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SCIENTIFIC SURVEYS OF LAKE ERIE: A Historical Review

Prepared by

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Research vessel *Hydra* operated by The Ohio State University, Center for Lake Erie Area Research.

SCIENTIFIC SURVEYS OF LAKE ERIE:
A Historical Review

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INTRODUCTION

Biological and physical science investigations of Lake Erie are historically tied to the collapse of the commercial fishery and later to the advent of cultural eutrophication (excellerated aging of the lake) and other pollution problems, all stemming from human activities on the lake and in its drainage basin. As the shallowest, warmest, and most southerly of the Laurentian Great Lakes (Figure 1), for several millennia before European settlement Lake Erie had a natural propensity for higher biological productivity than the other lakes. However, draining of the coastal marshes and clearing of the upland forests for settlement in the 19th century accelerated the aging process as erosion carried nutrient-rich soils to the lake (Fuller et al. 1995). Early in the 20th century oxygen depletion was first noted in the hypolimnion and by the 1950s major shifts were observed in the lake's benthic fauna along with massive algal blooms and a reduction in the diversity of coastal wetland plants. At the same time, lake-wide declines in fish populations were recorded throughout the lake.

The first measurements of total phosphorus loadings in the 1960s indicated an annual input of 28,000 metric tons and open lake concentrations of phosphorus in excess of 60 μg liter^{-1}. Eutrophication models were developed which predicted that a phosphorus load reduction to 11,000 metric tons and concentrations lowered to 10–15 μg liter^{-1} would be needed to prevent nuisance algae and restore oxic conditions to the hypolimnion. Canada-United States agreements and coordinated plans were implemented to achieve these targets in the 1970s and by the 1980s significant environmental signs of lake restoration were documented (Herdendorf 1984; Dolan 1993; Richards and Baker 1993). However, colonization by invading dreissenid mussels in the 1990s confounded of results water-quality trend analyses based on phosphorus reduction models, which initiated a new direction of biological research. This paper traces the more important biological and limnological surveys that have taken place on Lake Erie over the past two centuries.

Lake Erie Hydrography

To place the history of Lake Erie biological investigations into perspective it is important to have some understanding of the physical features of the lake and how these factors influence the biotic communities of the lake. Lake Erie is one of the largest lakes in the world, ranking 11th by area and 17th by volume (Herdendorf 1990). As the southernmost of the Great Lakes, the Lake Erie basin was the first to hold meltwaters from the receding Wisconsinan glacier some 14,000 years ago—in response to crustal rebound the lake has had its present surface area and elevation for less than 3,000 years (Holcombe et al. 2003)—and as the shallowest (mean depth 18.9 m), it has the smallest volume (484 km^3) and shortest water retention time (2.6 years).

The water temperatures of Lake Erie have the widest seasonal fluctuation of the Great Lakes, and it is the only one that typically freezes from shore to shore (Bolsenga and Herdendorf 1993). Lake Erie lies between 41°21' N and 42°50' N latitude, and 78°50' W and 83°30' W longitude. It is a relatively narrow lake, with its long axis oriented east-northeast (Figure 2). This axis parallels the prevailing wind direction, which causes the lake to react violently to storms, with high waves and wide fluctuations in water level (over 4 m). Lake Erie is 388 km long, 92 km wide, has a surface area of 25,700 km^2, and a drainage basin of 78,000 km^2. Geomorphically, Lake Erie can be divided into three basins—western, central, and eastern—which has important implications for the eutrophication of the lake (Figure 2).

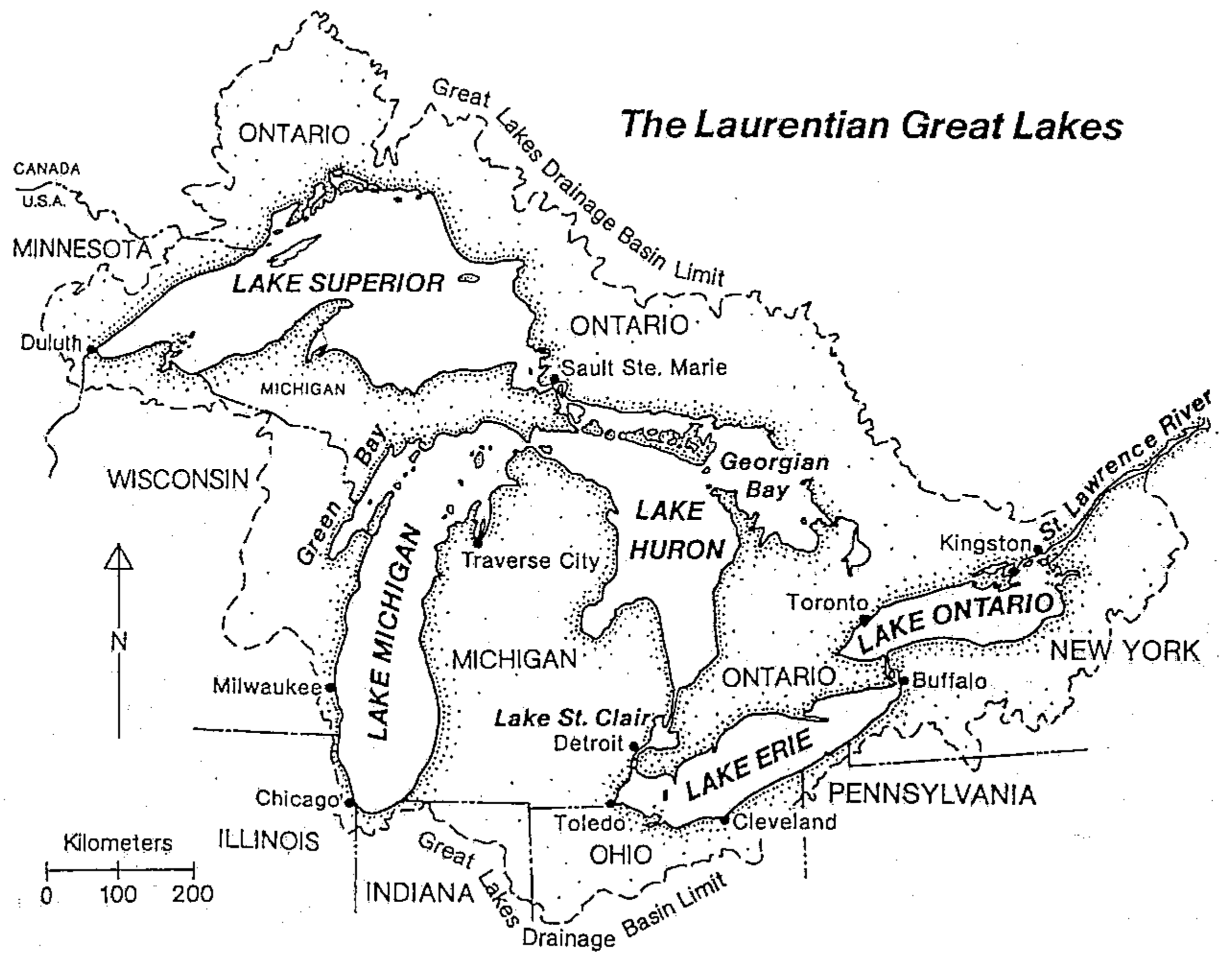


Figure 1. Drainage basin of the Laurentian Great Lakes.

Lake Erie Basins. The western basin, lying west of a line from the tip of Point Pelee, Ontario, to Cedar Point, Ohio, is the smallest and shallowest basin, with most of the bottom at depths between 8 and 11 m. In contrast with the other basins, a number of bedrock islands and shoals are situated in the western basin and form a partial divide between it and the central basin. The bottom of the western basin is flat except for the steep-sided islands and shoals in its eastern part. The deepest soundings are 19 m in a small depression north of Starve Island Reef and 16 m in another depression south of Gull Island Shoal (Herdendorf and Braidech 1972). The central basin is separated from the eastern basin by a relatively shallow sand and gravel bar between Erie, Pennsylvania and the base of Long Point, Ontario. The central basin has an average depth of 19 m and a maximum depth of 26 m. Except for the rising slopes of a low morainal bar extending south-southeast from Point Pelee, Ontario, the bottom of the central basin is extremely flat. The eastern basin is relatively deep and bowl-shaped; a considerable area lies below 35 m, and the deepest sounding of 64 m, "deep hole," is about 13 km east-southeast of Long Point.

Geological Structure. The varying depths of the Lake Erie basins are attributed to differential erosion by preglacial streams, glacial scour and deposition, and postglacial lacustrine processes. The strata underlying Lake Erie consists of Middle Paleozoic carbonate and shale formations that gently dip to the southeast under most of the lake. Resistant Silurian limestones and dolomites of the Niagara Escarpment control the lake's outlet at the Niagara River. The central and eastern basins of Lake Erie are underlain by nonresistant shale of Upper Devonian age. The southward advance of Pleistocene glacial ice was obstructed by the Allegheny Plateau and the ice was directed westward along the outcrop of the softer Upper Devonian shales. These shales were deeply eroded to form the narrow eastern basin. Farther west, where the dip of the beds is less and the width of the soft shale belt is greater, glacial erosion resulted in the broader, but shallower central basin. The Devonian shales trend inland between Cleveland and Sandusky, Ohio and the shallow western basin is underlain by Silurian and Devonian limestone and dolomite on the northward plunging end of the Findlay Arch. Glacial erosion had a

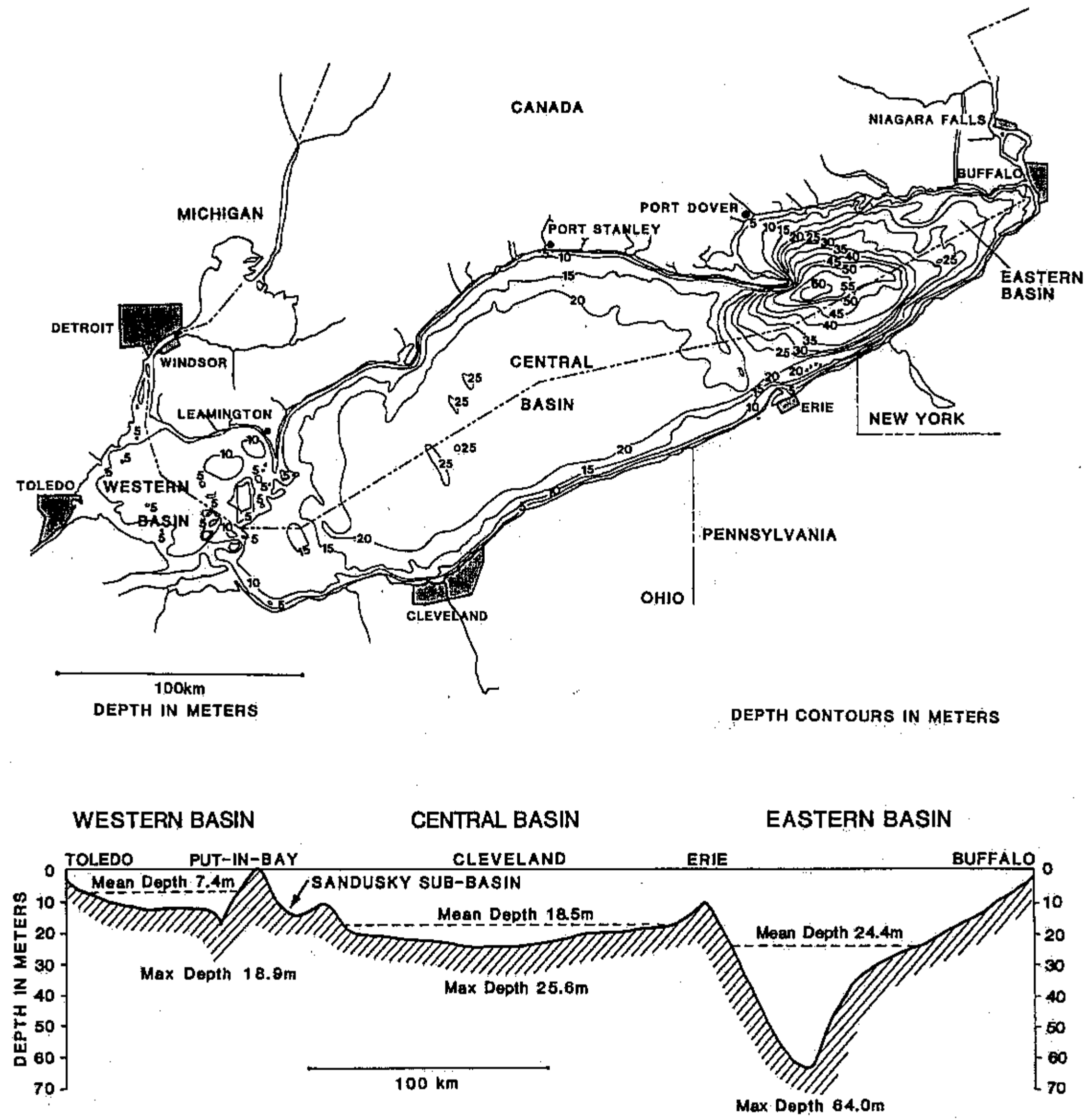


Figure 2. Bathymetric map (above) and cross-section (below) of Lake Erie.

relatively slight effect on these resistant rocks, except for impressive grooves on some of the islands. The islands in western Lake Erie are arranged in two north-south belts that correspond with the outcrop patterns of two resistant rock formations.

Bottom Deposits. The bottom sediments of Lake Erie consist of silt and clay muds, sand and gravel, peat, compact glacio-lacustrine clays, glacial till, shoals of limestone and dolomite, shelves of shale, and erratic cobbles and boulders composed chiefly of igneous and metamorphic rocks. The distribution of bottom sediments is related to the bottom topography. The broad, flat areas of the western and central basins, and the deep areas of the eastern basin have mud bottoms. Midlake bars and nearshore slopes are comprised of mostly sand and gravel or glacial till. Rock is exposed in the shoals of western Lake Erie, along the south shore of the central basin, and on both the north and south shores of the eastern basin.

Thermal Structure and Oxygen Depletion. In the western basin, winds tend to keep the shallow waters well mixed, which generally precludes the formation of a thermocline and the basin rarely experiences thermal stratification. However, the main inflows of water to the basin, the Detroit and Maumee Rivers, historically have carried heavy nutrient loads that stimulate excessive algal production (e.g., frequent blue-green blooms and dense growths of the attached green alga *Cladophora glomerata*). The Detroit River accounts for approximately 90% of the water inflow to Lake Erie and 37% of the total phosphorus load; whereas the Maumee River, although it is the largest tributary to the Great Lakes, supplies only 3% of the water and 12% of the phosphorus load to Lake Erie (Herdendorf 1984). Large sediment loads from these rivers, wave resuspension of fine-grained sediment, and algal masses produce turbid conditions in this basin. Under very quiescent conditions the western basin can stratify, causing unusually low oxygen concentrations. Britt (1955) showed that this condition resulted in massive die-offs of benthic invertebrates such as the mayfly *Hexagenia limbata* in the 1950s.

The central basin of Lake Erie is more susceptible to depletion of oxygen in waters near the bottom because it stratifies in summer, producing a relatively thin hypolimnion (mean 4.5 m), which is isolated by a strong thermocline from oxygen-rich surface waters (Figure 3). Oxygen is rapidly depleted from the bottom waters (Figure 4) at a rate of approximately 0.1 mg liter^{-1} day^{-1} as a result of decomposing organic matter, especially settled algal cells (Herdendorf 1984). Once the dissolved oxygen reaches zero and anoxic conditions exist, chemical processes change, which tend to self-perpetuate the nutrient availability. When the hypolimnion is oxic, soluble phosphorus is pulled from the bottom waters and precipitated as insoluble ferric phosphate. Under anoxic conditions, the reduction of iron causes precipitation of ferric sulfide freeing phosphate to dissolve in the hypolimnion waters (Figure 5).

Figure 5 shows the relationship between dissolved oxygen concentrations and the regeneration of soluble reactive phosphorus in the lower hypolimnion of central Lake Erie as observed in the late summer of 1974. As dissolved oxygen approached zero (as measured 1 m above the lake bottom), a sharp increase was observed in soluble phosphorus resulting in levels over 10 times background concentrations for oxic conditions. Figures 6 and 7 demonstrate the dramatic increase in phosphorus concentrations as the summer progresses and oxygen is depleted from the bottom waters. This regenerated phosphorus, which can amount to 2,500 metric tons, is approximately 25% of the total annual loading to the lake. As the lake cools in October, phosphorus is mixed throughout the water column at turnover, typically resulting in autumn algal blooms (Herdendorf 1980).

Although the central basin receives over 95% of its water from the western basin, the water is considerably less turbid and biologically productive. Unlike the western basin, tributary imputs do not have a significant influence on offshore water quality.

The eastern basin is considerably deeper than the other basins, which results in a thicker hypolimnion (mean 12.5 m) that is not readily subject to anoxic conditions.

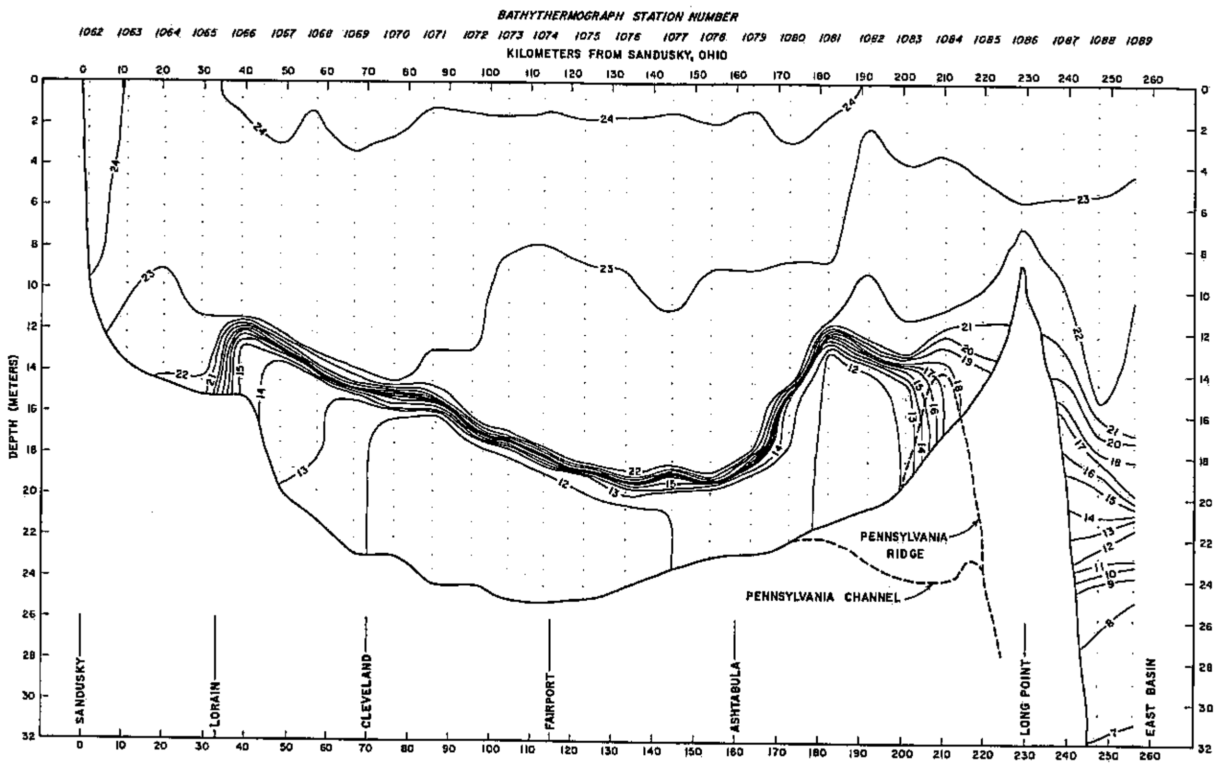


Figure 3. Temperature structure (°C) along the longitudinal axis (northeast-southwest) of the central basin of Lake Erie in August 13-14, 1957, showing the development of a strong summer thermocline and a thin hypolimnion (after Herdendorf 1967).

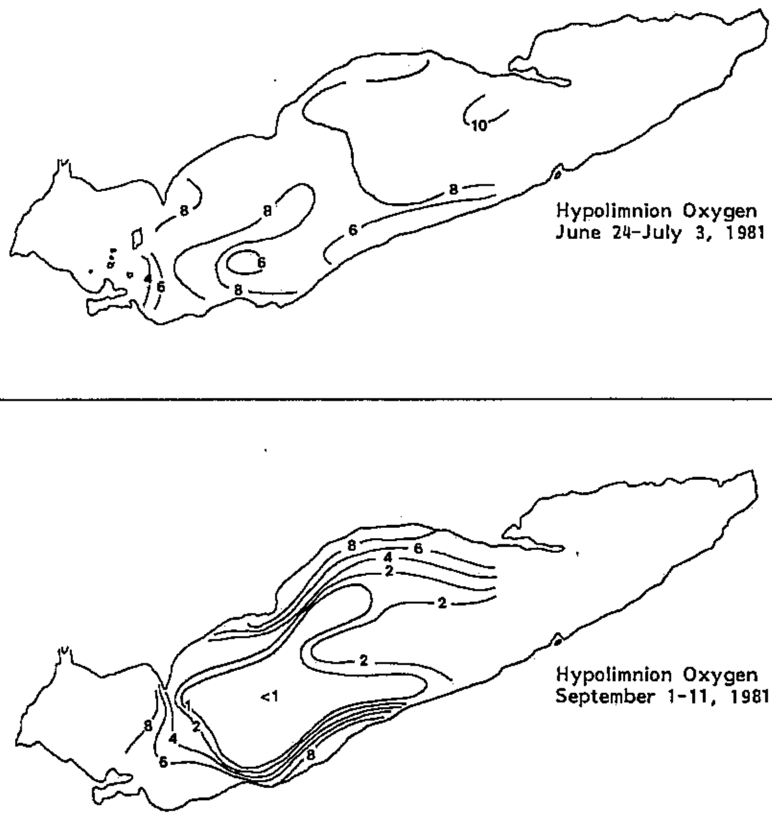


Figure 4. Hypolimnetic dissolved oxygen concentrations (mg liter^{-1}) at the onset of stratification (above) and shortly before turnover (below) in the central basin of Lake Erie (after Herdendorf 1984).

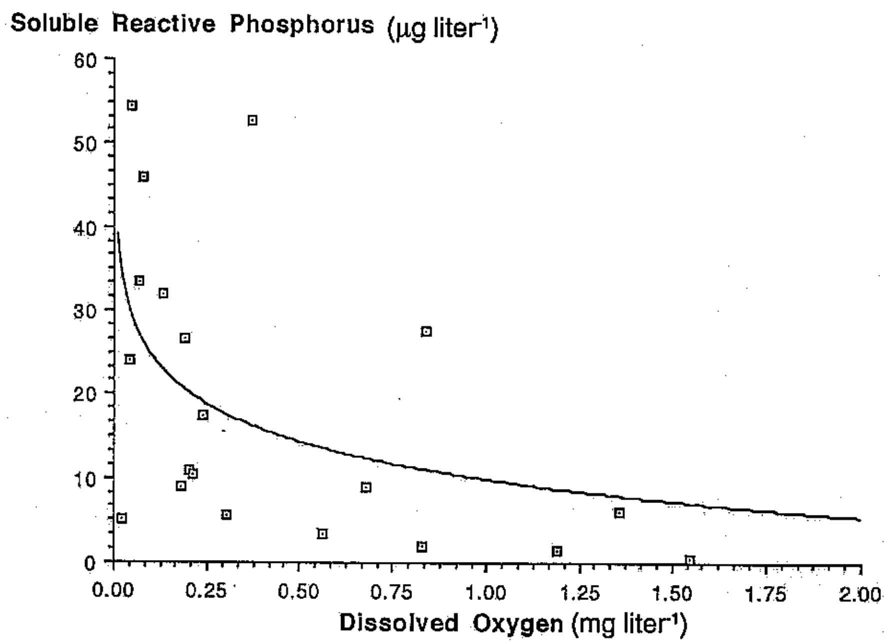


Figure 5. Relationship of dissolved oxygen concentrations to the regeneration of soluble reactive phosphorus (logarithmic curve fit) in the lower hypolimnion of central Lake Erie during the late summer of 1974 (Herdendorf 1980).

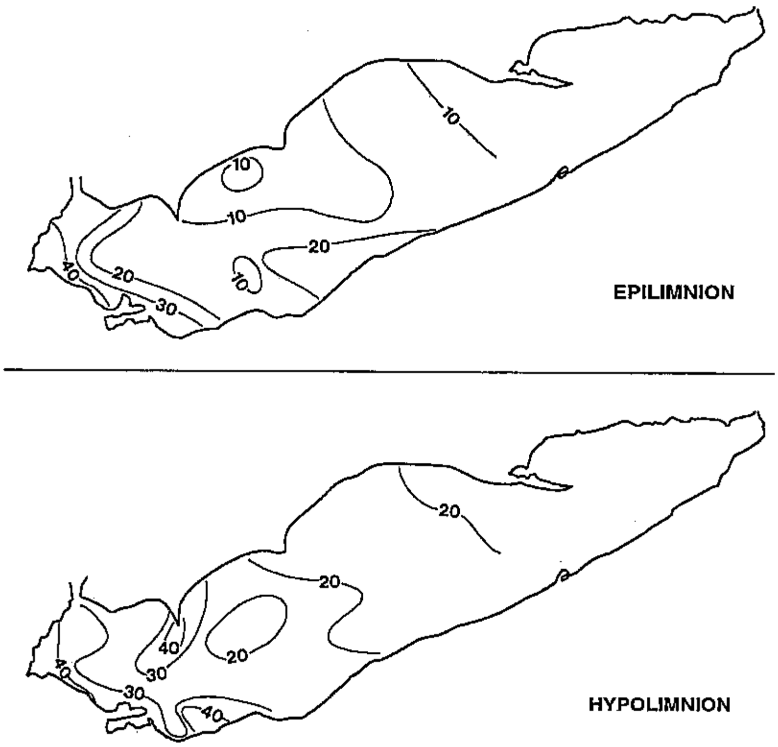


Figure 6. Comparison of epilimnetic (above) and hypolimnetic (below) total phosphorus concentrations (μg liter^{-1}) in the central basin of Lake Erie at the onset of stratification (June 1974), showing relatively similar concentrations under oxic conditions (after Herdendorf 1980).

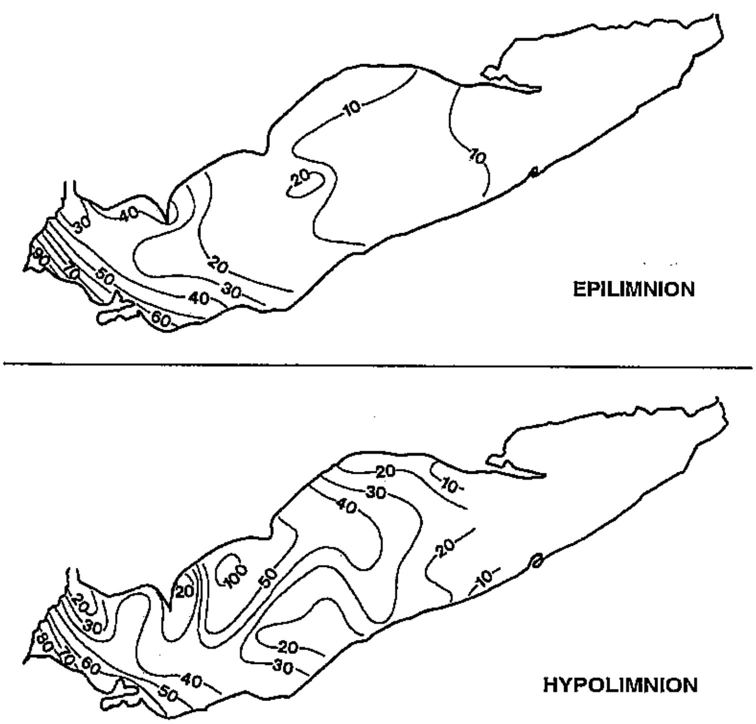


Figure 7. Comparison of epilimnetic (above) and hypolimnetic (below) total phosphorus concentrations (μg liter^{-1}) in the central basin of Lake Erie shortly before turnover (early September 1974), showing relatively large amounts of regenerated phosphorus under oxic conditions (after Herdendorf 1980).

Although the dissolved oxygen content in the hypolimnion declines in the summer (~0.05 mg liter^{-1} day^{-1}), it rarely drops below 50% saturation. The eastern basin receives over 95% of its water from the central basin, but in general it is less turbid and biologically productive than the other two basins.

Water Circulation. In terms of circulation, the western basin is strongly influenced by Detroit River inflow composed of three distinct water masses. The mid-channel flow predominates and is characterized by lower temperature, turbidity, specific conductance, total phosphorus, and chloride-ion concentration, and by higher transparency and dissolved oxygen than the flows on the east and west sides of the river (Herdendorf 1969). The mid-channel flow penetrates deeply into the western basin where it mixes with other masses and eventually flows into the central basin largely through Pelee Passage north of the islands. The mid-channel flow is flanked by side flows, which generally cling to the shorelines.

In the central basin the prevailing southwest winds parallel the longitudinal axis of the lake and initiate flows toward the east. Owing to the Earth's rotation, there is transport of water toward the American shore. The convergence of water along the basin's south shore results in a rise in lake level, which is equalized by the sinking of nearshore water masses (Figure 8). At the same time the lake level is lowered along the Canadian shore as surface water masses move offshore. Current measurements show a compensating subsurface movement of water toward the north and an upwelling along the Ontario shore. The thermocline is approximately 10 m shallower adjacent to the north shore (Figure 8) which has been interpreted as an upwelling influenced by prevailing southwest winds (Herdendorf 1970). This cycle of water transport in the central and eastern basins is analogous to following the coils of a spring as it tapers toward the eastern end of the lake.

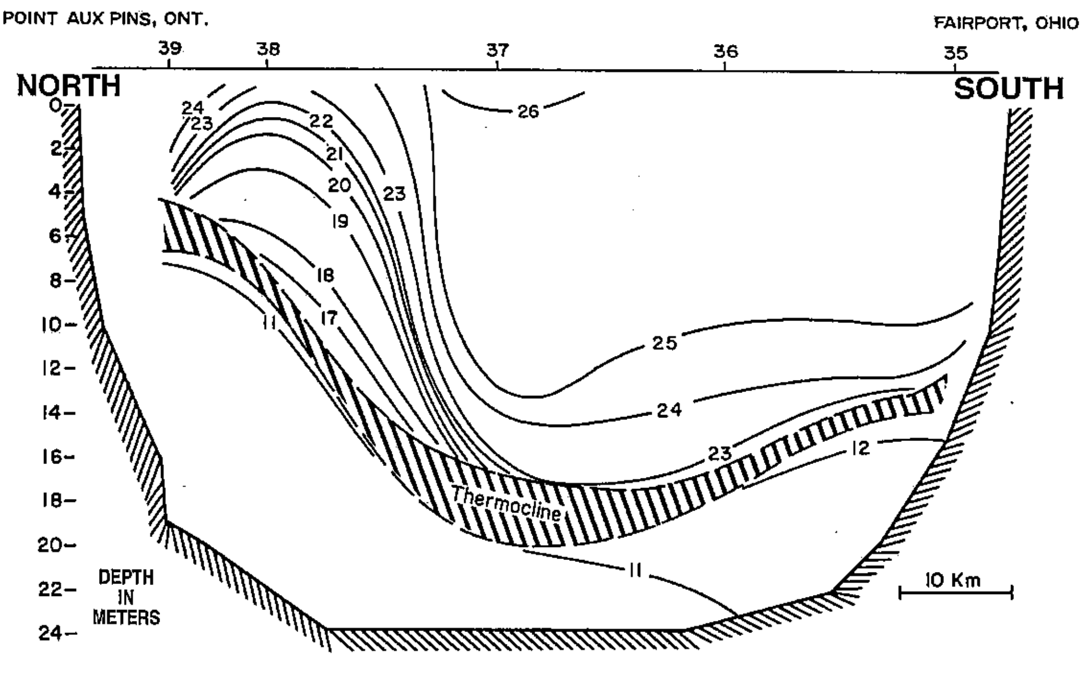


Figure 8. Cross-section of the north—south thermal structure (°C) of the central basin of Lake Erie on August 9, 1973, showing sinking epilimnetic water off the south shore and upwelling of hypolimnetic water off the north shore (after Zapoptsky and Herdendorf 1980).

HISTORY OF BIOLOGICAL AND LIMNOLOGICAL SURVEYS

Early Biological Investigations

Biological studies of Lake Erie span nearly two centuries, staring with the collection and description of fish species by LeSueur (1817, 1818), Rafinesque (1817, 1818), Mitchill (1824), Kirtland (1838, 1844), Cuvier and Valenciennes (1842), and Cope (1864, 1865). In all, a total of 15 new species of fish were described for Lake Erie and its connecting channels (Table 1). David Star Jordan (1878 with John H. Klippart, 1879, 1882) prepared reports on the fishes of Ohio for the Ohio Fish Commission and the Ohio Geological Survey that included Rafinesque's and Kirtland's work on Lake Erie species and details of their habitats. Early work on plankton typically related to public water supply of fisheries. Kellicott (1878) and Mills (1882) studied microscopic life in the Buffalo, New York water supply from Lake Erie and in the Niagara River, while Vorce (1881, 1882) examined microscopic forms from Lake Erie at Cleveland, Ohio.

In 1894, Dr. David S. Kellicott, zoologist at The Ohio State University, initiated field work in the Sandusky Bay region of western Lake Erie and requested authorization from the University to establish a field station at Sandusky. The Lake Laboratory was established there in 1896, with headquarters in the State Fish Hatchery. The Lake Laboratory was relocated a few kilometers to the east in 1903 on the Cedar Point sand spit. Here, it was the base for many studies of local flora and fauna under the direction of Dr. Herbert Osborn from 1899 to 1917, with publications on the fungi, algae, mites, insects, birds, protozoans, rotifers, bryozoans, sponges, and other forms (Langlois 1954). Next the Lake Laboratory moved to the Federal Fish Hatchery at Put-in-Bay and made studies there from 1918 to 1936 under Dr. Raymond C. Osburn, including those of fishes, parasites, mollusks, insects, and other aquatic forms. Completed in 1928, the Franz Theodore Stone Laboratory on Gibraltar Island in Put-in-Bay harbor became the permanent home of the field

Table 1. Fish species originally described from Lake Erie environs and their type locality.

Common Name	Scientific Name	Reference	Type Locality
Family Petromyzontidae (lampreys)			
Silver lamprey	*Ichthyomyzon unicuspis*	Hubbs & Trautman 1937: 53	Lake Erie at Toledo, OH
Family Acipenseridae (sturgeons)			
Lake sturgeon	*Acipenser fulvescens*	Rafinesque 1817: 288	Great Lakes (Lake Erie?)
Family Salmonidae (salmons); Subfamily Coregoninae (whitefishes and ciscoes)			
Cisco or Lake herring	*Coregonus artedii*	LeSueur 1818: 232	Lake Erie at Buffalo, NY
Family Hiodontidae (mooneyes)			
Mooneye	*Hiodon tergisus*	LeSueur 1818: 366	Lake Erie at Buffalo, NY
Family Esocidae (pikes)			
Muskellunge	*Esox masquinongy*	Mitchill 1824: 297	Lake Erie
Family Cyprinidae (minnows)			
Redside dace	*Clinostomus elongatus*	Kirtland 1838: 193	Lake Erie off Cleveland, OH
Silver chub	*Hybopsis storeriana*	Kirtland 1844: 71	Lake Erie
Emerald shiner	*Notropis atherinoides*	Rafinesque 1818: 204	Lake Erie
Blackchin shiner	*Notropis heterodon*	Cope 1864: 281	Detroit River at Grosse Isle, MI
Sand shiner	*Notropis stramineus*	Cope 1864: 283	Detroit River at Grosse Isle, MI
Mimic shiner	*Notropis volucellus*	Cope 1864: 283	Detroit River at Grosse Isle, MI
Longnose dace	*Rhinichthys cataractae*	Cuvier & Valenciennes 1842: 315	Niagara River at Niagara Falls
Family Catostomidae (suckers)			
Northern hog sucker	*Hypentelium nigricans*	LeSueur 1817: 102	Lake Erie
Family Atherinidae (silversides)			
Brook silverside	*Labidesthes sicculus*	Cope 1865: 81	Detroit River at Grosse Isle, MI
Family Percidae (perches)			
Blue pike	*Stizostedion vitreum glaucum*	Hubbs 1926: 58	Lake Erie off Ashtabula, OH

station, with Dr. Dwight M. DeLong (1937), Dr. Thomas H. Langlois (1938-1955), Dr. Loren S. Putnam (1955-1973), Dr. Charles E. Herdendorf (1973-1988), and Dr. Jeffrey M. Reutter (1988-) serving as directors. The early research accomplishments at the Laboratory are documented in a bibliography by Abrams and Taft (1971).

First Biological Survey 1898–1901

The first biological survey of Lake Erie was conducted from 1898 to 1901 under the auspices of the U.S. Fish and Fisheries Commission. In 1898 Professor Jacob E. Reighard of the University of Michigan was placed in charge of a staff of competent, but uncompensated, scientists and a laboratory at Put-in-Bay on South Bass Island to investigate the reasons for a decline in commercial fish species. The survey was organized to examine the conditions for fish life and the chain of biological relations existing in the lake and tributaries that sustain the fishery. Operating mainly in the western basin from the steamer *Shearwater* (Figure 9) for four years, the survey produced much useful information about the organisms in the lake, but the original plans for a unified program of research were not realized (Wright 1955). However, methods were developed for the quantitative study of plankton (Reighard and Ward 1901) and their report of exceedingly abundant planktonic algae, with respect both to number of individuals and species, was one of the first signs of eutrophication. The results of this survey are discussed by Stuckey (1988). Following the abandonment of the laboratory in 1902, limnological investigations of a survey type were not taken up again until 1926.

Western Lake Erie Limnological Surveys 1926-1930

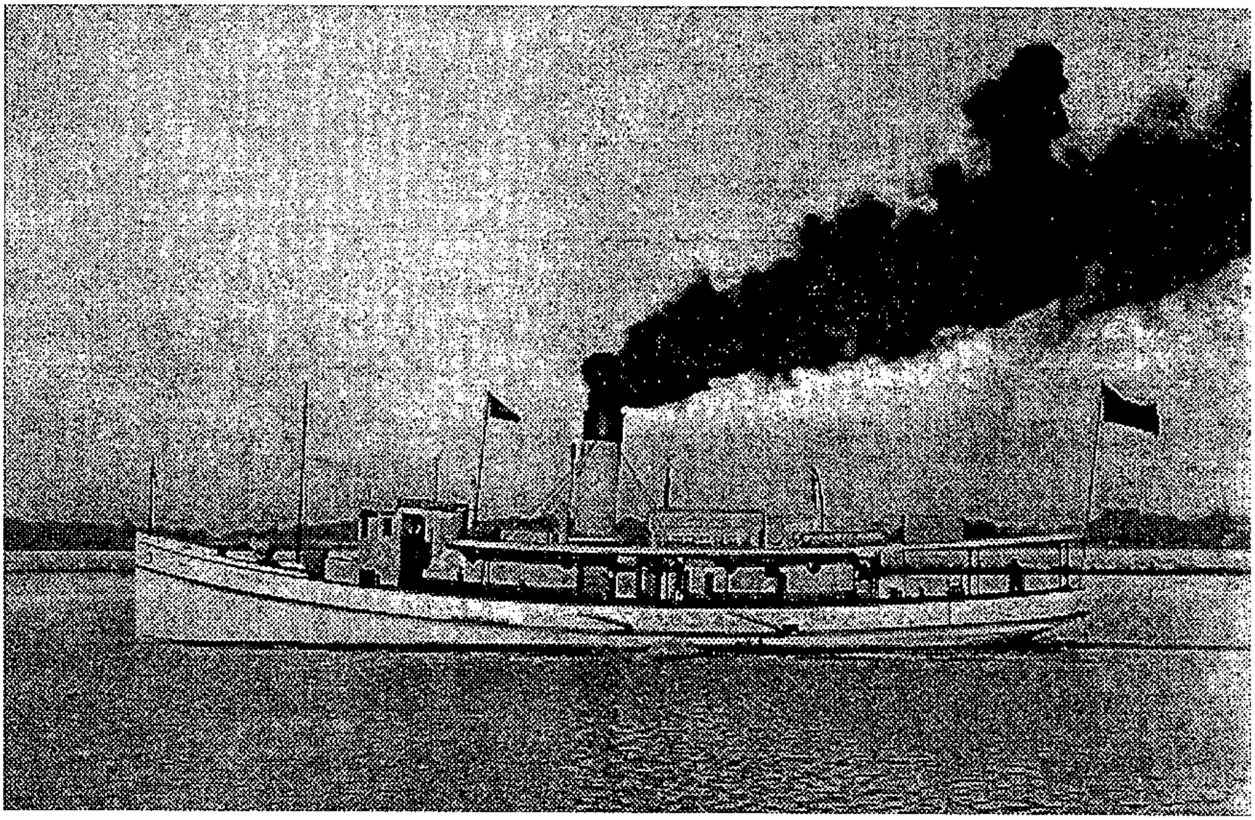
Limnology is that branch of science which attempts to describe lakes as ecological systems, involving biological, physical, and social processes as they influence lakes and their drainage basins. The first comprehensive limnological surveys of Lake Erie were undertaken in 1926–1930 by the U.S. Bureau of Fisheries (Figure 9) in cooperation with state agencies (Tidd 1928; Fish 1929a, b; Wright and Tidd 1933; Tiffany 1934, 1937; Wright 1955; Fish and Associates 1960). During that period Stillman Wright, fisheries biologist with the U.S. Bureau of Fisheries directed investigations in western Lake Erie, while Charles J. Fish, Director of the Buffalo Museum of Science, led a team of scientists working in central and eastern Lake Erie. For many decades Lake Erie supported a highly productive commercial fishery, but starting in the 1880s an alarming decline occurred in production of the more highly prized fish species, particularly lake whitefish (*Coregonus clupeaformis*). With the decrease in the supply of whitefish, the cisco (*Coregonus auredii*) was sought in increasing intensity, and this species held first place in production in Lake Erie until it suddenly became almost commercially extinct in 1925 (Wright 1955, Hartman 1973). The collapse of the cisco fishery was the impetus for the limnological survey that took place throughout the lake for the next five years.

Evidence of pollution was found in most of the lake's harbors and its major tributary streams, particularly high numbers of tubificid worms, but very few detectable problems were noted in the open lake. Unfortunately phosphorus was not one of the parameters measured during these surveys, but dissolved oxygen measurements showed a small area of near-anoxia in the bottom water (0.8 mg liter^{-1}) at the western edge of the central basin. Elsewhere in the central basin hypolimnion, the lowest value was 4.4 mg liter^{-1} at a station 40 km north of Cleveland, Ohio.

The criteria of pollution employed by Wright (1955) were as follows: A mud bottom having less than 100 tubificid worms and more than 100 *Hexagenia* mayfly nymphs per square meter was considered to be free from pollution; a larger number of tubificids and smaller number of *Hexagenia* was regarded as evidence of pollution. Three degrees of pollution were recognized, based on the number of tubificids per square meter, as follows: light pollution, 100-999; moderate pollution, 1,000-5,000; heavy pollution, more than 5,000. On other than mud bottoms, only the tubificids were used as a criterion of pollution.

In the western basin, conditions in the lower parts of the Maumee and Raisin Rivers, and small areas of the lake near their mouths, were found to be to polluted and unfavorable to all but the most tolerant fish species by reason of low dissolved oxygen and the deposition organic debris and silt. Wright (1955) saw these harmful results of pollution as being offset by the increases in planktonic organisms, which are used by all juvenile fish and the adults of certain species. The overall conclusion of the surveys, in view of the tendency of the harmful and helpful effects to balance each other, was that it seemed highly improbable that pollution in the western part of the lake was the controlling factor in the depletion of the fishery of Lake Erie.

Need for Investigation. In the introduction to the final report on the limnological survey of western Lake Erie, Wright (1955) points out that the fishes of the Great Lakes constitute a natural resource of immense commercial and recreational value. Conservation of this resource had become a major problem confronting various governmental agencies in Canada and the United States.



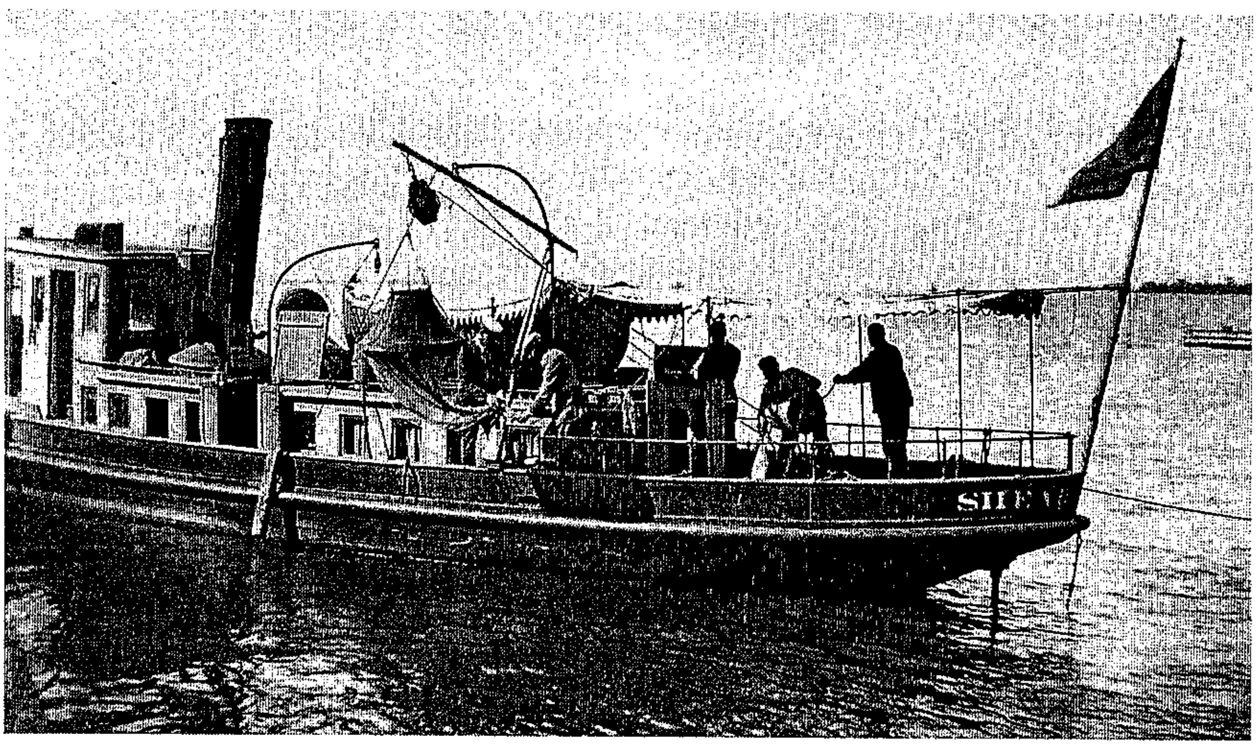


Figure 9. **U.S. Bureau of Fisheries steamer *Shearwater*, a 29-m vessel of 95 gross tons, used to conduct Lake Erie surveys from 1898 to 1930. Upper view in eastern Lake Erie during 1928 survey (after Fish 1929a). Lower view shows the deployment of a plankton net at the Bass Islands in 1901 (after Reighard and Ward 1901).**

For a period of 50 years (1875-1925) the average annual production of commercial fish in the Great Lakes was nearly 50,000,000 kg, and in many years Lake Erie accounted for roughly one half of the total catch. As early as the decade prior to 1870 there was definite evidence of a decline in the abundance of fish, but production was been maintained at a high level by increasing the intensity of fishing effort, and by seeking the less desirable species.

Concern had been felt particularly for the fishery of Lake Erie because of the great decline in the highly prized whitefish and cisco. Milner (1874) reported the presence of a lucrative whitefish fishery in Detroit River, but in the last decade of the century, this fishery was abandoned as a commercial venture and there was evidence of depletion in Lake Erie (Rathbun and Wakeham, 1897). With the decrease in the supply of whitefish, the cisco was sought with increasing intensity, and this species held first place in production in Lake Erie until it suddenly became almost commercially extinct in 1925 (Van Oosten, 1930). Certain other species had shown unmistakable evidences of depletion. For more detailed information on the fishery, the reader may refer to Koelz (1926), U.S. Tariff Commission (1927), Higgins (1928a and 1929), Van Oosten (1929a), and Fiedler (1931).

Following the virtual collapse of the cisco fishery, fishermen, conservation officers, and fisheries biologists alike realized the necessity of a scientific investigation to determine the cause or causes of the decline of the fishery, and to determine possible remedial measures. Since depletion was first noted, two possible explanations have been especially prominent in discussion of the problem: (1) excessive fishing and destructive methods of fishing and (2) pollution of the tributaries and of the lake by domestic sewage and industrial wastes. Fishermen, particularly, were persistent in their claim that pollution had made parts of the lake unsuitable for fishes. It was held that the deposition of sludge had rendered large areas unfit for spawning; that there was not sufficient oxygen in the water; and that the quality and quantity of food had declined. Further, many claimed that poisonous substances had caused the death of large numbers of fish. Attention was directed to the western part of the lake because of a number of conditions which made it especially subject to pollution, and because of its importance in the fishery.

The conditions which made western Lake Erie especially subject to pollution were: (1) the presence of large industrial communities on the shores of Maumee, Raisin, and Detroit Rivers, which empty into this part of the lake; (2) the extreme shallowness and consequent small volume of water; and (3) the presence of two peninsulas and numerous islands which partially separate this area from the rest of the lake and which tend to prevent free outflow of the water. The importance of western Lake Erie in the fishery arises from the facts that (l) large numbers of fish are caught there, (2) the area is used as a spawning ground by all of the commercial species except, possibly, the blue pike (*Stizostedion vitreum glaucum*). Because of the supposed intensity of pollution in Lake Erie and the unusual opportunity for it to be harmful to fishes, particularly during their early stages of development, it was generally believed that investigation should center in the western part of the lake. It was also believed that if it could be shown that pollution was not the controlling factor in the depletion of the fishery here, pollution could be ruled out as a controlling factor elsewhere in the Great Lakes.

In his comprehensive report of the limnological survey of western Lake Erie during the period 1926 through 1930, Stillman Wright (1955) noted that at the time the survey was begun the plants and animals of the lake were quite well known from a qualitative point of view, but quantitatively very little information was available. Almost nothing was known of the actual or relative abundance of plankton, or its vertical, horizontal or seasonal distribution and still less was known of the abundance and distribution of benthic organisms. The chemistry of the lake's water with respect to dissolved gases and nutrients, particularly near sources of pollution and tributary mouths, had not been studied. In summary, Wright concluded there was a general lack of definite information regarding the suitability of the lake for fishes.

Rather than an integrated investigation, in a sense the western Lake Erie survey was a series of investigations. Although ultimate objective to ascertain the reasons for the decline in commercial fish stocks remained the same, the personnel of the scientific staff, the bases of operation, and methods of procedures changed from time to time. The survey can conveniently be subdivided into the accomplishments of the five field seasons from 1926 to 1930. The following summary of each field season was derived from Osburn (1926a,b) Tidd (1928,1955), Wickliff (1931), Wright and Tidd (1933), Tiffany (1955), Wright (1955) and Ronald L. Stuckey (personal communication).

1926 Field Season. At the urgent request of fishermen and others interested in commercial and game fishing in Lake Erie, in the summer of 1926 the Ohio Division of Fish and Game undertook a study of the extent and degree of pollution in the Lake, with special reference to its effect upon the fishes. Dr. Raymond C. Osburn, Head of the Department of Zoology and Entomology at The Ohio State University was asked to direct the study, which he generously agreed to do without remuneration. The scientific staff and field of investigation included: R. C. Osburn, The Ohio State University (benthic fauna), Ralph V. Bangham, College of Wooster (zooplankton), Lewis H. Tiffany, The Ohio State University (phytoplankton), H. R. Eggleston, Marietta College (bacteriology), and B. P. Hanan, Rocky River High School (water chemistry).

As early as 1920, Dr. Osburn had obtained funds from the State Bureau of Fish and Game to study fisheries related problems, particularly the recovery of waters that had been cleared of pollution. At that time the Bureau was undertaking a vigorous campaign to clean the streams of the state, but no data was available on how long it would take for such waters to become productive of fish life nor how long a time should elapse before fish could successfully be introduced to the rehabilitated streams. As a member of the Bureau's advisory board he was able to guide many of the activities of this agency. From 1920 to 1923, Dr. Osburn and Edward L. Wickliff (originally with the Department of Zoology and Entomology at the University and later with the State Division of Fish and Game) conducted research on the fishes of Ohio with special emphasis on numbers, condition, breeding, and food supply of game fishes. In 1925, Milton B. Trautman joined this survey and their combined efforts resulted in the publication of "A Revised List of the Fishes of Ohio" (Osburn et al. 1930) and *List of the Fishes of Ohio* (Wickliff and Trautman 1934). As a part of the survey, Dr. Lewis H. Tiffany (1921) of The Ohio State University investigated the algal food of young gizzard shad (*Dorosoma cepedianum*).

Dr. Osburn, as Director of The Ohio State University's Franz Theodore Stone Laboratory at Put-in-Bay, offered the facilities of the laboratory for the scientific staff. The steamtug, *O. H. Perry*, and the motor cruiser, *Veto*, of the State of Ohio's fleet, were used for work on the Lake. Eleven days in the month of August 1926 were devoted to fieldwork. A total of 48 stations were visited. These were established at points in the open Lake and near sources of known pollution so that some determination could be made as to the extent of the pollution. Observations were made of temperature, dissolved oxygen, hydrogen ion concentration (pH), benthic organisms, bacteria, phytoplankton, and zooplankton. The studies of benthic organisms and plankton were quantitative only in a general way.

The results of this preliminary study were printed in mimeographed form (Osburn, 1926a,b), and were reviewed in the appropriate chapters in Wright (1955). In summary, numerous localities were noted where the dissolved oxygen was considered reduced, but none where the oxygen deficiency alone would prevent fishes from existing. The lowest observed was 3.7 mg liter^{-1}. Oxygen was found in sufficient quantity almost everywhere, even over bottoms that were foul with decaying matter. In the deeper water of the open lake, even when not far offshore from sources of pollution, the oxygen content of the water was never dangerously low. There was an abundance of oxygen near the mouth of Detroit River; in one sample the water was completely saturated. No acid water was encountered; the hydrogen-ion concentration ranged from 7.0 to 8.6 pH units.

Sulfur bacteria were found abundantly in the most polluted areas, and the colon bacillus, *Bacillus coli*, was widely distributed. Enclosed areas and regions near large cities showed large numbers of sewage bacteria, but the number diminished rapidly as the distance from sources of pollution increased. Pollution of shore waters and enclosed bays rendered these areas unsafe for recreational purposes and unsatisfactory as a source of municipal water supply. The study also showed that plankton was scanty near the mouth of Detroit River, but very abundant in certain areas where there was definite evidence of pollution.

Considerable areas of the lake bottom near the large cities, particularly in the harbors and channels leading from them, were covered with organic debris, which made the area unsuitable for fish spawning. In some cases, as in Maumee Bay, the steamship channel tended to retain the suspended organic matter and permitted it to be carried much farther from the river than it otherwise would have been carried. The principal organisms present on the polluted bottoms were oligochaete worms.

The work by Osburn's team brought out clearly that the lake was heavily polluted near the large cities, and that the intensity of pollution diminished rapidly with increased distance from the sources. Aside from the reduction of space available to spawning fishes, pollution appeared not to be sufficiently intense or widespread to constitute a serious menace to life in the lake.

1927 Field Season. In 1927 active direction of field work was taken over by Mr. E. L. Wickliff of the Ohio Division of Fish and Game. However, Dr. R. C. Osburn retained close connection with the investigation in an advisory capacity. A field station was established at Sandusky, Ohio, and work was carried out in the autumn and winter of 1927. In addition to Mr. Wickliff, the scientific staff consisted of W. M. Tidd biologist and M. K. Young, chemist, both of The Ohio State University. During this season attention was given principally to the fishes themselves, rather than to environmental factors.

Study was made of the food and parasites of several fish species taken in Sandusky Bay and in the lake proper. Data on length and weight, and scales from a considerable number of fish were taken results The results of the fisheries studies were reported by Wickliff (1931). Other environmental studies were made by Wickliff's group in 1927, principally outside of western Lake Erie. Thus, the results were not discussed by Wright (1955).

1928 Field Season. In 1928 the base of operations was again shifted to Put-in-Bay, and a laboratory was established in the fish hatchery maintained by the State of Ohio. The personnel of the scientific staff were the same as in the preceding year. In the 1928 season, for the first time, parallel studies of the fishes and their environment were made. The principal immediate objective was to correlate the distribution and abundance of the larval, post-larval, and adult stages of the fishes with such environmental factors as temperature, currents, dissolved gases, plankton, and benthic organisms. Of necessity the limnological observations were made subordinate to those on the fishes.

The motorboat *Investigator* was outfitted especially for use of the scientific staff. Work was concentrated in the area west of Point Pelee, although some observations were made in the central basin of the lake. A large number of stations were established and these were visited at fairly regular intervals during the season in order to determine seasonal changes as far as possible. The results the fisheries investigations were reported by Wickliff (1931) and Tidd (1928) reported on zooplankton investigations in the west end of Lake Erie for the spring, summer, and fall of 1928. Large parts of the physical, chemical, and biological data were incorporated in the comprehensive report by Wright (1955).

1929 Field Season. In making plans for the 1929 field season, it was decided to continue the parallel studies of 1928, but to facilitate the work, the staff was divided into two groups. One group included those working in fisheries biology, and the other those working in limnology. At the request of the Ohio Division of Conservation, the United State Bureau of Fisheries assigned Stillman Wright to the task of directing the fieldwork in limnology, under the supervision of Dr. John Van Oosten, scientist in charge of Great Lakes fishery investigations for the Bureau of Fisheries. The Ohio Division of Conservation employed the other members of the staff, as well as bearing the costs of equipment and maintenance of the survey. This plan of administration was continued in 1930. Members of the scientific staff and their field of investigation included: Edward L. Wickliff, Chief, Bureau of Scientific Research, Ohio Division of Conservation (Director of the Survey); Wilbur M. Tidd, The Ohio State University (zooplankton); Lewis H. Tiffany, The Ohio State University (phytoplankton); William C. Beaver, Wittenberg College (bacteriology); Elbert B. Ruth, University of Wisconsin (benthic fauna); Doris Ann Wright, University of Wisconsin (plankton); and C. J. Munter, The Ohio State University (chemistry). The headquarters were established in the Ohio State Hatchery at Put-in-Bay. As in the earlier years, additional space and equipment were made available at the Stone Laboratory on Gibraltar Island. The use of two motorboats, *Investigator* and *Veto*, made possible independent but parallel studies of the fisheries and limnology phases of the survey.

The first observations were made on May 14 and the last on October 22. With minor exceptions the full staff was on duty from June 15 to September 15, and in the remaining time the program was carried on by Wilbur Tidd and Stillman Wright. The general plan of investigation was the same in 1929 and 1930. The details of station locations and frequency of observations are discussed under the 1930 field season. In addition to the observation of physical conditions at the time of sampling, samples were taken regularly for chemistry, phytoplankton, zooplankton, and bottom organisms. Bacteriological samples were taken at less frequent and regular intervals. The details of methods employed in the field and laboratory are presented by Wright (1955).

1930 Field Season. The same plan of administration was continued in 1930, but field investigations on fishes were discontinued, and the fisheries staff was engaged in studies of the collections made in the two preceding years. The limnological program was continued along essentially the same lines as in 1929. The scientific staff was also the same, with the exception that Beaver, Ruth, Tidd, and Tiffany were replaced by Barbara Metz, Winthrop College (phytoplankton); Elbert H. Ahlstrom, Marietta College (benthic organisms); Lee S. Roach, Ohio University (benthic organisms); and Doris Ann Wright, now with the Ohio Division of Conservation, (zooplankton).

The headquarters for the survey were established at the Franz Theodore Stone Laboratory on Gibraltar Island. The first observations were made on April 1 and the last on October 3. The full staff was in residence from June 15 to September 15; in the remaining time the program was carried out on a reduced schedule. Aside from the discontinuance of bacteriological work, and expansion of chemical work, the 1930 program was essentially the same as in 1929.

The general plan of investigation followed in 1929 and 1930 was based on a knowledge of the lake gained in the earlier years. It had been found that there was definite evidence of heavy pollution near the mouths of certain tributary streams, and that the intensity decreased rapidly with increased distance from the source of pollution. The open waters of the lake, far from large sources of domestic and trade wastes, were free from the more obvious evidences of pollution. In the open waters, only bacteriological analyses were adequate to show that the lake was contaminated by sewage.

To the survey planners, it seemed advisable, then, to divide western Lake Erie into sections, and to make parallel studies in each section. The way in which the lake was divided into 5 sections is shown in Figure 10. Western Lake Erie was defined as that part of the lake west of a line which touches the Canadian shore at 82°30' west longitude, runs due south to the International Boundary, and then to the west tip of Cedar Point. The sections were designated by names which described their positions in general: Island, Portage River, Maumee Bay, River Raisin, and Detroit River. Early in the season of 1929, a small number of stations were established, and with minor exceptions these were maintained in 1930. Stations were designated as "regular stations," as they were visited at fairly regular intervals. In addition to the regular stations, a large number of special stations were established for special purposes (not shown in Figure 10, but many are shown on Figure 18).

The original plan was to make observations at each station in twice each month during the season. For various reasons this program could not be adhered to strictly. On a lake as large as Lake Erie, winds commonly give rise to seas which are unfavorable for carrying out limnological work. In 1930 the program was followed with few irregularities and the data set for that year was found to be the best of the series of surveys.

Typically, field observations and samples were taken in the morning, and the boat returned to the laboratory about noon to permit analysis of the samples in the afternoon. For the more distant stations, particularly those at the extreme western end of the lake, a run was made to Toledo or Amherstburg in the afternoon, and samples were taken the following morning. Where possible, stations were located by means of landmarks. In the case of stations far from land, they were reached by running the boat at a known speed for the proper length of time along the proper course (dead reckoning). While this method does not make possible the occupation of exactly the same point on successive attempts, experience showed that it was adequate for the needs of the investigation. Details concerning methods employed in the field and laboratory are provided by Tidd (1955), Tiffany (1955), and Wright (1955).

The following is a summary of the acknowledgements prepared by Stillman Wright (1955) for the 5-year survey. In 1926, the survey was in charge of Dr. R. C. Osburn, Director of the Franz Theodore Stone Laboratory, and he was closely associated with the work in following years. After 1926, the investigation was under the general direction of Mr. E. L. Wickliff, Chief of the Bureau of Scientific Research, Ohio Division of Conservation. Participation of the U.S. Bureau of Fisheries in 1929 and afterward was under the direction of Dr. John Van Oosten, in charge of Great Lakes fishery investigations. In an investigation of this magnitude, covering five seasons of field study and several categories of aquatic biology, it is only natural that those intimately associated with the work would seek aid from others in a position to render it. The number of persons who have made contributions of general or professional nature is great. A large measure of the success of the undertaking is owing to such contributions, and they are gratefully acknowledged. A number of these have been of such outstanding importance as to require individual mention.

Although the Franz Theodore Stone Laboratory was one of the cooperating organizations engaged in the survey, it is fitting that acknowledgment of the important role of the laboratory and its staff be made to the director, Dr. R. C. Osburn. A number of employees of the Ohio Division of Conservation were associated with the survey for the entire period. Harry C. Crossley and George F. Miller, as well as the men working under their direction at Sandusky and Put-in-Bay, extended many courtesies and material aids to the scientific staff. Special thanks were given to Robert Shortliff, captain of the *Investigator*, 1928-1930, who rendered services far beyond the dictates of duty. Many scientific investigators in institutions not associated with the survey made valuable contributions. Professor Chancey Juday, of the University of Wisconsin, corresponded frequently with the survey director concerning the progress of the work, and it would be difficult to overestimate the value of his counsel. Professor Jacob Reighard, Professor Emeritus of Zoology, University of Michigan, generously permitted the use of data from his unpublished report on pollution in the lower part of River Raisin. Dr. Paul S. Welch of the Zoology Department, University of Michigan, loaned a number of pieces of equipment, and was very helpful in an advisory capacity. Dr. Carl L. Hubbs, of the Museum of Zoology, University of Michigan, loaned chemical equipment and made many helpful suggestions. Innumerable services were rendered by Ann Arbor colleaguess of the Bureau.

Results of Western Lake Erie Surveys 1926-1930

Following completion of field work in autumn of 1930, the Bureau of Fisheries assumed the responsibility of assembling the data and preparing a report of the investigation. Owing to the great diversity of subject matter and of contributing workers, the task of writing a complete and unified report required a long period of time. Dr. Lewis H. Tiffany collaborated in writing the chapter on phytoplankton and Dr. Wilbur M. Tidd in writing the chapter on zooplankton; the remainder of the report was prepared by Stillman Wright (1955).

Wright's report is based principally on data obtained in the seasons of 1929 and 1930. From the data of the 1928 field season, certain ones were selected for inclusion. Selection was based primarily on the possibility of fitting the data into the plan of presentation for those of 1929 and 1930. No data of 1927 were included. Those of 1926 were treated as published data (Osburn 1926a,b), and where possible, were introduced to supplement the data of later years. Although the report was completed in 1933, it unfortunately languished for over 20 years until the pollution problems became more acute and the U.S. Fish and Wildlife Service recognized the importance of this survey. An alternative suggestion for the reluctance of the U.S. Bureau of Fisheries to publish the results is the unpopular conclusion that overfishing, not pollution, was primary reason for the decline in commercial fish species.

Context of Surveys. For many decades Lake Erie supported a highly productive commercial fishery, but within the 25 years before the surveys there had been an alarming decline in production of the more highly prized

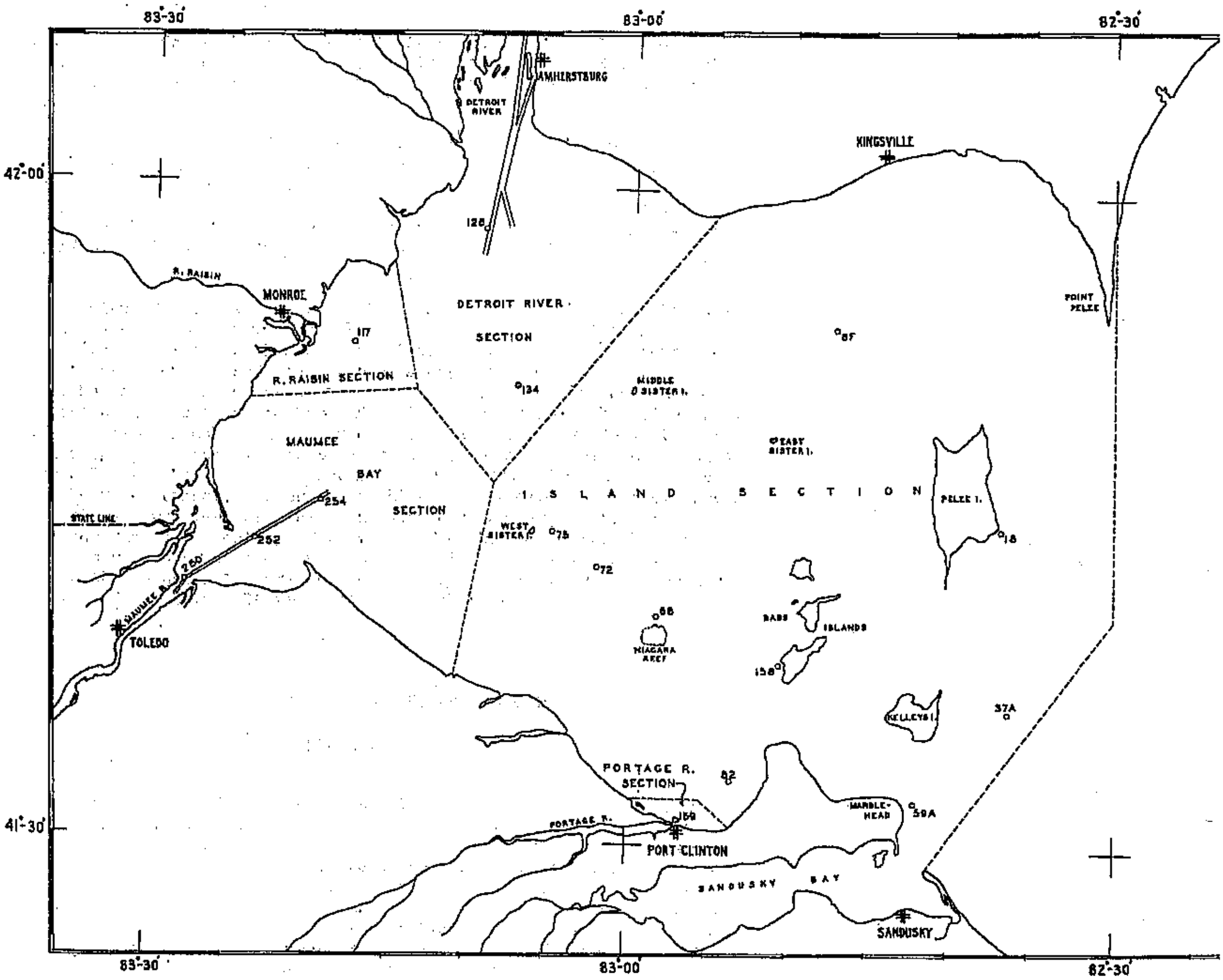


Figure 10. Western Lake Erie showing survey sections and principal stations (after Wright 1955).

species, in spite of an increase of fishing intensity. The Division of Conservation of the State of Ohio was the first to investigate the degree and extent of pollution with reference to its effect on the fishery of Lake Erie. In the month of August, 1926, and in autumn and winter of 1927, special parts of the lake, particularly along the Ohio shore from Toledo to Cleveland, were studied. In 1928, 1929, and 1930, work was concentrated on the part of the lake west of Point Pelee.

In developing the general plan of investigation, the planners assumed that the offshore areas of the lake, far from sources of pollution, would be most nearly normal, and that the areas near the rivers would show the maximum effect of pollution. Accordingly the lake was divided arbitrarily into five sections, and parallel studies were made in each section to facilitate comparisons of the results. The offshore area, near the islands, was designated the Island Section, and areas near the mouth of the four rivers studied were designated the Portage River, Maumee Bay, River Raisin, and Detroit River Sections. With minor exceptions the fieldwork was done in the months of April to October, inclusive.

Physical Limnology. A general description of Lake Erie and a detailed description of western Lake Erie, with hydrographic maps and morphometric data were presented by Wright (1955). The literature on fluctuations of lake levels, waves, seiches, tides and currents were reviewed briefly. Studies of currents based on drift bottles show that the surface currents of western Lake Erie are not constant in direction, but depend upon the direction of the wind (Figure 11).

Because of its extreme shallowness, western Lake Erie is usually homothermous from top to bottom; thermal stratification appears only occasionally and for short periods. The seasonal water temperature cycle for 1929 and 1930 at Station 8F (north of the islands) is shown on Figure 12. Data on weather was presented. Transparency of the water was found to be low, particularly in spring and autumn.

Chemistry. In the Island Section the oxygen content of the surface water ranged from 7.1 to 13.0 mg liter^{-1}, and from 83 to 133% of saturation. Almost all of the samples fell between 90 and 99% of saturation. Free carbon dioxide ranged from -5.9 to 3.1 mg liter^{-1}; methyl orange alkalinity (in terms of calcium carbonate) from 85 to 103 mg liter^{-1}; pH from 7.7 to 8.5 (Figure 13). In general the chemistry of the surface and bottom water were nearly the same. Only one case of nearly total depletion of oxygen in the lower water was found in the three seasons of study. The low oxygen content (8.6% of saturation) was found in the eastern part of the Island Section near the close of a period of temporary thermal stratification, and apparently was restricted to the lower three meters of water.

The average amounts of the different forms of nitrogen (in mg liter^{-1}) in the Island Section were as follows: free ammonia, 0.013; albuminoid ammonia, 0.151; nitrite, 0.005; nitrate 0.10. While it is probable that the nitrogen content has been increased by pollution, it is equally probable that the additional demand upon the dissolved oxygen had been small as compared with demands resulting from natural phenomena. From a chemical point of view, polluting materials known to enter the lake apparently have had no harmful effect on the water of the Island Section.

The chloride content of Lake Erie was higher than that of other of the Great Lakes. Chloride has little value as an index of pollution in Lake Erie because of the numerous natural sources of sodium chloride in the drainage basin.

A number of chemical samples were taken in western Lake Erie near the mouths of four tributary streams (Portage, Maumee, Raisin, and Detroit Rivers), and a few were taken in the rivers themselves. All of the rivers were known to receive sewage from municipalities located on their shores. In relation to its mean discharge, Maumee River received sewage from the largest population; in this respect River Raisin was second; Portage River third; and Detroit River fourth. Over considerable areas in and near the rivers the bottom was covered by organic debris, which would have a marked effect on the chemistry of the water immediately in contact with it.

The following descriptions apply only to the water one meter or more above the bottom. Parts of the lake in which there was definite evidence of pollution, as indicated by high albuminoid ammonia, were characterized by low nitrite and nitrate as compared with parts of the lake in which the evidence of pollution was less definite or lacking. This is believed to have resulted from the utilization of nitrite and nitrate by plankton algae, for there was a direct relationship between the abundance of phytoplankton and the intensity of pollution.

Chemical results obtained in Portage River at Port Clinton, and in the lake near the mouth of the river indicate light pollution. The only definite evidence of pollution was in the content of albuminoid ammonia, which was somewhat higher than in the Island Section. In most of the samples the dissolved oxygen content was in excess of 90% of saturation, and in no sample was it less than

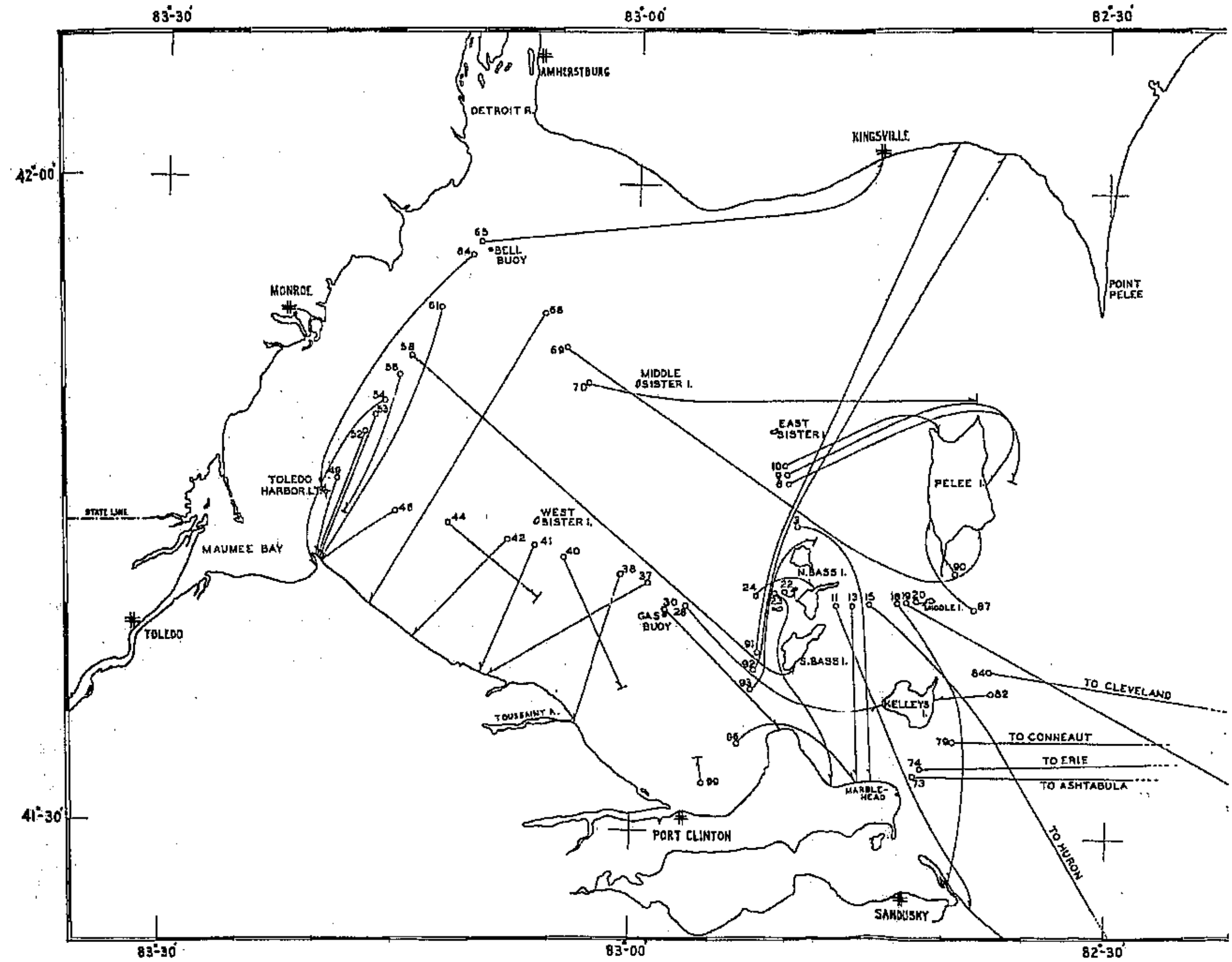


Figure 11. Presumed courses taken by current drift bottles released in May and June of 1928 (after Wright 1955).

77% of saturation. Correspondingly satisfactory results were obtained for free carbon dioxide and pH. It may be concluded that pollution in Portage River has had no harmful chemical effect on the water of western Lake Erie.

The Maumee River near its mouth was heavily polluted as indicated by high free and albuminoid ammonia (0.618 and 0.708 mg liter^{-1}), and by low dissolved oxygen (not exceeding 49% of saturation). Immediately outside the mouth of the river free and albuminoid ammonia were consistently high, and there was definite evidence of the effect of the river water at a distance of 13.7 kg from the mouth. The oxygen content immediately outside the mouth was sometimes low and sometimes high (range: 12 to 112% of saturation), but there were no marked withdrawals of oxygen at a distance of 3.6 km or more from the mouth of the river. In Maumee Bay the harmful chemical effect of the river water appeared to be restricted to a small area near the mouth of the river.

The River Raisin at its mouth was definitely polluted as shown by the high albuminoid ammonia (mean, 0.433 mg liter^{-1}), and by low oxygen content. In one case there was total exhaustion of oxygen. The effect of pollution was evident in the analyses for albuminoid ammonia in the lake at a distance of at least two miles from the mouth of the river, but no marked withdrawals of oxygen definitely referable to pollution were noted at a distance greater than one-half mile, and only then in water recently discharged from the river. Thus, the harmful effect of pollution apparently was restricted to a very small area near the mouth of the river.

There was no definite chemical evidence of pollution in the lake near the mouth of Detroit River, nor in the river near its mouth. In most respects the chemical results were similar to those obtained in the Island Section. On the average there was less decomposing organic matter, as shown by albuminoid ammonia, than in the Island Section. In most of the samples the oxygen content was

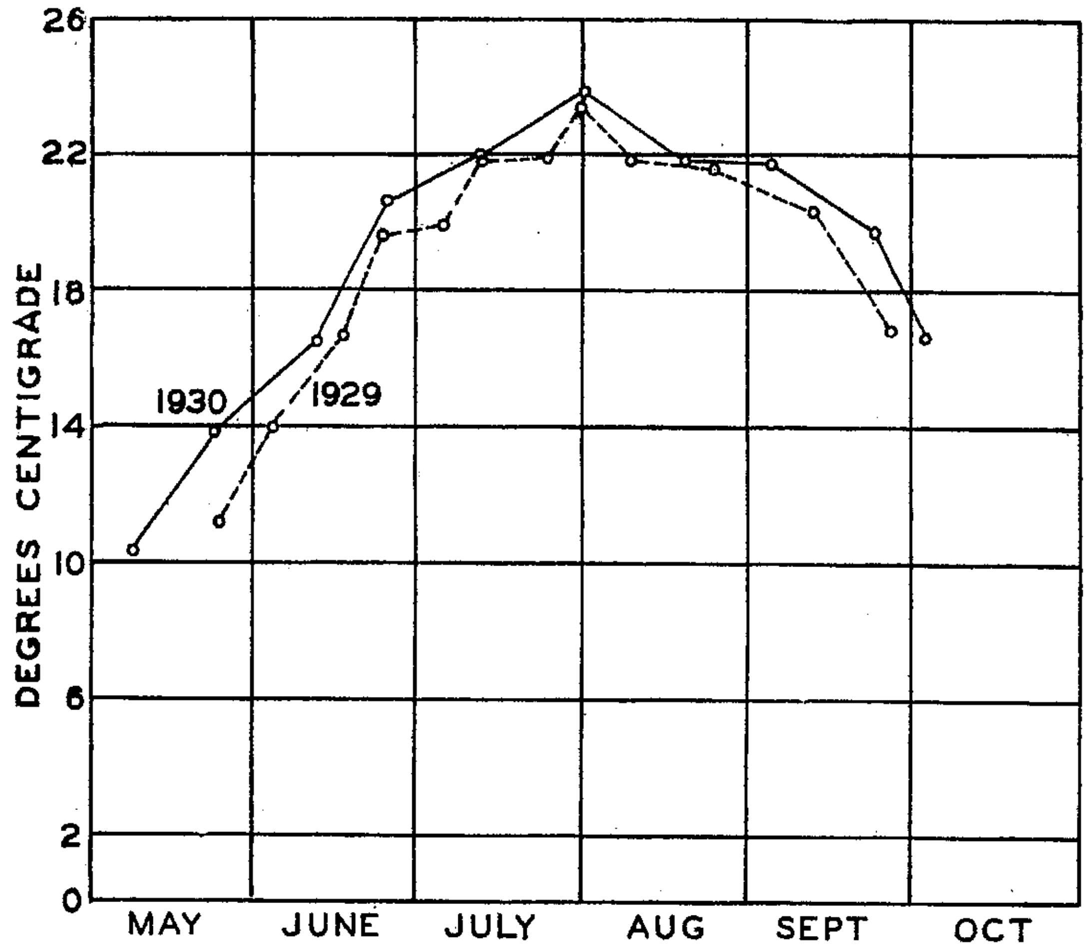


Figure 12. Comparison of mean water temperatures of western Lake Erie at Station 8F for two years (after Wright 1955).

in excess of 90% of saturation, and in only a few samples was it less than 60% of saturation. Doubtless the nitrogen content of the river water had been increased as a result of pollution, but probably the increase had been too small to have an appreciable effect on the oxygen content of the water. Wright (1955) concluded that pollution in Detroit River has had no harmful chemical effect on the water of western Lake Erie.

The relative positions of the different sections with respect to intensity of pollution as indicated by the chemical data, particularly albuminoid ammonia, were: (l) Maumee Bay; (2) River Raisin: (3) Portage River; (4) Island; and (5) Detroit River. In the lower parts of Maumee and Raisin Rivers and sometimes in small areas in the lake near the mouths of these rivers, pollution was sufficiently intense to make the chemical conditions harmful to aquatic organisms which would normally inhabit such areas. In the Portage River, Island, and Detroit River Sections there was no evidence of pollution of sufficient intensity to cause harmful chemical conditions.

The results and conclusions referred to the period when the lake was free of ice. Determinations of oxygen, carbon dioxide, and pH, made under the ice near the west shore when the period of ice-closure was about three-fourths completed, indicate that chemical conditions there were little, if any, less favorable than those prevailing during the summer.

The available evidence, both direct and indirect, indicates that poisonous substances are not present in the lake in concentrations sufficient to affect aquatic organisms harmfully.

The final conclusion to be drawn from the chemical data was that pollution has had both harmful and helpful effects on chemical conditions in western Lake Erie. The harmful effect had been the marked reduction in oxygen content of water discharged into the lake from Maumee and Raisin Rivers. The helpful effect has been the addition to the lake water of large quantities of nutritive materials, which probably have made possible a great increase in the abundance of plankton organisms. Wright (1955) concluded that it is probable that the harmful effect had been offset, largely if not entirely, by the helpful effect.

Phytoplankton. A qualitative study of the quantitative samples showed the presence of 80 genera and 150 species of algae in western Lake Erie (Tiffany 1934, 1955). The list is composed principally of representatives of the Chlorophyceae, Diatomeae, and Myxophyceae. Representatives of other classes were relatively few in number.

The horizontal distribution of the phytoplankton was not uniform in the Island Section. There was little evidence that some stations had consistently high counts and others consistently low counts. Indirect evidence from a comparison of seasonal distribution for 1929 and 1930 indicates that the lack of uniformity was not such as to invalidate a determination of average abundance for the area based on samples from several stations.

The vertical distribution was essentially uniform. Differences in abundance at different levels were found, but in general they were not large and were not consistently of the same kind. That is, the greatest abundance maybe found near the surface at one time, and near the bottom at another time. In general, samples taken at surface and bottom yielded about the same average count as samples taken at four depths.

Only in the Island Section was sampling continued long enough to trace the seasonal changes in abundance

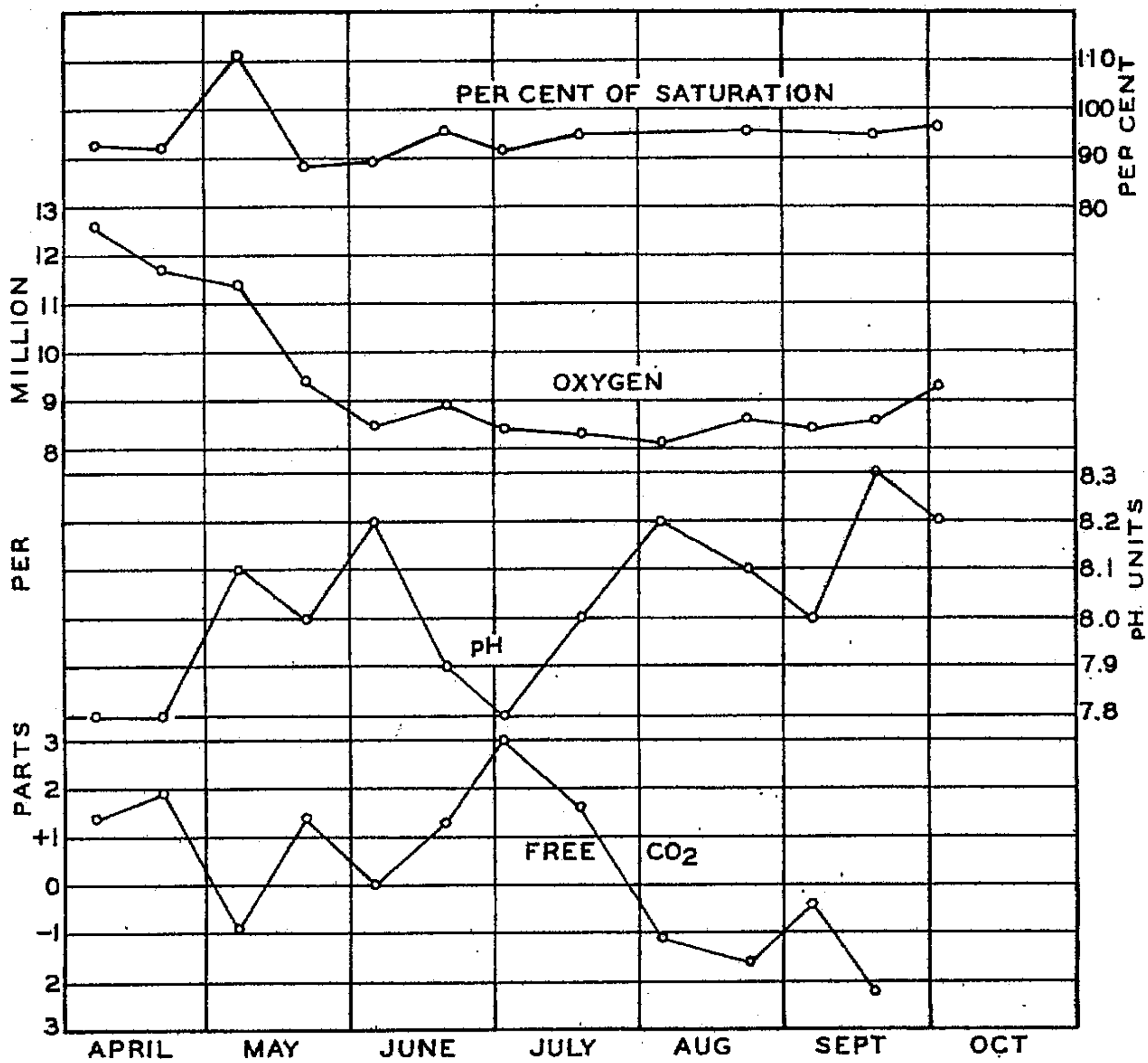


Figure 13. Chemical constituents of western Lake Erie at Station 37A (east of Kelleys Island) in 1930 (after Wright 1955).

clearly (Figure 14). Nothing is known of the abundance in November, December, January, February, or March; the following summary is based on a study of the remaining months of the year. Diatoms as a group had two maxima, one in spring and another in autumn. In 1929 the spring maximum came in early June; in 1930 in late May. Earlier appearance of the maximum in 1930 probably resulted from earlier warming of the water in that year as compared with 1929 (Figure 12). In autumn of 1929 the diatoms reached their greatest abundance in late October, but may have continued to increase for some time after the close of the sampling season. In 1930 only *Stephanodiscus* was, abundant in autumn. It seems probable that the diatoms as a group reached their autumn maximum after the close of the sampling season in early October of that year. Diatoms were more abundant in autumn than in spring of 1929; this may or may not have been the case in 1930. Greens had one maximum and this came in autumn (late September in both years). Blue-greens had one maximum and this coincided with the maximum of greens. Groups other than diatoms, greens, and blue-greens did not make important contributions to the abundance of phytoplankton.

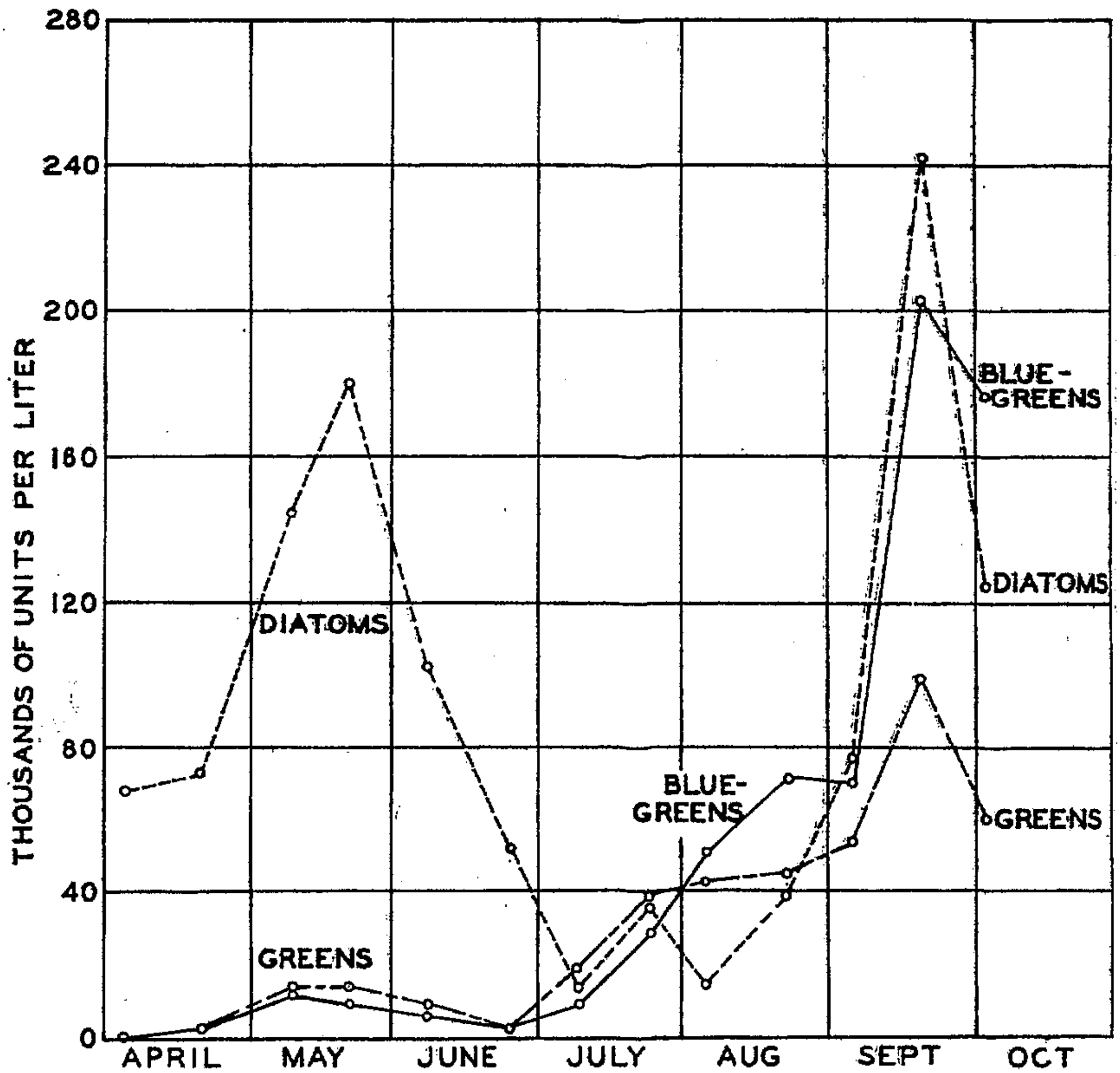


Figure 14. Seasonal distribution of phytoplankton (diatoms, greens, and blue-greens) in the Island Section for 1930 (after Tiffany 1955).

In spring the phytoplankton was composed almost exclusively of diatoms. In summer all groups were rare, although the diatoms were definitely dominant in 1929. The autumn maximum was composed of large numbers of all three groups.

For comparable periods of time, the two years agreed closely with respect to (1) average abundance of phytoplankton groups, (2) times of changes in abundance, and (3) degree and direction of change. For the period late May to early October, the two-year averages, stated in thousands of units per liter, were as follows: diatoms, 90; greens 38; and blue-greens 58. The highest average counts in periods of two weeks (not necessarily the same period for each group) were: diatoms, 261; greens, 128; and blue-greens, 203. The lowest were: diatoms, 14; green 0.5; and blue-greens, 0.5. The highest average count of all groups combined for a single period was 544, and the lowest 33.

The genera of diatoms and blue-greens which made important contributions to the plankton were almost the same in both years, but there were about twice as many important genera of greens in 1930 as in 1929.

The Island Section of western Lake Erie is richer in plankton than Lake Erie east of that area, and richer than Lake St. Clair. Comparisons with Lake Mendota, a eutrophic lake, and Green Lake, an oligotrophic lake, on the basis of the dry weight of organic matter in the centrifuge plankton in autumn (and other considerations), showed that western Lake Erie stands between the two in richness; nearer to Lake Mendota than to Green Lake. Since these two lakes are fairly typical of their classes, and since eutrophic lakes are generally rich and oligotrophic lakes generally poor, the Island Section of western Lake Erie might be described by Tiffany (1955) as "moderately rich" in plankton.

Large and highly consistent inequalities in horizontal distribution of phytoplankton existed in western Lake Erie as a whole. For the months of July, August, and September of 1930, the average abundance per unit volume of water in the Detroit River Section was 25% of that in the Island Section; 9% of that in the Portage River Section; 6% of that in the River Raisin Section; and 4% of that in the Maumee Bay Section. The data did not permit such a definite statement of relative abundance for 1929. As far as comparisons can be made, they indicate that the relative positions of the sections were the same in both years (with one minor exception), but that differences in abundance were not as marked in 1929 as in 1930. The algae were distinctly more abundant in Maumee Bay and River Raisin Sections in 1930 than in 1929. Qualitatively, the sections having the most abundant plankton were characterized by the dominance of blue-greens over greens and diatoms.

The most probable explanation of the differences in abundance between sections was as follows. The sections which were now especially abundant in plankton (Maumee Bay, River Raisin, and Portage River Sections) were abundant in plankton under natural conditions. Shallowness of the water was believed to have been the principal contributing factor in this richness, with the added factor, in the case of the Maumee and Portage River Sections, of the lacustrine (or estuarine) character of the lower river. Superimposed upon this natural richness was the richness caused by the nutritive salts derived from domestic sewage. Figure 15 shows strikingly the marked reduction of the ammonias and green and blur-green algae with increasing distance from the Maumee River mouth.

The Detroit River Section was poor in plankton because the source of the river, Lake St. Clair, was poor in plankton, and not because of the destructive effect of poisonous chemicals derived from industrial wastes. There was little or no local increase of abundance resulting from domestic pollution in this section. The natural abundance of plankton in the Island Section had been increased as a result of pollution, by the eastward drift of organisms produced near the rivers, and by the use of the excess of nutritive salts. The relative positions of the different sections of the lake with respect to abundance of phytoplankton was the same as with respect to intensity of pollution as indicated by the content of albuminoid ammonia.

Zooplankton. The crustacea zooplankton were not uniformly distributed in the Island Section, but there was no evidence that they were consistently abundant at certain stations and consistently rare at others. Comparisons of seasonal distribution of individual genera in 1929 and 1930 indicate that the lack of uniformity was not such as to invalidate a determination of average abundance in the section based on samples from several stations.

Vertical distribution was studied only during the hours of daylight, so that nothing is known regarding diurnal migrations. In the daytime the adult crustacea were usually rare at the surface and near the bottom, and were most abundant at some intermediate depth. Nauplii and rotifers appeared not to avoid the water near the surface, but were commonly concentrated at more

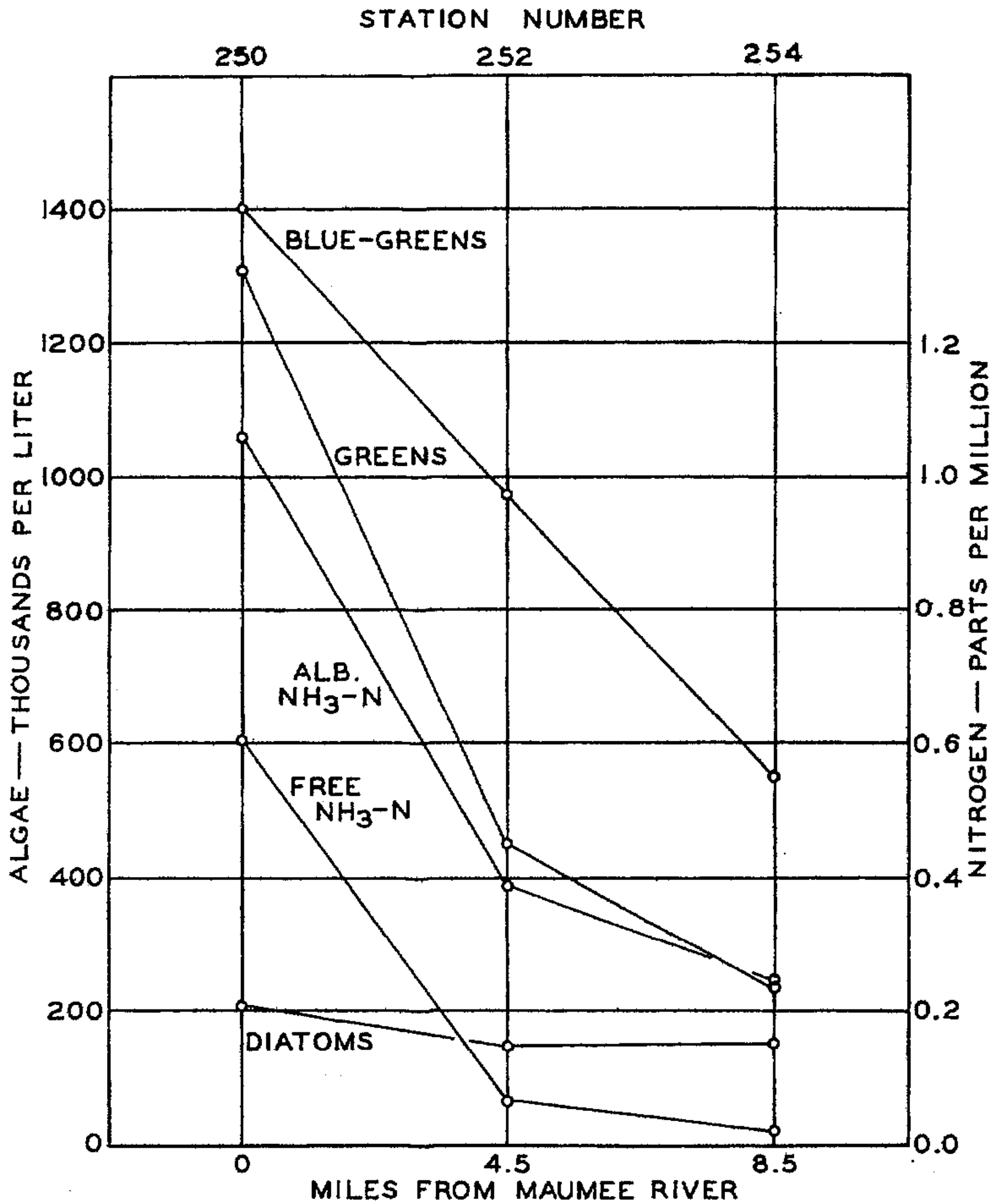


Figure 15. Average abundance of phytoplankton groups, and ammonia, in the Maumee Bay Section in July, August, and September 1930 (after Tiffany 1955).

than one level. There were numerous exceptions to any general rule regarding vertical distribution of the zooplankton organisms.

Only in the Island Section was sampling continued over a sufficiently long period to show seasonal distribution clearly (Figure 16). Nothing is known definitely regarding abundance in the months of December, January, February, and March, but there are reasons for believing that the crustacea are rare during that period. During the remaining months the adult crustacea were rare in spring and autumn, and were most abundant in summer. In 1930 copepod nauplii were most abundant in late spring, and probably was the case in 1929.

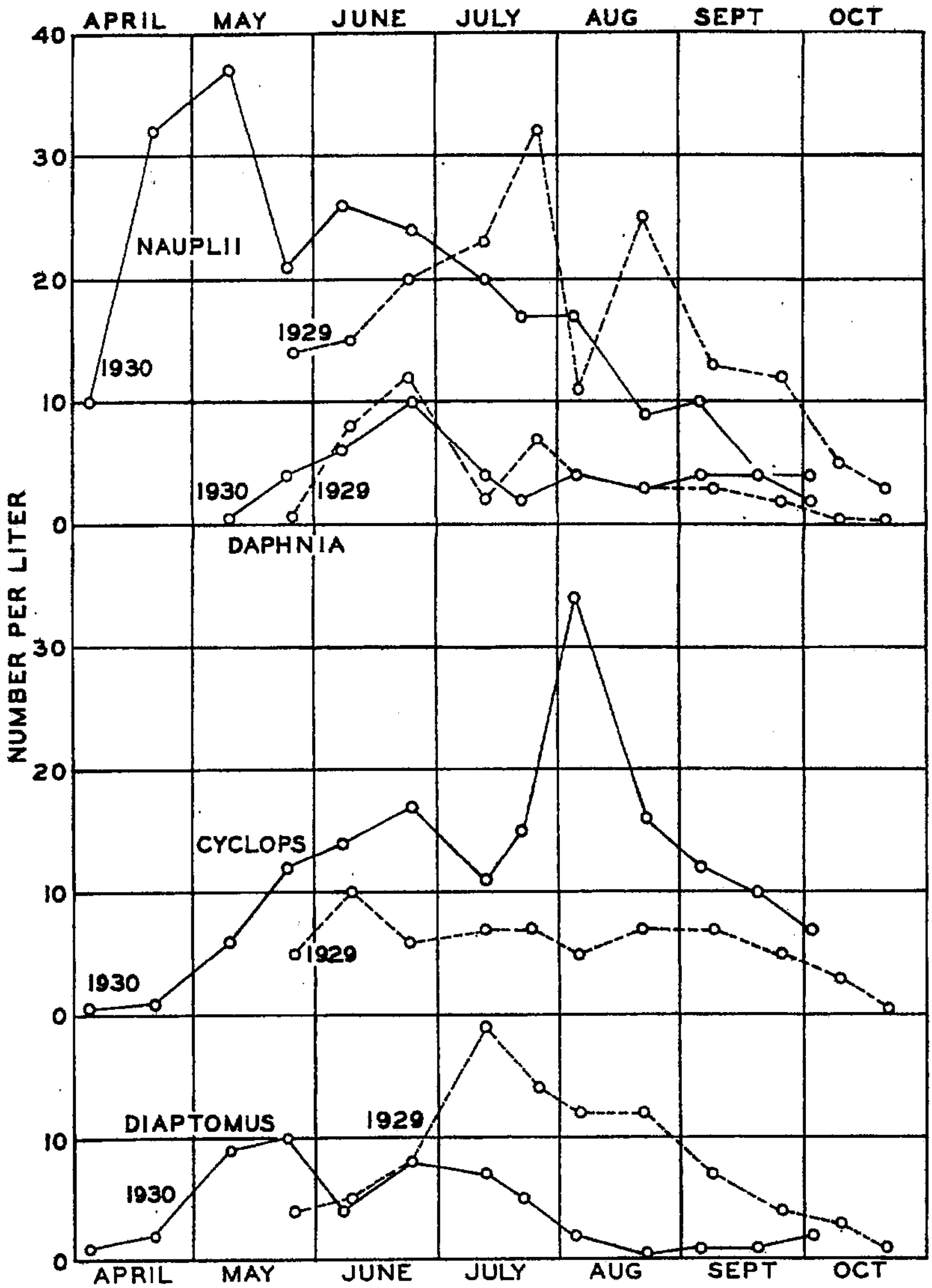


Figure 16. Comparison of the seasonal distribution of crustacea zooplankton in the Island Section of western Lake Erie for 1929 and 1930 (after Tidd 1955).

The four most prominent genera of crustacea were *Cyclops*, *Diaptomus*, *Daphnia*, and *Diaphanosoma*. For the period late May to early October for the years 1929 and 1930, the mean counts per liter in the Island Section were as follows: *Cyclops*, 10; *Diaptomus*, 6; *Daphnia*, 4: *Diaphanosoma*, 1. The corresponding mean for the nauplii was 16 per liter. Comparisons of these figures with corresponding figures from a typical eutrophic lake and a typical oligotrophic lake show that the Island Section held an intermediate position with respect to abundance of crustacea. Since eutrophic lakes are characteristically rich in plankton and oligotrophic lakes are poor, western Lake Erie in the Island Section was described by Tidd (1955) as "moderately rich" in plankton crustacea.

Large and highly consistent inequalities in horizontal distribution existed in western Lake Erie as a whole. For the months of July, August, and September of 1930, the mean number of crustacea in the Detroit River Section was 8% of that in the Island Section; 6% of that in the River Raisin Section; and 5% of that in the Maumee Bay Section. Differences of similar magnitude were found for about the same period of time in 1929. These differences in abundance of the plankton crustacea were believed to be dependent upon the amount of food available to them, for in 1930, and probably in 1929 also, the different sections just mentioned held the same positions with respect to abundance of phytoplankton as they did with respect to plankton crustacea. That is, the Maumee Bay Section was first in abundance of both kinds of plankton organisms, the River Raisin was second, the Island Section third, and the Detroit River Section fourth. The Portage River Section is not included in the list because it is represented by less adequate data.

Tidd (1955) believed that the observed differences in abundance in different sections were in part the result of natural conditions, and in part the result of pollution. In all probability, the increase of phytoplankton and organic detritus resulting from pollution had made possible an increase of the crustacea.

Benthic Organisms. The criteria of pollution employed by Wright (1955) were as follows: A mud bottom having less than 100 tubificid worms and more than 100 *Hexagenia* nymphs per square meter was considered to be free from pollution; a larger number of tubificids and smaller number of *Hexagenia* was regarded as evidence of pollution. Three degrees of pollution were recognized, based on the number of tubificids per square meter, as follows: light pollution, 100-999; moderate pollution, 1,000-5,000; heavy pollution, more than 5,000. On other than mud bottoms, only the tubificids were used as a criterion of pollution.

In the Island Section quantitative samples were taken only on mud bottoms. Nymphs of the burrowing mayfly, *Hexagenia*, were more abundant than all other organisms combined. In 1929 the average number of *Hexagenia* for seven stations was 283 m^{-2}, which was 65% to the total number of organisms. In 1930 the average number for five stations was 510 m^{-2}, which was 87% of the total. Considering only the four stations sampled in both years, *Hexagenia* was about one and one-half times as abundant in 1930 as in 1929. In both years most of the sampling was done after the period of emergence of the insects. Very probably sampling throughout the year would have shown much higher counts of *Hexagenia*. Tubificid worms were rare in both years. Areas with mud bottoms in the Island Section may be regarded as free from pollution by organic debris. Hauls of the bottom sled in the shallower areas having hard bottom showed that these also were not polluted.

The average dry weight of *Hexagenia* nymphs for the two years was 43.2 kilograms per hectare (38.5 pounds per acre). This figure was close to that for all organisms in a similar zone of Lake Mendota; it is below that of Lake Wawasee, but above that of three other North America lakes. Thus, the Island Section compared favorably with inland lakes with respect to the weight of bottom organisms per unit of area.

There was no evidence of pollution of the bottom in the Portage River Section near the mouth of the river. Definite evidence of pollution was found near the mouths of the rivers in the Maumee Bay (Figure 17), River Raisin, and Detroit River Sections. The estimated extent of the zones of heavy, moderate, and light pollution for each section is shown in Figure 18. The areas of the zones of pollution were as follows: Heavy pollution, 29.2 km^2; moderate pollution, 46.3 km^2; and light pollution, 191.6 km^2. The total area in the three zones of pollution was 262.9 km^2, or 7.7% of the water area of western Lake Erie exclusive of Sandusky Bay. Of the total area in the three zones of pollution, 72.8% fell within the zone of light pollution, and an unknown but considerable part of this zone was free of organic debris.

Effects of Pollution on the Fishery. By the end of 1930, the extent and degree of pollution in western Lake Erie had been determined with some degree of exactness, but interpretation of the facts in terms of the effects on the fishery had to be based largely on conjecture. Some of the effects of pollution were obviously harmful to fishes and hence to the fishery, while others were clearly advantageous. However, there were no standards by which these factors could be measured and compared quantitatively to determine the residual effect on the

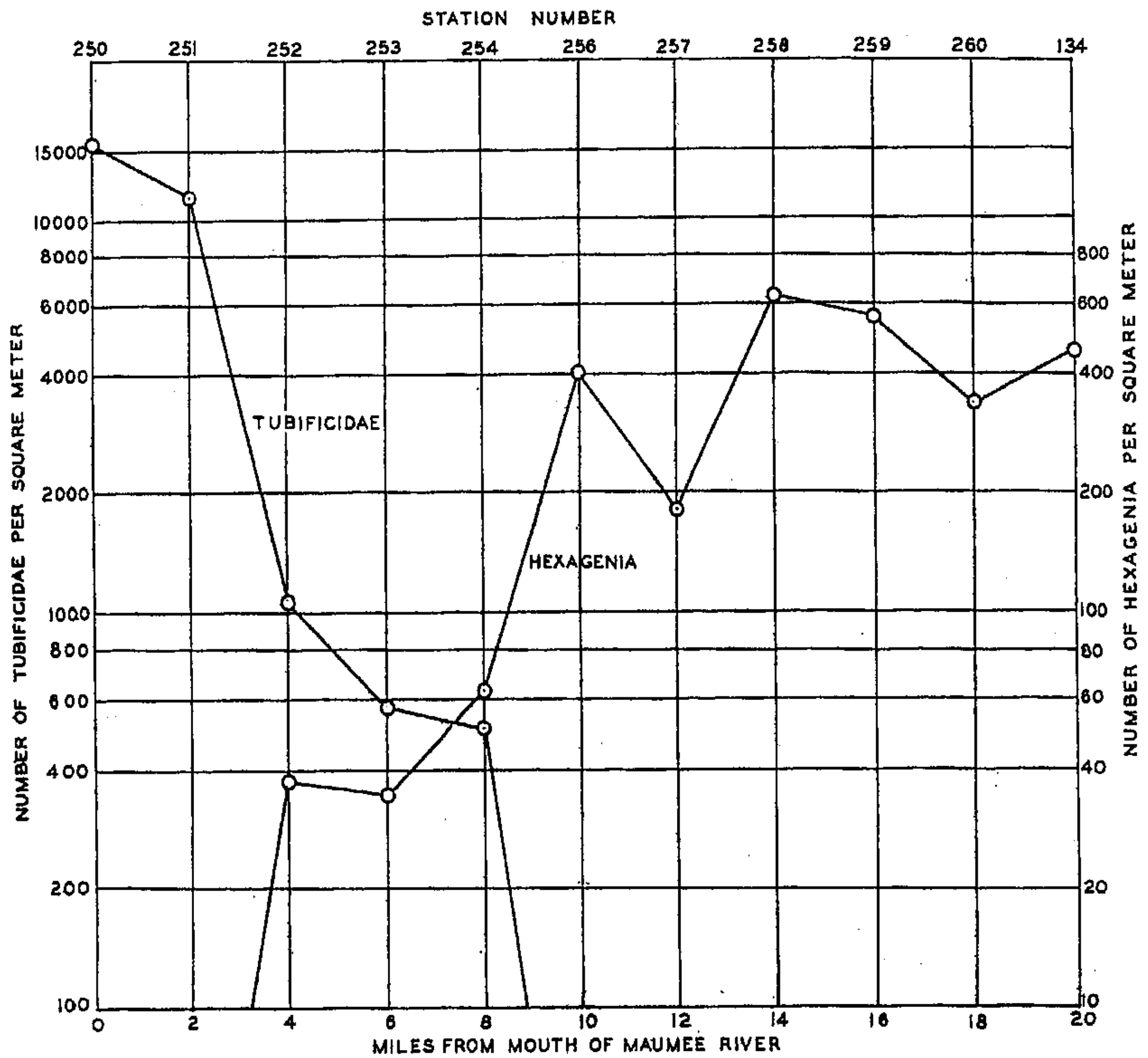


Figure 17. Abundance of tubificid worms and the mayfly *Hexigenia* along a line from the mouth of the Maumee River to open Lake Erie in 1930 (after Wright 1955).

fishery. Wright (1955) made no attempt to enter into a detailed discussion of the problem, but briefly stated, the conclusions reached were as follows. Conditions in the lower parts of Maumee and Raisin Rivers, and in small areas of the lake near their mouths, had been made unfavorable or prohibitive to all except the most tolerant fishes by reason of the low content of oxygen and high content of free carbon dioxide. In addition, considerable areas of the bottom near Maumee, Raisin, and Detroit Rivers had been rendered unfit for spawning purposes by the deposition of organic debris, but (Wright (1955) pointed out that a large part of the polluted area probably never was suitable for spawning because of the deposition of silt. He concluded that these harmful results of pollution had been offset, partially or wholly, by the increase in plankton organisms which are used as food by all young fishes and the adults of certain species. In view of the tendency of the harmful and helpful effects to balance each other, it seemed highly improbable that pollution in the western part of the lake had been the controlling factor in the depletion of the fishery of Lake Erie.

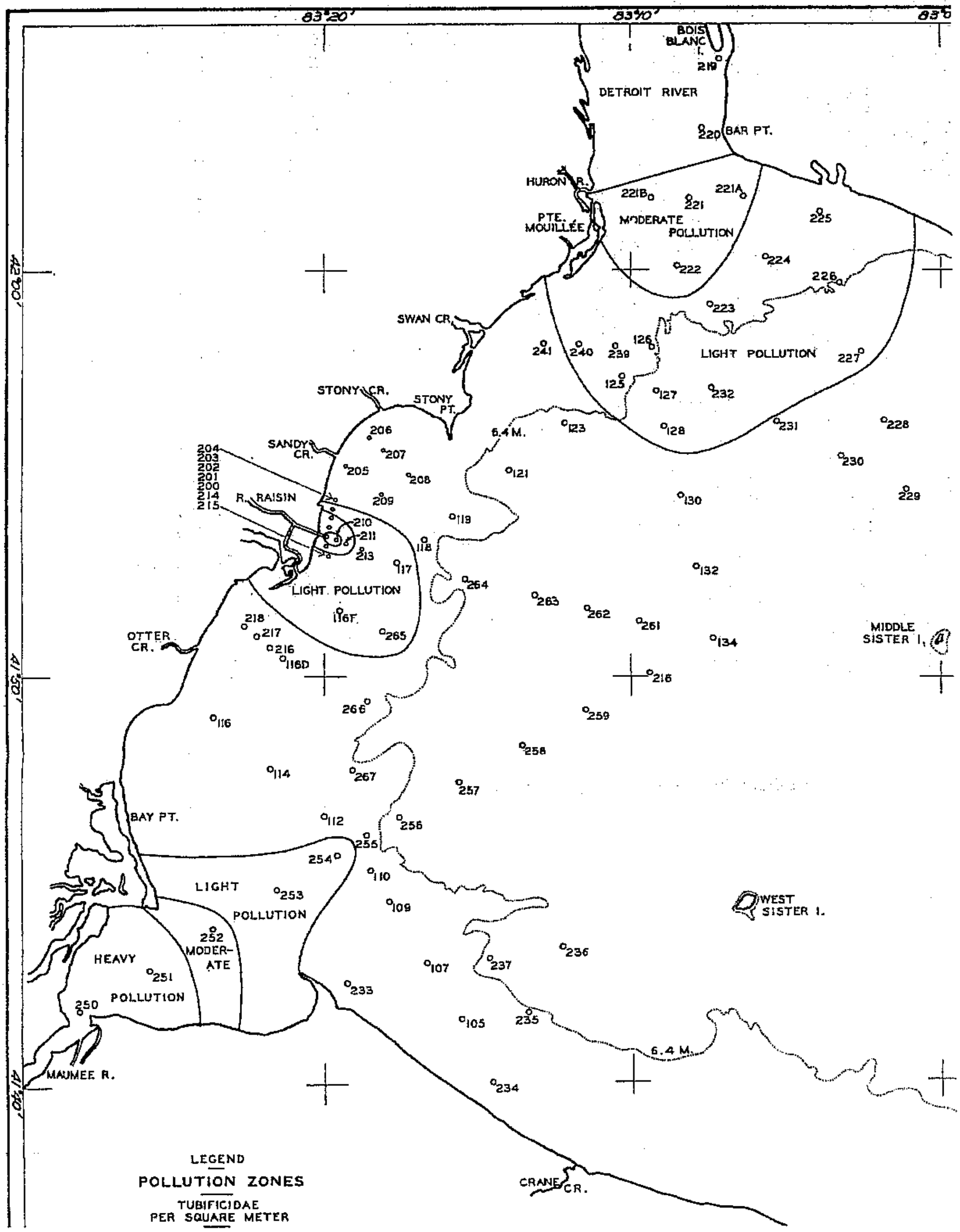


Figure 18. Zones of Pollution in western Lake Erie in 1930 based on the numbers of tubuficid worms per square meter (after Wright 1955).

History of Central and Eastern Lake Erie Surveys 1928-1929

In the introduction to the final report on the limnological survey of western Lake Erie, Fish et al. (1960) points out that the serious decline in fish populations in Lake Erie in the early decades of the 1900s made obvious the need for more extended knowledge of conditions affecting the .fishery The report states, "Of one thing all are certain: the decline is due to man's influence, but how? As a large shallow lake, Erie offers the greatest possibilities for rich animal life and plant life: in fact, there is no lake in the world more favorable for the production of fish than this body of water under its normal conditions; and the records bear out this statement. One has only to refer to the large catches of former years to learn what a varied and extensive fish fauna Lake Erie is capable of supporting."

The rapid decline in the fishery of a century ago was a matter of serious concern to not only the fishermen, but to the American and Canadian governments. Obviously legislative action was needed, but the problem was an international one, and enlightened legislation was not possible as long as the factors for the decline were elusive. Various explanations were advanced prior to the surveys of 1928-1929. Some claimed that Lake Erie was being overfished; others that chemical and sewage wastes from cities were polluting the waters to such an extent that the fish were being extirpated. Some fishermen attributed the decline to sewage silt deposition on the spawning grounds which rendered the beds unfit for the production of young fish. The possibility that the lack of food was responsible for the decline was also advanced. However, as long as these claims remained unanswered there could be little grounds upon which to base effective legistation.

The 1928-1929 surveys in central and eastern Lake Erie was led by Charles J. Fish, Director of the Buffalo Museum of Science. He assembled a team of notable scientists, including:

Richard Parmenter, Hydrographer, U.S. Bureau of Fisheries
Charles K. Green, Physical Hydrographer, U.S. Coast & Geodetic Survey
Reginald H. Pegrum, Topographer, Buffalo Museum of Science, NY
Roger C. Williams, Chemist, Buffalo City Health Department, NY
Casimir J. Munter, Chemist, Ohio State University, OH
Andrew M. Zillig, Bacteriologist, Buffalo City Health Department, NY
Charles B. Wilson, Macroplanktonologist, Westfield Normal School, MA
Ralph M. Buchsbaum, Phytoplanktonologist, University of Wisconsin, WI
Paul R. Burkholder, Microplanktonologist, Cornell University, NY
Willis L. Tressler, Microplanktonologist, University of Wisconsin, WI
Marie Poland Fish, Ichthyologist, Buffalo Museum of Science, NY
Albert E. Allin, Ichthyologist, University of Toronto, ON
Arthur Louden, Ichthyologist, Queens University, ON
Vernon S. L. Pate, Scientific Artist, Cornell University, NY
Elizabeth L. Saunders, Scientific Assistant, Brown University, RI
Anne Burnham, Assistant to the Director, Buffalo Museum of Science, NY

The need for correlation in limnological work was recognized in the planning of the surveys. In order to ascertain the cause for the decline in the fishery, the investigations were designed to determine the specific physical, chemical, and biological conditions in the lake and the extent to which human interference had affected the natural environment of the animal population. The specialties of the scientific staff reflect the diversity of the studies that were undertaken to explore these objectives.

In 1928 the investigations covered that portion of Lake Erie lying east of a line from the New York–Pennsylvania boundary to Long Point, Ontario. In this area of 4,400 km^2, 23 stations were located and observations were made weekly as far as possible from July 26 to September 15. For this work the U.S. Bureau of Fisheries steamer *Shearwater* was used (Figure 9). Owing to the fact that there were no laboratory facilities on board the *Shearwater* during the first season, the work could be carried out only in reasonably calm weather. For that reason the typical 3-day curises did not always take place as scheduled. During the interval from June 15 to July 26, a program was established to cover the shallow margins of the lake using the New York State gasoline launch *Navette*. The shallow water observations proved to be very useful because the spawning grounds for several summer-spawning fish species were found to lie within this area.

In response to the increased vessel facilities and assistance from Ohio, the area of investigation was extended to cover the entire lake with the exception of the area west of the islands which were being investigated by representatives of the State of Ohio and the Federal Bureau of Fisheries (Wright 1955). Four regular monthly cruises were made between May 15 and September 20 starting in each case as nearly as possible on the first of the month as weather conditions permitted. The cruises started in Buffalo and terminated at Put-in-Bay, Ohio, requiring usually 15 days. Each of the 50 regular stations where occupied on each cruise, in addition to 20 special stations for water samples at were made during the field season. In all 250 station visits were made in the 11,487-km² study area.

These surveys resulted in the first comprehensive map of bottom sediment distribution for the eastern basin of Lake Erie (Figure 19) and the finding that bottom of the deeper parts of this basin were covered with mud washed into the lake by currents probably during glacial times. The shallower parts of the basin were found to consist of sand and gravel moraines mixed with clay. The sand spits at Long Point and Erie harbor were interpreted as the result of shore currents, which are predominantly eastward; easterly currents were also indicated by the migration of stream mouths in that direction.

The dissolved oxygen content throughout the summer months was relatively high. Analysis of the surface water samples indicated high percentage saturation at all stations in the open lake. The mean percentage of saturation at the surface in the summer of 1929 was 94.9. The bottom water mean for the same period was 83.3%. These values are higher than those obtained in the eastern basin in 1928, when the surface saturation was 81.5% and the bottom 72.5%. The lowest oxygen saturation in the open lake was found at in August at two stations, 17 and 23 km offshore of Rondeau, Ontario, where the values were 52 and 44%, respectively. At all other times and places reduction in oxygen of the bottom waters in the western part of the central basin and in the "deep hole" off Long Point, Ontario usually ran between 60 and 70%. Figure 20 shows the areas of central and eastern Lake Erie where oxygen concentrations on the bottom fell below 81% for each month of 1929.

One of the most outstanding accomplishments of the 1928-1929 investigations was the presentation of detailed drawings of several life history stages of 18 of the most common fish species in Lake Erie (Figure 21). In addition to these drawings, descriptions were made of the young forms of 49 other fish species from the lake. This study of the early life history stages of Lake Erie

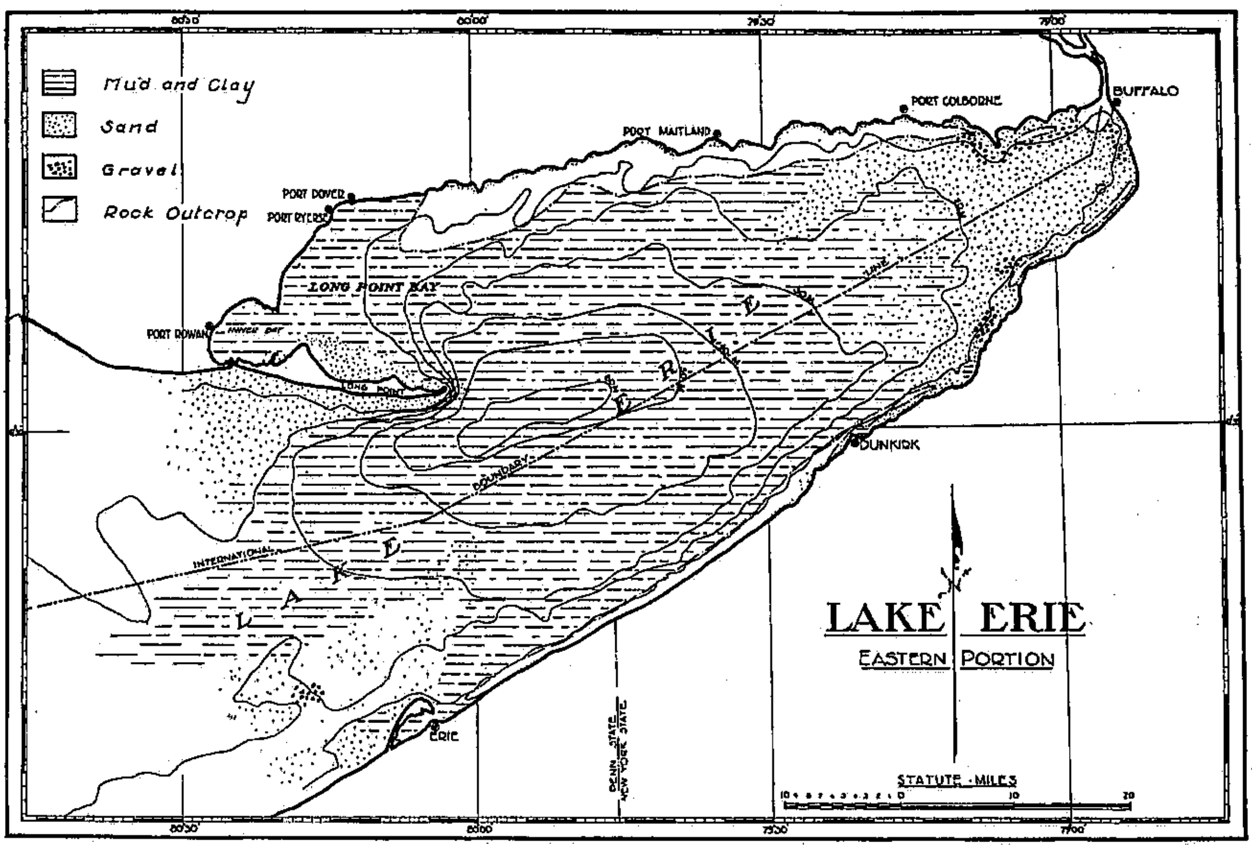


Figure 19. Bathymetric map of eastern Lake Erie showing distribution of bottom deposits (after Fish 1929b).

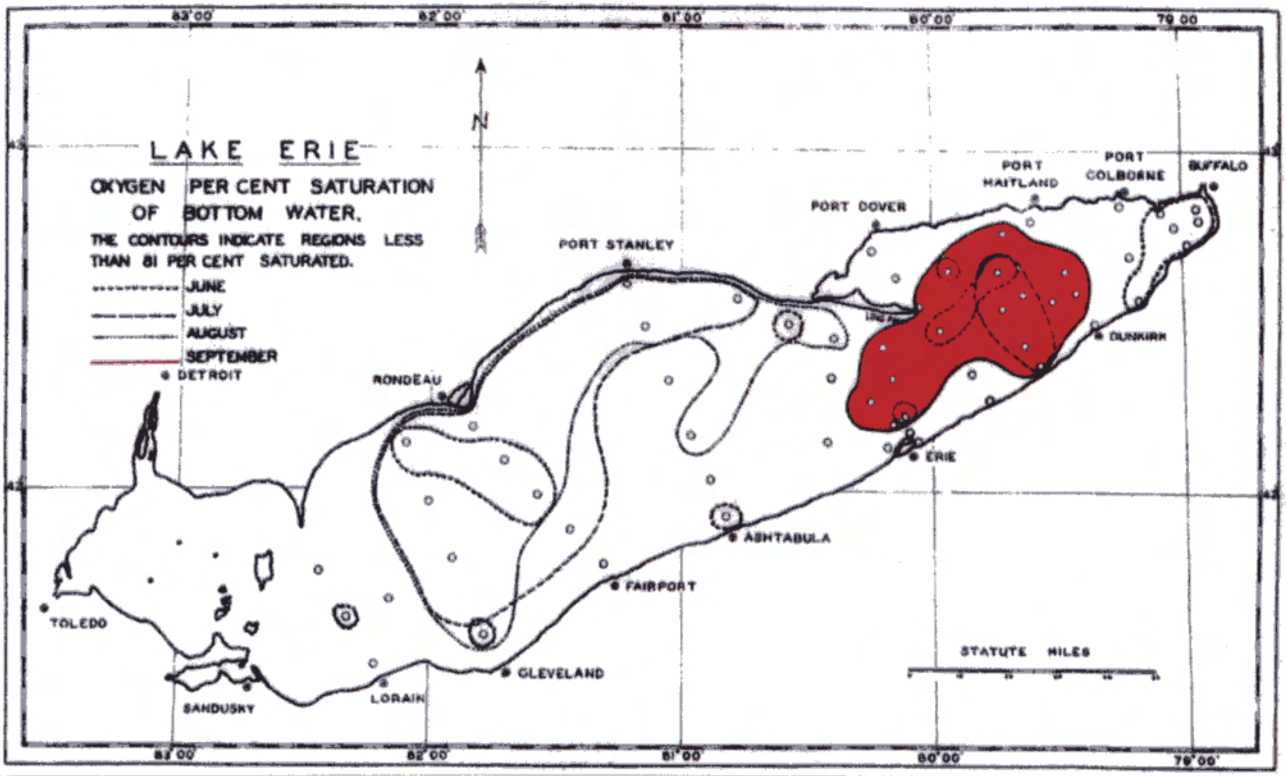


Figure 20. Area of oxygen concentration below 81% saturation in the bottom waters of central and eastern Lake Erie (after Fish et al. 1960).

fish permitted more accurate identification of larval fishes in the lake and assessment of hatching and recruitment success. The study showed that lake whitefish (*Coregonus clupeaformis*) eggs are demersal, some 21,000 eggs sinking to the bottom from a single female and lying there until hatched. Although few enemies were found at this time, the greatest losses occur due to a lengthy incubation period and shortly after the free-swimming larva emerge. Cisco (*Coregonus artedii*) were found to gorge on them.

The general conclusion of the surveys in the central and eastern basins was that Lake Erie is capable of supporting a very large fauna of open lake fishes. No dangerous silt deposits were found that would affect spawning beds. Sufficient food was present to support a larger fish population than extant in the lake. The fish had diminished, but their food source had not, leading to the observation that no environmental changes of significance had taken place. The physical, chemical, and biological conditions thus afforded no explanation for the decline in the fishery, suggesting that it would be advisable to examine the effects of fishing on the fish stocks (Fish et al. 1960).

Lake Erie Pollution Survey 1950–1951

Recognizing that sewage pollution and excessive discharges of silt were serious contamination problems in Lake Erie, in 1949 the Ohio General Assembly appropriated $100,000 in funds to the Ohio Department of Natural Resources (ODNR) to conduct a survey of the pollution of Lake Erie. The survey was directed by the ODNR's Division of Water with the purpose of determining the chemical, physical, and bacterial quality of the waters of Lake Erie and of the principal rivers in Ohio emptying into Lake Erie, and to make recommendations for the curtailment or elimination of pollutants found (Youngquist 1951, 1953). The survey was organized into three work groups. The Division of Water was responsible for chemical and physical water quality, including stream-flow quantities and silt loads. The Ohio Department of Health's Division of Engineering determined pollution loads, made bacterial counts, and conducted sanitary analyses. The Ohio State University's Franz Theodore Stone Institute of Hydro-biology was charged with conducting biological investigations of streams and sampling the biota of Lake Erie, as well as measuring lake currents. This paper will concentrate on the accomplishments of the latter group.

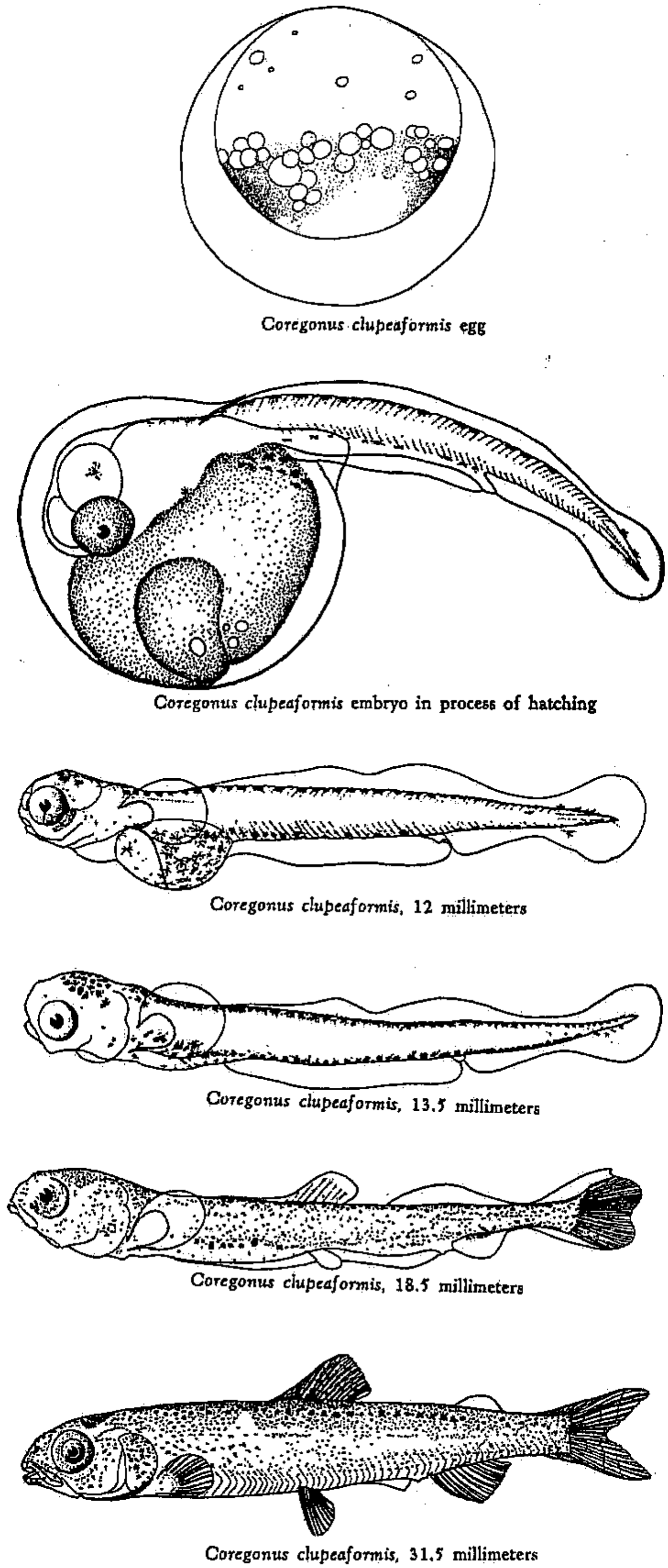


Figure 21. Early life history stages of lake whitefish *(Coregonus clupeaformis)* in eastern Lake Erie (after Fish 1929b).

The biological studies associated with the Lake Erie Pollution Survey were conducted under the direction of Dr. T. H. Langlois, Director of the University's Franz Theodore Stone Institute of Hydro-biology at Put-in-Bay (Langlois 1953). The biological program was divided into seven studies, each supervised by an staff member at the Institute: (1) suspended silt in western Lake Erie (Verduin 1953), (2) distribution of phosphorus in western Lake Erie and its utilization by phytoplankton (Curl 1953), (3) studies of water movements in Lake Erie (Verber 1953), (4) toxic materials at the mouths of streams discharging to Lake Erie (Poppen 1953), (5) phytoplankton survey at the mouths of streams entering Lake Erie (Sullivan 1953), (6) abundance and composition of bottom fauna at the mouths of south shore rivers and use as an index of pollution (Brown 1953), and (7) Cleveland Harbor industrial pollution survey (Davis 1953). The results of the seven studies were abstracted by Langlois (1953).

Study No. 1. This investigation dealt with the concentration and distribution of suspended silt in the western basin of Lake Erie during a period of six weeks ending April 27,1951. The years 1950 and 1951 were marked by unusually high runoff in the Lake Erie Basin, and the spring of 1951 was one of exceptionally high inflow of tributary waters into the lake. From limnological data on file at the Stone Institute, a relationship was established between suspended silt (mg liter^{-1}) in the lake water and the depth of light penetration (Figure 22). From this curve an estimate of the silt content of the lake at any point could be made by lowering a submarine photometer to a depth at which light equals 1% of the surface light intensity. Measurements thus made indicated that in a zone of turbidity water surrounded the islands with an average suspended silt concentration of 11 mg liter^{-1}. A clear zone to the west was influenced by injection of clear Detroit River water. The turbid area represented about 2,900 km^2 with an average depth of 10 m. The estimated weight of suspended sediment in the turbid area was 350,000 metric tons during a period observation.

The growth-inhibiting effects of turbidity in aquatic habitats were noted. During dry springs the western basin of Lake Erie supports phenomenal diatom crops. In the springs of 1950 and 1951 the heavy siltation of the lake waters resulted in failure of these crops, and thus afforded an instance of one of the most serious aspects of the lake pollution problem.

Study No. 2. This research concerned the role of phosphorus in the growth of phytoplankton in western Lake Erie. This study was carried on from July 1950 to June 1951. Phosphorus is a relatively scarce element in nature, occurring usually as phosphates, which are leached from the soil into streams, lakes, and ultimately the ocean. Much of the phosphorus in Lake Erie is found in the bottom sediment, but it also appears in solution in small quantities. A rough estimate indicated that the southern tributaries discharged some 136 metric tons, and the Detroit River, 312 metric tons of phosphate phosphorus into the lake during the year 1945, making a total of 448 tons. The portion of this amount utilized in fertilization of aquatic plants is probably small, and cannot become effective until clarification of the water permits photosynthesis to proceed. Because of the wet spring in 1951, it was not possible to observe the normal pulse of phytoplankton growth as related to the injection of phosphorus into the lake environment. Based on the average yearly catch of commercial fish (10.2 million kg during the years 1935-1945), about 38,000 kg of phosphate, or 12,000 kg of phosphorus were removed yearly in the form of fish; about 3% of the calculated yearly addition of soluble phosphorus to the lake.

Study No. 3. This project summarized water movements in Lake Erie. Five major types of movement were considered: (1) longshore and major contour currents; (2) seiche movement; (3) hydraulic currents; (4) wind currents; and (5) density and thermal currents. Longshore currents tend to parallel major depth contours, whether the shore line or a sub-surface ridge. This results in a current moving from west to east parallel to the American and Canadian shores. In two regions a major ridge plays a part—the division between the western and central basins, and the division between the central and eastern basins. In the former this results in a division of water flow, one moving southeast and the other northeast.

In Lake Erie, seiche movement is an oscillation of water in the central and eastern ends of the lake, with a periodic rise and fall every 14.2 hours. This results in a derived wave in the western end of the lake, because of the offset position. The derived wave rotates in a clockwise movement around the basin, producing a northeast component, with greatest outflow through the Pelee Passage channel. Seiches may have an important bearing on the lake pollution problem. At the ends of the lake, they generate powerful flushing actions at the mouths of the tributaries, but near the center, where the node of the longitudinal seiche lies; this flushing action is much less pronounced. Cleveland, which lies near the node, is the most highly congested area of the lakeshore, but unfortunately it is where seiche-flushing action is at a minimum. This may partially explain the heavy beach pollution recorded by the 1950-1951 survey.

Hydraulic currents appear to be more effective in the lower strata of the lake than near the surface. The

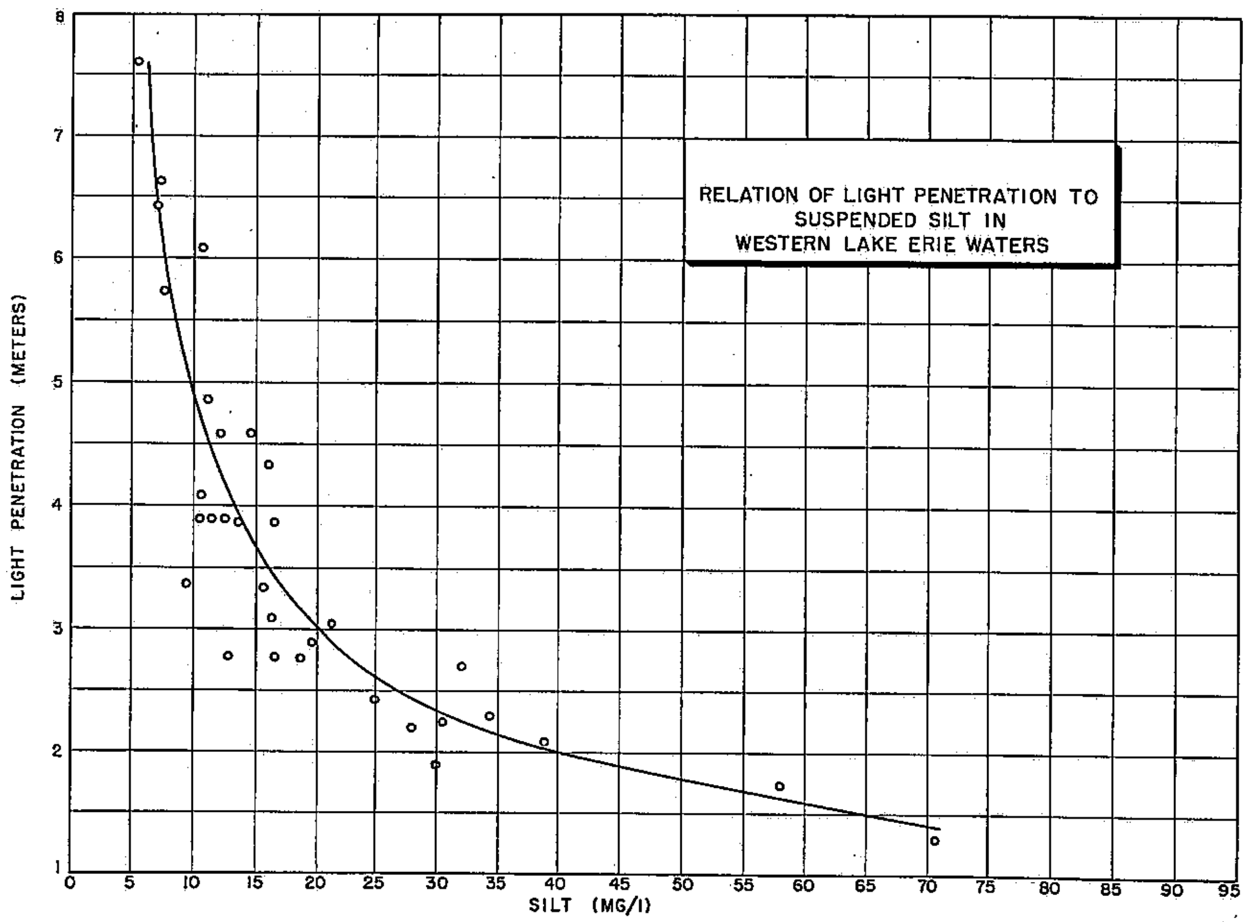


Figure 22. Relationship of light penetration to suspended sediment in western Lake Erie water (after Verduin 1953).

hydraulic set of currents in the western basin is to the southeast, whereas in the central and eastern parts it is to the northeast. Wind currents are produced by direct frictional stress of the wind upon the water, and thus are one of the prime movers of surface water. The prevailing wind over Lake Erie is from the southwest for ten months in the year, and from the west or northwest during one or two spring months. This prevailing wind produces a northeast component to the surface currents. Density currents are the least important of all currents during most of the year. They are important, however, in the spring when the tributaries empty large quantities of warm muddy water into the lake. This water, because it is warmer than the deeper lake strata, tends to spread a large surface layer of muddy water over the lake. In the fall season, the temperature relation is reversed and the colder tributary waters tend to sink below the clearer surface water.

This study concluded that within the lake proper, wind and seiche currents are the primary water movers in the lake. Exceptions are noted during long calm periods when hydraulic currents are most effective, and in the spring, when thermal and density currents are important during short periods. Along the major depth contours, the water tends to run parallel to the contour, thus producing west to east longshore movement. The tendency of this movement to remain fixed is due principally to the hydraulic head produced in the western basin by the inflow from the Detroit and Maumee Rivers.

Study No. 4. This study concerned with the presence of toxic materials at the mouths of the lake tributaries as indicated by a test organism, the cladoceran *Daphnia magna*, sometimes designated by the name, "water flea." This organism is a minute crustacean, found in most natural waters, and it has a lower tolerance for toxic substances than fish and aquatic invertebrates. Moreover, it is an important link in the fish food chain. For these reasons it was considered as suitable organism for the biological assay of industrial wastes.

In order to test the reaction of *Daphnia* to various tributaries, daily to weekly waters samples were obtained from the Maumee, Portage, Sandusky, Huron, Vermilion, Black, Rocky, Grand, Ashtabula, and Conneaut Rivers during the period of April–September 1951. To determine toxicity, samples from streams of known heavy industrial pollution (Grand River from Painesville to Fairport where Diamond Alkali Company discharged wastes and the Black River in Lorain where U.S. Steel had waste outfalls) were used to determine the presence of toxic zones by recording at least 50% immobilization of *Daphnia*.

Of the 169 samples taken at river mouths only 14 were toxic. No toxicity was observed in samples taken at the mouths of the Vermilion, Sandusky and PortageRivers. A number of samples along the Black River were lethal to *Daphnia*, but surface oil film, rather than toxicity, was the cause of death. The results of toxicity tests in the Grand River indicated that this stream probably produced the greatest degree of toxicity in the lake. The results of testing showed, however, that toxic materials discharged into this river were rendered innocuous by the time they reached the mouth of the river. This was not true, however, at other rivers in which samples were toxic. Although the daily chemical load of these other streams was lower than that of the Grand River, isolated cases of toxicity in them were attributed to incidents of batch chemical disposal. Also, the great dilution provided by the lake tended to reduce the pollution hazard in these cases. Periodic flushing of the river mouths also contributed to this dilution effect.

Although toxic discharges from industries were not found to directly affect the aquatic life in the open lake, the occurrence of toxic zones in the tributaries indirectly produced adverse effects. The principal indirect effect was the reduction of available fish food entering the lake from these tributaries. Another adverse effect is to create barriers against fish, thereby preventing their entering the streams to feed or spawn. The toxicity of industrial pollutants was but a small segment of the complete industrial pollution picture as affecting fish life. The most significant effects were created by the physical properties of the pollutants. The deposition of insoluble chemical wastes on the lake floor in the vicinity of the tributary outlets resulted in smothering the growth of bottom organisms, which are an important element in fish food.

In the Black River at Lorain the principal industrial pollutant was the coal-tar waste resulting from the steel mill coking plant. The lethal effect of the massing of this material on the water's surface was clearly demonstrated, and likewise that of the material adhering to silt particles on the stream bottom. With respect to the recreational values of the streams, as to sport fishing and scenic beauty of these areas, both of these values were greatly depreciated at the Black and Grand Rivers as the result of industrial pollution.

Two relationships were noted with regard to industrial pollution and public health. The inadequacy of sewage treatment along the tributaries burdened the streams with the disposal of domestic waste. The capacity of these rivers for self-purification was directly dependent on their biological populations, which were further reduced by industrial pollution, thus made less effective as sewage decomposers. Industrial pollution also affected domestic uses of water by imparting tastes and odors.

Study No. 5. The study was a survey of phytoplankton at the mouths of ten Ohio tributaries of Lake Erie. A total of 245 samples were collected over a period of twelve months, trips being made usually once each month. From two to four stations were visited at each river, and a lake sample was taken at filtration plants near the mouths of six rivers. In counting the various species of plant organisms, allowance was made for their differences in size, and a system of cubic units was adopted, whereby the total content was expressed in terms of total volume.

Four classes and 30 genera of algae were represented in the samples collected. With a few exceptions on any one date, lake and river mouth samples contained the same genera of organisms. As upstream samples showed small volumes of phytoplankton, this similarity suggests that lake water has mixed with river water, and the organisms have been carried into the river mouths from the lake. In a majority of river mouth samples, the closer they were taken to the lake the higher their volume of phytoplankton. This finding supported the supposition that the great majority of plankton found in the river samples is brought in by inflow from the lake. Plankton volumes varied from zero in early January to 12.5 billion cubic units liter^{-1} in late August of 1951.

The most common genera of phytoplankton were: *Melosira*, *Fragilaria*, *Asterionella*, and *Stephanodiscus*, all diatoms, widely distributed in nature. *Synedra*, another diatom, was one of the few genera appearing more often in river water than in lake water. Diatoms in general are troublesome in water filtration because of their filter-clogging tendencies. *Melosira* was the most common genus of those named, being found throughout the year.

The rivers showing high turbidity values were the Black, Sandusky, Portage, and Maumee. Chandler and Weeks (1945) found that in general turbidity values greater than 20 mg liter^{-1} prevent growth of phytoplankton in western Lake Erie. As the turbidity of these four rivers was higher than this threshold, phytoplankton growth was probably negligible in all of them; hence the presence of these organisms, which were as high in these turbid rivers as in the clearer ones, was most likely due to their having been pushed into the estuaries from the lake by the seiches. The population density, therefore, was not an index of the productivity of the river, but was simply an index of the ratio of lake water to river water in the estuary. A study of the data for the Portage River, for example, indicated that water sampled in the Portage estuary was three parts of lake and one part river water.

Another factor, which should not be overlooked, is the possibility that currents set up by seiches in an estuary may cause resuspension of the estuary bottom and thus generate an important amount of turbidity. If this is true, then the turbidities observed in an estuary at any given time cannot be regarded as a recent tributary contribution. It seems likely, however, that these estuary bottoms had acquired their silt-covered character since the invasion of the plow on their watershed; hence the turbidity of estuary waters was still river contributed. In any case it presented a serious pollution problem.

Study No. 6. This investigation was a survey of the bottom fauna of ten Ohio tributaries of the lake at their mouths, and their use as an index of stream pollution. Preliminary work was started on this survey in the fall of 1950. The western rivers flow through a relatively flat, swampy country, whereas those to the east drain a higher, rougher terrain. Man-made changes in the channel, due to industrialization, plus such processes as siltation, had rendered the estuaries quite different from their original natural conditions. Most evident of the effects of these changes was the near-absence of higher aquatic plants which were formerly abundant in many of the areas.

Out of a total of 269 bottom samples collected over a period of 12 months, 79 were taken at the Maumee mouth, 30 samples in Maumee Bay, and 15 samples in open water of western Lake Erie. This emphasis was placed on the Maumee because it had a greater flow than all the other Ohio tributaries combined, and enters the lake at a major human population center.

The use of benthic animals as indicators of stream and lake conditions stems from the basic concept that the long-term physical and chemical conditions of a body of water influence the numbers and kinds of organisms that may use it as a habitat. Physical and chemical conditions may vary considerably in time and space, but the river bottom with its communities of animals represents a more stable unit, with fauna being the summation of all environmental factors combined.

For indicating degrees of stream pollution, the use of bottom animals is limited mainly to those affected by organic pollution. In general, the numbers of different kinds of animals living in a stream tend to decrease, whereas numbers of individuals among the few remaining species tend to increase heavily as organic pollution rises. The tolerant animals, which survive, and the intolerant animals which do not survive, are both of index value. Certain other forms may be found equally abundant in both clean and polluted areas, and hence are of questionable index value. However, the use of bottom animals as pollution indicators is made valueless by any toxic chemical waste, which may exterminate both tolerant and intolerant organisms.

Several systems for placing sections of a polluted stream into zones according to the presence or absence of certain index organisms have appeared in the literature. These classifications have resulted from observations of self-purification phenomena brought about by biological action. Wright and Tidd (1933) devised a scale of pollution for western Lake Erie based on the relative numbers of just two animals of known index value; these were pollution tolerant aquatic worms of the family Tubificidae and pollution sensitive nymphs of the mayfly, *Hexagenia*. The relative abundance of tubificid worms at the various stations was one of the main means of comparison used for the different rivers. These worms are extremely tolerant to areas in which organic decomposition takes place. Counts, weight measurements (live), and generic ratios were made on the tubificids in a number of samples. Other macroscopic benthic animals were counted and later identified. A series of samples were taken in Maumee Bay in 1951 to determine if any changes in the extent of organic pollution had taken place since 1930.

The bottom mud at the Maumee mouth was black and rich in decomposing organic matter, which tended to keep the dissolved oxygen content of the supernatant water at a low level during the critical summer season. Average data during the period of June-October, 1950 showed a dissolved oxygen content of 4.2 mg liter^{-1} (48% saturation). The environmental severity thus indicated was reflected in the numbers and kinds of bottom animals taken at the Maumee stations (Figures 23 and 24). Tubificid worms reached their peak opposite the Toledo Sewage Treatment Plant. The highest number of worms found at that station (March 8, 1951) was 355,110 individuals m^{-2}. Wright and Tidd (1933) classified areas with tubificid population >5,000 m^{-2} as heavily polluted. From weight measurements of the live worms, it was estimated that the total weight of tubificids at this station was 907 g m^{-2}, indicating the tremendous productivity attainable by a tolerant animal in the presence of a large food supply. The extent of organic pollution in Maumee Bay had expanded lakeward since the investigations of Wright and

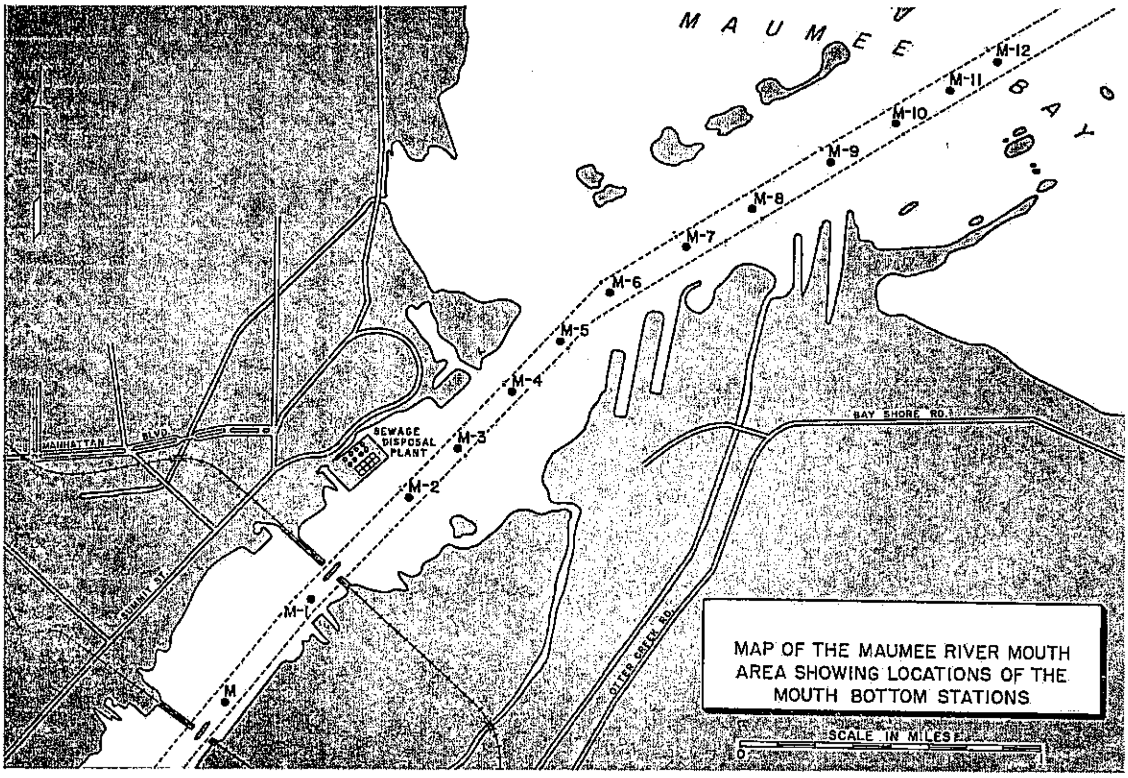


Figure 23. Monitoring stations for benthic organisms at the mouth of the Maumee River in 1951, showing the location of the Toledo sewage disposal plant (after Brown 1953).

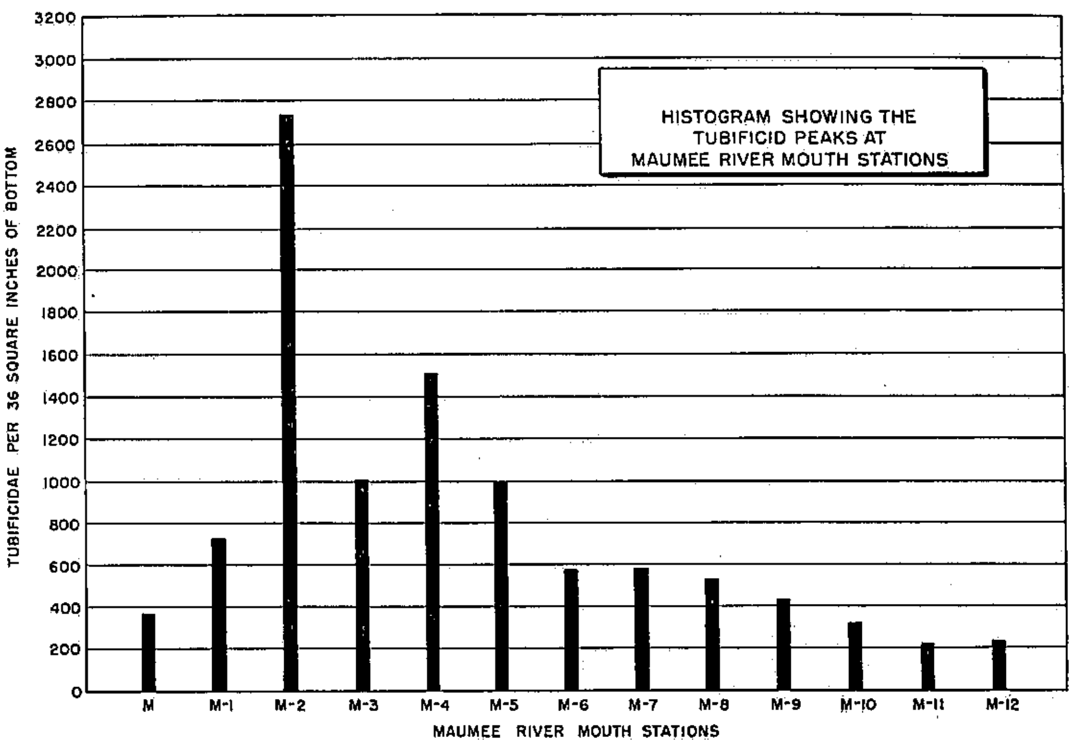


Figure 24. Peak numbers of tubificid worms found at Maumee River mouth benthic stations in 1951; reported values inducate the number of organisms found in samples collected with 6 x 6-inch Ekman dredge (after Brown 1953).

Tidd (1933). These changes were ascribed to a human population increase of 10,640 at Toledo, to expanded industrial developments, and to deepening of the shipping channel from 6 to 9 m.

Of the other nine rivers covered in the survey, the Rocky, Black, Vermilion, and Huron were sampled most frequently. Physical and chemical conditions at the Black River stations were similar to those at the Maumee mouth. The bottom deposits at Rocky River stations were not so homogeneous as those in the Black. At the Vermilion and Huron River stations, bottom conditions were similar. The following, pollution scheme for these four rivers was based on physical, chemical, and biological conditions: Black River mouth—polluted to sub-polluted; Rocky River mouth—sub-polluted to clean water; Huron River mouth—sub-polluted to clean water; and Vermilion River mouth—clean water.

Of the five remaining rivers sampled less frequently during the survey, the Portage and Sandusky showed numbers of tubificids small as compared to the rivers previously discussed. Except at Oak Harbor, the Portage represented clean water conditions in its upper reaches. In the Sandusky, conditions below Fremont were sub-polluted, but it is doubtful if such conditions extend very far downstream. Bottom conditions in the Grand River were different from anything found at the other rivers. The bottom animal population in this river below the Diamond Alkali plants was almost absent, probably because of the effect of wastes from these plants. In the absence of industrial pollution, the mouth of this river probably would be suitable for benthic animals. Bottom deposits at the mouths of the Conneaut and Ashtabula Rivers consisted of organically rich, dark-colored muds, with numbers of tubificids approximating those of the Rocky and Huron Rivers. No typical clean water animals were found in either of these two rivers; both were classed as sub-polluted.

In conclusion, the study found considerable lakeward influence at the Maumee River mouth, but that those rivers classed as non-polluted (clean water) showed little lakeward effects. Of the remaining streams, the Black was found to be the most heavily polluted, but harmful effects on the lake were limited to small local areas near its mouth. In summary, heavy organic pollution was found at only two of the river mouths, the Black and Maumee, and only the Maumee had an appreciable pollution effect on Lake Erie, which had increased in the past 20 years.

Study No. 7. This survey concerned industrial pollution in Cleveland Harbor. The study consisted of 27 fortnightly field trips in the harbor area from September 15, 1950 to September 30, 1951. Nine stations were established in the harbor, and five stations in the Cuyahoga River. On each trip, at each station, observations and sample collections were made at the surface and at a depth of 6.5 m. Field observations included temperature, pH, and a qualitative test for ferrous iron; the collections included samples for dissolved oxygen determination, for total iron content, for turbidity, and soluble iron content. In addition, a sample of the plankton captured by means of a plankton trap, and qualitative net samples of plankton using No. 20 and No. 12 mesh nets, were collected at each point. Daily observations were made from the roof of the Standard Building for two periods during the year in order to note the pattern of distribution of gross pollution (indicated by water coloration) and its relation to wind direction. These latter observations took advantage of known chemical reactions—hydrolysis of ferrous iron and its oxidation to ferric hydroxide in the presence of dissolved oxygen in the water, thereby imparting a distinct reddish color of ferric oxide to the water. At the time, large amounts of ferrous iron salts were discharged into the Cuyahoga River as pickling liquors from the steel mills, and thus found their way to the harbor.

The observations made from the vantage point described indicated that the discolored water remained mostly within the harbor, but some of it usually flowed out through the harbor entrance opposite the mouth of the Cuyahoga River and occasionally through the western entrance to the harbor (Figure 25). Both inside and outside the harbor breakwater the distribution of discolored water was affected by the direction of the wind. The prevailing water movement appeared to be from west to east, but this direction could be reversed by a northeasterly or easterly wind. Occasionally a situation existed in which the river water was clear around its outlet into the harbor, but discolored further lakeward around the breakwater entrance. In these cases the dissolved oxygen had been exhausted near the river outlet, and hence none was available for oxidizing the ferrous iron until the river water became admixed with oxygen-rich harbor water. The most highly polluted locality was just inside the mouth of the river where the iron content was always much higher than at any other point, as also was the sulfate content. Ferrous iron occurred here frequently, indicating proximity to the source of pollution.

Conditions for the existence of aquatic life were in general unsatisfactory at the Cuyahoga River mouth. Stations near the harbor mouth were also highly influenced by the river effluents and here again the iron content was high, and conditions were unfavorable to aquatic life. Other stations within the harbor were polluted, but conditions were never extreme. At stations located in the

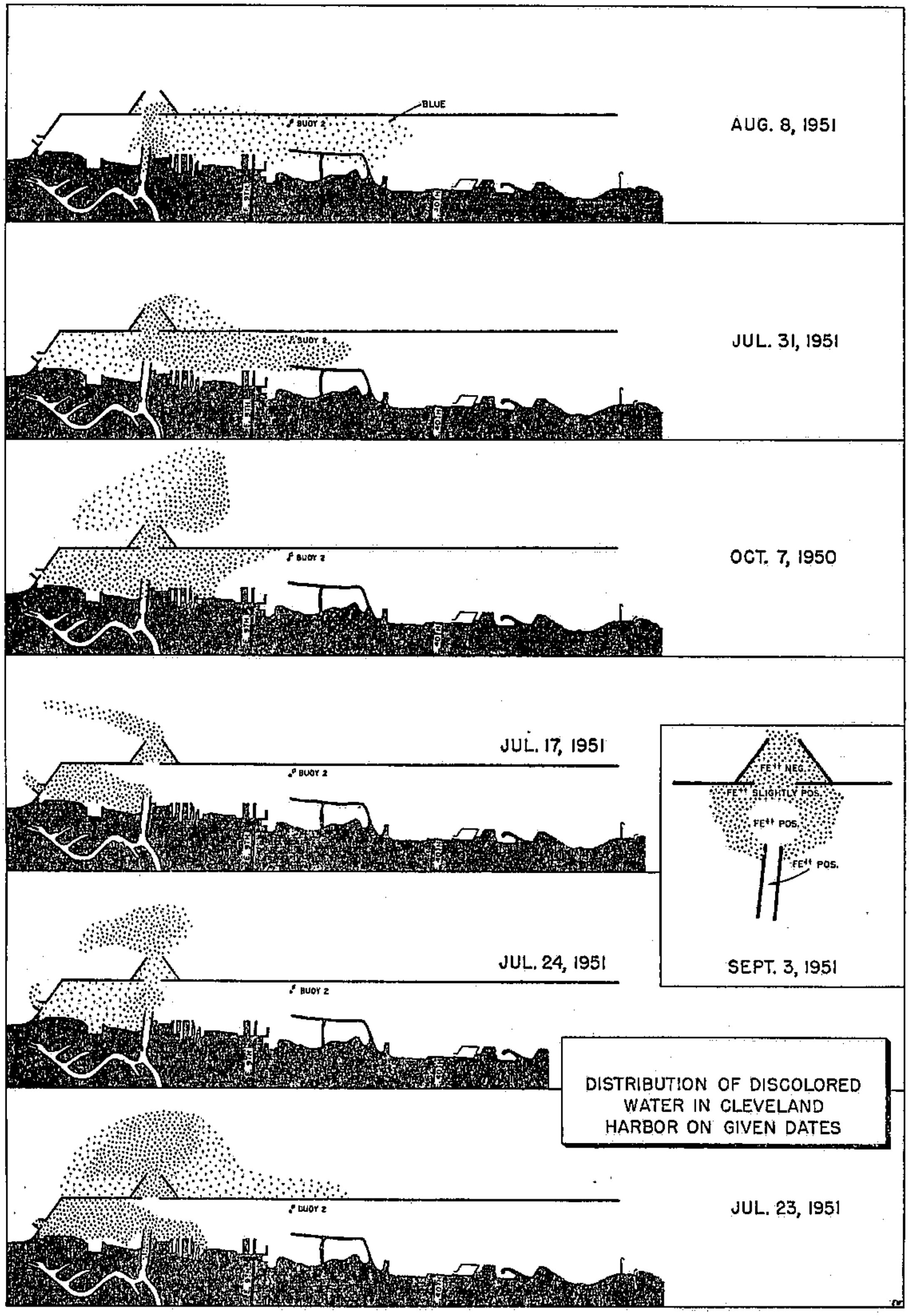


Figure 25. Observations of discolored water in Cleveland Harbor 1950-1951. Discoloration caused by a red-brown iron precipitate which formed when pickling liquors (ferrous sulfate or coperas) released from steel mills on the Cuyahoga River encountered oxygen-rich lake water in the harbor where the liquors hydrolized and oxidized (after Davis 1953).

lake outside the breakwall, the iron content and turbidity were relatively low, and evidences of phytoplankton blooms appeared earlier than at the inner stations. On the other hand, bottom samples the lake stations showed very little animal life as compared to some of the harbor stations.

The study concluded that industrial pollutants poured into the Cuyahoga River were deleterious to aquatic life in the river itself, and sometimes in the area surrounding the mouth of the river. These deleterious effects were probably effective as far up the river as the steel mills. Beyond the mouth of the river, aside from the unpleasant appearance and sickening odor of the water, there may have been some harmful effects from oil deposits in the bottom muds, from reduced photosynthesis caused by high turbidities, and from lowered oxygen content deleterious to animal life. A driving-away, or possibly poisoning, of fish (especially game fish) may have occurred from untested chemical pollutions, such as phenols. In part these deleterious effects may be compensated for by increased availability of plant nutrients in sewage effluents discharged into the river, both from Cleveland and from the villages and cities upstream.

Summary. The Lake Erie Pollution Survey demonstrated that pollution barriers existed at the mouths of most of the lake's tributaries in the form of toxic materials, phenols, or deficient oxygen, which adversely affected the propagation of fish that normally utilized these estuaries. During the one-year study, over 2.6 million metric tons of sediment moved into Lake Erie from four principal Ohio tributaries. The damage to fish habitat, particularly spawning areas, was believed to be heavy and some offshore areas were found to be unsuitable for fish survival. A significant portion of the sediment loads was identified as eroded from the top soil of farms in the basin and represented a serious soil loss. While all public water supplies had satisfactory bacterial quality, some were borderline. Lakeward extensions of water intake pipelines were recommended. Sewage, either untreated or inadequately treated, was found to be the principal offender along the marginal waters of the lake and its tributaries. Additionally, organic waste loads from industrial sources were estimated as equivalent to population approaching one million persons. Industrial wastes of an inorganic nature were indicated in many of the chemical analyses of tributary streams and lake water. Many of the streams had toxic substances at times, which were traced to industrial operations. The lake water off the northeastern Ohio shore revealed extensive contamination by industrial chloride wastes. All the evidence indicated that the marginal waters of Lake Erie along the Ohio shore and tributary streams were in a condition, which demanded, concerted cleanup action (Youngquist 1953).

Surveys by the Ohio Divisions of Shore Erosion and Geological Survey (1950-1971)

The Lake Erie Geological Program operated within these divisions of ODNR and conducted numerous physical limnology surveys throughout the lake. Initiated by Dr. Howard J. Pincus of the Department of Geology at The Ohio State University, for the first several years the program concentrated on nearshore characteristics and processes (Pincus 1951, 1953). In 1953 the research program was expanded with the establishment of a year-round office of the Division of Shore Erosion in Sandusky, Ohio, which was staffed by full-time personnel including geologists, a hydrographer, a research boat captain, and technicians. James L. Verber was in charge of this office form 1953 to 1958, Robert P. Hartley from 1959 to 1963, and Charles E. Herdendorf from 1964 to 1971. In 1961 the Division of Shore Erosion's research program was transferred to the newly formed Lake Erie Section of Division of Geological Survey. The types of research conducted included the complete mapping of the Ohio Lake Erie shoreline and offshore areas with emphasis on engineering geology (Pincus 1960; Hartley 1964), bottom deposits (Verber 1957; Hartley 1961a, b; Herdendorf 1968; Hobson et al. 1969; Herdendorf and Braidech 1972), and physical limnology (Verber 1955, 1960; Hartley, et al. 1966; Herdendorf 1966, 1967, 1969, 1970).

The main emphasis of research in the early years was placed on identifying and understanding shore processes along the lake's shoreline. In later years, research was expanded to achieve a better understanding of lake processes and water quality, and to contribute information on the natural resources lying within the state's boundaries. Between 1952 and 1966 the Lake Erie Geological Research Program of took hundreds of temperature recordings throughout Lake Erie (Herdendorf 1967). Woods Hole Oceanographic Institution type bathythermographs (BT), on loan from the Department of the Navy, were used to record water temperatures. The instruments used were capable of recording the temperature of a vertical column of water within a range of 0 to 65 m and can be made both from a stationary research vessel and underway. Recordings were taken routinely on many cruises in which the study of bottom sediments and water movements was the primary objective, while other cruises were made specifically to study the vertical temperature structure of the lake. A particular study from 1953 to 1955 involved measurements in central and eastern Lake Erie as part of a project to study the thermal structure of the lake along its longitudinal and transverse axes (Figure 3). During this project a station was also established over the deepest part of the lake and repetitive recordings were made at half-hour intervals for 20 hours.

On June 23, 1963 a synoptic survey of physical and chemical properties of the water in western Lake Erie was conducted by several research vessels of the Divisions of Geological Survey and Wildlife (Figure 26). The main objective of the survey was to determine the feasibility and value of a 300-station, synoptic (one day) survey as a method of mapping water masses, determining their origins, and ascertaining their velocity and paths of movement. Measurements of water temperature (below the zone of diurnal heating) and specific conductance, as well as recordings of water level fluctuations for several days prior to the survey, proved to be the most reliable indicators of distinct water masses and their movements (Hartley et al. 1966; Herdendorf 1969). Subsurface temperatures obtained with a BT at 3-m depths, when plotted and contoured, showed a definite southward movement of cold, mid-channel Detroit River flanked by warmer water that moved along the shorelines (Figure 27). Surface conductivity also showed a similar flow pattern, but the mid-channel water mass appeared to be composed of a series of four low-conductance pods from the Detroit River mouth to the Ohio shore. Labeled A through D on Figure 27, these pods proved useful in computing the velocity of the flow.

Lake level fluctuations in western Lake Erie for several days preceding the synoptic survey are shown on Figure 28. On each of the four days immediately before the survey, seiche activity caused the lake to rise and fall noticeably. The low points of these fluctuations are also

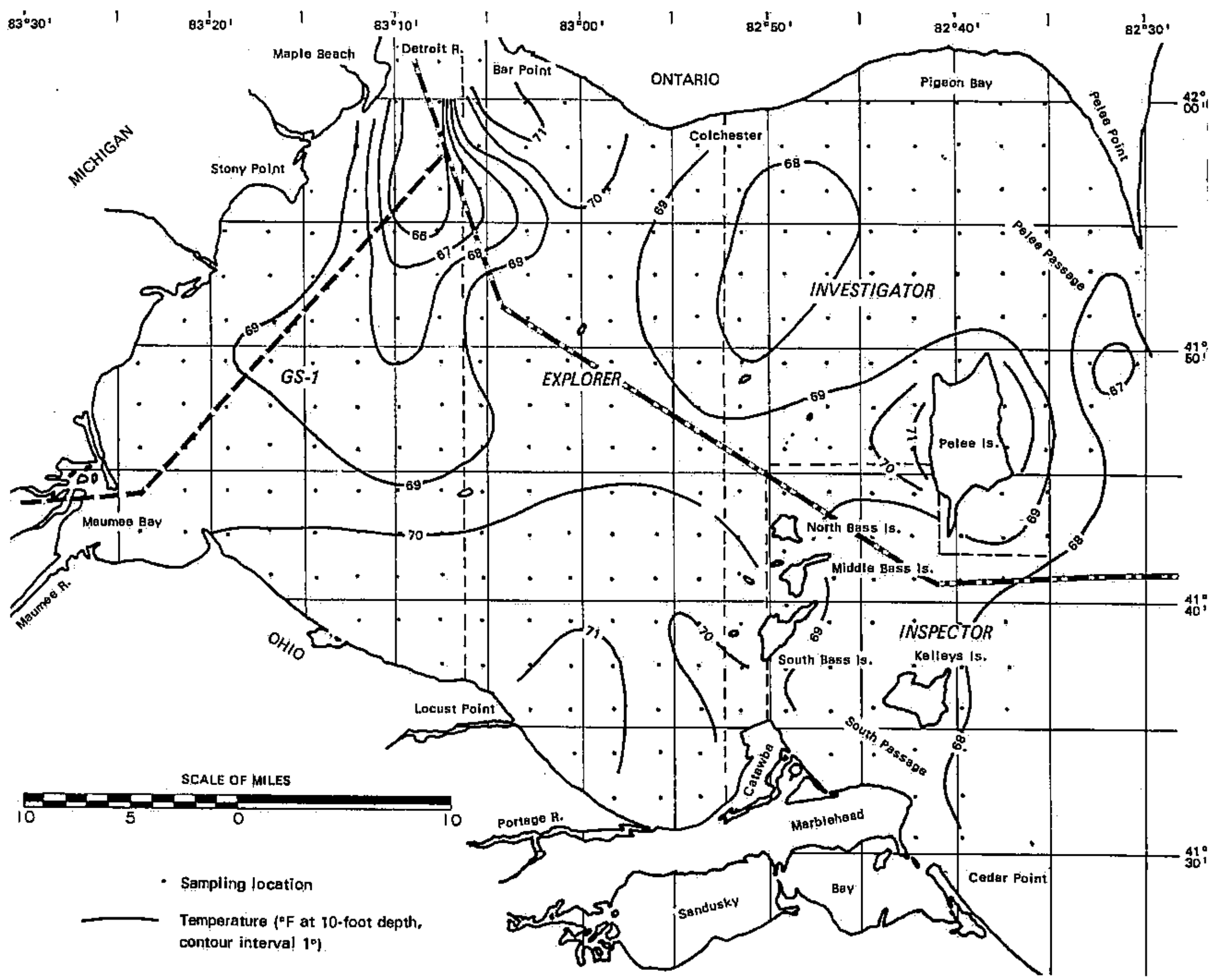


Figure 26. Water temperatures at 3-m depths in western Lake Erie on June 23, 1963, showing sampling stations and segments of the study area covered by each research vessel (after Herdendorf 1969).

Figure 27. Surface conductivity of western Lake Erie water on June 23, 1963, showing four pods of Detroit River mid-channel flow penetrating deeply into the western basin (after Herdendorf 1969).

labeled A through D on Figure 28, suggesting a relationship between the low water levels and the low-conductance pods of water. During the four low water events, a larger volume of mid-channel Detroit River water entered the lake because of the increased surface gradient. The succeeding higher water levels decreased the hydrostatic head, thereby partially pinching off flow and forming a pod-like water mass. Matching the four pods with the low-water events permitted the calculation of a velocity ranging from 23 to 13 cm second^{-1} for the southward moving water mass, which reached the Ohio shore near Locust Point about four days after entering the western basin from the Detroit River (Herdendorf 1969).

In July and August 1967 a cruise was undertaken to provide new information on the physical limnology of Lake Erie, with particular attention to circulation patterns and to changes that occur in the quality of the water as it passes through the lake (Herdendorf 1970). The objective of the field survey was to measure several physicochemical properties of Lake Erie water from its major inflow at the Detroit River to outflow in the Niagara River. This was done by making thirteen transects across Lake Erie and its connecting waterways, a cruise distance of 800 km. Observations of water properties and movements were made at 110 stations (at 400-m to 8,000-m intervals on each transect), and in most cases consisted of profile measurements with readings and samples taken at various depths from surface to bottom from aboard the Division of Geological Survey's research vessel, *GS-1* (Figure 29). The properties and conditions investigated on the cruise were (1) water temperature, (2) specific conductance, (3) water color, (4) transparency, (5) hydrogen-ion concentration (pH), (6) dissolved-oxygen content, (7) chloride-ion concentration, (8) turbidity, (9) currents, (10) waves, (11) water level, (12) meteorological conditions, (13) water depth, and (14) bottom deposits. The study was completed within a two-week period to give the data collected some degree of synopticity.

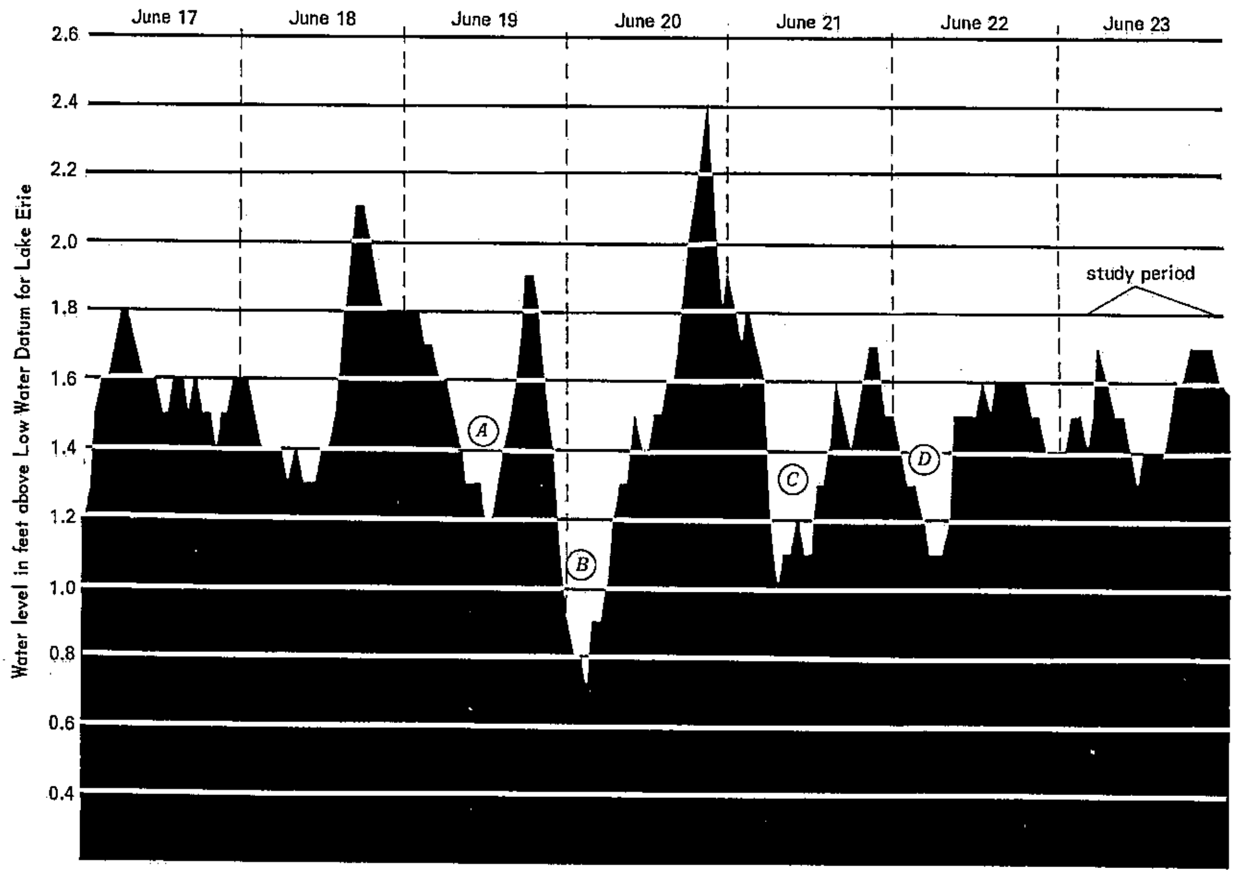


Figure 28. Water level fluctuations in western Lake Erie for June 17-23 as recorded at the U.S. Army Corps of Engineers gauge in Toledo Harbor, Ohio. Low water events (labeled A, B, C, & D) correspond to low-conductance water masses (A, B, C, & D) on Figure 27 (after Herdendorf 1969).

The results of the 1967 survey showed that the physical limnology of western Lake Erie is strongly influenced by Detroit River flow. This inflow is composed of three distinct water masses. The mid-channel flow predominates and is characterized by (1) lower temperature, (2) lower specific conductance, (3) greener color and higher transparency, (4) lower pH, (5) higher dissolved-oxygen content, (6) lower chloride-ion concentration, and (7) lower turbidity than the flows on the east and west sides of the river. The mid-channel flow penetrates deeply into the western basin (Figure 30) where it mixes with other masses and eventually flows into the central basin via Pelee Passage, and to a lesser extent through South Passage. The side flows generally cling to the shoreline and recycle in large eddy currents.

In the central basin, the prevailing southwest winds are parallel to the longitudinal axis of the lake. Because of the rotation of the earth these winds generate currents, which cause a geostrophic transport of water to the right toward the United States shore. This convergence of water along the south shore resulted in a rise in lake level, which was equalized by sinking of water off the shore. At the same time the lake level was lowered along the Canadian shore as surface currents moved water offshore. The sinking along the south shore appeared to be compensated by a subsurface movement of water toward the north and an upwelling along Ontario shore.

The thermocline was found to be approximately 10 m shallower adjacent to the north shore than on the south side of he lake; this was interpreted as an upwelling influenced by the prevailing southwest winds. The resultant surface currents indicated a net eastward movement, while subsurface readings showed a slight net westward movement. This was explained by the cycle of (l) surface transport of water toward the southeast, (2) sinking of water off the south shore, (3) subsurface transport toward the north-northwest, and (4) upwelling adjacent to the north. The pattern of this type of circulation would be analogous to coils of a spring that tapers toward the eastern end of the lake.

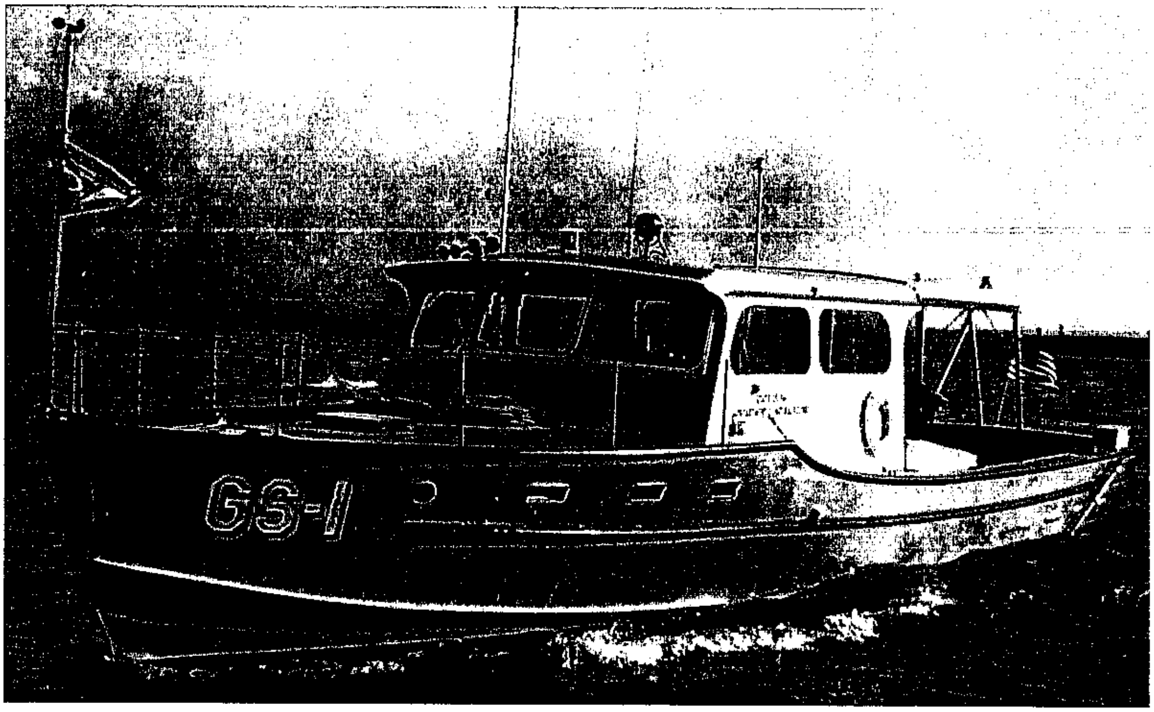


Figure 29. Research vessel *GS-1* operated by the Ohio Department of Natural Resources, Divisions of Shore Erosion and Geological Survey from 1952 to 2004.

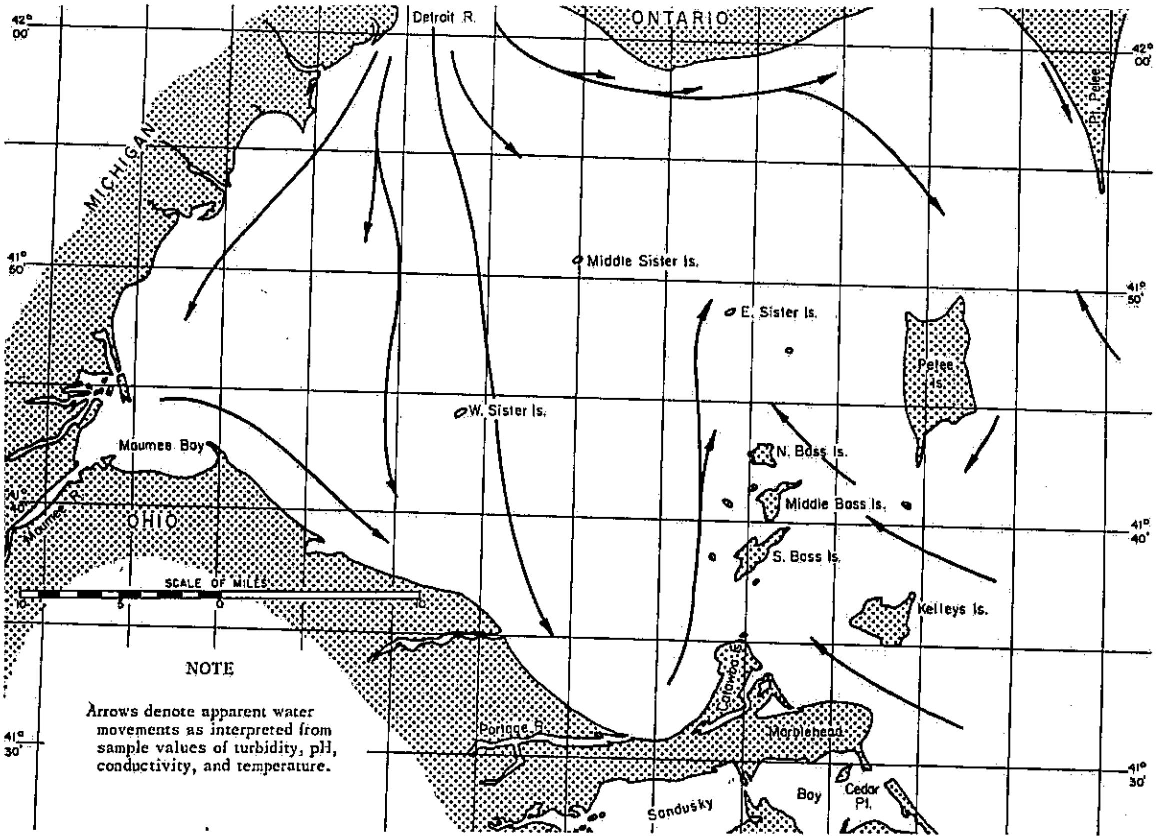


Figure 30. Current flow patterns in western Lake Erie as interpreted from water quality measurements (after Hartley et al. 1966).

The formation of a deep thermocline in the southern half of the central basin resulted in a relatively thin hypolimnion, which is highly susceptible to oxygen depletion by organic-rich sediments with high oxygen demands. These circumstances presumably resulted in the presence of bottom water with as low as 15% dissolved oxygen saturation in the southwestern part of the basin.

Bottom surface samples or cores were collected and described at about half of the physical limnology stations. Perhaps the most significant information obtained from these samples was the delineation of (1) areas of deposition and (2) areas of erosion or nondeposition (Figure 31). Large areas of sand and glacial till bottom adjacent to the north shore and sizable reaches of sand and gravel, bedrock, and glacial till bottom along the south shore were assumed to be areas of nondeposition. Silt and clay mud bottoms in the deeper parts of the basins were the only areas of recent deposition other than littoral sand accumulations along the shoreline. Calculations showed that approximately 58% of the lake bottom is within the regions of deposition—western basin: 56%; central basin: 60%; and eastern basin: 52%. The bottom deposits of the northern part of the central basin were predominately glacial till, which do not have the high oxygen demand of the clay muds in the southern half of the basin. This fact coupled with a thicker hypolimnion of the north shore apparently accounted for the more abundant dissolved oxygen at the bottom. In the eastern basin the thermocline over the "deep hole" was at a depth of 12 m allowing a considerably deeper hypolimnion (52 m) than in the central basin. As a result, the dissolved oxygen content of the bottom water was approximately 70% of saturation.

Dissolved solids showed a marked increase from Lake St. Clair to the Niagara River. Specific conductance indicated an approximate rise of 40%, while threefold chloride increases were even more dramatic. In general, midlake water in the central and eastern basins of Lake Erie, lakeward of a narrow band of shore-influenced water, is relatively uniform and of good quality. Some variation in the concentration of dissolved substances occurs between the epilimnion and hypolimnion waters and was probably caused by the anoxic conditions and the dissolving of the chemicals absorbed on sediment particles.

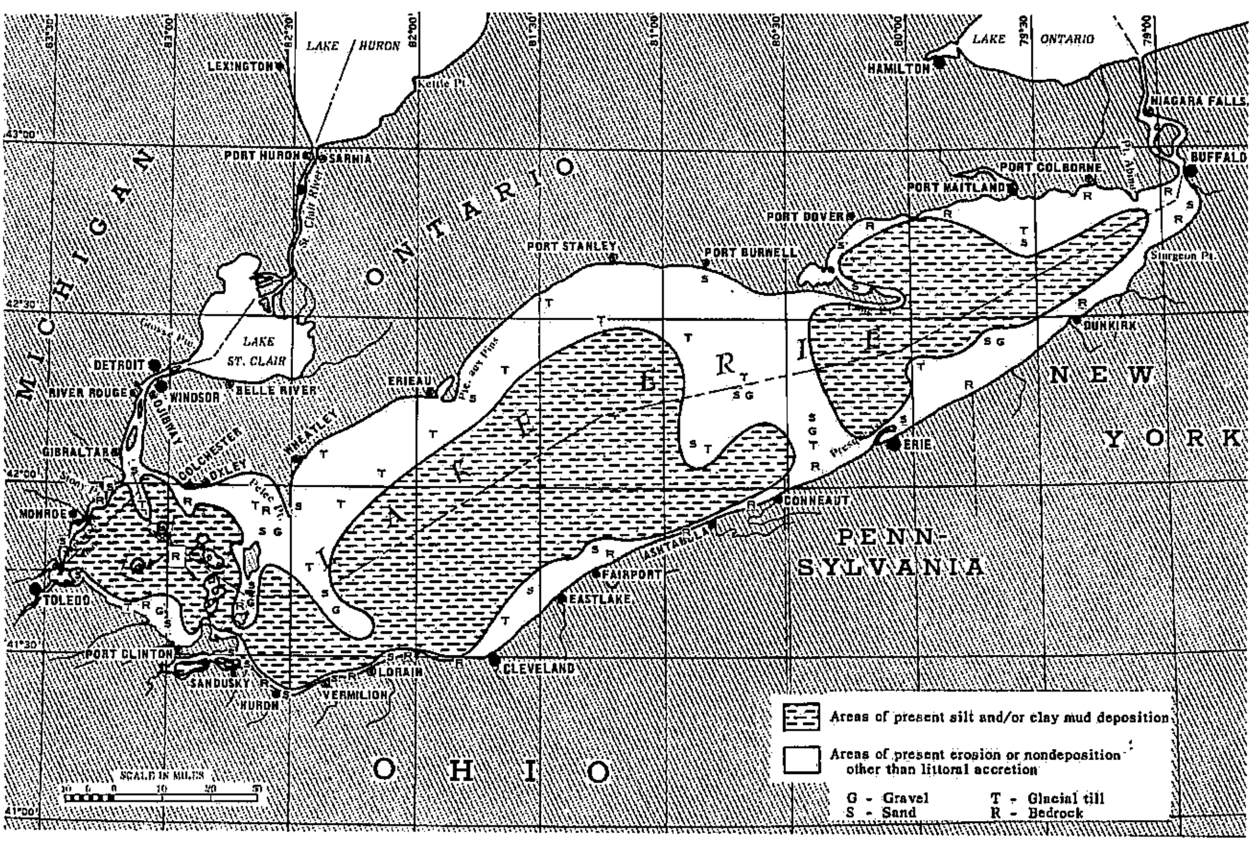


Figure 31. Distribution of Lake Erie bottom deposits in 1967, showing depositional basisns and areas of erosion and/or nondeposition (after Herdendorf 1970).

Dissolved Oxygen Surveys 1947-1953 and 1959-1960

The University of Western Ontario undertook open-lake work during the period 1947–1953. These studies failed to show any anoxic conditions, but recorded dissolved oxygen levels as low as 2.0 mg liter^{-1} at mid-lake stations off Cleveland (Powers et al. 1960). Under typical conditions the central basin hypolimnion contains about 9.5 mg liter^{-1} of dissolved oxygen in early June when the basin stratifies, but concentrations can be dramatically reduced by September when turnover usually occurs (Zapotosky and Herdendorf 1980).

Federal, provincial, state, and university organizations participated in a coordinated investigation to determine the extent of low dissolved oxygen waters in the central basin in 1959 and 1960 (Beeton 1963). This work was continued to a limited degree in 1961 by the U.S. Public Health Service (Thomas 1963). Earlier surveys had failed to adequately sample the southwestern portion of the basin, known as the Sandusky sub-basin (Figure 2). Typically this sub-basin experiences anoxia in August, which later spreads eastward to the main portion of the basin (Zapotosky and Herdendorf 1980). The 1959 and 1960 surveys revealed areas of 3,600 km^2 and 1,660 km^2 with hypolimnetic oxygen values <1.0 mg liter^{-1}, respectively, and 780 km^2 with <0.5 mg liter^{-1} in 1959 (Beeton 1963). Subsequently throughout the 1960s, every survey detected anoxic conditions in the central basin (Carr 1962; Thomas 1963; Great Lakes Institute 1964, 1965; Federal Water Pollution Control Administration 1968a; Herdendorf 1970; Dobson and Gilbertson 1972), but only the surveys of 1961 and 1964 had dense enough sampling patterns to permit crude estimates of anoxic areas—3,640 km^2 and 5,570 km^2, respectively (Herdendorf 1984).

In the western basin, Britt (1955) reported the oxygen concentration at a stratified station 3 km west of South Bass Island fell to 0.1 mg liter^{-1} after 28 days of calm weather in the summer of 1953. At the same station in 1966, the oxygen concentration near the bottom dropped from 3.0 to 0.1 mg liter^{-1} in a 5-day period in early summer (Britt et al. 1968).

Federal Water Pollution Control Administration Surveys (1963-1968)

Surveillance observations by the Federal Water Pollution Control Administration from 1963 to 1968 demonstrated that phosphorus was the limiting nutrient for algal productivity in Lake Erie (Hartley and Potos 1971), whereas nitrogen is in sufficiently large supplies in the waters of the lake that it is not considered limiting. The findings of this investigation supported recommendations for an 80% reduction of municipal and industrial soluble phosphorus to reduce the population of green and blue-green algae in Lake Erie.

Lake Erie's eutrophication problems stemmed from sewage pollution, agricultural runoff, industrial contamination, coastal wetland losses, and possibly introductions of exotic species (Federal Water Pollution Control Administration 1968b). Fisheries over-exploitation and toxic waste discharges further damaged the lake. The early settlers to the region drained vast coastal wetlands and stripped away much of the natural vegetation that formed a protective cover over the rich upland soils. From the denuded watersheds, tributaries carried high amounts of sediment to the lake, which silted over fish spawning reefs in the shallow western basin (Egerton 1985). Industry and urban development followed agriculture along banks and at the mouths of the lake's main tributaries: the Detroit, Maumee, Black, Cuyahoga, and Buffalo Rivers giving rise to the cities of Detroit, Toledo, Lorain, Cleveland, and Buffalo. Increased population, along with the use of artificial fertilizers on farmlands, brought more and more nutrients, especially nitrogen and phosphorus compounds, to the lake which hurried the aging process—the public was introduced to the concept of "cultural eutrophication" in the 1960s. The most obvious consequence of this nutrient pollution was to nourish the lake's algal populations, creating mats of blue-green plankton that blanketed most of the western basin and fouled long reaches of the central basin's south shore (Herdendorf 1995).

Citizen indignation over the deplorable condition of Lake Erie reached the Ohio statehouse and in August 1965 Governor James Rhodes hosted an interstate enforcement conference in Cleveland with participation by governors of all the states in the Lake Erie watershed and the federal government. Researchers from state and federal agencies documented the deteriorated condition of the lake and predicted a dire future unless immediate steps were taken to halt pollution and reverse the worsening trends in water quality. By 1965, most of the causes of Lake Erie's over-enrichment problem had been identified; most notably an annual loading of over 28,000 metric tons of phosphorus that predominantly entered the lake via the Detroit and Maumee Rivers (Herdendorf 1995). Even more serious than the unsightly surface algae, over-enrichment produced latent problems, which disrupted the natural balance of the lake, especially hypolimnetic oxygen depletion. As the excess organic matter sank to the bottom, became incorporated in the sediment, decayed, and anoxia ensued—major changes took place in the aquatic food web and sensitive benthic forms were eliminated (Britt 1955; Carr and Hiltunen

1965). Eventually, desirable fish stocks were stressed by the deteriorating conditions in the western and central basins causing recruitment failure (Regier et al. 1969; Hartman 1973; Regier and Hartman 1973).

The key recommendations of the enforcement conference formed the basis for later actions that initiated the recovery of Lake Erie. The conferees concluded that eutrophication was a major concern and that the reduction of one or more of the nutrients in the lake would be beneficial in controlling algal growths. Of major importance in getting the federal government involved was the finding that interstate pollution of Lake Erie existed, thus pollution was subject to abatement under the Federal Water Pollution Control Act of 1961. Specific recommendations dealt with (1) secondary and tertiary treatment of municipal wastes to reduce phosphates, BOD, and other deleterious substances, (2) designs to prevent by-passing of untreated waste water, (3) prohibition of combined storm and sanitary sewers, (4) improved industrial management practices in waste management, and (5) programs to control agricultural runoff. A series of water pollution surveillance stations were proposed for Lake Erie and a Technical Committee was established to evaluate water quality problems and recommend further abatement measures. In addition to mandates of the states and federal government, binding pollution abatement agreements and remedial schedules were established for 118 municipal governments and 146 industries to meet compliance standards within five years (Herdendorf 1995).

The Cleveland conference in 1965 was a major turning point in the fight against the cultural eutrophication of Lake Erie. For the first time, all of the states in the lake's drainage basin decided to work together with the federal government to solve an interstate problem. The passage of the Federal Water Quality Act later in 1965 gave new urgency and support to the cooperative effort already underway. In 1967 the Lake Erie Technical Committee issued its final report (Harlow 1967), which pinpointed phosphorus as the limiting nutrient that could best be controlled by reductions in (1) phosphates in detergents, (2) phosphorus from municipal discharges, and (3) phosphorus in rural runoff. The report stopped short of identifying Lake Erie eutrophication as an international problem, but it soon became apparent that both Canada and the United States would need to cooperate to solve the problem.

Coordinated Canadian–American Surveys (1970–1986)

Starting in with Project Hypo in 1970, a joint Canadian–American effort to investigate eutrophication in Lake Erie (Burns and Ross 1972), consistent shipboard and laboratory procedures and a uniform station plan (Figure 32) have been utilized by the several research organizations monitoring the status of the open waters of Lake Erie. Throughout the 1970s and 1980s coordinated cruises were undertaken by researchers from the Canada Centre for Inland Waters, the Center for Lake Erie Area Research at The Ohio State University (Figure 33), the

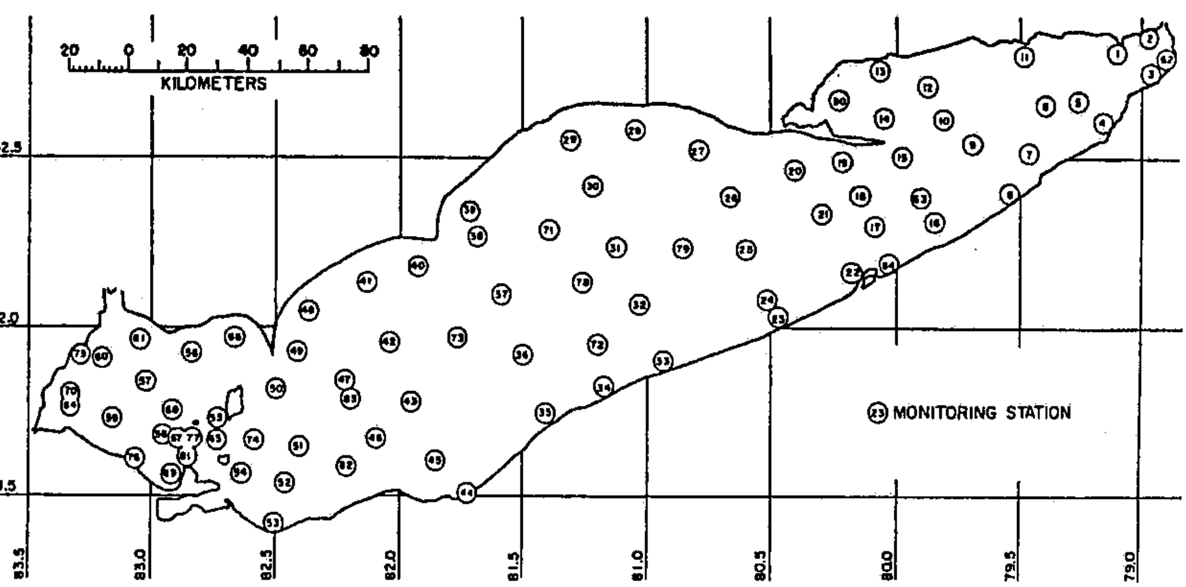
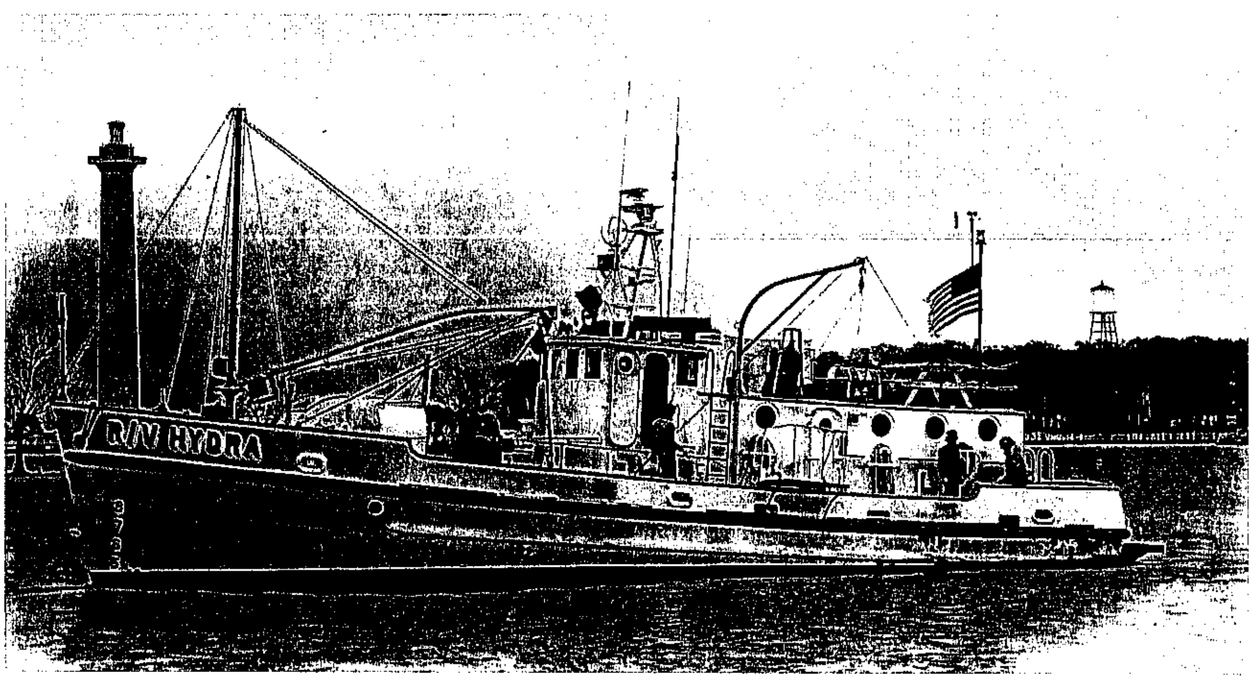


Figure 32. Water quality monitoring stations in the three basins of Lake Erie utilized by American and Canadian investigators in the 1970s and 1980s (after Herdendorf 1980).



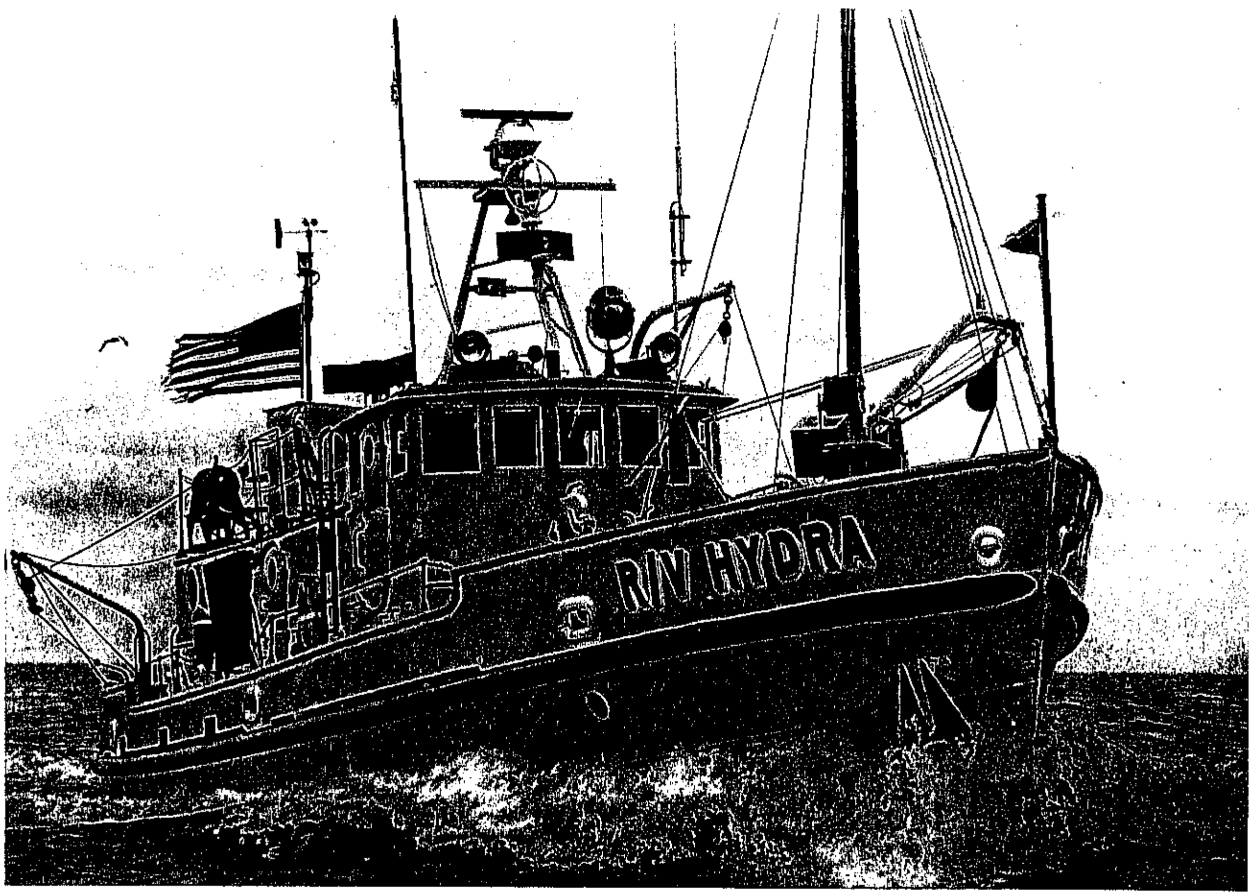


Figure 33. Research vessel *Hydra* operated by the Center for Lake Erie Area Research at The Ohio State University from 1973 to 1988.

Great Lakes Laboratory at the State University of New York, and the Great Lakes National Program Office of U.S. Environmental Protection Agency (USEPA).

In 1970, Project Hypo measurements indicated a 6,600-km^2 area of 0% saturation of dissolved oxygen in the central basin (Burns and Ross 1972; Burns 1976). By 1973, the anoxic area had increased in size to 11,270 km^2 when nearly 94% of the central basin's hypolimnion had oxygen concentrations <0.5 mg $liter^{-1}$ (Herdendorf 1980). The size of the anoxic area remained large in 1974, 10,250 km^2, but in 1975 a dramatic change occurred which has been attributed to meteorological conditions (Zapotosky and Herdendorf 1980). Although the hypolimnetic oxygen depletion rate remained high (0.10 mg $liter^{-1}$ day^{-1} in 1975 as compared to 0.12 mg $liter^{-1}$ day^{-1} in 1973), a relatively small portion of the basin experienced anoxia (400 km^2 or about 4% of the hypolimnion). The spring season of 1975 was characterized by unusually calm weather, resulting in a thick hypolimnion (mean thickness of 7.1 m in 1975 as compared to 4.1 m in 1973 and 3.0 m in 1970).

Surveys from 1975 through 1986 (Herdendorf 1984; Fay et al. 1988) indicated wide fluctuations in the size of the anoxic area in the central basin of Lake Erie (Table 2), presumably owing to meteorological factors. Figure 34 is a mosaic of Lake Erie maps from 1930 to 1982 showing the 15 years where reasonably good data exits for the areal extent of anoxia (anoxia is here defined as dissolved oxygen concentrations of <1.0 mg $liter^{-1}$ as measured 1.0 m above the sediment–water interface). These maps can lead to a conclusion that although meteorological conditions have a major influence on the formation of anoxia, the area of the central basin experiencing anoxia appears to have increased dramatically from 1930 to the mid-1970s and thereafter declined to approximately half the maximum area by the early1980s. However, this method of gauging the spread of eutrophication may not be indicative of the actual rates of oxygen loss in the hypolimnion (Barica 1982).

An alternative method of determining trends in hypolimnetic oxygen concentrations involves measuring the rate of oxygen loss between survey intervals, corrected for vertical mixing and other factors (Rosa and Burns 1987). Table 2 also lists the uncorrected and corrected oxygen depletion rates for the central basin from 1929 to 1986. The general inference that can be drawn from these data is that the hypolimnetic oxygen demand in the central basin increased dramatically from 1929 to 1974; thereafter the rate declined somewhat, but remained high until 1981 when it dropped to the 1950s level. However, in the ensuing years it again rose, reaching record-high levels in 1986 (Herdendorf 1984; Rosa and Burns 1987; Fay et al. 1988). To confuse the situation even more, geological and paleontological evidence presented by Delorme (1982) suggests that anoxia has been present in the central basin long before European settlement in the watershed and oxygen depletion calculations carried out by Charlton (1980) indicate that there has been little or no long term trend of changing oxygen depletion in the half century prior to 1980. However, the failure of dissolved oxygen to respond rapidly to reductions in phosphorus loadings was predicted by eutrophication models, which predicted lags in the range of 5 to 10 years (Di Toro and Connolly 1980; Charlton 1987).

Records for the period 1900 to the early1960s in nearshore waters of central Lake Erie show startling increases in total dissolved solids, chloride, calcium, sulfate, and sodium plus potassium (Beeton 1961, 1965, 1969). From 1966 to 1980 conductivity values indicate a decline in the total dissolved solids, falling approximately 9% during this period (Figure 35). Chloride showed the most notable change, a drop of about 30% from 25 to 18 mg $liter^{-1}$ (Herdendorf 1984). Much of this decline can be attributed to elimination of waste brine discharge from the Grand River at Fairport, Ohio in the early 1970s. Other conservative ions (e.g., calcium, sodium, and sulfate) ceased to increase after the 1960s and show modest declines into the 1980s (Figure 35).

Chlorophyll pigment has also been used as an indicator of algal productivity in Lake Erie (Herdendorf 1984). In 1975 chlorophyll *a* concentrations for the western, central, and eastern basins were 13.7, 5.9, and 3.6 µg $liter^{-1}$, respectively. By 1980, a noticeable reduction had occurred with values of 8.4, 3.1, and 1.9 µg $liter^{-1}$ for the same three basins. The basin-wide blooms of blue-greens, which were so prevalent in the mid-1960s, decreased in the 1970s and were virtually absent in the 1980s. The filamentous, epilithic green alga *Cladophora glomerata* is well adapted to the rocky littoral reaches along portions of all three basins, where it grows in profusion, particularly in the western end of the lake. This alga has been reported in Lake Erie since the late 1800s, but in the 1960s it became increasingly abundant (Lorenz and Herdendorf 1982). Massive growths of *Cladophora* created nuisance accumulations and obnoxious odors along recreational beaches, as well as clogging water intakes, fouling fishing nets, and impeding nearshore navigation. Thomas (1975) determined that *Cladophora* starts to become a nuisance at total phosphorus concentrations above 15 µg $liter^{-1}$. This finding was incorporated into the target limits for phosphorus concentrations in the Great Lakes Water Quality Agreement (Table 3).

Table 2. Trends in anoxic areas and dissolved oxygen depletion rates in the central basin of Lake Erie from 1929 to 1986. Data sources: Dobson and Gilbertson 1972; Herdendorf 1980, 1984; Fay et al. 1988. Corrected values per method of Rosa and Burns (1987).

Year	Anoxic hypolimnion		Depletion rate (mg liter^{-1} day^{-1})	
	Area (km^2)	Percent (%)	Uncorrected	Corrected
1929			0.05	0.07
1930	300	3.0		
1948			0.08	
1949			0.08	0.08
1950			0.07	0.09
1951			0.07	0.10
1952			0.07	
1953			0.08	
1959	3,600	33.0	0.09	
1960	1,660	15.0	0.09	
1961	3,640	33.0	0.10	0.12
1962			0.13	0.11
1963			0.11	0.12
1964	5,870	53.0		
1967			0.13	0.11
1968			0.12	
1969			0.12	0.11
1970	6,600	60.0	0.11	0.13
1971				0.13
1972	7,970	72.5		
1973	11,270	93.7	0.12	0.12
1974	10,250	87.0	0.13	0.15
1975	400	4.1	0.10	0.11
1976	7,300	63.0	0.13	
1977	2,870	24.8	0.12	0.12
1978	3,980	31.4	0.11	0.11
1979				0.12
1980	4,330	35.9	0.11	0.11
1981	4,820	37.7	0.08	0.10
1982	5,470	46.5	0.11	0.12
1983				0.11
1984				0.11
1985				0.12
1986				0.16

The 1972 and 1978 Great Lakes Water Quality Agreements between Canada and the United States contained a requirement to reduce the phosphorus concentrations in municipal discharges to 1.0 mg liter^{-1} for all the Great Lakes. The agreement also called for phosphorus reductions in all discharges and non-point source inputs, primarily agricultural runoff, to achieve an annual target loading of only 11,000 metric tons (Table 3). Models had been developed which predicted loadings at this level would leave the western basin no longer choked with algae and summer oxygen concentrations would be high enough to support fish populations in the bottom waters of the central basin (Di Toro and Connolly 1980; Di Toro et al. 1987). As a consequence of aggressive remedial action programs, the loading of phosphorus to the lake declined from an estimated high of 28,000 metric tons in 1968 to a low of only 7,841 metric tons in 1988—well below the target level (Herdendorf 1984; Dolan 1993). For the decade 1981-1991, loadings were equal to or below the target except for the years 1982, 1984 and 1990. Because all large sewage treatment plants met the 1.0 mg liter^{-1} effluent limitation, municipal contributions

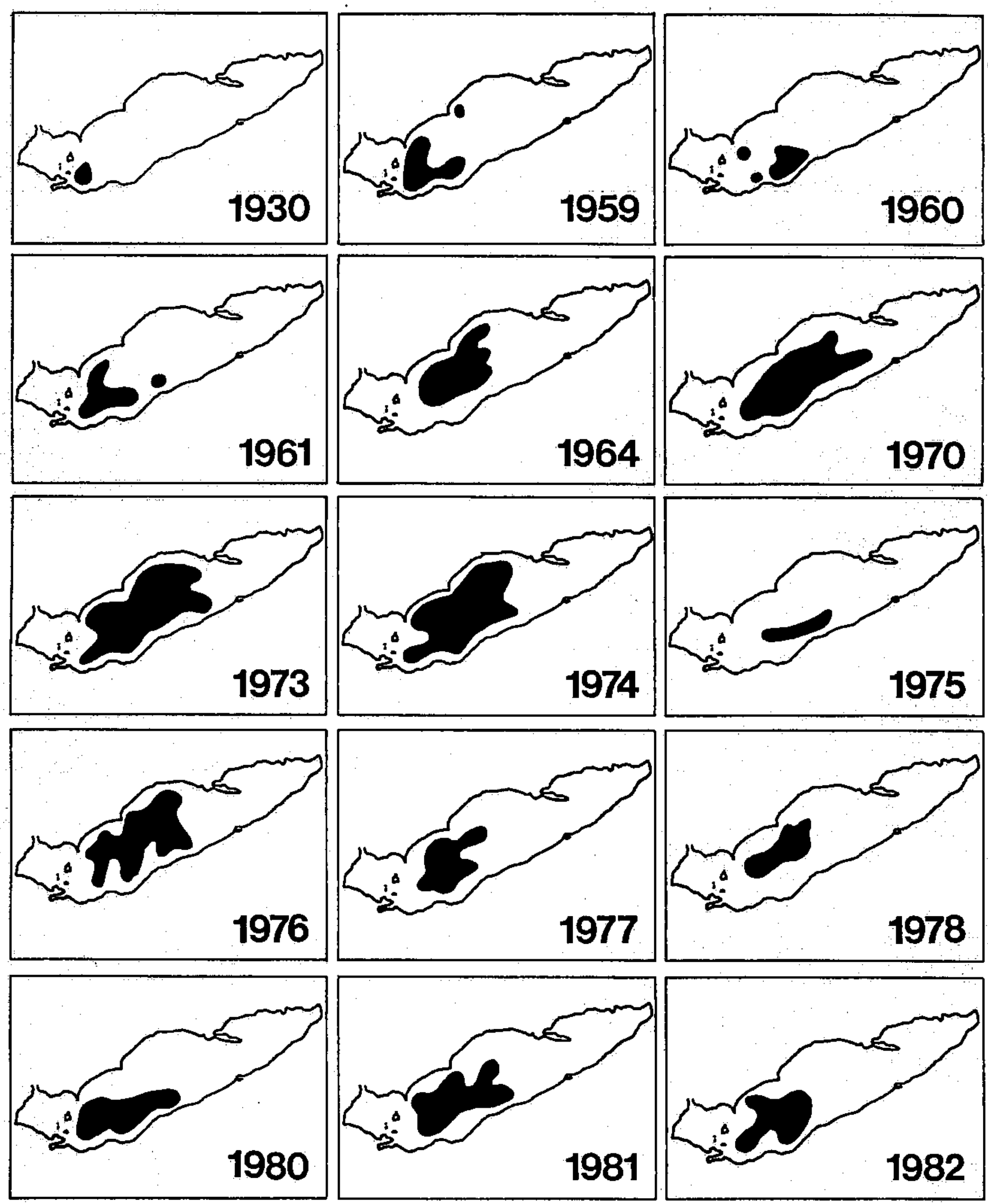


Figure 34. Distribution of anoxia in the central basin of Lake Erie from 1930 to 1982 (after Herdendorf 1984).

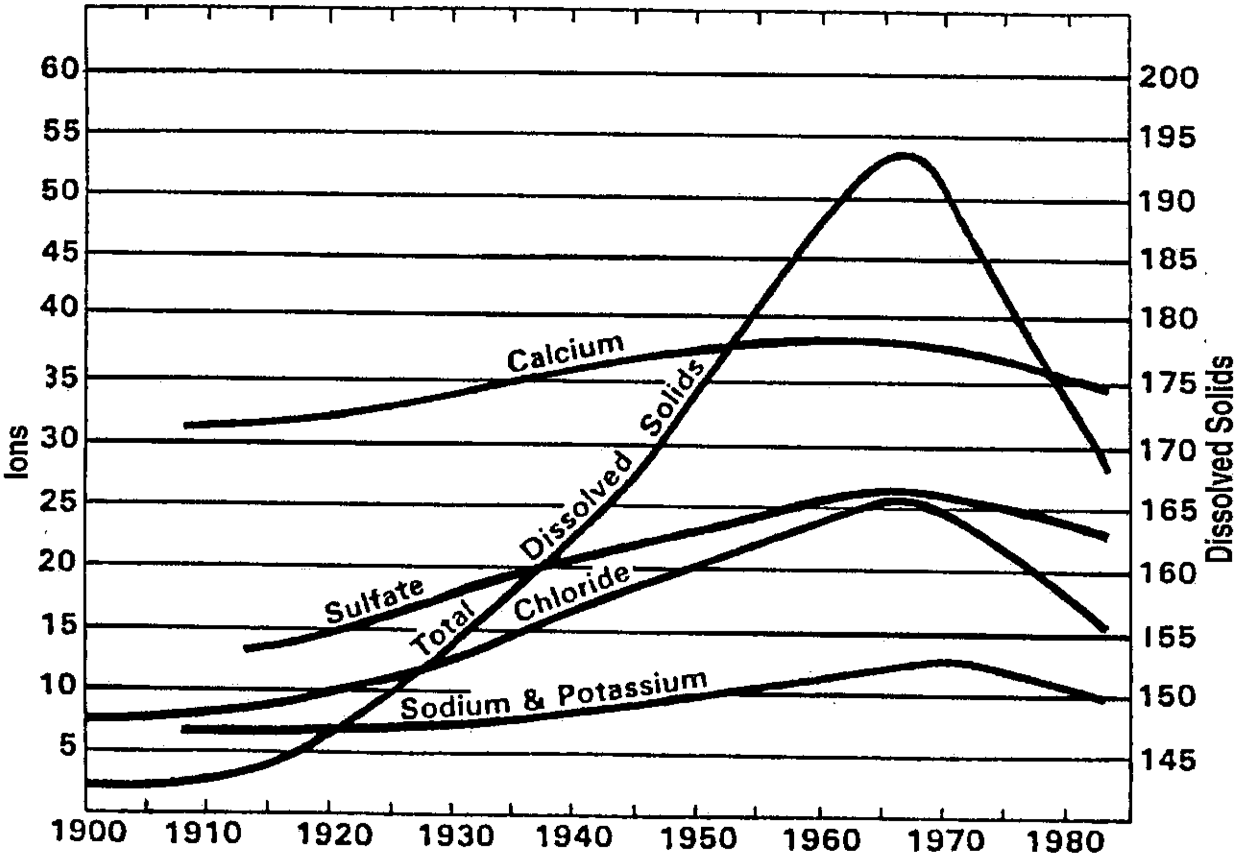


Figure 35. Changes in the chemical character of Lake Erie central basin water from 1900 to 1982, expressed in mg liter^{-1} (after Beeton 1969; Sutfin et al. 1984; Herdendorf and Monaco 1988).

Table 3. Total phosphorus concentrations (μg liter^{-1}) in the three basins of Lake Erie from 1963 to 1992. Target limit concentrations and goals established by the International Joint Commission under the 1978 Canada–United States Great Lakes Water Quality Agreement. Data sources: Federal Water Pollution Control Administration 1968a; Herdendorf 1980, 1984; Fay et al. 1988; Bertram 1993.

Basin	1963-1965	1973-1975	1980-1986	1990-1992	Target	Goal
Western	160	37.3	33.5	19.9	15	Prevent nuisance algae
Central	65	18.5	15.7	10.6	10	Restore oxic bottom
Eastern	60	26.5	13.4	9.4	10	Prevent nuisance algae

do not appear to determine whether the target is reached in a particular year. Rather, phosphorus loads appear to be directly related to the amount of precipitation falling in the basin, indicating the importance of non-point source contributions via the tributaries to the lake. For example 1990, the wettest year recorded by the National Weather Service for the Lake Erie basin, caused an approximate doubling of tributary loads, which resulted in the highest phosphorus load (12,899 metric tons) since 1980 (Dolan 1993).

Recent Survey Findings

In June 1991 a symposium was convened at the 34th Conference on Great Lakes Research to focus on evidence for the restoration of the Lake Erie ecosystem. The cumulative evidence presented at the symposium strongly supported the widely held perception that environmental conditions in Lake Erie were tending toward improvement (Makarewicz and Bertram 1993). Specifically, the western and central basins had shifted from eutrophic to more mesotrophic (Figure 36), point and non-point source loadings of phosphorus had been dramatically reduced, ambient phosphorus concentrations in the central basin had approached target levels of 10 µg liter^{-1} (Table 3), and some lowering in the hypolimnetic dissolved oxygen depletion rate had been observed. Equally encouraging, benthic and pelagic biotic communities had shown signs of recovery, particularly the reestablishment of the burrowing mayfly *Hexgenia* (Krieger et al. 1996) and the resurgence of the walleye (*Sander vitreus*) population in the western basin (Hatch et al. 1987). This relatively short-term turnaround in the state of Lake Erie speaks to the resiliency of large lakes.

Unfortunately a number of the recovery indicators associated with nutrient controls are coincident with the alteration of benthic habitats linked to extensive colonization by dreissenid mussels (Leach 1999), which makes it difficult to establish cause and effect relationships. The introduction of zebra and quagga mussels (*Dreissena polymorpha* and *D. bubensis*) to Lake Erie from overseas ballast water in the late 1980s (Griffiths et al. 1991; May and Marsden 1992) has changed everything. These mussels which can reach densities in excess of 30, 000 m^{-2}, have altered the Lake Erie ecosystem by displacing indigenous benthic populations, improving water clarity, depleting selective phytoplankton populations, and dramatically modifying the lake's food web through their filtering activity (Dermott et al. 1999). Because Lake Erie is currently undergoing multiple changes in its nutrient status and its food web, an understanding of this transitional phase is difficult in light of existing information. Trends in the eutrophication history of Lake Erie have been confounded by these unforeseen invasions. To complicate the situation even more, in the last several years phosphorus concentrations have risen, blooms of blue-greens have reappeared, and dissolved oxygen in the central basin hypolimnion has been dropping to the point where the media is again carrying stories of a "dead zone" (Reutter et al. 2002). Most likely near-record low water levels and turbulent spring weather in recent years have negatively impacted the thickness of the hypolimnion and the dilution capacity of the lake. The biological manifestations of these physical changes have yet to be worked out. Only once these factors, coupled with the impacts of dreissenids, become more fully understood and placed in the context of nutrient availability will it be possible to assess trophic status of Lake Erie and judge the effectiveness of phosphorus reduction programs in the recovery of Lake Erie.

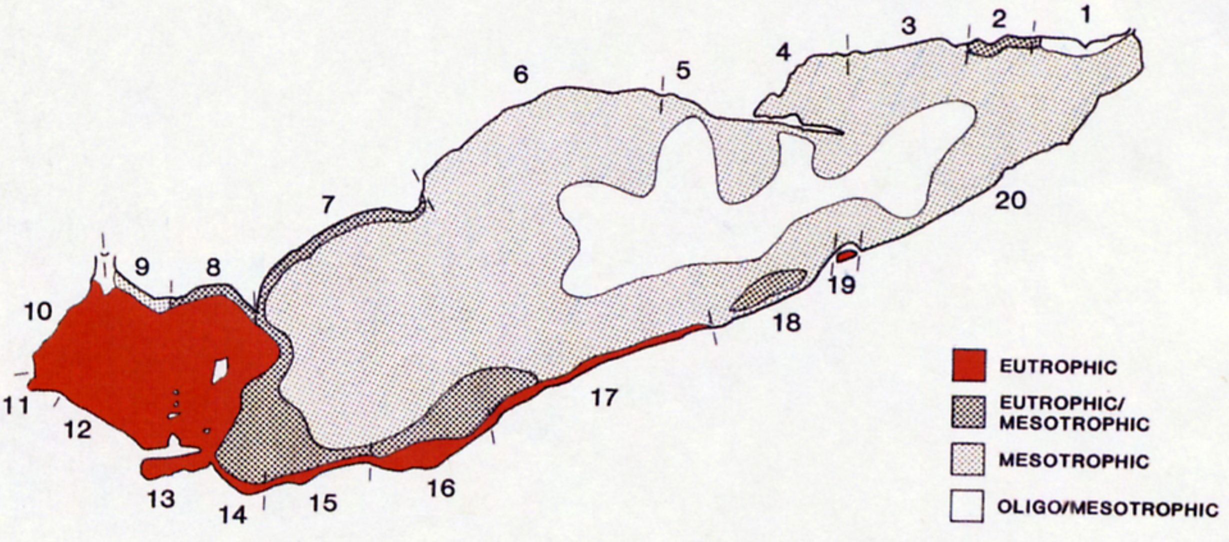


Figure 36. Trophic status of Lake Erie in the mid-1980s based on the phosphorus loading and concentration, phytoplankton biomass, and primary productivity criteria of Vollenweider et al. (1974). Numbers along the shoreline indicate reaches used to determine nearshore trophic status (after Bolsenga and Herdendorf 1993).

LESSONS LEARNED

A century of research on the eutrophication phenomenon in Lake Erie has provided the scientific community with some lessons regarding the study of large lakes and has yielded some generalizations specifically about Lake Erie.

1. Large lakes, and the Great Lakes in particular, are complex ecosystems that require coordinated international programs of limnolgical study which span multiple years to ascertain reliable tends in water quality and biotic response to environmental change.
2. To construct long-term trends, standard observational protocols and surveillance stations must be established for all investigators to follow, as well as frequent group intercomparison studies to insure data compatibility.
3. The study of large lakes typically requires oceanographic-scale vessels and observational/ measurement hardware.
4. Large lakes, as demonstrated by Lake Erie, are susceptible to cultural eutrophication.
5. Bathymetry is a prime factor in the depletion of dissolved oxygen in large lakes; unfortunately Lake Erie's central basin is just the wrong depth—if it were 10 m shallower it would not stratify or 10 m deeper it would sustain oxic condition throughout summer stratification.
6. Meteorological variations can have a more profound impact on dissolved oxygen concentrations in certain hypolimnetic situations than controls on nutrient inputs.
7. Large lakes with water retention periods of a few decades or less are good candidates for reversing eutrophication if a significant portion of the nutrient delivery is from anthropogenic sources.
8. Determined governments can stop, and possibly reverse, eutrophication in a large lakes; for the test case of Lake Erie it took a concerted international efforts to control phosphorus inputs through modified agricultural practices, tertiary treatment of municipal wastes, non-phosphate detergents, industrial discharge controls, and citizens committed to enlightened stewardship for a period of two decades at a cost approaching $10 billion.
9. Large lakes appear to posses a high degree of resiliency as demonstrated by the recolonization of the burrowing mayfly and the resurgence of the walleye in Lake Erie.
10. The introduction of exotic species can have profound effects on large lakes, often more dramatic than human attempts at modifying water quality.
11. Large lakes are not static; research findings should be viewed as a transitory images of bodies of water in transition.

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REFERENCES CITED

Abrams, D. A. and C. E. Taft. 1971. A bibliography of research conducted at the Franz Theodore Stone Laboratory, and its predecessor, of The Ohio State University from 1896-1968. *Ohio J. Sci.* 71(2): 81-105.

Barica, J. 1982. Lake Erie dissolved oxygen controversy. *J. Great Lakes Res.* 8: 719-722.

Beeton, A. M. 1961. Environmental changes in Lake Erie. *Trans. Amer. Fisheries Soc.* 90:153-159.

Beeton, A. M. 1963. Limnological survey of Lake Erie, 1959 and 1960. Great Lakes Fish. Comm. Tech. Rep. 6. 32 pp.

Beeton, A. M. 1965. Eutrophication of the St. Lawrence Great Lakes. *Linmol. Oceanogr.* 10: 240-254.

Beeton, A. M. 1969. Changes in the environment and biota of the Great Lakes, p. 150-196. *In* G. A. Rohlich [ed.], *Eutrophication: causes, consequences, correctives.* Nat. Acad. Sci. Washington, DC.

Bertram, P. E. 1993. Total phosphorus and dissolved oxygen trends in the central basin of Lake Erie, 1970–1991. *J. Great Lakes Res.* 19:224-236.

Bolsenga, S. J. and C. E. Herdendorf [eds.]. 1993. *Lake Erie and Lake St. Clair Handbook.* Wayne State Univ. Press, Detroit. 467 pp.

Britt, N. W. 1955. Stratification in western Lake Erie in the summer of 1953: effects on the *Hexagenia* (Ephemeroptera) population. *Ecology* 36: 239-244.

Britt, N. W., E. J. Skoch, and K. R. Smith. 1968. Record low dissolved oxygen in the island area of Lake Erie. *Ohio J. Sci.* 68: 175-179.

Brown, E. H., Jr. 1953. Survey of the bottom fauna at the mouths of ten Lake Erie, south shore rivers: its abundance, composition, and use as index of stream pollution, p. 156-170. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus

Burns, N. M. 1976. Oxygen depletion in the central and eastern basins of Lake Erie. *J. Fish. Res. Bd. Can.* 33: 512-519.

Burns, N. M. and C. Ross [eds.]. 1972. *Project Hypo, an intensive study of the Lake Erie central basin hypolimnion and related surface water phenomena.* Canada Centre for Inland Waters Paper 6 and U.S. Environmental Protection Agency Tech. Rep. TS-05-71-208-24. 182 pp.

Carr, J. F. 1962. *Dissolved oxygen in Lake Erie, past and present.* Univ. Michigan, Great Lakes Res. Div. Pub. 9: 1-14.

Carr, J. F. and J. K. Hiltunen. 1965. Changes in the bottom fauna of western Lake Erie from 1930 to 1961. *Limnol. Oceanogr.* 10: 551-569.

Chandler, D. C. and O. B. Weeks. 1945. Limnological studies of western Lake Erie. V. Relation of limnological and meteorological conditions to the production of phytoplankton in 1942. *Ecological Mon.* 15: 435-456.

Charlton, M. N. 1980. Oxygen depletion in Lake Erie: has there been any change? *Can. J. Fish. Aquat. Sci.* 37: 72-81.

Charlton, M. N. 1987. Lake Erie oxygen revisited. *J. Great Lakes Res.* 13: 697-708.

Cope, D. E. 1864. Partial catalogue of the cold-blooded vertebrata of Michigan. Pt. I. *Proc. Acad. Natur. Sci. Philadelphia* 16(5): 276-285.

Cope, D. E. 1865. Partial catalogue of the cold-blooded vertebrata of Michigan. Pt. II. *Proc. Acad. Natur. Sci. Philadelphia* 17(2): 78-88.

Curl, H. C. 1953. A study of the distribution of phosphorus in western Lake Erie and its utilizatioin by natural phytoplankton populations, p. 133-136. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus.

Cuvier, G. A. and M. A. Valenciennes. 1842. *Histoire naturelles des poisons. Les Cyprinoides.* Vol. 16. Levrault, Strasborg, France. 472 pp. [Valenciennes authored volume]

Davis, C. C. 1953. Cleveland harbor industrial pollution survey, p. 170-188. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus.

Delorme, L. D. 1982. Lake Erie oxygen: the prehistoric record. *Can. J. Fish. Aquat. Sci.* 39: 1021-1029.

Dermott, R., M. Munawar, L. Witzel, and P. A. Ryan. 1999. An assessment of food-web changes in eastern Lake Erie: impact of *Dreissena* spp. and phosphorus management on rainbow smelt, *Osmerus mordax*, p. 367-385. *In* M. Munawar, T. Edsall, and I. F. Munawar [eds.], *State of Lake Erie past, present and future.* Backhuys Publ., The Netherlands.

Di Toro, D. M. and J. P. Connolly. 1980. *Mathematical models of water quality in large lakes. Part 2: Lake Erie. U.S.* Environmental Protection Agency, Environ. Res. Lab.–Duluth, EPA-600/3-80-065. 230 pp.

Di Toro, D. M., N. A. Thomas, C. E. Herdendorf, R. P. Winfield, and J. P. Connolly. 1987. A post audit of a Lake Erie eutrophication model. *J. Great Lakes Res.* 13: 801-825.

Dobson, H. H. and M. Gilbertson. 1972. Oxygen depletion in the hypolimnion of the central basin of Lake Erie, 1929 to 1970, p. 3-8. *In* N. M. Burns and C. Ross [eds.], *Project Hypo, an intensive study of the Lake Erie central basin hypolimnion and related surface water phenomena.* Canada Centre for Inland Waters Paper 6 and U.S. Environmental Protection Agency Tech. Rep. TS-05-71-208-24.

Dolan, D. M. 1993. Point source loadings of phosphorus to Lake Erie: 1986–1990. *J. Great Lakes Res.* 19: 212–223.

Egerton, F. N. 1985. *Overfishing or pollution? Case history of a controversy on the Great Lakes.* Great Lakes Fish. Comm. Tech. Rep. 41. 28 pp.

Fay, L. A., H. E. Kundtz, and D. E. Rathke. 1988. *1986 Lake Erie water quality conditions for Lake Erie's western, central and eastern basins.* Ohio State Univ., Center Lake Erie Area Res. Tech. Rep. 317. 287 pp.

Federal Water Pollution Control Administration. 1968a. *Lake Erie environmental summary 1963–1964.* Federal Water Pollution Control Admin., Great Lakes Region. 170 pp.

Federal Water Pollution Control Administration. 1968b. *Lake Erie report—a plan for water pollution control.* Federal Water Pollution Control Admin., Great Lakes Region. 107 pp.

Fiedler, R. H. 1931. Fishery industries of the United States, 1929. *Report of the Commission of Fisheries for fiscal year 1930.* Appendix XIV, pp. 705-1068. Washington, D. C.

Fish, C. J. 1929a. A preliminary report on the joint survey of Lake Erie, p. 39-106. *In* E. Moore [ed.], *A biological survey of the Erie-Niagara system.* New York Conservation Dept. 18th Annual Rep. Suppl., Albany.

Fish, C. J. [ed.]. 1929b. Preliminary report on the cooperative survey of Lake Erie. *Bull. Buffalo Soc. Natur. Sci.* 14: 7-220.

Fish, C. J. and Associates. 1960. *Limnological survey of eastern and central Lake Erie, 1928–29.* U.S. Fish and Wildlife Service Spec. Sci. Rep.–Fisheries 334. 198 pp.

Fuller, K., H. Shear, and J. Wittig [eds.]. 1995. *The Great Lakes: an environmental atlas and resource book, 3rd ed.* U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago and Environment Canada, Toronto. 46 pp.

Great Lakes Institute. 1964. *Great Lakes Institute data record, 1962 surveys, part 1, Lake Ontario and Lake Erie.* Univ. Toronto, Great Lakes Inst. Rep. PR 16. 97 pp.

Great Lakes Institute. 1965. *Great Lakes Institute data record, 1963 surveys, part 1, Lake Ontario, Lake Erie, and Lake St. Clair.* Univ. Toronto, Great Lakes Inst. Rep. PR 23. 195 pp.

Griffiths, R. W., D. W. Schloesser, J. H. Leach, and W. P. Kovalak. 1991. Distribution and dispersal of the zebra mussel (*Dreissena polymorpha*) in the Great Lakes region. *Can. J. Fish. Aquat. Sci.* 48: 1381-1388.

Harlow, G. L. 1967. *Report of the Lake Erie Enforcement Conference Technical Committee.* Federal Water Pollution Control Administration, Lake Erie Office. 25 pp.

Hartley, R. P. 1961a. *Bottom deposits in the Ohio waters of central Lake Erie.* Ohio Dept. Natur. Resources, Div. Shore Erosion Tech. Rep. 7, Columbus. 14 pp.

Hartley, R. P. 1961b. *Bottom sediments in the island area of Lake Erie.* Ohio Dept. Natur. Resources, Div. Shore Erosion Tech. Rep. 9, Columbus. 22 pp.

Hartley, R. P. 1964. *Effects of large structures on the Ohio shore of Lake Erie.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest. 53, Columbus. 30 pp.

Hartley, R. P. and C. P. Potos. 1971. *Algal–temperature–nutrient relationships and distribution in Lake Erie 1968.* U.S. Environmental Protection Agency, Region V, Lake Erie Basin Office. 87 pp.

Hartley, R. P., C. E. Herdendorf, and M. Keller. 1966. *Synoptic Survey of Water Properties in the Western Basin of Lake Erie.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest. 58, Columbus. 19 pp.

Hartman, W. L. 1973. *Effects of exploitation, environmental changes and new species on the fish habitat and resources of Lake Erie.* Great Lakes Fish. Comm. Tech. Rep. 22. 43 pp.

Hatch, R. W., S. J. Nepszy, K. M. Muth, and C. T. Baker. 1987. Dynamics of the recovery of western Lake Erie walleye (*Stizostedion vitreum vitreum*) stock. *Can J. Fish Aquat. Sci.* 44(suppl. 2): 15-22.

Herdendorf, C. E. 1966. *A preliminary report on currents and water masses in Lake Erie.* Ohio Dept. Natur. Resources, Div. Geological Survey, Columbus. 57 pp.

Herdendorf, C. E. 1967. *Lake Erie bathythermograph recordings, 1952–1966.* Ohio Dept. Natur. Resources, Div. Geological Survey Inform. Circ. 34, Columbus. 36 pp.

Herdendorf, C. E. 1968. Sedimentation Studies in the South Shore Reef Area of Western Lake Erie, p. 188-205. *In*: A. M. Beeton (chairman), *Proceeding of the Eleventh Conference on Great Lakes Research.* Internat. Assoc. Great Lakes Res., Ann Arbor, MI.

Herdendorf, C E. 1969. *Water masses and their movements in western Lake Erie.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest. 74, Columbus. 7 pp.

Herdendorf, C E. 1970. *Lake Erie physical limnology cruise, midsummer 1967.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest. 79, Columbus. 77 pp.

Herdendorf, C. E. [ed.]. 1980. *Lake Erie nutrient control program: an assessment of its effectiveness in controlling lake eutrophication.* U.S. Environmental Protection Agency, Environ. Res. Lab.–Duluth, EPA-600/3-80-062. 380 pp.

Herdendorf, C. E. 1984. *Lake Erie water quality 1970–1982: a management assessment.* U.S. Environmental Protection Agency, Great Lakes Nat. Program Office, EPA-905/4-84-007. 152 pp.

Herdendorf, C. E. 1990. Distribution of the world's large lakes, p. 3-38. *In* M. M. Tilzer and C. Serruya [eds.], *Large Lakes, Ecological Structure and Function. Springer–Verlag, Berlin.*

Herdendorf, C. E. 1995. Five states agree to halt Lake Erie pollution, p. 838-843. *In* F. N. Magill [ed.], *Great events in history II: ecology and the environment.* Salem Press, Pasadena, CA.

Herdendorf, C E. and L. L. Braidech. 1972. *Physical characteristics of the reef area of western Lake Erie.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest. 82, Columbus. 90 pp.

Herdendorf, C. E. and M. E. Monaco. 1988. Physical and chemical limnology of the island region of Lake Erie, p. 30-42. *In* J. F. Downhower [ed.], *The biogeography of the island region of western Lake Erie.* Ohio State Univ. Press, Columbus.

Higgins, E. 1928. Cooperative fishery investigations in Lake Erie. *Scientific Monthly* 27: 301-306.

Higgins, E. 1929. Can the Great Lakes fisheries be saved? *Outdoor American* 7(8).

Hobson, G. D., C. E. Herdendorf, and C. F. M. Lewis. 1969. High resolution reflection seismic survey, western Lake Erie, p. 210-224. *In*: J. F. Carr (chairman), *Proceeding of the Twelfth Conference on Great Lakes Research.* Internat. Assoc. Great Lakes Res., Ann Arbor, MI.

Holcombe, T. L., L. A. Taylor, D. F. Reid, J. S. Warren, P. A. Vincent, and C. E. Herdendorf. 2003. Revised Lake Erie postglacial lake level history based on new detailed bathymetry. *J. Great Lakes Res.* 29: 681-704.

Hubbs, C. L. 1926. A check list of fishes of the Great Lakes and tributary waters, with nomenclatorial notes and analytical keys. *Misc. Publ. Mus. Zool. Univ. Mich.* No. 15: 1-77.

Hubbs, C. L. and M. B. Trautman. 1937. A revision of the lamprey genus Ichthyomyzon. *Misc. Publ. Mus. Zool. Univ. Mich.* No. 35: 1-109.

Jordan, D. S. and J. H. Klippart. 1878. Catalogue of fishes of Ohio. Ohio State Fish Comm. *1st Annual Rep. 1875-1876*: 43-87.

Jordan, D. S. 1879. Descriptions of Ohio fishes. Ohio State Fish Comm. *2nd Annual Rep. 1877-1878*: 83-116.

Jordan, D. S. 1882. Report on fishes of Ohio. *Ohio Geological Survey.* 1(4): 735-1020.

Kellicott, D. S. 1878. Notes on the microscopic life in the Buffalo water supply. *Amer. J. Microscop. Pop. Sci.* 3(11): 250-252.

Kirtland, J. P. 1838. Report on the zoology of Ohio, p. 157-200. *In* W. W. Mather [ed.], *Second annual report of the Geological Survey of the State of Ohio.* Columbus, OH.

Kirtland, J. P. 1844. Descriptions of *Acipenser rubicundus*, *A. platyrhynchus* and *Rutilus Storerianus*. *Proc. Boston Soc. Natur. Hist. (1841-1844)* 1: 71.

Koelz, W. 1926. *Fishing industry of the Great Lakes.* Report of the Commission of Fisheries for fiscal year 1925. Appendix XI, pp. 553-6178. Washington, D. C.

Krieger, K. A., D. W. Schloesser, B. A. Manny, C. E. Trisler, S. E. Heady, J. J. H. Ciborowski, and K. M. Muth. 1996. Recovery of burrowing mayflies (Ephemeroptera: Ephemertidae: *Hexagenia*) in western Lake Erie. *J. Great Lakes Res.* 22: 254-263.

Langlois, T. H. 1953. Biological studies of the Lake Erie pollution survey, p. 124-130. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus.

Langlois, T. H. 1954. *The western end of Lake Erie and its ecology.* Edwards Publ., Ann Arbor, MI. 479 pp.

Leach, J. H. 1999. Lake Erie: passages revisited, p. 5-22. *In* M. Munawar, T. Edsall, and I. F. Munawar [eds.], *State of Lake Erie past, present and future.* Backhuys Publ., The Netherlands.

LeSueur, C. A. 1817. A new genus of fishes of the order Abdominales, proposed under the name *Catostomus*, and the characters of this genus, with those of its species, indicated. *J. Acad. Natur. Sci. Philadelphia* 1(1): 222-235; 359-368.

LeSueur, C. A. 1818. Descriptions of several new species of North American fishes. *J. Acad. Natur. Sci. Philadelphia* 1(2): 88-96; 102-111.

Lorenz, R. C. and C. E. Herdendorf. 1982. Growth dynamics of *Cladophora glomerata* in western Lake Erie in relation to some environmental factors. J. Great Lakes Res. 8: 42-53.

Makarewicz, J. C. and P. E. Bertram [eds.]. 1993. Evidence for the restoration of Lake Erie. *J. Great Lakes Res.* 19: 197-496.

May, B. and J. E. Marsden. 1992. Genetic identification and implication of another invasive species of dreissenid mussel in the Great Lakes. *Can. J. Fish. Aquat. Sci.* 49: 1501-1506.

Mills, H. 1882. Microscopic organisms in the Buffalo water-supply and in the Niagara River. *Proc. Amer. Soc. Microscop., 5th Annual Meeting 1882*: 165-175.

Milner, J. W. 1874. *Report on the fisheries of the Great Lakes; results of inquiries prosecuted in 1871 and 1871.* Report of United States Commissioner of Fish and Fisheries for 1872 and 1873. Appendix A, pp. 1-78. Washington, D. C.

Mitchill, S. L. 1824. Articles in mirror, p. 297 [reference from p. 222, DeKay, J. E. 1842. *Natural history of New York.* Part I Zoology. Part IV. Fishes: 1-415. White & Visscher, Albany]

Osburn, R. C. 1926a. *A preliminary study of the extent and distribution of sewage pollution in the western end of Lake Erie.* Ohio Dept. Agriculture, Div. Fish and Game, Columbus, Ohio. 6 pp. [mimeographed report]

Osburn, R. C. 1926b. *Details regarding pollution survey of Lake Erie.* Ohio Dept. Agriculture, Div. Fish and Game, Columbus, Ohio. 14 pp. [mimeographed report]

Osburn, R. C., E. L. Wickliff, and M. B. Trautman. 1930. A Revised List of the Fishes of Ohio. *Ohio J. Sci.* 30(3): 169-176.

Pincus, H. J. 1951. *1950 investigations of Lake Erie sediments, vicinity of Sandusky, Ohio.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest. 9, Columbus. 37 pp.

Pincus, H. J. 1953. *1951 investigations of Lake Erie shore erosion.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest. 18, Columbus. 138 pp.

Pincus, H. J. 1960. *Engineering Geology of the Ohio Shore Line of Lake Erie.* Ohio Dept. Natur. Resources, Div. Shore Erosion Tech. Rep. 7, Columbus, OH. 7 sheets (A–G).

Poppen, R. 1953. The presence of toxic materials at the mouths of Ohio streams discharging into Lake Erie, as indicated by the test organism, Daphnia magna. P. 137-152. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus.

Powers, C. F., D. L. Jones, P. C. Mudinger, and J. C. Ayres. 1960. *Application of data collected along shore to conditions in Lake Erie.* Univ. Michigan, Great Lakes Res. Div. Pub. 5. 78 pp.

Rafinesque, C. S. 1817. Additions to the observations of sturgeons of North America. *Amer. Monthly. Mag. Crit. Rev.* 1: 288.

Rafinesque, C. S. 1818. Description of two new genera of North American fishes, *Opsanus* and *Notropis*. *Amer. Monthly. Mag. Crit. Rev.* 2: 203-204.

Rathbin, R. and W. Wakeham, 1897. *Report of the Joint Commission relative to the preservation of fisheries in waters contiguous to Canada and the United States.* House of Represenatives, 54th Congress (Second Session), Document No. 315, 178 pp. Washington, D. C.

Regier, H. A. and W. L. Hartman. 1973. Lake Erie's fish community: 150 years of cultural stress. *Science* 180: 1248-1255.

Regier, H. A., V. C. Applegate, and R. A. Ryder. 1969. *The ecology and management of the walleye in western Lake Erie.* Great Lakes Fish. Comm. Tech. Rep. 15. 101 pp.

Reighard, J. E. and H. B. Ward. 1901. Methods of plankton measurement. *Science* 13: 376-377.

Reutter, J. M., D. Kelch, J. J. Banicki, and F. Lichtkoppler. 2002. Entering the zone. Ohio Sea Grant, *Twine Line* 24(5): 1-3, 5.

Richards, R. P. and D. B. Baker. 1993. Trends in nutrient loading and suspended sediment concentrations in Lake Erie tributaries, 1975-1990. *J. Great Lakes Res.* 19: 200-211.

Rosa, F. and N. M. Burns. 1987. Lake Erie central basin oxygen depletion changes from 1929–1980. *J. Great Lakes Res.* 13: 684-696.

Stuckey, R. L. 1988. Jacob E. Reighard and the first biological survey of Lake Erie (1898–1901). *Michigan Academician* 20: 379-396.

Sullivan, C. R., Jr. 1953. Survey on the phytoplankton at the mouths of ten Ohio streams entering Lake Erie, 152-156. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus.

Sutfin, C. H., G. D. Pratt, and T. C. Henry. 1984. *Progress in clean water: The Great Lakes example.* U.S. Environmental Protection Agency, V, Chicago, IL. 63 pp.

Thomas, N. A. 1963. *Oxygen deficit rates for the central basin of Lake Erie.* U.S. Public Health Service, Robert A. Taft Sanitary Engineering Center, Cincinnati. 8 pp.

Thomas, N. A. 1975. Physical-chemical requirements, p. 81-82. *In* H. Shear and D. E. Konasewich [eds.], Cladophora *in the Great Lakes.* International Joint Commission, Windsor.

Tidd, W. M. 1928. *Zooplankton investigations in the west end of Lake Erie for the spring, summer and fall of 1928.* Ohio Div. Fish and Game. 3 pp.

Tidd, W. M. 1955. The zoooplankton of western Lake Erie, p. 200-249. In S. Wright [ed.], *Limnological survey of western Lake Erie, 1928–29.* U.S. Fish and Wildlife Service Spec. Sci. Rep.–Fisheries 139.

Tiffany, L. H. 1921. Algal food of the young gizzard shad. *Ohio J. Sci.* 21(4): 113-122.

Tiffany, L. H. 1934. *The plankton algae of the west end of Lake Erie.* Ohio State Univ., F. T. Stone Lab. Contrib. 6. 112 pp.

Tiffany, L. H. 1937. The filamentous algae of the west end of Lake Erie. *Amer. Midland Natur.* 18(6): 911-951.

Tiffany, L. H. 1955. The phytoplankton of western Lake Erie, p. 139-200. *In* S. Wright [ed.], *Limnological survey of western Lake Erie, 1928–29.* U.S. Fish and Wildlife Service Spec. Sci. Rep.–Fisheries 139.

United States Tariff Commission. 1927. *Lake fish.* Tariff Information Series No. 36, Washington D. C. 176 pp.

Van Oosten, J. 1929. Some fisheries problems on the Great Lakes. *Trans Amer. Fish. Soc.* 60: 204-214..

Van Oosten, J. 1930. The disappearance of the Lake Erie cisco—a preliminary report. *Trans Amer. Fish. Soc.* 59: 63-85.

Verber, J. L. 1953. Tentative summary of studies of water movements in Lake Erie, p. 136. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus.

Verber, J. L. 1955. *Bibliography of physical limnology 1781–1954.* Ohio Dept. Natur. Resources, Div. Geological Survey Rep. Invest 25, Columbus. 57 pp.

Verber, J. L. 1957. *Bottom deposits of western Lake Erie.* Ohio Dept. Natur. Resources, Div. Shore Erosion Tech. Rep. 4, Columbus. 4 pp.

Verber, J. L. 1960. *Long and short period oscillations in Lake Erie.* Ohio Dept. Natur. Resources, Div. Shore Erosion, Columbus. 80 pp.

Verduin, J. 1953. The suspended silt in western Lake Erie during the spring of 1951, p. 130-133. *In* C. V. Youngquist [ed.], *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus.

Vollenweider, R. A., M. Munawar, and P. Stadekmann. 1974. A comparative review of phytoplankton and primary production in the Laurentian Great Lakes. *J. Fish. Res. Bd. Can.* 31: 739-762.

Vorce, C. M. 1881. Forms observed in the waters of Lake Erie. *Proc. Amer. Soc. Microscop.*, 4: 50-60.

Vorce, C. M. 1882. Microscopical forms observed in waters of Lake Erie. *Proc. Amer. Soc. Microscop.*, 5: 187-196.

Wickliff, E. L. 1931. Fisheries research by the Ohio Division of Conservation. *Trans Amer. Fish. Soc.* 61: 199-207.

Wickliff, E. L. and M. B. Trautman. 1934. *List of the Fishes of Ohio.* Ohio Dept. Agriculture, Div. Fish and Game, Bureau of Sci. Research Bull. 1, Columbus, Ohio. 3 pp. [mimeographed report]

Wright, S. 1955. *Limnological survey of western Lake Erie, 1928–29.* U.S. Fish and Wildlife Service Spec. Sci. Rep.–Fisheries 139. 341 pp.

Wright, S. and W. M. Tidd. 1933. Summary of limnological investigations in western Lake Erie in 1929 and 1930. *Trans Amer. Fish. Soc.* 63: 271-285.

Youngquist, C. V. [ed.]. 1951. *Lake Erie pollution survey—interim report.* Ohio Dept. Natur. Resources, Div. Water, Columbus. 26 p.

Youngquist, C. V. [ed.]. 1953. *Lake Erie pollution survey—final report.* Ohio Dept. Natur. Resources, Div. Water, Columbus. 201 p.

Zapotosky, J. E. and C. E. Herdendorf. 1980. Oxygen depletion and anoxia in the central basin of Lake Erie, 1973–1975, p. 71-102. *In* C. E, Herdendorf [ed.], *Lake Erie nutrient control program: an assessment of its effectiveness in controlling lake eutrophication.* U.S. Environmental Protection Agency, Environ. Res. Lab.–Duluth, EPA-600/3-80-062.