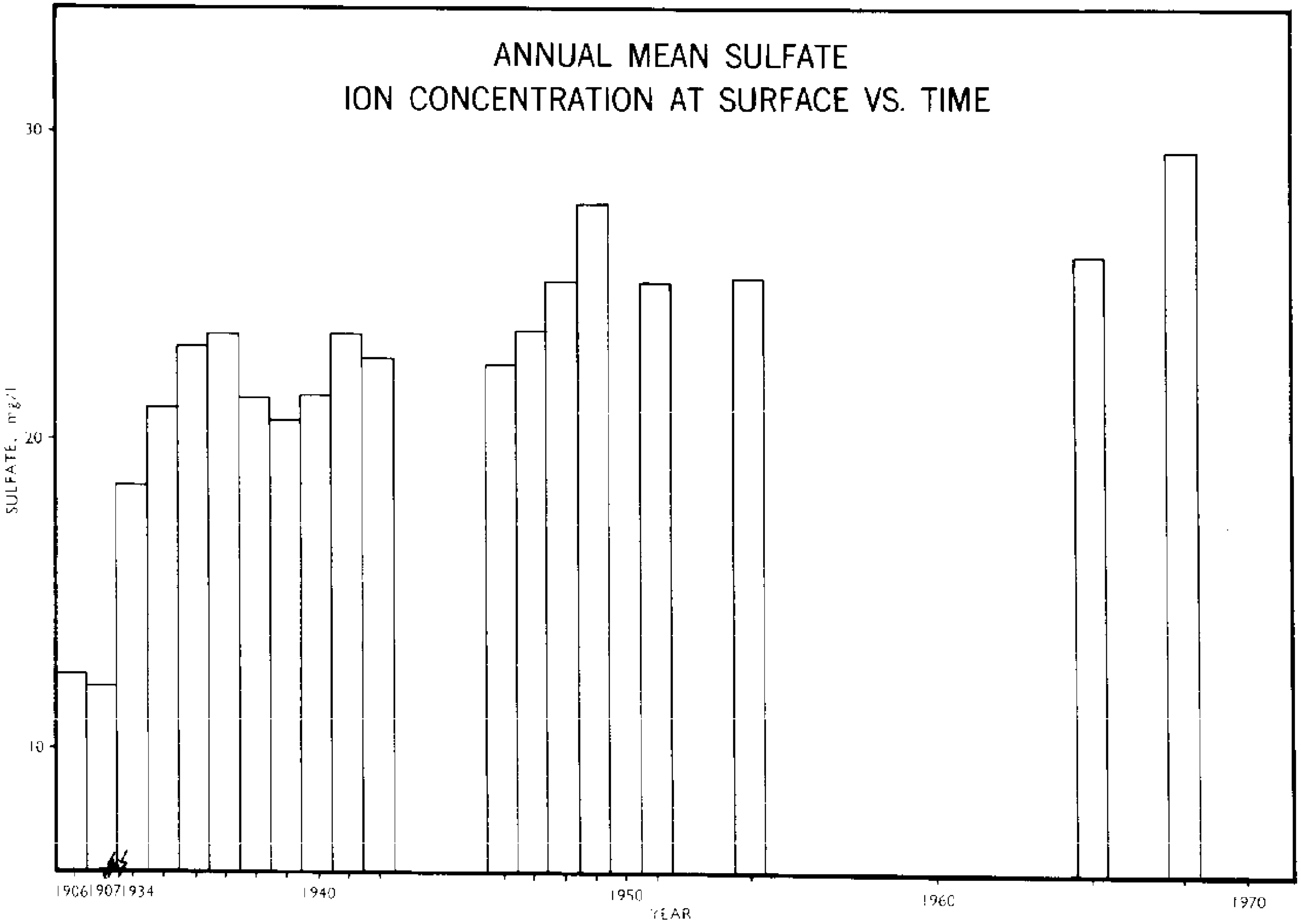
Bar graph of annual mean bicarbonate ion concentrations ($mg\ HCO_3/\ell$) at surface, 1906-1968

FIGURE 55



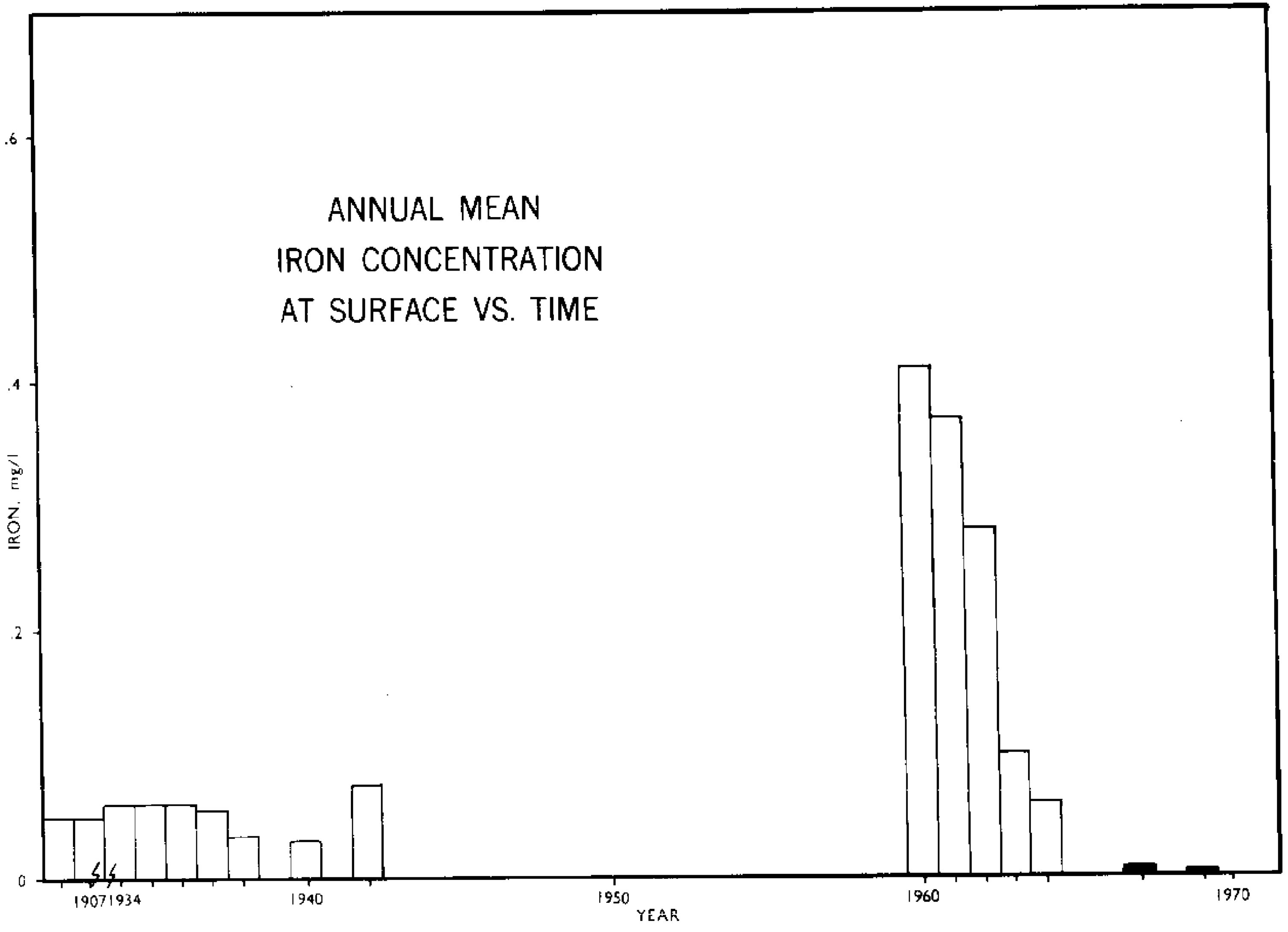
Variation in sulfate ion concentrations (mg $SO_4/\ell$) at surface with time, 1906-1968

FIGURE 56



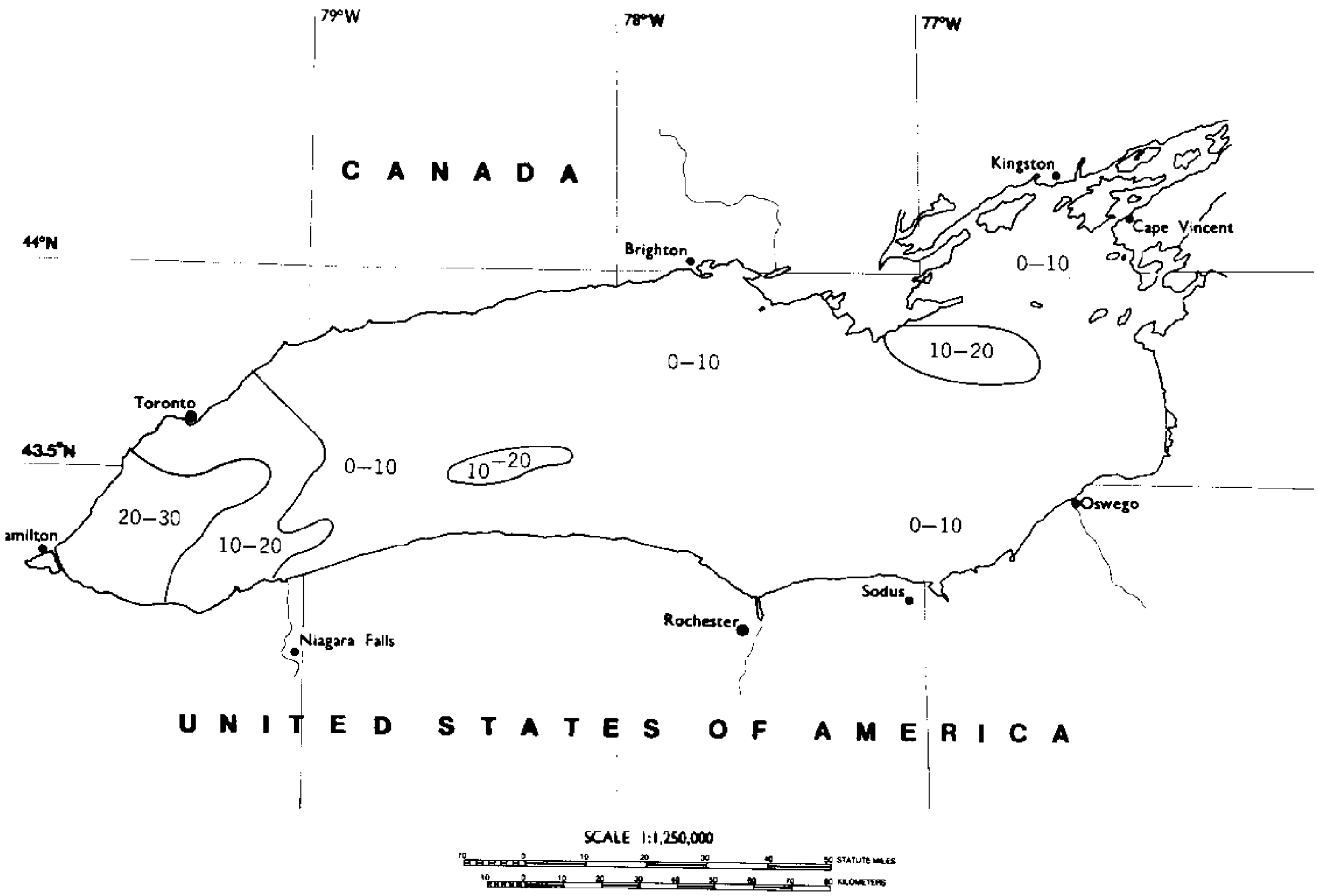
Bar graph of annual mean sulfate ion concentrations (mg $SO_4/\ell$) at surface, 1906-1968

FIGURE 57



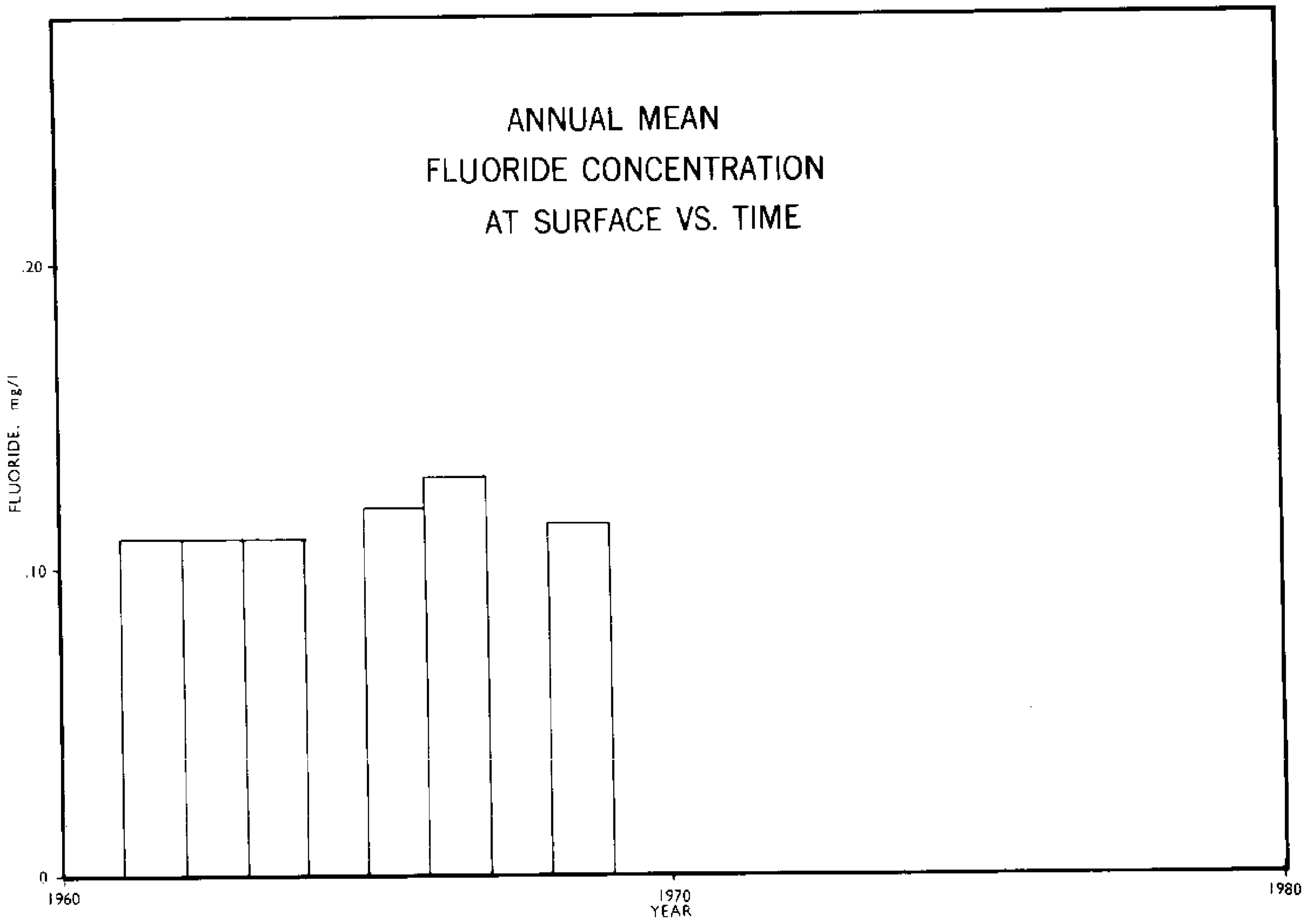
Bar graph of annual mean total-iron concentrations (mg Fe/ℓ) at surface, 1906-1964. Values for 1967 and 1969 (filled bars) correspond to biologically-available iron only.

FIGURE 58



Surface distribution of biologically-available iron (μg Fe/ℓ), Spring 1967

FIGURE 59

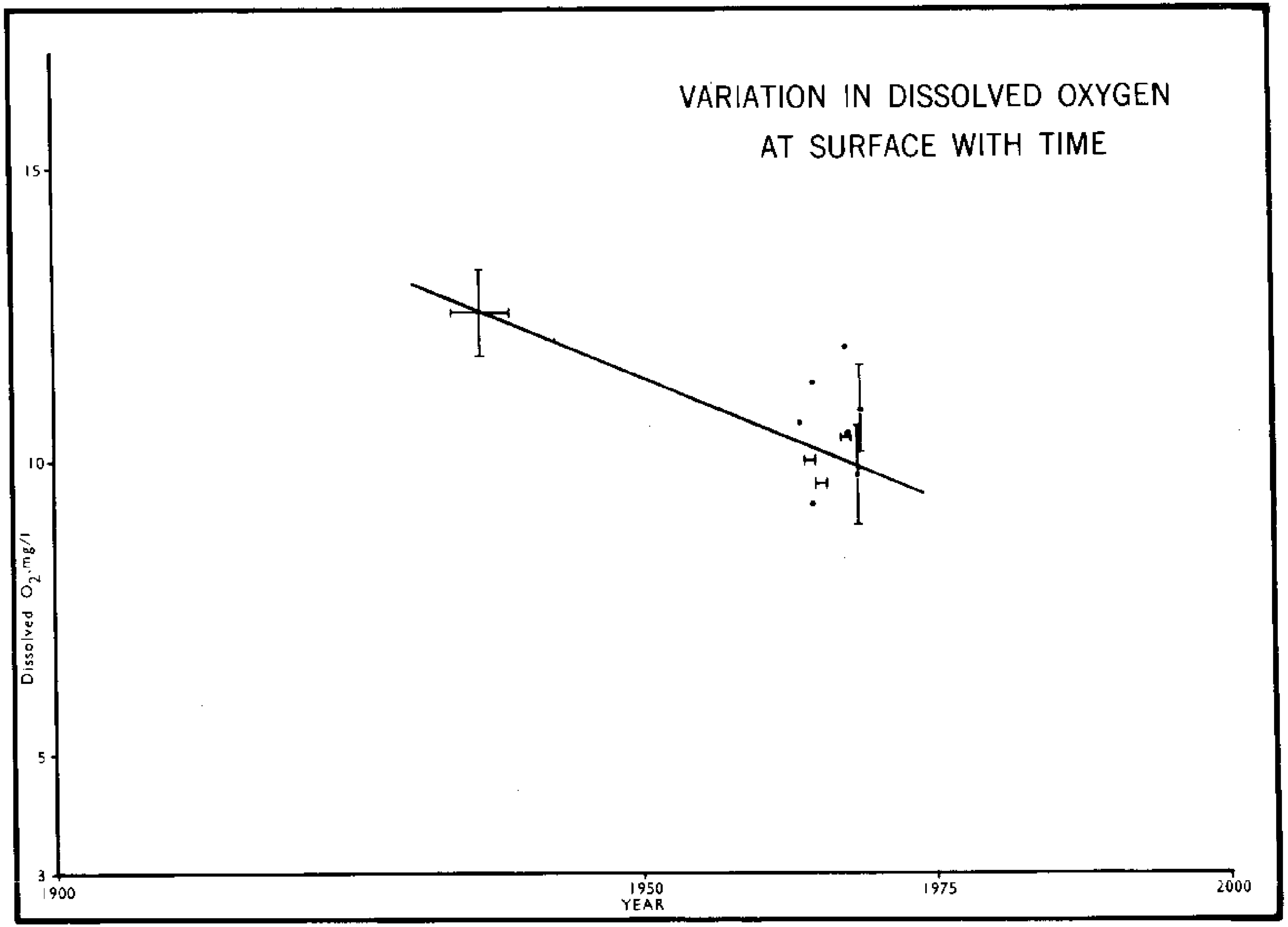


Bar graph of annual mean fluoride concentrations (mg F/ℓ) at surface, 1961-1968

FIGURE 60

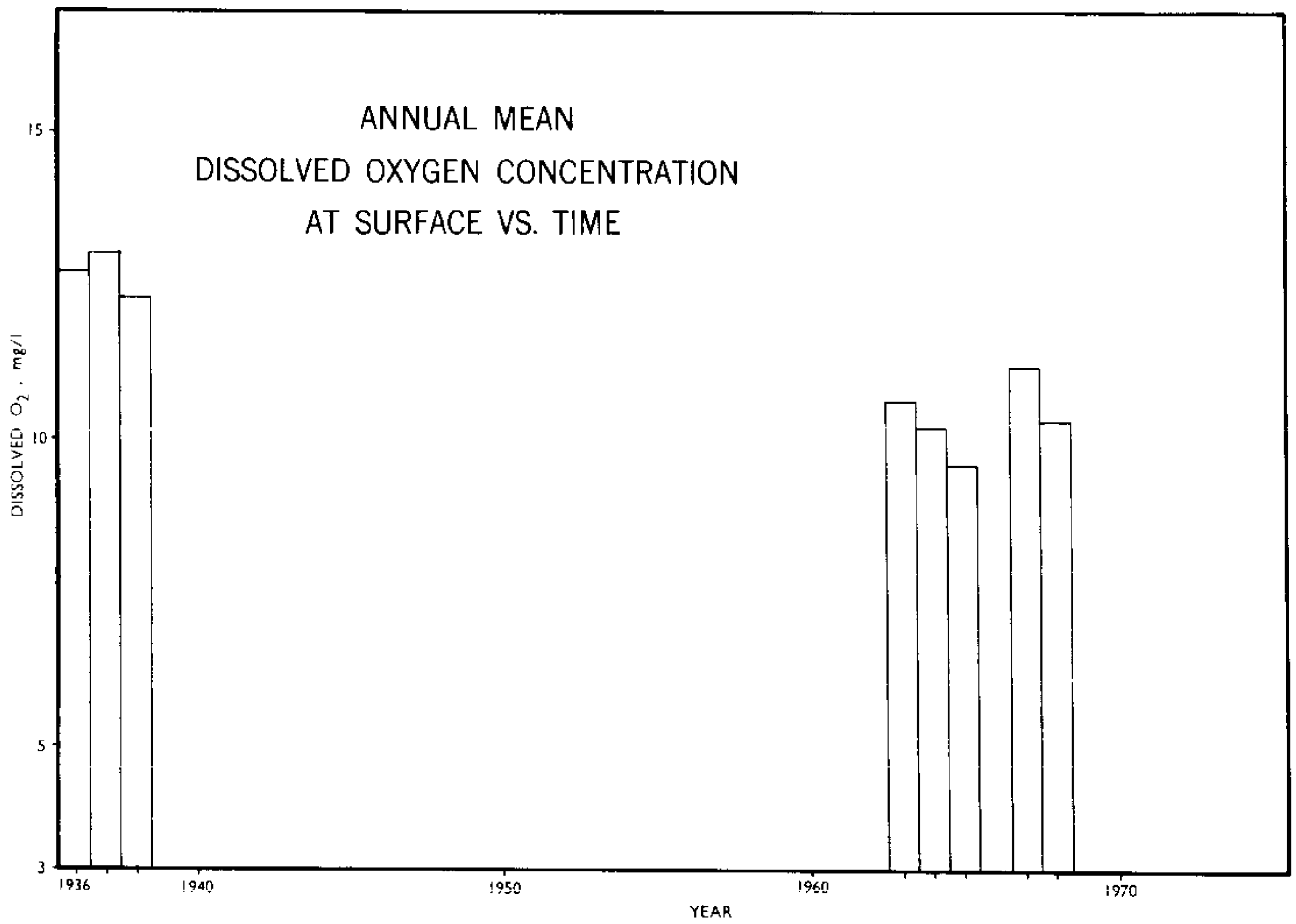
Surface distribution of total-mercury (μg Hg/ℓ), 1970-71

FIGURE 61



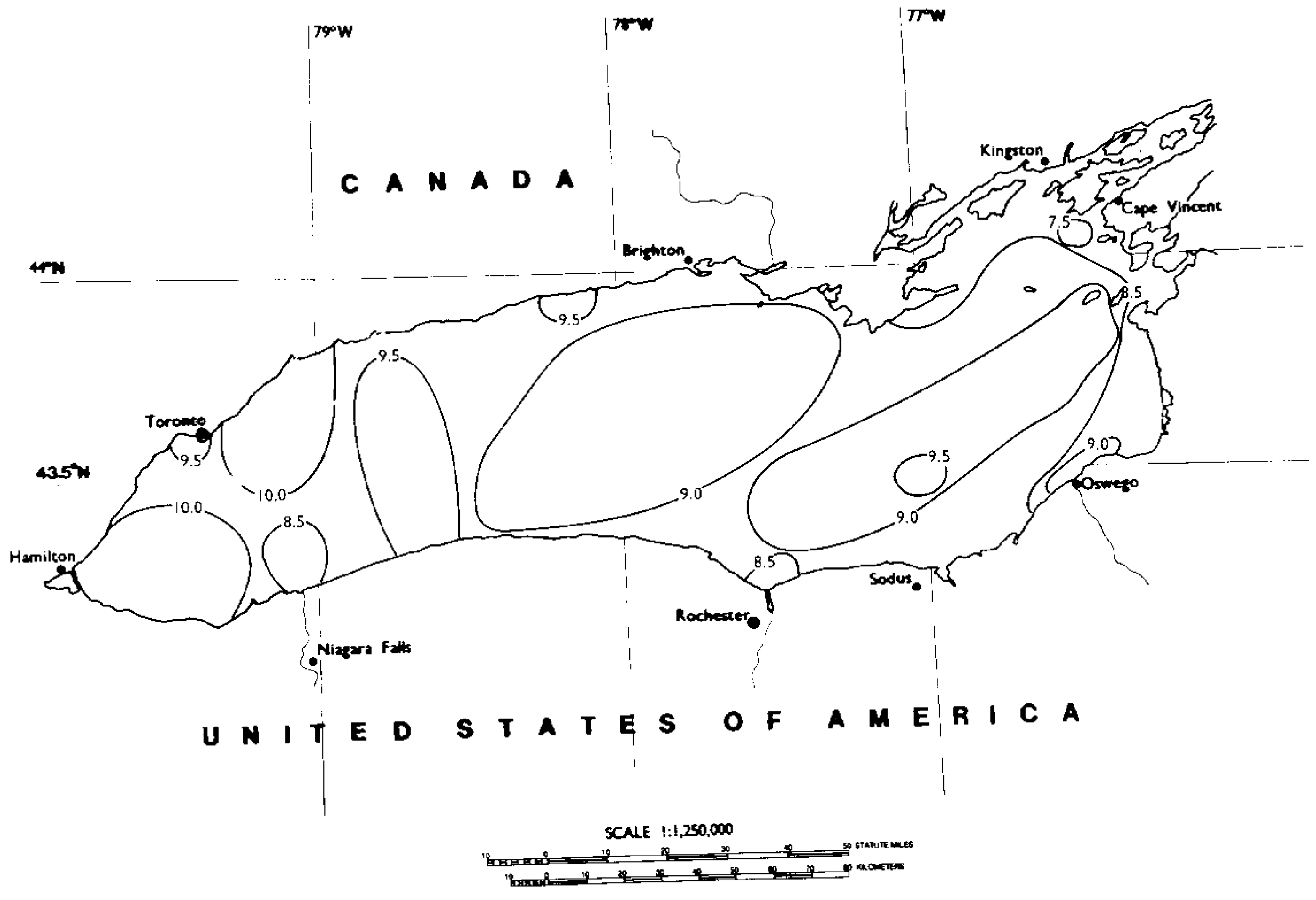
Variation in dissolved oxygen concentrations (mg $O_2/\ell$) at surface with time, 1936-1968

FIGURE 62



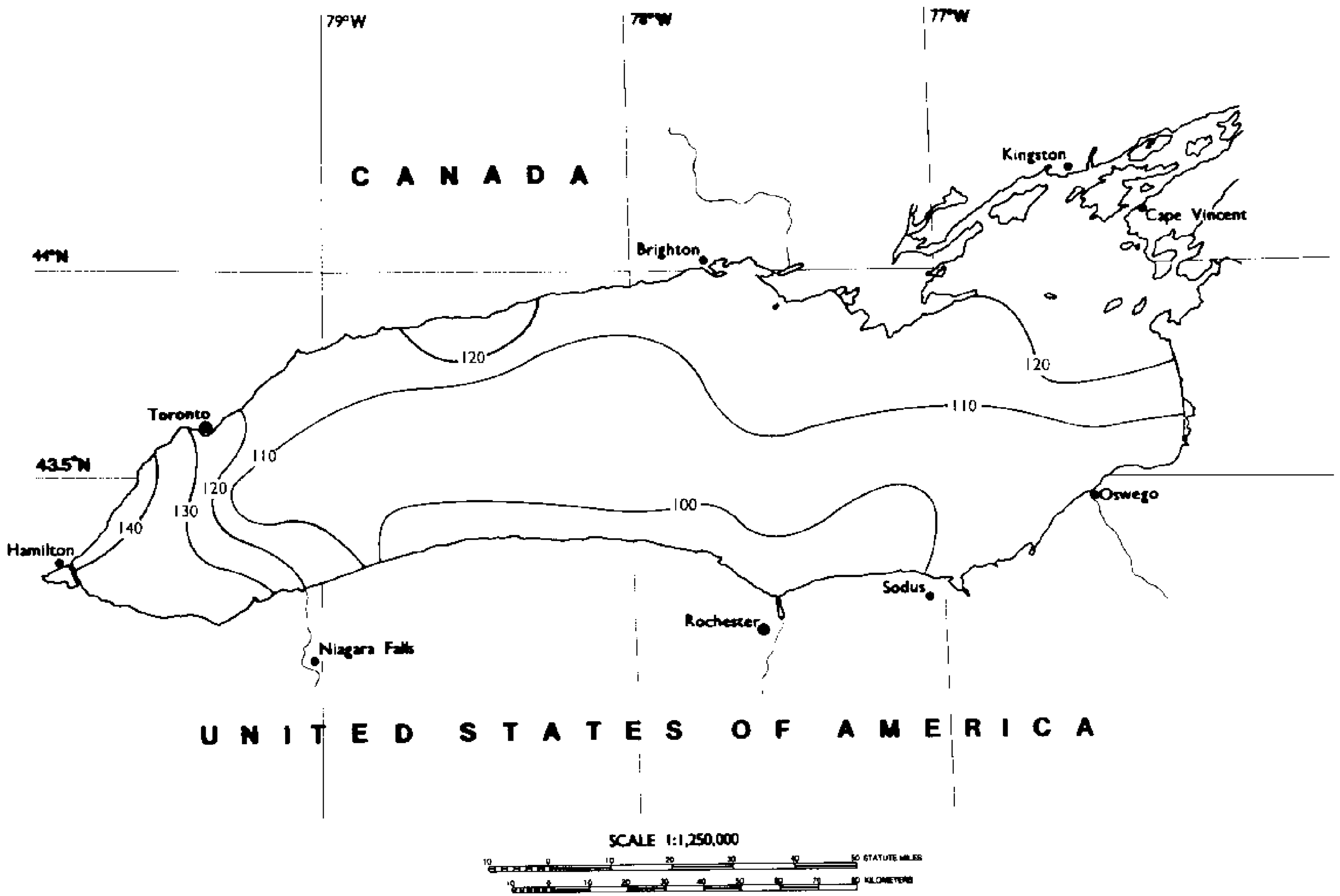
Bar graph of annual mean dissolved oxygen concentrations ($mg\ O_2/\ell$) at surface, 1936–1968

FIGURE 63



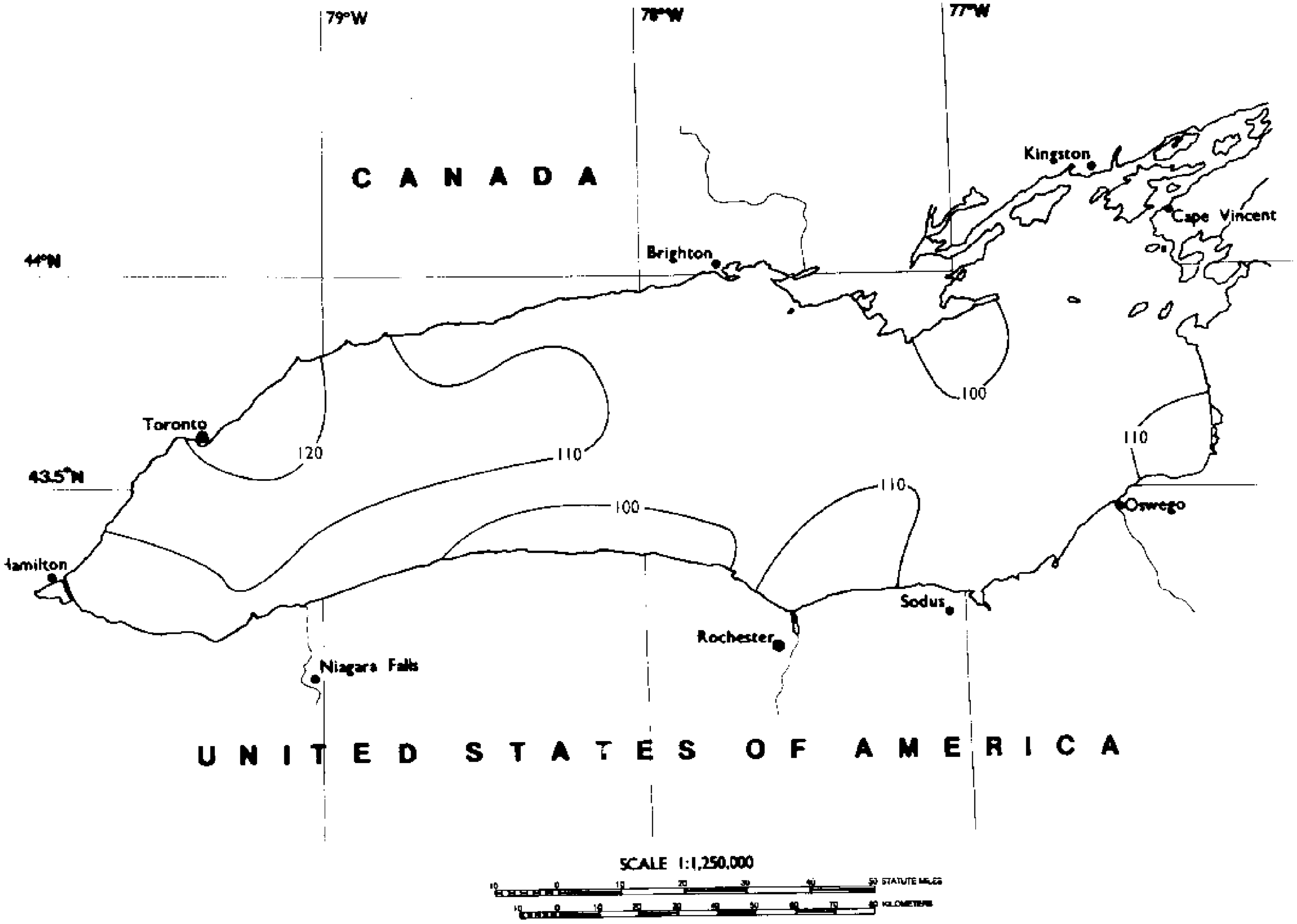
Surface distribution of dissolved oxygen concentrations (mg $O_2/\ell$), Fall 1964

FIGURE 64



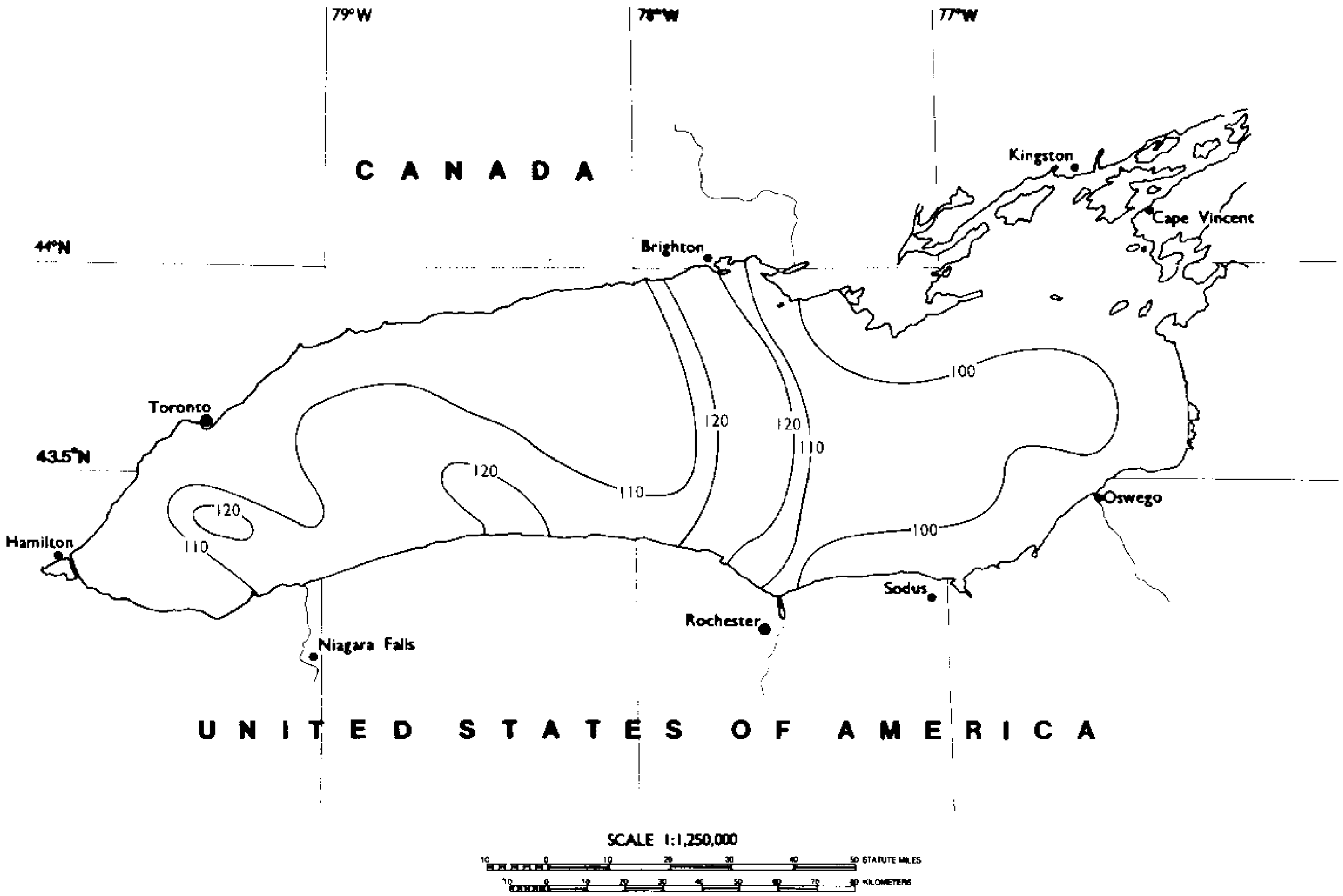
Surface distribution of dissolved oxygen, percent saturation, Spring 1965

FIGURE 65



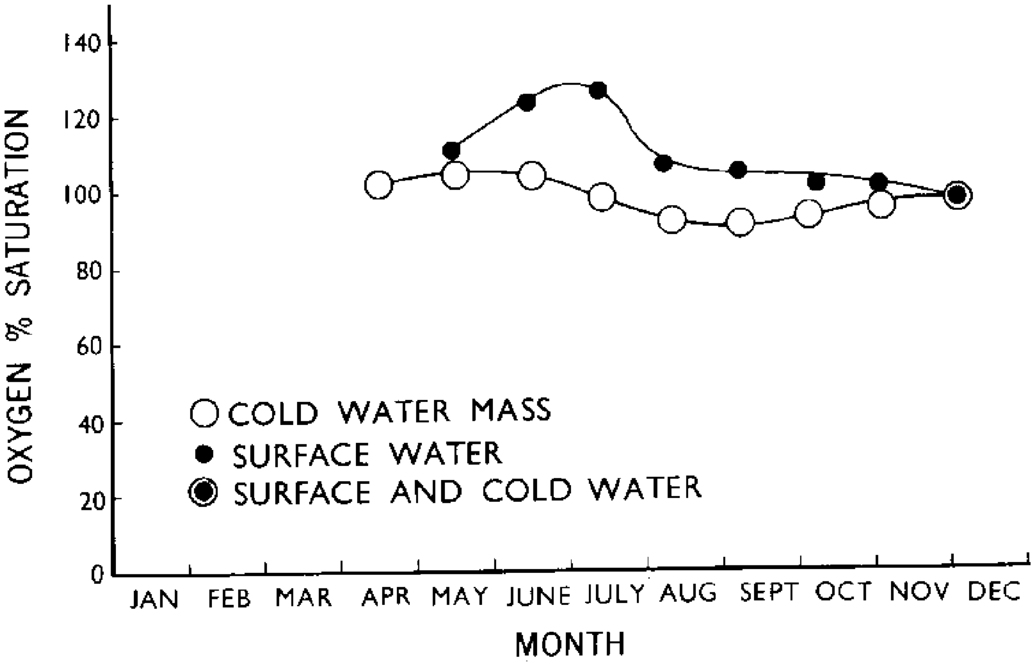
Surface distribution of dissolved oxygen, percent saturation, Summer 1965

FIGURE 66



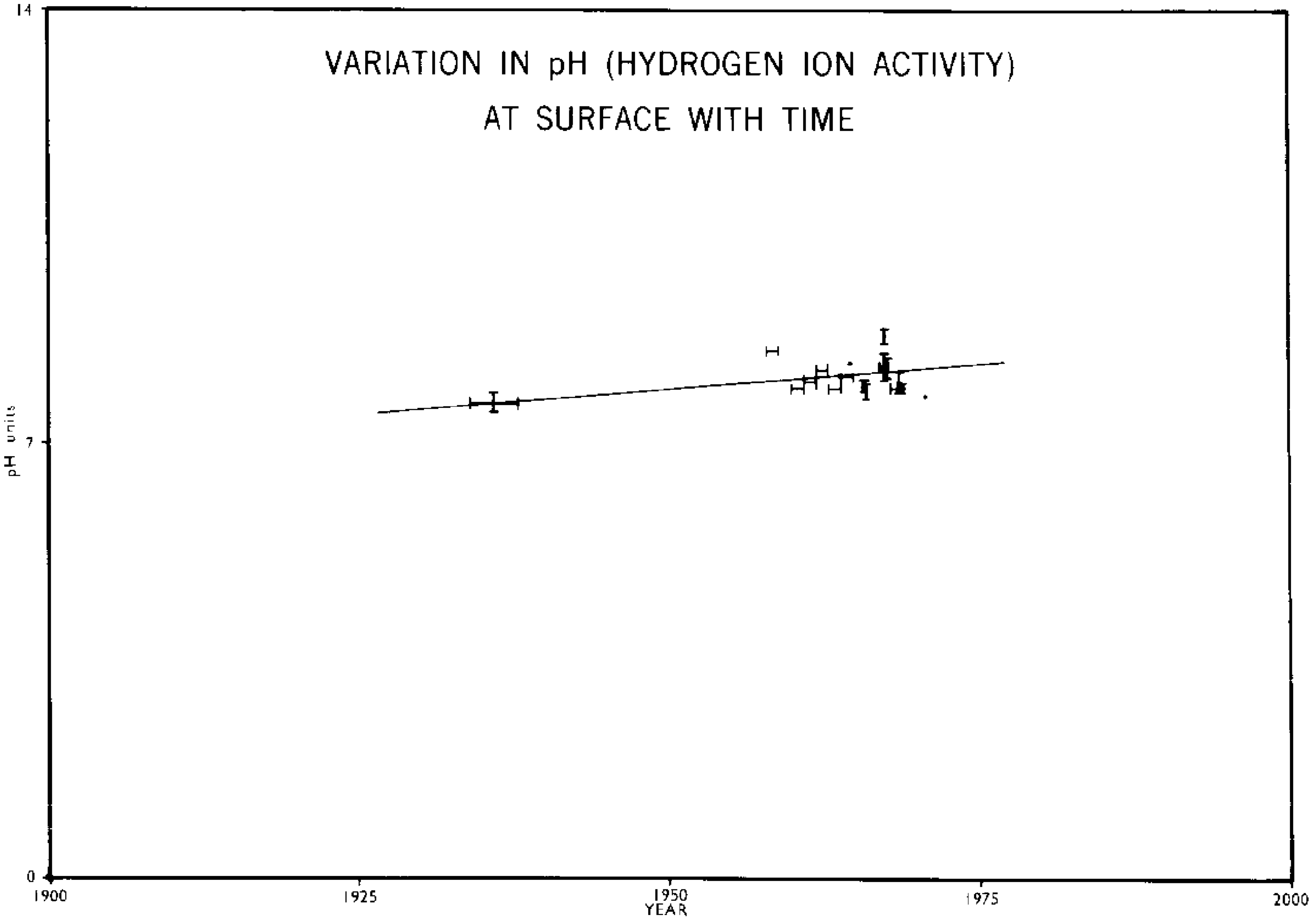
Surface distribution of dissolved oxygen, percent saturation, Fall 1965

FIGURE 67



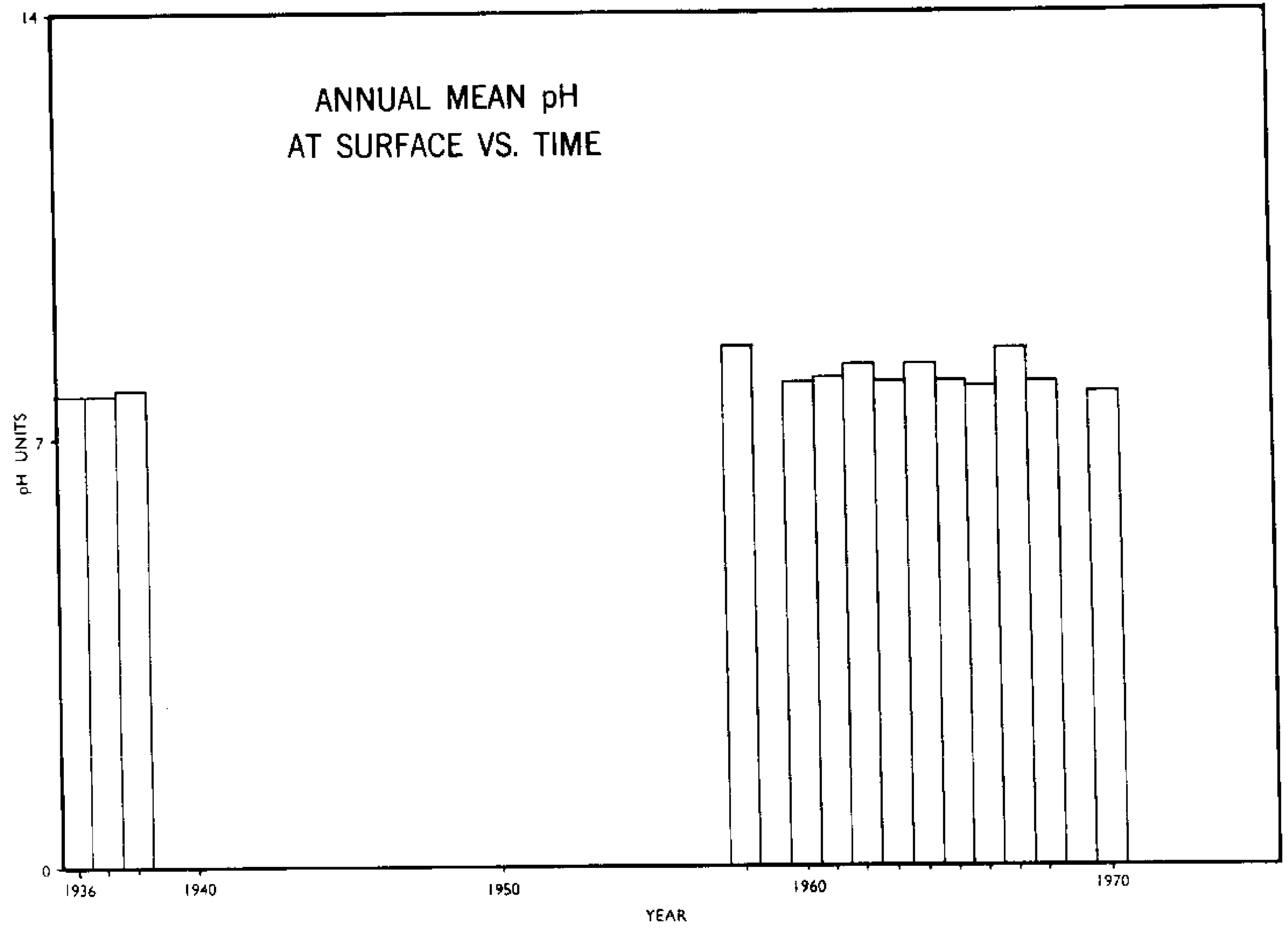
Seasonal variations of dissolved oxygen, percent saturation, in the epilimnion (filled circles) and the hypolimnion (open circles)

FIGURE 68



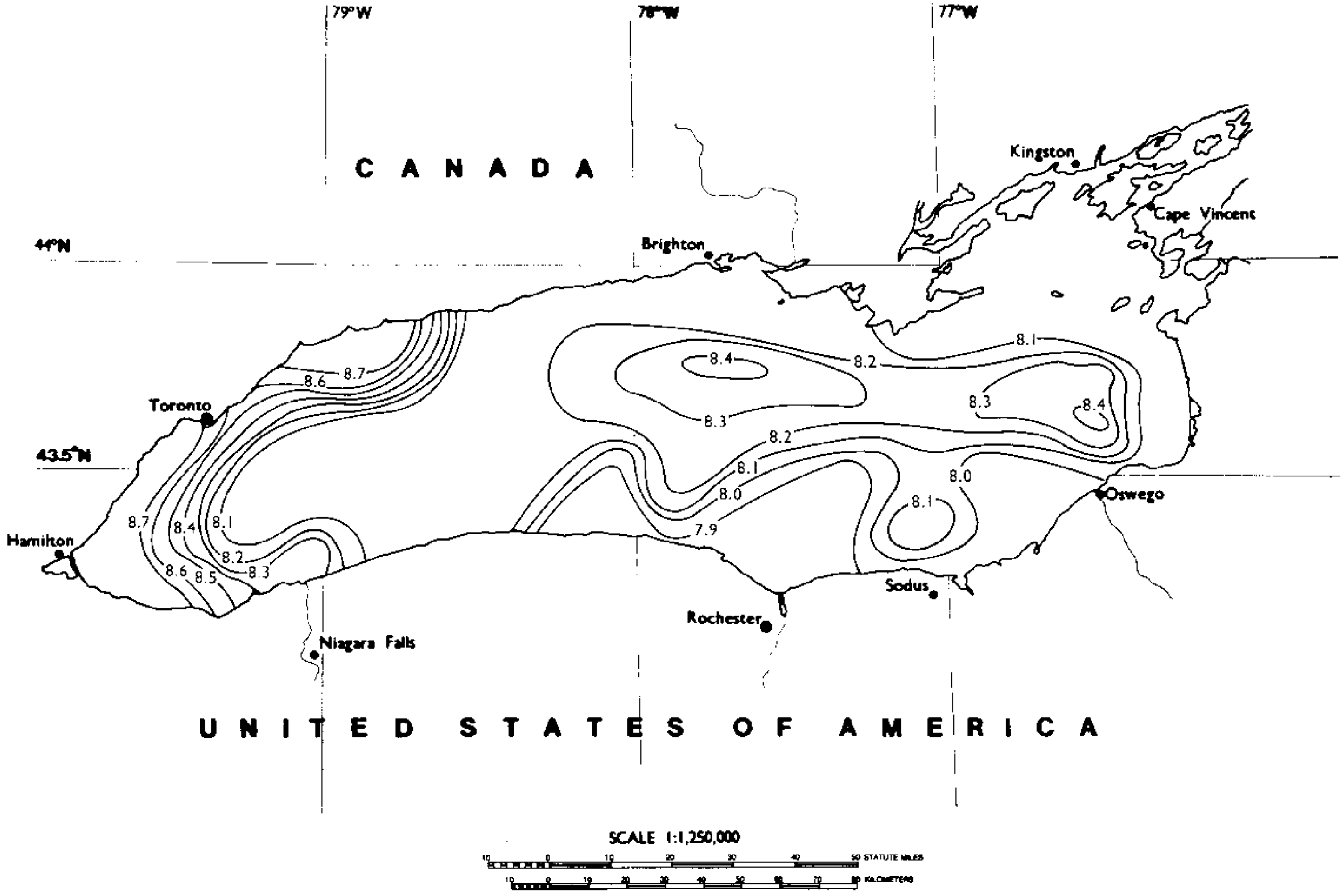
Variation in pH at surface with time, 1936-1970

FIGURE 69



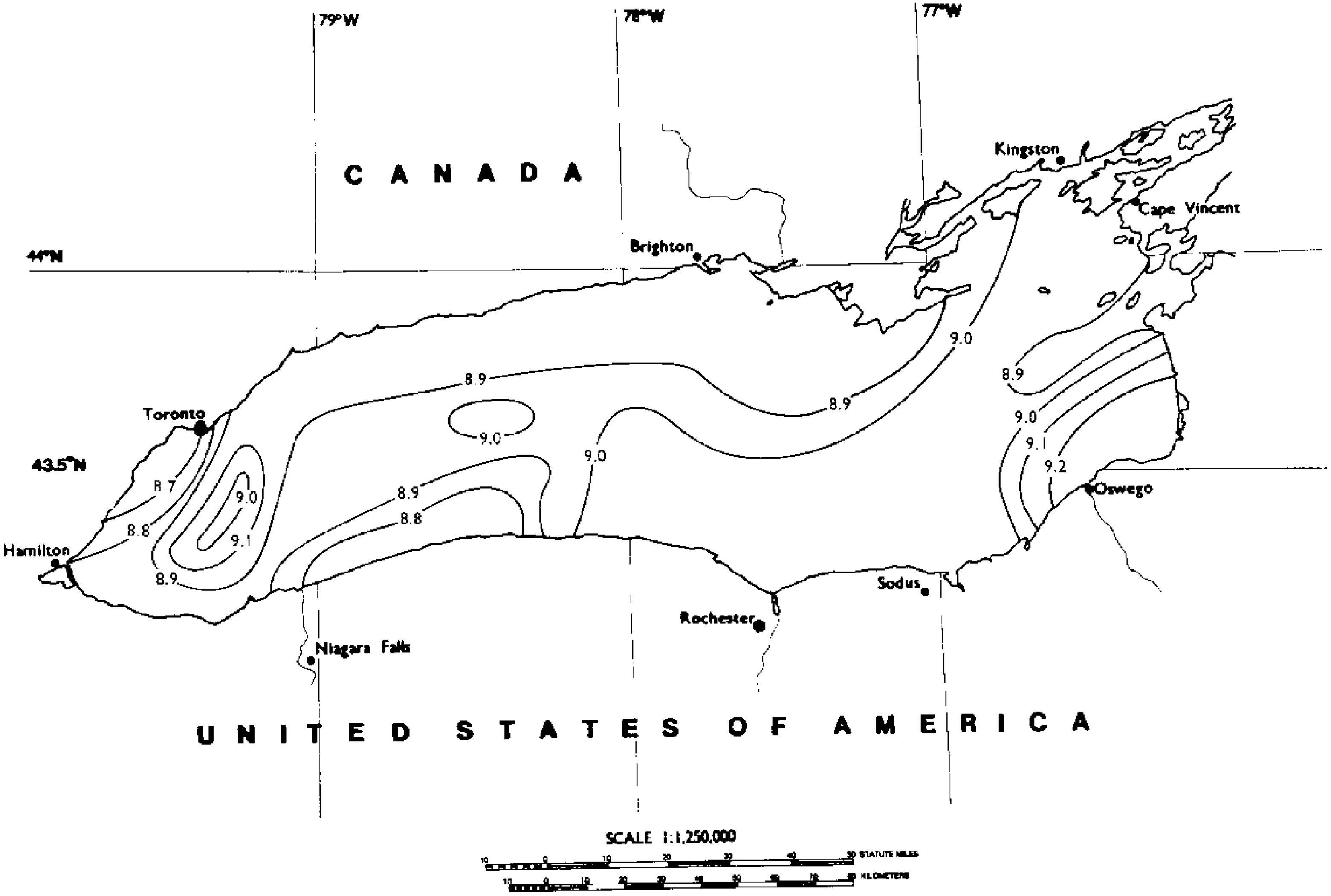
Bar graph of annual mean pH at surface, 1936-1970

FIGURE 70



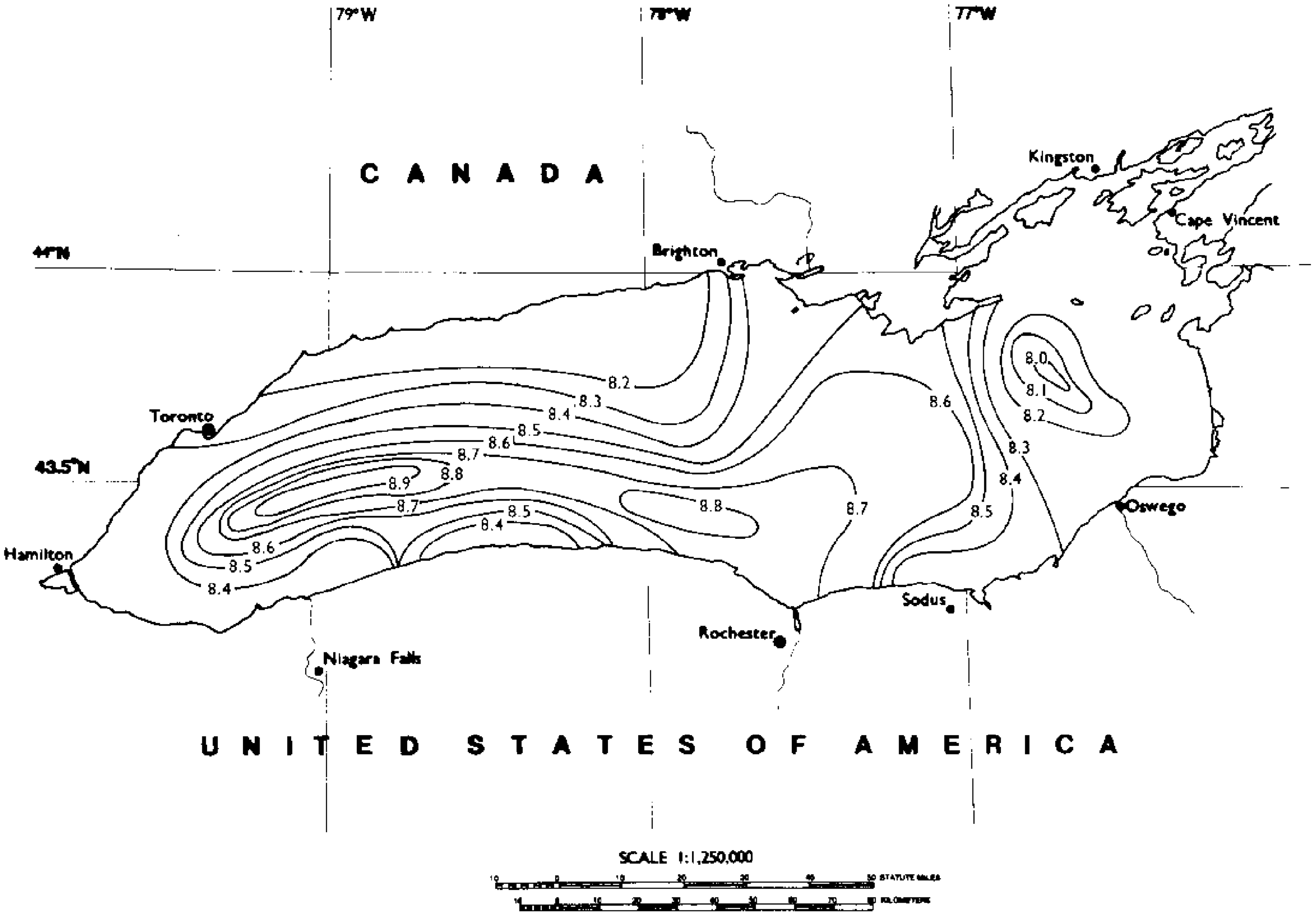
Surface distribution of pH, Spring 1965

FIGURE 71



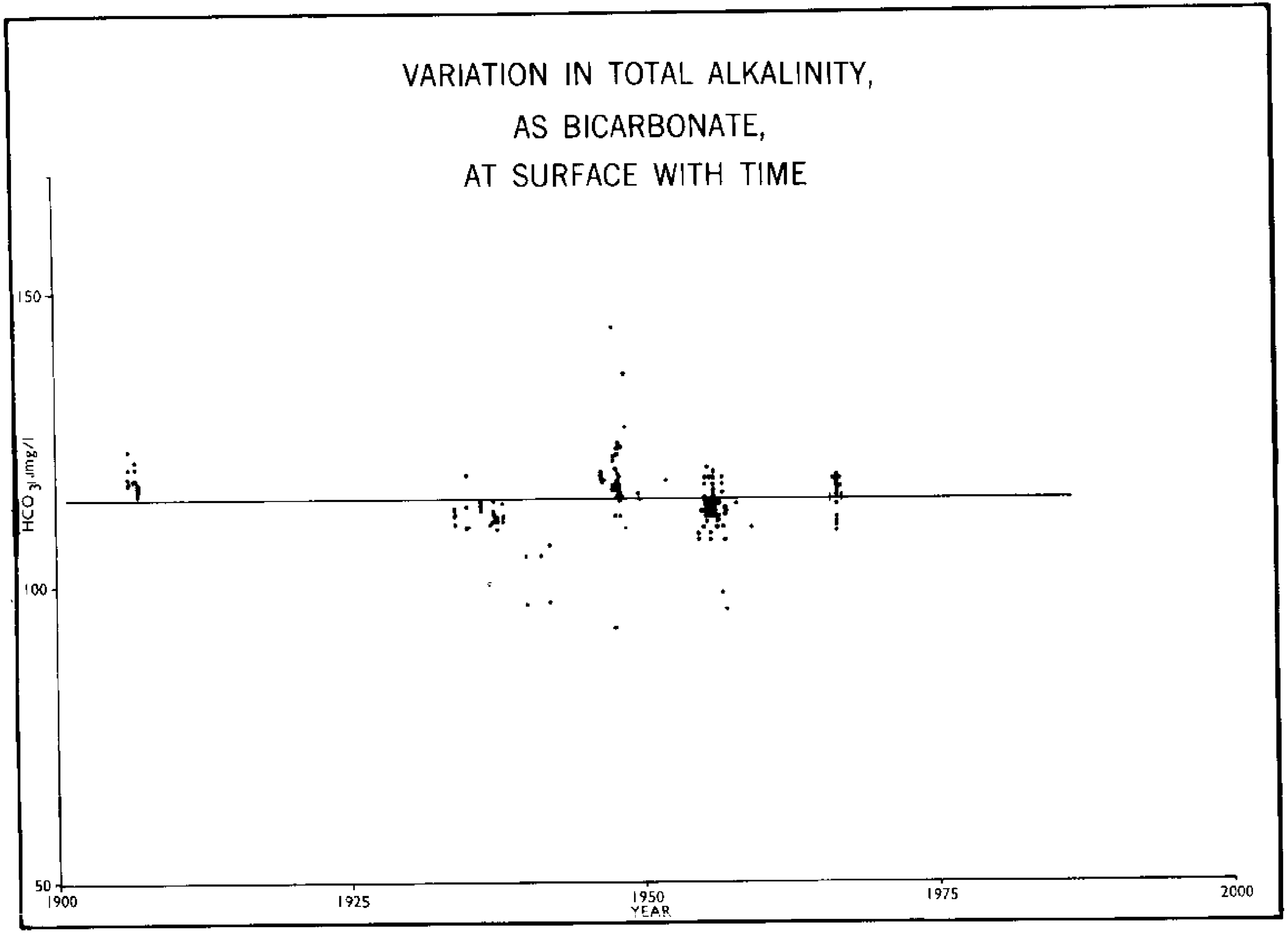
Surface distribution of pH, Summer 1965

FIGURE 72



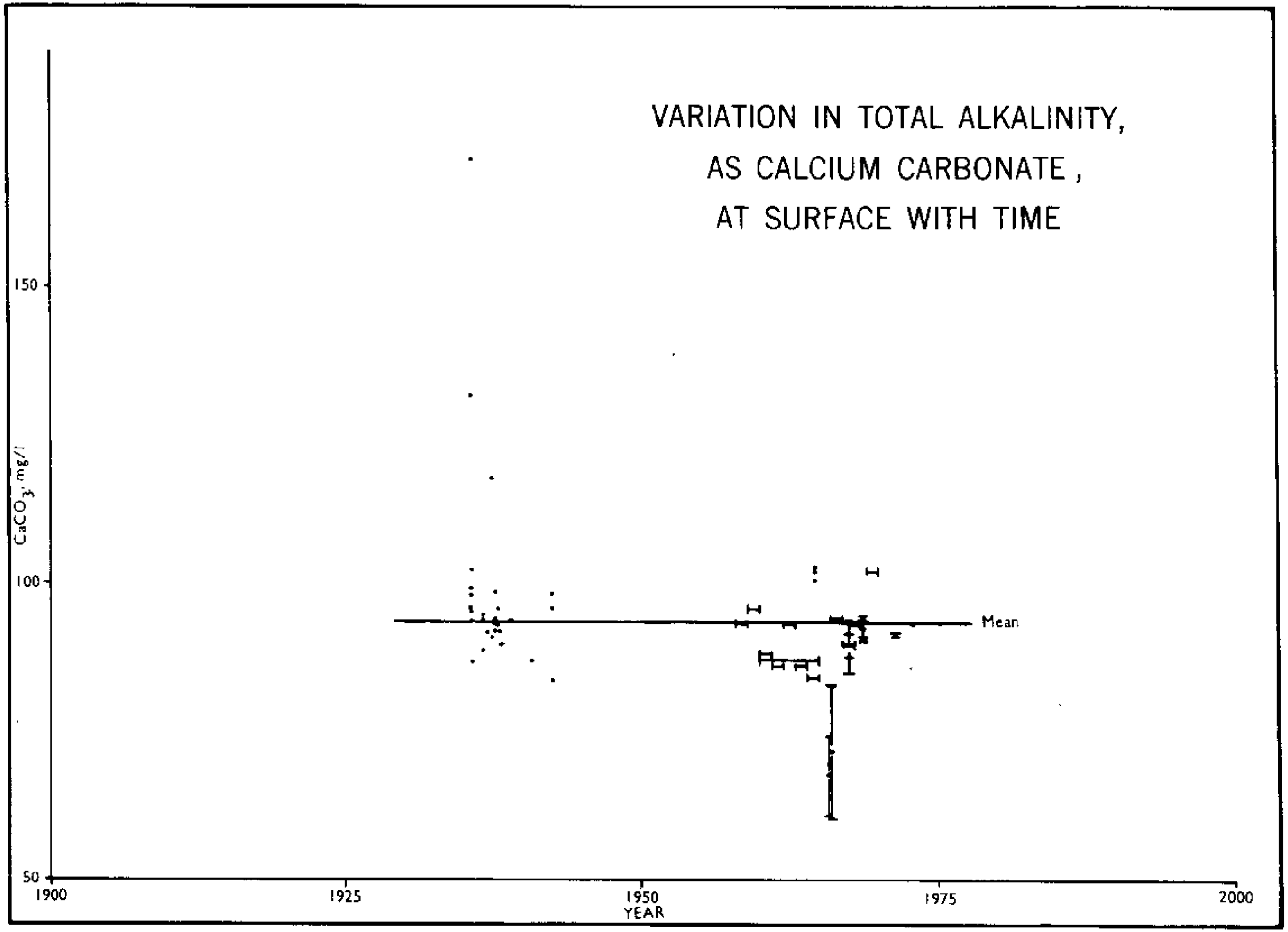
Surface distribution of pH, Fall 1965

FIGURE 73



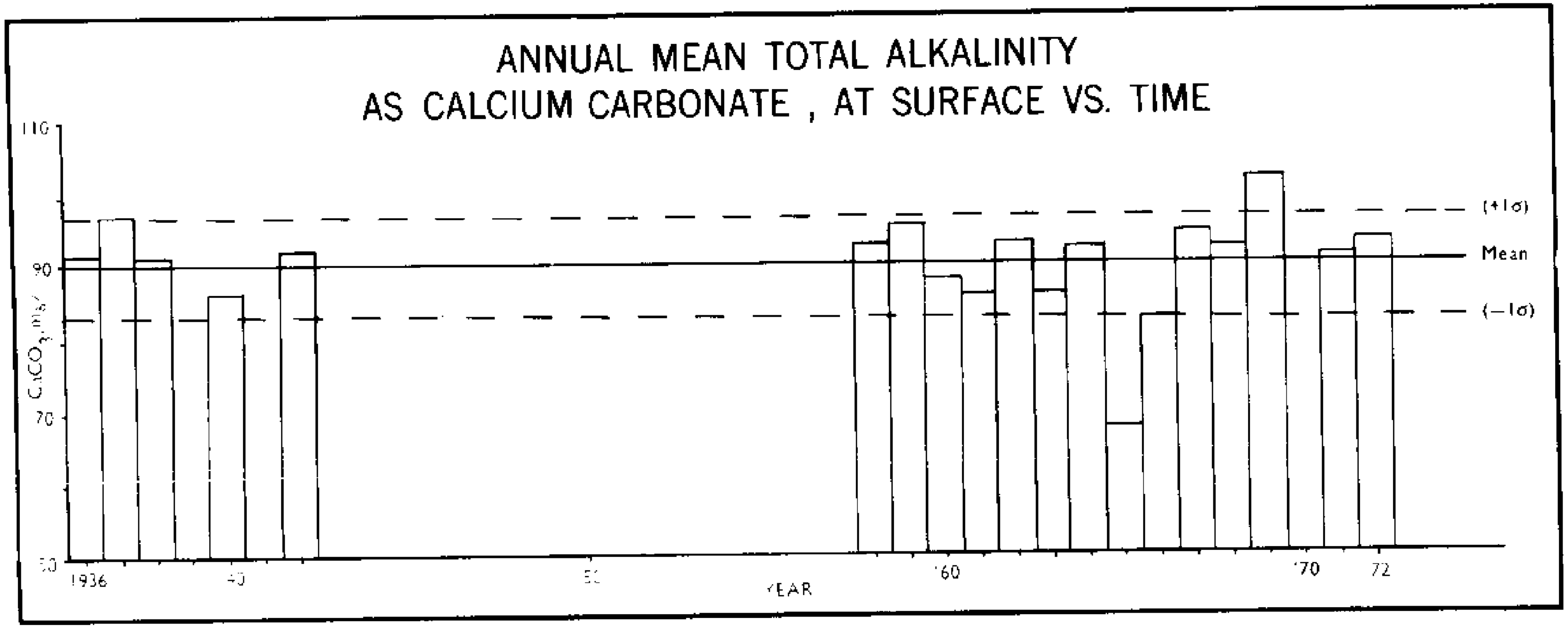
Variation in total alkalinity (mg $HCO_3$/ℓ) at surface with time, 1906-1967

FIGURE 74



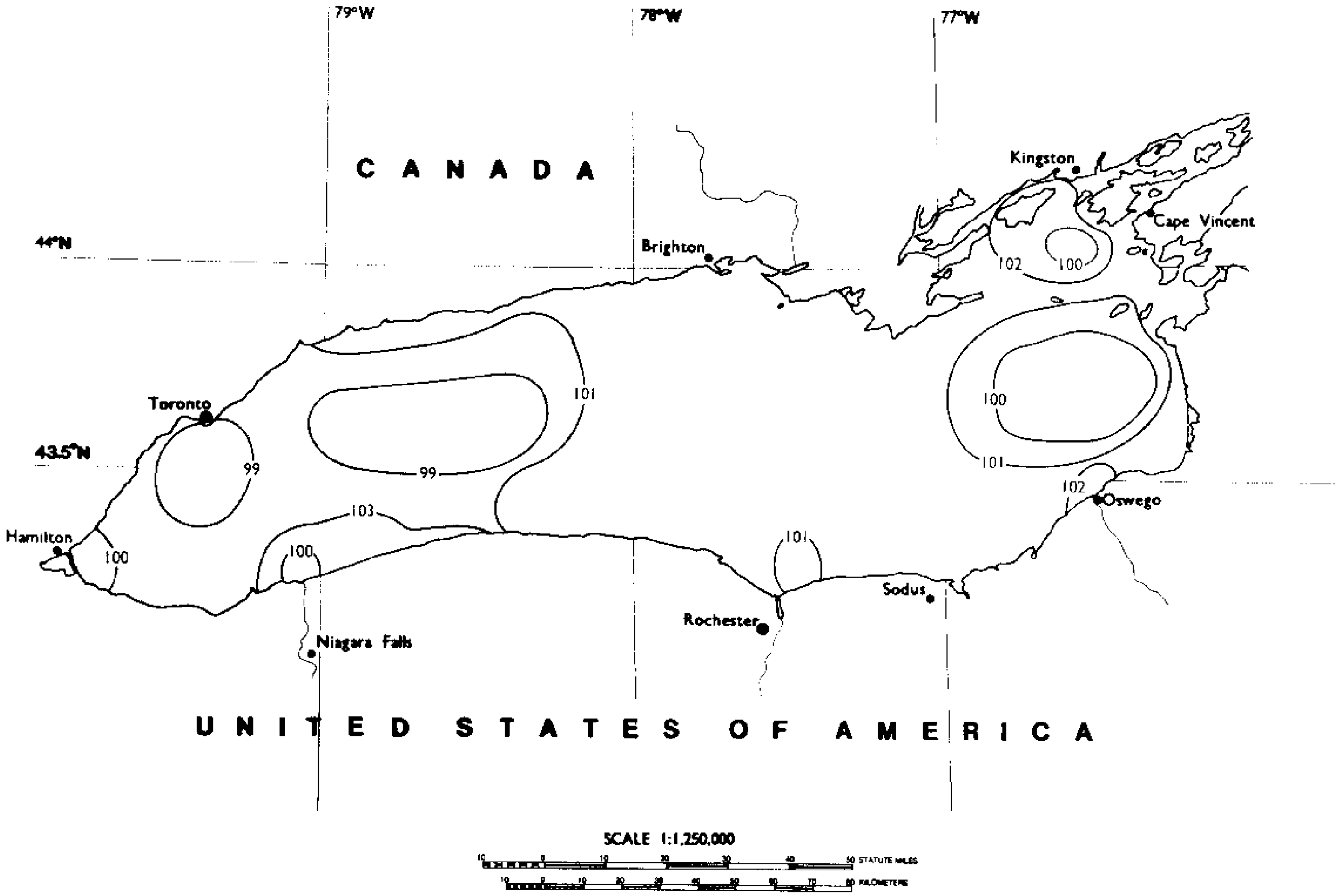
Variation in total alkalinity (mg $CaCO_3/\ell$) at surface with time, 1936-1972

FIGURE 75



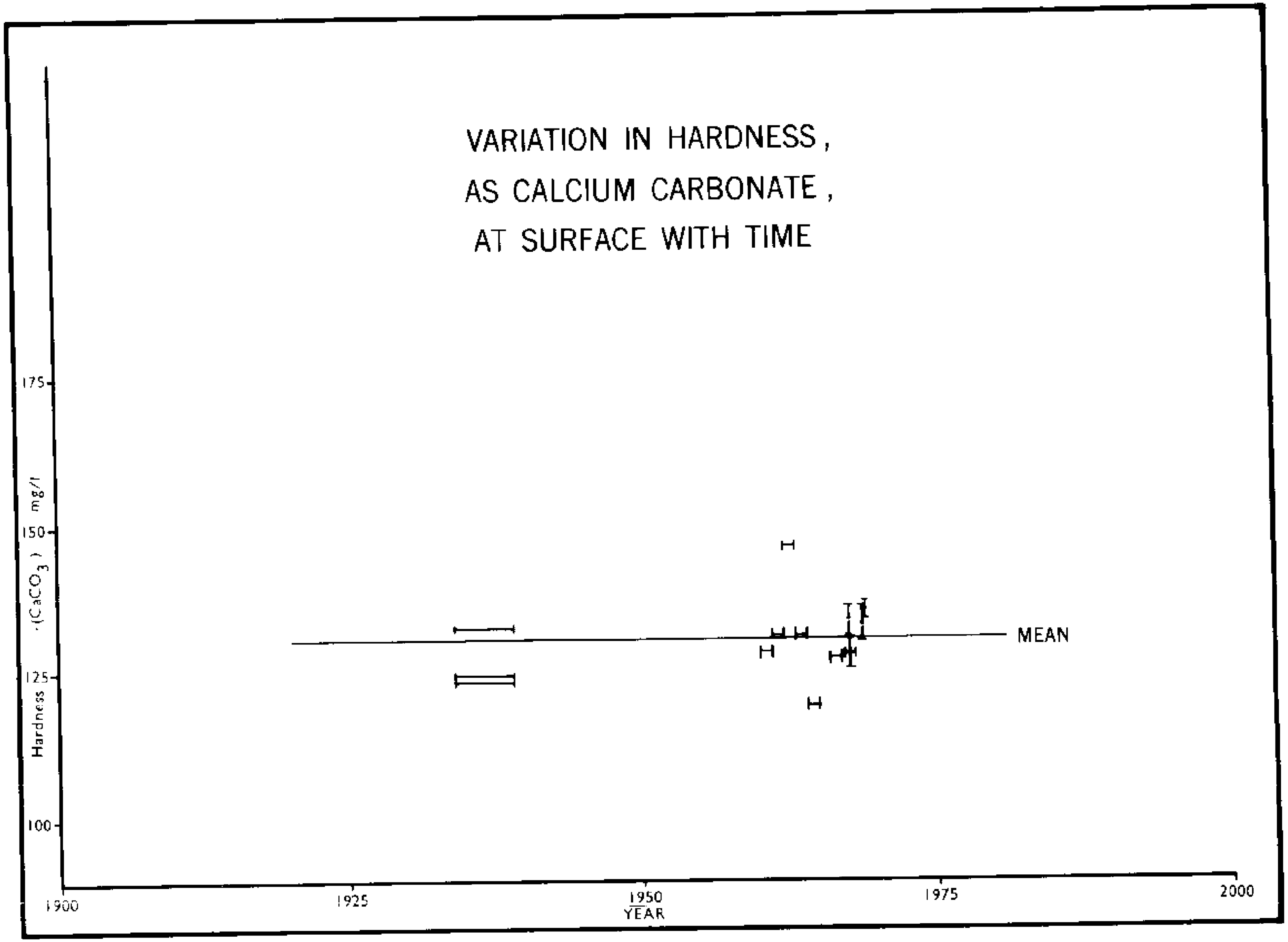
Bar graph of annual mean total alkalinity (mg $CaCO_3/\ell$) at surface, 1936-1972. The consistency of the data is seen with reference to the mean and unit standard deviation (±1σ) boundaries.

FIGURE 76



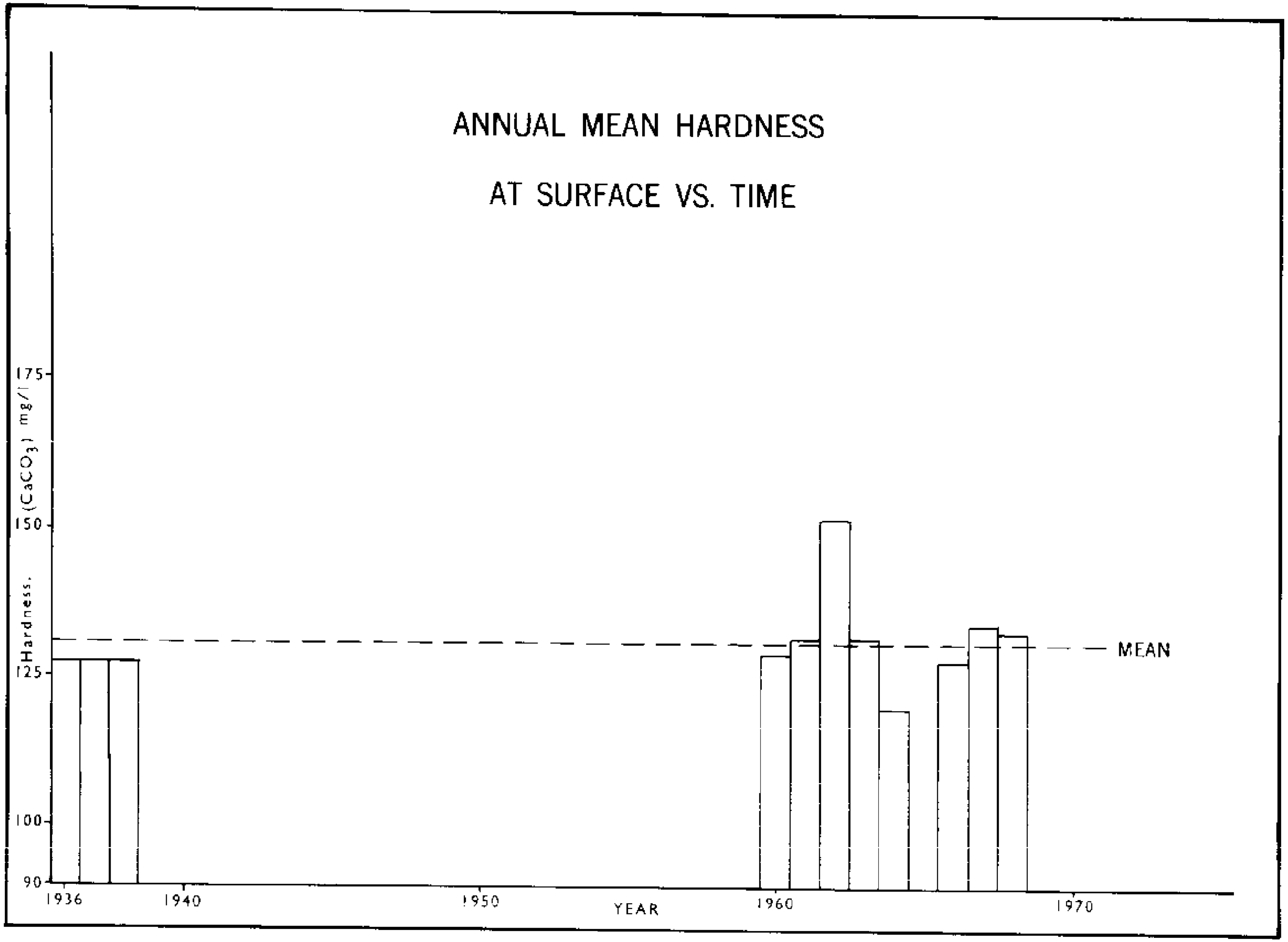
Surface distribution of total alkalinity (mg $CaCO_3/\ell$), Fall 1964

FIGURE 77



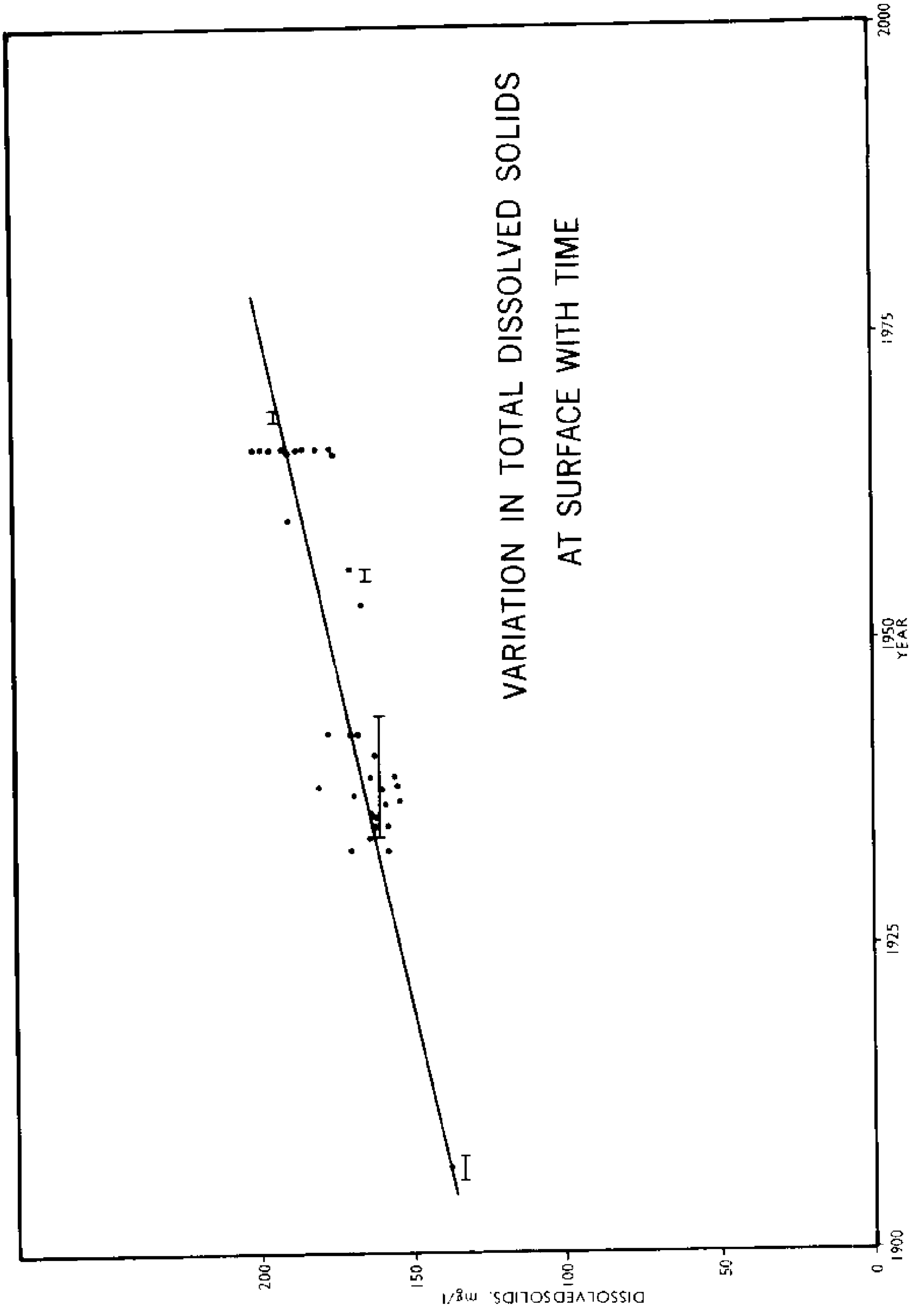
Variation in hardness (mg $CaCO_3/\ell$) at surface, 1936-1968

FIGURE 78



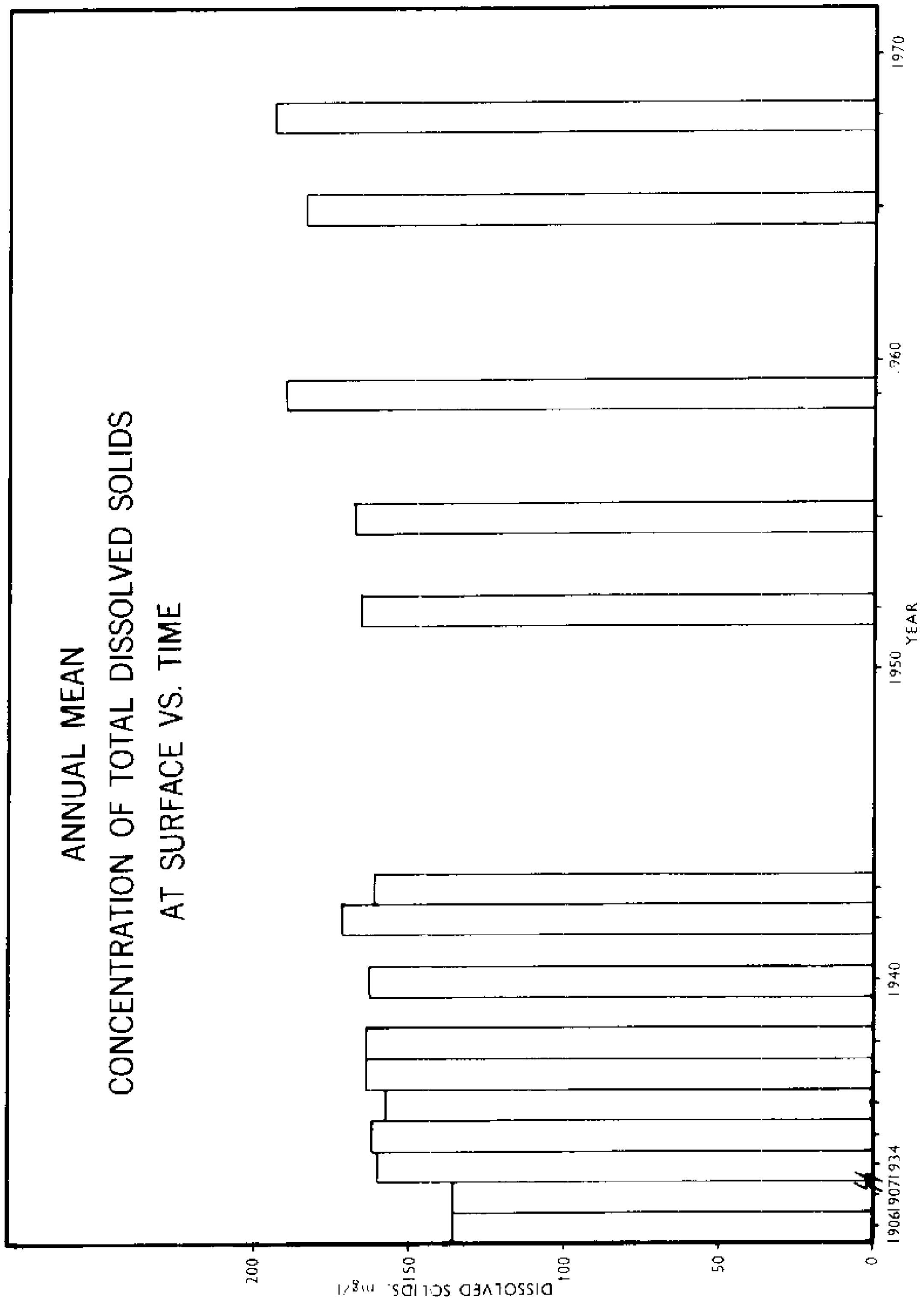
Bar graph of annual mean hardness (mg CaCO$_3$/ℓ) at surface, 1936-1968

FIGURE 79



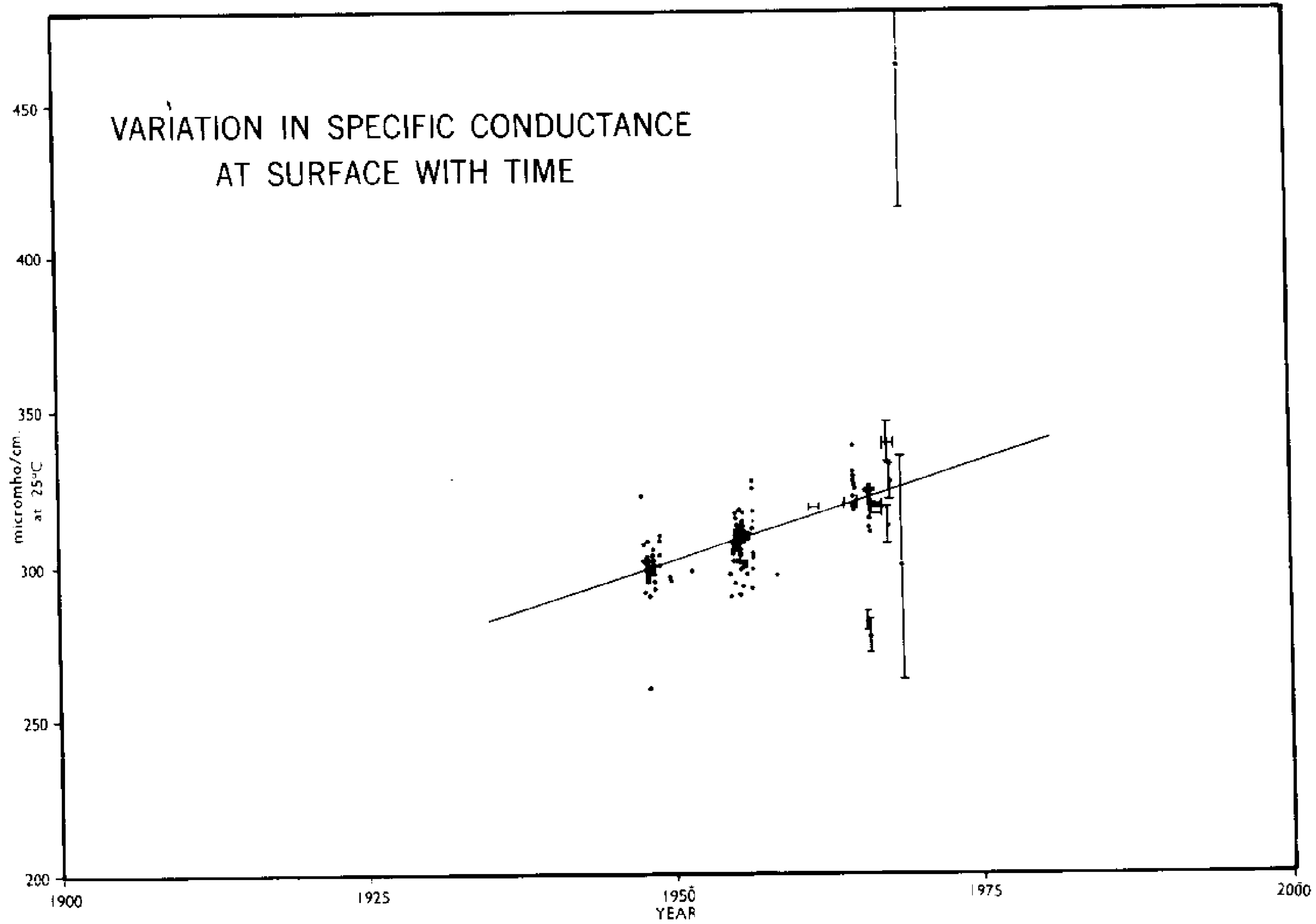
Variation in total dissolved solids (mg/ℓ) at surface with time, 1906-1968

FIGURE 80



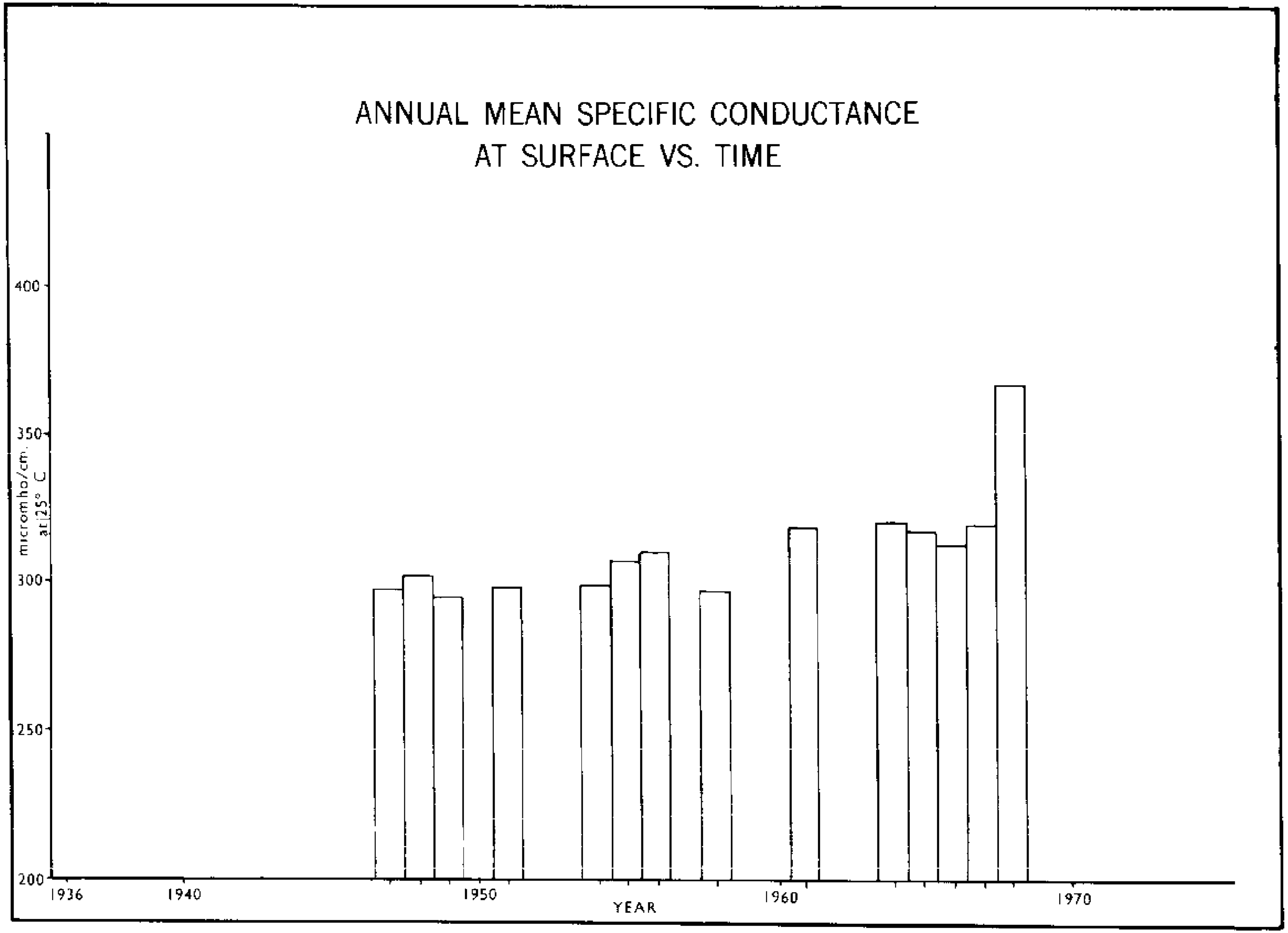
Bar graph of annual mean total dissolved solids (mg/ℓ) at surface, 1906-1968

FIGURE 81



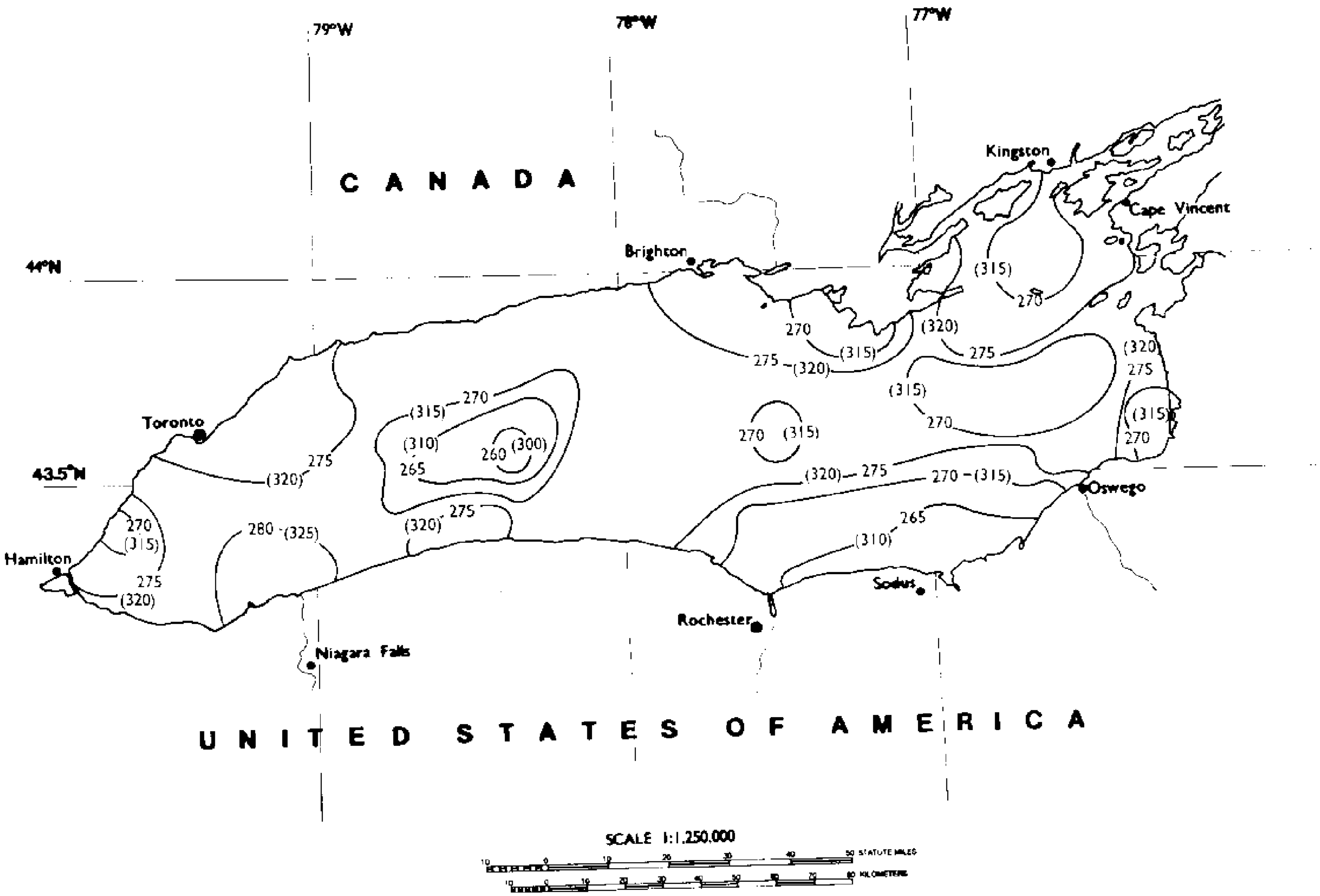
Variation in specific conductance (micromho/cm at 25°C) at surface with time, 1947-1968

FIGURE 82



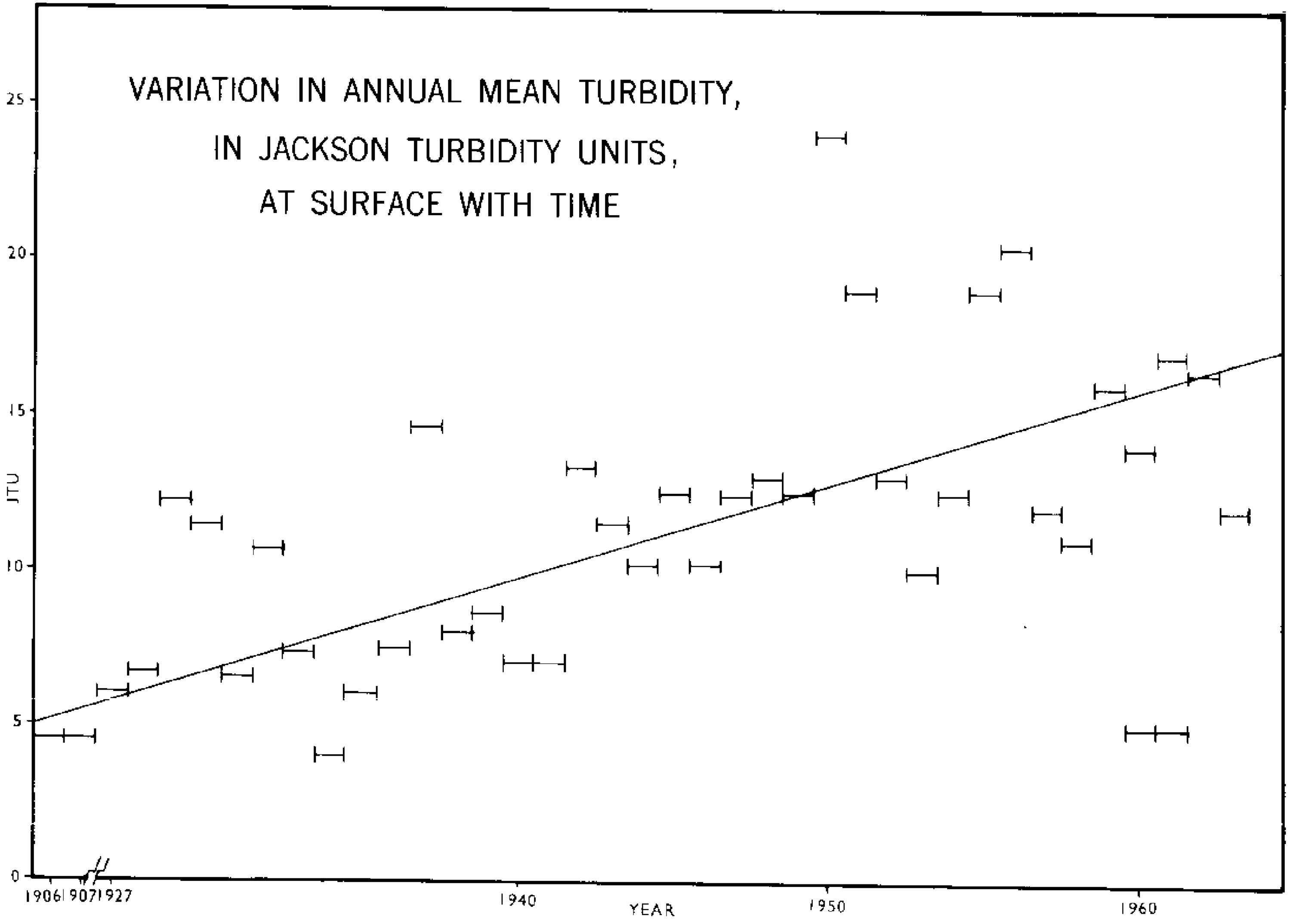
Bar graph of annual mean specific conductance (micromho/cm at 25°C) at surface, 1947-1968

FIGURE 83



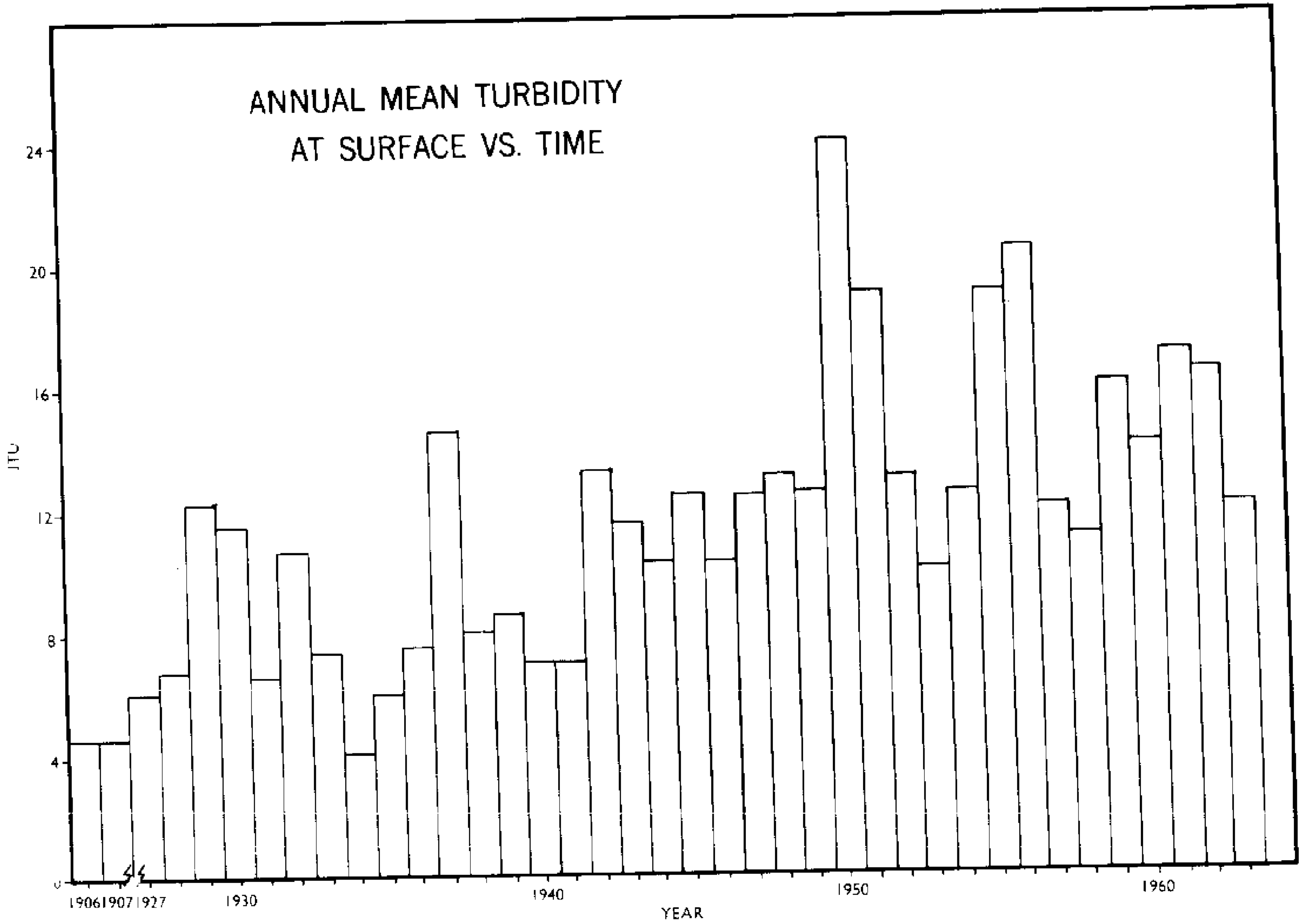
Surface distribution of specific conductance (micromho/cm) at 18°C and 25°C (in parentheses), Fall 1964

FIGURE 84



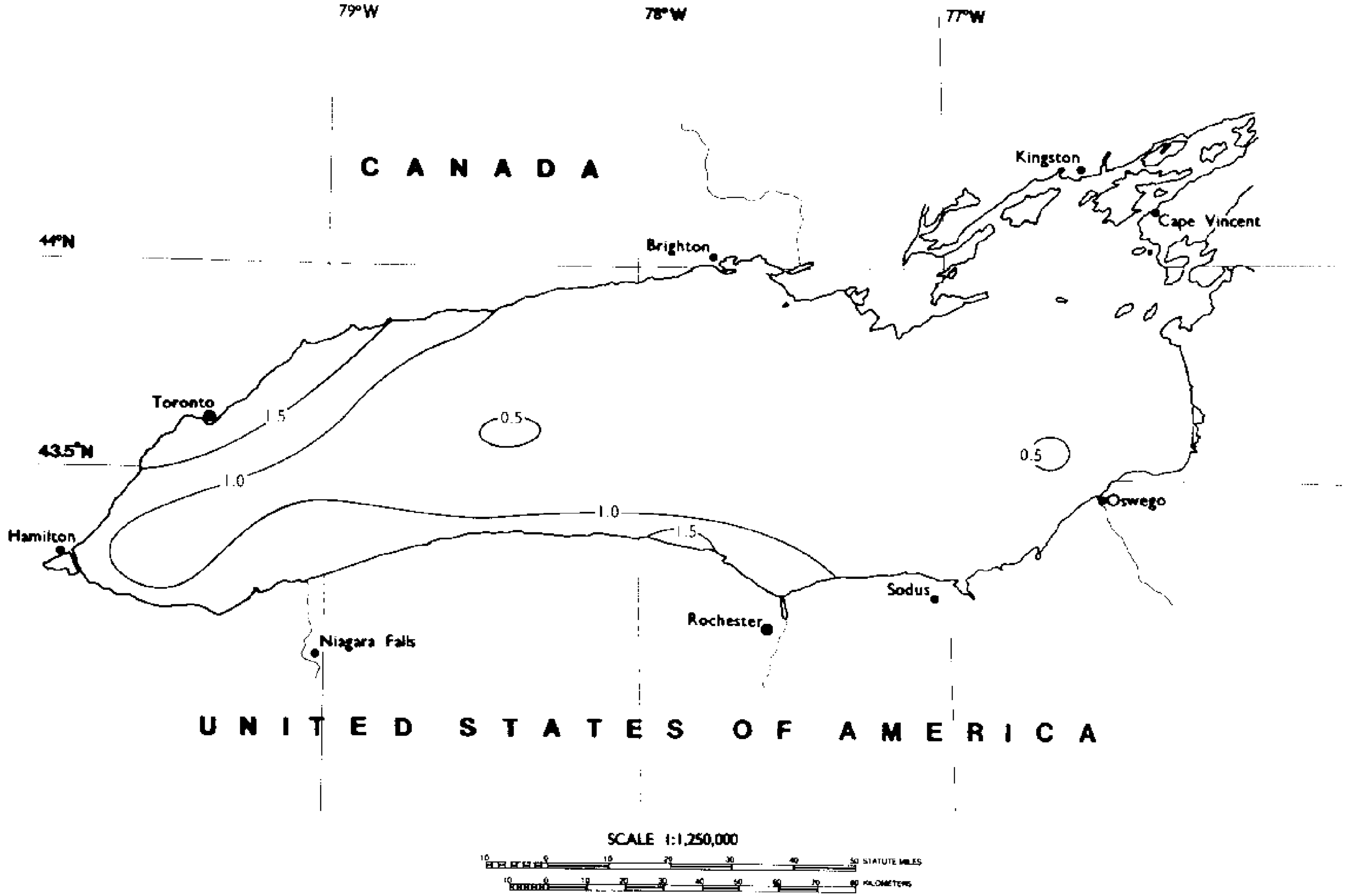
Variation in annual mean turbidity (JTU) at surface with time, 1906-1963

FIGURE 85



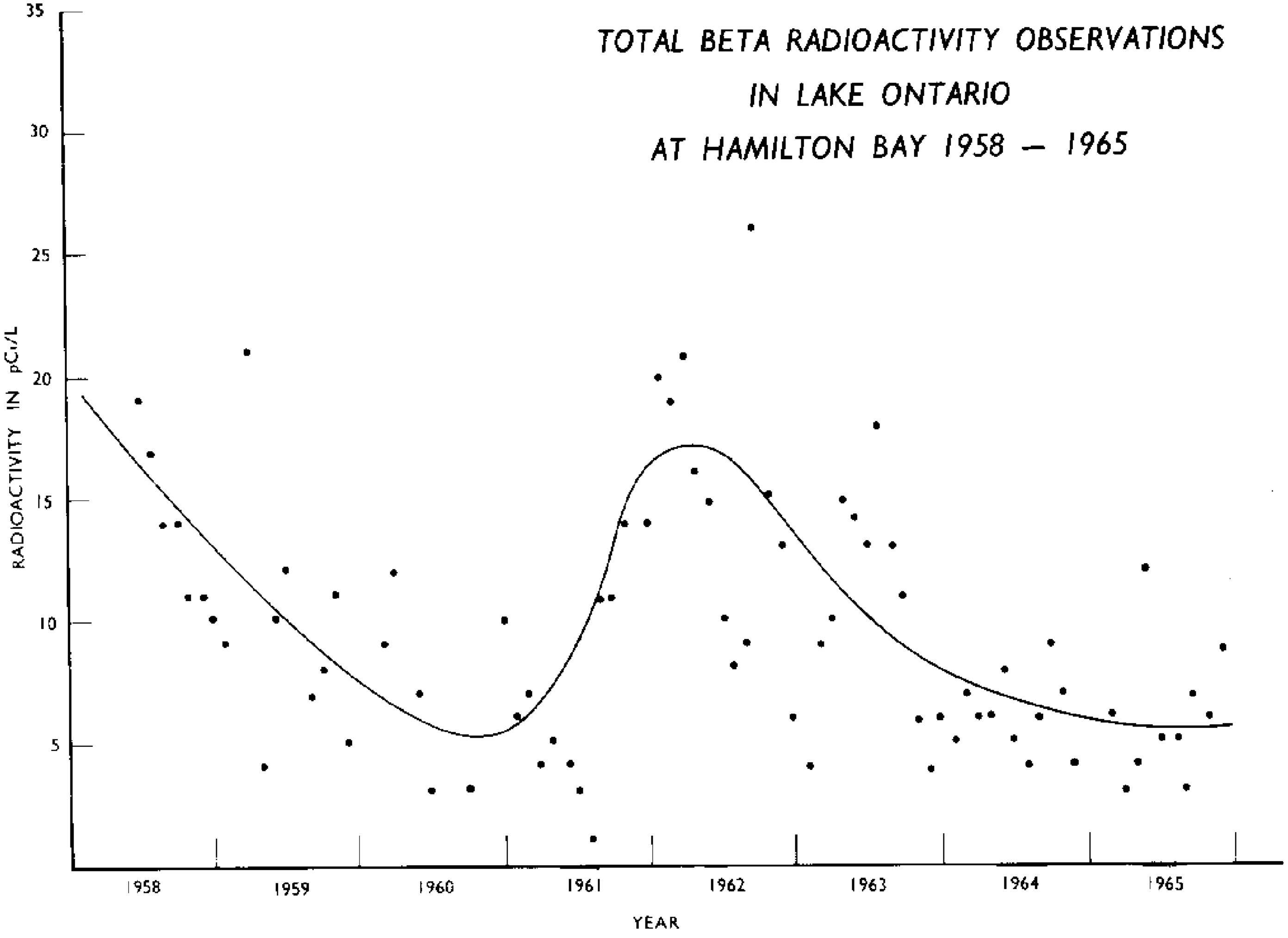
Bar graph of annual mean turbidity (JTU) at surface, 1906-1963

FIGURE 86



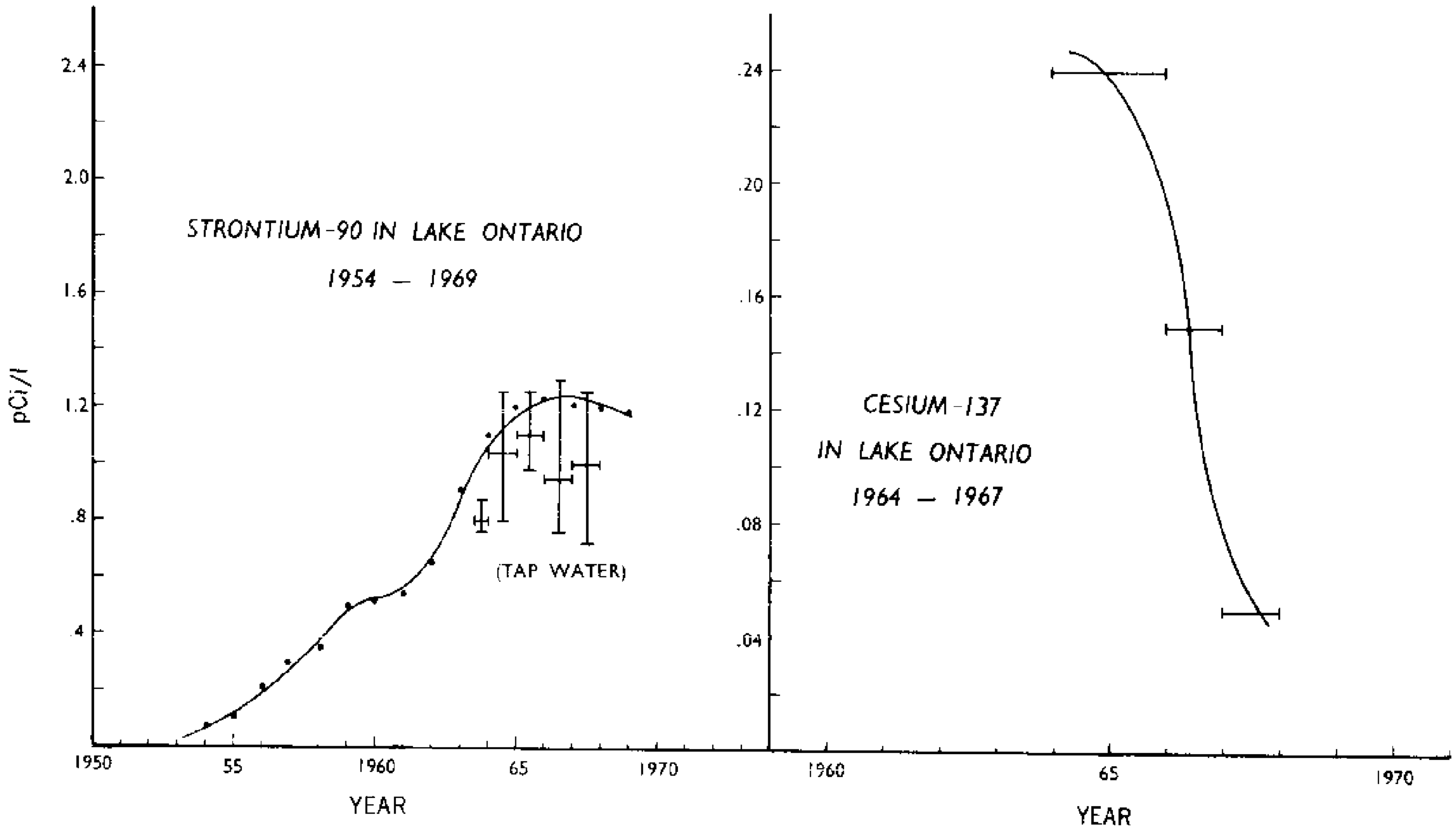
Surface distribution of mean turbidity (JTU), 1967

FIGURE 87



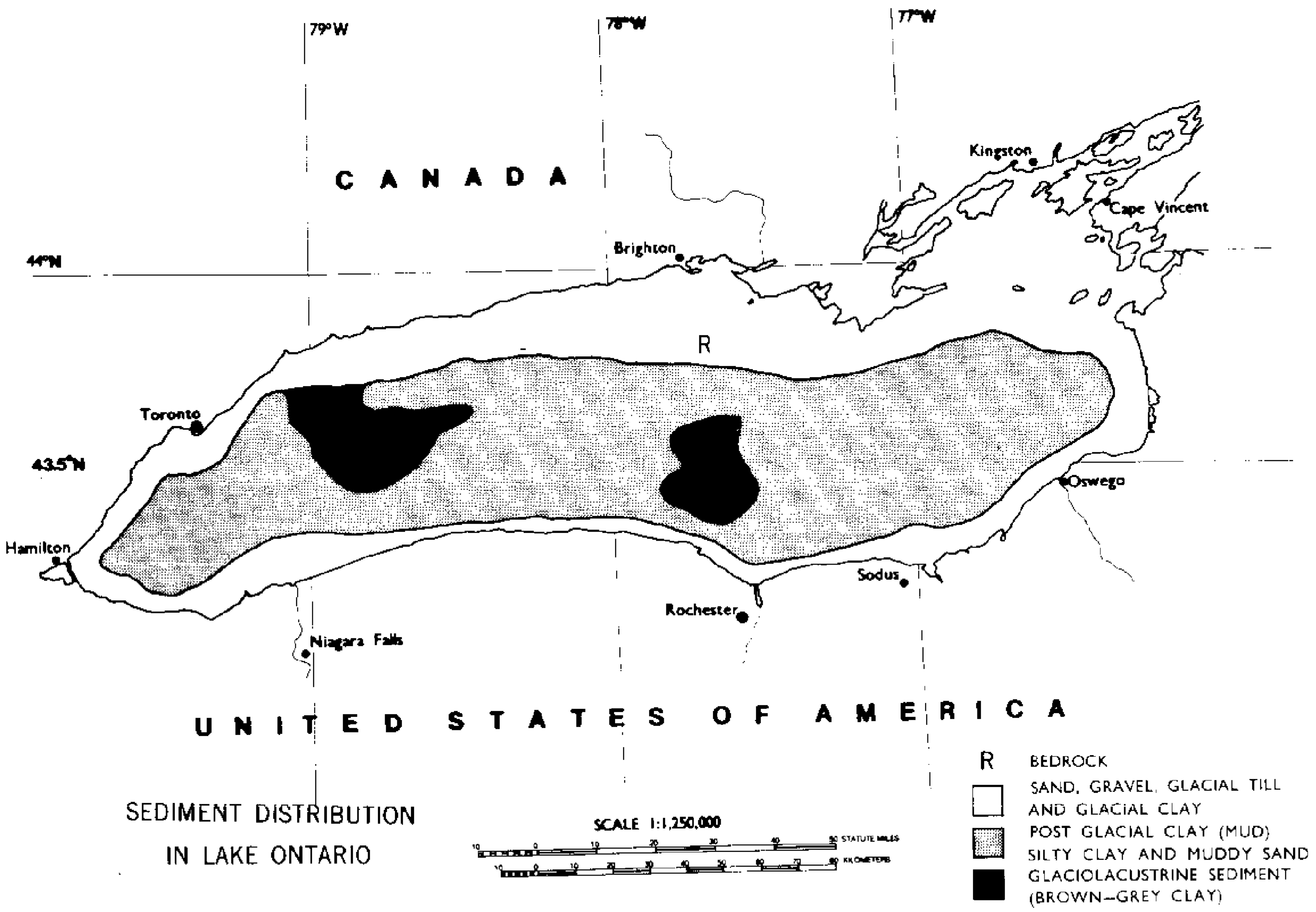
Variation in total beta radioactivity (pCi/ℓ) in Lake Ontario water with time, 1958-1965

FIGURE 88



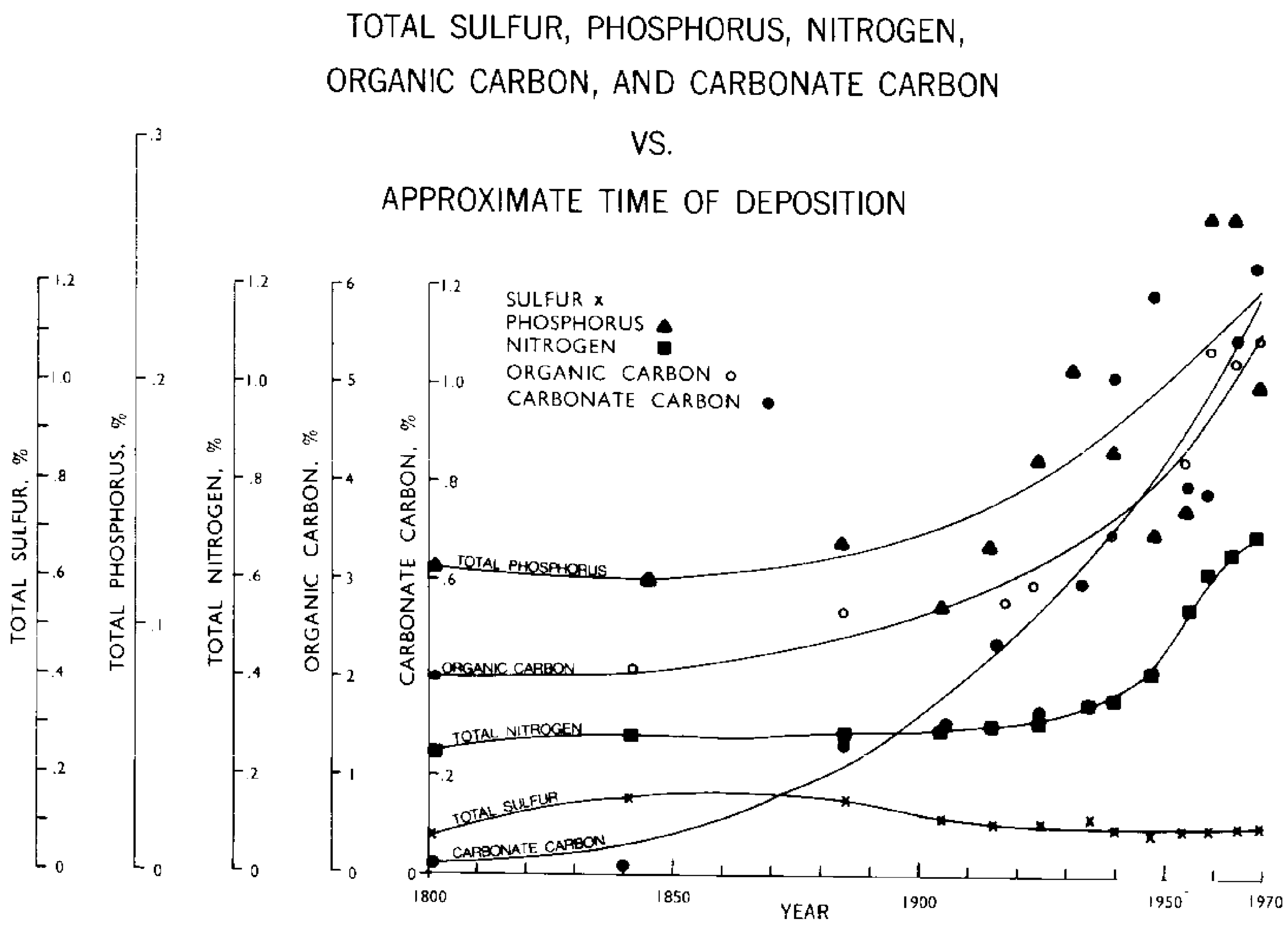
Variations in strontium-90 and cesium-137 radioactive nucleides (pCi/ℓ) in Lake Ontario water with time, 1954-1969

FIGURE 89



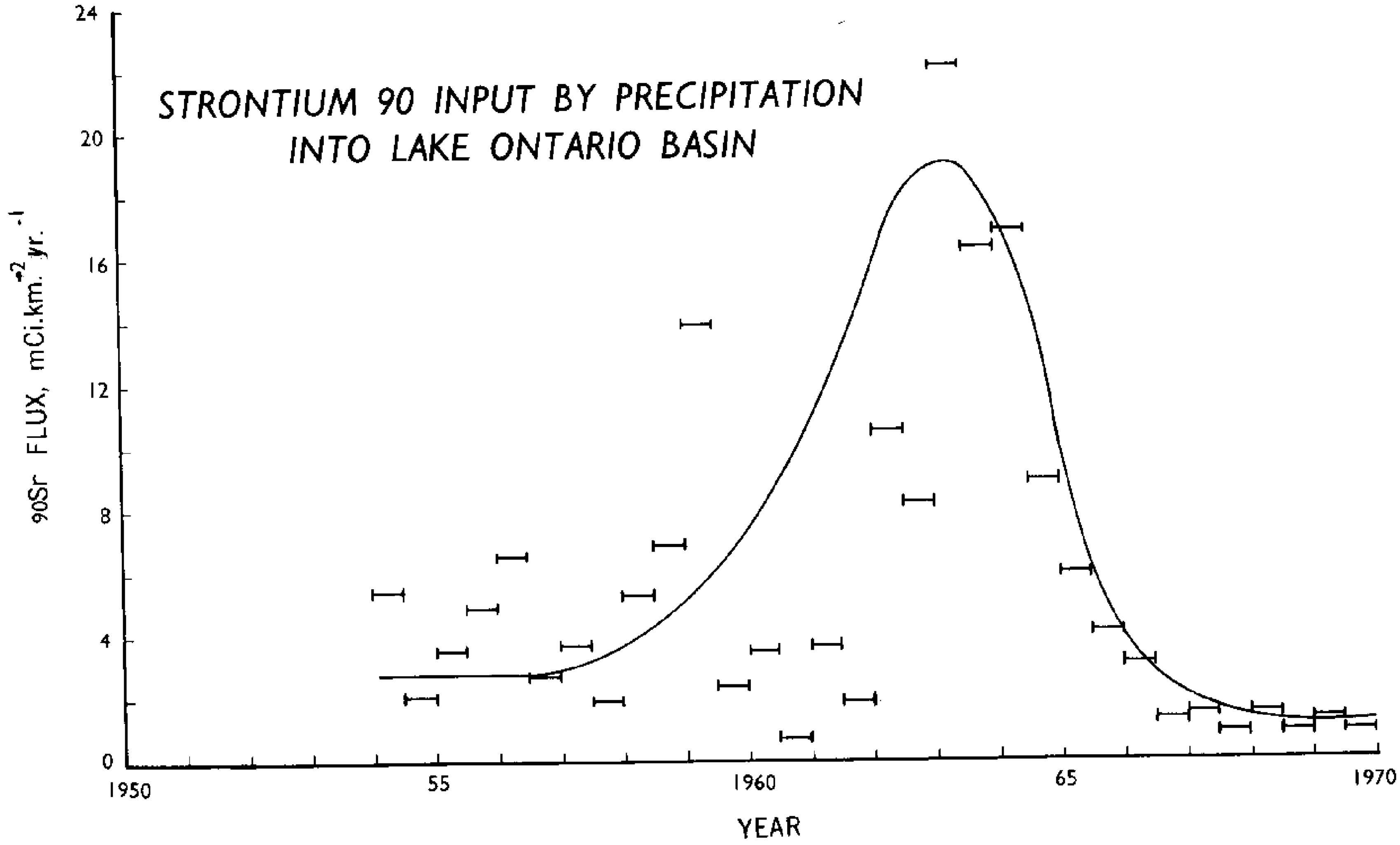
The distribution of sediments in Lake Ontario

FIGURE 90



Variations in the constituents of Lake Ontario sediments with time of deposition, 1800-1970

FIGURE 91



Variation in the annual deposition flux of strontium-90 (mCi/km$^2$/yr) by precipitation with time, 1954-1969