

SPECIAL REPORT NO. 11

**Statement on Pollution and Eutrophication
of the Great Lakes**

by

A. M. BEETON

**Associate Director, Center for Great Lakes Studies
University of Wisconsin-Milwaukee**

**Statement delivered to the U. S. Senate
Subcommittee on Air and Water Pollution
of the
Committee on Public Works**

May 1970

TABLE OF CONTENTS

Section	Page
Introduction	1
Lake Erie	3
Lake Ontario	5
Lake Huron	7
Lake Michigan	9
Lake Superior	12
The Eutrophication Problem	13
The Pollution Problem	15
Some Remedial Measures	16
Specific Recommendations	17
References	20

Figure

1. Population growth in the basins and changes in total dissolved solids of the Great Lakes	21
2. Changes in the chemical characteristics of Lake Erie	22
3. Distribution of dissolved oxygen in the bottom water of Lake Erie, 1960	23
4. Changes in distribution and abundance of mayfly nymphs and oligochaetes in western Lake Erie, 1930 and 1961	24

Figure	Page
5. Commercial fish production in Lake Erie	25
6. Changes in the chemical characteristics of Lake Ontario	26
7. Commercial fish production in Lake Ontario	27
8. Changes in the chemical characteristics of Lake Huron	28
9. Commercial fish production in Lake Huron	29
10. Changes in the chemical characteristics of Lake Michigan	30
11. Commercial fish production in Lake Michigan	31
12. Chemical characteristics of Lake Superior	32
13. Commercial fish production in Lake Superior	33

Table

I. Inputs of phosphorus from municipal, industrial and major tributary sources 1966-67	34
II. Materials balance for lower Great Lakes 1966-67	35

Introduction

The St. Lawrence Great Lakes and their connecting waterways, because of their size and the generally excellent quality of their waters, constitute one of the most important resources of North America. They have been the most important single factor for the settlement, growth, and development of the mid-continent of North America, primarily because the Lakes and the St. Lawrence River provided a transportation route extending over 2,000 miles inland from the Atlantic Ocean. Today this waterway continues to provide the most economical means of transportation, and it has further developed through the St. Lawrence Seaway. Commercial fisheries became important about 130 years ago, and these fisheries were very important to the economy of the region for many years. With the growth of large metropolitan areas, the Lakes became more and more important as a source of high quality water, for waste disposal, hydroelectric power, and a variety of recreational activities. The multiple use of the Lakes has resulted in a number of serious problems for which we are attempting to find solutions. Some obvious problems have been: the collapse of certain fisheries due to the invasion and population explosion of the alewife, a marine fish, the periodic die-offs of which have made many beaches unusable and worked a great economic hardship on the tourist industry; pollution which has resulted in accelerated eutrophication of the Lakes; and regulation of water levels to meet the needs of shipping, hydroelectric power, and shoreline property owners.

Despite the importance of the Great Lakes, it has been only within the past eighteen years that any major efforts have been made to study the physical, chemical and biological characteristics of the Lakes. The few early studies were undertaken because of concern over the commercial fisheries, such as the collapse of the cisco fishery in Lake Erie in the 1920's; public health problems, such as water-borne typhoid at the turn of the century; the need for water level regulation; or because of the curiosity of some early investigators. The realization that Lake Erie and areas of the other Lakes were becoming seriously polluted has led to increased interest in the Lakes and resulted in support for a wide spectrum of limnological research. Most previous investigations have been undertaken because of some crisis. Consequently, many gaps exist in our knowledge of the limnology of the Lakes. In fact, it was not widely recognized, prior to 1960, that the Lakes could be undergoing accelerated eutrophication, i. e., increases in nutrient content and associated changes in the biota. It was thought that the Lakes were so large that if they were changing, it would not be detected and certainly the rate of change could not be measured. Nevertheless, it has been demonstrated that Lakes Erie and Ontario have changed substantially in fifty years, and similar changes are taking place in Lake Michigan.

Studies of the Lakes have been hampered because their large size requires the use of medium to large vessels and rugged equipment, which frequently have not been available. Much of the limnological equipment and methods used on small lakes have not been satisfactory and oceanographic methods and equipment have been adopted. Consequently, work on the Great Lakes has provided a link between limnology and oceanography. It is quite reasonable that the Great Lakes have been specifically included in most of the legislation in support of oceanography.

A thorough discussion of all the changes which have occurred in the Great Lakes is not possible in a brief statement. Consequently, the purpose of this paper is to present a resumé of those aspects which are especially pertinent to an understanding of what has happened to the Lakes and which serve as a basis for remedial measures.

Changes in the environment and biota of the Lakes can be related to man's activities, either directly or indirectly, in most instances. The Lakes which have shown the greatest deterioration, and concomitant change in biota, are those subjected to the greatest population pressures and use. About 10.1 million people were living in the Lake Erie drainage basin in 1960 (Fig. 1), a population equivalent of 1,010 people per square mile of the Lake. It is not surprising that Lake Erie has undergone significant changes with this many people using the Lake as a receptacle for treated and untreated domestic and industrial wastes. Furthermore, what happens to Lake Erie determines the fate of Lake Ontario, since 86 per cent of the inflow to Lake Ontario is from Lake Erie. Other waters showing signs of deteriorating quality, such as Green Bay, southern Lake Michigan, and Saginaw Bay, are in areas of great population and/or industrial growth.

Environmental changes can be considered in three main categories, (1) pollution of inshore areas including harbors and tributaries, (2) long-term changes in the open waters of the Lakes, and (3) long-term changes in the sediments. The first category presents a problem in all of the Lakes and represents conditions which are maintained by continued pollution of these waters. Substantial improvement in water quality in these areas could occur in a relatively short time with proper pollution abatement because of the tremendous influx of high quality open lake waters into these areas. Long-term changes in the open waters of Lakes Erie, Michigan and Ontario have several characteristics of eutrophication associated with small lakes. Major changes in Lake Erie appear to be more closely related to substantial changes in the sediment however. Biotic changes may be due to direct activities of man, such as overfishing and introduction of new species such as carp and smelt, or indirect, such as discharge of wastes or construction of the Welland Canal, which permitted migration of the sea lamprey (Petromyzon marinus) and alewife (Alosa pseudoharengus) from Lake Ontario into the upper Great Lakes.

Lake Erie

A number of studies were made of Lake Erie during the past forty years. Consequently, considerable information exists for documenting the changes which have occurred.

Total dissolved solids, calcium, chloride, sodium-plus-potassium, and sulfate have increased significantly during the period of record (Fig. 2). Total dissolved solids were about 56 ppm higher in 1965 than in 1910. Calcium, chloride, sodium-plus-potassium, and sulfate have increased by 8, 16, 5 and 12 ppm, respectively, during the same period. Magnesium has not changed. Data from the few open lake studies of the western basin indicate that ammonia-N increased five-fold and total nitrogen about three-fold between 1930 and 1958. Total phosphorus concentrations appear to have doubled between 1942 and 1958.

Recent studies of seasonal and local changes in dissolved oxygen indicate a much greater oxygen demand in the Lake today than in the past. Synoptic surveys conducted jointly by a number of organizations in 1959 and 1960 demonstrated the extent and severity of oxygen depletion when the Lake is stratified, especially in the central basin (Fig. 3). Dissolved oxygen concentrations of less than 3 ppm were found in bottom waters in about 75 per cent of the total area of the central basin. Subsequent studies by the U.S. Public Health Service substantiated the conclusion that low dissolved oxygen concentrations probably affect a similar area each year after the Lake is thermally stratified. A few other observations have been made of low dissolved oxygen since 1930, but the degree of depletion and the area affected has become greater recently. Only five days of calm weather and subsequent stratification were necessary for dissolved oxygen to drop below 3 ppm in the western basin in 1963, whereas 28 days were required in 1953. Oxygen depletion in the hypolimnetic waters is probably due to the high oxygen demand of the sediments. All of the surveys, mentioned previously, showed that the severest oxygen depletion developed in the western part of the central basin, where oxygen demand of the sediments was greatest, and conditions improved toward the east. The western basin is usually homothermous. Consequently, oxygen depletion is not detected as frequently as in the deeper central basin, but the high oxygen demand of the sediments removes the oxygen rapidly when stratification occurs.

Major changes in the benthos of the western basin of Lake Erie first directed our attention to accelerated eutrophication. Nymphs of the mayfly, Hexagenia, a "clean-water" organism which formerly dominated the benthic community of western Lake Erie, have almost disappeared and pollution tolerant oligochaetes have become the dominant organisms, since 1930 (Fig. 4). Pollution tolerant species of

finger nail clams, midges, and snails also have become considerably more abundant. The number of oligochaetes per square meter have been used by several scientists to indicate the degree of pollution. On this basis the zones of heavy and moderate pollution had moved 5.5 and 8 miles lakeward from Maumee Bay between 1930 and 1951. The area of western Lake Erie affected by heavy pollution was 10 times greater in 1961 than in 1930. The benthos of most of the central basin consists of animals considered to be pollution tolerant, although organisms such as Hexagenia may have been abundant in the past. Some other "clean-water" organisms, such as Mysis relicta and Pontoporeia affinis, which were found throughout the Lake forty years ago, now are confined to the eastern part of the central basin and the eastern basin.

Severe oxygen depletion probably has been a major factor for change in the benthos, especially for Hexagenia. The Hexagenia population was reduced to about 10% of its former abundance, after a period of low dissolved oxygen, in the western basin, in 1953.

Blooms of blue-green algae have appeared in Lake Erie within recent years. Between 1919 and 1963 the abundance of algae has increased three-fold, spring and fall maxima are greater and last longer, and different diatom genera than in the past have become dominant. Melosira binderana, a diatom favored by nutrient rich waters which was not reported from the United States until recently, has become a major species making up as much as 90% of the phytoplankton at times. Microscopic animals, such as copepods and cladocerans, increased in abundance between 1939 and 1958. Diaptomus siciloides, a copepod which was found occasionally in 1929 and 1930 and is usually found in eutrophic waters, has become a dominant zooplankton. Recently, a brackish water copepod, Eurytemora affinis, has become established in the Lake.

Lake Erie continues to produce about 50 million pounds of fish per year, about 50% of the total Great Lakes production. The species composition of the catch has changed markedly. The major species, in order of importance in the 1899 catch, were lake herring (cisco), blue pike, carp, yellow perch, sauger, whitefish, and walleye. The lake herring fishery collapsed after 1925, the sauger started to decline after 1920, and the walleye was becoming more abundant (Fig. 5). Consequently, the commercial fishery had changed by 1940 and was dominated by blue pike, whitefish, yellow perch, walleye, sheepshead, carp, and suckers. The past 25 years have been the period of greatest change in the fish populations. Blue pike, lake herring, sauger, and whitefish have almost disappeared from the Lake (Fig. 5). The dramatic collapse of the blue pike population has been especially alarming. Apparently conditions were not suitable for reproduction and no recruitment to the blue pike population occurred

after the mid-fifties. The decline in the whitefish population also started about the same time and it was almost as rapid as that of the blue pike. The lake herring continued to decline after the collapse of the fishery in the twenties. Good year classes contributed substantially to the commercial fishery in 1938-39 and 1945-46 (Fig. 5), indicating that the population did have the ability of rapid recovery when conditions were suitable. Sauger production continued the downward trend, which started around 1920, until 1950 when the population collapsed. The commercial fishery turned to other species which were abundant, especially yellow perch and smelt. The smelt started to become important in the fishery in 1952. The present (1968) fishery, in order of importance, consists of yellow perch, smelt, sheepshead, carp, white bass, catfish, and walleye.

No one single factor has been responsible for bringing about the changes in the fish populations of Lake Erie. The sea lamprey has never been as important in Lake Erie as in the upper Lakes, since only a few streams are suitable for lamprey spawning. Fishing pressure obviously has been intense on some species. The effect of fishing is difficult to determine, however, especially since the combined commercial and sports fishing effort are not known, although the sports fishing pressure on some species must be significant. The marked changes in the environment must have affected most species. The lake trout fishery was never especially important but the long term decline and eventual disappearance of this species (Fig. 5) indicates development of an unsuitable environment. It also appears that the areas of the Lake suitable for lake herring and whitefish became progressively less so that these species are now found primarily in the eastern part of the Lake. These changes are shown by their disappearance first from the Detroit River and then from western Lake Erie. The early production in the Detroit River was as much as 1 million pounds, mostly whitefish and lake herring in the 1870's and 1880's. The catch was declining by 1890. Lake herring was the first to disappear; only a few hundred pounds per year were being caught around 1900 and the last recorded catch was 100 pounds in 1913. Whitefish production was less than 100,000 pounds after 1888, except for 1912, and had declined to 300 pounds in 1925, the last recorded catch. The lake herring and whitefish production declined in the Michigan waters of the extreme western end long before elsewhere in the Lake (Fig. 5). Collapse of the blue pike and sauger populations occurred during the same period when extensive oxygen depletion and changes in the benthos were first reported.

Lake Ontario

Increases in total dissolved solids, calcium, chloride, sodium-plus-potassium, and sulfate in Lake Ontario (Fig. 6) are the same as in Lake Erie, as would be expected, since the main inflow to Lake Ontario

is from Lake Erie. The somewhat higher concentrations of salts in Lake Ontario than in Lake Erie is probably related to the growth of the Hamilton, Rochester, and Toronto metropolitan areas. The agreement among the few early analyses, of 1854, 1884, and 1907, is close and indicates that increases in the chemical content of Lake Ontario, as well as Lake Erie, started around 1910.

The mean annual amount of plankton almost doubled at the Toronto water intake between 1923 and 1954, and a shift in dominant genera similar to that observed in Lake Erie occurred. Asterionella has been replaced or shared dominance with Cyclotella and Melosira since 1938. This observation may apply to the entire lake, since the dominant genera are the same ones which were important in the open Lake.

The commercial fishery was well developed in Lake Ontario before the first statistics were collected, so that records of early changes are not available. It is known, however, that some changes took place in the fish population prior to 1900. The Atlantic salmon (Salmo salar salar), which had ascended various streams from Lake Ontario in the pioneer days, first declined in abundance and had almost disappeared by 1880. Changes in the streams, with development of settlements, which made the streams unsuitable for spawning was undoubtedly the main cause for the decline. The commercial fishery never has been as important as in the other Lakes and has been one of great fluctuation in the catch of the major species (Fig. 7). Consequently, the relative importance of a species in the commercial catch frequently has changed during the period of record, although certain long term trends are apparent. Lake herring and chubs, catfish and bullheads, yellow perch, whitefish, northern pike, suckers, and sturgeon (in order of importance) dominated the catch in 1899. The combined lake herring and chub catch was 1.4 million pounds, and only catfish and bullheads (mostly bullheads) and yellow perch yielded over 0.5 million pounds. The 1940 production consisted of lake herring and chubs, carp, whitefish, blue pike, lake trout, catfish and bullheads, and yellow perch. The recent catch (1968) reflects the major declines in abundance of lake herring, lake trout, whitefish, and blue pike (Fig. 7), and consisted of carp, white perch (a recent immigrant to the Lake), yellow perch, eel, bullheads, and sunfish. Total production was about 2.3 million pounds, a substantial decrease from the 4.3 million pound catch of 1940 and the 7.5 million pounds of 1890. Whitefish production was around 0.5 million pounds prior to and after the peak production years of 1914-29, with a previous low of 122,000 pounds in 1903. Present walleye production is at about the level it was before the 1921-25 and 1951-62 peaks. The catch of eel has not changed significantly over the years, but it has assumed a more prominent place in the catch because of the decline in other species.

Carp production was not of any importance until 1914 and only reached a catch of 1 million pounds once in 1939. The white perch (Roccus americanus) recently made its way into Lake Ontario and is starting to become important in the commercial fishery.

The major changes of importance are the lake herring, lake trout and blue pike fisheries (Fig. 7), which indicate the development of an environment unsuitable for these species. The collapse of the lake herring population is similar to that which occurred in Lake Erie, although the major decline started fifteen years after that of the Lake Erie population. Lake trout production was 1 million pounds at least twice since 1867, in 1879 and 1925. The decline of the lake trout population started around 1930 and was more gradual than in the other Lakes. The sea lamprey has been in Lake Ontario for many years and does not appear to be the only cause of the lake trout decline. The collapse of the blue pike population in Lake Ontario occurred during the same period as in Lake Erie and it is remarkably similar.

Lake Huron

This Lake receives most of its inflow from Lakes Michigan (55,000 cfs) and Superior (73,300 cfs). The outflow is via the St. Clair and Detroit Rivers into Lake Erie. The water is of excellent quality as it leaves Lake Huron, but its quality is seriously impaired before it enters Lake Erie.

Population growth in the drainage basin has been relatively minor, especially in the Canadian part of the basin. The major urban centers, which are in the Saginaw River drainage, account for most of the 1 million increase in population since 1900 and some significant changes have occurred in Saginaw Bay.

Chloride, sulfate, and total dissolved solids have increased slightly in the past 30 to 40 years (Fig. 8). The source for these increased concentrations is mainly in the Lake Huron basin. Much of the increased chemical content can be attributed to urbanization and industrial growth in the Saginaw Valley. The Saginaw River usually has a high chloride (60-600 ppm) and sulfate (70-115 ppm) content.

Little information is available on past biological conditions, except for data from the commercial fishery. What information we do have indicates that the same mayfly (Hexagenia), which was replaced by pollution tolerant worms in Lake Erie, has become much less abundant in Saginaw Bay.

Several significant changes have taken place in the fish population as shown by the commercial catch. Lake trout, lake herring, yellow perch, walleye, whitefish and suckers were important in the fishery at the turn of the century. The fishery had not changed much

by circa 1940, in terms of the relative importance of species. Lake herring, lake trout, walleye, whitefish, suckers, yellow perch, and carp dominated the catch, but the catch of yellow perch had declined and carp had become an important commercial species. The statistics from the commercial fishery do not, however, necessarily indicate the abundance of these species of lower value. The next 25 years was a period of dramatic change so that carp, yellow perch, chubs, whitefish, walleye and suckers, in that order, were important in the catch of 1968. Total production for the Lake was only 5.1 million pounds compared to 14.6 million in 1940 and 21.6 million pounds in 1900.

Lamprey predation is considered the major cause for the decline of the lake trout and the sea lamprey became established earlier in Lake Huron than in Lakes Michigan and Superior. Prior to 1940, the fishery had produced 4 to 6 million pounds annually without major fluctuations (Fig. 9). The catch decreased first in the Lake proper, then in Saginaw and Georgian Bays. The slight change in rate of decline, 1950-52, was due to a temporarily increased production in Georgian Bay. The lake trout was not an especially important or stable fishery in Saginaw Bay where production fluctuated between 9,000 and 325,000 pounds between 1900 and the early 1950's. Decline of the whitefish in the thirties is attributed to excessive exploitation by deep trap nets. The whitefish continued to decline, however, after the use of trap nets was restricted to water less than 80 feet deep. One exceptionally abundant year class of 1943 contributed to increased production, especially in Saginaw Bay, in 1946-48. This year class disappeared rapidly there so that production was less than 1000 pounds in the Bay in 1955, 1956, and 1958 (Fig. 9). The greater catch in 1950-54 was due to increased production in Georgian Bay, but this population also declined rapidly. Recent production has been mainly from Lake Huron proper. The continued decline of the whitefish was probably caused by heavy sea lamprey predation. Changes in production for lake herring reflect changes in catch in Saginaw Bay where lake herring production was greatest (Fig. 9). Production has declined significantly in all areas of the Lake, especially in Saginaw Bay, since 1954. Walleye production has declined, primarily because of the collapse of the fishery in Saginaw Bay (Fig. 9). Overfishing apparently was not a significant factor but pollution has been considered important. The sauger (*Stizostedion canadense*) has not been an important commercial species in Lake Huron, although production was 210,000 pounds, mostly from Saginaw Bay, in 1930 (Fig. 9). Production data are included here because of the significant decline in catch after 1935. The catch has been less than 500 pounds in recent years.

Several factors have been significant in the changing fish populations of Lake Huron. Sea lamprey predation, overfishing, and changes in the environment must have all contributed to collapse of

the major fisheries. Changes in the fish populations of Saginaw Bay cannot be attributed only to sea lamprey predation. The decline of the lake herring has occurred in the past ten years, well after the sea lamprey reached its peak. The changing environment of Saginaw Bay may be of importance, but the lake herring has also declined in Georgian Bay. The other important change during this period has been the build-up of the alewife population. The dramatic decline in the sauger, walleye, and whitefish populations in Saginaw Bay indicates development of an environment not suitable for these species.

Lake Michigan

Two areas of Lake Michigan—Green Bay and the southern basin—are of especial concern from the standpoint of pollution, although increases in the salt content of the waters are occurring throughout the whole Lake. The physical, biological and chemical characteristics of Green Bay, as well as the restricted exchange of Bay waters with the Lake, make the Bay almost a separate lake.

The Lake Michigan basin has experienced significant population growth (Fig. 1). Rapidly expanding urban areas have used the Lake increasingly for water supply and waste disposal. Population pressure on the Lake had increased to about 4 million by 1900 but some of the effect of this population increase was alleviated by completion of the Chicago Sanitary Canal in 1900 to divert sewage from the Lake. The population of Chicago is not included in the total for the basin after 1900, since the Chicago area is not considered in the Lake Michigan watershed after this date. Nevertheless, the population increased from 2.7 million to 5.7 million from 1910 to 1960.

Chloride, sulfate and total dissolved solids have increased substantially during the past 90 years (Fig. 10). Calcium and magnesium have remained constant. Magnesium data are not presented, but concentrations have been about 10 ppm since 1877. Total dissolved solids have increased by 30 ppm in 90 years at a rate of 0.33 ppm per year. Sulfate increased 13 ppm and chloride about 6 ppm.

The extent of depletion of dissolved oxygen in southern Green Bay is probably more severe in recent years than in the past. The lowest dissolved oxygen concentrations were between 2 to 3 ppm in 1938-1939. The main tributary, the Fox River, has a severe oxygen deficiency as it enters the Bay during the summer. Very low oxygen concentrations occur in the southern part of the Bay under ice cover.

Several changes have been observed in Lake Michigan plankton. The cladoceran Bosmina coregoni is apparently being replaced by B. longirostris, and Diaptomus oregonensis has become an important copepod species. A brackish water copepod, Eurytemora affinis, is a recent addition to the zooplankton. Data from the Chicago water intake show that the plankton abundance has increased at an average of 13 organisms per ml per year, 1926 to 1958. This may represent conditions only in the extreme southern part of the Lake, however, since the amount of plankton in the open lake has been about one-third of that reported for recent years.

Two diatoms, Stephanodiscus hantzschii and S. binderanus (probably Melosira binderana Kütz.) not previously reported from Lake Michigan, have become abundant enough at the Chicago water intake to cause filtration problems. Blooms of the blue-green alga, Aphanizomenon, were observed in Green Bay in 1938-39, while Schizothrix was reported in 1952 and during recent surveys. Evidently growths of Cladophora have increased substantially, since floating mats of detached Cladophora have become a serious problem on the beaches in recent years.

Major changes have occurred in the species composition and abundance of benthic organisms in southern Green Bay. Nymphs of the mayfly, Hexagenia, which were an important component of the benthic community, occurred in 31 per cent of the samples from a survey in 1938-39, but they were found in only one area in 1952 and 1955 and had disappeared by 1966. Numbers of midge larvae increased substantially between 1939 and 1966. The distribution and abundance of oligochaetes have changed during the past 27 years. A greater number of oligochaetes is found today, but the zone of maximum abundance is found farther out in the Bay from the mouth of the Fox River. Evidently conditions near the river mouth have become unsuitable for even the more pollution tolerant organisms.

Lake herring, lake trout, yellow perch, whitefish, chubs and suckers, in this order, were important in the fishery about 1900. By the late thirties, the commercial catch, in order of importance, consisted of lake trout, chubs, lake herring, yellow perch, smelt, suckers, carp, and whitefish. The carp was introduced in the 1880's. Smelt were introduced into the drainage in 1912 and subsequently migrated to the other Great Lakes. Fish populations have changed substantially in recent years, with the most apparent changes in the commercial catch records in lake trout, whitefish, and lake herring, and a tremendous increase in the alewife (Fig. 11). The present fishery (1968) consists of alewife, chubs, carp, coho salmon, smelt, and whitefish.

The lake trout catch dropped from 5.4 million pounds in 1945 to less than 500 pounds in 1953. Prior to 1945 the lake trout had provided

a stable fishery without major fluctuations. The decline of the lake trout in Lake Michigan was very sudden and started when the sea lamprey population was relatively small. If these fish were being exploited at the optimum rate, the additional mortality caused by lamprey may have been sufficient to bring about the collapse in the lake trout population. Other changes were taking place in the environment which probably placed an additional stress on the lake trout. Nevertheless, all evidence to date indicates that sea lamprey predation triggered the decline of the lake trout.

The whitefish catch declined from 3.5 million pounds in 1949 to a low of 25,000 pounds in 1957 (Fig. 11). This decline was undoubtedly caused primarily by lamprey predation. The present upward trend in the commercial catch may be among the first indications of successful control of the lamprey in Lake Michigan.

The decrease in catch of lake herring, from 7.7 million pounds in 1954 to 116,000 pounds in 1962, took place when the alewife was becoming abundant in the Lake. The lamprey, as well as the alewife, has probably contributed to the decline of the lake herring, but it should be noted that the major lake herring fishery was in Green Bay where accelerated eutrophication probably contributed to collapse of the lake herring population. Only 53,000 pounds of lake herring were caught in 1968.

Chub populations have changed significantly, although this is not obvious from the commercial catch records. The chub fishery became important after the collapse of the Lake Erie cisco fishery in 1925. By 1932 the larger chubs (Coregonus johannae and C. nigripinnis) were becoming scarce so that mesh size of the nets was gradually reduced to capture the smaller species. Increased commercial fishing and sea lamprey predation resulted in substantial changes in the chub population to the extent that intermediate sized chubs (C. alpenae, kiyi, reighardi, and zenithicus), which made up about 66 per cent of the population in the thirties, had declined to about 24 per cent in 1955 and to about 6 per cent in 1960. The smallest species, C. hoyi, an important food of lake trout and too small for lamprey predation, made up less than a third of the population in 1930 and about 94 per cent in 1960. This species has responded to its changed environment as shown by an increase in mean length of 2 inches and an increased growth rate.

Lake Superior

This Lake has the largest surface area of any lake in the world, and it remains in a nutrient poor, oligotrophic condition. The population pressure has been slight, increasing from about 400,000 in 1900 to almost 800,000 in 1960 (Fig. 1). The major pollution problem is that of taconite waste from the iron-ore enrichment process, the consequences of which are not clearly delineated but pose a significant threat to spawning grounds of fish and fish food organisms.

No long term changes have been detected in Lake Superior except for some localized pollution of harbors, bays, or tributaries. Concentrations of calcium, chloride, sodium-plus-potassium, and sulfate have remained the same since at least 1886 (Fig. 12). A slight downward trend in total dissolved solids is not significant, especially in view of the limited data for the early years; concentrations probably have been somewhere between 55 to 60 ppm during the past 81 years. Phosphorus concentrations are somewhat higher in the waters of the littoral current which flows from west to east along the south shore and then into the open Lake, and may indicate some increase in these waters. This littoral current receives the outflow from various tributaries and urbanized areas and carries it to Whitefish Bay and the outflow of Lake Superior. Consequently, it may divert some pollution from the open Lake.

Some major changes have occurred in the fish population of Lake Superior, which have resulted from man's activities. The early fisheries, circa 1900, consisted of lake trout, whitefish, lake herring, chubs, and walleyes, respectively. The exact importance of lake herring relative to chubs is not known, since catch figures for this group of fish were combined for the early years; however most of the catch was probably lake herring. Lake herring became the major species in the commercial catch commencing about 1900. Chubs have not attained major importance until recently. By 1940, the catch, in order of importance, consisted of lake herring, lake trout, whitefish, chubs, and walleye. The recent decline in the lake trout and whitefish populations (Fig. 13) and the successful establishment of the smelt have resulted in the present (1968) fishery of lake herring, smelt, chubs, whitefish, and lake trout. The decline in the lake trout and the whitefish coincides with the establishment of the sea lamprey. The successful control of the sea lamprey has led to rapid recovery of the lake trout. The re-establishment of this major predator and introduction of salmon will undoubtedly result in additional changes in the fish population.

The Eutrophication Problem

Many of the changes which had taken place in Lakes Erie, Michigan, and Ontario indicate accelerated eutrophication. Increases in nitrogen and phosphorus, and decreases in dissolved oxygen content, are accepted indices of eutrophication. Increases in the major ions may indicate environmental change not necessarily associated with eutrophication, but these increases also reflect what is happening to the nutrients. Most of the changes in the biota have considerable significance as indices of eutrophication. Changes in the species composition and increased abundance of plankton, and decline and disappearance of salmonid fishes, have occurred in a number of small lakes undergoing eutrophication. It appears, however, that the important changes in the Great Lakes are those taking place in the sediments due to the tremendous amounts of polluttional materials entering the Lakes. About 1.4 million pounds of suspended solids are discharged daily to the Detroit River in the municipal and industrial wastes of the Detroit metropolitan area. The major changes in the benthos and the extensive depletion of dissolved oxygen offer evidence of change in the sediments. Present information suggests that depletion of dissolved oxygen in the hypolimnetic waters of western and central Lake Erie is greater than what could be accounted for by organic synthesis in the epilimnion. The oxygen demand of Lake Erie sediments is about three times that of Lake Michigan sediments and at least ten times greater than that of Lake Huron sediments. Changes in the fish population of Lake Erie also may be closely related to changes in the sediments, since all Great Lakes fishes, except sheepshead, have eggs that settle to the bottom. Consequently, most fish are part of the benthos during a critical period in their life histories. Elsewhere in the Great Lakes there is evidence of change in the sediments. Significant changes have occurred in the benthos of southern Green Bay. Increased abundance of benthic organisms in Lake Michigan, especially in the southern end, indicates organic enrichment of the sediments. Oligochaete species, which are associated with eutrophic conditions, are important in the benthic communities of southern Green Bay, southern Lake Michigan, Saginaw Bay, Lake Erie, and in the inshore zone of Lake Ontario.

Changes in the Great Lakes, such as increases in chemical content, increased abundance of plankton, and changes in the benthos, have been subtle and were not recognized until conditions were substantially altered. It is not happenstance, however, that the major changes have taken place in the Lakes with the large metropolitan areas in their basins. The greatest population growth has been in the Lake Erie basin, and this Lake has shown the greatest changes in the environment and biota. Increases in the chemical content and abundance of plankton in Lake Ontario closely parallel changes in Lake Erie and do not indicate changes occurring just within the Lake Ontario basin. The effect

of a rapidly increasing population is beginning to show up in Lake Michigan, although changes have been more gradual than in Lake Erie and probably will continue to be more gradual, because the volume of Lake Michigan is much greater than that of Lake Erie. The extent of change in Lake Michigan undoubtedly would have been much greater if the Chicago Sanitary Canal had not been constructed to divert wastes from Chicago away from Lake Michigan. The long term outlook for Lake Michigan is not encouraging, since the net addition and flow through of water is only 55,000 cfs, and most of the major tributaries are seriously polluted. The possibility of improving conditions in Lake Erie is somewhat better, since high quality Lake Huron water enters the St. Clair and Detroit Rivers. Abatement of pollution of the rivers should lead to eventual improvement of conditions in Lake Erie since it is theoretically possible to exchange the entire volume of the Lake in about three years because of the magnitude of the flow through and shallowness of the Lake.

It is an over-simplification to equate changes in the Laurentian Great Lakes to those which have taken place in smaller lakes, since it appears that eutrophication progresses somewhat differently in very large lakes than in small lakes. The concept, developed from studies of small lakes, that eutrophication progresses due to increased nutrient input, which stimulates the growth of algae, favoring those species requiring high nutrient levels, and that the increased productivity is eventually reflected in the dissolved oxygen regime of the hypolimnion and subsequently in changes in the sediments, cannot be applied to the Great Lakes. Very large lakes simply cannot respond to increased nutrient input in the above manner because their size and diversity of aquatic habitats preclude any such over-all response. Nutrient inputs are into bays and littoral areas which respond initially and may undergo significant changes in their environmental conditions and biota. Comparable changes eventually may occur in the open Lake, but unless the Lake is uniformly shallow the kinds of changes will be different in the offshore areas because of the greater depths. Consequently, morphometric factors are especially important in determining the response of large lakes to nutrient loading. Thus while the suggestion that deep lakes can withstand greater nutrient loading than shallow lakes is theoretically sound on the basis that deep waters do not facilitate full utilization of nutrients, it has the limitation that it does not take cognizance of the great differences between inshore and offshore waters and in the various other shallow littoral areas. The shallow water environments are of greatest importance to us for fish production, water supply, waste disposal, and recreation, but they are the first to be altered by pollution.

Recent studies have demonstrated significant differences between inshore and open lake waters. The results of these studies indicate that

inshore environments are deteriorating at a much faster rate than the offshore ones. These findings make it unrealistic to assume that the entire volume of a lake is available for dispersion and dilution of domestic, industrial, and thermal wastes.

Inshore (less than 10 miles from shore) and offshore waters of Lake Michigan have pronounced differences in concentrations of major nutrients, especially in the vicinity of urban centers and along the east shore where most of the major tributaries enter the Lake. Inshore concentrations of ammonia, nitrate, organic-N, and soluble phosphate were 0.13, 0.14, 0.21, and 0.04 mg/liter, respectively. Offshore waters had concentrations of 0.06, 0.13, 0.19, and 0.02 mg/liter, respectively, in 1962-63. The abundance of algae reflected the inshore-offshore differences in nutrients with low densities of 100 to 300 organisms per milliliter offshore and over 500 organisms per milliliter inshore. Diatoms were the major phytoplankters and they had an obvious influence on silica concentrations which were 2.5 mg/liter offshore and 1.7 mg/liter inshore.

Continuous inputs of large quantities of nitrogen and phosphorus compounds are necessary to maintain high concentrations of these nutrients inshore. Furthermore, the greater abundance of algae inshore in Lake Michigan indicates the biological response. This response is not limited, however, to an increased abundance of algae. The species composition is different inshore and in bays from offshore with eutrophic species in bays and inshore in many areas. Similar inshore-offshore differences have been demonstrated for Lakes Erie and Ontario.

The Pollution Problem

The major pollution problems in the Great Lakes are bacteria and viruses, chemical wastes, oxygen depletion, oil spills, disposal of dredged materials, pesticides and herbicides, and thermal discharges. Major sources of these pollutants are continuous discharges of treated, untreated, and partially treated wastes from municipalities and industries, as pointed out by the International Joint Commission and the Federal Water Quality Administration. Certainly runoff from agricultural land contributes its share of sediments, pesticides, and organic wastes. Unfortunately, accurate data are not available on the agricultural contributions.

Municipalities contribute major inputs of phosphorus to the Lakes as shown by data from the International Joint Commission report on pollution of Lakes Erie and Ontario (Table 1). Ten per cent of the total phosphorus is from direct inputs to Lake Erie. The municipalities also contribute about 55 per cent of the phosphorus inputs from tributaries

to Lake Erie. Municipal and industrial wastes account for about 75 per cent of the estimated total phosphorus input to Lake Erie, and it is estimated that up to 70 per cent of the phosphorus comes from detergents. This ever-increasing discharge of nutrients to the Lakes is a major factor in the accelerated eutrophication of the Lakes. The inputs of nitrogen and phosphorus stimulate the growth of algae, leading to large blooms of blue-green algae and Cladophora. The problem is compounded, however, since these nutrients are retained or stored in the Lake, especially in the sediments (Table 2). It is highly significant that 80 per cent of the phosphorus is retained in Lake Erie.

The recent discovery of high mercury concentrations in the sediments and fish of Lake St. Clair illustrates one of the industrial waste problems and our serious lack of knowledge about many pollutants in our environment. A wide variety of new pollutants are being discharged into the Lakes. For example, plasticizer compounds show up as DDT in analyses, and it is possible that these compounds may be as harmful as DDT itself.

As pointed out previously, pollution inputs are into the inshore areas, bays, and harbors. The critical areas now adversely affected are Green Bay, southern Lake Michigan, Saginaw Bay, Detroit River, western Lake Erie, southern shore of Lake Erie, and western Lake Ontario.

Some Remedial Measures

Intensive pollution abatement programs in the seven critical areas mentioned in the previous section will undoubtedly be a major step towards improving conditions throughout the Great Lakes. Certainly any improvements made in the water quality of Lake Erie will be of direct benefit to Lake Ontario.

Despite the magnitude of the changes which have occurred in Lakes Erie and Ontario we have a better possibility of correcting the situation in these Lakes than halting eutrophication of Lake Michigan. It is theoretically possible for all of the water to be exchanged in Lake Erie within three years because of the tremendous flow-through and the shallowness of the Lake. It would take around 100 years to exchange the water in Lake Michigan. Consequently, for Lakes Erie and Ontario, the incoming pollutants must be greatly reduced by treating all inputs and by upgrading existing sewage treatment facilities. Conditions could be improved throughout the Lakes by greatly reducing the phosphorus content of detergents or by finding a suitable substitute for phosphorus in detergents.

It is evident that pollution problems and eutrophication of Lake Michigan would be more severe if sewage from the Chicago metropolitan area had not been diverted out of the basin. The possibility of additional diversions of treated wastes away from the Lake should be given serious consideration. Our present technology would permit us to build an interceptor sewer extending from Milwaukee and including the industrial complex at the southern end of the Lake. This would improve water quality by a trade-off between diversion of high quality water into the basin, such as is already being done in Canada, and diverting sewage effluents away from the Lake. Before the accusation is made that this would merely shunt Great Lakes pollution elsewhere, it should be remembered that lakes act as traps for pollutants. Rivers, because of continued dilution, turbulence, and flow, can withstand pollution better than lakes, and can offer better possibilities for recovery.

Before any large scale project is undertaken to improve any of the Great Lakes, such as the proposal to remove sediments or increasing mixing in Lake Erie, studies should be conducted in areas representative of the Lakes. The concept that such studies of remedial measures can be studied in small lakes and scaled up to the Great Lakes does not recognize the uniqueness of the Great Lakes. Studies could more profitably be conducted in several of the Great Lakes harbors, such as at Cleveland or Milwaukee, which are actually enclosed areas of the Lakes.

Specific Recommendations

Collectively the Great Lakes, their connecting waters, and tributaries are a resource of inestimable value. The system is subject to so many diverse and conflicting uses that it is impossible to attempt management for present or additional uses without a comprehensive water resources plan for the region. Admittedly, development of such a plan is a very formidable task but one which, nevertheless, must eventually be accomplished. A start can be made by developing water resources plans for subregions, such as the Apostle Island area, Green Bay, metropolitan areas, or even smaller harbors.

Specific recommendations for investigations and actions to improve management of the Great Lakes are as follows.

1. Establish an organization of representatives from diverse interests and institutions to serve as a central clearing house for developing a priority list of unsolved problems and for channeling projects to individuals, agencies and institutions most capable of working on them.

2. Coordinate efforts and goals of all governmental agencies, from local townships to the federal governments of the United States and Canada.

3. Rapidly disseminate information among all people concerned with use, conservation and management of the Great Lakes.

4. Increase enforcement of all water laws now in effect.

5. Improve basic authority for management through constructive legislation as understanding develops on the dynamics of the Great Lakes system.

6. Separate storm and sanitary sewer systems, generally provide sewage treatment beyond the secondary stage, and treat all municipal wastes to remove at least 90 per cent of the biological oxygen demand and 80 per cent of the phosphates. These actions are essential to abate pollution and to maintain and improve water quality.

7. Accelerate land acquisition and zoning to maintain and provide suitable boat landing sites, observation areas, and parks on the Great Lakes for public recreation..

8. Establish environmental monitoring systems to detect any improvement or additional degradation of water quality in the Great Lakes. Data obtained by this approach are essential to evaluate present management efforts and to plan new procedures.

9. Conduct a socio-economic study to determine the costs and benefits of improving water quality through pollution control. Some of the benefits are increased land values, reduced cost of operating water treatment plants, minimizing public health hazards, upgrading aesthetic appeal, increasing the tourist industry, and enhancing water-based activities such as swimming, water skiing, boating and fishing.

10. Develop water quality models for subregions of the Great Lakes. A comprehensive systems analysis model would aid in examining and interrelating a wide variety of diverse variables. As there is no one goal that can be optimized for the Great Lakes region, a mixture of goals and objectives must be considered. Some of these goals are complementary, while others are incompatible. A simulation model would allow the planner to observe effects of different policies over time and make comparisons to select the most reasonable alternatives.

11. Examine long-range aspects of problems and accept, or at least consider, new or revolutionary ideas. A few examples illustrate current proposals. Two cities are considering development of airports

on diked fill-ins constructed in the Lake basins. Benefits and consequences of such proposals need careful study. Marshland for ducks and other wildlife could be created by filling enclosed areas with dredging spoil to provide shallow water. The usual practice is to destroy marshland by using it as a dump for dredging spoil. Such spoil might also be used beneficially to develop other recreational lands such as shore parks, marinas, or golf courses, close to central cities. Development of deep water harbors could eliminate many dredging problems. Offshore waters of the Lakes are of good quality and, with ever-increasing knowledge of currents and improved engineering techniques, it should be possible in some cases to divert high quality waters onto beaches now closed because of pollution. Imagination and technology should combine to benefit the aquatic resources and their users.

Note: Portions of the text are taken from: Beeton, A. M. 1969. Changes in the environment and biota of the Great Lakes. In: Eutrophication: Causes, consequences, correctives. Proc. Symp. on Eutrophication, National Academy of Sciences, Washington, D.C. 661 p.

References

- Beeton, A. M. 1963. Limnological survey of Lake Erie 1959 and 1960. Great Lakes Fish. Comm., Tech. Rept. No. 6, 32 p.
- Beeton, A. M. 1965. Eutrophication of the St. Lawrence Great Lakes. Limnol. Oceanogr. 10: 240-254.
- Beeton, A. M. 1966. Indices of Great Lakes eutrophication. Proc. 9th Conf. Great Lakes Res., Univ. Michigan, Great Lakes Res. Div., Publ. No. 15: 1-8.

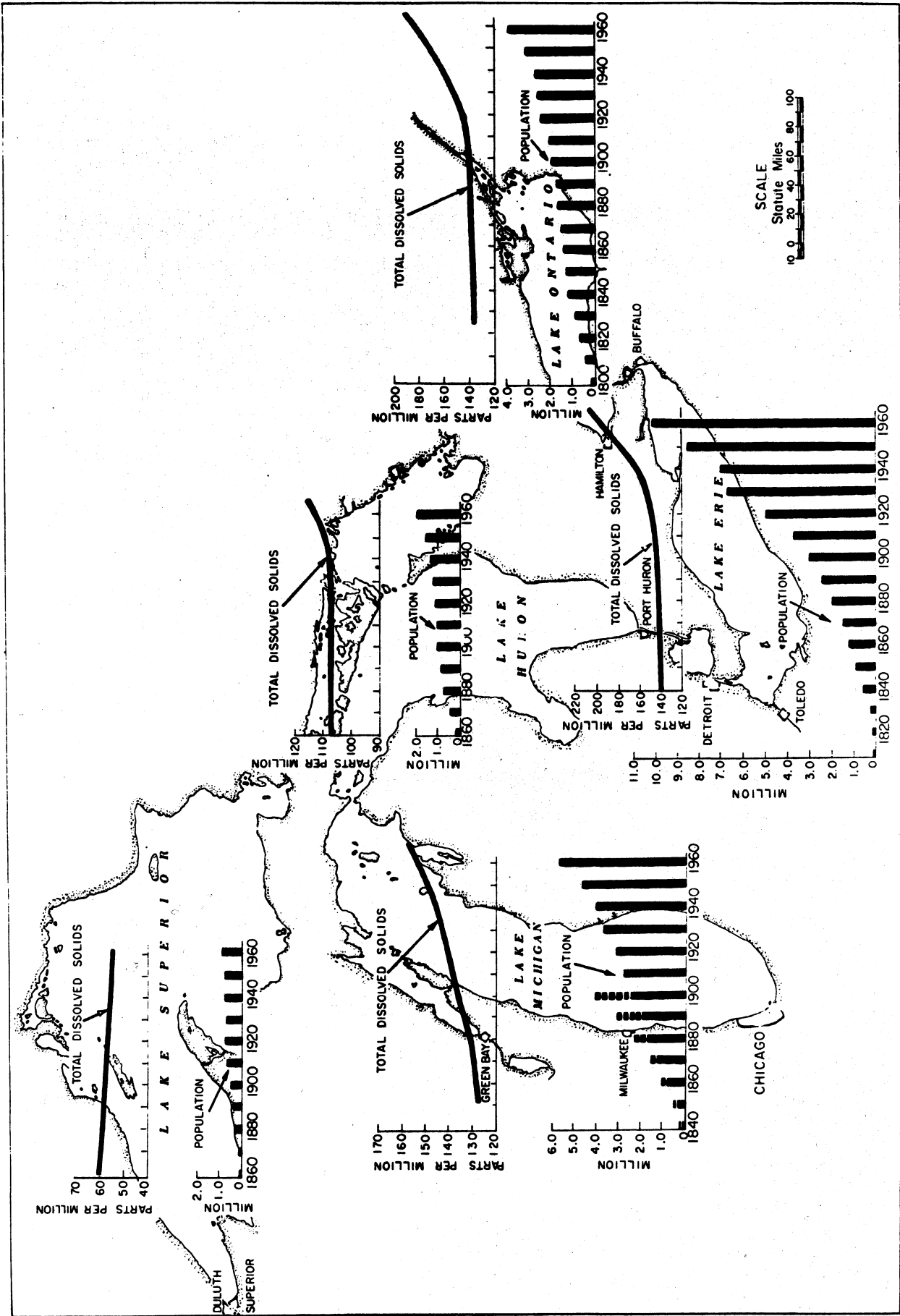


FIG. 1. Population growth in the basins and changes in total dissolved solids of the Great Lakes. (Adapted from Beeton, 1969.)

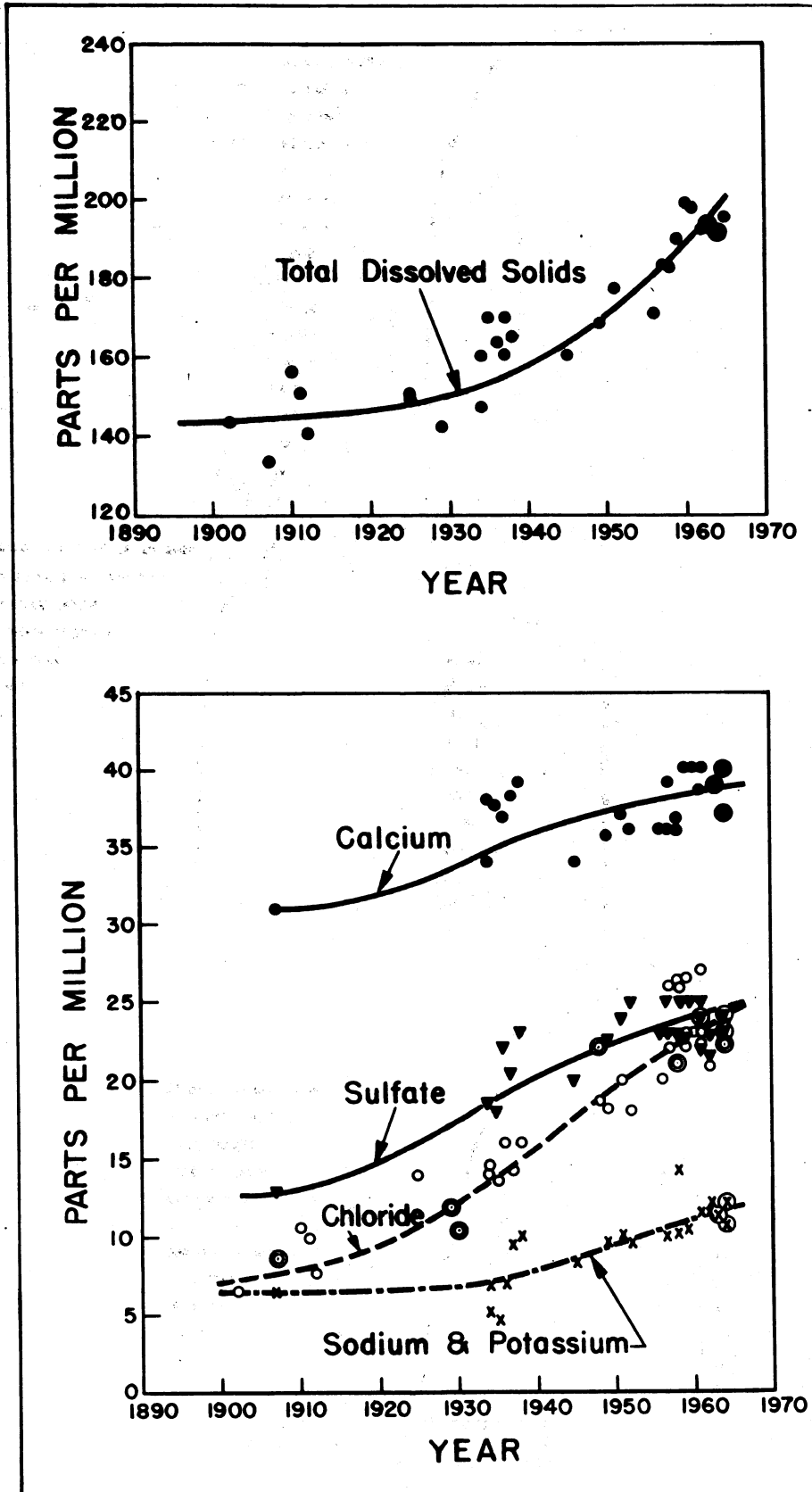


FIG. 2. Changes in the chemical characteristics of Lake Erie (from Beeton, 1969).

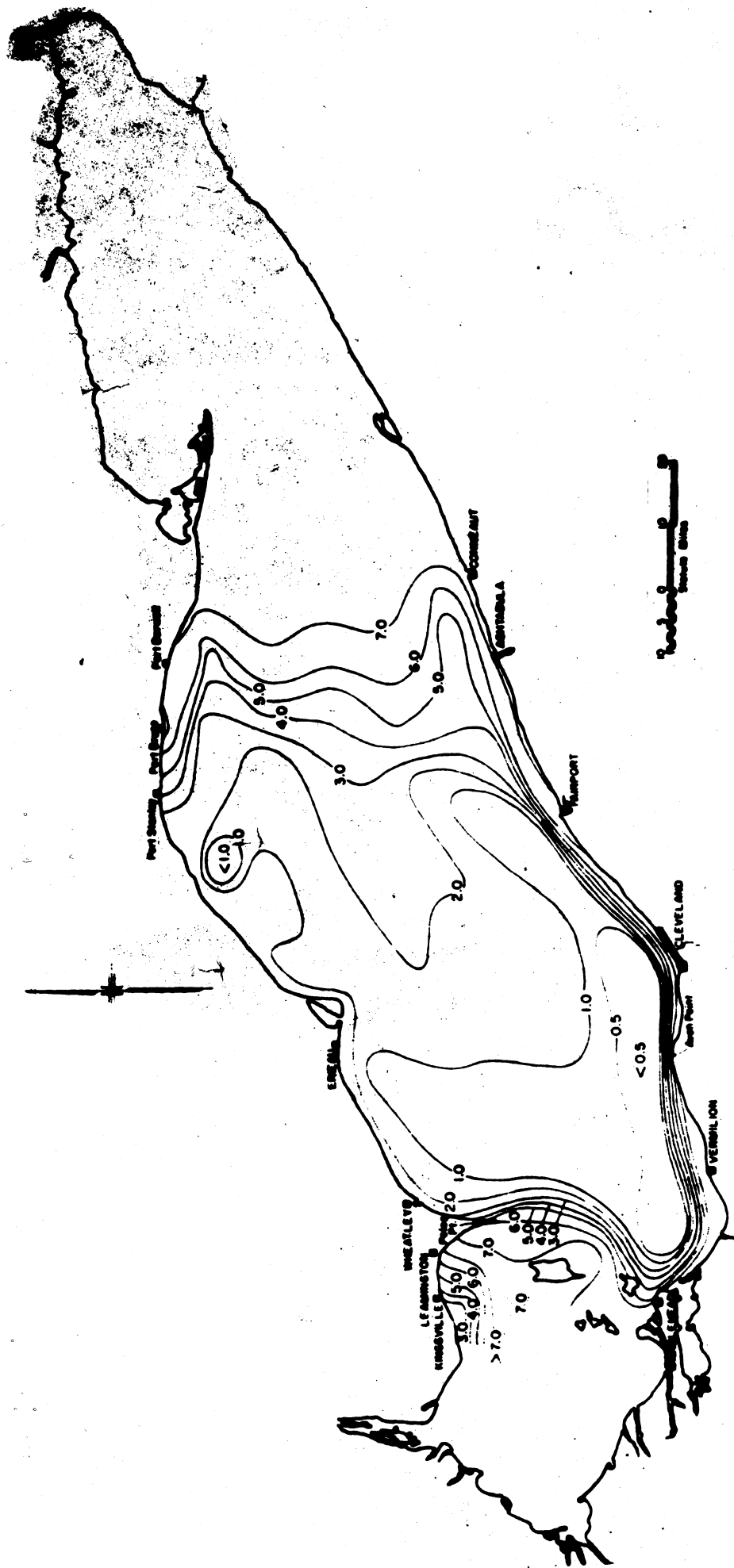


FIG. 3. Distribution of dissolved oxygen (ppm) in the bottom water of Lake Erie, 1959.
 (From Beeton, 1963.)

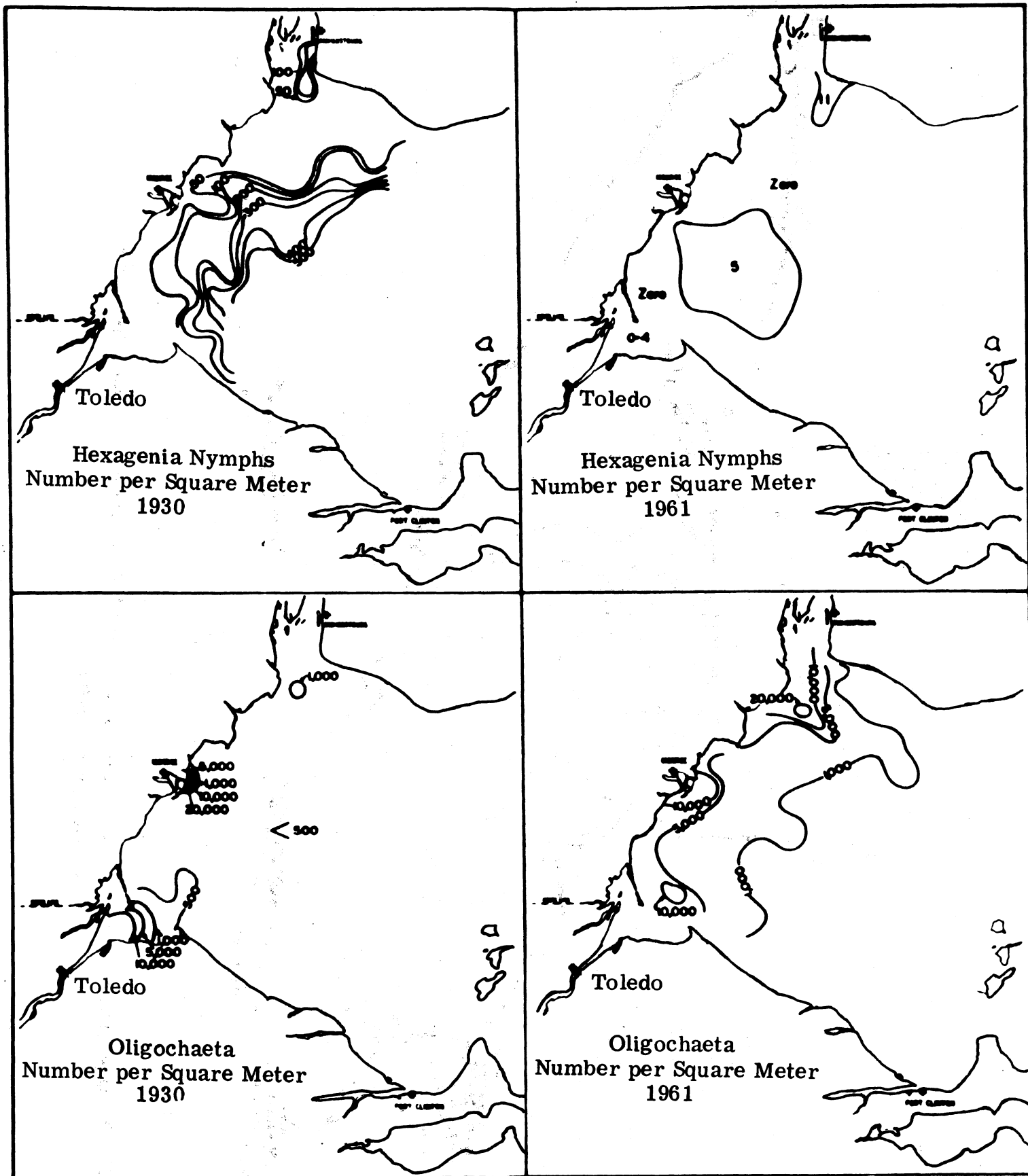


FIG. 4. Changes in distribution and abundance of mayfly nymphs (*Hexagenia* spp.) and oligochaetes in western Lake Erie, 1930 and 1961 (from Beeton, 1965).

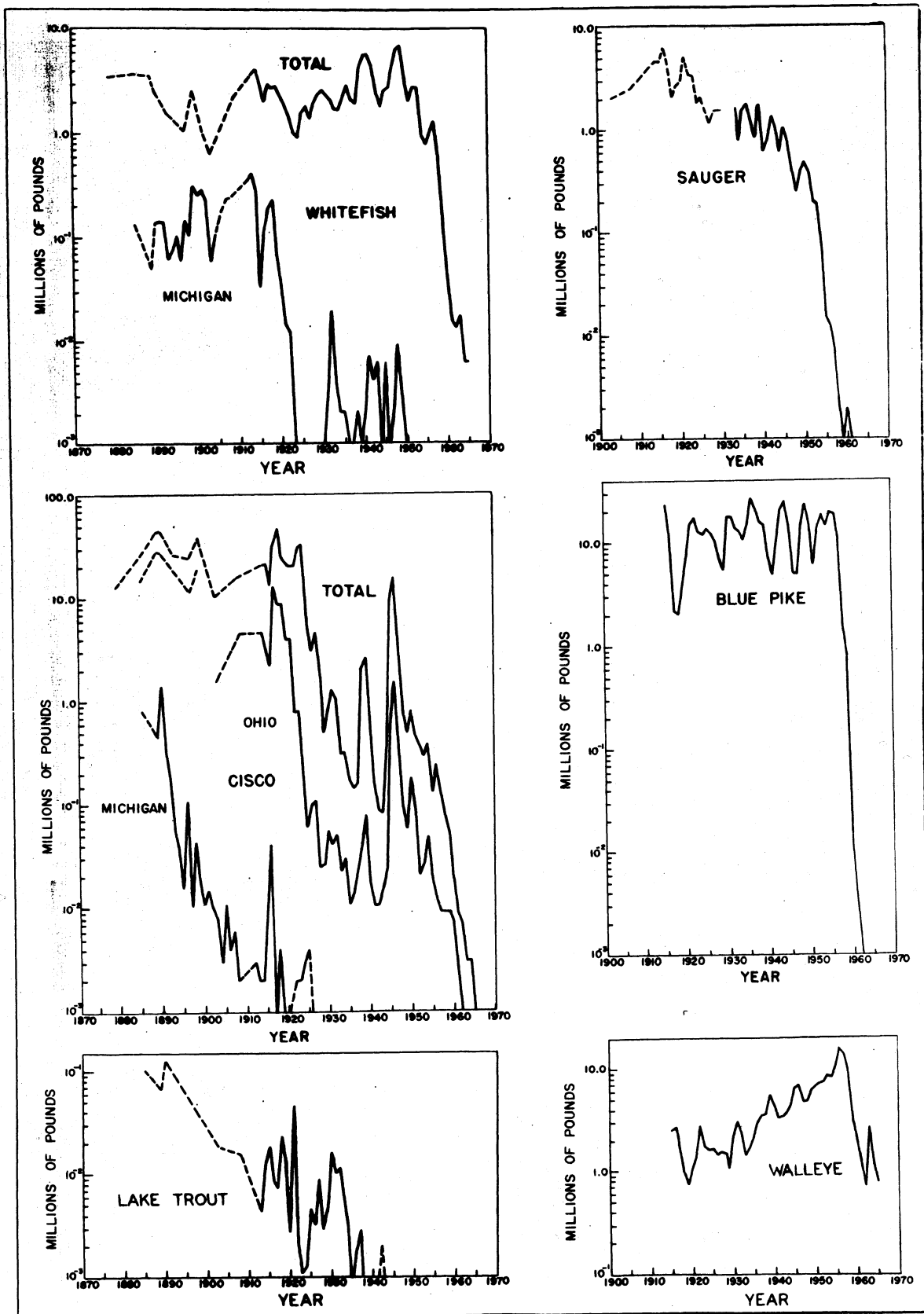


FIG. 5. Commercial production of blue pike, cisco (lake herring), Lake trout, sauger, walleye, and whitefish in Lake Erie. Broken lines represent production during periods when annual data were not available.

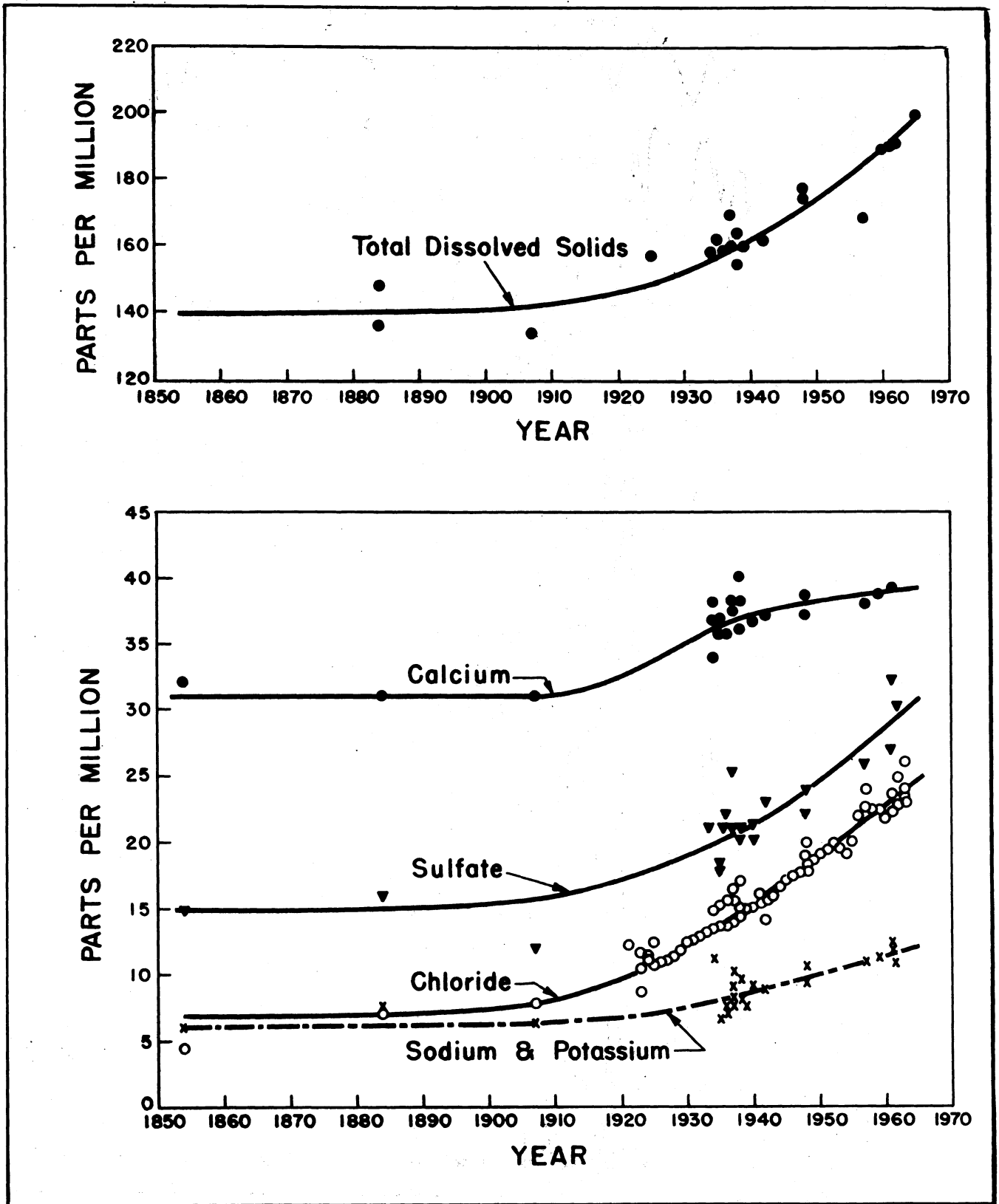


FIG. 6. Changes in the chemical characteristics of Lake Ontario (from Beeton, 1969).

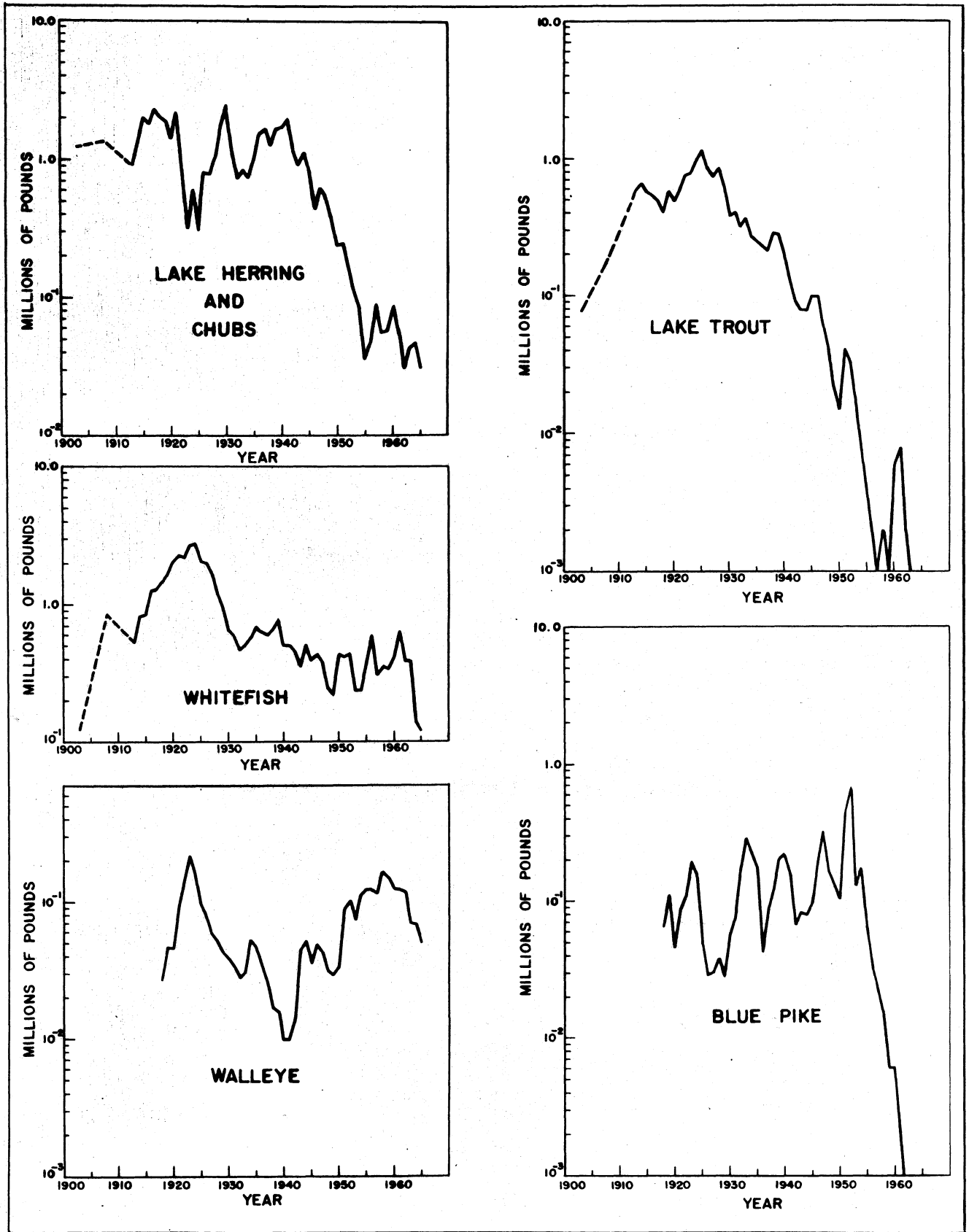


FIG. 7. Commercial production of blue pike, lake herring and chubs, lake trout, walleye, and whitefish in Lake Ontario.

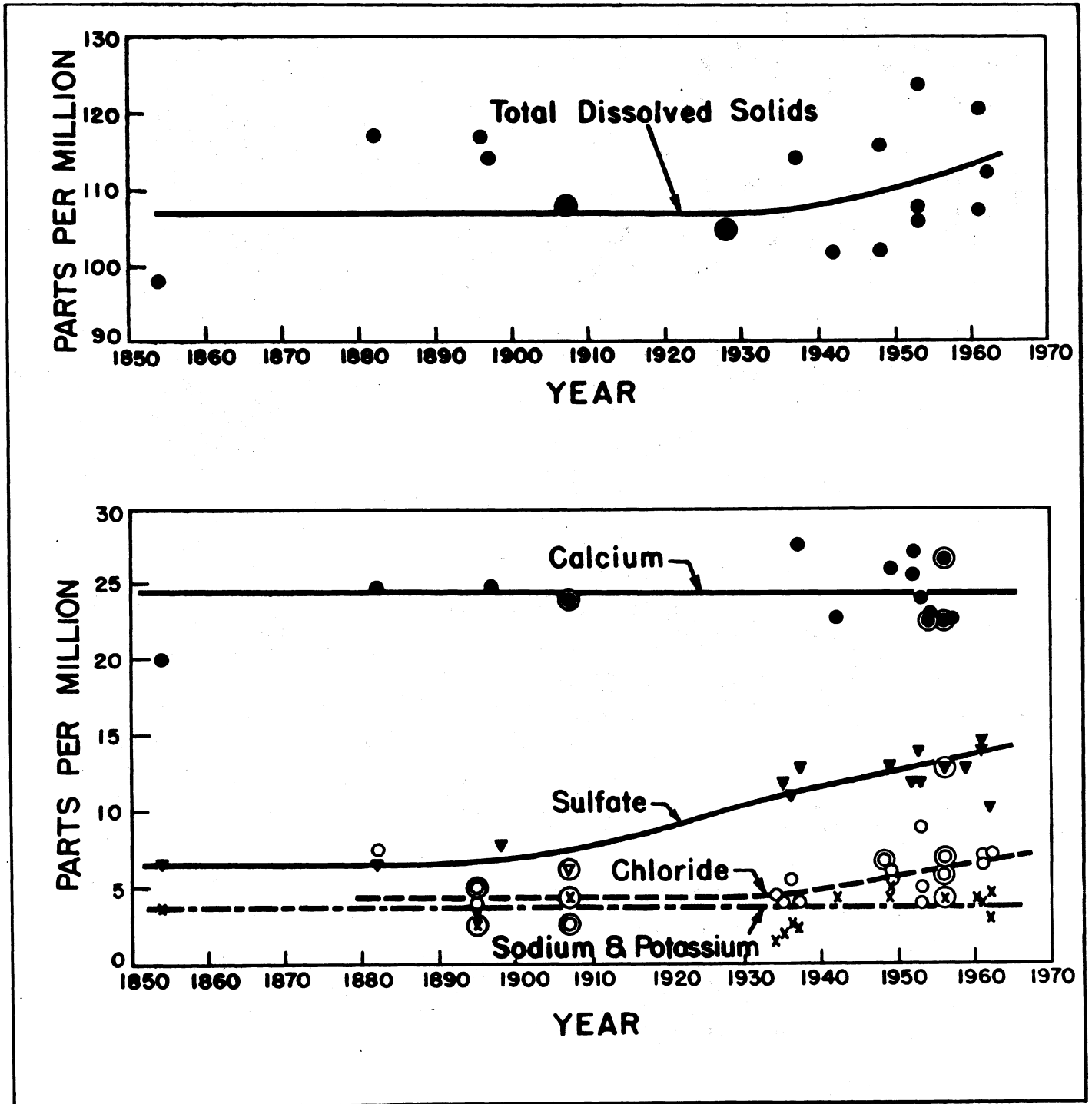


FIG. 8. Changes in the chemical characteristics of Lake Huron (from Beeton, 1969).

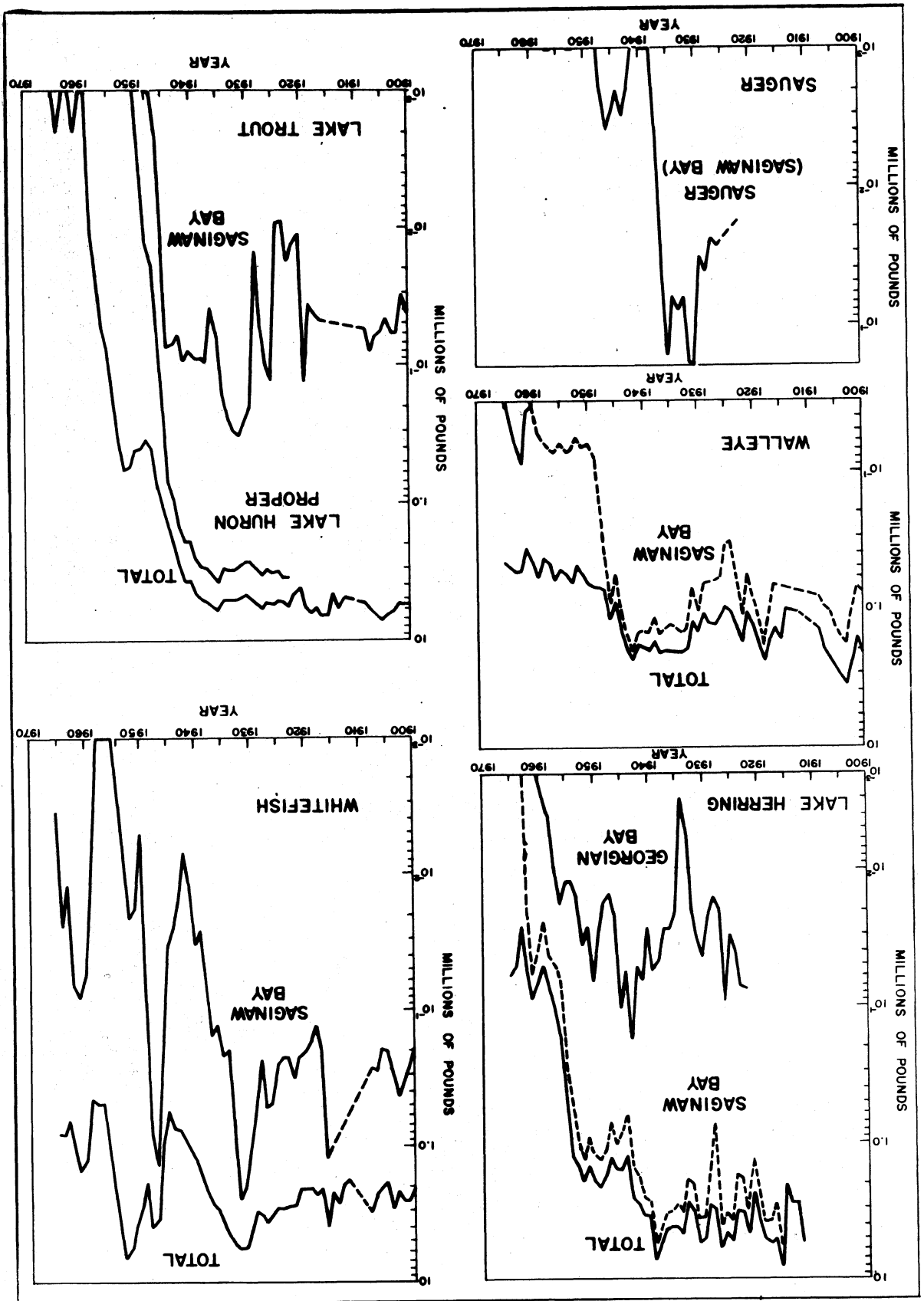


FIG. 9. Commercial production of lake herring, lake trout, sauger, walleye, and whitefish in Lake Huron.

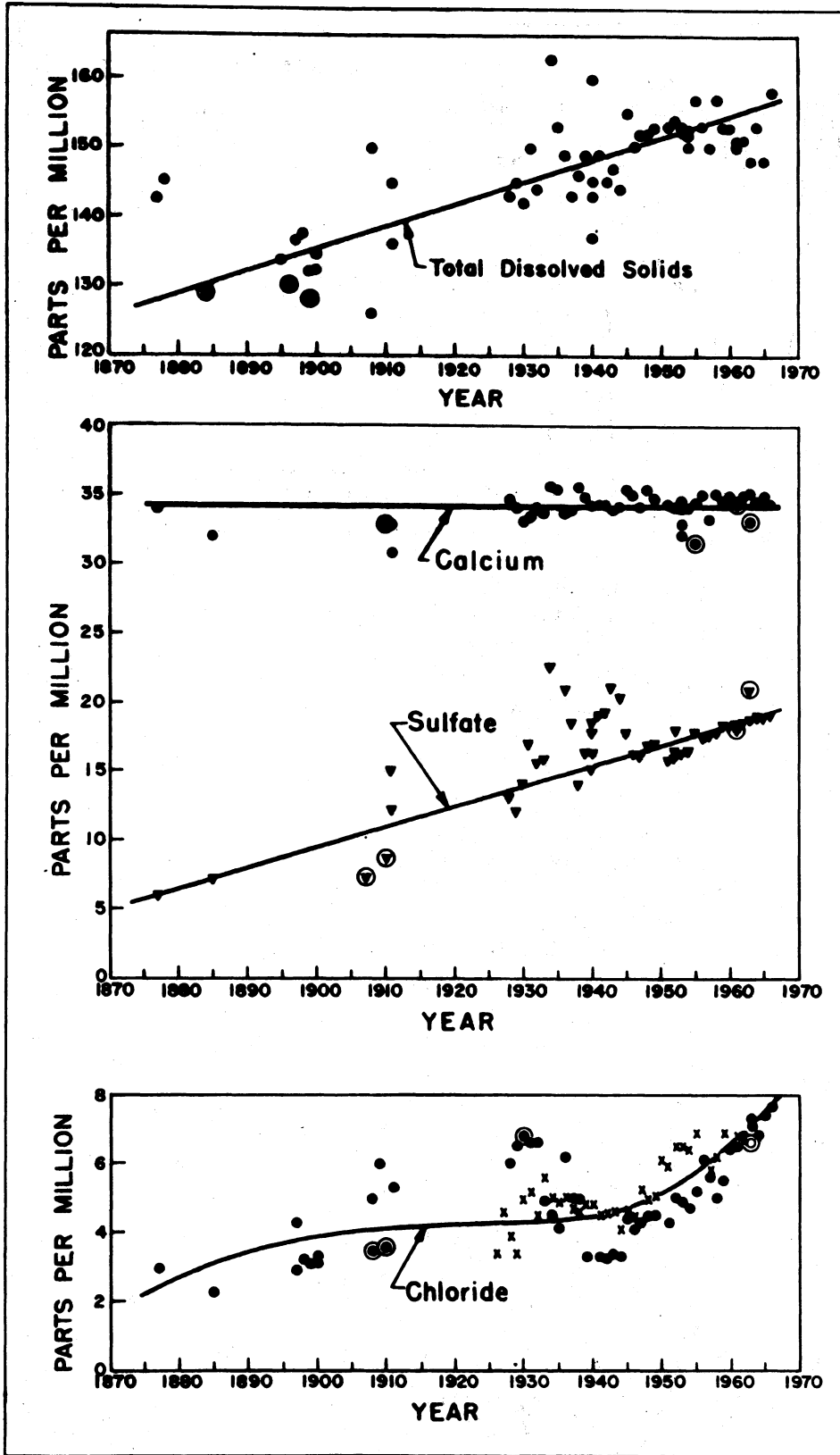


FIG. 10. Changes in the chemical characteristics of Lake Michigan (from Beeton, 1969).

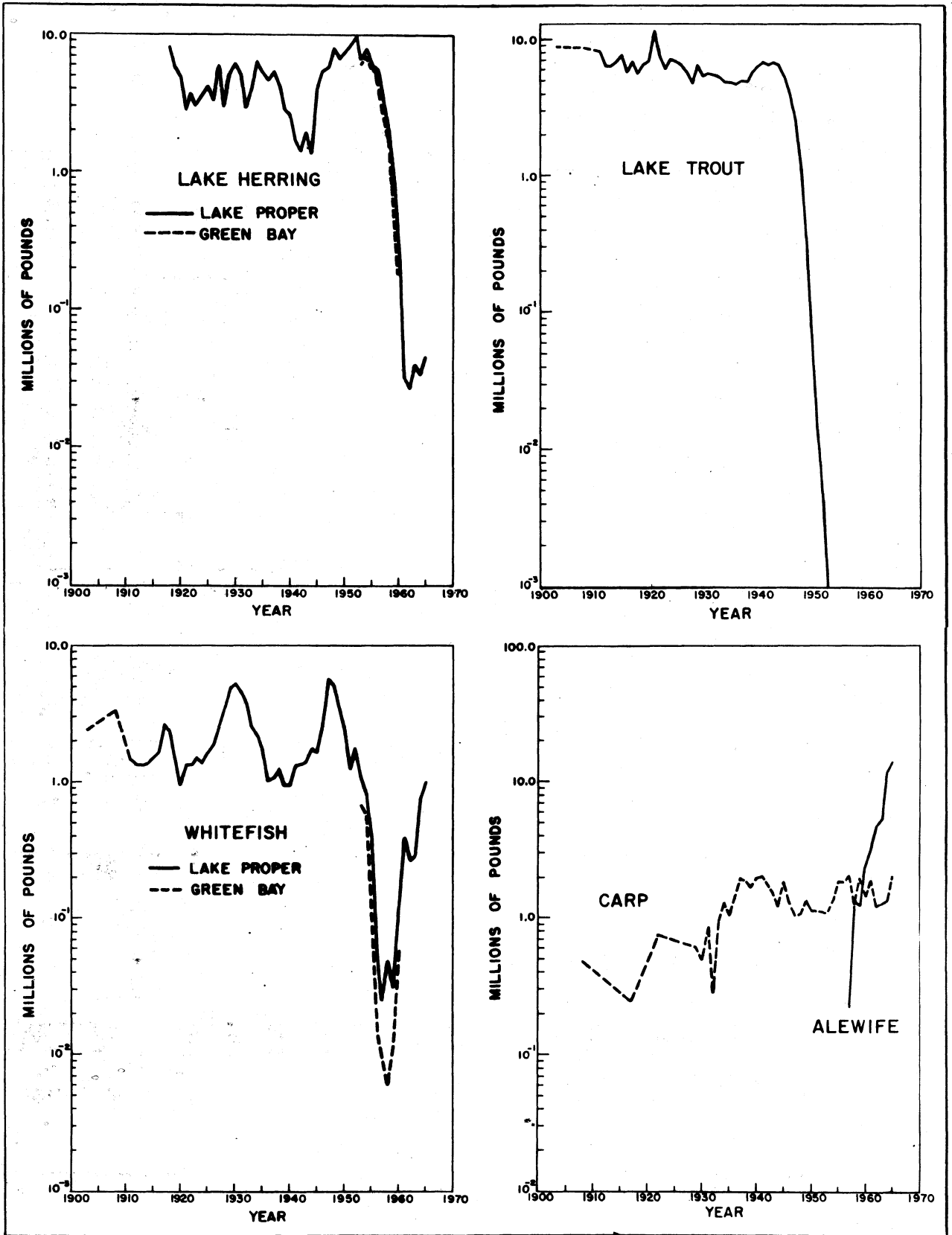


FIG. 11. Commercial production of alewife, carp, lake herring, lake trout, and whitefish in Lake Michigan.

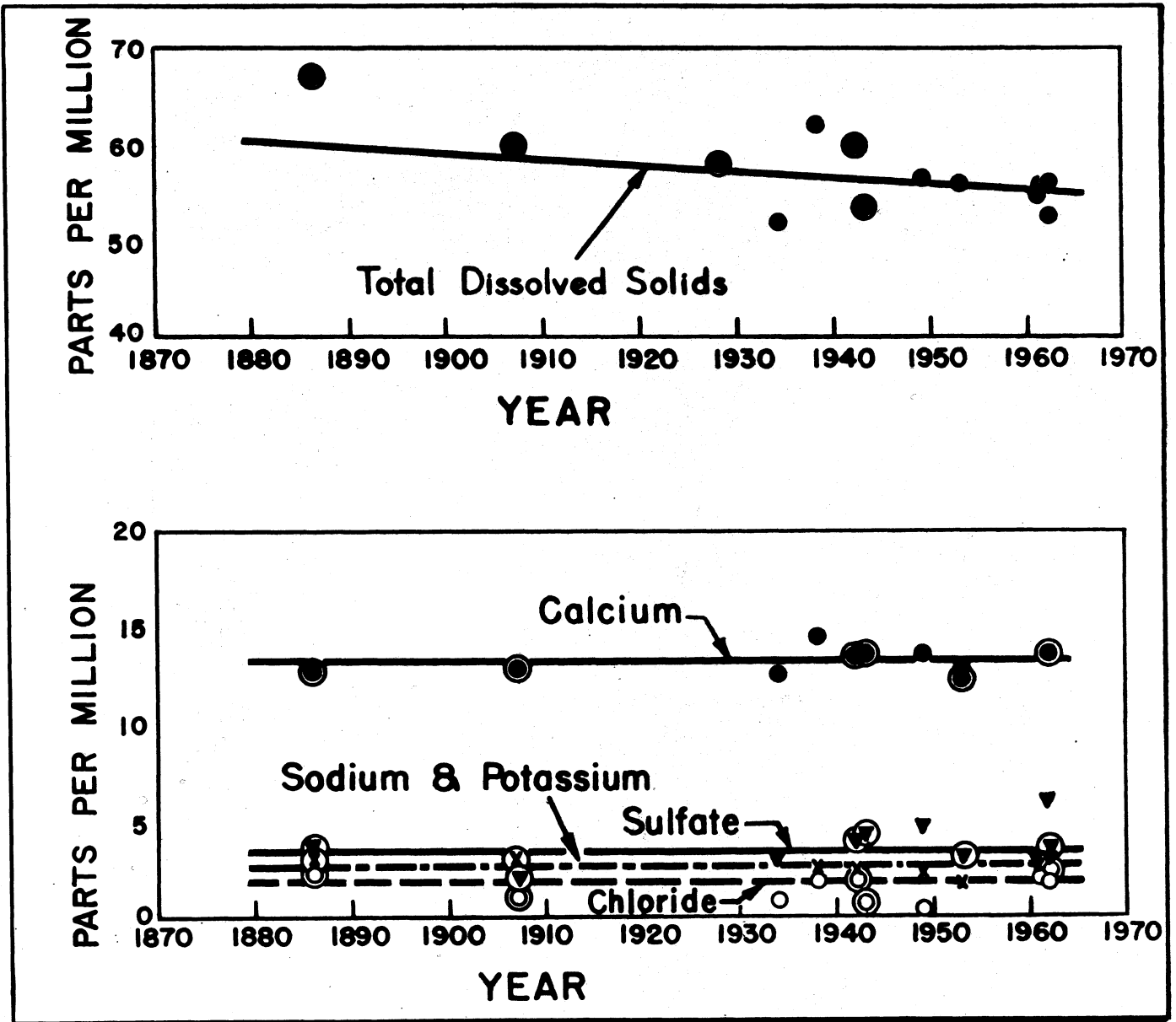


FIG. 12. Chemical characteristics of Lake Superior (from Beeton, 1969).

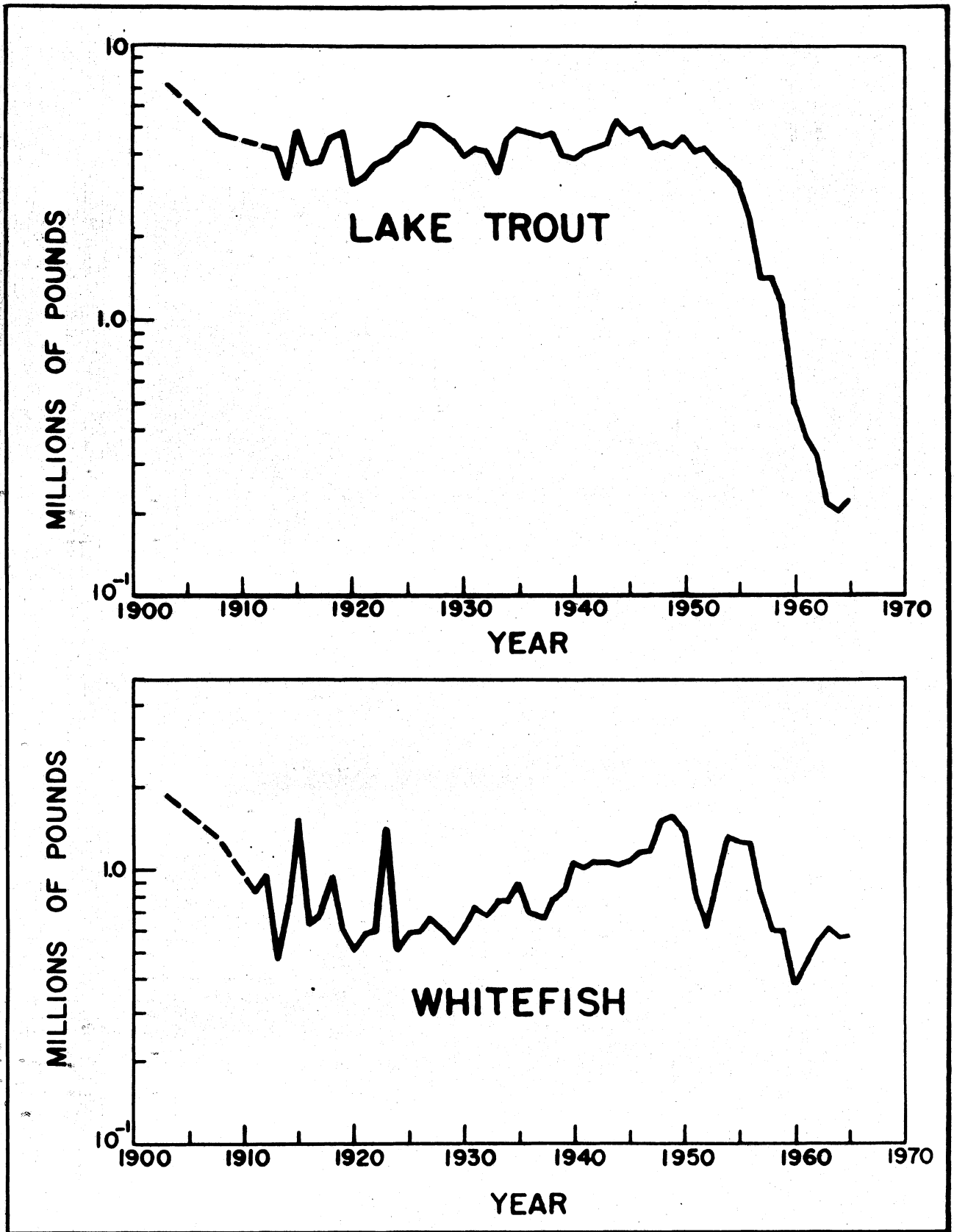


FIG. 13. Commercial production of lake trout and whitefish in Lake Superior, 1900-1965. Broken lines represent production during periods when annual data were not available.

TABLE I. Inputs of phosphorus from municipal, industrial and major tributary sources 1966-67
(short tons per year)

	Direct Municipal US Canada	Direct Industrial US Canada	Detroit River	Maumee River	Cuyahoga River	Other tributaries US and Canada	TOTALS			
Lake Erie	2710	30	Nil	20	17,600	2690	2600	4450	30,100	
	Direct Municipal US Canada	Direct Industrial US Canada	Niagara River	Oswego River	Genesee River	Twelve Mile Creek	Other Tribu- taries	TOTALS		
Lake Ontario	950	2010	Nil	180	7700	620	310	590	1320	13,680

Taken from: International Joint Commission. 1969. Pollution of Lake Erie, Lake Ontario and the international section of the St. Lawrence River. Int. Joint Comm., Summary Rept. Vol. 1, 150 p. mimeo.

TABLE II. Materials balance for lower Great Lakes 1966-67 (in thousands of short tons per year).[†]

	Chlorides [‡]	Total Dissolved Solids	Total Nitrogen	Total Phosphorus
Lake Huron output	1000	23,657	66	2.2
Detroit River output	3300	29,000	126	17.6
Lake Erie				
Total input	4500	35,000	194	30.1
Total output	5000	36,000	85	4.7
Difference	500	1,000	109	25.4
Per cent difference or retained	11	3	56	86.0
Niagara River output	5200	38,000	95	7.7
Lake Ontario				
Total input	6900	46,000	173	13.7
Total output	6100	37,000	113	3.1
Difference	800	9,000	60	10.6
Per cent difference or retained	12	20	35	77.0

[†] from International Joint Commission Report on Pollution of Lake Erie, Lake Ontario, 1969.

[‡] The difference between the inputs and outputs of chlorides cannot be interpreted as an indication of the per cent retained, but as a measure of the reliability of the determination of the materials balance. The differences of 11 and 12 per cent between the total inputs and outputs for chlorides for both lakes provides a good example of this reliability. It is assumed that the determination of the materials balance for total nitrogen and phosphorus is of comparable reliability.