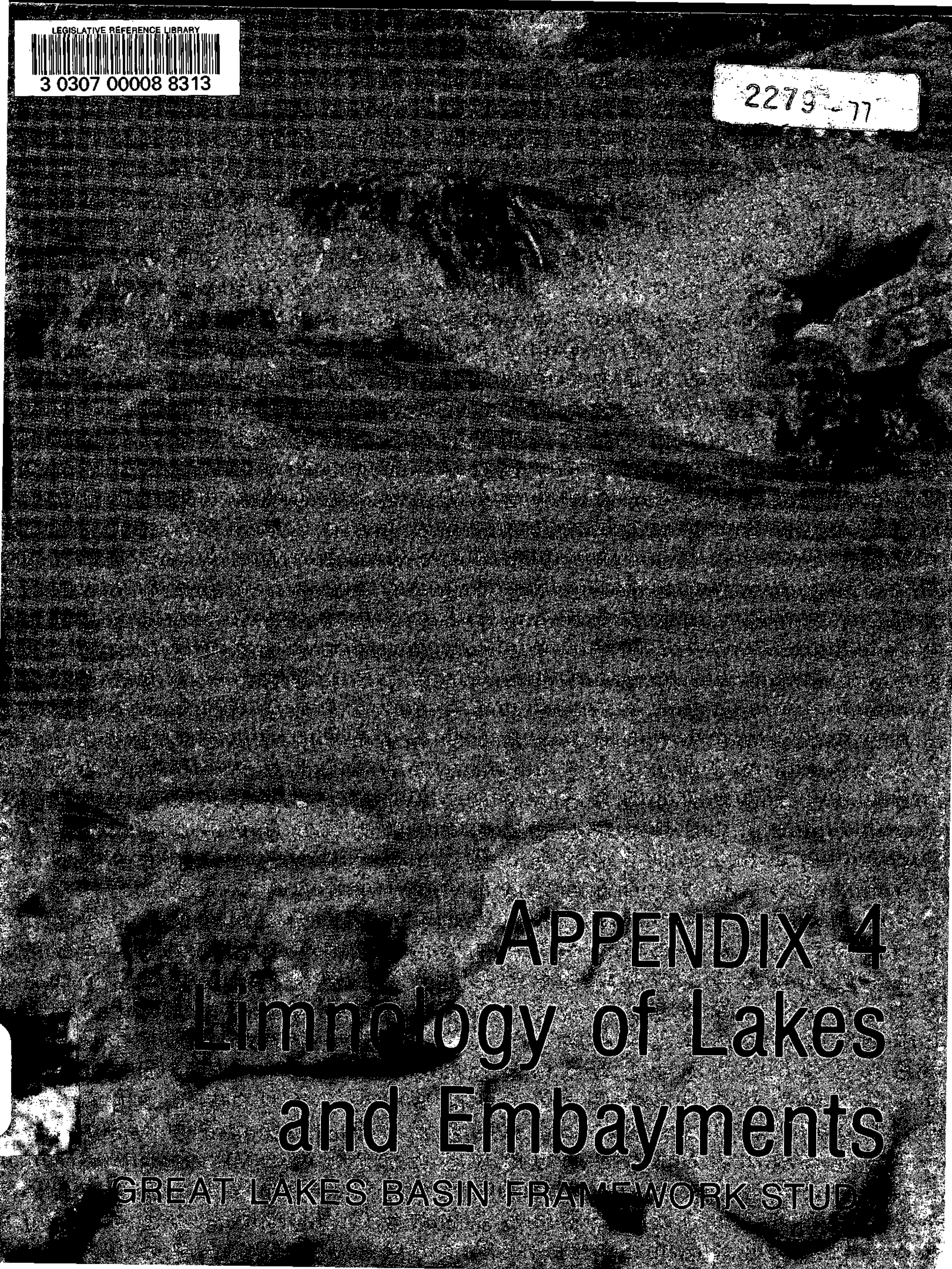

APPENDIX 4
Limnology of Lakes and Embayments

GREAT LAKES BASIN FRAMEWORK STUD

Great Lakes Basin Framework Study

APPENDIX 4

LIMNOLOGY OF LAKES AND EMBAYMENTS

GREAT LAKES BASIN COMMISSION

Prepared by Limnology Work Group

Sponsored by National Oceanic and Atmospheric Administration

U.S. Department of Commerce

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Cover photo by Kristine Moore Meves.

This appendix to the *Report* of the *Great Lakes Basin Framework Study* was prepared at field level under the auspices of the Great Lakes Basin Commission to provide data for use in the conduct of the Study and preparation of the *Report*. The conclusions and recommendations herein are those of the group preparing the appendix and not necessarily those of the Basin Commission. The recommendations of the Great Lakes Basin Commission are included in the *Report*.

The material in this appendix is current through 1970. Because water and related land resources have been the subject of considerable attention recently, the statutes cited herein may have been repealed or amended, new statutes enacted, and judicial interpretations of statutory and common law revised.

OUTLINE

SYNOPSIS

The appendix was designed to present in a logical fashion the processes that underlie the hydrology, hydrodynamics, biology, geology, and chemistry of the Great Lakes and upland lakes in the Great Lakes Basin. In establishing criteria for the preparation of the appendix, it was felt that discourses on dynamic processes would be more meaningful than presentations of lake-by-lake data arrays. Inasmuch as natural phenomena are interrelated within the environment, a minimum number of sensitive parameters can be used to characterize certain processes and responses. A goal of this appendix is to define those interrelationships so that the reader may be able to anticipate the nature of the responses. The scope of such a project is really beyond development in a single document. In fact, in many ways this one appendix includes material on the Great Lakes analogous to the material contained in the series of appendixes that deal with natural phenomena of the Great Lakes Basin. Therefore, emphasis had to be placed on conceptualization rather than data-array presentation. The extensive list of references will allow further study of specific problems.

Bedrock geometry has a strong influence on the configuration of the Great Lakes. The bottoms of Lakes Michigan, Huron, Erie, and Ontario are almost wholly in shales. Sills that separate the lakes are mostly Silurian carbonate rocks. The more subtle physiographic features in the Basin result from modification of Pleistocene glacial debris. The distribution of glacial debris influences the distribution and types of upland lakes.

Distribution of population centers and land uses are largely a function of physiography, climate, and natural resources. The physiographic factors have caused many of the environmental problems of the Great Lakes and upland lakes that now exist. Much of the northern half of the Great Lakes Basin is poorly drained swamp and forest with lumbering and mining as major industries. The southern half of the Basin is better drained and is highly developed for agriculture and urban utilization. Population concentration is in a few epicenters in the southern half of the Basin. As a result of these factors, there are two different inputs to the lakes. Drainage to the upper lakes generally reflects the natural system and is relatively stable. Lower Lake Michigan, and Lakes Erie and Ontario, by contrast, have well-developed drainage systems that are out of equilibrium with the natural system because they carry large amounts of human, industrial, and agricultural wastes into the lakes.

The Great Lakes strongly influence the Basin climate, which in turn affects land usage. In the vicinity of the Great Lakes the continental climate characteristic of the northern United States is modified to a semimaritime climate, and the lake effect is pronounced. Coastal temperatures, precipitation, and some winds are controlled by the lakes. However, the water budget, chemistry, surface disturbances, and circulation in the lakes are controlled largely by the land adjacent to the lakes.

Concepts of water motion commonly include the terms waves and currents, but they also include the free and forced lake oscillations as well as long- and short-term variations in lake levels. Although the implication of surface motion is extremely significant in management and development of the Great Lakes, efforts to understand these forces have been made only during the past 20 years. Much has been accomplished, but available studies are localized. Internal motions are also extremely important in the Great Lakes. Eddy diffusivity has probably received the most attention because it plays a role in dispersion of contaminants, especially near shore. Currents detrimental to navigation have historically been of prime importance in harbor design, but with increased cultural input, disposition of pollutants has also become a factor. Knowledge of circulation patterns in harbors and embayments provides a base for aiding navigation, forecasting sedimentation patterns, determining flushing rates, and selecting locations for water intakes and outfalls.

Knowledge of the magnitude of dissolved

material in a lake is useful in identifying the degree to which pollution and natural influx are affecting the lake. Present open-lake concentrations are below the standards established by the States, but these are averages, so the standards are exceeded locally. All the lakes, except Lake Superior, have had an increase of dissolved material over the period of record, and extrapolation indicates that average loads may exceed standards by the year 2000 if influx is not reduced. In addition to long-term changes, there are annual cylical changes in dissolved constituents in the Great Lakes. Short-term variations result from dilution, runoff, organic production, variations in supplies, and lake thermal structure.

A major factor in management of the lakes is the time required to flush or cleanse the lakes if loads are reduced. Most calculations are based on a mass balance and consider conservative indicators; as such they may be misleading. The complex interactions of sediment, biota, and water in the lakes result in storage of constituents. Reduction in loading of any of these constituents most likely will cause releases from the lake bottom in an attempt to establish a new equilibrium and delay actual flushing time. In the case of a constituent such as chlorinated-hydrocarbon pesticides, one that has no natural background level and can be eliminated from use on the drainage basin, the time estimate for complete removal ranges up to approximately 400 years. Current treatment criteria for wastewater may be insufficient to cause desired reductions in waste inflow to the lakes.

Bacteria other than coliform and fungi have received little attention in the Great Lakes. These organisms are extremely important because of their role in nutrient recycling, a process fundamental to the aging process in the lakes. Phytoplankton and phytobenthos are of critical importance to the lake ecosystem because they support the food chain. These organisms are the first to reflect nutrient enrichment and environmental imbalance. However, large gaps exist in our understanding of production in the lakes, methods to control plant growth, and the effects of plant growth and decay on the physical and chemical quality of the lakes and on the other elements of the biota. Zooplankton and zoobenthos are of interest primarily as indicators of environmental quality and as part of the food chain. The literature on these organisms is extensive, but it contains large gaps that inhibit systematic evaluation of the role of the faunal elements in an environmental planning context.

Many gaps in the data base must be filled before modeling can be fully utilized as a primary tool for multidisciplinary coordination and planning. In light of the anticipated changes in use and quality of lakes in the next few decades, it is imperative that forecasts that reflect multiuser interests be based on the maximum available information.

The Great Lakes are in need of restoration. With the exception of Lake Superior, the lakes show varying degrees of impairment in quality of the biomass and water. This degradation has limited the various uses of the lakes. Should the process of eutrophication be retarded significantly, the improvement of Lakes Erie and Ontario will be obvious. However, the large volumes and long flushing times of the upper lakes may preclude obvious improvements in the near term except for embayments and restricted areas. Rapid action geared to population growth and responsive to causal rather than symptomatic factors is needed to halt further deterioration and initiate future Basinwide restoration. Biomanipulation, waste treatment, soil conservation, and structural design of protective and regulatory devices are within existing capabilities. In conjunction with Canadian authorities and the individual water users, these preventive treatments should be given immediate consideration.

FOREWORD

This volume constitutes a part of the Basin resource information for the *Great Lakes Basin Framework Study* prepared by the Great Lakes Basin Commission as an initial step in development of a comprehensive plan for the conservation, development, utilization, and management of the water and related land resources of the Great Lakes Basin. It is hoped that this study will encourage the optimum use and development of these resources under authority of and in accordance with provisions of the Water Resources Planning Act of 1965 (P.L. 89–80) for major river basin framework studies.

Information contained in this volume was derived from available published sources relating to the Great Lakes Basin and from available unpublished files, data repositories, and documents maintained by State and Federal agencies and public and private institutions and organizations.

The work group charged with responsibility for preparation of this volume was established by the Great Lakes Basin Commission. Chairman of the group was Arthur P. Pinsak, National Oceanic and Atmospheric Administration, who initiated the plan of study and acted as coordinator and principal editor of the appendix, with major support from Sam B. Upchurch and David C. Norton.

Portions of this volume were prepared by principal authors as indicated by the credits at the beginning of appropriate sections. Pinsak and Upchurch prepared the draft material for the introductory, applications, and summary sections. Other work group members were involved in providing recommendations, information, and consultation concerning appendix format and content; and in review and comments. The following are the work group members and their State or agency affiliations:

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In addition to members of the Great Lakes research community, all of the Great Lakes Basin Commission member States and agencies reviewed manuscript drafts. Comments

from Michigan, New York, Ohio, and from the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency were especially helpful in attempts to develop a useful and meaningful document.

Graphic material was prepared for inclusion by the Reproduction Branch, Lake Survey Center, National Ocean Survey, National Oceanic and Atmospheric Administration, Detroit, Michigan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Purpose

This appendix synthesizes the current knowledge about the limnological processes of the Great Lakes, and of the harbors and embayments and upland lakes in the Great Lakes Basin.

The appendix also aids the development of a comprehensive plan for optimum utilization of water and related land areas, by doing the following:

(1) synthesizing the limnological data applicable to regional planning considerations

(2) describing the limnological processes of the Great Lakes and of the upland lakes of the Great Lakes Basin in such a fashion that they may be logically interrelated

(3) identifying those regions in which insufficient data exist for water resource planning and defining the data deficiencies

(4) identifying those physical, chemical, and biological processes that are inadequately understood and require further study

(5) defining those Great Lakes water resource problems that exist or that may arise by the year 2020

(6) serving as a basic data source for the resource use and management appendixes.

Scope

Discussions are restricted to the Great Lakes and their connecting channels. Inputs from the tributary rivers are discussed as point sources at the lake-river interface. Harbors are classified and discussed by group, so that the reader may gain an overall understanding of the special water quality problems of harbors. Upland lakes are similarly treated, with discussions based on genetic and limnological classifications.

Limnology was originally understood as the study of the organisms of an upland lake or pond and the relationship of those organisms to the aquatic environment. More recently limnology has been expanded to include the study of the physical and chemical aspects of lakes. The subject matter contained in this appendix is limited to the physical, chemical, and biological processes that directly affect the Great Lakes and upland lakes. Atmospheric and terrestrial processes are discussed where necessary as they relate to the lake systems. The gravitational, geostrophic, and solar stimuli that supply energy to the natural system are discussed. Finally, a discussion of the relationship of geology to limnology is also included.

The data used in this report were obtained from material either in print or readily accessible from local, State, and Federal agencies. Much of the available Great Lakes data are suitable only for developing historical trends so it was necessary to be selective and work with the data most applicable to understanding and characterizing the limnological processes. Much knowledge of large lake limnology derives from the study of other large lakes and of other aquatic systems. Where applicable, these studies are referenced.

Philosophy of Presentation

The Great Lakes comprise a dynamic rather than a static system, and therefore, discussions of dynamic processes are more important to an understanding of Great Lakes limnology than are presentations of lake-by-lake data. An understanding of the interrelationships of natural processes in the environment can be used to accurately predict natural responses to certain processes. The goal of this appendix is to describe these interrelationships to the extent that the reader may be able to anticipate the nature of the responses.

Conventions

The metric system is used in this appendix. Where possible the English system equivalents are expressed parenthetically. This convention was employed because there is mixed usage of systems of units in Great Lakes limnology. The majority of technical studies, including those of most chemical, biological, and hydrodynamical processes, use the metric system, while a few studies concerned with the chemical budget, biota, and basin hydrology still use English units. Thus, inclusion of English units is justified. In tables and figures reproduced from a previously published resource, no attempt was made to change the author's selection of units.

Lake Aging and Eutrophication

Hopefully, this appendix will dispel the prevalent confusion and misinformation about lake aging in the Great Lakes and upland lakes. The layman tends to overreact to the terminology and predictions of the limnologist. For example, one often hears both the assertion that Lake Erie is dead and the counter statement that this is not true and that, in fact, Lake Erie today has more life than ever before. These statements and other predictions about the Great Lakes reflect a lack of perspective with respect to large lakes and often reflect a tenuous correlation of Great Lakes processes with principles derived from the study of small, upland lakes. In fact, the sensitivity and the responses of the two types of lakes to physical and chemical processes are in many cases different, even though basic physical processes are similar.

All lakes undergo a sequence of events that lead to their ultimate destruction. This natural aging was first described regarding upland lakes which, compared to the Great Lakes, are shallow and contain a small amount of water. Upland lakes undergo seasonal thermal changes that involve most or all of the water in the lake, and contain a biota that is dependent on the surrounding land. The time scale is completely different in the Great Lakes because they contain large volumes of water, much of which is semi-isolated from seasonal thermal changes and is much less responsive. The large water volume allows for much assimilation of chemical inputs without appreciable change in water quality or the biota, and minimizes the effects of infilling of the lake by sedimentation as a major cause of deterioration. The biota of the Great Lakes is somewhat similar to that of upland lakes, but because of the large volume of cold, well-oxygenated water in the Great Lakes, there are also many differences between the two. Therefore, the correlation with classical studies of small, upland lakes exists, but it cannot be used indiscriminantly when considering the Great Lakes.

The classic sequence of aging in an upland lake is a well-understood series of stages that have been given names that reflect the food (energy) supply available in the lake. Thus, a relatively deep lake that has abundant oxygen, a low rate of supply of the materials required for plant growth (nutrients), and relatively few individuals from a large number of taxa has been called oligotrophic, which means limited food and energy supply. As time passes, more nutrients enter the lake from the drainage basin. Plants flourish, and upon death, they form organic sediment that fills in the lake and is a source of nutrient recycling. During this period of mesotrophy, the biota begins to increase in terms of numbers of individuals present, but the number of species may drop slightly. Ultimately, the lake becomes shallow due to the accumulation of organic debris. The decomposition of the organic debris leads to oxygen depletion and to the release of nutrients to the water. At this stage in lake aging there is much food, hence the name eutrophic lake. Life is abundant, although the number of species present is often reduced to those tolerant of stress conditions such as low oxygen. The shallow nature of the eutrophic pond enables the lake to become heated throughout, and the warmer water reduces the solubility of oxygen. Decomposition of the organic sediment consumes oxygen in the water resulting in low oxygen levels, which are toxic to many species. Therefore, eutrophic lakes can be characterized by warmwater and/or low-oxygen-tolerant taxa. The cyclic release of nutrients from the drainage basin and from the organic sediment, cyclic changes in water temperature, and other factors lead to rapid increases and decreases in the growth of certain of the taxa, especially the plants. These increases and decreases in growth are reflected by phenomena such as algal blooms. Finally the lake is completely filled in with plant debris and becomes dry land. The aging and destruction of the lake and associated changes in biota may happen without the influence of man. At most times during the natural sequence, the processes that lead to the ultimate destruction of the lake are essentially balanced. Man's greatest impact on the aging of the upland lake is to accelerate the influx of nutrients and sediment so as to hasten the changes in the aquatic community.

Larger lakes, such as the Great Lakes, undergo certain of the same natural changes in aging as upland lakes. However, the Great Lakes contain vast quantities of water, much of which is never warmed during the summer. Therefore, under natural conditions, these lakes age differently than upland lakes. The nutrients are assimilated by the great volume of water; there is a large reservior of oxygen, so oxygen-tolerant organisms prevail; and sedimentation is volumetrically unimportant. Upon aging, large lakes may build up large volumes of nutrients and take on some of the characteristics of a eutrophic lake, but the volume and cold temperature of the deep water in the lake resist aging in the upland lake sense. Lake Erie is somewhat of an exception to this generalization, because it is relatively small and shallow.

The term eutrophic lake, which is used in this appendix for both upland lakes and the Great Lakes where applicable, should not be interpreted in the strict sense. The term describes the general state of a lake of any size, when it is characterized by disruption of the biota by environmental stresses such as oxygen depletion and excess nutrient supply. In this sense the Great Lakes, which are in no danger of infilling, could approach eutrophy through either natural causes or through the influence of man. Lake Erie and some other areas of the Great Lakes system that receive pollutants cannot assimilate them; so these waters are approaching or have reached a state of euptrophy, meaning that nutrient supplies and biotic disruption approximate those typical of an aging, upland lake. Odum[585] presents a different classification of the trophic state of upland lakes and Great Lakes (Table 4–1) that has not yet been generally adopted. According to Odum's classification, those Great Lakes that develop high nutrient supplies upon aging would be termed morphometrically oligotrophic. This indicates that the lakes still retain the geometric aspect of an oligotrophic lake, although the nutrient concentration is high. This distinction is particularly critical when those changes in the Great Lakes that are induced by man are given the term eutrophication. Those changes represent imbalances that are symptomatic of eutrophication and ultimately may lead to some form of true eutrophication. However, at the present time the induced changes are, for the most part, reversible given enough time, and should not be considered as signifying the death of any Great Lake or major portions thereof.

This appendix explains the biological, chemical, and physical aspects of the process of lake aging in terms of the natural sequence and also in terms of the acceleration in nutrient enrichment, toxification, and general deterioration caused by man. Sections 1 and 2 outline the physiography and general hydrology of the Great Lakes and the Great Lakes Basin in order to identify natural and man-caused inputs. Section 3 discusses the thermal character of the lakes, including some of the possible impacts of thermal discharges. Section 4 summarizes the meteorological inputs to the lakes and the effects of the lakes on the atmosphere. Section 5 discusses Great Lakes ice cover and its effect on Great Lakes navigation. Section 6 discusses the hydrodynamics of the system, including waves, currents, and special physical problems associated with the water masses of the lakes. Section 7 covers the chem-

TABLE 4–1 Lake Aging Classification

Depth	Nutrient Concentration: Low		Nutrient Concentration: High
Shallow	Morphometric Eutrophy	(upland lakes) →	Eutrophic
	↑ (upland lakes)		↑ (Great Lakes)
Deep	Oligotrophic	(Great Lakes) →	Morphometric Oligotrophy

SOURCE: Modified from Odum, 1959

NOTE: Arrows represent succession or aging paths for the Great Lakes and upland lakes.

ical aspects of the lakes, including sediment and water chemistry, toxic constituents, and predicted chemical quality, given specified treatment alternatives. The biological implications of natural and man-induced aging are discussed in Section 8. Sediment texture and mineralogy are detailed in Section 9. Section 10 summarizes for upland lakes much of the information given in the preceding sections for the Great Lakes. Finally, Sections 11 and 12 summarize the appendix and discuss some important, current research and planning projects for the Great Lakes, including systems analyses, the International Field Year on the Great Lakes, and lake restoration.

The reader is referred to the other appendixes of the *Great Lakes Basin Framework Study* for more information on the Great Lakes and upland lakes. Appendix 2, *Surface Water Hydrology*; Appendix 3, *Geology and Ground Water*; Appendix 7, *Water Quality*; Appendix 8, *Fish*; Appendix C9, *Commercial Navigation*; Appendix R9, *Recreational Boating*; Appendix 10, *Power*; Appendix 11, *Levels and Flows*; Appendix 12, *Shore Use and Erosion*; and Appendix 18, *Erosion and Sedimentation*, contain particularly pertinent sections.

Section 1

THE GREAT LAKES BASIN

Sam B. Upchurch

1.1 Location

The Great Lakes Basin is located along the international boundary between Canada and the United States, between 40°30′ and 50°30′ north latitude and 74°30′ and 93°10′ west longitude. The Basin includes portions of eight States: Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York; and the Province of Ontario.

Five major lakes comprise 32 percent of the Basin area: Lakes Superior, Michigan, Huron, Erie, and Ontario. In addition, Lakes Nipigon, St. Clair, Nipissing, Simcoe, and Winnebago are important to the Basin. The locations of the lakes and connecting channels are shown in Figure 4–1.

1.2 Geology of the Great Lakes Basin

The lithologic units that underlie the Great Lakes Basin affect the Great Lakes in two ways. The strata differ in their resistances to erosion which in turn govern landform development. Thus, the more erosion-resistant beds form uplands and interlake sills while the less resistant strata form lowlands and lake basins. Also, the mineralogical composition of the strata governs the natural composition of the ground and surface waters in the Basin.

The lithologic units that underlie the Great Lakes Basin range in age from Precambrian (age greater than 570,000,000 years) to Recent. The strata can be grouped into three different time-stratigraphic divisions that represent completely different origins and impacts on the Great Lakes Basin: the Precambrian, the Paleozoic, and the Cenozoic (Table 4–2). Although these three time-stratigraphic divisions represent great intervals of geologic time, their main importance to the Great Lakes Basin lies in the different geologic events that led to the formation of the strata during each interval. The Precambrian lithologic units consist of complexly folded and faulted igneous, metamorphic, and sedimentary units. The majority of the Precambrian rock units are either granitic or gneissic, surrounded by volcanic, metavolcanic, and metasedimentary rock bodies.

Overlying the Precambrian are the Paleozoic strata, which are largely of marine or strandline origin. Cambrian and Ordovician strata are predominantly composed of limestones, dolomites, and quartz sandstones. Silurian strata, composed of limestones and dolomites, are found at the surface and over the structural arches within the Basin (Figure 4–2). Intercalated with the carbonate strata at depth in the Michigan and Appalachian structural basins (Figure 4–2), there are thick sequences of salt and gypsum/anhydrite. Devonian and Mississippian strata are composed of limestones and shales, with minor thicknesses of Devonian salt and gypsum/anhydrite deep in the structural basins. Pennsylvanian strata are predominantly quartz-feldspar sandstones and shales.

The Cenozoic strata represent largely unconsolidated sediment deposited during the Pleistocene epoch by a series of four major glacial episodes and subsequently modified by post-glacial erosion and deposition that continues to the present. The Pleistocene sediment consists of locally-derived material eroded from the Precambrian and Paleozoic strata within the Basin and from regions north of the Basin.

The sedimentary rock strata were deposited in more-or-less horizontal beds. During and subsequent to deposition of the beds, they were subjected to regional folding. Five major tectonic features have resulted from modification of the beds. These features are the two forks of the Cincinnati Arch (Kankakee and

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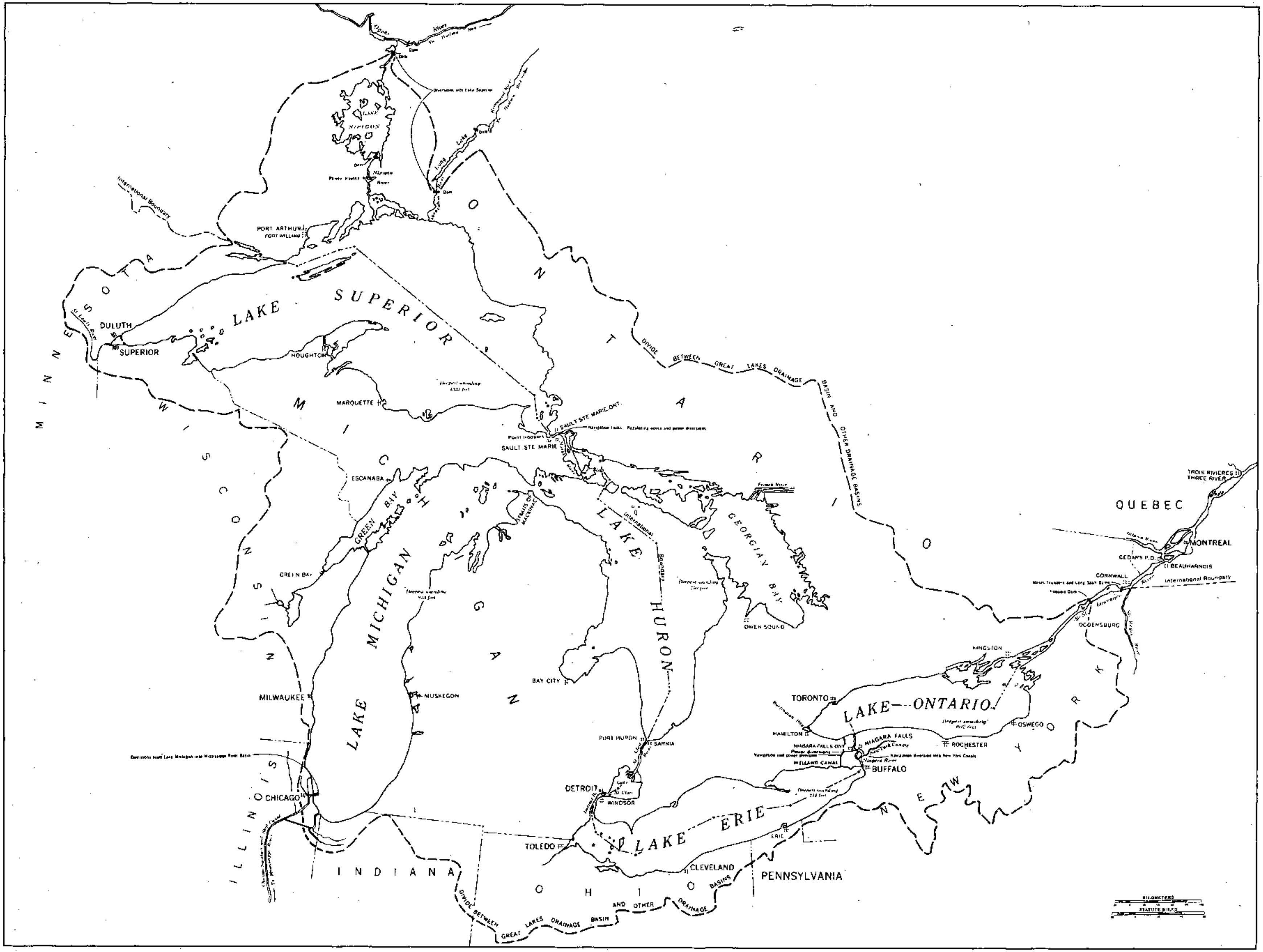

FIGURE 4-1 Location of Major Lakes and Connecting Channels

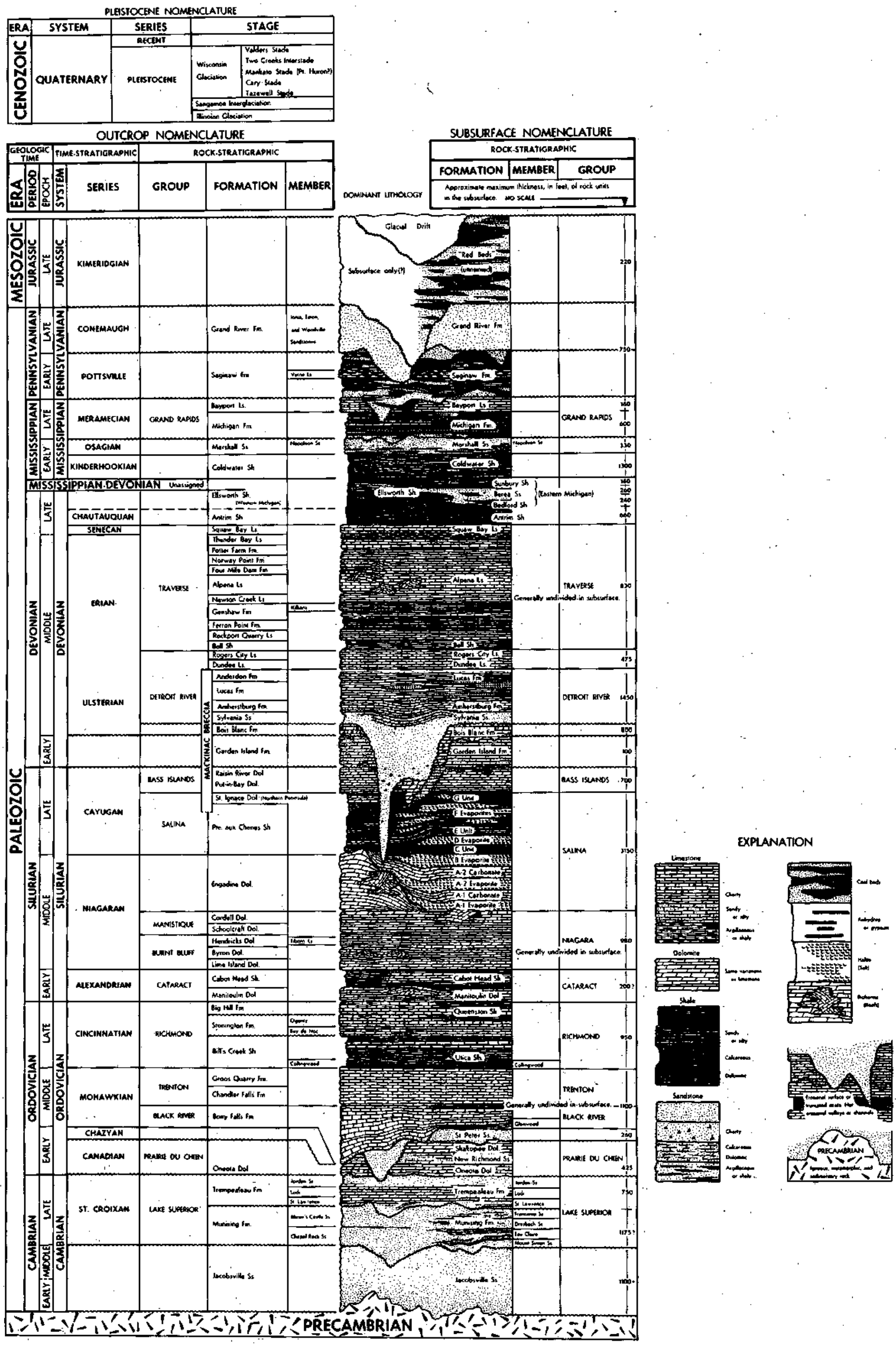

FIGURE 4–2 Stratigraphic Succession in Michigan

From Michigan Geological Survey, 1964

TABLE 4–2 Stratigraphic Summary of the Great Lakes Basin

	Lithology[1]		
System	Wisconsin Arch	Michigan Basin[2]	Appalachian Basin[2]
Recent	Varying thicknesses of unconsolidated sediment.		
Cenozoic			
Pleistocene	Complex accumulations of glacial, lacustrine, eolian, and fluvial debris. Textures range from coarse conglomerates to clays and silts. Debris principally derived locally, with large exotic clasts. Thickness from 0 to 1000 plus feet. Moraines and other strata containing coarse clasts are resistant to erosion.		
Palezoic			
Permian	Absent	May be present in Michigan structural basin.	Present in Allegheny Plateau outside of basin.
Pennsylvanian	Absent	0 to 750 feet of continental sediment (e.g. coal, sandstone, minor limestone). Resistant to erosion.	Lithologies similar to Michigan Basin. Thickness up to approximately 1300 feet within basin.
Mississippian	Absent	0 to 2500 feet of marine shale, sandstone, and minor limestone. Resistant to erosion.	0 to 500 feet of sand and shale in basin. Resistant to erosion.
Devonian	Absent	0 to 5000 feet of limestone and shale. Evaporites at depth in the Michigan structural basin. Not resistant to erosion.	0 to 2500 feet of shale and limestone. Not resistant to erosion.
Silurian	0 to 1500 feet of dolomite and limestone Resistant to erosion.	0 to 4500 feet of dolomite, limestones, and minor shale at surface and evaporite-carbonates at depth. Carbonates are resistant to erosion.	0 to 1500 feet of dolomite, limestone, and minor evaporites. Carbonates are resistant to erosion.
Ordovician	0 to 1000 feet of dolomite, limestone, shale, and sandstone. Carbonates are resistant to erosion.	0 to 2800 feet of limestone, shale, sandstone, and dolomite. Carbonates are resistant to erosion.	0 to 3000 feet of shale and and minor limestone. Not resistant to erosion.
Cambrian	0 to 3000 feet of dolomite and sandstone. Carbonates are resistant to erosion.	0 to 3000 feet of sandstone and carbonates. Resistance to erosion variable.	0 to 1500 feet of sandstone and carbonates. Resistance to erosion variable.
Precambrian			
Proterozoic			
Keweenawan	Thickness indeterminate. Complex assemblage of sedimentary, volcanic, and plutonic rocks. Resistances to erosion vary with rock type and degree of weathering.		
Huronian	Thickness indeterminate. Complex assemblage of sedimentary, volcanic, and plutonic rocks. Resistances to erosion vary with rock type and degree of weathering.		
Archeozoic	Thickness indeterminate. Complex assemblage of intrusive and metamorphic rocks. Resistances to erosion vary with rock type and degree of weathering.		

[1]Data from Sloss, Dapples, and Krumbein, 1960.
[2]Michigan and Appalachian Basins are structural rather than drainage basins. (cf. Figure 4-3)

Findlay-Algonquin Arches), the Appalachian Basin, the Michigan Basin, the Wisconsin Dome, and the Canadian Shield (Figure 4–3). Precambrian rocks of the Canadian Shield are exposed across the northern third of the Great Lakes Basin. Folded into the igneous and metamorphic rocks of the Canadian Shield are the unmetamorphosed to moderately metamorphosed sedimentary and volcanic rocks of the Lake Superior Syncline. At the crest of the Wisconsin Dome, granitic intrusive rocks crop out, ringed by Paleozoic sandstones, dolomites, and limestones. The Michigan Basin is a saucer-shaped structural and depositional basin with Paleozoic strata dipping toward the center from all directions. The Findlay-Algonquin Arch, on the eastern side of the Michigan Basin, separates the westward-dipping strata of that basin from the southeastward-dipping strata of the Appalachian Basin.

Prior to the Pleistocene glaciation, the Precambrian and Paleozoic rocks cropped out at the surface. Figure 4–4 shows the relative abundances of lithologic types at the pre-Pleistocene erosional surface. The strata have

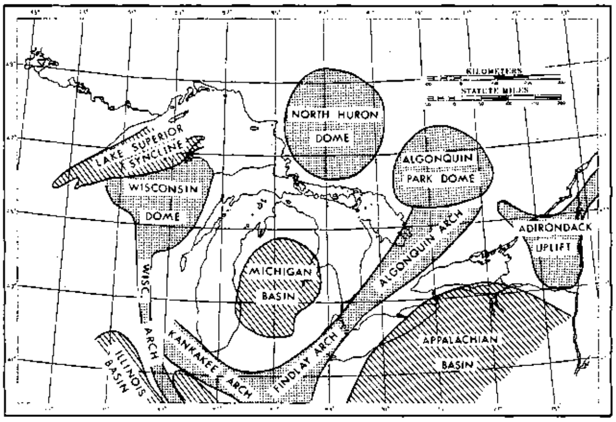

FIGURE 4–3 Major Tectonic Features in the Vicinity of the Great Lakes Basin
Modified from Riggs, 1960

varying resistances to erosion. Limestones, well-cemented sandstones, and some igneous rocks withstand erosion, while shales do not. The preglacial drainage pattern (Figure 4–5) reflected the structural attitude of the beds at the pre-Pleistocene erosional surface. Highlands developed where limestones and sandstones cropped out, and stream valleys developed in terrain characterized by a large proportion of shale (compare Figures 4–4 and 4–5). Subsequent to the development of the pre-Pleistocene drainage system, glaciation modified the topography by scouring and filling. Much of the debris remaining from the glaciation is locally derived and the accumulations are thin. Subsequent erosion has exposed Precambrian and Paleozoic strata in some of the regions of thin accumulation, and elsewhere the thin deposits cause the present surface to reflect the pre-Pleistocene surface. Figure 4–6 depicts the composition of the surficial deposits of glacial and post-glacial origin.

1.3 Basin Physiography

The areal geology of the Basin allows separation of the Great Lakes and the Great Lakes Basin into three major physiographic provinces (Figure 4–7). Lake Superior and the northern third of the Great Lakes Basin are in the Laurentian Uplands Province, the remainder of the Great Lakes and much of the Great Lakes Basin are in the interior Lowlands Province, and minor portions of the Lakes Erie and Ontario basins are in the Appalachian Plateau Province.

The Laurentian Uplands are characterized by low-lying swamps, poorly drained areas, and occasional ranges of hills. The hills are underlain by resistant Precambrian rock masses, and the low areas by a thin veneer of glacial debris. For the most part the Laurentian Uplands coincide with the Canadian Shield. The Interior Lowlands are better drained than the Laurentian Uplands. The major ridges of the lowlands are glacial moraines and outcrops of resistant, dipping pre-Pleistocene strata. An example of the non-glacial, resistant ridges is the Niagara Escarpment (Figure 4–7), which consists of limestones and dolomites (Figure 4–8) that dip into the Michigan structural basin and form a more-or-less continuous ridge from the Niagara region of New York and Ontario, through the Bruce Peninsula and Manitoulin Island in Lake Huron, to the Door Peninsula in Lake Michigan.

Bedrock geometry has a strong influence on the configuration of the Great Lakes. The bottoms of Lakes Michigan, Huron, Erie, and Ontario lie in strata that are largely shales (Figure 4–8) and were easily eroded prior to and during glaciation. With few exceptions the sills that separate the lakes are underlain by resistant strata predominantly composed of limestone and dolomite largely of Silurian age. Figure 4–8 shows examples of differentially eroded bedrock and its control on the geometry of the Great Lakes Basin.

The more subtle topographic features of the Great Lakes Basin result from modifications of Pleistocene glacial features. Glacial sediment may be divided into two general types: morainal debris, which forms the major ridges and hill systems in much of the Interior Lowlands, and non-morainal debris, which forms much of the low-lying terrain of the Basin. The non-morainal debris consists of glacio-lacustrine, glacio-fluvial, and eolian sediment. Figure 4–9 shows the distribution of major morainal systems in the U.S. portion of the Basin. Where moraines intersect the lake shore, they resist erosion, form points, and serve as sediment sources. The parallelism of moraines with lake shores is a result of the pre-Pleistocene drainage system, which channelized ice movement and caused the borders of the ice lobes to conform to the geometry of the pre-glacial river basins.

Subsequent to glacial recession, the Great Lakes Basin has been subjected to isostatic rebound (i.e., uplift of the land mass after the weight of the ice was removed) and to accelerated stream erosion. Variations in the rate of

TABLE 4–3 The Great Lakes Drainage Basins

	Lake					
	Superior	Michigan	Huron	St. Clair	Erie	Ontario
Area of Drainage Basins:[1]						
Total basin area[1] - sq. miles	49,300	45,600	51,700	6,900	22,700	27,300
Land area - sq. kilometers	127,700	118,100	133,900	17,900	58,800	70,700
U.S. basin area[1] - sq. miles	16,900	45,600	16,200	2,800	18,000	15,200
Land area - sq. kilometers	43,800	118,100	42,000	7,300	46,600	39,400
Canada basin area[1] - sq. miles	32,400	0	35,500	4,100	4,700	12,100
Land area - sq. kilometers	83,900	0	91,900	10,600	12,200	31,300
Percent of basin in U.S.	34	100	31	40	79	56

[1]Including connecting channels

SOURCE: Lake Survey Center, NOS, Dec. 1970

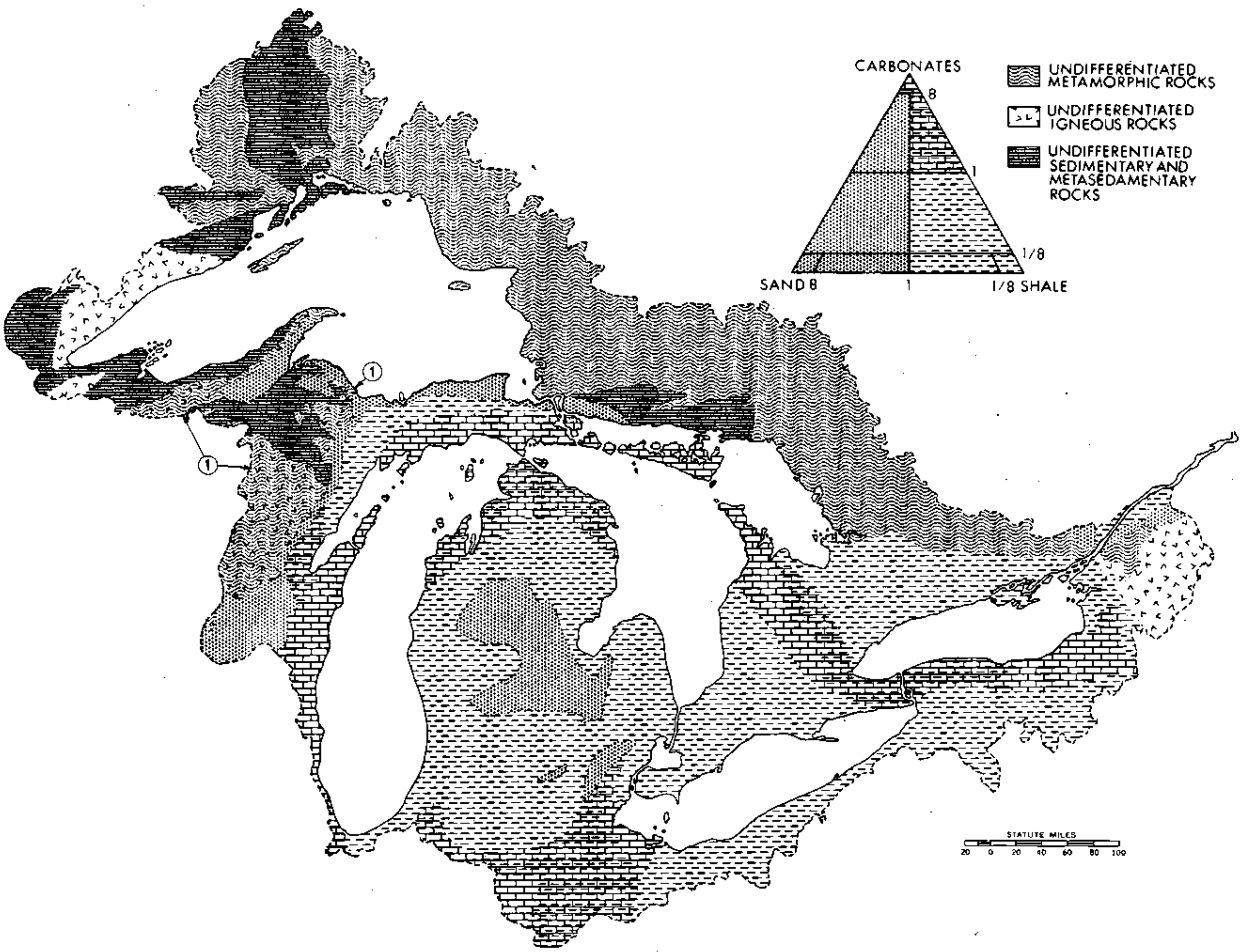

FIGURE 4–4 Lithofacies of Strata at the Pre-Pleistocene Erosional Surface. Symbols represent relative proportions of beds composed of carbonates (limestone, dolomite), sand (sandstone), and shale, by thickness. Note 1 indicates regions of mixed metamorphic and igneous rocks.

Data from Sloss, Dapples, and Krumbein, 1960

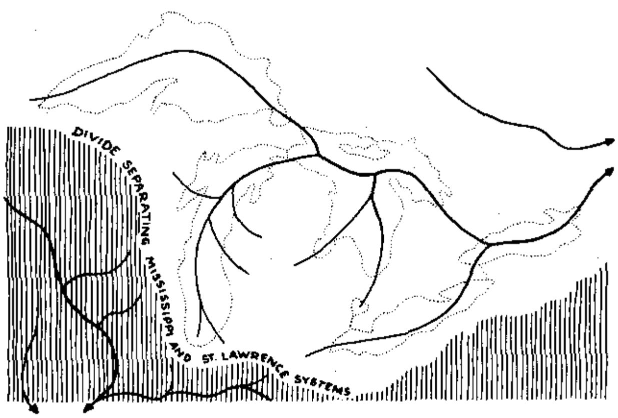

FIGURE 4–5 Proposed Pre-Pleistocene Drainage System in the Great Lakes Basin
From Kelley and Farrand, 1967

uplift and erosion have caused the drainage patterns in various parts of the Great Lakes Basin to be in different stages of development (Table 4–3). Lakes Michigan, Superior, and Huron have larger drainage basins than the remaining lakes. In newly formed glacial terrain, large drainage basins have poorly developed drainage networks. Because glacial retreat most recently exposed the drainage basins of Lakes M.chigan, Superior, and Huron, and because isostatic uplift of these basins has not yet reached a maximum, these drainage basins are more poorly developed. In poorly drained regions the residence time of water within the watershed is greater than elsewhere.

The individual basins of the Great Lakes, including Lake St. Clair, can be classified on

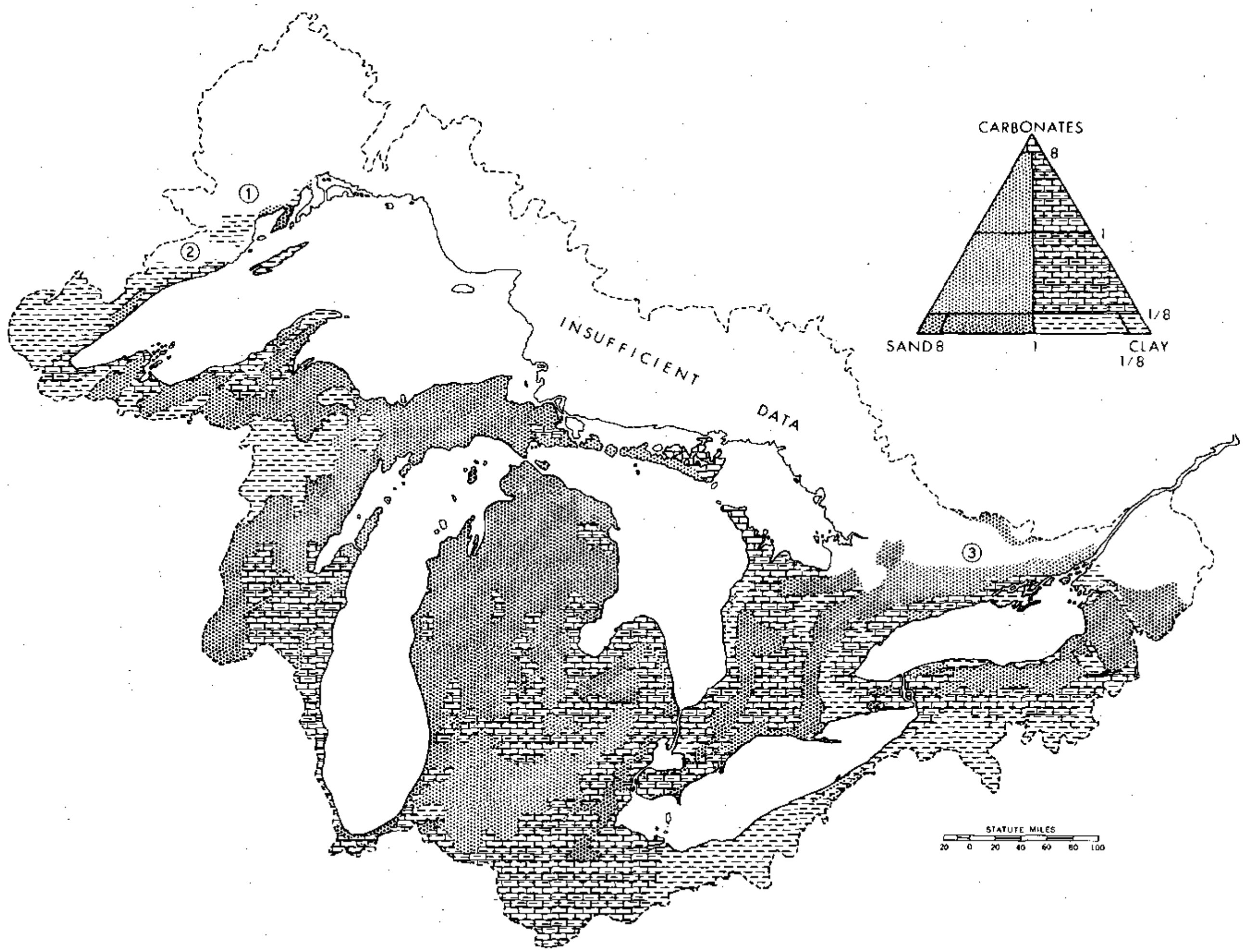

FIGURE 4–6 Composition of Pleistocene and Recent Surficial Deposits of the Great Lakes Region. Note 1 indicates regions of thin soil on Precambrian rocks. Note 2 indicates regions where soils are undifferentiated. Note 3 indicates areas of thin organic soil on Precambrian rock.
From Upchurch, 1972

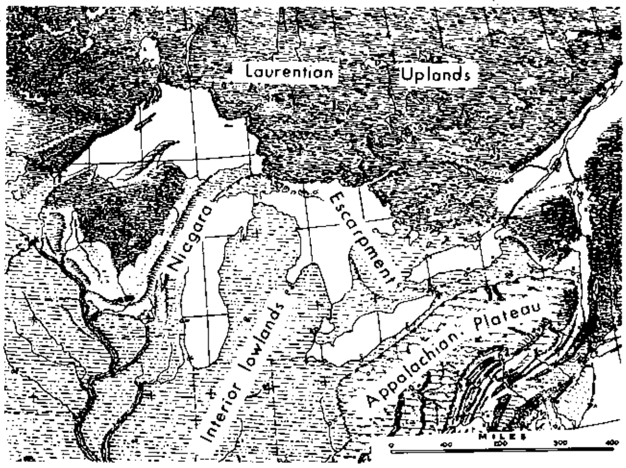

FIGURE 4–7 Physiography of the Great Lakes Region

Modified from Lobeck, 1957

the basis of bedrock geology, topography, and degree of development (maturity) of the present drainage system. The lakes can be classified as to the physiographic province in which their basins occur, and the lithology of the bedrock. Table 4–4 shows the resulting classification. The lake classification scheme is useful in predicting water residence times in the various watersheds, the natural chemical composition of the watershed runoff, and the bathymetric configuration of the various lakes.

1.4 Basin Population and Culture

Population density and cultural development are highly variable in the Great Lakes Basin. The distribution of cities and towns and of land uses is a function of Basin physiography and resources. Many of the geologic factors discussed in the preceding sections are responsible for the present cultural development of the Basin. For example, many of the larger cities were established along geologically formed straits or harbors, which afford economic or political advantages.

Unfortunately, these same factors have led to many of the environmental problems faced by the inhabitants of the Basin. Figure 4–10 shows the nature of land use in the Basin.

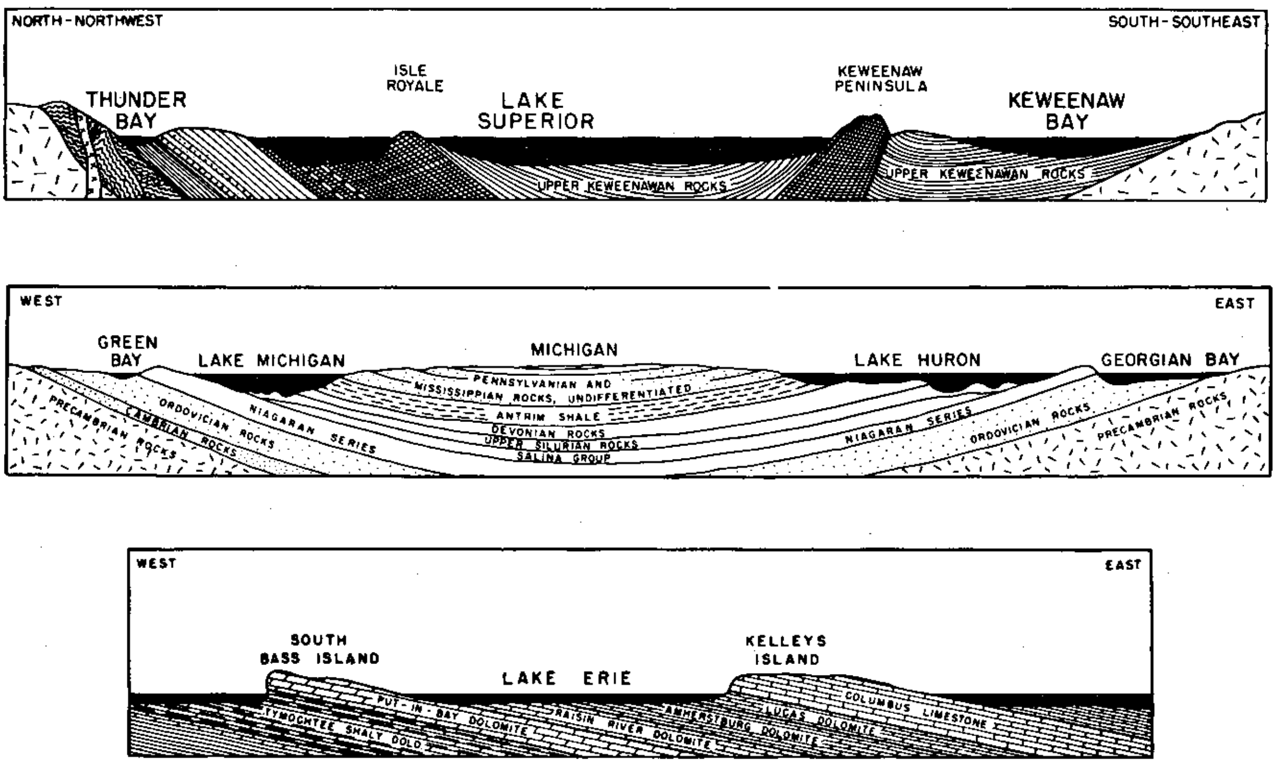

FIGURE 4–8 Examples of Stratigraphic Control on the Configuration of the Basins of the Great Lakes Showing Geologic Cross Sections of Lake Superior Syncline (top), Michigan Structural Basin (middle), and Western Lake Erie Basin through South Bass and Kelleys Islands (bottom)

From Hough, 1958

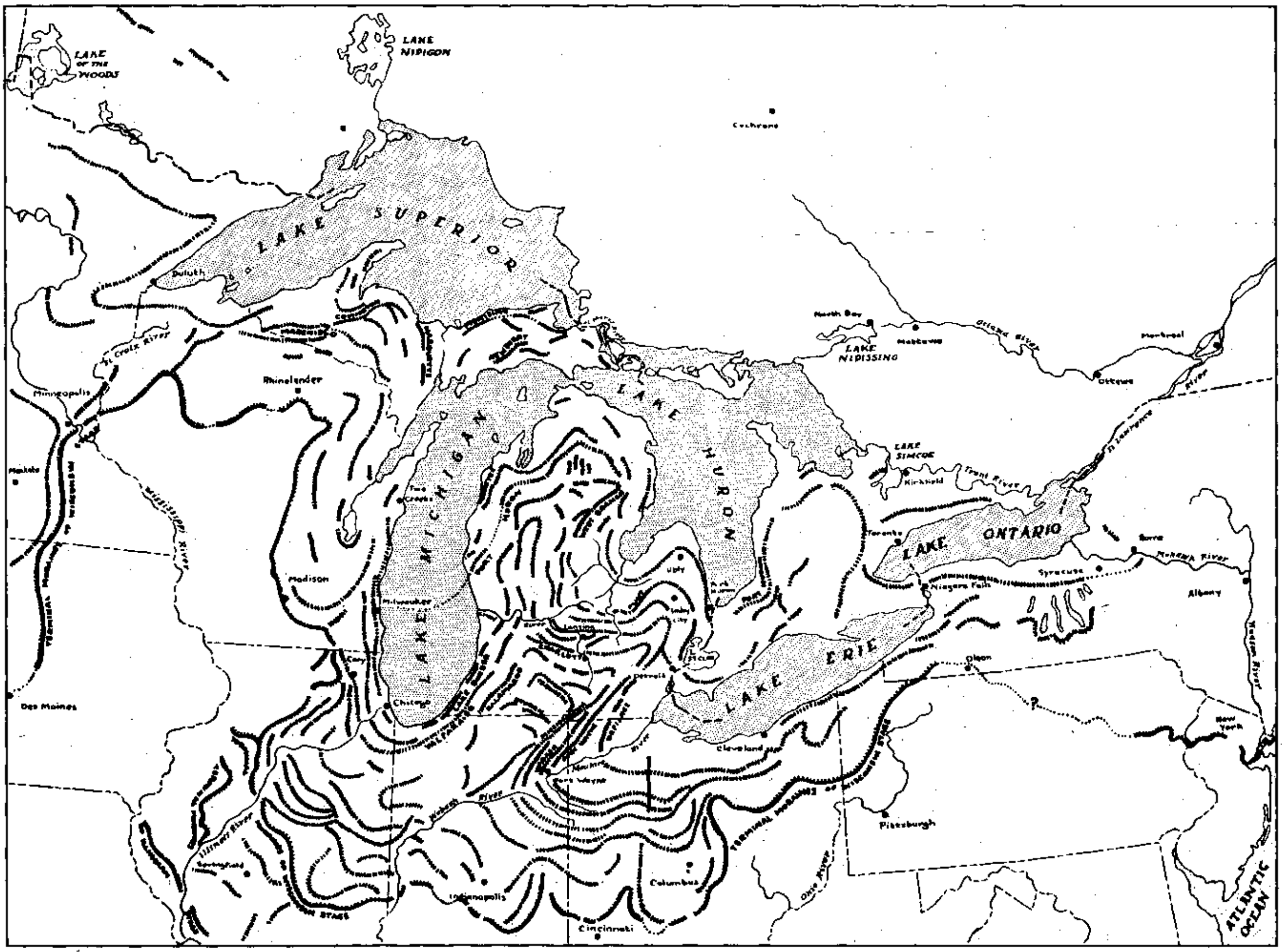

FIGURE 4–9 Principal Morainic Systems in the Great Lakes Region

After Kelley and Farrand, 1967

TABLE 4–4 Summary of the Geology and Drainage Maturity of the Great Lakes and Adjacent Basins

Criterion	Lake Michigan	Superior	Huron	St. Clair	Erie	Ontario
Borders Canadian shield?	No	Yes	Yes	No	No	No
Bottom primarily in shales?	Yes	No	Yes	No[1]	Yes	Yes
Drainage basin minerology:						
A. Igneous and metamorphic minerals common ?	No	Yes	Yes	No	No	No
B. Quartz, clay minerals, carbonates common?	Yes	Yes–quartz and clays in glacial debris	Yes–see Superior	Yes	Yes	Yes
Drainage basin maturity:						
A. Small drainage basin area?	No	No	No	Yes	Yes	Yes
B. Well developed drainage ?	No	No	No	Yes	Yes	Yes
Drainage Basin Classification	Immature Lowland	Immature Upland	Immature Upland	Mature (?) Lowland	Mature Lowland	Mature Lowland

[1]Lake St. Clair is situated in an intermorainal trough and bedrock has little influence on the lake.

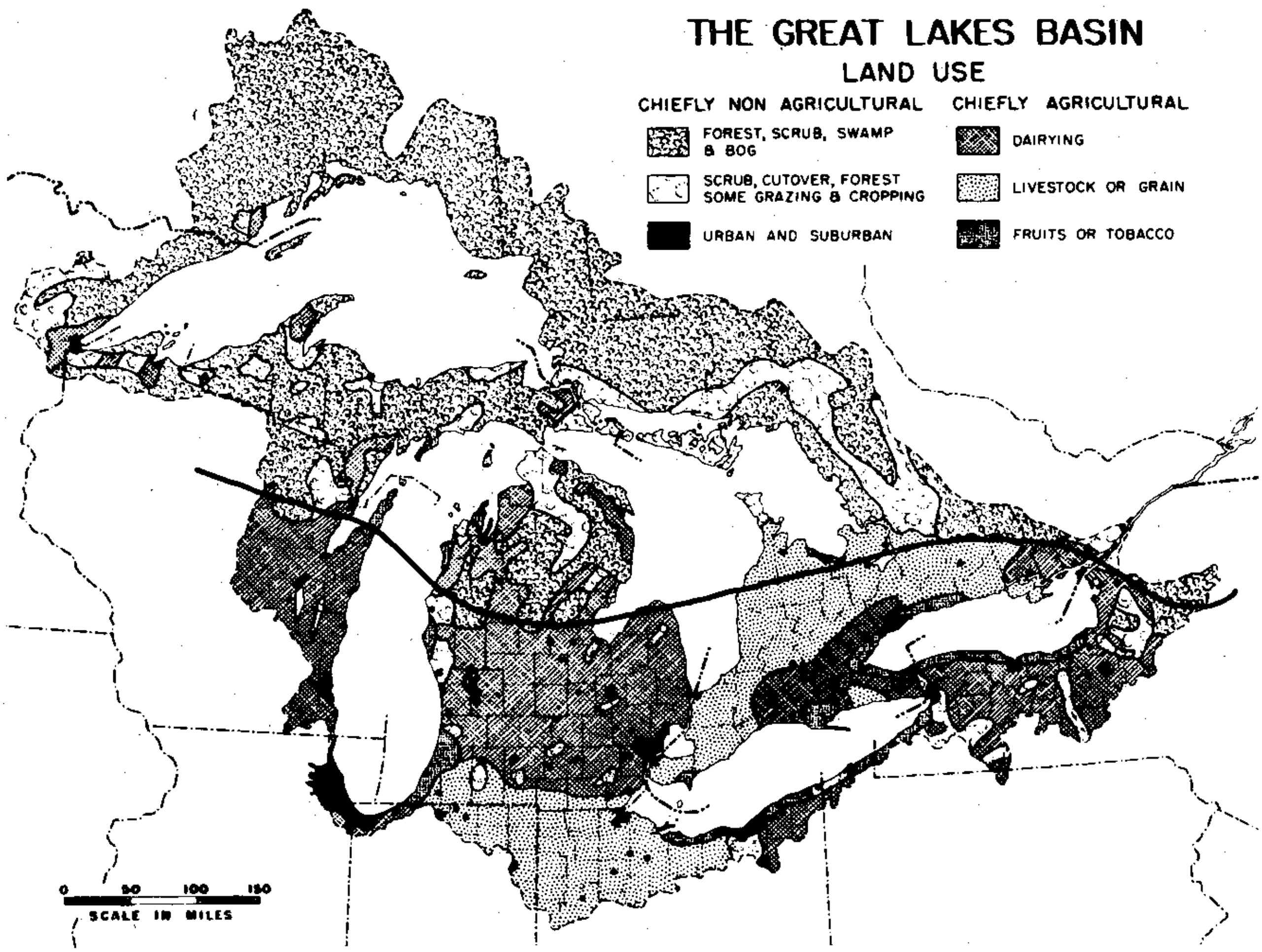

FIGURE 4–10 Major Categories of Land Use in the Great Lakes Basin. Heavy line separates urban and agricultural land-use area from nonagricultural area.

Much of the northern half of the Basin is wetland or is forested, with tourism, mining, and lumbering as the major industries. The southern half of the Basin is highly developed for agricultural and urban land utilization. The distinct separation in land use reflects geological characteristics of the Laurentian Uplands and the Interior Lowlands.

The population distribution (Figure 4–11) varies from an average of less than seven people per square kilometer (30/mi^2) in the Lake Superior basin to more than 140 per square kilometer (600/mi^2) in the Lake Erie basin. Most of the population is concentrated in the three urban complex areas on the southern edge of the Basin: the Gary-Chicago-Milwaukee complex, the Detroit-Toledo-Cleveland complex, and the Rochester-Buffalo-Toronto complex.

Because of differences in land use and population density, the upper Great Lakes experience a different type of input than the lower Great Lakes. The upper lakes (Superior, Huron, and northern Michigan) are little affected by man. The drainage systems are geologically immature and carry water that is, with local exceptions, adjusted to the natural system. On the other hand, southern Lake Michigan, Lake Erie, and Lake Ontario, have well-developed drainage systems that carry large amounts of agricultural and urban waste into the lakes.

1.5 Basin Climate

The Great Lakes have a strong influence on the climate of the Great Lakes Basin. Section 4 will treat over-lake climate and the lake effect on adjacent land areas in greater detail.

Northern, mid-continent North America is characterized by a cool, continental climate. In the vicinity of the larger lakes, this climate is modified, and a semi-maritime climate results. The interaction between the lakes and surrounding land areas affects the water budget, water surface motions, thermal re-

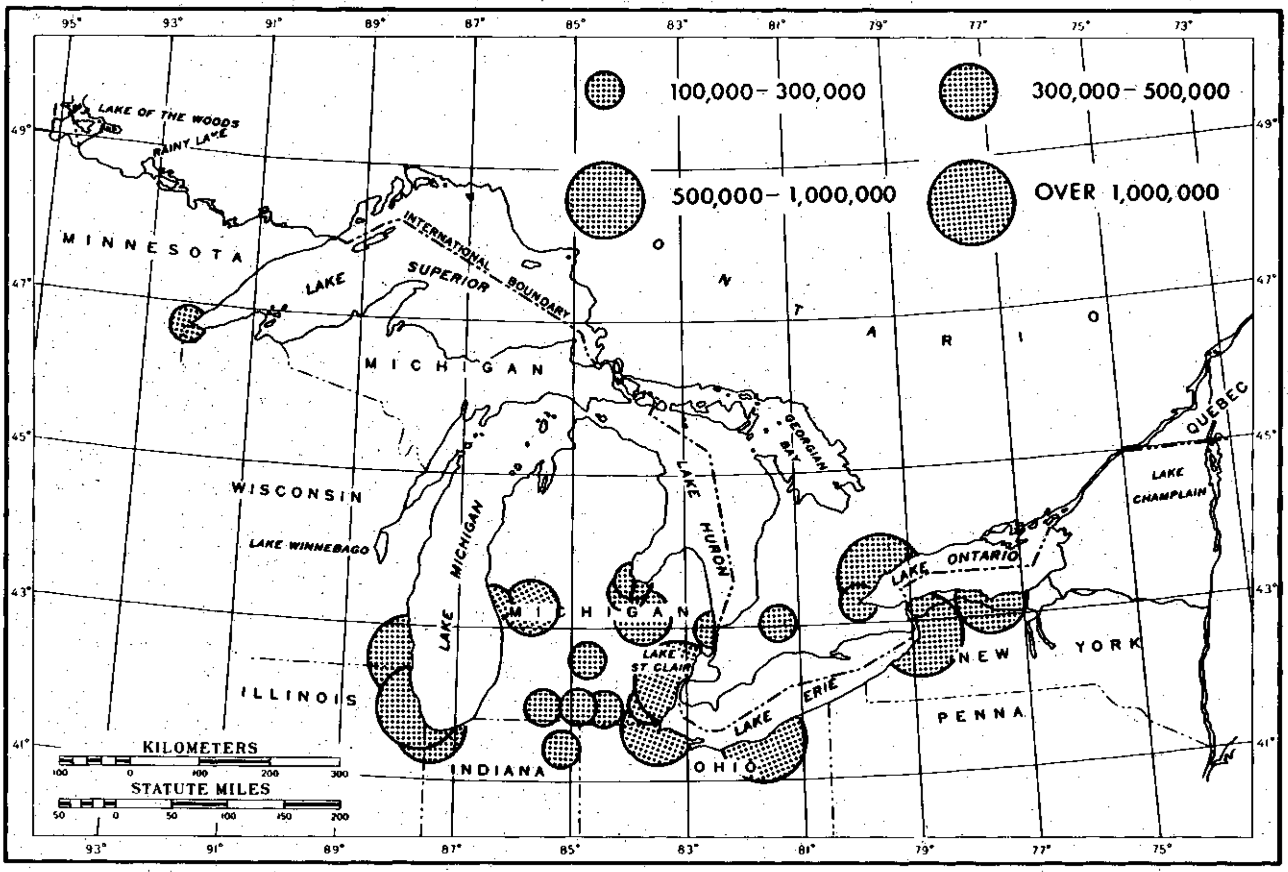

FIGURE 4–11 Population Centers in the Great Lakes Basin

After Great Lakes Basin Commission, 1968

gime, and solid and dissolved constituents of the lakes. These factors are emphasized in subsequent chapters.

1.6 Winds and Storms

Climatic disturbances that produce winds and storms are critical to the lake system because they aid in regulating the thermal budget of the lakes and adjacent land by heat dissipation or transfer; they affect precipitation and the resulting water budget; and they generate waves, seiches, and surges.

Prevailing winds in the Great Lakes area are generally from the west (Figure 4–12), although winds come from all sectors. During winter, winds of highest frequency of occurrence and velocity come from the west in the western half of the Basin. In the eastern half of the Basin, winter winds are most frequently from the west, southwest, and northwest. Summer winds are usually from the southwest and south throughout the Basin. In all the wind roses of Figure 4–12, there is a strong tendency for the maximum wind vectors to be aligned with the long axes of the lakes.

Major weather systems originate either in western Canada, or in southern and southwestern United States (Figure 4–13). Those cells from the northwest usually bring less moisture and are considerably cooler than the southern air masses (U.S. Weather Bureau[827]).

Local weather may be caused by local thermal gradients, and by lake effect. Local thermal gradients, for example, in the vicinity of a city or other heat source, cause restricted breezes and thunder showers and squalls. Although these storms are often violent, they are of little regional importance. Lake breezes are low intensity winds that result from differences in surface temperatures over the lakes and adjacent land areas. The lake breezes usually occur on clear days when there is little interference by regional pressure systems. Offshore breezes occur when the water is warmer than the land. A convection cell develops and air over the water tends to

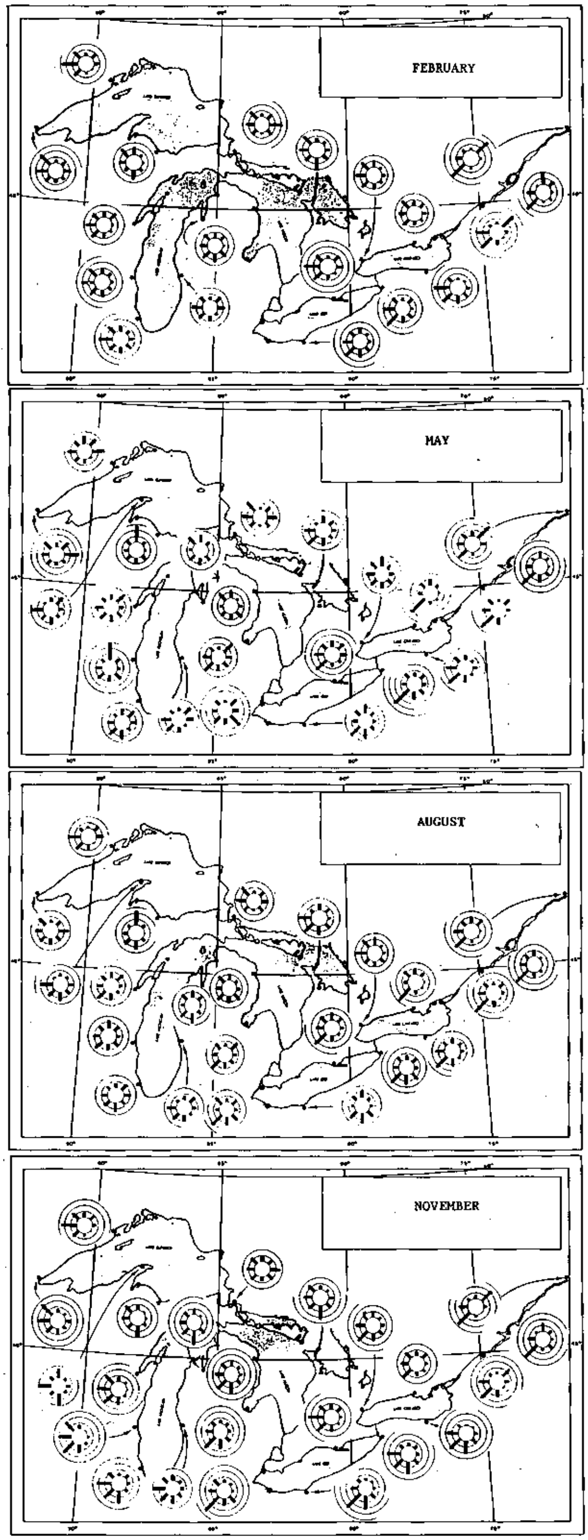

FIGURE 4–12 Wind Distribution in the Great Lakes Basin. Bars represent percentage frequency of wind observed from each direction. Each circle equals 10%.

From U.S. Weather Bureau, 1959a

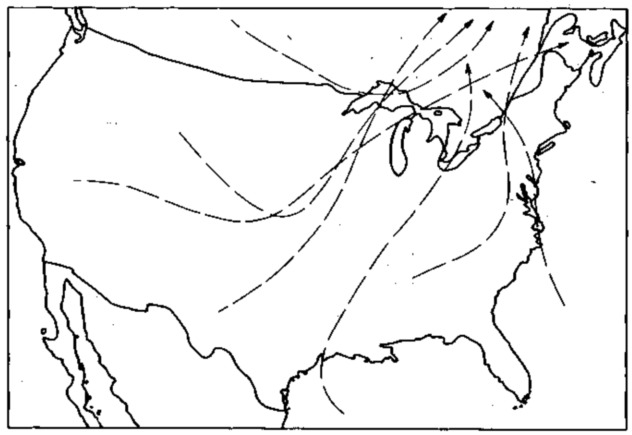

FIGURE 4–13 Major Storm Tracks that Affect the Great Lakes Basin

From U.S. Weather Bureau, 1959a

rise, relative to that over land (Figure 4–14). Onshore breezes result from the opposite condition. Lake breezes rarely extend inland for more than 2 or 3 kilometers (1.5 miles to 2 miles).

1.7 Temperature

Surface air temperature greatly influences the thermal regime of the Great Lakes. In return, the lakes, which comprise approximately one-third of the area of the Great Lakes Basin, act as heat sinks or sources, moderating the temperatures of adjacent land areas. Heat exchange between water and atmosphere also governs the distribution of lake breezes; the water budget of the Great Lakes Basin through evaporation and precipitation; stratification and circulation within the water mass; and, to a degree, the kinetics of chemical and biochemical reactions within the lakes.

The lake effect includes the moderating influence of the lakes on adjacent land temperatures. The lakes store heat more efficiently than does the surrounding land. When the surface temperatures over the land are cooler than those over water, the lakes release heat and warm the coastal regions. Conversely, if the atmosphere over land is warmer than over water, heat is absorbed by the water and the coastal regions are cooled.

Mean annual surface air temperatures in the Great Lakes Basin vary from less than 0°C (32°F) in the north to over 10°C (50°F) in the south (Figure 4–15). The moderating effect is evident in the vicinity of the lakes. The interiors of major peninsulas (e.g., the upper and

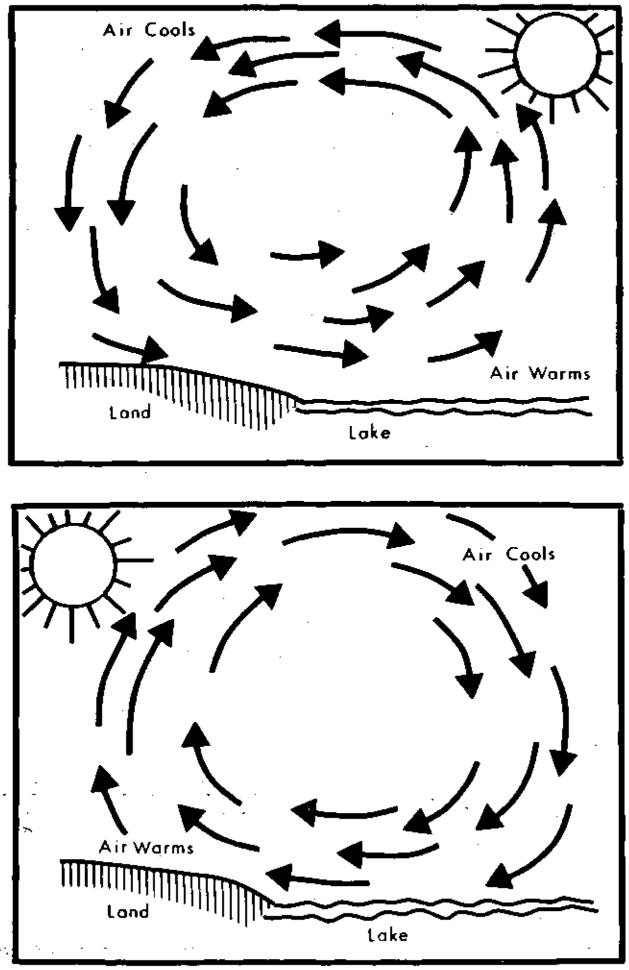

FIGURE 4–14 Generation of Offshore (top) and Onshore (bottom) Breezes

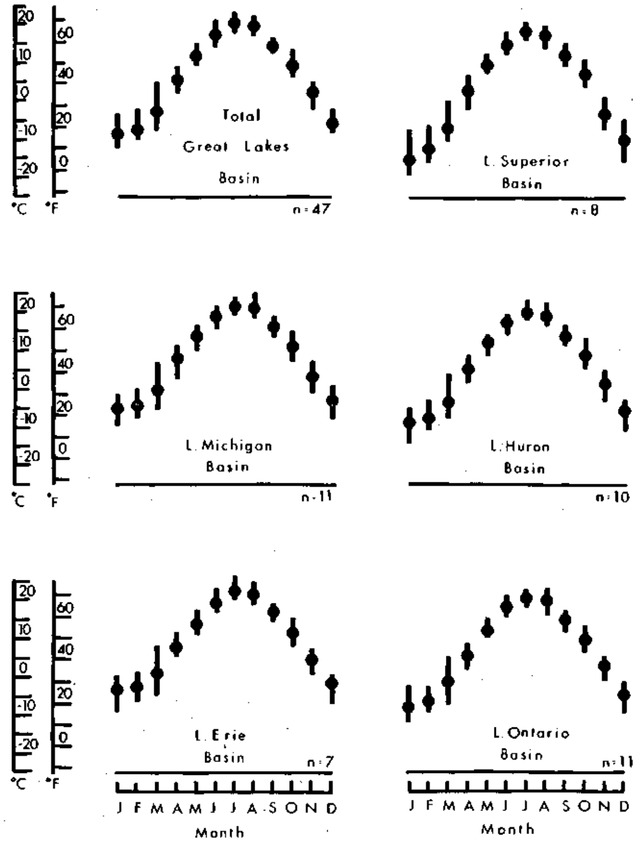

FIGURE 4–16 Monthly Mean and Range of Temperatures in each Lake Basin. "n" is the number of stations used in calculations.

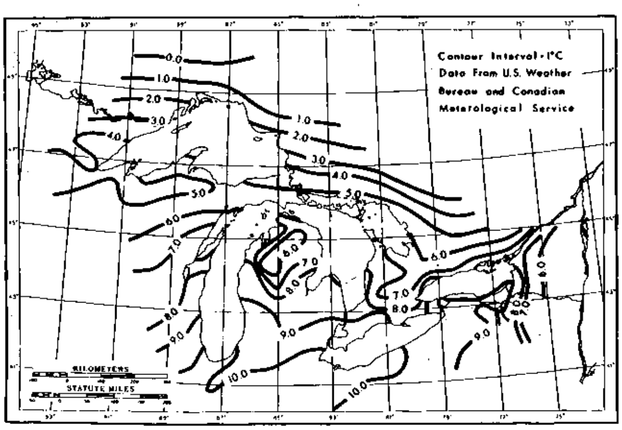

FIGURE 4–15 Mean Annual Temperature in the Great Lakes Basin

lower peninsulas of Michigan, and the Huron peninsula of southern Ontario) are colder than the coastal areas at equivalent latitudes. In response to the prevailing westerly and southwesterly winds, the mean annual temperatures on the lee coasts of the lakes tend to be slightly warmer than on the windward coasts.

Latitude causes a decrease in average monthly temperature and in average monthly maximum and minimum temperatures of about 10°C (18°F) from south to north within the Basin. Aside from gradients resulting from differences in latitude, temperatures within each of the lake basins are comparable (Figure 4–16). Greatest variability between temperature maxima and minima occurs during the winter and spring months. For example, in the Lake Superior basin the difference between average maximum and average minium temperatures ranges from 7°C to 15°C (approximately 13°F to 27°F) during the winter, to 5°C to 7°C (approximately 9°F to 13°F) during the summer. The small range of average summer maximum and minimum temperatures results from three factors: greater heat retention, when vegetation acts as a heat source; greater similarity of the water temperature to the atmospheric temperature; and dominance of southerly winds.

Short-term, local variations in near-surface atmospheric temperatures can be extreme. For example, intense cells of cold, arctic air may lower temperatures as much as 28°C (approximately 50°F) in the period of a day. If the lakes are not covered with ice, the lake effect can cause as much as 11°C (20°F) higher temperatures on the lee side of the lakes.

The Basinwide temperature regime governs the thermal budget of the lakes, including such factors as water temperature, ice season and extent, circulation, and structure of the aquatic community.

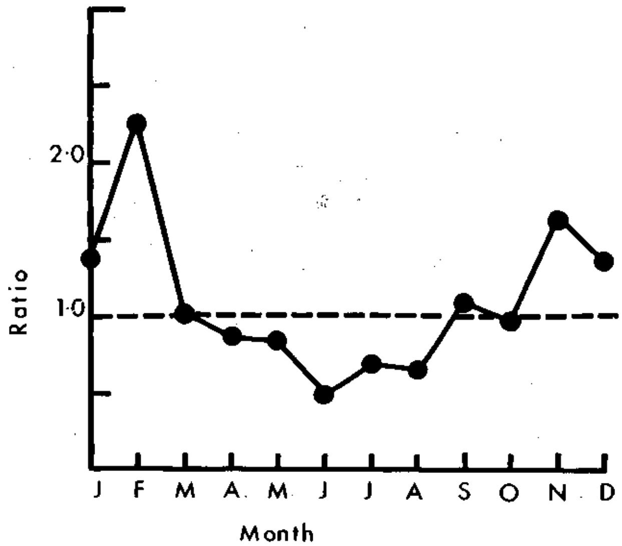

FIGURE 4–18 Ratio of Average Monthly Precipitation over Water to Average Monthly Precipitation over Land in the Northern Lake Michigan Area. Overwater sites were Ile aux Galets, South Fox Island, North Manitou Island, and Beaver Island. Overland sites were Long Lake Dam, Minocqua Dam, Willow Reservoir, and Rhinelander, Wisconsin.

1.8 Precipitation

Annual precipitation, including rainfall, snow, and less important modes of transfer of water from the atmosphere to the earth surface ranges from less than 70 cm to more than 95 cm (28 in to 37 in) (Figure 4–17). In the southeastern and eastern portions of the Basin (the Adirondack Mountains and the Allegheny Plateau) the total annual precipitation increases to more than 120 cm (47 in). The uniformity of the precipitation distribution is due to the lack of major topographic variation in the Basin and to the uniformity of weather patterns that move into the area.

Precipitation decreases from the south to north and from east to west. Precipitation decreases with increased latitude because the colder air masses at high latitudes cannot contain as much moisture as the warmer, southern air masses. The east to west precipitation decrease is caused by the interaction of the lakes (moisture sources), the prevailing westerly winds, and Basin configuration and elevations. The prevailing winds are reduced in moisture content after having crossed the plains to the west of the Basin. They receive moisture from the lakes, and precipitation amounts increase toward the east. The cooling of moisture-laden air in the Allegheny and Adirondack Highlands triggers orographic precipitation on the southeastern edge of the Basin.

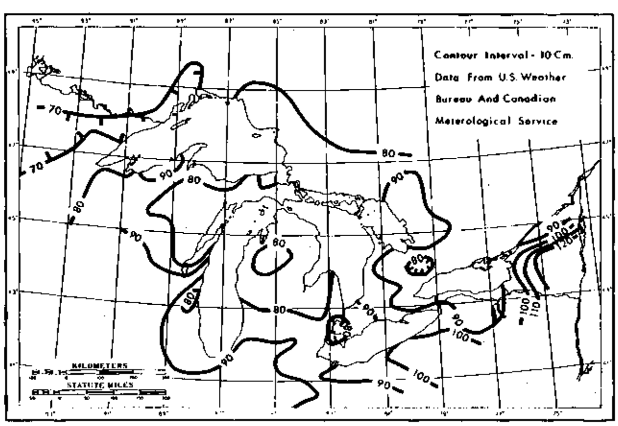

FIGURE 4–17 Mean Annual Precipitation on the Great Lakes Basin

During spring and summer, precipitation is greater over the land than over the lakes or over leeward coastal areas (Figure 4–18). This is due to convection caused by over-land warming. The air convected upward over land during summer is cooled and precipitation forms (Kresge et al.[476]). During winter, air passing over the lakes picks up moisture and becomes unstable, especially close to shore. Therefore, during winter more precipitation occurs over the water and the coastal areas than inland. The lake effect on coastal areas is apparent in the areal precipitation pattern

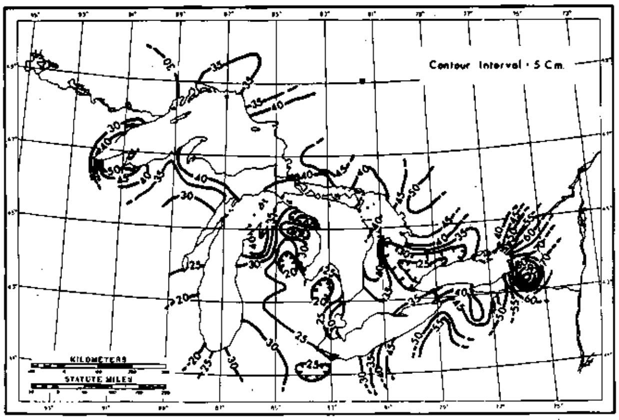

FIGURE 4–19 Mean Annual Runoff in the Great Lakes Basin

From Derecki, 1966

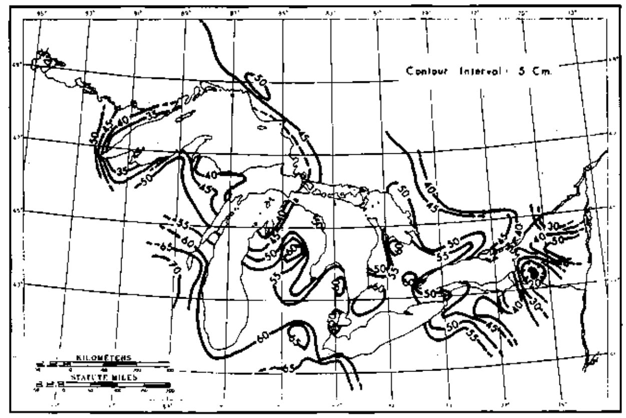

FIGURE 4–20 Mean Annual Surface Water Loss through Interception, Evaporation, and Infiltration as Ground Water

From Derecki, 1966

(Figure 4–17). On all of the lakes, precipitation is greater on the eastern (lee) side of the lake.

1.9 Runoff

Basin runoff is a function of precipitation, amount of storage in snowpack, saturation and storage in soil interstices, slope, channel storage, interception, and evapotranspiration. Variations in average annual runoff (Figure 4–19) correspond to the precipitation distribution. Throughout most of the Great Lakes Basin, the average runoff is between 20 cm and 30 cm (8 in to 12 in) on the windward portions and 30 cm to 40 cm (12 in to 16 in) on the leeward portions of the individual lake basins. The Adirondack Mountains and Allegheny Plateau have higher than average runoff because of orographically induced precipitation and increased slopes. Runoff is discussed in greater detail in Appendix 2, *Surface Water Hydrology*, and in Appendix 11, *Levels and Flows*. Sections 2 and 4 of this appendix develop those aspects of runoff necessary to the limnology of the respective lakes.

1.10 Evapotranspiration, Interception, and Ground Water

Not all of the water that reaches the ground as precipitation flows into the lakes as surface runoff. There are four possible processes for removing water from the surface drainage system: evaporation; transpiration, the process by which water escapes a living plant and enters the atmosphere; interception, the diversion of water by physical structures; and infiltration as ground water. Much of the precipitation diverted from runoff by interception and infiltration is eventually returned to the drainage network or to the lakes themselves by artificial drainage structures or subsurface flow. Figure 4–20 shows the difference between precipitation and runoff for the Basin. This difference is attributed to loss through interception, evapotranspiration, and/or infiltration as ground water. Water losses in the Lakes Huron, Michigan, and Superior basins tend to increase away from the respective lakes. These losses probably are due to the rather poorly developed drainage systems of these lake basins. The slight increase in water loss from north to south results from evapotranspiration induced by longer growing season, higher transpiration by deciduous trees compared to conifers, and higher temperatures in the southern half of the Great Lakes Basin.

1.11 Influence of Lakes on Basin Climate

Detailed discussions of the energy balance and over-water climate of the lakes in subsequent sections will elaborate on lake effects in the Great Lakes Basin. The lake effect is pronounced. Coastal temperatures, precipitation, and winds are controlled by the lakes. The water budget, chemistry, thermal regime, and circulation of the lakes are influenced by the interaction of land and the lakes.

Section 2

LAKE BASIN PHYSIOGRAPHY

Sam B. Upchurch

2.1 International Great Lakes Datum

Accurate measurement of lake levels is difficult, yet necessary for navigation, power generation, shore use, and lake regulation. Prior to 1955, lake level elevations were determined using mean sea level as datum. However, due to the rotation of the earth and variation in gravity with latitude and topography, a perfectly still lake surface is not parallel to mean sea level (Figure 4-21). Measurements taken at different locations on a lake were, therefore, difficult to correlate. In 1955 the dynamic-height system, utilizing the concept of an equipotential surface, was adopted by the United States and Canada for use in determining lake levels. This system accommodates the variations in lake level due to latitudinal differences in gravity (Feldscher and Berry[260]). Under the dynamic-height system all points at equivalent latitude are assumed to have an equivalent gravitational potential, which is sought by fluid bodies such as lakes. The datum used for dynamic-height measurements is called the International Great Lakes Datum (IGLD) and is the mean water elevation in the Gulf of St. Lawrence at Father Point, Quebec. A discrepancy in this technique is that lake surfaces are not parallel to the theoretical equipotential surfaces. Local gravity variations are of sufficient magnitude to cause measurable disparities in gage measurements referenced to IGLD. Feldscher and Berry[260] have recommended adoption of the geopotential method, which accounts for local gravity variations, to eliminate the discrepancies in lake-level measurements.

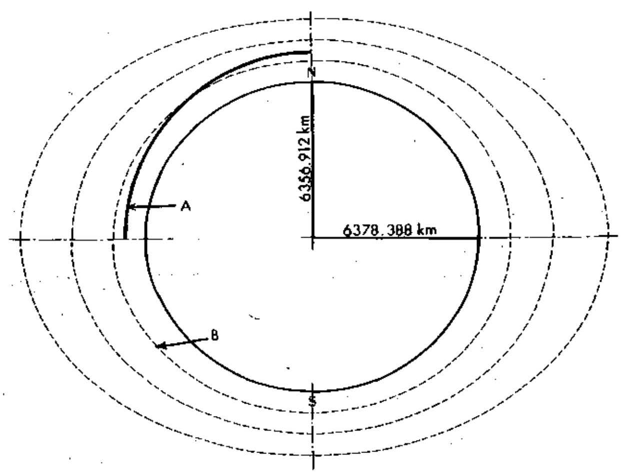

FIGURE 4–21 Comparison of Equipotential and Geometric Surfaces as Survey Datums. A is a surface generated by the radius of the earth at 45° latitude. B is the equipotential or level surface.

After Feldscher and Berry, 1969

2.2 Low Water Datum

Many of the measurements concerning levels, water areas, and water volumes of the Great Lakes are referenced to a low water datum (LWD). LWD is an arbitrary datum for each lake, selected with the purpose of simplifying calculations and interpretations from navigation charts. Lake areas and volumes referenced to LWD are, therefore, less than true areas and volumes by an amount calculated from the difference between LWD and the lake surface elevation.

2.3 Great Lakes Drainage System

Lake Superior is the northernmost of the Great Lakes and is the uppermost Great Lake in the Great Lakes-St. Lawrence drainage system (Figures 4–1 and 4–23). The Lake Superior outlet is the St. Marys River, which flows into Lake Huron. Lake Michigan and Lake Huron are at the same level, thus they are

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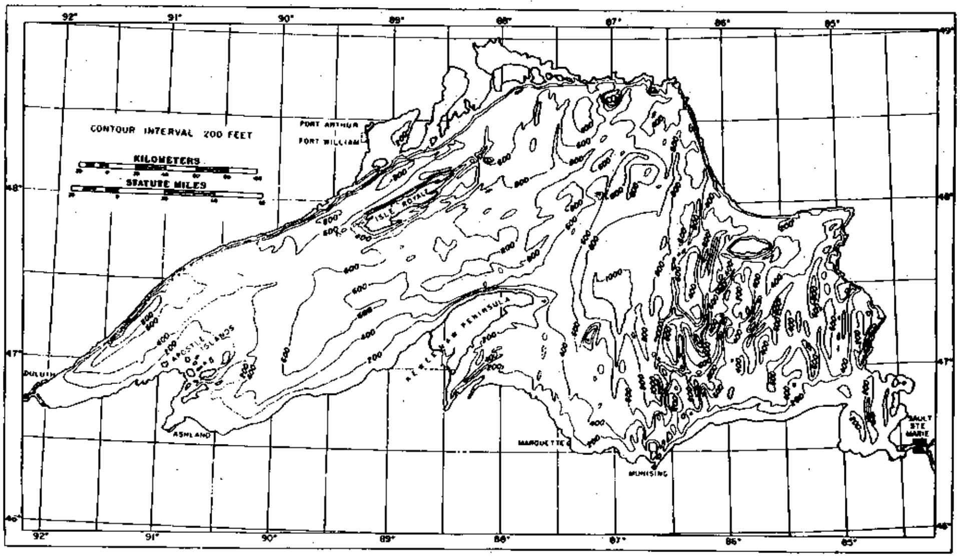

FIGURE 4–22 Physical Characteristics of Lake Superior Figure from Hough, 1958

	Metric	Standard
Low water datum (LWD):	182.9 m	600.0 ft
Length:	563 km	350 mi
Breadth:	259 km	160 mi
Shoreline length:	4795 km	2980 mi
Total surface area:	82,100 km²	31,700 mi²
Surface area in U.S.:	53,350 km²	20,600 mi²
Volume at LWD:	12,230 km³	2,935 mi³
Average depth below LWD:	149 m	480 ft

	Metric	Standard
Maximum depth below LWD:	407 m	1333 ft
Average surface elevation (IGLD):	183.11 m	600.37 ft
Maximum surface elevation (IGLD):	183.63 m	602.06 ft
Minimum surface elevation (IGLD):	179.23 m	598.23 ft

regarded as one hydrologic entity. Surface disturbances on each lake change the hydraulic head, causing flow reversals between the two lakes. Net flow, however, is from Lake Michigan into Lake Huron through the Straits of Mackinac. The St. Clair River connects Lake Huron and Lake St. Clair and the Detroit River flows from Lake St. Clair into Lake Erie. The Niagara River connects Lakes Erie and Ontario, and Lake Ontario discharges through the St. Lawrence River. Levels of Lakes Superior and Ontario are regulated by an international board.

2.3.1 Lake Superior

Lake Superior is the largest of the Great Lakes, with a volume of 12,230 km³ (2,935 mi³) and a surface area of 82,100 km² (31,700 mi²) at LWD (Figure 4–22).

The lake bottom is divided into two basins (Figure 4–22). The Keweenaw Peninsula and a prominent north-south ridge at a depth of 150 m to 180 m (500–600 ft) separate the eastern and western basins. The western basin is characterized by a comparatively smooth bottom, consisting of a thick (up to 120 m) sequence of varved lake sediment and till (Reid,[643] and Zumberge[922]). The eastern basin is characterized by a north-south trending valley and ridge system. Sediment cover is variable in this region and outcrops of pre-Pleistocene rocks are common.

The western basin of Lake Superior reflects the Lake Superior syncline (Figures 4–3 and 4–8), a trough-like structural feature that plunges to the northeast. Keweenawan (Precambrian) erosion-resistant volcanic and sedimentary rocks outcrop at the surface along the western arm of the syncline. The Apostle Islands, Isle Royale, and the connecting submarine ridge are outcrops of the same, resistant, Precambrian strata. The eastern flank of the syncline causes the strata to be exposed in the Keweenaw Peninsula and in the submarine ridge that extends northward from the Peninsula.

The eastern basin is less well understood. The southern border of the basin is in Paleozoic strata. The remainder of the basin is in the Precambrian, but is not further differentiated. Possibly, the valley and ridge portion of the eastern basin reflects a pre-Pleistocene drainage pattern that may have followed the structures of the Precambrian rocks.

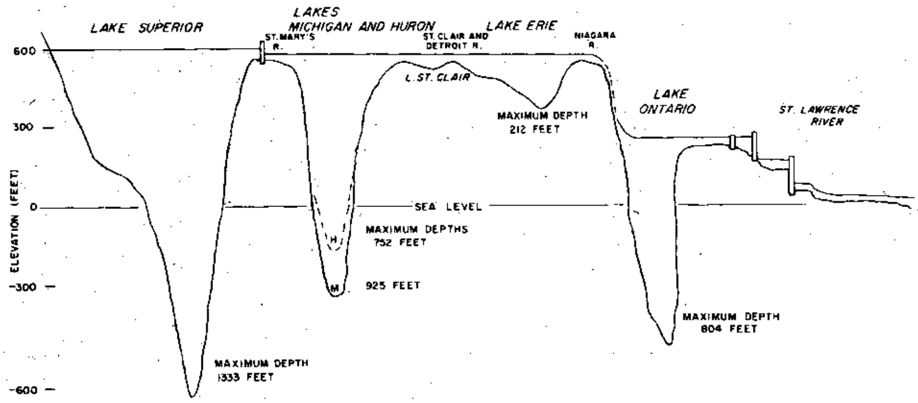

FIGURE 4–23 Profile of the Great Lakes System. Horizontal distance is not to scale.

From Rodgers, 1969

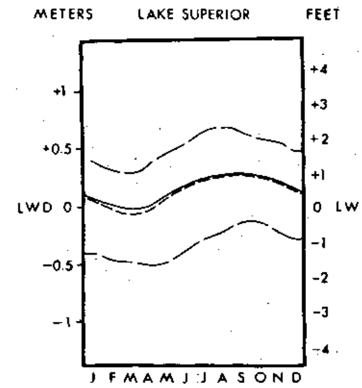

FIGURE 4–24 Average Monthly Lake Levels for Lake Superior for the Period 1860–1970 (solid line), and for the Period 1960–1970 (short-dashed line). Long-dashed lines represent the monthly, all-time maximum and minimum lake levels.

The shoreline of Lake Superior is one of its greatest resources. Throughout the region the coast tends to be precipitous, with sea cliffs 120 m to 240 m (400 ft to 600 ft) high and depths adjacent to shore to 150 m to 270 m (500 ft to 900 ft). Interspersed with these spectacular cliffs are small, rocky, pocket beaches. The south shore of Lake Superior is characterized by wave-cut terraces and abundant sediment of sand size or greater (Adams and Kregear[4]). Offshore slopes on the south shore are generally gentle. The shore in the vicinity of Whitefish Point is characterized by shallow reaches composed of sand derived from nearby glacial deposits and transported into the area by longshore currents.

Lake level is a function of total inflow by ground water, surface runoff, diversions, and over-water precipitation; and of outflow through ground water, the outflowing river, diversions, and evaporation. Local, brief variations in level are caused by barometric and over-water wind stresses. Lake Superior levels fluctuate (Figure 4–24) with a maximum level occurring in the early fall and a minimum level in early spring. The mechanisms that cause these variations are discussed in Sections 4 and 6.

Average annual flows of major tributaries to Lake Superior are shown in Table 4–5. Stream discharge in the lake is highly variable, depending on the season. Absolute flow maxima and minima show extremely large variations, often exceeding an order of magnitude in difference. Not all of the inflow is from natural runoff. Diversions from the Hudson Bay watershed add a combined 142 m^3/s (5,000 cfs) of water to Lake Superior: the Ogoki River has been diverted into Lake Nipigon and Long Lake has been diverted into the Aguasabon River. Outflow from Lake Superior is regulated in the St. Marys River. The St. Marys River (Table 4–6) drops a total distance of 7.1 m (23.3 ft) in a distance of 113 km (70 mi) with most of the drop at the control structure. The average discharge is 2,100 m^3/s (74,500 cfs).

2.3.2 Lake Michigan

Lake Michigan is the third largest of the Great Lakes in area and second largest in volume. The volume is 4,920 km^3 (1,180 mi^3) LWD. The volume corrected to average lake level is 4,924 km^3 (1,181 mi^3). Other physical data are shown in Figure 4–25.

The bottom of Lake Michigan is characterized by three basins (Figure 4–25). The southern basin is separated from the others by a sill that extends from Sheboygan to Ludington. For the most part, the sill is underlain by Devonian limestones with a veneer of morainic material forming the upper portion of the ridge. The southern basin has a relatively smooth bottom that consists of 0 m to more than 90 m (300 ft) of fine-grained lake sediment over Devonian-Mississippian shales. The uniformity of the bottom is due, in part, to the ease with which the shale was eroded prior to and during the Pleistocene. North of the mid-lake sill is a second basin with an irregular floor. The basin bottom is characterized by outcrops of resistant Devonian limestones separated by sediment-filled declivities. The

TABLE 4–5 Discharge of Major Great Lakes Tributaries

Tributary	Mean Discharge (m^3/s)	Range (m^3/s)	Period of Record (years)
Lake Superior Basin			
Tahquamenon River	25	4-198	14
Carp River	1	0.1-9	6
Trap Rock River	1	0.2-2	1
Sturgeon River	23	4-439	25
Ontonagon River	39	5-1,189	25
Iron River	4	0.8-224	5
Presque Isle River	8	0.6-131	22
Black River[1]	6	0.3-419	13
Montreal River[1]	9	0.06-187	29
Bad River	17	1-784	27
White River[1]	8	0.09-178	19
Bois Brule River	5	2-43	25
St. Louis River	62	2-1,073	60
Baptism River	5	0.01-265	40
Poplar River	3	0.07-53	32
Pigeon River	14	0.8-312	44
Kaministikwia River	58	5-575	37
Black Sturgeon River	ungaged	---	--
Nipigon River	366	59-640	12
Pic River	ungaged	---	--
Black River[2]	ungaged	---	--
White River[2]	54	1-306	6
Magpie River	26	4-233	26
Michipicoten River	70	4-688	39
Montreal River[2]	40	0.6-433	33
Lake Michigan Basin			
Black River[3]	0.7	0.1-24	16
Manistique River	38	8-479	29
Indian River	11	0.6-57	29
Sturgeon River	5	1-32	1
Escanaba River	25	3-297	26
Ford River	10	0.7-215	13
Menominee River	88	5-935	55
Pestigo River	24	2-277	14
Oconto River	16	3-238	56
Fox River	118	4-680	71
Kewaunee River	2	0.1-184	1
Sheboygan River	7	0.03-202	25
Milwaukee River	11	0-428	53
Root River	13	3-147	40
Burns Ditch	4	---	1
St. Joseph River	86	12-572	37
Paw Paw River	11	3-47	16
Black River[4]	3	0.6-18	1
Kalamazoo River	37	2-496	37
Grand River	95	11-1,529	41
Muskegon River	54	9-423	45
White River	11	5-106	10
Pere Marquette River	18	9-78	28
Big Sable River	4	2-16	25
Little Manistee River	5	2-16	11
Manistee River	56	28-193	16
Boardman River	5	0.8-35	15
Jordan River	5	3-20	1
Lake Huron Basin			
Cheboygan River	22	3-46	25
Thunder Bay River	12	3-115	22
AuSable River[4]	26	---	13
AuGres River	3	0.2-56	17
N. Br. Kawkawlin River	2	0-44	16
Saginaw River	ungaged	---	--
Pigeon River	1	0.003-72	15
AuSable River[2]	9	0.03-317	18
Maitland River	22	0.06-881	17
Saugeen River	55	6-896	51
Sauble River	12	0.5-170	8
Sydenham River	3	0.03-68	28
Lake Huron Basin (cont.)			
Bighead River	4	0.2-88	8
Beaver River	6	2-60	7
Nottawasaga River	9	0.9-267	16
Severn River	16	3-67	1
Muskoka River	69	0.1-368	28
Maganatawan River	ungaged	---	--
French River	171	24-581	35
Wanapitei River	34	4-295	13
Spanish River	122	3-1,286	18
Aux Sables River	18	2-210	47
Mississagi River	133	0.6-569	1
Lake St. Clair Basin			
Black River	8	0.05-408	23
Mill Creek	--	0.02-67	--
Clinton River	13	?-600	33
Thames River	52	2-1,090	10
Sydenham River	7	0.2-158	17
Lake Erie Basin			
Rouge River	6	--	20
Huron River[4]	16	0.1-165	63
River Basin	19	0.06-365	30
Maumee River	136	0-5,098	42
Portage River	11	0.009-326	35
Sandusky River	26	0.1-793	41
Huron River[5]	8	0.06-731	17
Vermilion River	6	0-578	17
Black River	8	0-680	23
Rocky River	7	0.006-606	36
Cuyahoga River	24	2-702	36
Chagrin River	9	0.08-793	38
Grand River[5]	18	0-598	42
Ashtabula River	4	0-329	36
Conneaut Creek	7	0.006-481	31
Cattaraugus Creek	20	0.2-1,017	28
Cayuga Creek	3	0-248	30
Buffalo River	22	---	--
Cazenovia Creek	6	0.07-382	28
Grand River[2]	68	9-404	10
Lynn River	1	0.08-53	8
Young Creek	1	0.04-13	1
Dedrich Creek	1	0.04-17	1
Big Creek	7	1-306	11
South Otter Creek	1	0.02-37	1
Big Otter Creek	7	0.03-210	15
Catfish Creek	3	0.1-162	1
Lake Ontario Basin			
Eighteenmile Creek	3	---	--
Genesee River	76	<0.3-974	48
Oswego River	174	10-1,062	35
Sandy Creek	6	0.06-334	11
Black River	108	4-1,039	47
Napanee River	9	0.03-96	28
Salmon River	8	0.03-110	7
Moira River	30	0.4-351	50
Trent River	97	11-456	1
Ganaraska River	3	0.5-103	14
Soper Creek	1	0.06-21	6
Rouge River	1	0.03-46	1
Little Don River	1	0.2-28	1
Humber River	5	0.03-838	17
Etobichoke River	--	?-24	1
Credit River	7	0.08-317	17
Oakville Creek	1	0.01-?	7
Bronte Creek	3	0.1-29	1
Grindstone Creek	1	0.003-21	6
Spencer Creek	2	0.03-46	1
Twentymile Creek	2	0-130	8

[1]Wisconsin [2]Ontario [3]Michigan Upper Peninsula [4]Michigan Lower Peninsula [5]Ohio

northeastern part of Lake Michigan consists of numerous north-south trending valleys and ridges that are reminiscent of those in eastern Lake Superior. Green Bay constitutes a fourth physiographic element of Lake Michigan. It is a relatively shallow embayment separated from the main lake by the Door Peninsula (the Niagara Escarpment).

The shoreline of Lake Michigan ranges from glacial debris and precipitous cliffs of pre-Pleistocene strata along the northern and western shores, to expansive sandy beaches

TABLE 4–6 Great Lakes Connecting Channels, Rivers, and Diversions

	St. Marys River	Straits of Mackinac	St. Clair River	Detroit River	Niagara River	St. Lawrence River
Length (km)	113	------	43	51	60	808
(m)	70	------	27	32	37	502
Total (m)	7.1	0	1.5	1.0	99.3	74.0
Drop (ft)	23.3	0	4.9	3.3	325.8	242.8
Average Discharge (1860-1968)						
(m^3/s)	2,100	1,500	5,300	5,400	5,700	6,700
(cfs)	74,000	52,000	187,000	190,000	202,000	239,000
	Diversions					
	L. Superior	L. Michigan	L. Huron	L. St. Clair	L. Erie	L. Ontario
	Ogoki R. & Long Lake	Chicago R. & Calumet Canal	None	None	Welland Canal & New York State Canal System (Welland)	(NYSCS)
Flow (m^3/s)	142	88	------	-------	198	20
(cfs)	5,000	3,100	------	-------	7,000	700
Effect on L. Huron & Michigan Levels						
(m)	+0.11	-0.07	-------	-------	-0.03	insig.
(ft)	+0.37	-0.23	-------	-------	-0.10	"
Effect on St. Clair R. Outflow						
(m^3/s)	+142	-88	-------	-------	0	0
(cfs)	+5,000	-3,100	-------	-------	0	0
Effect on L. Erie Level						
(m)	+0.07	-0.04	-------	-------	-0.10	insig.
(ft)	+0.23	-0.14	-------	-------	-0.32	"
Effect on St. Clair R. Outflow						
(m^3/s)	+142	-88	-------	-------	-198	-20
(cfs)	+5,000	-3,100	-------	-------	-7,000	-700

with large dune ridges on portions of the eastern shore. Offshore slopes are gentle in most cases.

Because Lakes Michigan and Huron are connected by the relatively deep Mackinac Straits, the LWD of both lakes is the same, and the lakes are treated hydrologically as one lake. As with Lake Superior, Lakes Michigan and Huron show cyclic fluctuations of surface levels (Figure 4–26). These fluctuations are induced by winter water retention on the watershed and subsequent release during spring and early summer.

Most of the major tributaries have low mean discharges (Table 4–5). There are no diversions of water into Lake Michigan. Outflow from the Lake is through the Straits of Mackinac into Lake Huron and, via diversions at Chicago, through the Chicago River and the Calumet Sag Canal into the Mississippi River system. Combined withdrawals from Lake Michigan through the two Chicago outlets are regulated

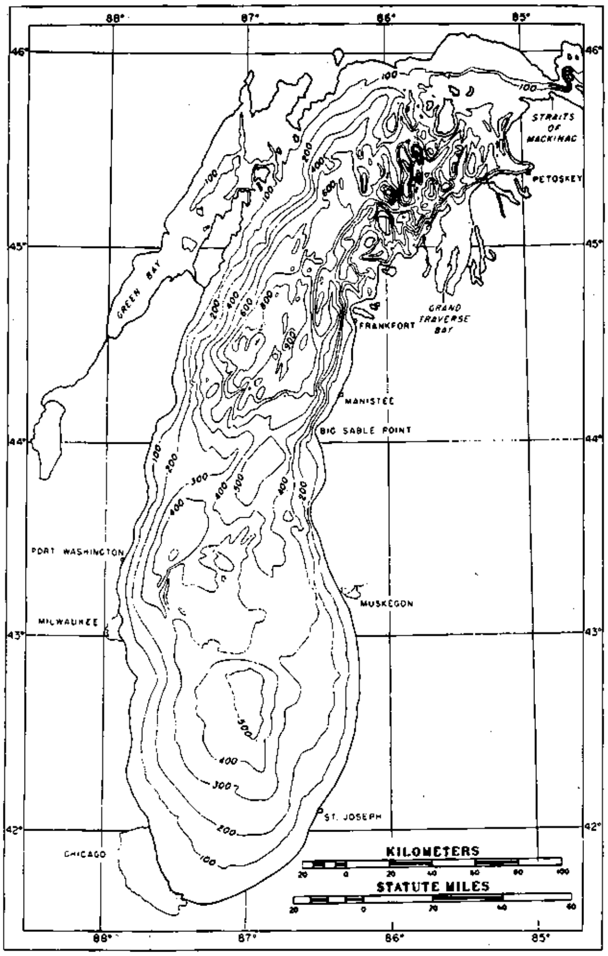

FIGURE 4-25 Physical Characteristics of Lake Michigan

Figure from Hough, 1958

	Metric	Standard
Low water datum (LWD):	175.8 m	576.8 ft
Length:	494 km	307 mi
Breadth:	190 km	118 mi
Shoreline length:	2,670 km	1,660 mi
Total surface area:	57,750 km²	22,300 mi²
Surface area in U.S.:	57,750 km²	22,300 mi²
Volume at LWD:	4,920 km³	1,180 mi³
Average depth below LWD:	85 m	279 ft
Maximum depth below LWD:	282 m	923 ft
Average surface elevation (IGLD):	176.50 m	578.68 ft
Maximum surface elevation (IGLD):	177.49 m	581.94 ft
Minimum surface elevation (IGLD):	175.48 m	575.35 ft

to equal 88.0 m³/s (3,100 cfs). Natural outflow through the Straits of Mackinac has been estimated to average 1,500 m³/s (52,000 cfs).

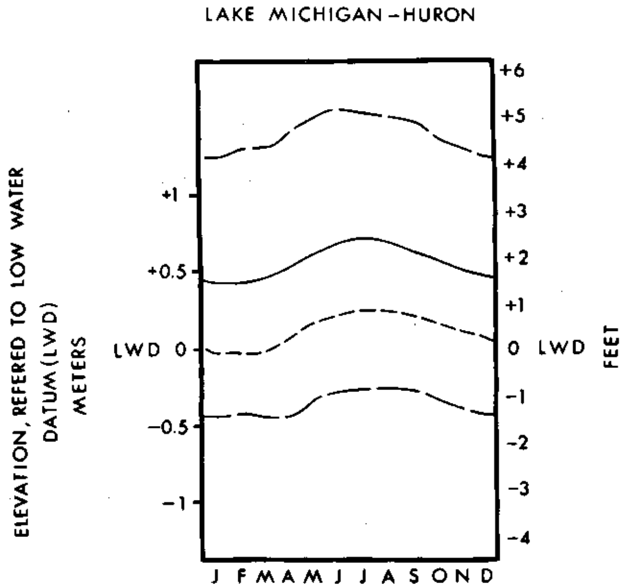

FIGURE 4-26 Average Monthly Lake Levels for Lakes Michigan and Huron for the Period 1860–1970 (solid line), and for the Period 1960–1970 (short-dashed line). Long-dashed lines represent the monthly, all-time maximum and minimum lake levels.

2.3.3 Lake Huron

Lake Huron has the second largest surface area of the Great Lakes and is third in volume. Its surface area is 59,500 km² (23,000 mi²) LWD, and its volume is 3,537 km³ (849 mi³) LWD (Figure 4-27).

The lake bottom is composed of three basins. The eastern basin, Georgian Bay, is separated from the main lake by the Niagara Escarpment, which forms the Bruce Peninsula, Manitoulin Island, Cockburn Island, and Drummond Island. The bay is formed in shales (Figure 4-8) that were less resistant to erosion than the limestones and dolomites of the Niagara Escarpment. Lake Huron proper is nearly equally divided into two basins by a ridge that extends northwest-southeast from Alpena, Michigan to Kincardine, Ontario. This ridge is a cuesta of Devonian limestone with the basins on each side in softer shales and sandstones. The floor of Lake Huron contains thick sequences of sediment and scattered outcrops of Paleozoic bedrock.

The Lake Huron shoreline is variable. Sandy beaches with dune ridges occur where morainal or glacio-lacustrine strata act as sediment sources. Thus, the shore of the

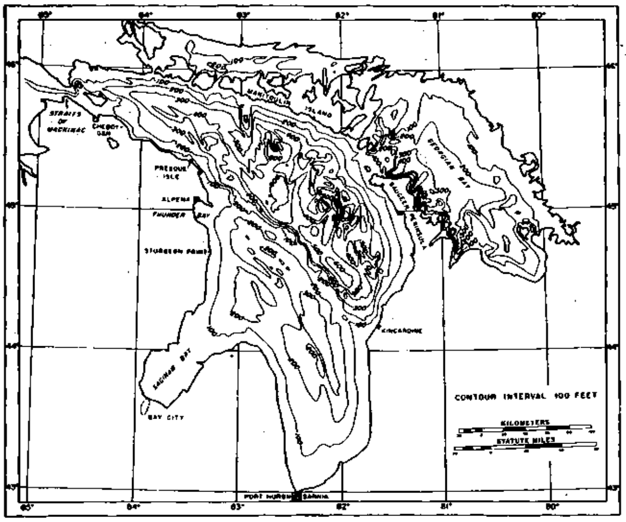

FIGURE 4–27 Physical Characteristics of Lake Huron

Figure from Hough, 1958

	Metric	Standard
Low water datum (LWD):	175.8 m	576.8 ft
Length:	331 km	206 mi
Breadth:	294 km	183 mi
Shoreline length:	5,120 km	3,180 mi
Total surface area:	59,500 km²	23,000 mi²
Surface area in U.S.:	23,600 km²	9,100 mi²
Volume at LWD:	3,537 km³	849 mi³
Average depth below LWD:	59 m	195 ft
Maximum depth below LWD:	229 m	750 ft
Average surface elevation (IGLD):	176.50 m	578.68 ft
Maximum surface elevation (IGLD):	177.49 m	581.94 ft
Minimum surface elevation (IGLD):	175.48 m	575.35 ft

southern basin, and the southwestern shore of the northern basin are low and have well-developed beaches. Areas bordered by erosion-resistant rock, such as the carbonates of the Bruce Peninsula, Manitoulin Island, and the Presque Isle Peninsula, and by Precambrian rocks of the North Channel shores, have sheer cliffs and small, rocky, pocket beaches.

Water level fluctuations in Lake Huron are the same as in Lake Michigan (Figure 4–26). Major tributaries to Lake Huron are Lake Superior and Lake Michigan, which flow through the St. Marys River and the Straits of Mackinac respectively (Table 4–6). There are no diversions into or out of the lake. Table 4–5 lists the other important tributaries to Lake Huron and their mean discharges. Outflow from Lake Huron is through the St. Clair River (Table 4–6). The St. Clair River is 43 km

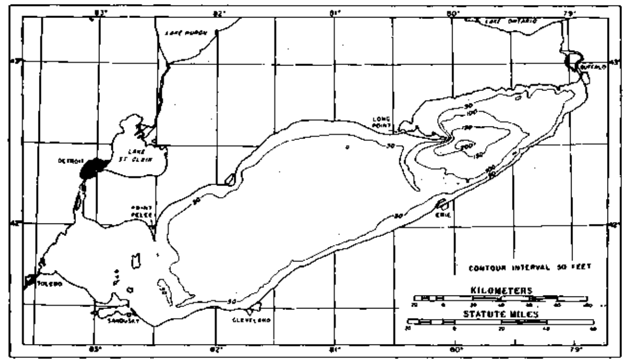

FIGURE 4–28 Physical Characteristics of Lakes St. Clair and Erie

Figure from Hough, 1958

	Lake St. Clair		Lake Erie	
	Metric	Standard	Metric	Standard
Low water datum (LWD):	174.3 m	571.7 ft	173.3 m	568.6 ft
Length:	42 km	26 mi	388 km	241 mi
Breadth:	39 km	24 mi	92 km	57 mi
Shoreline length:	272 km	169 mi	1,377 km	856 mi
Total surface area:	1,113 km²	430 mi²	25,657 km²	9,910 mi²
Surface area in U.S.:	419 km²	162 mi²	12,893 km²	4,980 mi²
Volume at LWD:	4 km³	1 mi³	483 km³	116 mi³
Average depth below LWD:	3 m*	10 ft*	19 m	62 ft
Maximum depth below LWD:	6 m*	21 ft*	64 m	210 ft
Average surface elevation (IGLD):	174.77 m	573.01 ft	173.96 m	570.37 ft
Maximum surface elevation (IGLD):	175.59 m	575.70 ft	174.69 m	572.76 ft
Minimum surface elevation (IGLD):	173.81 m	569.86 ft	173.08 m	567.49 ft

**natural depths*

(27 mi) in length and has a total drop of 1.5 m (4.9 ft). The average discharge is 5,300 m³/s (187,000 cfs).

2.3.4 Lake St. Clair

Lake St. Clair is not generally considered one of the Great Lakes. However, it is usually considered in discussions of the Great Lakes because it is important as a link in the Great Lakes system, and is a major recreational resource.

The lake has an area of 1,113 km² (430 mi²) LWD and a volume of 4 km³ (1 mi³) LWD. Average depth is 3 m (10 ft) and the maximum natural depth is 6 m (21 ft). A navigation channel is maintained at a depth of 8.2 m (27 ft) by dredging. Other physical data are given in Figures 4–28 and 4–29.

The lake consists of a single, heart-shaped basin, with its inlet, the St. Clair River, at the center of the northeastern side. The floor of the lake is in glacial till and it is bordered on the north and south by moraines. Sediment carried into the lake has resulted in the formation

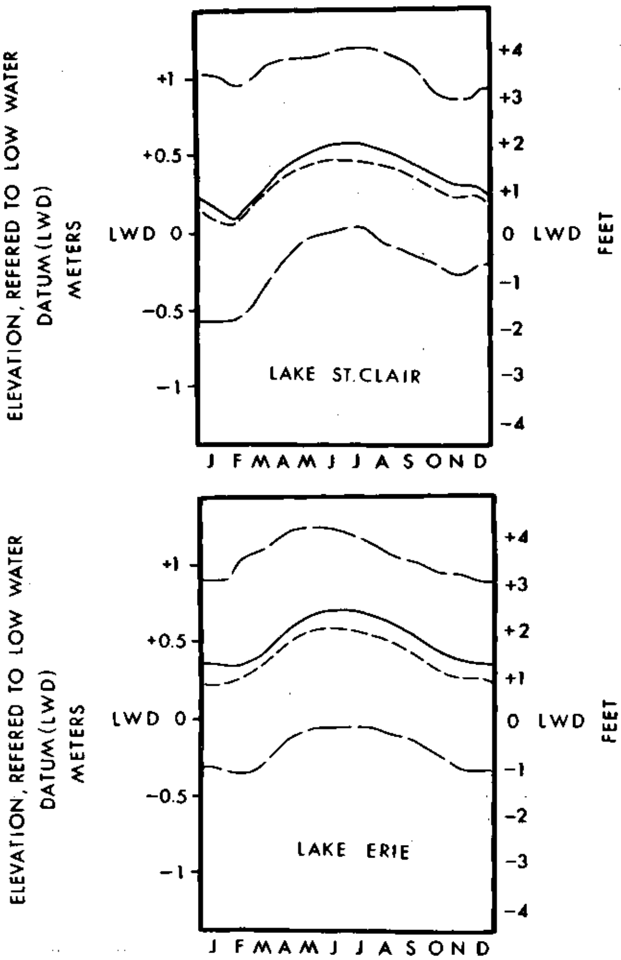

FIGURE 4–29 Average Monthly Lake Levels for Lakes St. Clair and Erie for the Periods of Record (1860–1970, Erie; and 1898–1970, St. Clair) (solid line), and for the Period 1960–1970 (short-dashed line). Long-dashed lines represent the monthly all-time maximum and minimum lake levels.

of a bird-foot delta at the mouth of the St. Clair River.

The shoreline of Lake St. Clair is low and marshy. The delta is a scenic, swampy area, portions of which serve as a large wildlife refuge.

There are no major diversions into or out of Lake St. Clair and it has only three major tributaries in addition to the St. Clair River (Table 4–5). Outflow from Lake St. Clair is through the Detroit River (Table 4–6). The average discharge is 5,400 m^3/s (190,000 cfs).

2.3.5 Lake Erie

Lake Erie has recently become the focus of much attention because of deterioration in lake water quality. Many of the problems of Lake Erie exist because the lake is the shallowest of the Great Lakes and has the least volume. The surface area of the lake is 25,657 km^2 (4,980 mi^2) LWD, and its volume is 483 km^3 (116 mi^3) LWD. Figures 4–28 and 4–29 give other pertinent physical data on Lake Erie.

Lake Erie has three major physiographic provinces. The western basin is a shallow platform separated from the central basin by an escarpment that extends from Point Pelee, Ontario, to Marblehead, Ohio, and runs east of the islands southwest of Point Pelee. The islands at the eastern end of the western basin are a result of differential erosion of resistant Silurian and Devonian carbonates (Figure 4–8). The central basin is somewhat deeper than the western basin and is a rather featureless plain underlain by shale. The central basin is separated from the eastern basin by a sand and gravel ridge that extends south from the base of Long Point, Ontario, to Erie, Pennsylvania. The eastern basin is the deepest of the three basins and contains organic muds and silty clays. Sediment distribution is discussed in Section 9.

Most of the shoreline of Lake Erie consists of low, marshy coast or high bluffs of clay-rich glacial sediment or shale. The strandline in these areas consists of narrow, muddy or cobbled beaches. In areas where there is an abundance of sandy material, sandy points and bars such as Point Pelee, Long Point, Presque Isle, and Cedar Point have been formed.

The major tributaries and their average discharges into Lake Erie are shown in Table 4–5. There are two diversions of water out of Lake Erie: the Welland Canal and the New York State Barge Canal. Average withdrawal into the Welland Canal System is 198 m^3/s (7,000 cfs). The diversion through the New York State Canal System averages 20 m^3/s (700 cfs), an insignificant amount. The natural outlet of Lake Erie is the Niagara River, which has a length of 60 km (37 mi), a total drop of 99.3 m (325.8 ft), and an average discharge of 5,700 m^3/s (202,000 cfs).

2.3.6 Lake Ontario

Lake Ontario is the fourth largest of the Great Lakes, with an area of 19,000 km^2 (7,340 mi^2) LWD and a volume of 1,637 km^3 (393 mi^3) LWD (Figure 4–30).

The Lake Ontario bottom consists of two basins, separated by an indistinct sill that ex-

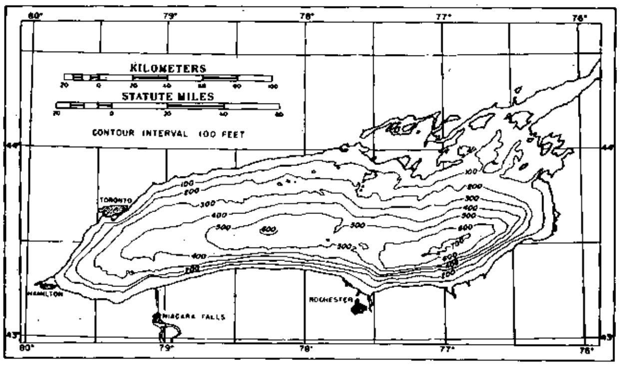

FIGURE 4–30 Physical Characteristics of Lake Ontario

Figure from Hough, 1958

	Metric	Standard
Low water datum (LWD):	74.0 m	242.8 ft
Length:	311 km	193 mi
Breadth:	85 km	53 mi
Shoreline length:	1,168 km	726 mi
Total surface area:	19,000 km^2	7,340 mi^2
Surface area in U.S.:	8,960 km^2	3,460 mi^2
Volume at LWD:	1,637 km^3	393 mi^3
Average depth below LWD:	86 m	283 ft
Maximum depth below LWD:	245 m	802 ft
Average surface elevation (IGLD):	74.65 m	244.77 ft
Maximum surface elevation (IGLD):	75.66 m	248.06 ft
Minimum surface elevation (IGLD):	73.64 m	241.45 ft

tends north of Rochester, N.Y. (Figure 4–30). The configuration of the basin reflects the structural attitude of the Paleozoic strata which dip to the south, away from the Algonquin Arch (Figure 4–3). Because of the differential erosion of the southward dipping beds, the floor of the lake drops away from shore gently on the northern side and abruptly on the southern side.

The shoreline of Lake Ontario consists of cliffs of varying heights. The bluffs are interrupted by embayments that are drowned valleys of streams that fed Lake Ontario when it was at a lower level. Beaches are poorly developed along most of the shore. The embayments often serve as traps for sand-sized sediment that is transported eastward by littoral drift. For this reason the embayments often have bay-head or bay-mouth bars.

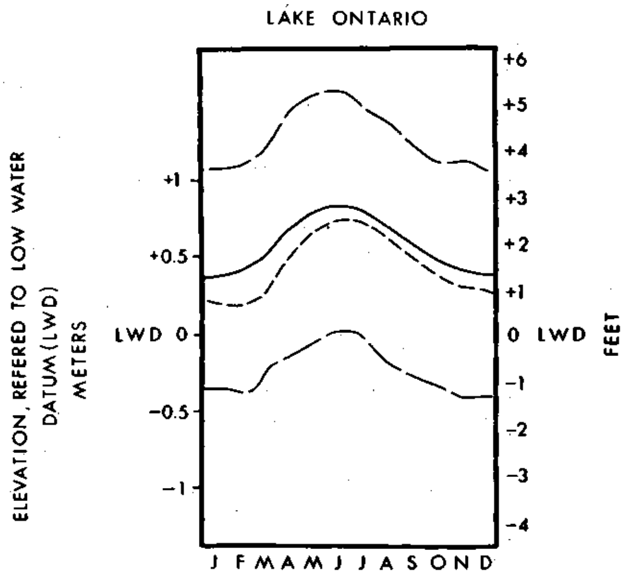

FIGURE 4–31 Average Monthly Lake Levels for Lake Ontario for the Period 1860–1970 (solid line), and for the Period 1960–1970 (short-dashed line). Long-dashed lines represent the monthly all-time maximum and minimum lake levels.

Lake Ontario has the lowest level of all of the Great Lakes at 74.0 m (242.8 ft) IGLD (Figure 4–31). The major tributaries to Lake Ontario are shown in Table 4–5. There are no major diversions of water out of the lake. The Welland Canal and New York State Barge Canal empty water into the lake from Lake Erie. The New York State Barge Canal System discharges into Lake Ontario through the Genesee and Oswego Rivers. Outflow from Lake Ontario is through the St. Lawrence River.

Section 3

PHYSICAL CHARACTERISTICS

Arthur P. Pinsak

3.1 Introduction

Physical properties of water are fundamental to the study of basin climate, precipitation, evaporation, water circulation and waves, stratification, energy and water budgets, ice formation and decay, sedimentation, distribution of suspended and dissolved materials, chemical reactions and interactions, biological productivity, variety and distribution of organisms within the environment, capability to assimilate inputs, eutrophication, and commercial and recreational uses. Inasmuch as these applications are universal and are developed and treated in other sections of this appendix and other volumes of the Framework Study, this section will review only the basic aspects of these properties.

The physical characteristics of water depend primarily on temperature and pressure. For example, density is affected by the temperature, pressure, and chemical composition of the water. However, in discussing thermal characteristics, we cannot restrict ourselves to a general category such as actual water temperature; rather we must consider more particular factors such as specific heat, coefficient of thermal conductivity, coefficient of eddy conductivity, and latent heats of fusion and vaporization. Electrical conductance is also a significant property used in water analyses.

Water transparency is extremely significant because it affects, through attenuation of incident radiation, temperature, heat storage and loss, photosynthesis, chemical reactions, evaporation, weather modification, and lake circulation.

3.2 Pressure

Although virtually all properties of water are affected by pressure it is not as significant as temperature. Applications in the Great Lakes are normally in detailed density analyses related to lake circulation but not in use or management programs. The basic unit is dynes/cm^2 with atmospheric pressure equal to 1 million of these units or 1 bar (1,000 millibars). For the convenience of workable units, atmospheric pressure is commonly expressed in millibars and approximates 1000 millibars. A decibar, equivalent to approximately 1½ lb/in^2, is used in the measure of water density: it is one-tenth of atmospheric pressure and is essentially equal to number of meters depth. Each ten meters of depth then represents a change of approximately one atmosphere, that is, 1000 millibars or 15 lb/in^2. The effect of pressure on temperature of water at maximum density reduces this temperature approximately 0.1°C/100 meters depth. For example, under stable thermal conditions, water at 300 meters and maximum density would have a temperature of about 3.7°C instead of 4°C, which is the usual temperature of water at maximum density.

3.3 Density

Most compounds and elements reach their maximum density in the solid state. Water, however, reaches maximum density while still in the liquid state at 3.98°C, and actually decreases in density as it cools from this temperature to its freezing point at 0°C (Figure 4-32).

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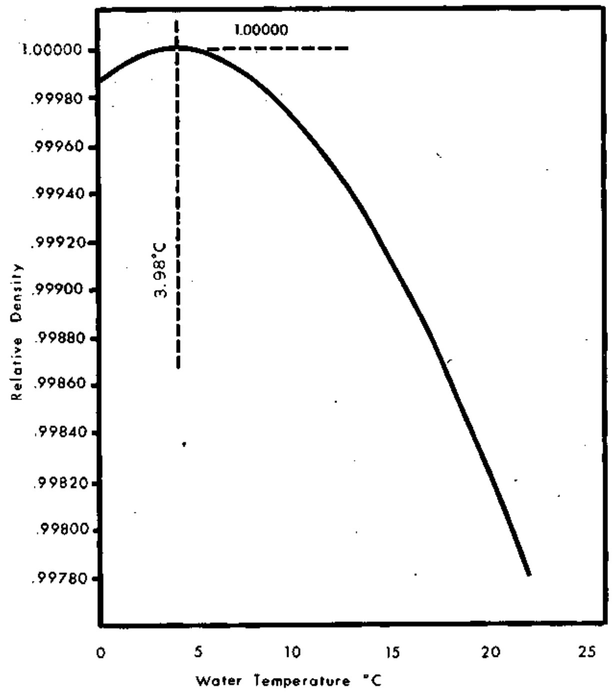

FIGURE 4–32 Water Density-Temperature Relationship at Atmospheric Pressure

This characteristic accounts for the seasonal physical changes that a lake undergoes in the temperate zone and aids in assimilation and regeneration. In response to annual weather variations that cause the water temperature to range above and below 4°C, the Great Lakes stratify with either overlying cold or warm water, they become isothermal, they mix more or less completely throughout their total depth, and they are prevented from freezing to the bottom. In winter the lakes become isothermal between 8°C and 4°C, and then surface cooling takes place until an ice cover is formed. This aspect of density is more fully developed in Subsections 3.4 and 3.6.

Changes in temperature and density of lake water are neither horizontally nor vertically uniform. Ayers,[26] using a technique usually applied to oceans, used the relationship between these spatial differences and the resulting geopotential topography of the lake surface to estimate current direction and magnitude. Net change in length of segments of a water column resulting from compression due to hydrostatic pressure of overlying water and expansion due to temperatures above or below 4°C was determined. Addition of this length change to the theoretical length of the column under standard conditions gives the calculated height of the column above an arbitrary reference level under the prevailing conditions of pressure and temperature. The differing heights of the columns at various geographic locations produce a topography or relief of the water surface. From this dynamic or geopotential topography current directions and velocities can be obtained. The reference level for such determinations in the oceans is the depth at which no movement exists. The fact that no such layer exists in the lakes makes the application of this method questionable. Thermally driven circulation is discussed further in Section 6.

When tributary influx is warmer than the lake water in spring and early summer, this warmer water with its dissolved and suspended solids floats across the cooler, more dense, lake water. In fall and early winter tributaries cool more rapidly than the lakes, and this denser mass plunges under the surface water and disperses along the lake bottom.

3.4 Thermal Properties

3.4.1 Specific Heat

Specific heat is the amount of heat required to raise the temperature of one gram of a substance 1°C. Water has the highest specific heat of any known liquid or solid except liquid ammonia. Because of this property, water can store great quantities of heat and is relatively resistant to short-term changes in temperature. Consequently large water bodies temper adjacent climatic extremes resulting in less change on the lee of the lake than in land areas farther removed.

3.4.2 Thermal Conductivity

Thermal conductivity is expressed as the time rate of transfer of heat across a unit distance. Even though this property is higher in water than in any other liquid, water is considered a poor conductor in comparison with solids. Thermal conductivity of glass is approximately 17 times greater than that of water and thermal conductivity of sandstone can be as much as 45 times greater. Thermal conductivity as a mode of heat transfer in water is normally of no consequence in nature because it is a measure of transfer through still water, a condition that normally does not exist and is insignificant compared to amount of heat transferred through laminar flow or turbulence. Turbulent flow and laminar flow are expressed in terms of the eddy coefficient which may be as much as 10^6 times greater than the coefficient of thermal conductivity.

The high specific heat and low thermal conductivity impart to water its outstanding capability to maintain identity of individual masses and to transfer heat by movement, thereby influencing mixing, stratification, circulation, and local climate.

3.4.3 Viscosity

Resistance of a fluid to a change in form or resistance to flow, both of which could be considered as functions of internal friction, is a measure of its viscosity. This force is expressed as dyne-seconds/cm². As temperature increases, viscosity decreases. Although water is most dense at about 4°C, its viscosity continues to increase as density decreases to 0°C. Viscosity is a relatively small physical force (0.01002 dyne-seconds/cm² at 20°C), but it is a significant property. The most important characteristic of viscosity in natural waters is that the change is not linear; rather, the gradient becomes increasingly steeper in the temperature range below 10°C and influences accelerated mixing that occurs below that temperature. Viscosity is a significant variable in turbulent transport, stratification, and in evaporation.

3.4.4 Turbulent Mixing

Turbulent mixing, considered to be the major mechanism in transfer of heat through a large body of water, derives from physical properties of the water itself in portions other than the boundary layers. The Reynolds number, $R = \rho vl/\mu$, is a geneal criterion applied to hydraulic properties of water that relates density (ρ), velocity (v), and viscosity (μ) to laminar flow and turbulent mixing. The letter (l) is length or depth. Laminar flow occurs below and turbulent mixing above a certain critical value. A number R = 310 has been cited (Hutchinson[402]) as the boundary above which turbulent mixing is initiated in a shallow lake. Viscosity (μ) and density (ρ) decrease with increasing temperature, and thereby a proportionally decreasing velocity (v) is required to maintain this threshold number. A steep temperature gradient, therefore, could be enough to produce a layer with turbulent flow overlying one with laminar flow. The critical or most sensitive temperature other than that of maximum density is at 10°C; this is the point at which the slope of both the density and viscosity curves change most abruptly. At a temperature of 10°C and Reynolds number 310, v = .015 cm/sec, a very low threshold velocity that obviously would preclude turbulent mixing as a significant factor below this boundary value.

An expression based on Fick's Law, which gives the rate of diffusion of a solute in an undisturbed solution, is commonly used for diffusion of heat by turbulent processes. It can be stated as:

$$d\Theta_z/dt = -c_p \, \rho \, A d\theta_z/dz$$

This rather straightforward relationship correlates the coefficient of eddy conductivity or turbulent transport (A) with change in heat storage ($d\Theta_z$) during a period of time (dt), temperature gradient ($d\theta_z/dz$) at depth (z), specific heat (c_p), and density (ρ) of the water. Although it is true that variations in c_p and ρ are much less than error in temperature determination, these two terms are significant in turbulent transport inasmuch as they are the controlling physical variables. The relation to temperature structure is only an indirect expression of these variables. Coefficient of turbulent transport is inversely related to change in heat storage and is directly related to temperature gradient. The lowest values for this coefficient indicate the greatest degree of stability of the water; all of these factors are exemplified in the thermocline. Conversely, the highest values indicate the least thermal stability as exemplified in the epilimnion.

3.4.5 Heats of Fusion and Vaporization

Latent heats of fusion and vaporization are defined as the energy required to change a substance from the liquid phase to the solid or vapor phase with no temperature change. The latent heats of fusion (80 cal/gm) and vaporization (595 cal/gm) of water are among the highest of all substances. This property exerts a buffering effect on interactions between air and water. The high energy input required for vaporization coupled with concommitant evaporation loss and surface cooling would preclude such a phase change in nature. However, at the other extreme, formation of ice can be accomplished with a mechanism for transferring the excess heat such as a breeze or great temperature difference.

When atmosphere is warmer than hydrosphere, heat transfer causes the lowest air to cool and uppermost water to warm. This relationship represents stable atmospheric and hydrologic conditions so any heat transfer is by thermal conductivity. When atmosphere is colder than hydrosphere, heat transfer warms the lowest air and cools the uppermost water. This relationship creates instability which results in turbulent or eddy transfer with intensity directly related to temperature difference. Inasmuch as the eddy coefficient can be 10^6 times greater than the coefficient of thermal conductivity, the sensible exchange of heat from hydrosphere is much more significant under unstable conditions.

3.5 Electrical Properties

Conductance of electricity in water is attributed to the presence of positive and negative ions in solution. For all practical purposes pure water can be considered as electrically neutral; even though there is dissociation into H^+ and OH^- ions, this dissociation is so weak at normal temperatures that it is negligible. The greater the concentration of salts, acids, or bases in the weak solutions encountered in natural waters, the greater the electrical conductance. Thus conductance is presumed to be proportional to the ion concentration.

Even though compounds ionize differently depending on their ionization constants, classes of water such as the Great Lakes are similar enough in their basic composition that variations in capability to conduct electricity can be used to indicate variations in concentration of dissolved substances. For natural waters the specific conductance, expressed in micromhos and multiplied by a factor of 0.65, is generally considered to approximate the concentration of dissolved substances in milligrams per liter. This factor is only an average because the conductance of a solution is dependent on the type and total quantity of ions in solution. More precise relations can be developed for specific water types. The factor of 0.65 is applicable only with comparatively dilute solutions and usually increases as the total dissolved-salt content exceeds 2,000 to 3,000 mg/l. For waters that contain significant concentrations of free acid, caustic alkalinity, or sodium chloride, the factor may be much less than 0.65. Pure sodium chloride solution, for example, has a factor of 0.50. The factor for other types of water may range to 0.80. Areal variations in specific conductance (Figure 4–33) conform generally with those of each of

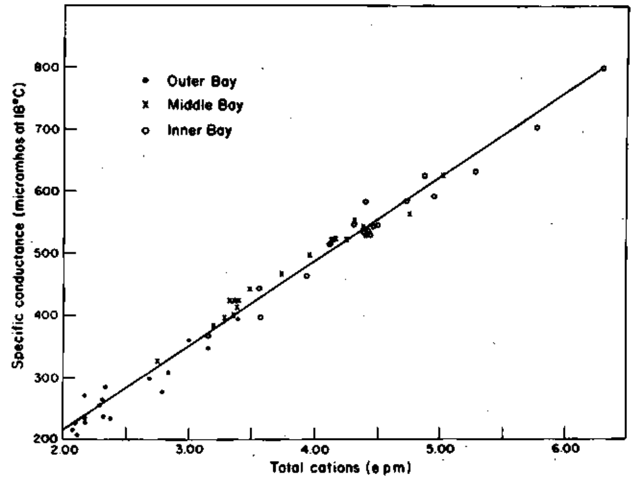

FIGURE 4–33 Relationship Between Specific Conductance and Total Cation Concentrations in Saginaw Bay, June 7, 1956

Beeton et al., 1967

the constituents (Figure 4–34). Deviations from this general pattern can indicate source points and sinks by emphasizing concentration of individual constituents. The specific conductance and dissolved ion concentration measured in each of the Great Lakes are increasing. On a long-term basis conductivity in the lower lakes is increasing due to the increased cultural input in the southern portion of the basin (Figure 4–35), and because dissolved ion content of the lower lakes is naturally higher due to continued enrichment as the water moves through the system at a rate slower than the input rate. Conductivity in the upper lakes is increasing at a slower rate in relation to input and volume (Figure 4–128, Subsection 7.5.1). On a shorter time scale seasonal fluctuations in specific conductance also occur (Figure 4–36). The greatest amounts of dissolved solids enter the system during the periods of heavy tributary influx in spring and fall. These disolved solids are diluted upon entry into the lake. Therefore, sensitivity to change relates to volume of the receiving body. Because vibrations after dilution in the receiving body are so slight, the increment of change, on a short-term basis, must be calculated from tributary influx.

Although the measurement is not sensitive to organic constituents nor to trace metals that may be present, specific conductance is a good pollution indicator. It easily identifies areas of high dissolved ion content which are usually associated with sources of pollution so that more detailed analysis of the areas in question may be initiated.

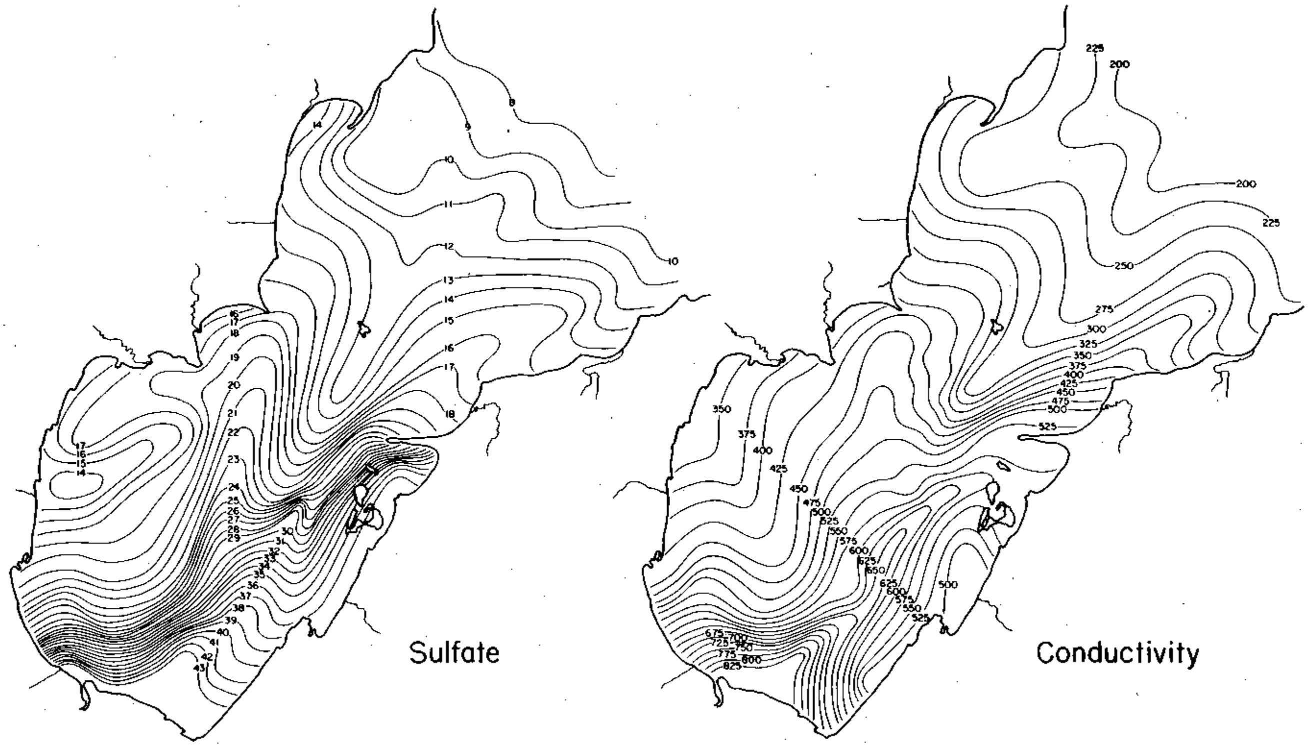

FIGURE 4–34 Distribution of Sulfate (ppm) and Conductivity (μmhos/18°C) in Saginaw Bay, June 7, 1956

Beeton et al., 1967

3.6 Temperature

Water temperature is a characteristic of primary concern in most lake investigations. In addition to the control of biology and chemistry of lakes it is fundamental in water storage, energy budget, lake circulation, and flushing and diffusion studies. A general discussion of water surface temperatures, with presentation of average monthly and annual values (Table 4–16, Subsection 4.9.1) and the seasonal cycle of water temperature profiles (Figure 4–96, Subsection 4.5.2) is included in Section 4, Hydrometeorology. Mechanics of vertical temperature distribution, including a description of the annual cycle of density distribution and thermal stratification, are discussed in Section 6, Internal Water Motions.

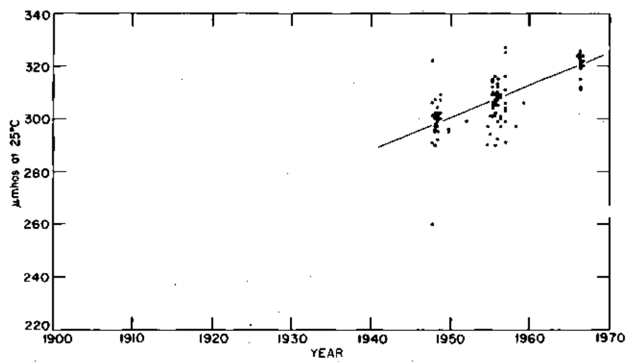

FIGURE 4–35 Specific Conductance of Lake Ontario Water versus Time

Dobson, 1967

3.6.1 Areal Variation

Great Lakes water temperatures vary primarily with latitude and lake depths. Insolation, the prime heat source, decreases with increasing distance from the equator providing less heat input and consequently lower water temperatures. The lake depths, a function of lake volume, control lake heat storage capacity. Deep lakes or deep portions of lakes warm more slowly during the warming season than shallow lakes, but because of their greater heat storage capacity they cool more slowly during the cooling season thereby causing lag in these annual cycles that results in phase differences between each of the lakes. Because of decreasing insolation with increasing latitude, temperatures in the open-water portions of the lakes are progressively lower

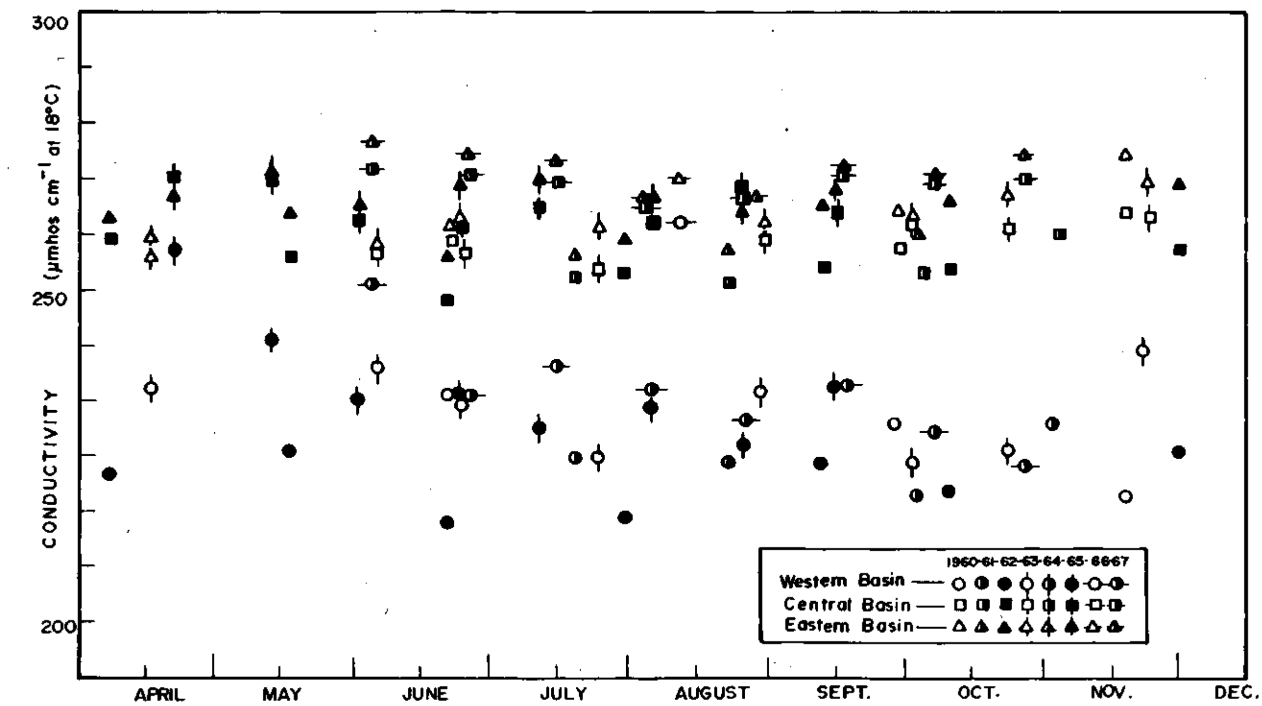

FIGURE 4–36 Average Conductivity in the Three Basins of Lake Erie for the Period 1960–1967

Weiler and Chawla, 1968

from south to north. Because of differences in storage capacity coupled with thermal properties of the water, temperature in the shallow coastal waters increases offshore during winter and inshore during summer.

Superimposed on this broad temperature distribution is the effect of mixing of the water masses induced by wind, the primary driving force in lake circulation. Wind-induced mixing of lake water is both vertical and horizontal. Wind-driven circulation produces sinking of the surface water on the windward shores and upwelling of the bottom water on the lee shores. Because winds in the Great Lakes Region are predominantly from the west during the warm season, sinking or concentration of warm water normally occurs along the eastern shores and upwelling of colder water occurs along the western shores.

Great Lakes water temperature records extend back to the latter part of the nineteenth century, but most of these early records are sporadic and are based on measurements taken along the shores, which makes them of little value for the construction of temperature distribution. Open-lake measurements were made initially by utilizing ships-of-opportunity, but these were taken at various depths depending on the draft of the ship. Present water temperature measurements are obtained through systematic surveys conducted by research vessels, and surface temperatures are obtained by satellites and by aircraft employing remote sensing radiometers. These types of surveys have been in progress for little more than a decade. Although they cannot be used to establish trends, they represent a substantial accumulation of usable water temperature data for investigation of processes.

Studies dealing with water temperature distribution are relatively common. However, the majority of these studies are limited both in scope and in time. Because of mobility of water masses and cyclical variations these short-period studies of restricted extent may suggest erroneous trends and projections. Mean water temperature distribution for all the lakes, based on records of several years were compiled by Millar.[543] Results are revealing but are limited because they are based only on surface or near-surface temperature. No report based on in-depth measurements that might be correlated with these Basinwide surface measurements is presently available. Millar developed temperature distributions by months for the entire year on Lake Ontario and for the ice-free season on all other lakes. His period of record covered 1935 to 1946 for Lake Ontario and 1935 to 1941 for the other

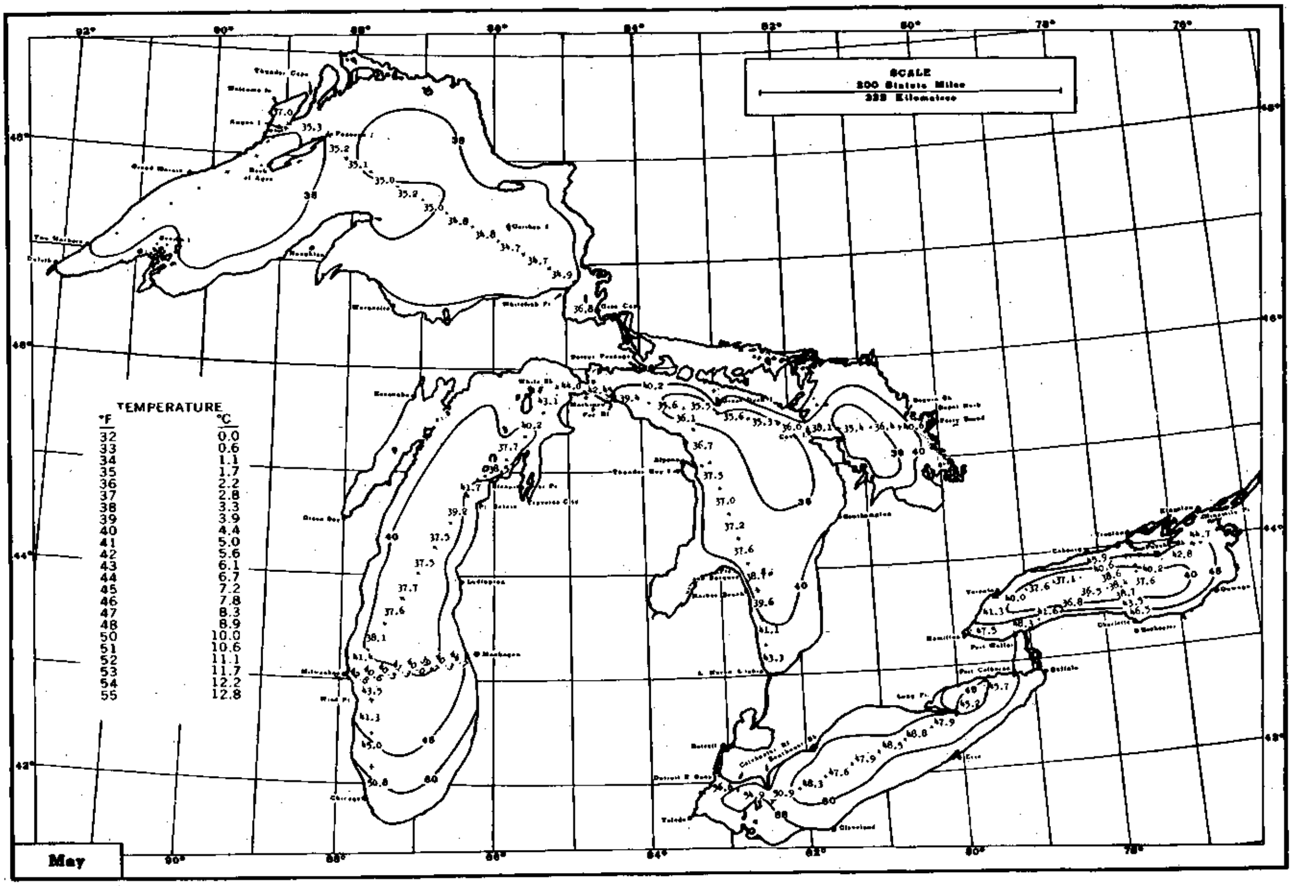

FIGURE 4–37 Distribution of Mean Surface Water Temperature (°F) in the Great Lakes in May
From Millar, 1952

lakes. May, August, and November (Figures 4–37, 4–38, and 4–39) represent spring, summer, and fall, respectively.

The range of variation in the mean water surface temperature of the Great Lakes reflects seasonal changes, differences in latitude, and variations in lake depths. Thus, during the spring warming season (Figure 4–37), while most of Lake Erie and the southern portion of Lake Michigan exceed 10°C (50°F), Lake Superior does not indicate any substantial warming and remains at a winter temperature of approximately 2°C (35°F). Much of this difference is due to the higher heat input in the south, but also the relatively shallow Lake Erie warms more rapidly than deep Lake Superior. Mean surface temperatures on Lakes Ontario and Huron, and on the northern two-thirds of Lake Michigan, which are at intermediate latitudes and have intermediate depths, indicate some warming, but they rarely exceed 5°C (41°F) at this time of the year.

The highest variation in the mean water temperature on the lakes occurs during midsummer (Figure 4–38) when the lakes attain highest surface temperatures. Lake Erie mean temperatures are rather uniform, varying from 22°C to 23°C (72°F to 74°F). Surface temperatures on Lakes Michigan and Huron decrease progressively northward, from 22°C to 21°C (72°F to 70°F) in the south to 18°C to 19°C (65°F to 66°F) in the north. Summer temperatures on Lake Superior attain only 16°C (61°F) along the shore, then decrease offshore to less than 8°C (46°F) in mid-lake.

In the fall (Figure 4–38), the range of variation in the mean surface temperature of the Great Lakes is reduced sharply. This is a period of instability in which hypolimnetic cooling predominates. Lake Erie is still the warmest of the lakes because it has the smallest hypolimnion to supply cold water; most of the lake surface is at approximately 10°C (50°F). Other lakes also have relatively uniform temperature. In Lake Michigan surface temperature varies between 9°C (48°F) in the southeast and 7°C (45°F) in the southern

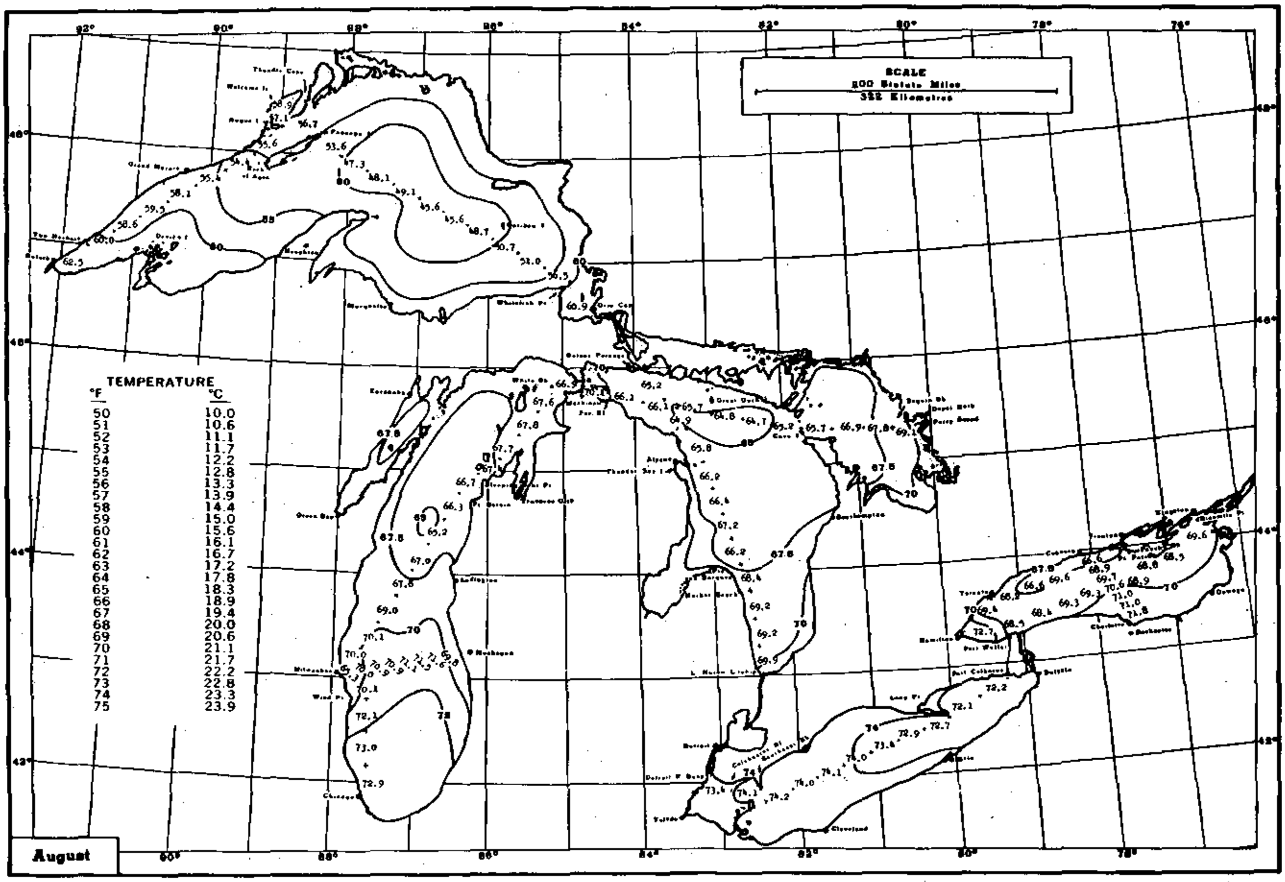

FIGURE 4–38 Distribution of Mean Surface Water Temperature (°F) in the Great Lakes in August
From Millar, 1952

extreme to 6°C (43°F) in the north. In Lake Ontario surface temperature decreases generally from east to west, from a high of approximately 9°C (48°F) to less than 5°C (41°F) at the western tip of the lake. Lake Superior is at approximately 5°C (41°F) in the eastern two-thirds and slightly more than 5°C in the western one-third of the lake, which contains less hypolimnetic water to cool the surface during mixing. The lakes are all out of phase during the heating and cooling cycles due to their different volumes and locations.

Obviously surface temperature distribution during late winter has the lowest variation. The mean water surface temperatures on the lakes vary from 0°C (32°F) along the shores and other areas with extensive ice cover to approximately 3°C (37°F) in open water areas associated with great depths. Most of the open water attains winter temperatures of approximately 2°C (35°F).

3.6.2 Vertical Variation

Vertical variation of Great Lakes water temperatures depends on solar heating, turbulent mixing and density stratification (Figure 4–96). Winds are the basic mixing mechanism, but turbulent transport created by physical differences related to water temperature is responsible for overall thermal structure.

The Great Lakes fit the definition of a dimictic lake (Hutchinson[402]) in which two complete cycles occur, one above and one below the temperature of maximum density. Inasmuch as a lake is not homogeneous, it cannot be simply characterized but rather must be depicted as the sum of all its component parts. Even though lakes may generally be the same, the major variables that impart peculiar characteristics to each are volume, depth, and geographic location. A dimictic lake is relatively

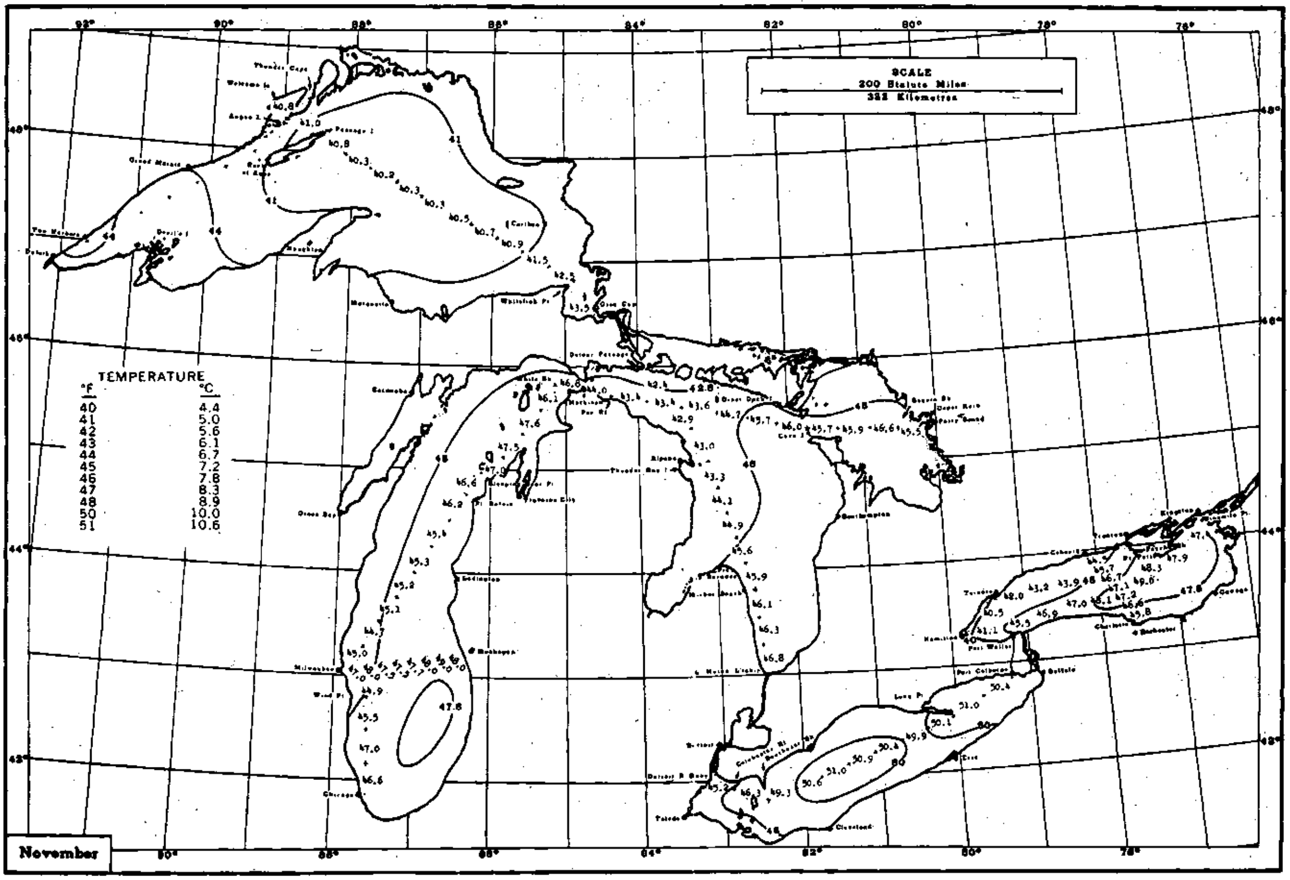

FIGURE 4–39 Distribution of Mean Surface Water Temperature (°F) in the Great Lakes in November

From Millar, 1952

cold in the spring; it progressively warms and separates into layers until autumn, at which time there is convergence of all layers at temperatures between 8°C and 9°C. The rate at which lower layers warm is determined by the volume-storage ratio. The basic difference in the warming pattern is that the upper level from 0 to 30 meters warms significantly and then reduces to the isothermal fall temperatures, whereas the temperature of the layers below 30 meters generally peak at that time and temperature. This basic difference relates directly to the development of stratification during summer. The lake thus can be divided into two basic elements coinciding with the position of the thermocline. These elements allow for realistic development of an annual thermal cycle. Lake Huron is used as a typical lake to illustrate this annual vertical variation (Figure 4–40). In this figure, zero on the ordinate represents the heat content of the lake at 4°C).

The epilimnion comprises 40 percent (1003 km^3) and the hypolimnion comprises 60 percent (1533 km^3) of the total volume of Lake Huron exclusive of Saginaw Bay, Georgian Bay, and North Channel. During the warming phase following ice breakup and the spring equinox, the deep lake water is colder than 4°C and is thus less than maximum density. The surface water warms past 4°C, becoming more dense than the deep water. This, in conjunction with wind stress, causes convection and weak turbulent mixing. By June the turbulent mixing has developed an isothermal condition to depth, at which time the lack of a density differential effectively isolates the hypolimnion from the rest of the lake. Heat input restricted to the less dense epilimnion causes the marked summer increase in storage in this layer and initiates formation of a thermocline directly below the water surface. The thermocline depresses rapidly to about 10 meters coincidental with warming of the hypolimnion to temperature of maximum density. In the middle of July the lake becomes stable. Excess heat entering the lake is transferred into the hypolimnion only by convection and by advec-

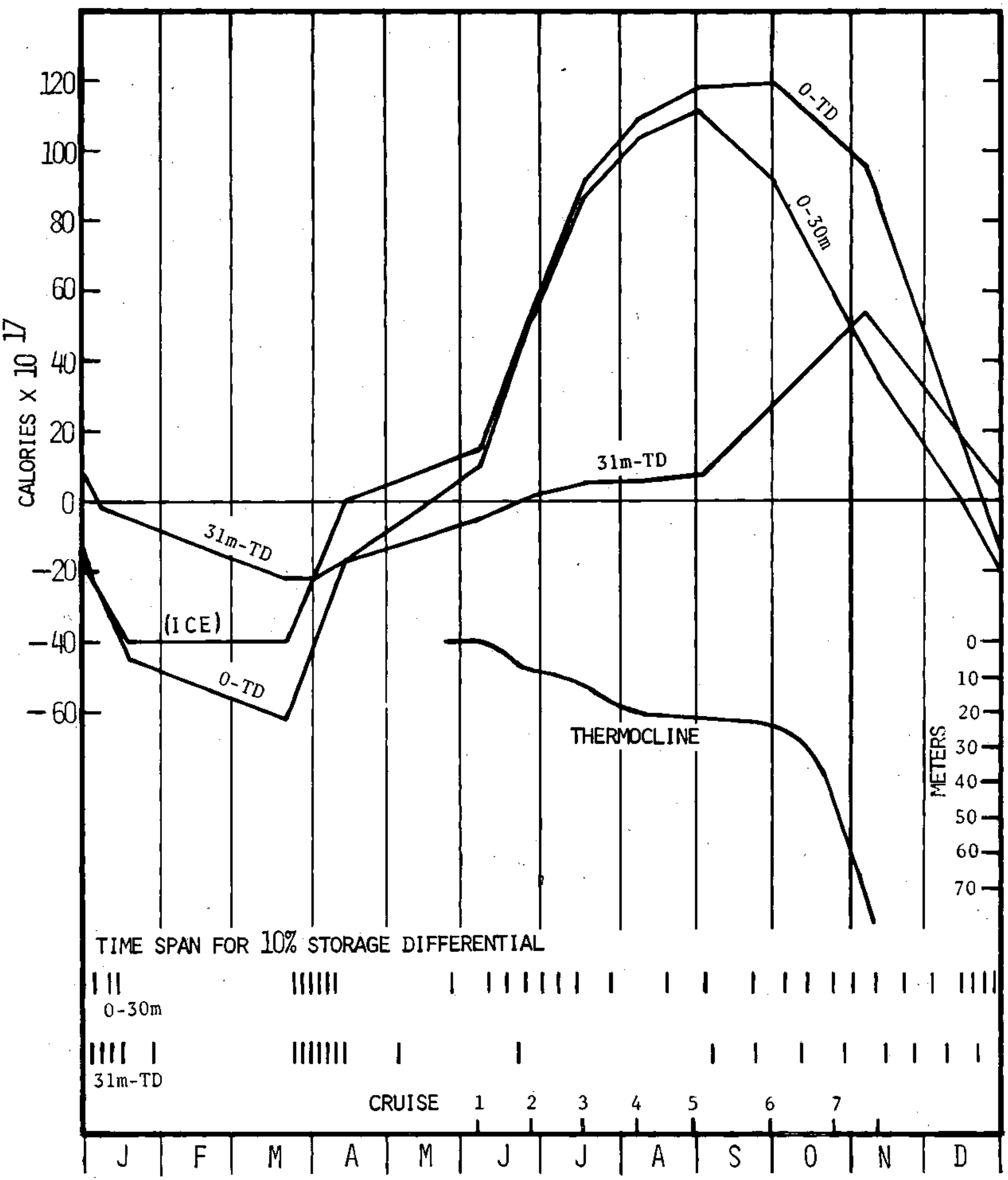

FIGURE 4–40 Seasonal Changes in the Thermal Structure of Lake Huron

Pinsak, 1970

tion resulting from the oscillating thermocline. Convection predominates; assuming an average gradient of 1°C/m through the thermocline, the advection term q = kGA amounts to 4 x 10^{14} cal/day or only about 10 percent of the total exchange during this time. The heat transfer increases the gradient of the thermocline while depressing it to 20 to 26 meters. Following the autumnal equinox the lake enters the cooling cycle. Even though heat loss

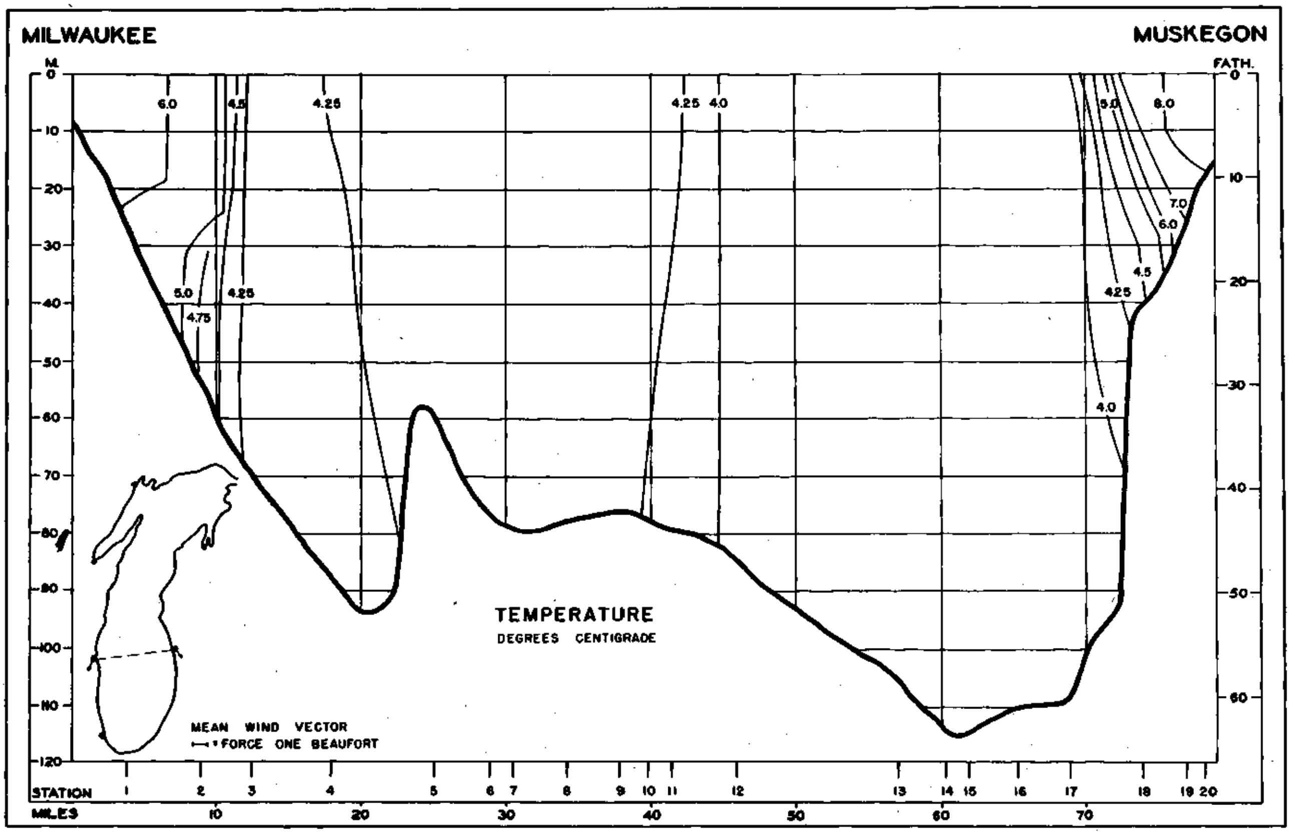

FIGURE 4–41 Lake Michigan Spring Temperature Distribution Between Milwaukee and Muskegon

From Church, 1945

from the epilimnion is extreme, averaging 46 percent during the month of October, the lake cools about 17 percent during the same period. About 20 percent of the loss is to the atmosphere and 80 percent is utilized in warming the hypolimnion. As a consequence of this warming the gradient of the thermocline is reduced, sharply decreasing the coefficient of turbulent transport and sharply lowering the boundary between thermocline and hypolimnion to about 50 meters. A most significant aspect of the annual thermal cycle occurs at the beginning of November. Density of the lower portion becomes less than that of the upper. The thermocline disappears completely and turbulent mixing takes place. Intensity of this critical episode is directly related to amount of heat available in the lake and indirectly related to volume of the hypolimnion.

In the study conducted, it was observed that the winter cycle began at about the time of the winter solstice. The lower part of the lake cooled to 4°C the first week in January. Then, the heat loss moved across the air-water interface until the ice sheet formed in mid-January. The lake then entered the stable winter phase with convective cooling of the lower portion, a function of intensity of the winter. This condition of winter stratification persisted until the warming surface water became more dense than deep water at the end of March and the lake again became weakly turbulent to depth until the summer cycle again was initiated with general warming to the temperature of maximum density.

In Figure 4–40, the heat loss during January to June is shown by the area between the 31 m-Total Depth curve and the zero line. This area is equal to area under the curve above the zero line during July to mid-December and truncated by the 0 to 30 m curve in November to December. Determination of the area of one could be used to forecast magnitude of storage gain or loss during the other half of the year.

Vertical variation of lake temperatures in Lake Michigan was reported by Church[142,143] based on 1941 to 1942 bathythermograph observations for the autumn to winter and spring to summer periods. Examples of temperature structure in spring, summer, fall and

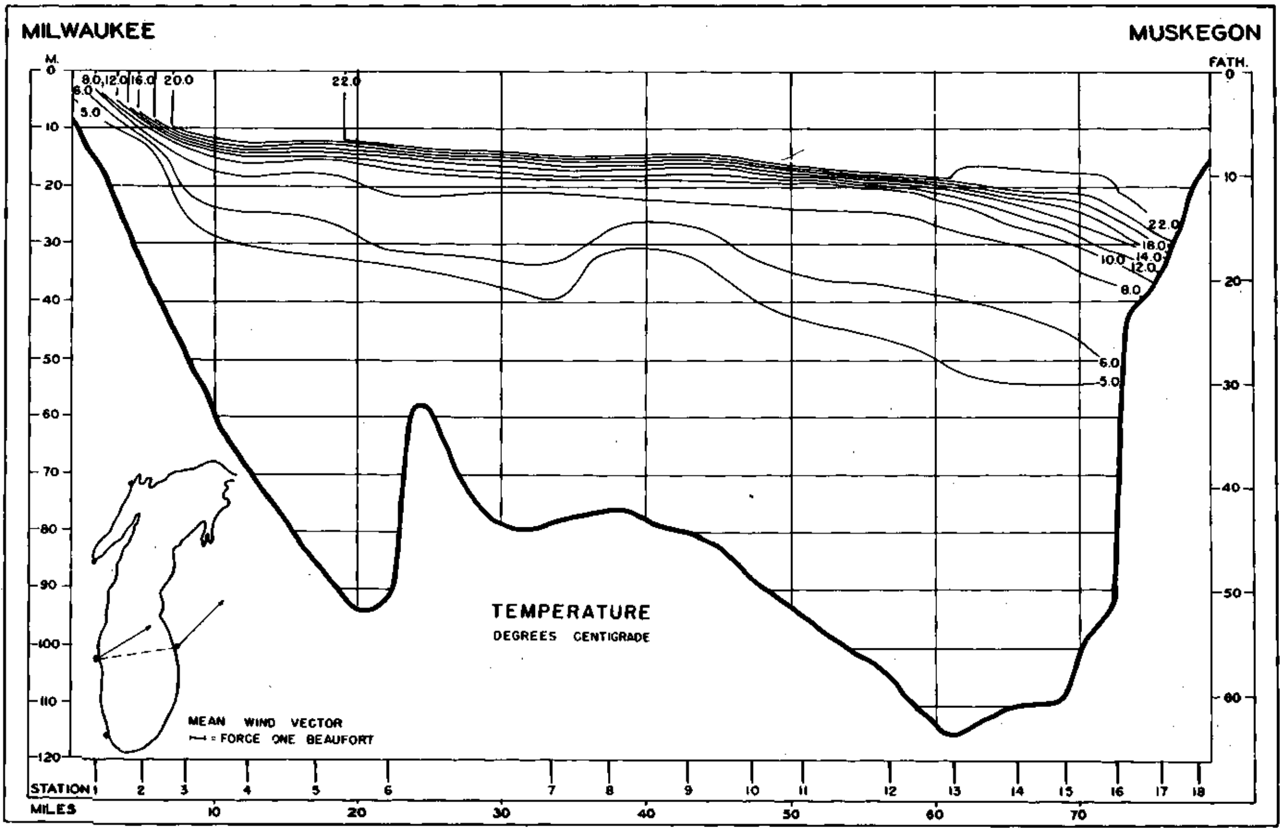

FIGURE 4–42 Lake Michigan Summer Temperature Distribution Between Milwaukee and Muskegon

From Church, 1945

winter (Figures 4–41, 4–42, 4–43, and 4–44) characterize only a cross-section of Lake Michigan between Milwaukee and Muskegon. However, they are similar to the seasonal temperature structure in other lakes with similar depths in temperate climatic zones.

During the spring (Figure 4–41), open lake water is almost isothermal to warming water close to shore. In mid-summer (Figure 4–42), the lake is stratified with a pronounced thermocline; water temperature varies from 22°C (72°F) at the surface to less than 8°C (46°F) below the thermocline, and then decreases to 4.5°C (40°F). Effect of wind stress on the thermocline is indicated by tilt of the thermocline surface with consequent upwelling caused by a westerly wind. By late fall (Figure 4–43), lake stratification has deteriorated preliminary to total mixing; 8°C (46°F) represents the least stable condition in which a lake tends toward an isothermal state. During late winter (Figure 4–43), the lake attains its low temperature. In a stable winter state deepest water should be slightly less than 4°C with colder, less dense surface water forming a stratified layer. The lake can only become isothermal below 4°C when there is extremely strong cooling from the top that causes a fully turbulent unstable state to exist.

3.6.3 Daily Variation

Lake surface water temperature responds to the daily cycle of insolation, which implies diurnal heating and cooling of the surface layer. During summer when day is longer than night heating exceeds cooling resulting in a net heat gain. Longer night than day in winter results in a net heat loss. When the air is colder or warmer than the water, turbulence is created at the interface resulting in so-called lake effect climatic modifications. These modifications are discussed in Section 4. Church[143] plotted mean daily change in water temperatures throughout the year at three depths in Lake Michigan (Figure 4–45); these typify the Great Lakes. As expected, the highest daily

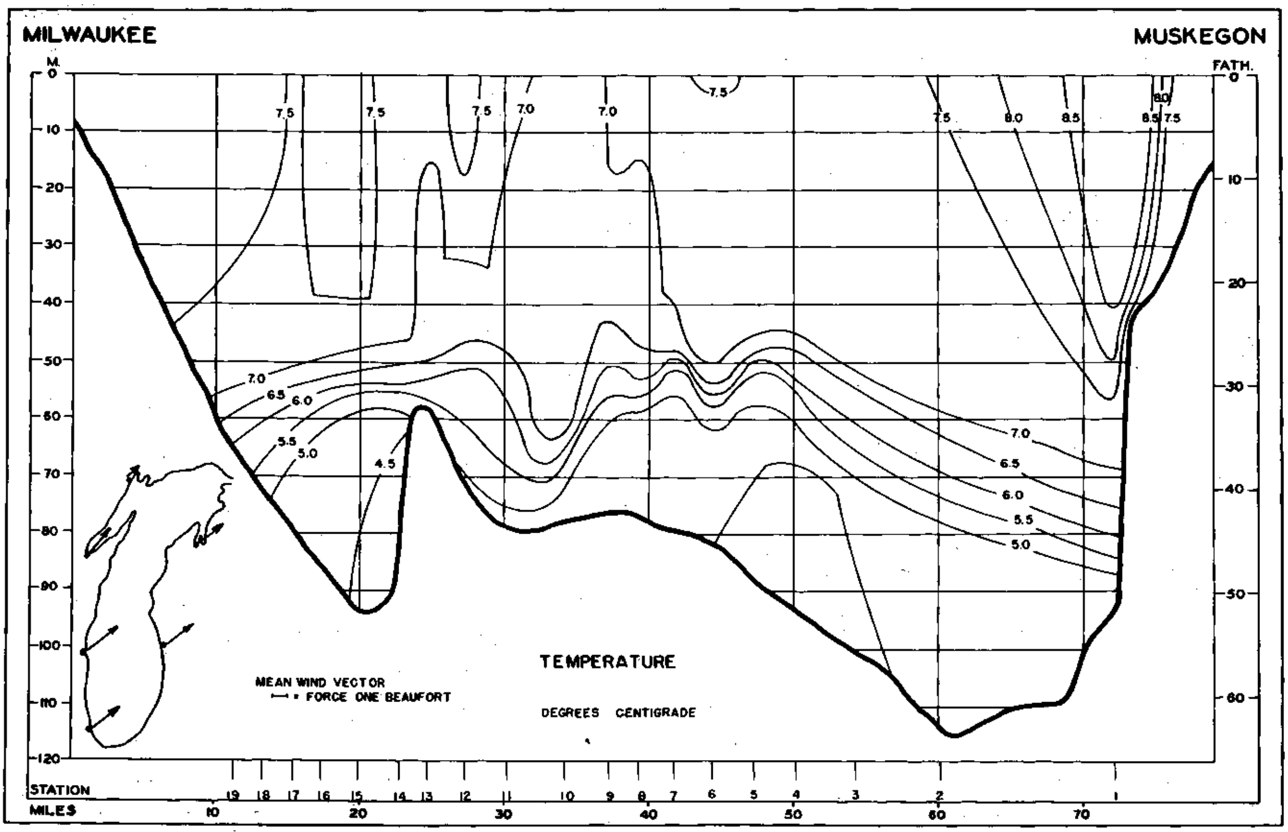

FIGURE 4–43 Lake Michigan Autumn Temperature Distribution Between Milwaukee and Muskegon

From Church, 1945

change occurs at the surface and decreases progressively downward because the bulk of the heat comes through the surface. The greatest positive change in the surface layer takes place during the summer period of maximum insolation, when the temperature increase may attain 0.4°C (0.7°F) per day. Negative temperature changes usually occur during winter, but the greatest decrease in surface temperatures is caused by increased turbulent mixing in fall when heat is transferred from the epilimnion to the hypolimnion rather than from the water to the air as the lake tends toward an isothermal state. A sustained wind in the first half of July (Figure 4–45) caused upwelling which reduced average surface temperature drastically and increased water temperature at the 40 m (130 ft) level; the increase at the 80 m (260 ft) level was only moderate. This phenomenon is common in the Great Lakes during summer.

In general, water temperature increases from the beginning of March through the beginning of July and decreases afterwards with slope of change relating to latitude (Figure 4–46). Irregularities in basic thermogram patterns may appear to be local or transitory, but some features recur from year to year and are persistent on records from different locations. For example, even though heat gain at Mackinaw City, Michigan, is 10 percent less than at Port Huron, Michigan, basic features are common to both and are evident in other thermograms around the lakes. The irregularity from mid-April to mid-June is the period of turbulent mixing during which the lake is trending toward a stable summer condition. Stratification after mid-June is indicated by the strong smooth gradients. The peak in mid-October marks the sharp subsidence of the thermocline. The sharp peak at about 8°C in early November marks the time that the upper part of the lake has cooled below the lower with initiation of turbulent mixing leading into the winter cycle.

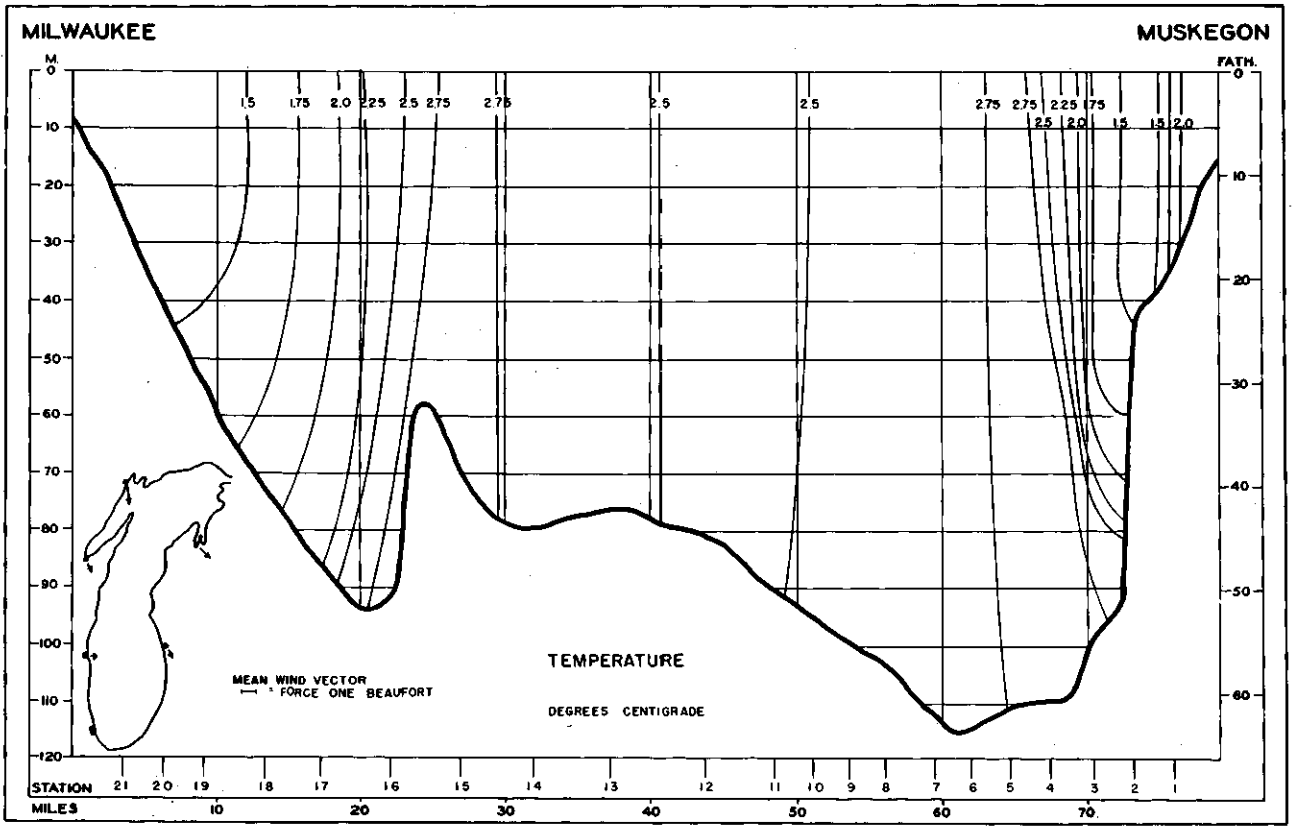

FIGURE 4–44 Lake Michigan Winter Temperature Distribution Between Milwaukee and Muskegon

From Church, 1945

3.6.4 Seasonal Variation

Because water temperature at all levels changes with the season, although at different rates for different depths, latitudes, and different times of year, seasonal variation of lake temperatures was discussed indirectly under preceding subsections. Maximum variation occurs at the surface, and the range throughout the year is about 20°C (36°F) for the lower lakes and about 15°C (27°F) for Lake Superior. The minimum range of variation of about 2°C (3.6°F) occurs at great depths.

Progression of surface temperature through an annual cycle based on a five year average of transects across each of the lakes (Millar[543]), illustrates intralake relationships, but it also points out the time-phase relationships on an interlake basis. It should be noted that temperatures exceed 10°C (50°F) only two months in the northernmost lake as contrasted with six month duration in the southernmost lake. Surface temperatures, although not representative of total lake temperatures nor adequate for budget estimates, at least depict changes in the epilimnion and indicate the maximum range of variations that can be expected in the water temperatures. Hypolimnion temperature lags behind the epilimnion both during heating and cooling. It is also less sensitive to short-term change.

3.6.5 Lake Superior

The annual variation of mean water surface temperature in Lake Superior (Figure 4–47), between Thunder Cape and Gros Cap (Ft. William and Sault Ste. Marie), ranges from about 0°C (32°F) to 2°C (35°F) during winter to more than 10°C (50°F) to 15°C (60°F) in the open water during summer. In open water, the winter minimum temperature is reached in mid-March and the summer maximum in early September. Along the shores these extremes are reached approximately a month sooner. This northernmost and deepest of the Great Lakes is the coldest, with offshore surface temperatures exceeding 10°C (50°F) only during two months of the year.

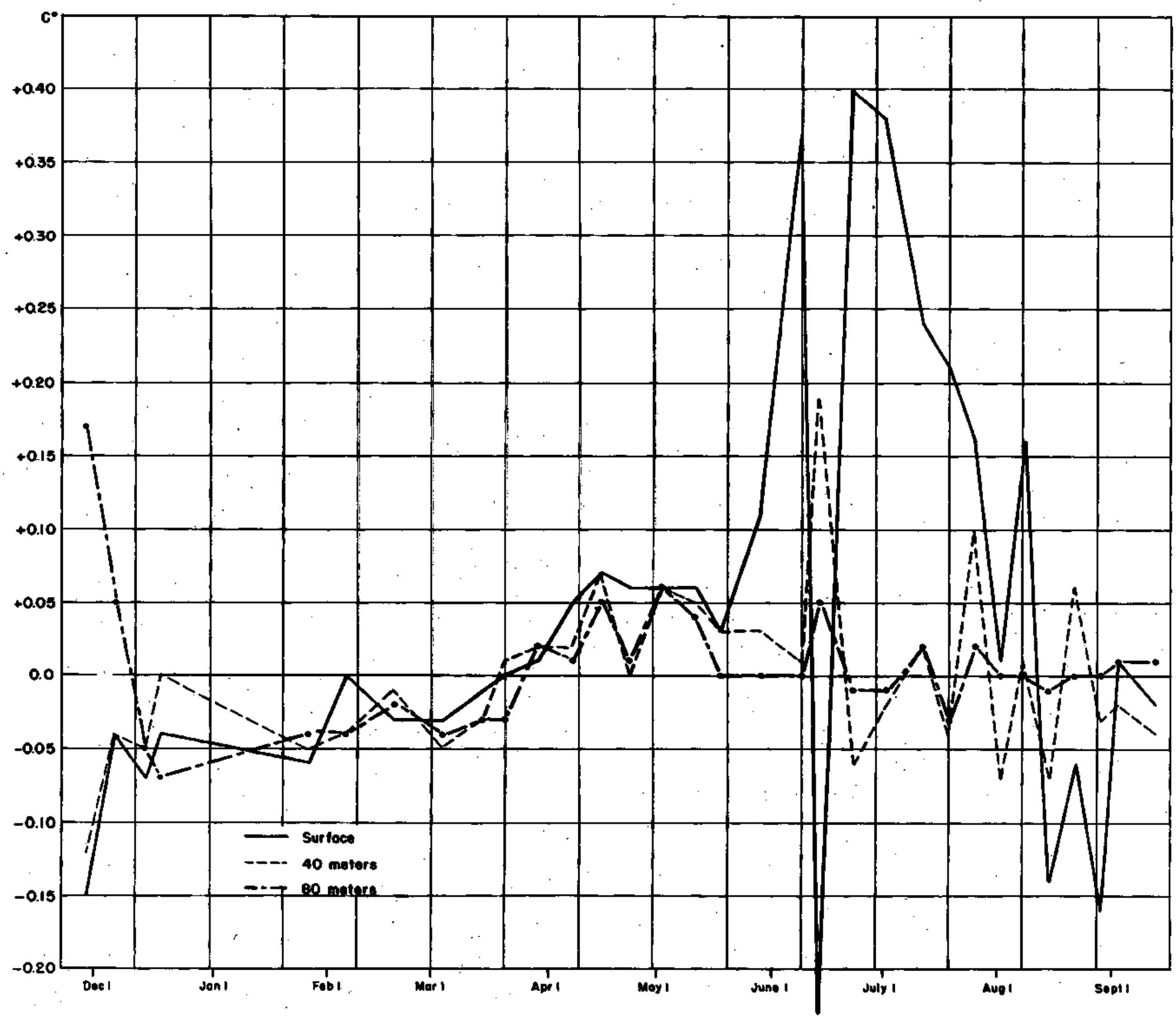

FIGURE 4–45 Daily Mean Change of Temperature for Various Water Depths Between Milwaukee and Muskegon

From Church, 1945

3.6.6 Lake Michigan

Mean water surface temperature in Lake Michigan (Figure 4–48), between Milwaukee and White Shoal (north of Beaver Island), varies from a winter low of approximately 2°C (35°F) to the summer high of 21°C (70°F). The winter minimum is generally reached during early March and the summer maximum during mid-August. Water temperature exceeds 10°C (50°F) from four to five months during the year, for both mid-lake and coastal waters.

3.6.7 Lake Huron

The mean water surface temperature variation in Lake Huron (Figure 4–49) along a north-south transect between the mouth of St. Marys River and Port Huron ranges from 2°C (35°F) during winter to 21°C (70°F) during summer. The winter minimum is reached during mid-February inshore and in mid-March in the open lake. The summer maximum is reached during mid-August. Water temperature exceeds 10°C (50°F) during five months in

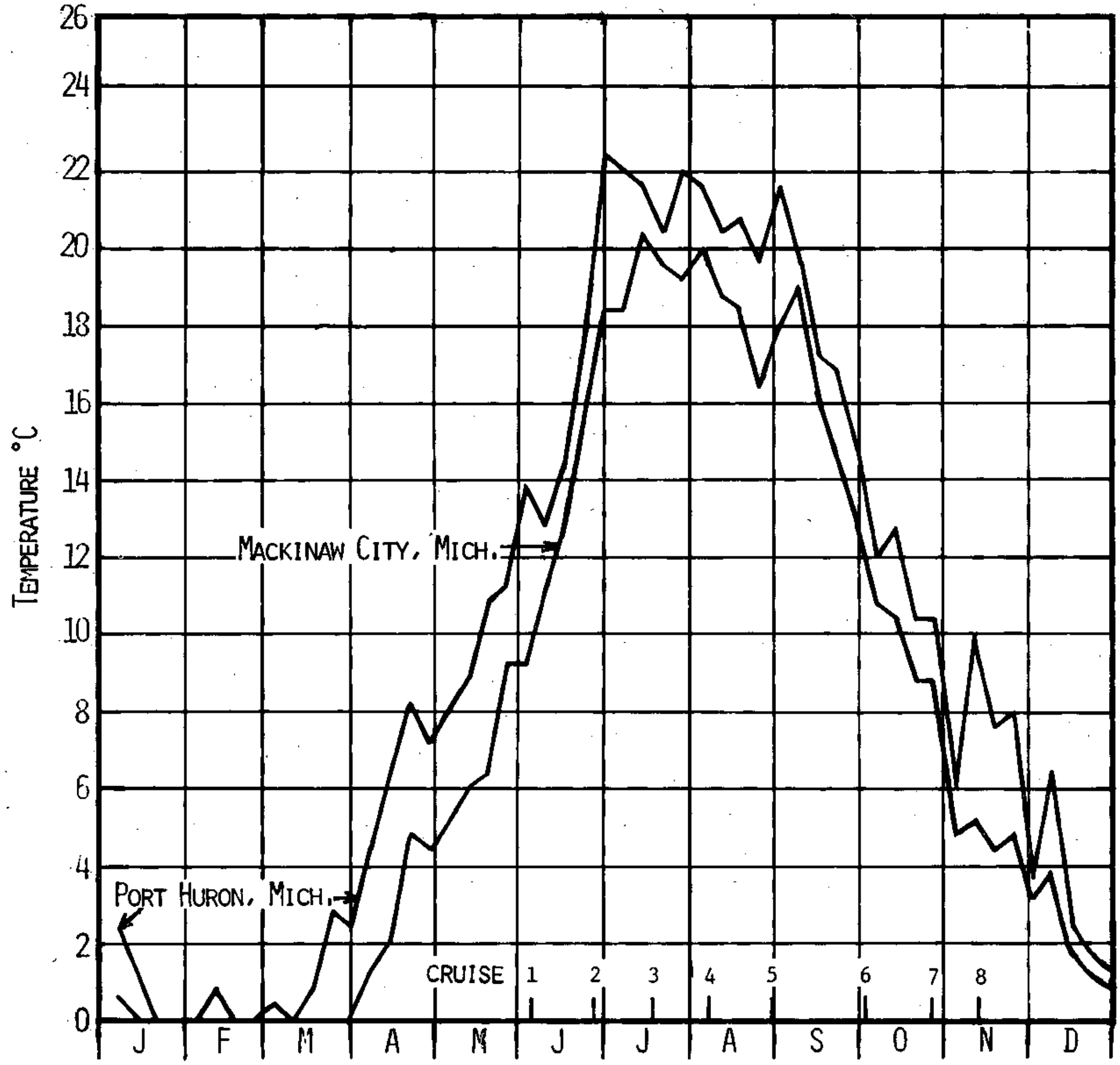

FIGURE 4–46 Temperature Regime at the North and South Extremes of Lake Huron
Pinsak, 1970

the south and approximately four months in mid-lake and in the north.

3.6.8 Lake Erie

The mean surface water temperature in Lake Erie (Figure 4–50), between the Detroit River and Port Colborne, Ontario, varies from a winter low of 2°C (35°F) to a summer high of 21°C (70°F). The winter minimum occurs progressively later from mid-February in the west to early March in the east coinciding with general deepening of water to the east. The summer maximum occurs during the first half of August. In this southernmost and shallowest of the Great Lakes, water temperature exceeds 10°C (50°F) during approximately six months of the year.

3.6.9 Lake Ontario

In Lake Ontario (Figure 4–51), between Cobourg and Charlotte, mean water surface temperature varies from 2°C (35°F) during

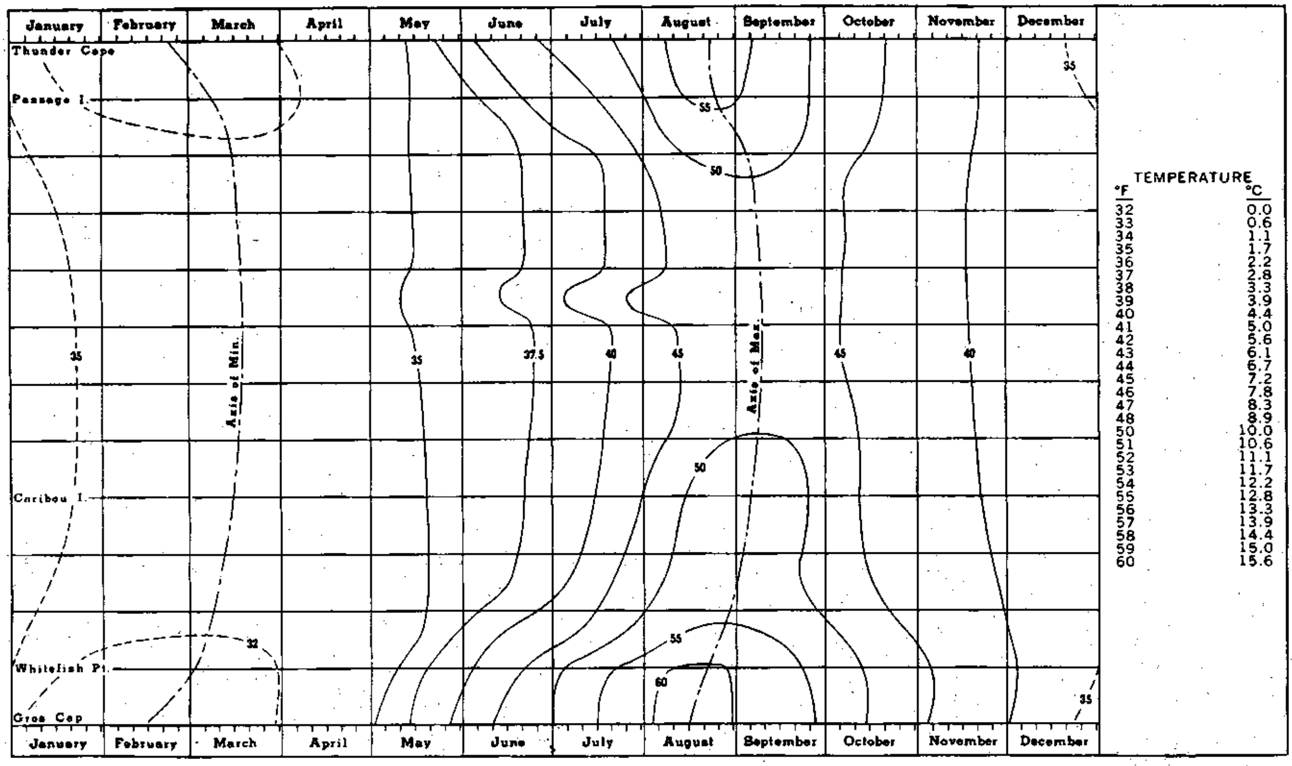

FIGURE 4–47 Annual Temperature Cycle (°F) in Lake Superior Between Thunder Cape and Gros Cap. Solid lines indicate values based on available data. Dotted lines indicate values that were estimated.

After Millar, 1952

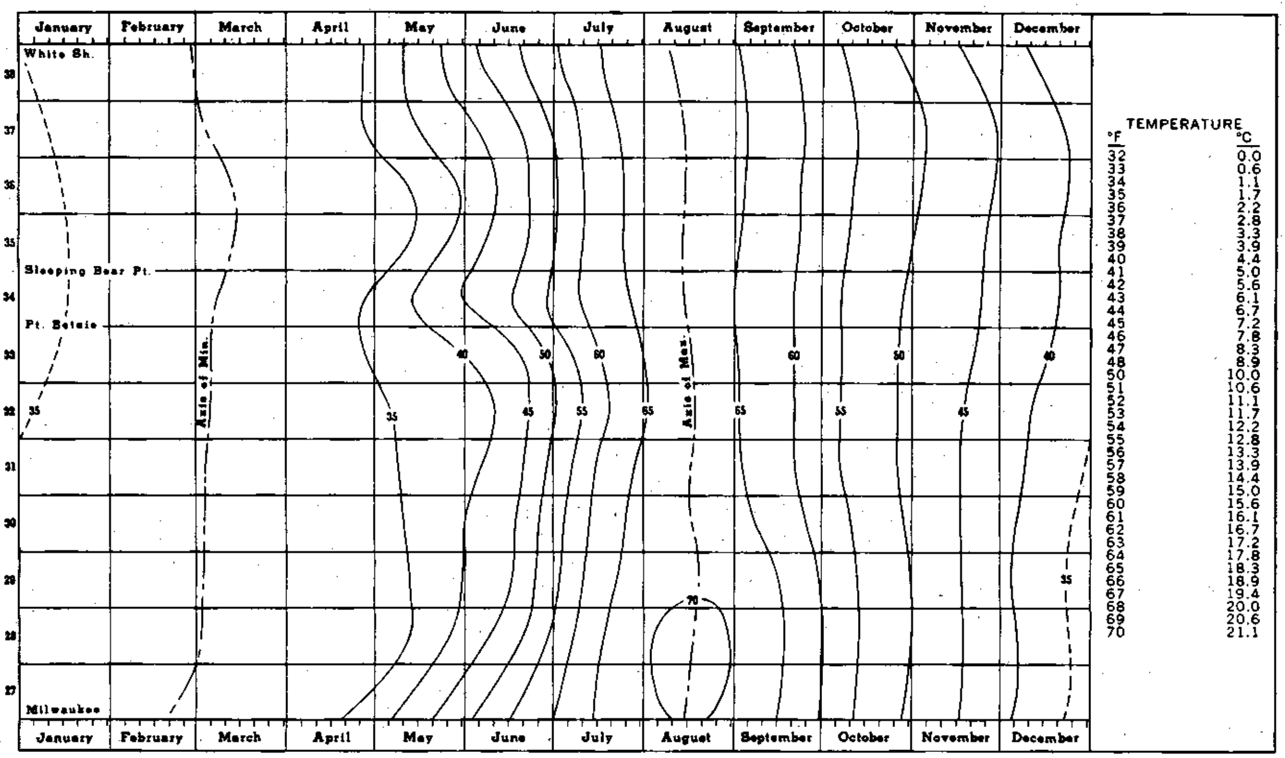

FIGURE 4–48 Annual Temperature Cycle (°F) in Lake Michigan Between Milwaukee and White Shoal. Solid lines indicate values based on available data. Dotted lines indicate values that were estimated.

After Millar, 1952

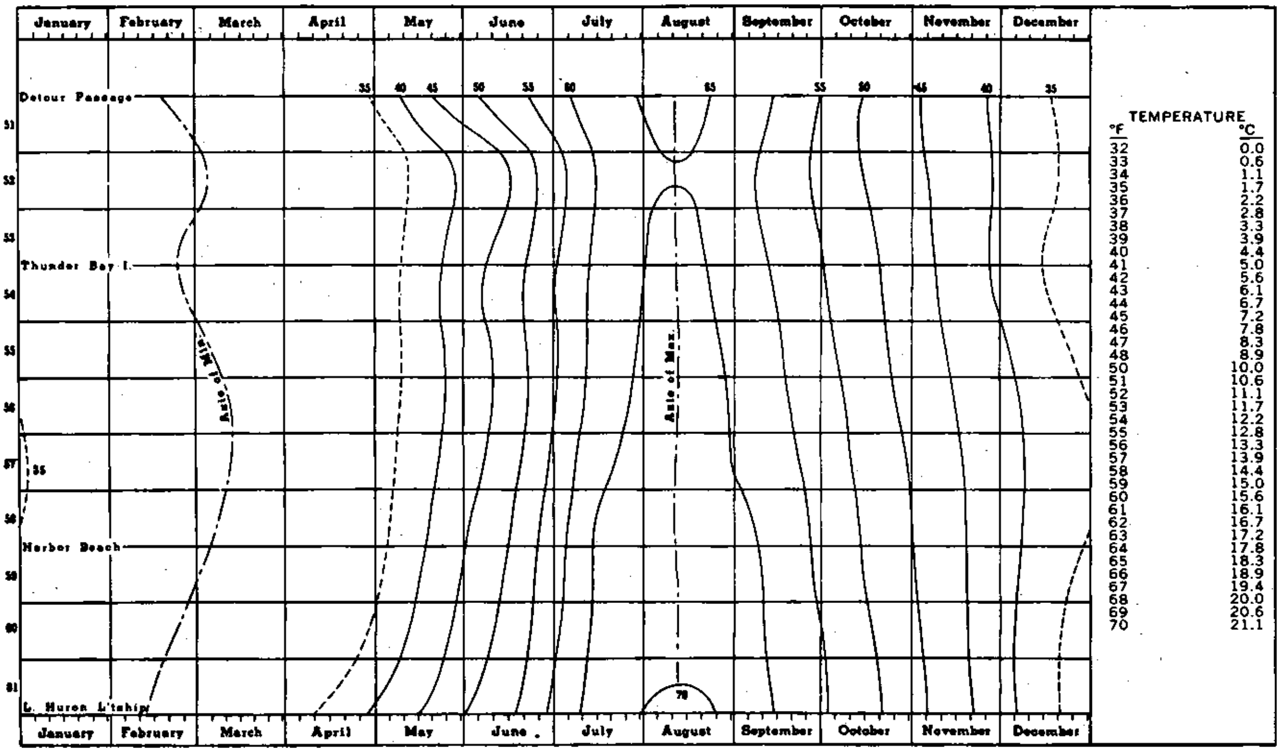

FIGURE 4–49 Annual Temperature Cycle (°F) in Lake Huron Between Detour Passage and Port Huron. Solid lines indicate values based on available data. Dotted lines indicate values that were estimated.

After Millar, 1952

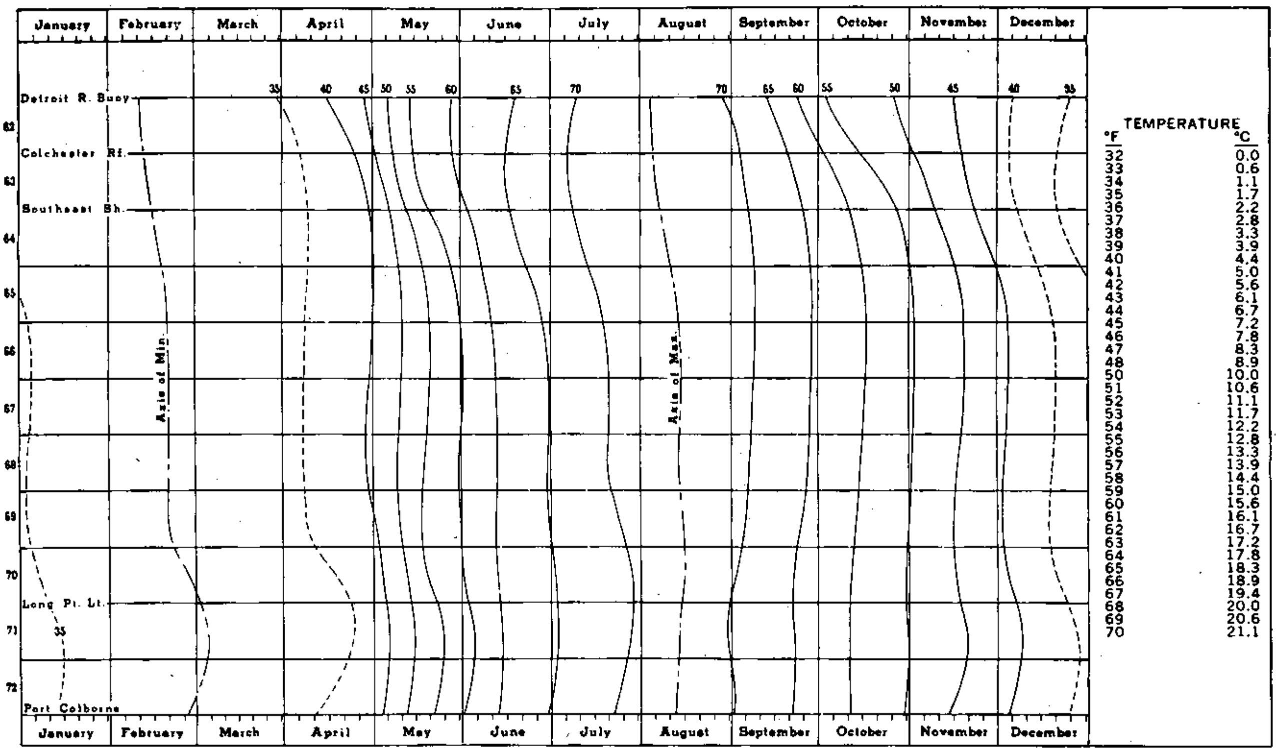

FIGURE 4–50 Annual Temperature Cycle (°F) in Lake Erie Between Detroit River and Port Colborne. Solid lines indicate values based on available data. Dotted lines indicate values that were estimated.

After Millar, 1952

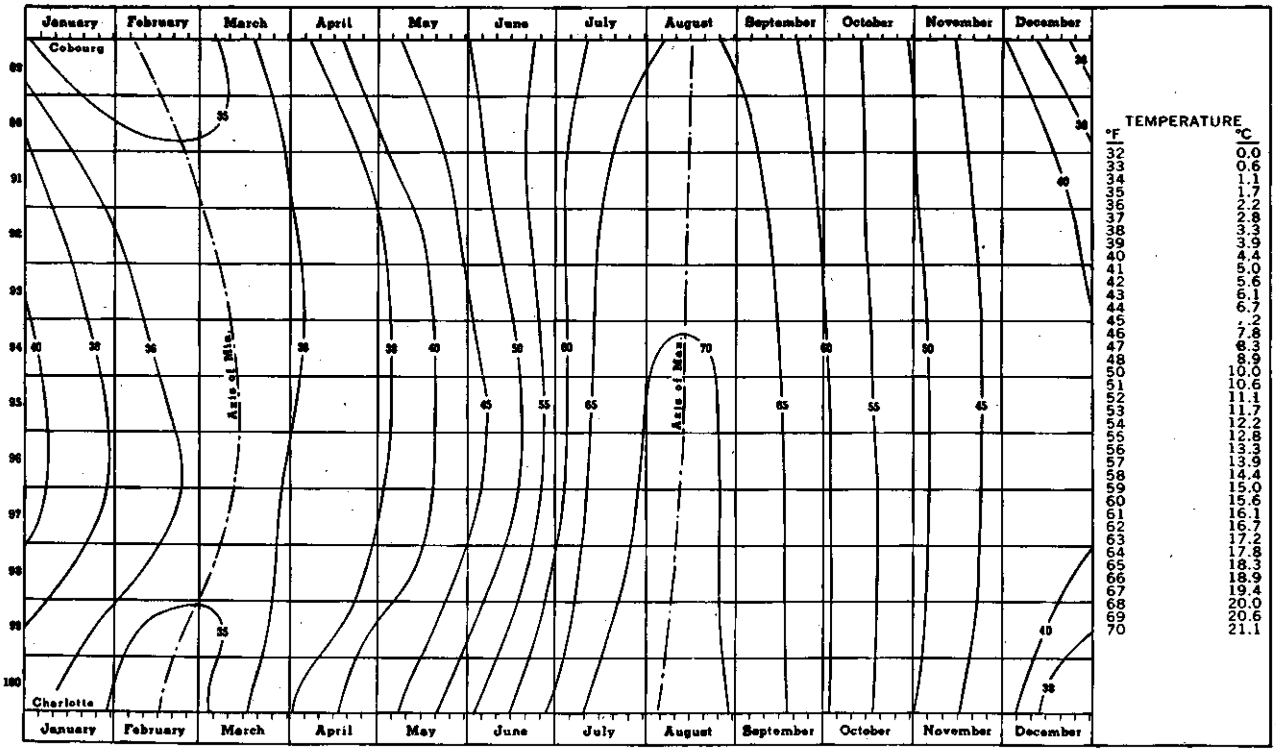

FIGURE 4–51 Annual Temperature Cycle (°F) in Lake Ontario Between Cobourg and Charlotte. Solid lines indicate values based on available data. Dotted lines indicate values that were estimated.
After Millar, 1952

winter to 21°C (70°F) during summer. The winter minimum is reached during mid-February along the shores and during mid-March in the open lake. The summer maximum is reached during early August in the south and mid-August elsewhere. Water temperature exceeds 10°C (50°F) for approximately five months of the year.

3.7 Heated Water Influx

The term heated water influx used in this discussion is defined as the introduction of heat into a large water or air mass intended to act as a heat sink. Heated water influx is a neutral term: it does not have the positive or negative connotations of terms such as thermal enrichment and thermal pollution.

In the past, discharge of heated water into receiving bodies was of little interest to the public because environmental impacts were relatively insignificant both in effect and scope. Also, public interest was focused in other areas. However, the development of large scale energy conversion, especially in the production of electric power, with the attendant need for large volumes of cooling water has increased heated water influx to the point where the net effect is becoming increasingly evident in localized areas.

3.7.1 Principle of Influx

Influx of heated water into a receiving water body creates a discrete water mass or "plume" whose dimensions and physical characteristics vary with the difference between the ambient water temperature and the influx water temperature ($\Delta\tau$), with the general circulation pattern of the receiving water, with depth of the discharge into the receiving body, and with the velocity and volume of the discharge. If $\Delta\tau$ is large, the plume will tend to be shallow with a large air-water interface area. If $\Delta\tau$ is small, the plume will have less tendency to flow out over the top of the receiving water and will therefore mix more readily. From these physical observations, it is evident that a large $\Delta\tau$ will permit much of the heat from the plume to be transferred directly to the atmosphere with consequent evaporation losses instead of being absorbed by the

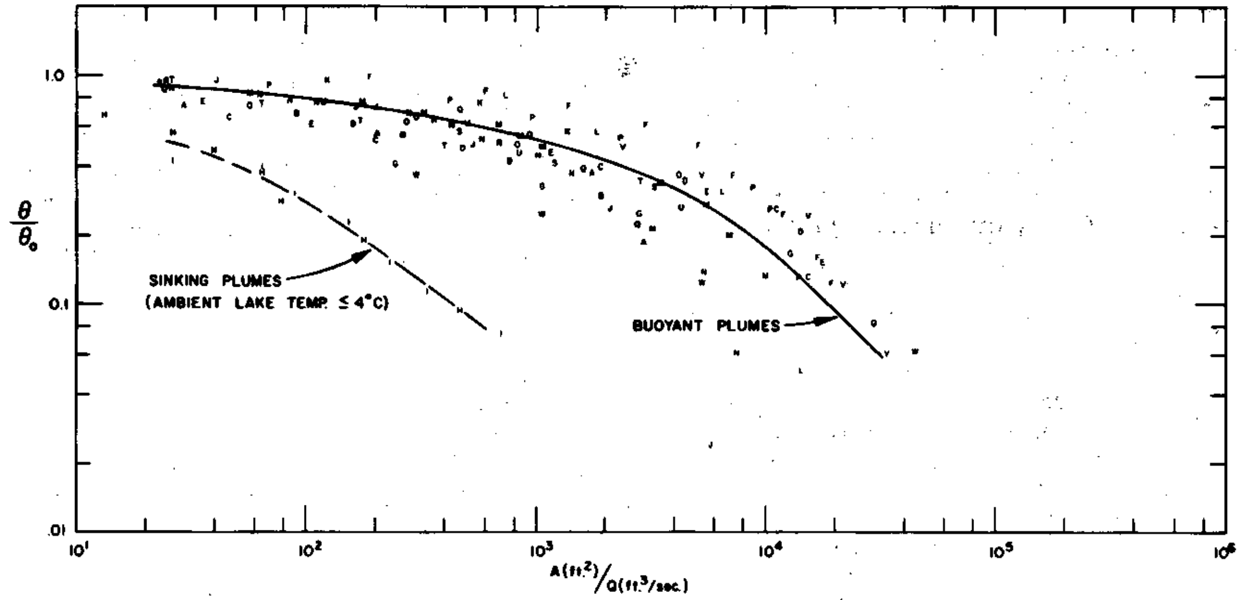

FIGURE 4–52 Curve Showing Relationship Between Fractional Excess Temperature ($\frac{\theta}{\theta_o}$) and the Quotient of Plume Surface Area (A) and Rate of Discharge (Q)

Asbury and Frigo, 1971

A. Waukegan (7/14/70, 12:30–13:37)
B. Waukegan (7/14/70, 14:50–16:10)
C. Waukegan (8/12/70, 12:00–13:57)
D. Waukegan (8/12/70, 16:22–17:53)
E. Waukegan (8/13/70, 12:12–13:26)
F. Big Rock Point (6/18/68)
G. Milliken (9/17/68)
H. Milliken (12/10/68)
I. Milliken (1/8/69)
J. Michigan City (6/26/69)
K. Michigan City (6/28/69)
L. Waukegan (6/30/69)
M. Allen S. King (8/20/69)
N. Allen S. King (9/4/69)
O. Allen S. King (7/30/69)
P. Allen S. King (6/5/70)
Q. Allen S. King (6/12/70)
R. Allen S. King (6/29/70)
S. Allen S. King (7/9/70)
T. Allen S. King (7/17/70)
U. Allen S. King (8/13/70)
V. Douglas Point (8/24/70)
W. Douglas Point (8/25/70)

receiving water body. However, if $\Delta\tau$ is small, the bulk of the heat load will be diffused into the receiving water in conformance with the general circulation. Assuming equal amounts of heat influx, the major physical difference in the effect of these two extremes on the receiving body will be in evaporation losses. Expected biological and biochemical impacts are not treated in this section.

The circulation pattern of the receiving water is influenced by the circulation of the atmosphere above it. If the receiving water is stratified, an offshore wind can create upwelling of cold hypolimnetic water in the area of the plume resulting in rapid offshore dissipation in the surface layer. Conversely, an onshore wind can cause downwelling holding the plume inshore. The heated water plume can also be held inshore by wind stress causing longshore currents to deflect the plume to the right or left of the outlet. In the latter two cases, heating would affect chemical-biological interactions within the water mass and at the sediment-water interface. Plume configuration changes constantly in response to the dynamics of the receiving water body. Therefore, influx of heated water at a given rate at a given location may at various times lead either to local thermal enrichment or to thermal pollution.

The behavior of thermal plumes has only recently come under intensive investigation. Most studies have been limited in scope and extent and have yielded data for only a specific or limited number of possible conditions. However, various field data and model studies have led to attempts at predicting thermal plume behavior. One approach (Asbury and Frigo[22]) deals with a phenomenological relationship for predicting the surface areas of thermal plumes in large lakes. A curve (Figure 4–52) relates fractional excess temperature ($\frac{\theta}{\theta_o}$) to the quotient of plume surface area and volumetric discharge flow rate. Although this study was limited in scope, the curve represents a useful rule of thumb for predicting surface areas of buoyant thermal plumes.

3.7.2 Volumes Related to Great Lakes

While the volume of the receiving water in the Great Lakes Basin is fixed within narrow limits, the volume of cooling water used in the generation of electric power has been increasing at a rapid rate. Volumes necessary to meet existing and projected condenser cooling water requirements in the Great Lakes Basin (from Appendix 10, *Power*) are as follows:

Year	Cubic Meter/Day	(Acre Feet/Day)
1965	44,053,738	35,715
1970	66,050,387	53,548
1980	128,697,603	104,337
2000	402,205,758	326,074
2020	849,370,628	688,597

The cooling water requirement forecast shows a spectacular rise, especially after 1980, but the effect of the increase will vary between each of the Great Lakes. For example, if the presumption is made, using the 1980 power projection for each of the Great Lakes, that the total heat from the condenser cooling water will enter the receiving water, and if the average $\Delta\tau$ will be 5.55°C to 11.11°C (Appendix 10, *Power*), then the average cal/day energy increase per unit surface area of each lake would be:

Lake	cal/cm²/day
Superior	0.017–0.022
Michigan	0.700–0.938
Huron	0.248–0.331
Erie	1.263–1.684
Ontario	0.926–1.234

The relative importance of this energy increase in the total energy budget of a lake may be assessed by comparing the projected Lake Ontario condenser cooling water energy load with the mean monthly values in Lake Ontario of significant natural energy factors as compiled by Rodgers and Anderson[675].

Item	cal/cm²/day
Net Radiation	−7 to +415
Heat Stored in Lake	−510 to +505
Evaporation	−35 to +240
Net Advection	−12 to +2
Sensible Heat Transfer	−95 to +260

It is apparent that influx of heated water from power development is of minor importance in the total lake energy budget. However, in Lakes Michigan, Erie, and Ontario, total heat influx from power plants, steel plants, sewage treatment plants and other industrial developments may become a significant factor in the next century.

3.7.3 Effect on Lake

Although the effect of heated water influx is small in relation to the total lake energy budget, thermal influx from a large megawatt power plant may cause severe disruption of the energy balance near the point of influx. For example, if a large power plant were located on a restricted harbor or embayment where circulation of the receiving water and the open lake was restricted, the dispersion of heat to the open lake would be limited, causing a rise in the local ambient water temperature. In this instance, the harbor or embayment would be functioning as a cooling pond and the influx could be considered thermal enrichment or thermal pollution. In fact, some older power plants are located so that their cooling water intakes extend into the open lake while the heated water discharge is located within an enclosed harbor or embayment. The newest power plants have generally been located so that thermal discharge is into the lake proper.

3.7.4 Effect on Local Climate

When power plants have been constructed in areas where the thermal assimilation capacity of the receiving water body is poor due to poor circulation patterns, lack of climatic cooling cycles, or inadequate water volume, the waste heat load is released directly into the atmosphere rather than into the water. The currently popular method of infusing heat into the atmosphere is done by means of the natural draft wet-type cooling tower. As the wet-type cooling tower depends upon the evaporative process, the wet-bulb temperature is the theoretical limit to which the water can be cooled through evaporation. The average evaporation loss for a cooling tower is 2 percent of the total circulating water, but this varies with temperature ranges. What happens to this 2 percent of the total circulating water after it leaves the cooling tower has become a subject of major concern in the design and placement of these installations.

Whether thermal discharge from a plant is accomplished by means of the flow-through process, by use of a cooling pond, or by means of wet- or dry-type cooling towers, the atmosphere becomes the ultimate heat sink. If waste heat is discharged into a large water body at a temperature close to that of the receiving body, the heat is transferred to the atmosphere at a relatively slow rate over a large geographic area. If waste heat is discharged at a temperature markedly different from that of the receiving body, movement of heat to the atmosphere is more rapid and localized. If waste heat is released directly into the atmosphere by means of a cooling tower, the rate of transfer to the atmosphere is extremely large within a small geographic area. The differing methods by which waste heat is released into the atmosphere are extremely critical to the effect on local climate. A few studies have been made recently regarding the generation of fog and icing conditions from cooling towers and the effects of towers on clouds and precipitation. Other studies have treated tower effluent and lake breeze interaction (Williams,[894] Huff et al.[389]). Although results of these studies are inconclusive, field data indicate that cooling tower plumes under some circumstances lead to additional snowfall under certain synoptic climatic conditions, and in a nearshore area a plume could extend naturally occurring fog from 1 to 2 miles inland. A comparison of heat output from cooling towers and urban areas (Huff, et al.[389]) gives some insight into the relative effect of cooling tower installations:

Emission Location	Computational Basis	Heat Output BTU/hr.
Zion Towers	Summer peak load	8.8×10^9
St. Louis	Average yearly output	55×10^9
Chicago	Average yearly output	180×10^9

The general lack of knowledge concerning the impact of thermal influx into the atmosphere by cooling towers indicates that more local and regional meteorological data are needed before the climatic effect of cooling towers can be assessed.

3.8 Water Transparency

Transparency as applied to water relates to the property or ability to transmit light such as direct solar radiation (sunlight), indirect radiation (light from the sky), or light from an artificial source such as an incandescent lamp. Water transparency is a fundamental factor in studies of photosynthesis, biological activity, chemistry of the environment, and in problems concerned with radiant energy, vertical and lateral circulation, stratification, and transport of material. The amount of radiant energy penetrating the lake water controls the production and distribution of phytoplankton, which in turn controls the zooplankton and ultimately the fish production.

Light attenuation is the restriction of light transmission by any included substance. Effect of color, dissolved solids, and suspended particles on the absorption coefficient of water are all additive (Hutchinson[402]) and the relationship that exists between water transparency and quantity of suspended material is directly linear (Jones and Wils,[437] Hutchinson[402]).

Transparency of the water is not constant; it fluctuates vertically, areally, and also with time. Vertical variance is generally related to thermal structure of the water mass and is a function of season. Lateral variations are largely a result of wind stress and circulation. These variations occur throughout the freely circulating epilimnion but are most predominant within the range of effective wave depth. On a short-term restricted basis, transparency reflects type and intensity of influx plus ability of the water mass to retain introduced material (Pinsak[615]).

Studies of water transparency are generally carried out as a measure of effective penetration of solar radiation. Impinging light at any depth then is only an integrated average of the light in the entire water column from that level to the surface. Vertical variations are thus nullified by this method and only generalizations can be made. If a device is used to measure water transparency *in situ*, the greatly detailed profiles can be applied, in conjunction with other tools, to solution of pertinent problems. A common means of measuring light penetration into the lake water has been the Secchi disc and more recently photoelectric cells with various wavelength filters.

3.8.1 Principal Factors

Factors which determine the amount of light penetrating water are intensity of light at the surface, angle of incidence with the water surface, dissolved materials, and suspended materials. Intensity of natural light from the sun and sky at the water surface is extremely variable depending upon the time of year and day, and the clarity of the atmosphere as determined by the presence or absence of clouds, smoke, dust, or fog. Maximum penetration of light occurs when the sun is directly overhead. At all other positions of the sun, a portion of the incident light will be reflected. Angle of incidence changes with both time of day and time of year. In addition, surface waves will change the angle of incidence producing rapid changes in the direction and depth of light penetration. The sun is never directly overhead in the Great Lakes so maximum penetration can never be expected. Depth of light penetration in natural water is further controlled by absorption and by scattering with the latter being the most significant. Absorption is directly related to the composition of the water and scattering is the actual reflection of light by the contained particulate matter.

Absorption by dissolved materials contributes to the variations in transparency between pure water and lake waters of different composition. However, with the exception of color, which has a pronounced effect, the effects of these dissolved materials are apparently negligible. On a scale of 0 to 1000 platinum units (Hutchinson[402]), the clearest water gives a color of zero and the darkest of the bog waters range up to 340. Coloring may be due to materials dissolved from soil, peat, humus, or to organic material produced by plankton. Circulation above the thermocline exposes the coloring matter to sunlight where it can be decomposed. The amount of color changes with rainfall and with seasonal changes. Welch[879] reports periods of maximum color in May-June and in November-December.

Suspended materials, inorganic or organic, have a considerable effect on light penetration. The more turbid the water, the less the light penetrates. Thus natural light penetration may be limited to a thin zone at the water surface under extremely turbid conditions. Finely divided particles of clay, silt, organic material, and plankton produce most of the light attenuation, especially in nearshore areas and shallow portions of the lakes. Larger particles, especially those which have a higher density than the water, settle rapidly and are little affected by water temperature variations. The settling of finely divided particles with densities approaching that of water is greatly affected by temperature variations and stratification. This creates a natural separation based on size and composition. Organic material especially tends to concentrate above the thermocline as settling is impeded by the underlying water of greater density and viscosity. Below the thermocline settling rate is more uniform because the hypolimnion is structurally more stable than the epilimnion. Suspended material may concentrate near the bottom. These materials may be colloidal (Welch[879]), or they may be due to transport or resuspension of materials. Pinsak[615] found a direct correlation between transparency and temperature structure in Lake Erie. The least transparency was found below the thermocline and above the sediment-water interface (Figure 4–53). This phenomenon (Figure 4–54) was observed repeatedly in the Corps of Engineers study of spoil disposal effects on the Great Lakes.[812]

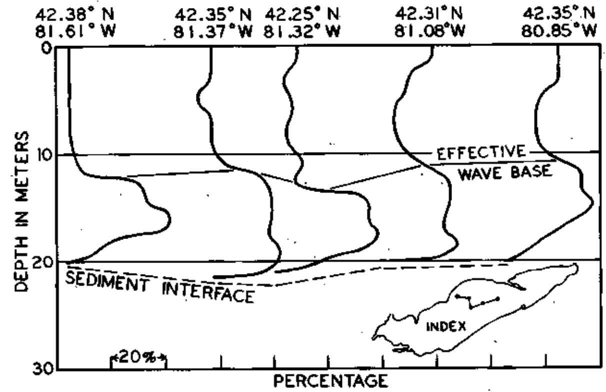

FIGURE 4–53 Profile Showing Water Transparency in the Central Basin of Lake Erie on September 22, 1965

Pinsak, 1968

The depth of light penetration into each of the Great Lakes is generally uniform (Beeton[50]), but maximum penetration does not occur at the same time in all of the lakes nor is the geographic extent of occurrence similar. However, wave length of light penetrating to depth varies between lakes. Red is less affected by dissolved and suspended materials than the other colors. Yellow penetrates to greater depths in lakes of medium transparency and in lakes of highest transparency the short wavelength blue penetrates farther than red. In lakes with predominantly red (6000 Å) penetration, very little light of lesser wavelength penetrates deeper than 1 meter (Welch[879]). Suspended solids, dissolved solids, and organic material increase through the system from Lake Superior to Lake Ontario. In Lakes Huron and Superior, transmission of short wavelengths (blue) predominates (Figure 4–55). In contrast, the more turbid waters

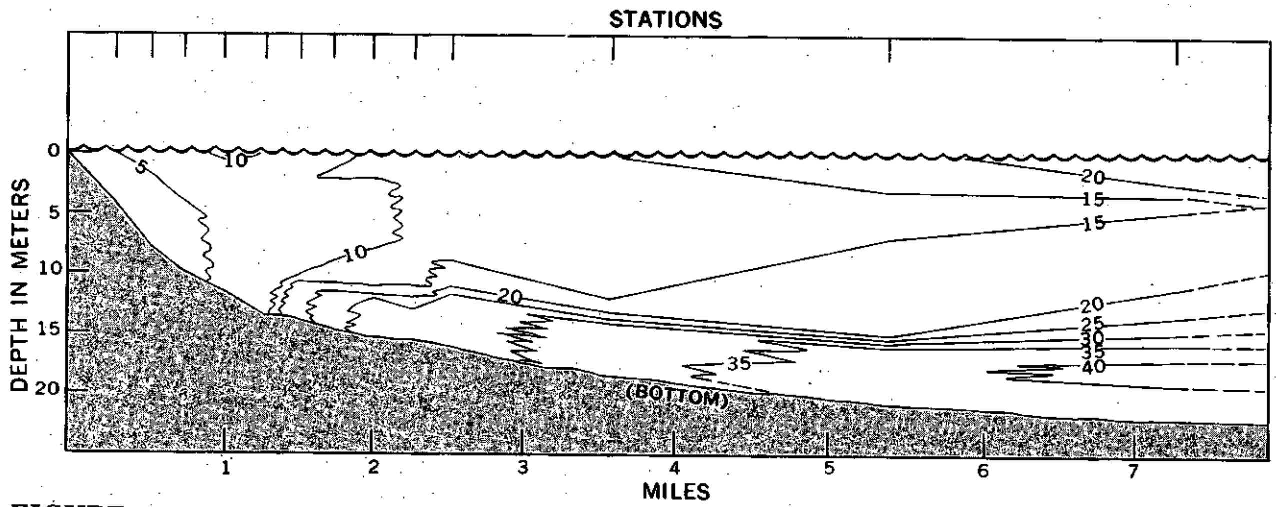

FIGURE 4–54 Percent Transparency along a Northwest-Southeast Traverse West of Ashtabula, Ohio

Corps of Engineers, 1968

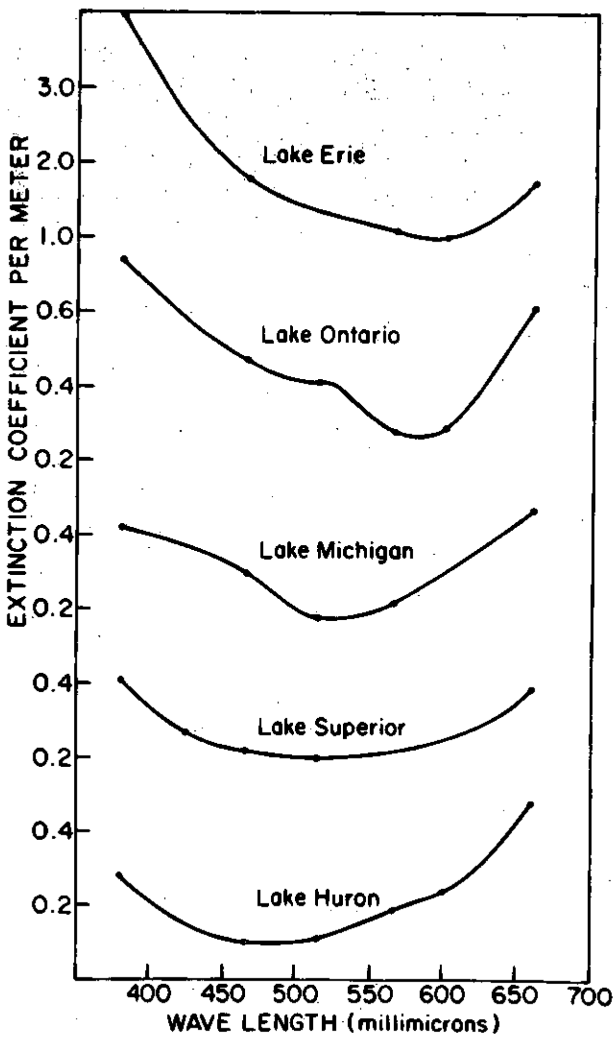

FIGURE 4–55 Vertical Extinction Coefficients (σ) for Various Wave Lengths of Light in the Great Lakes ($\sigma = -\log_e T$ where T equals transmissivity).

Beeton, 1962

of Lakes Erie and Ontario transmit the longer wavelengths (orange-red) to the greater depths.

3.8.2 Areal Variation

Variations in transparency are related to areal distribution of suspended material, which in turn is related to particle size, composition of the bottom sediment, proximity to shore, depth of lake, currents, storm activity and depth of mixing caused by resulting waves, variations in stream influx, windborne materials, and plankton blooms. The most significant short-term variations are produced by storm activity and plankton blooms. Spring and fall mixing of the lakes also produces widespread distribution of finely divided materials. High volume tributary influx also produces short-term effects. Several of these factors may occur simultaneously or in succession. Longer-term effects may be due to continued influx as from the connecting channels or waste discharge, to low density suspended materials which are essentially nonsettling, and to plankton such as algae.

Secchi disc and the various photocell arrangements used to integrate the percentage of natural light transmission into a lake with depth are good for specific purposes. However, in order to examine *in situ* transparency and to consider the effects of vertical variations, it becomes necessary to employ another means whereby a photocell and a light source are lowered into the lake to produce a transparency profile. This is the approach used by Pinsak,[615] Duntley,[230] Whitney,[887] and Ruttner and Sauberer,[694] and introduced by Peterson

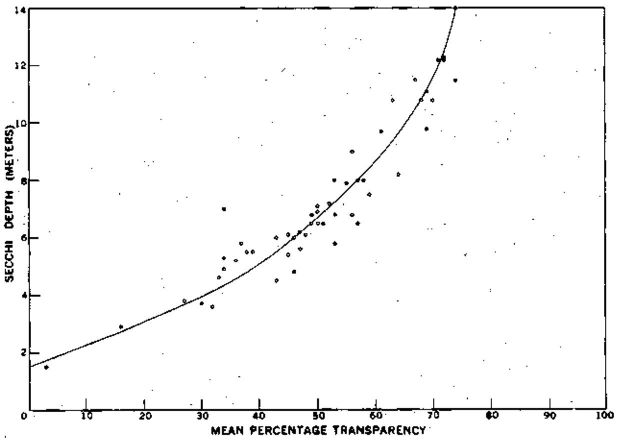

FIGURE 4–56 Relationship Between Secchi Disc and Mean Percent Transparency

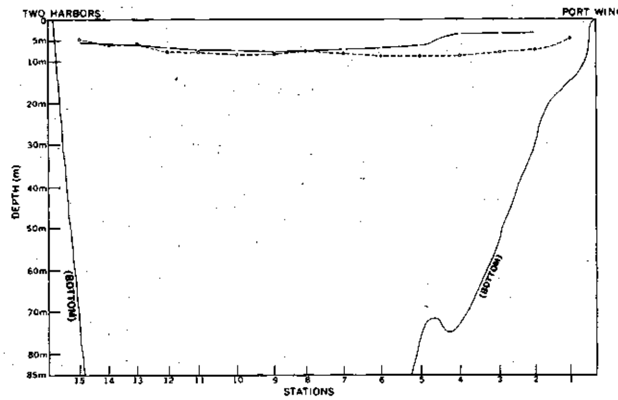

FIGURE 4–57 Secchi Disc Readings, Port Wing, Wisconsin, to Two Harbors, Minnesota; July 30, and August 21, 1956

Data from Ruschmeyer, Olson, and Bosch, 1956

(Hutchinson[402]). Water transparency is measured as a percentage of the transparency of air.

One problem in looking at historical data is the disparity in measurement techniques. In measuring transparency a historical base must rely on correlation of Secchi disc and photocell determinations. Using empirical data, a curve showing the relationship between Secchi disc and photocell transparencies was developed at the Lake Survey Center, National Ocean Survey (Figure 4–56). There is a positive correlation and the objective of establishing a means for comparison of different techniques was realized. Scatter could probably be reduced by classifying according to the variables involved in these types of readings and then producing a set of curves rather than one curve.

More intercomparisons are needed to correlate various measurements of turbidity and transparency in Great Lakes water such as Jackson Turbidity Units (J.T.U.), Secchi disc, percent transparency, suspended sediment, and color.

3.8.3 Lake Superior

Lake Superior has the lowest concentration of suspended solids, dissolved solids, and organic materials of all the Great Lakes. Green color (490–540 μ) penetrates deepest (Figure 4–53) (Beeton[50]) in the vicinity of the Apostle Islands. However, Lake Survey Center investigations indicate that the Apostle Island area is not representative of the lake as a whole. Violet light penetrated to only 7 meters in this area while Putnam and Olson[635] measured violet light penetration to 10 meters in the open lake.

Secchi disc readings (Figure 4–57) from Port Wing northward to Two Harbors (Ruschmeyer, Olson, and Bosch[691]) show a maximum natural light penetration to 8.5 m in mid-lake and to lesser depths in the nearshore areas. In the Superior Harbor area (Figure 4–58) the disc readings show low values which extend to approximately one mile outside of the har-

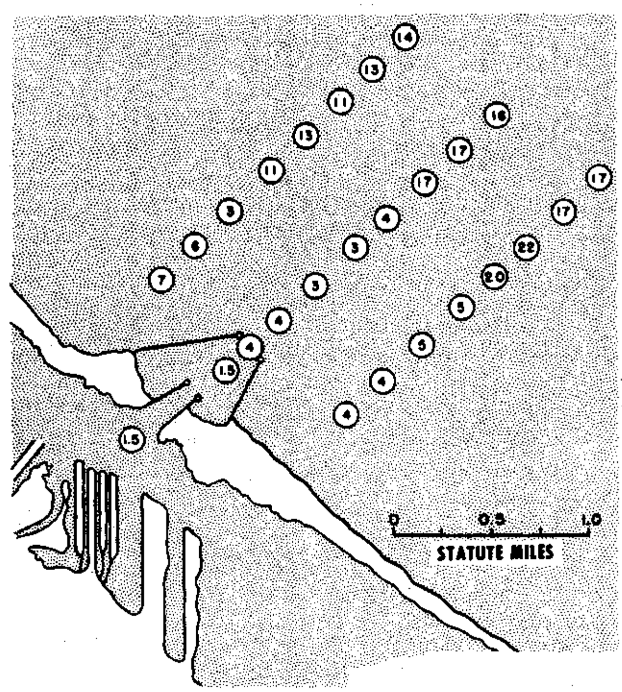

FIGURE 4–58 Secchi Disc Readings (m), Superior Harbor; September 5, 1956

Ruschmeyer et al., 1956

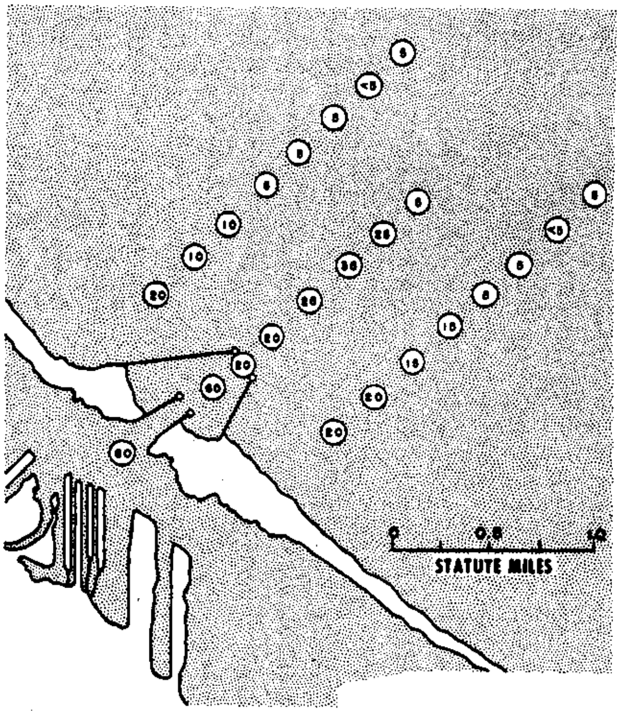

FIGURE 4–59 Color Readings, Superior Harbor Area; September 5, 1956. Color is measured on a 0–500 scale; 0 = transparent, 500 = opaque.
Ruschmeyer, et al., 1956

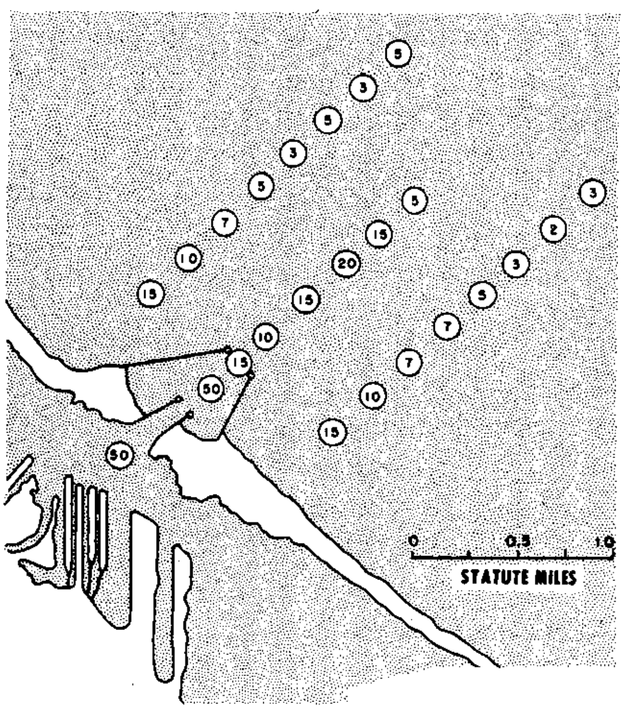

FIGURE 4–60 Turbidity Readings (Jackson Turbidity Units), Superior Harbor Area; September 5, 1956
Ruschmeyer, et al., 1956

bor. As would be expected, this same area shows high color (Figure 4–59) and high turbidity (Figure 4–60). These turbidity configurations and intensities in western Lake Superior correspond to determinations by the U.S. Lake Survey 13 years later in 1969. These later investigations, utilizing an *in situ* photocell, include all of western Lake Superior and thus put specific sites into perspective.

During summer (Figure 4–61) mean water transparency based on a 30 m thick surface layer was generally high (60 to 70 percent) over the entire western basin except along the extreme west and southwestern shore. As in the other lakes, transparency decreased in the fall, although to a lesser degree (Figure 4–62). This decrease is obvious in the more shallow areas such as the extreme western end of the lake west of the Apostle Islands. Minimum values are a result of influx near Silver Bay, Minnesota (20 to 30 percent) and near the Duluth-Superior outflow and the south shore (10 to 30 percent). The low transparency west of Silver Bay appears to correspond with the observations of "green water" during the period of lake stratification (Adams[3]).

Standard deviation as a measure of absolute dispersion can be used to bring anomalous areas into focus. A large standard deviation thus indicates a wide range of transparency during a given time period which in turn is indicative of variations in the quantity of suspended materials in the water column. Natural background standard deviation in western Lake Superior during 1969 ranged from 4 to 11 based on open lake values (Figure 4–63). Standard deviation in the western arm of the lake was consistently above background as was the mean transparency (Figure 4–64). Magnitude and gradient of change indicates fluctuations in variables that control transparency. Highest local anomalies are caused by a combination of both natural and man-made inputs.

The coefficient of variation (standard deviation/mean) is a measure of the relative dispersion of transparency about the mean value. This shows relative magnitude of change rather than actual differences at a particular place during the period that measurements were taken. It allows for direct comparison over large areas that have anomalies of relative significance. Coefficient of variance background in the open lake ranges from 6 percent to 17 percent (Figure 4–65). The open water area of the western arm has coefficient of variation values higher than the background range, but highest values were found

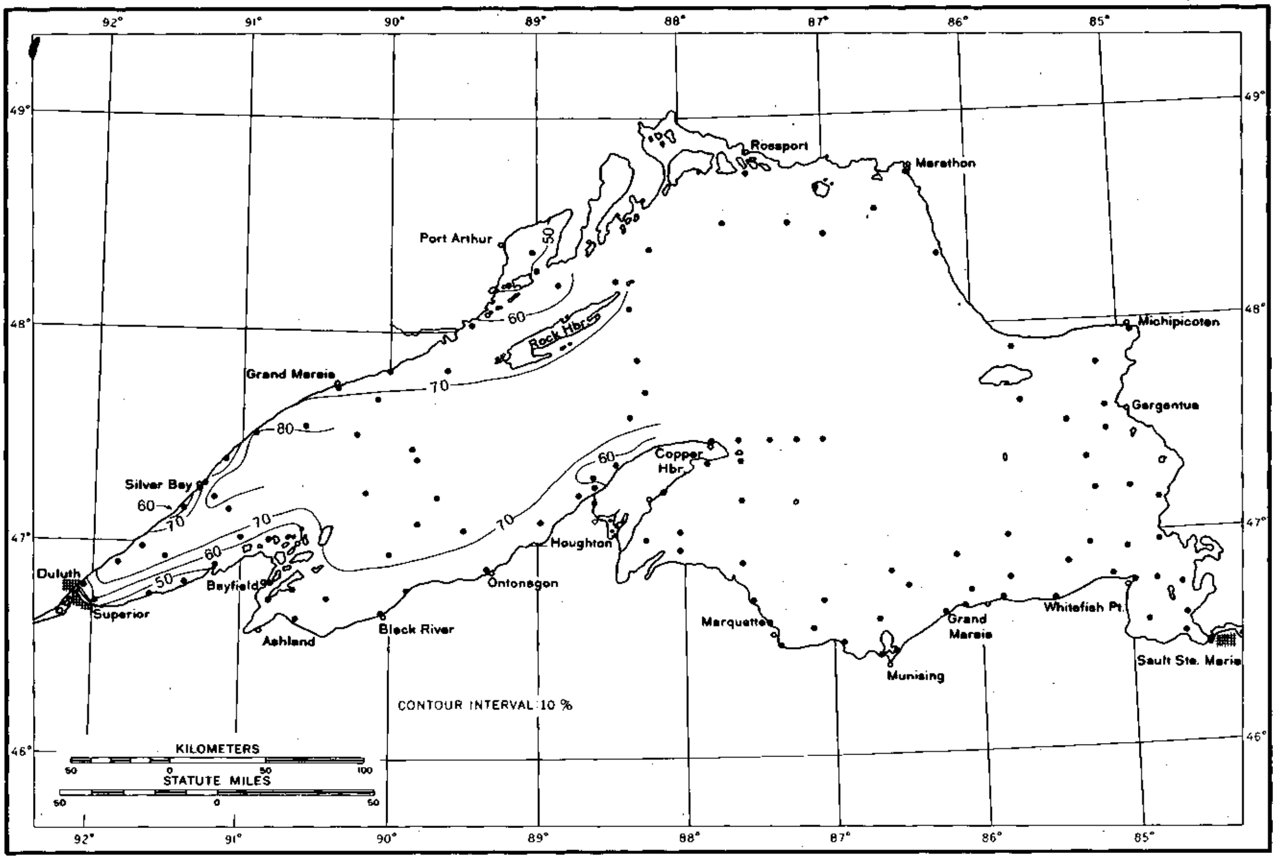

FIGURE 4–61 Percent Transparency of Lake Superior; Summer, 1969

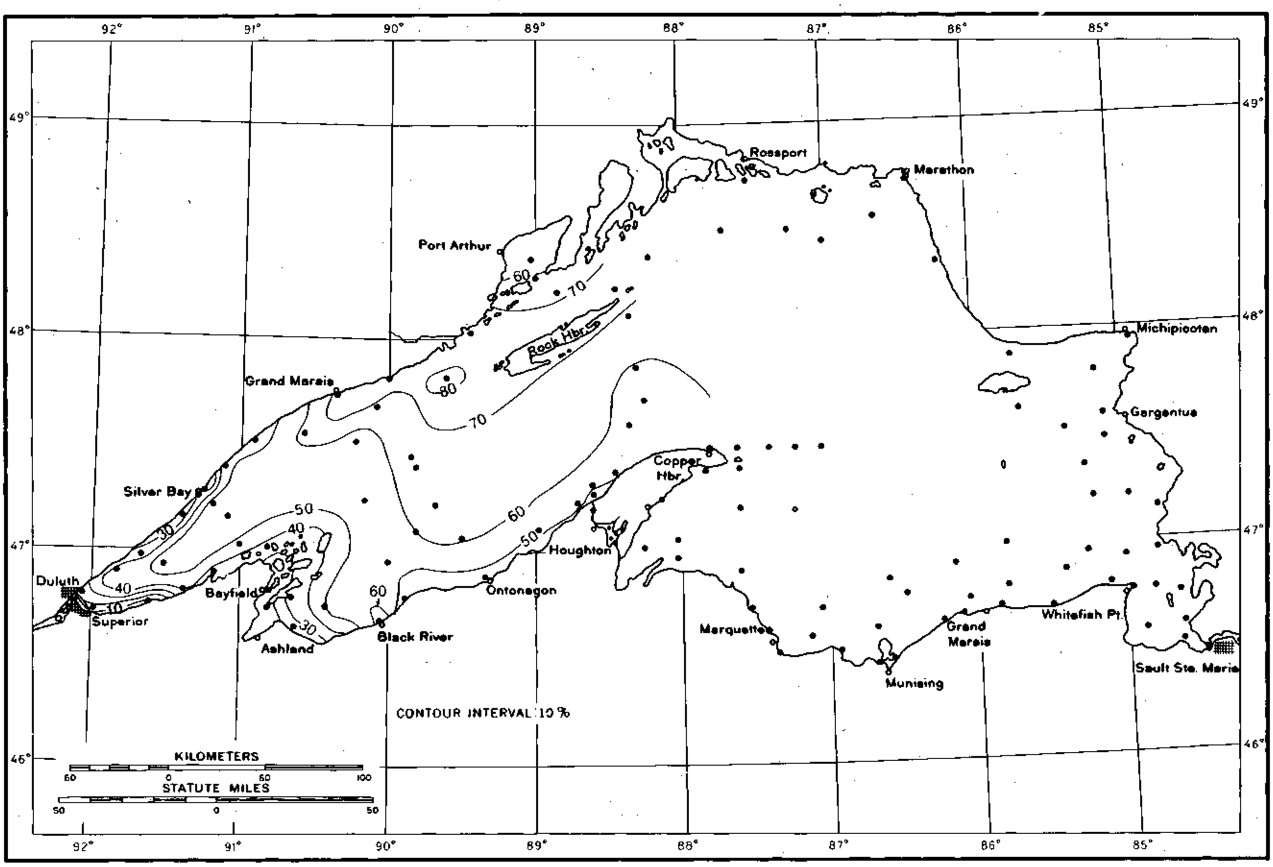

FIGURE 4–62 Percent Transparency of Lake Superior; Fall, 1969

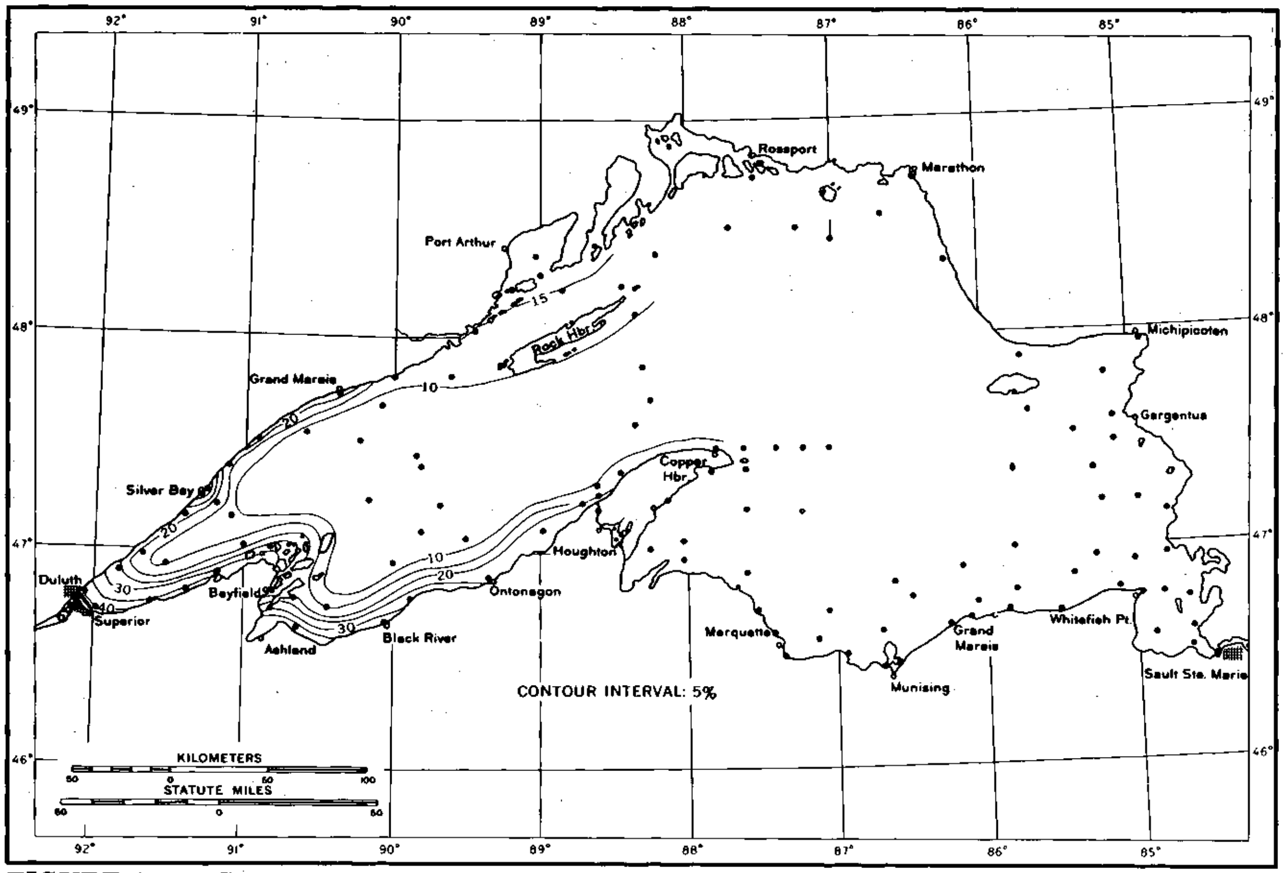

FIGURE 4–63 Standard Deviation of Transparency in Western Lake Superior; 1969

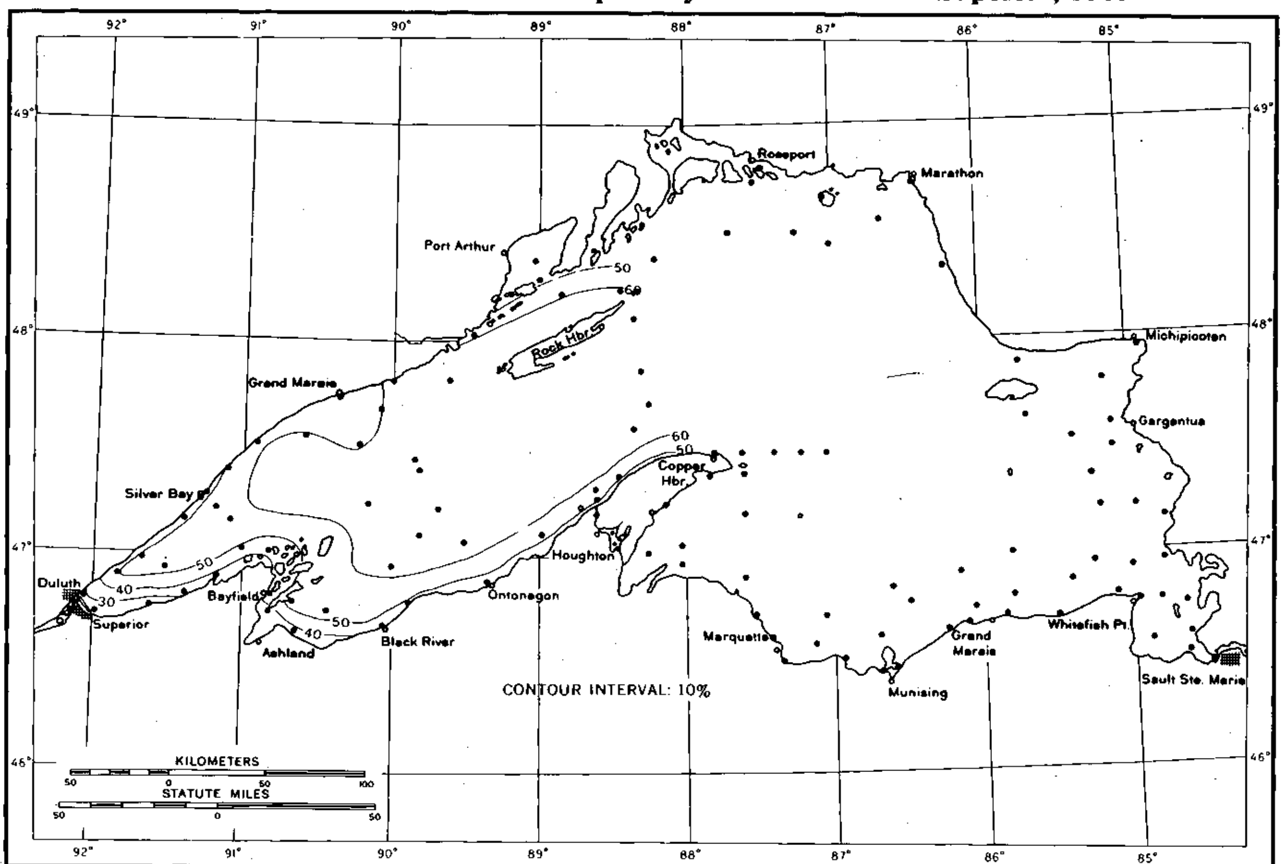

FIGURE 4–64 Mean Percent Transparency of Western Lake Superior; 1969

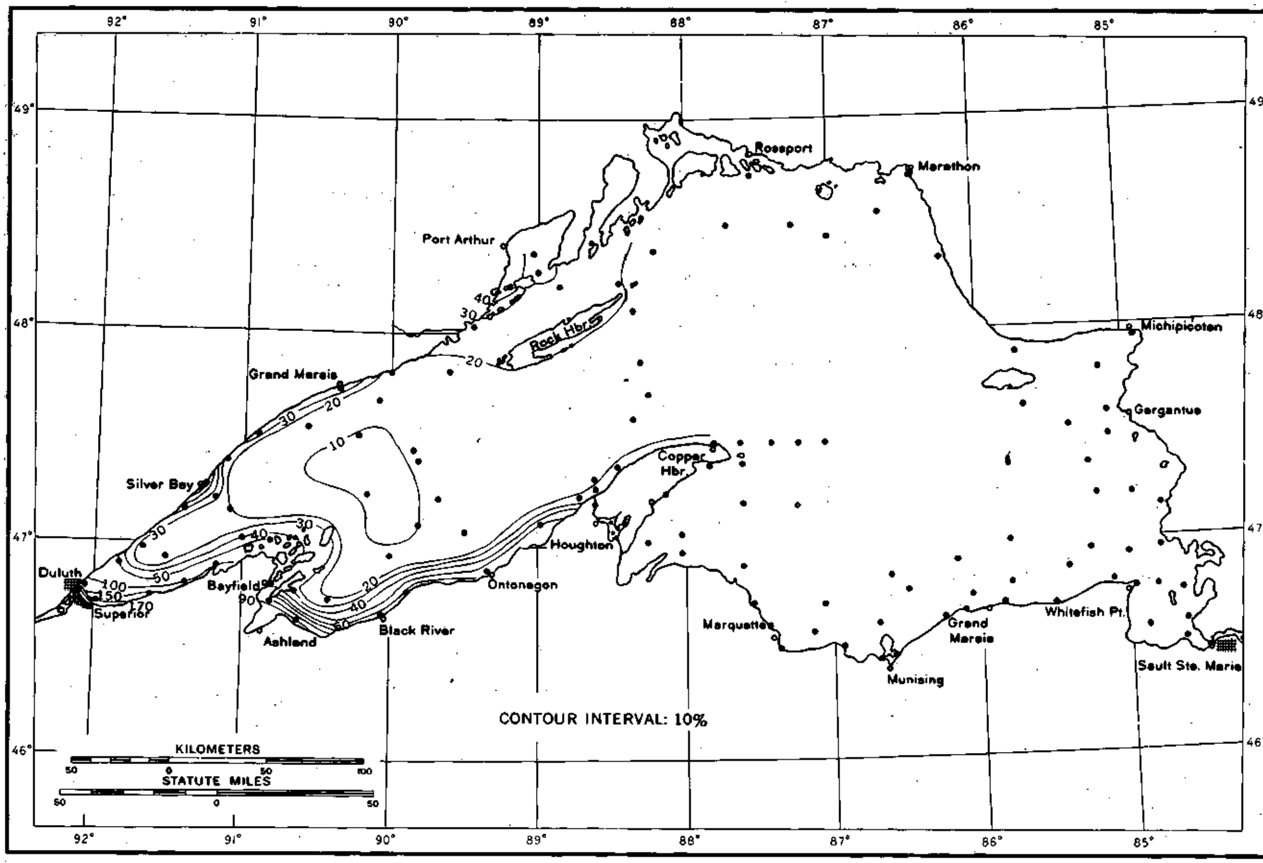

FIGURE 4–65 Coefficient of Variance in Transparency of Western Lake Superior; 1969

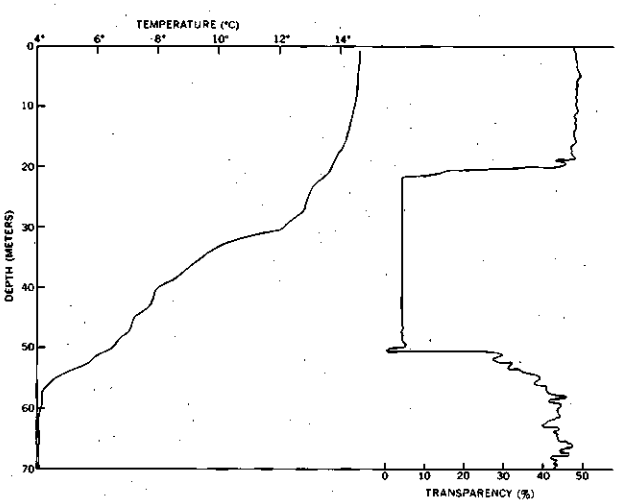

FIGURE 4–66 Turbidity-Temperature Relationship, Silver Bay, Minn.; Sept. 17, 1969

immediately adjacent to the shores, especially along the south shore eastward from the Duluth-Superior outflow (greater than 170 percent) indicating that the suspended sediment load along the south shore is relatively high and quite variable.

Extreme fluctuations in both standard deviation and coefficient of variance are indications of variations in the quantity of suspended particulate matter in the water. Those variations could result from intermittent releases of materials capable of remaining in suspension, or the intermittent development of physical conditions favorable for the suspension of particulate matter. The presence of extreme standard deviation and coefficient of variation near Duluth-Superior, Silver Bay, and the Ashland embayment in comparison with other harbors suggests that the discharge of suspended particulate material from these areas is not typical.

Adjacent to the outfall from the Reserve Mining operations (Figure 4–66), a thick (30 m) wedge of very turbid water was observed extending into the lake on top of the thermocline. The sharp top and bottom boundaries suggest a very finely divided material with a density approximating the underlying 4°C to 5°C water. This condition is similar to that observed by Kindle[456] in the laboratory. Such a phenomenon could not occur in an isothermal water column. The suspended material, in addition to being trapped, causes attenuation of the short wave length light and, in this case, results in the green coloration of the water.

Canada Centre for Inland Waters investigated surface turbidity in central and eastern Lake Superior in April 1970 (Figure 4–67) and found it to be less than 0.5 J.T.U. Anomalous shore areas are indicated at Ontonagon,

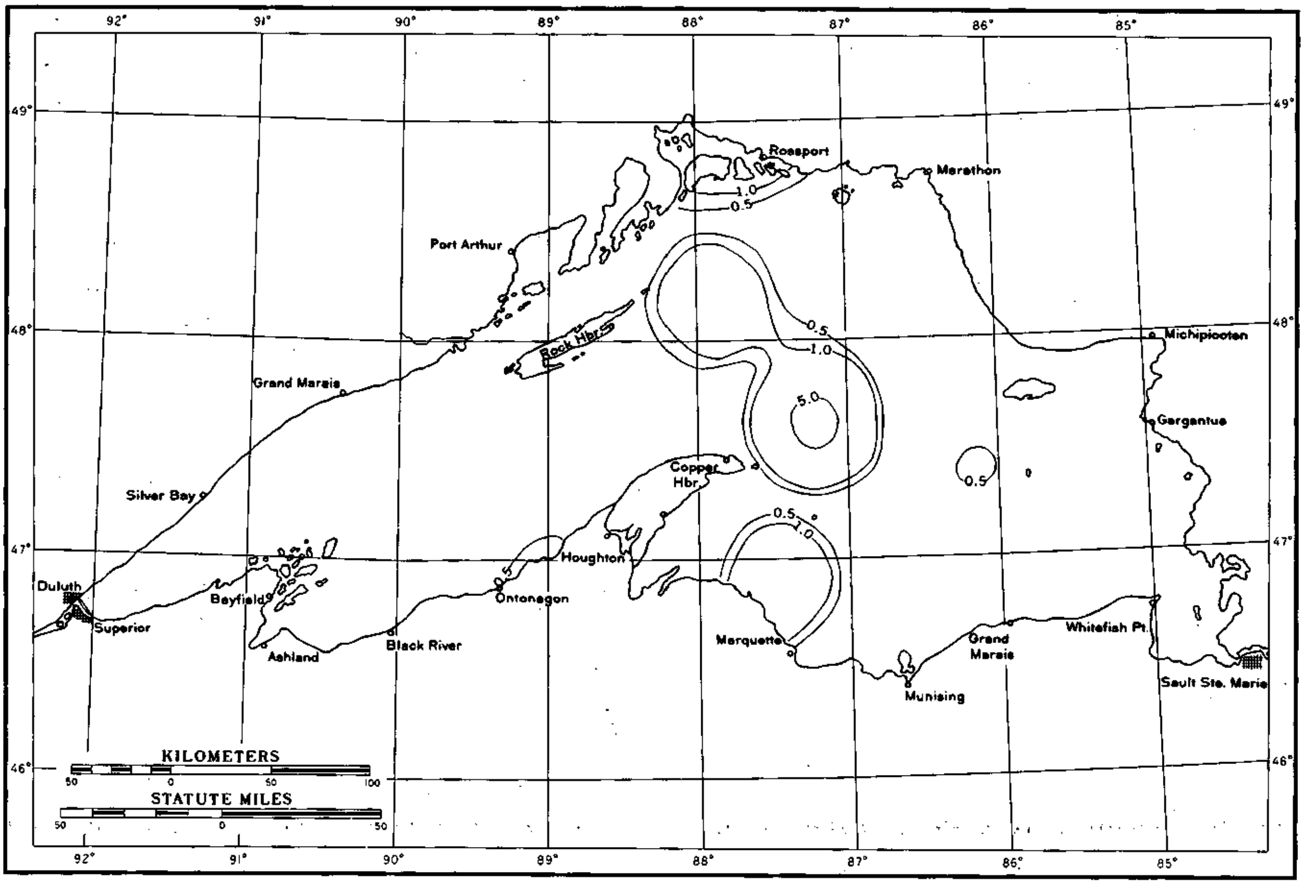

FIGURE 4–67 One Meter Turbidity (J.T.U.) in Lake Superior; April 13–23, 1970
Canada Centre for Inland Waters, 1970

Thunder Bay, and Marquette. The western arm was not included in the survey. A correlation between J.T.U. and photocell transparency has not been established. However, the anomalies are evident with either technique.

3.8.4 Lake Michigan

Light penetration in Lake Michigan (Beeton[50]) was somewhat similar to that of the Apostle Island area of Lake Superior in 1958 in that the greatest transparency was in the green (490–540 μ) wavelength range (Figure 4–55). A later comparison is not available.

In 1970 the U.S. Lake Survey, Corps of Engineers, conducted limnological investigations in the northern half of Lake Michigan. Seasonal variations in water clarity conform with the general annual lake cycle as earlier described, with differences in distribution primarily influenced by basin physiography and man-made developments. Mean transparency in late spring (Figure 4–68) was highest in the deepest portion of the lake with lower transparency in the nearshore and the shallower northern portion. Because the main body of the lake is still isothermal at this time of year, transparency varies little from water surface to bottom. The east shore from Little Traverse Bay to Mackinaw City has the highest transparency at this particular time because high clarity open lake water is being driven towards the shore. Transparency is low at the outflow from Green Bay into the lake. This turbid water disperses throughout the water column and moves with the general lake circulation contrasting with conditions later in the year when the lake is stratified and the outflow from Green Bay is largely dispersed within the epilimnion over broader areas.

3.8.5 Lake Huron

Most investigations in Lake Huron have been concerned with Saginaw Bay. Investigation of the bay and adjacent portions of southern Lake Huron (Beeton[53]) demonstrated that variations in transparency (Figure 4–69) correlate with flow of lake water into Saginaw Bay along the northwest shore and out along

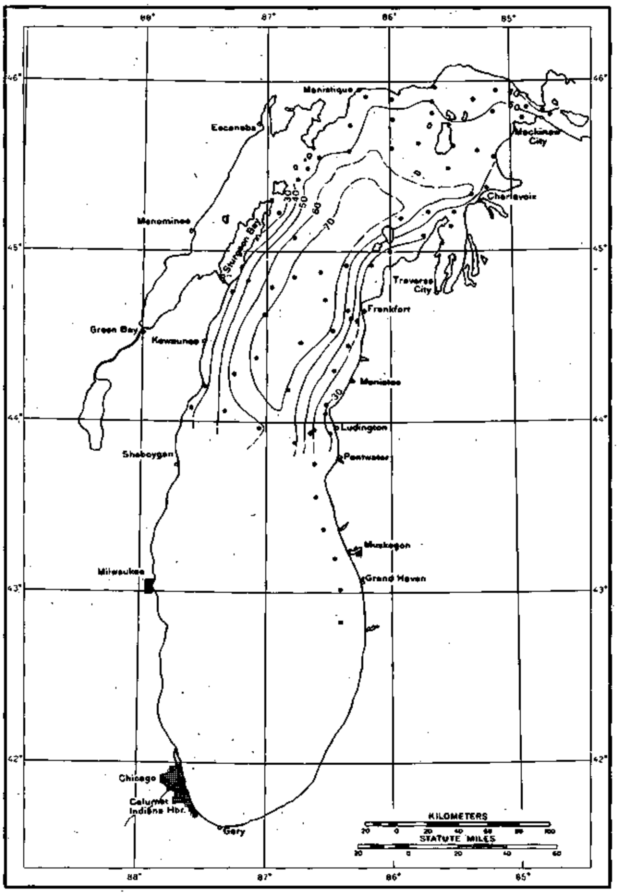

FIGURE 4–68 Mean Percent Transparency of Lake Michigan; Cruise 1, May 23 to June 8, 1970

the southeast shore. The pattern also matches that by Ayers[26] in one of the new lakewide investigations in Lake Huron which was conducted during 1954. In June (Figure 4–70) transparency was high in mid-lake and lower along the shore, especially in the region of Saginaw Bay and along the southeast shore. The transparency pattern was more complex in July (Figure 4–71). High transparency (16 m) water was entering from Lake Michigan while lower transparency (3 m to 8 m) water was entering from Lake Superior. Saginaw Bay water had transparency less than 3 m. The highest transparency, 19 m, was observed in the open lake between Oscoda, Michigan, and the Bruce Peninsula. In August during the stable summer period (Figure 4–72), the lake was characterized by more uniform structure and a large area of clear water with Secchi disc readings of more than 13 m.

Surveys by Canada Centre for Inland Waters in May and October, 1970 (Figures 4–73 and 4–74) show surface transparency expressed in J.T.U. to be uniform in mid-lake during both periods. The least transparency was observed in Saginaw Bay and off Bayfield, Ontario. Greatest turbidity (lowest transparency) occurs around the periphery of the lake and, as could be expected, is most intense in regions of greatest runoff and in areas of wave scour. The relative constancy in time and space of transparency in Lake Huron reflects the physiography of the lake, the bottom and

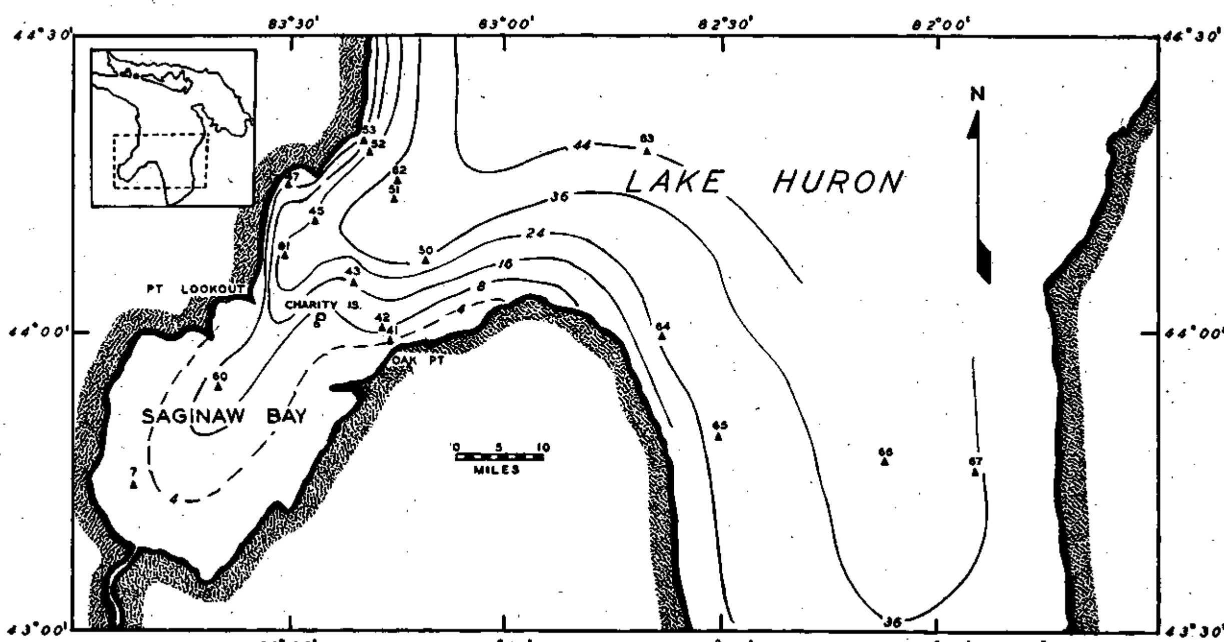

FIGURE 4–69 Average Secchi Disc Transparency (ft) in Saginaw Bay and Adjacent Lake Huron; June to August, 1956

Beeton, 1958

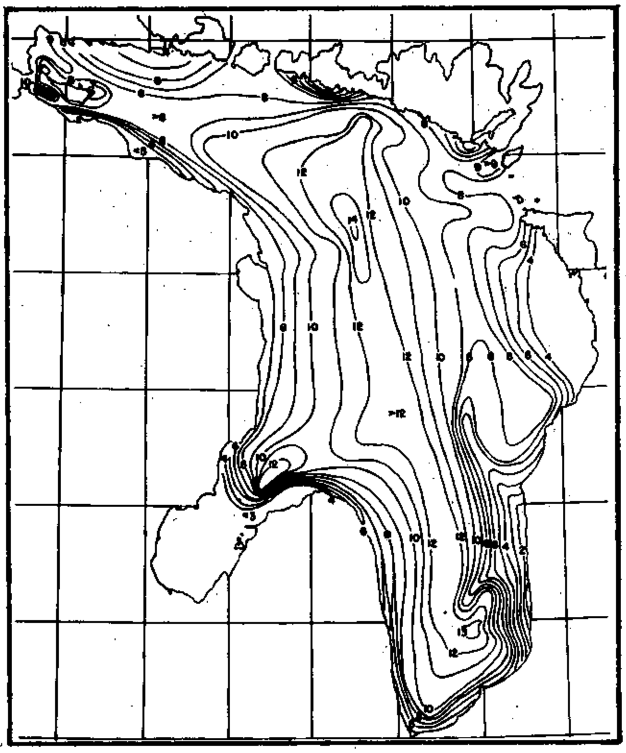

FIGURE 4–70 Secchi Disc Transparency (m) in Lake Huron; June, 1954

Ayers, 1956

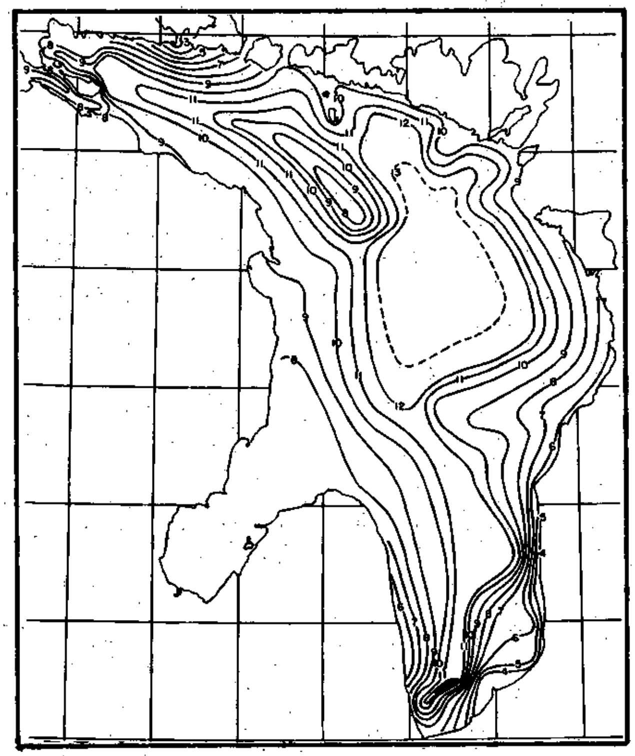

FIGURE 4–72 Secchi Disc Transparency (m) in Lake Huron; August, 1954

Ayers, 1956

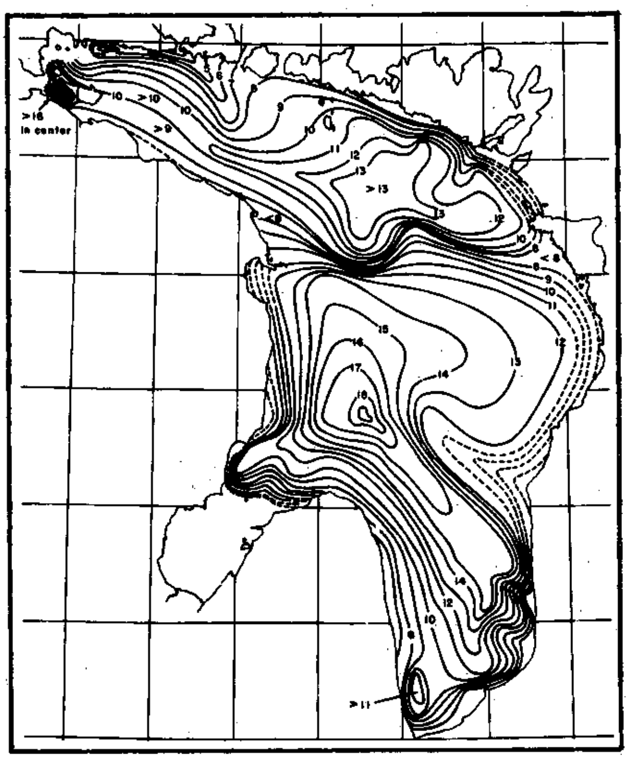

FIGURE 4–71 Secchi Disc Transparency (m) in Lake Huron; July, 1954

Ayers, 1956

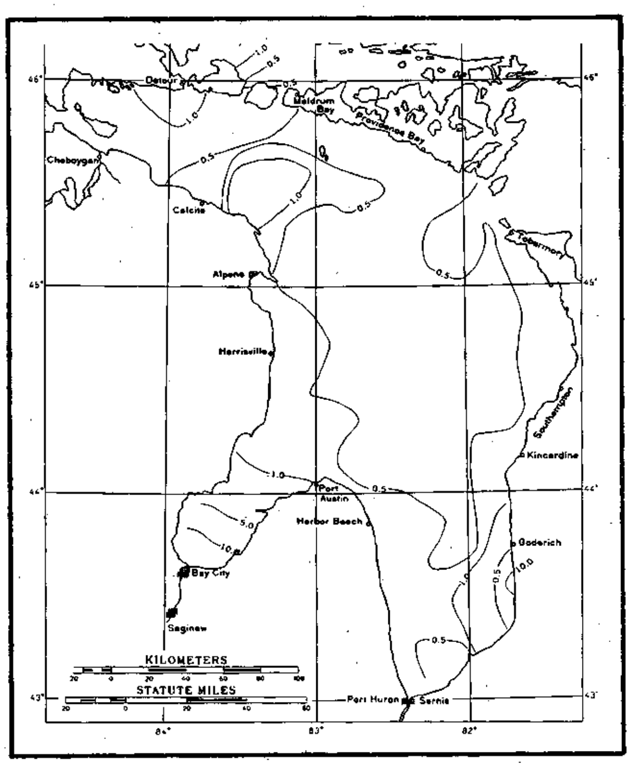

FIGURE 4–73 One Meter Turbidity (J.T.U.) in Lake Huron; May 11–21, 1970

After Canada Centre for Inland Waters, 1970

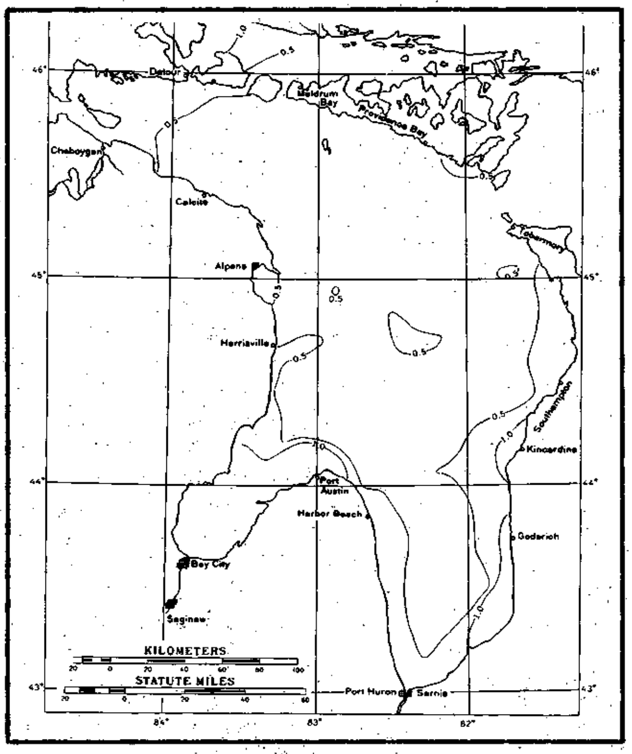

FIGURE 4–74 One Meter Turbidity (J.T.U.) in Lake Huron; September 29 to October 7, 1970
After Canada Centre for Inland Waters, 1970

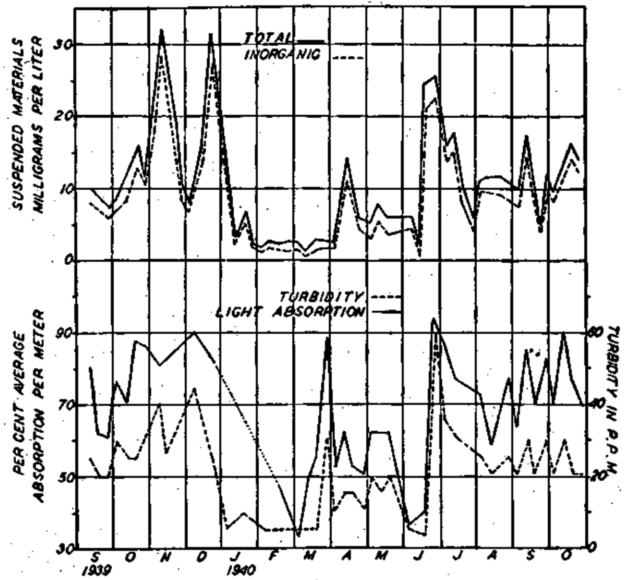

FIGURE 4–75 Weight of Suspended Matter in Western Lake Erie (upper section) and Relation Between Turbidity and Rate of Light Absorption (lower section)
Chandler, 1942

shore composition, and generally isolates through obvious contrasts those areas with man-made influx.

3.8.6 Lake Erie

Wright,[917] reporting on a 1929 to 1930 study of western Lake Erie, found that portion of the lake to be characterized by low transparency. Most Secchi disc readings were in the 1 m to 2 m depth range. A seasonal change was observed with maximum transparency in summer, next lowest in fall, and the lowest in the spring. The two factors listed by Verduin[857] as contributing most to the turbidity in the western basin are phytoplankton and fine silt primarily from the Maumee River.

Chandler[132] reported on the variations in turbidity in western Lake Erie during 1939 to 1940 in which rapid changes in the depth of light penetration affect the aquatic organisms. Turbidity ranged from a minimum of 5 ppm during periods of ice cover and periods of calm in late spring and early summer to a maximum of 230 ppm in autumn and late winter. Periods of high turbidity were related to high winds, high precipitation, or restricted ice cover. Inorganic suspended matter ranged from 50 percent to 95 percent of the total (Figure 4–75). The percentage of organic matter varied with plankton blooms. Chandler found that an ice cover of 40 cm thickness attenuated no more surface light than 40 cm of water containing 20 ppm or more turbidity. Since the turbidity may be 20 ppm or greater for 7 months and an ice cover may be present for 2.5 months, the combined effect is to greatly limit the light penetration. On the average, surface light penetration correlated with turbidity as follows: 8 m—5 ppm; 6 m—10 ppm; 4.5 m—15 ppm to 20 ppm; 2.7 m—25 ppm to 30 ppm; 2.0 m—35 ppm to 40 ppm; 1.5 m—60 ppm; and 0.8 m—115 ppm.

A Secchi disc survey of the western basin of Lake Erie in 1959 (Beeton[51]) indicated low transparencies ranging from 1.2 m to 1.8 m around the islands. In the central basin disc depths ranged from 1.2 m to 10.1 m with the lower values in shallow areas. In 1960 the western basin again had a low transparency with disc depth ranging from 0.6 m to 1.2 m. The majority of the disc readings were around 7.3 m in the central basin.

Pinsak[615] used a photocell device to measure *in situ* transparency in Lake Erie during summer and fall, 1965. Transparency measurements, relative to 100 percent in air, were made at each station and averaged from the surface to total depth. Spatial distribution of

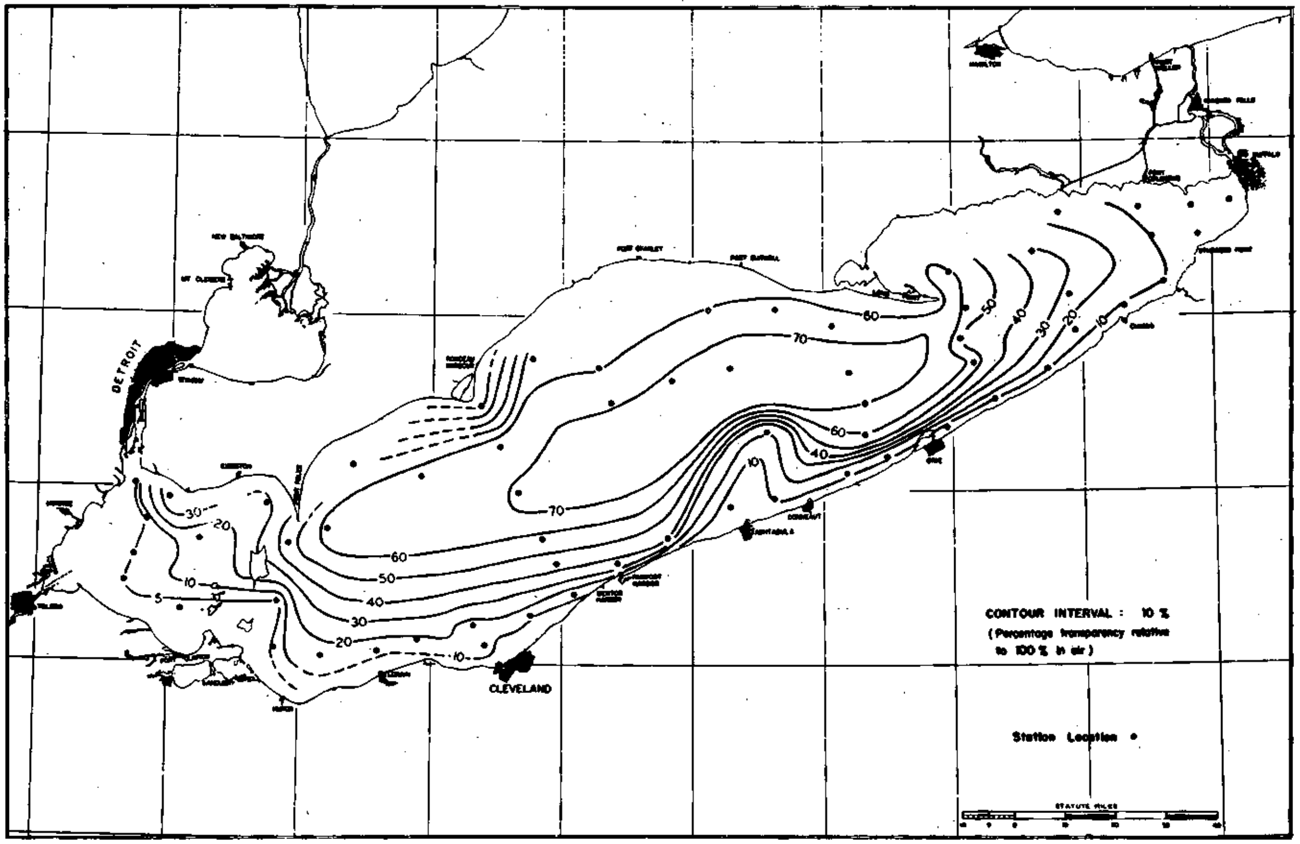

FIGURE 4–76 Water Transparency in Lake Erie During July 15–30, 1965 Pinsak, 1968

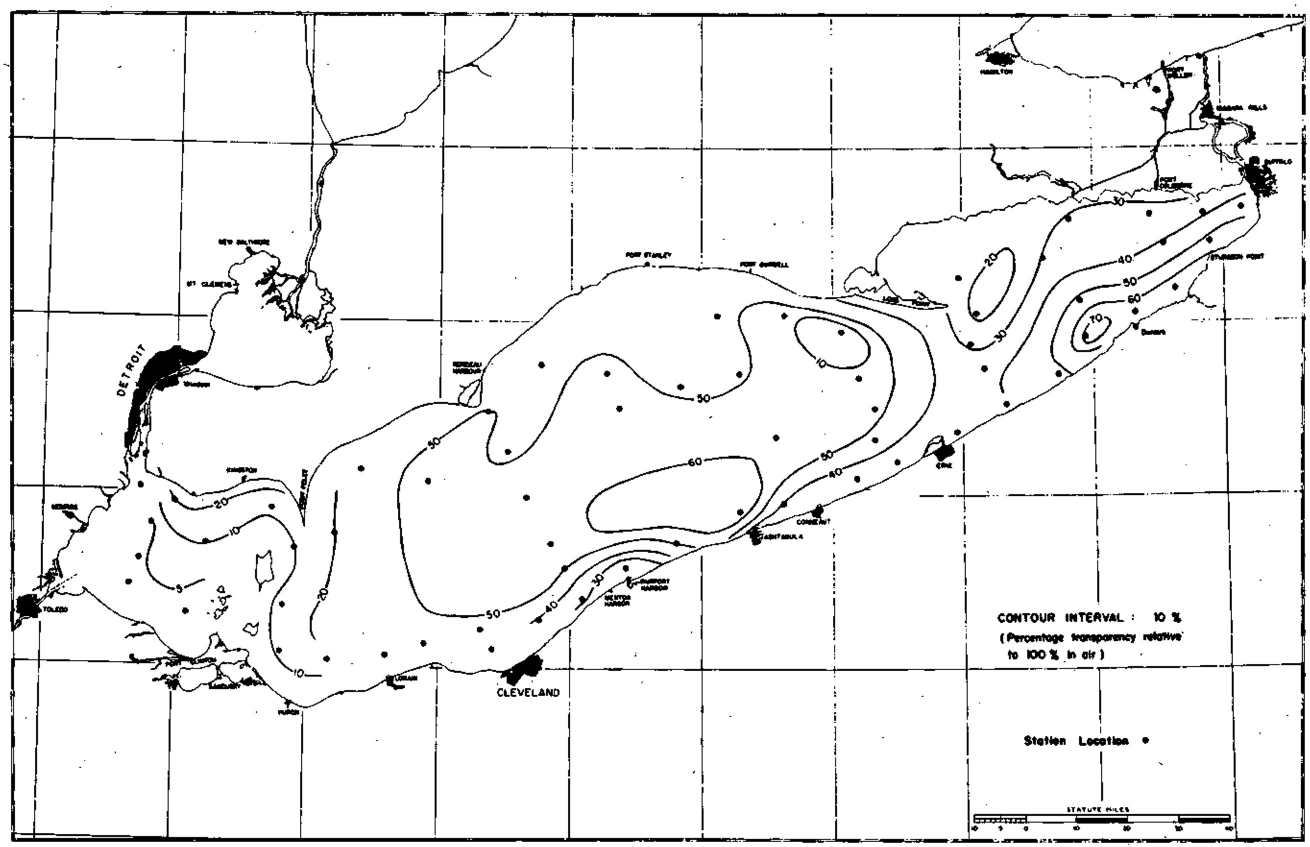

FIGURE 4–77 Water Transparency in Lake Erie During August 9–20, 1965 Pinsak, 1968

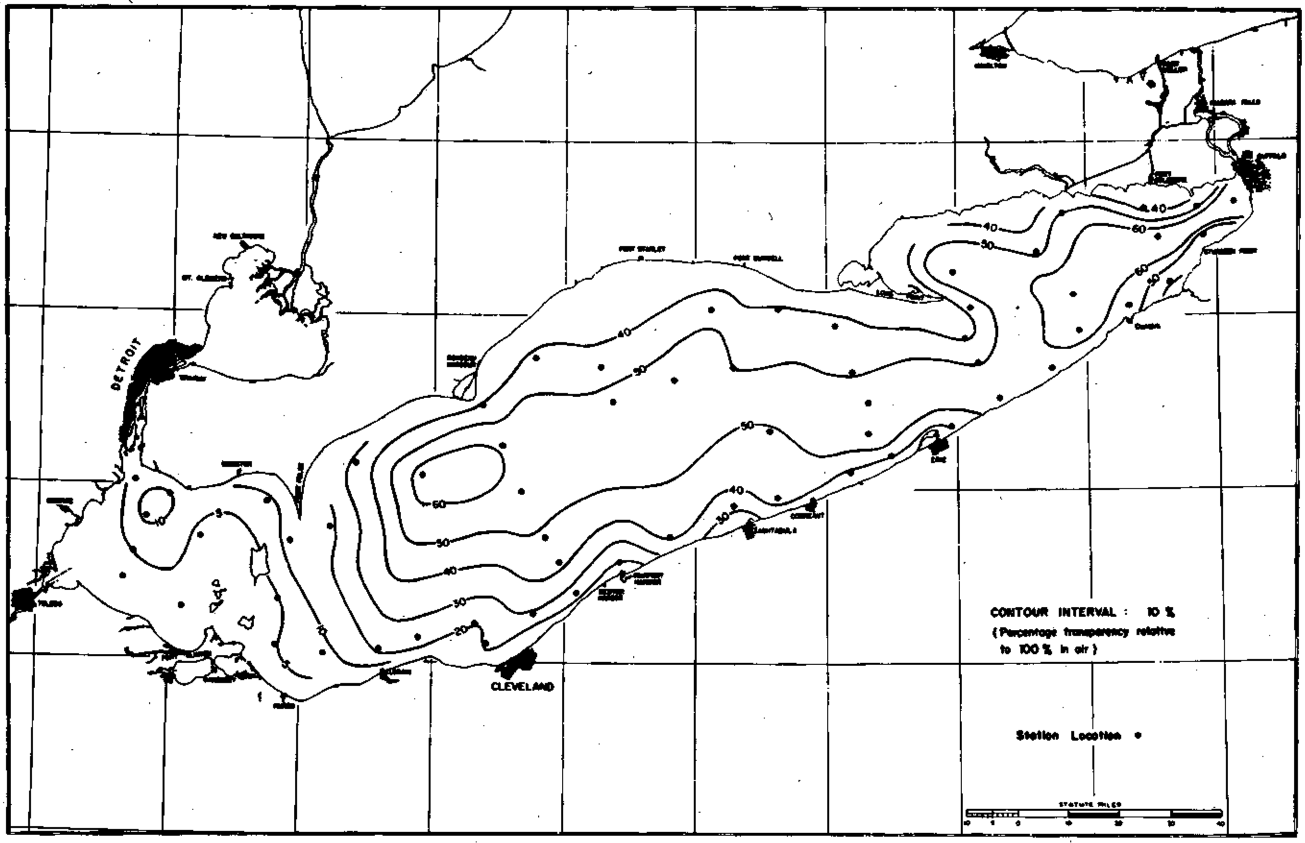

FIGURE 4–78 Water Transparency in Lake Erie During August 31 to September 10, 1965

Pinsak, 1968

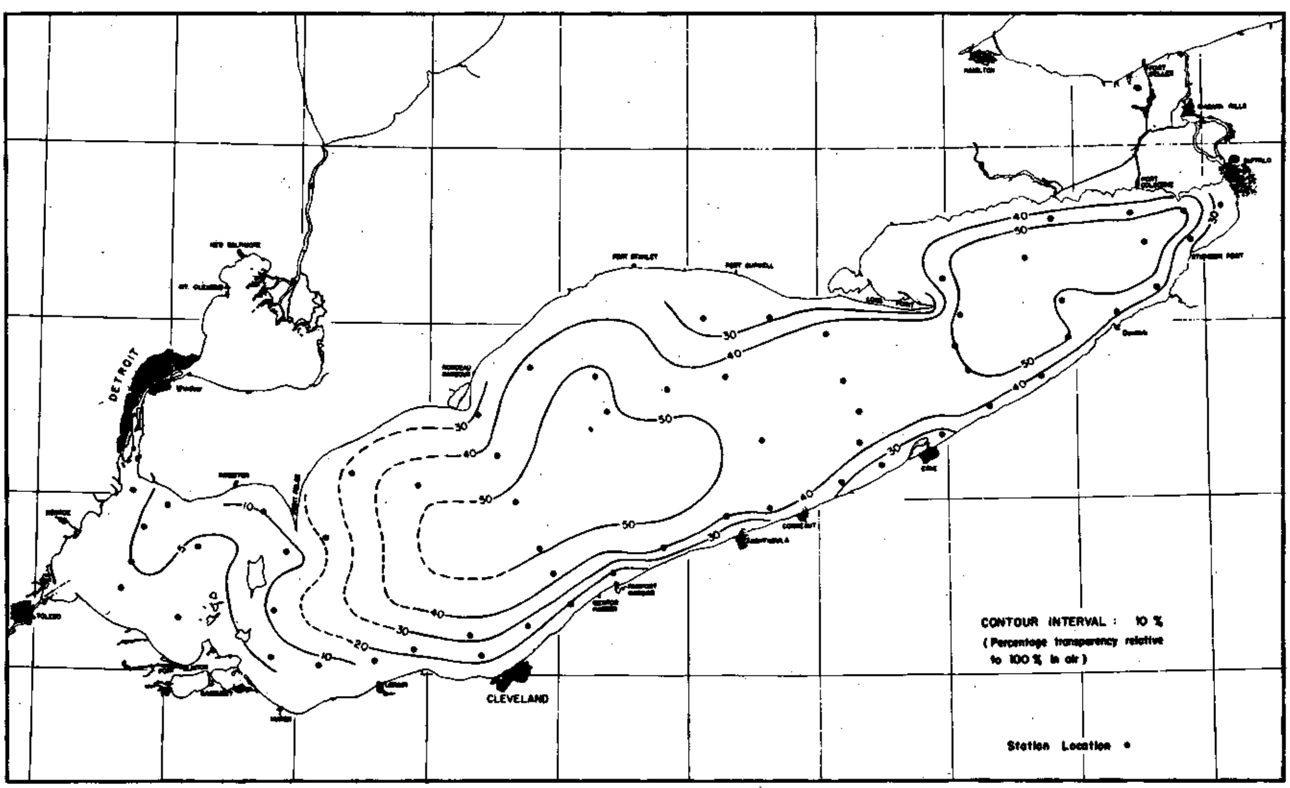

FIGURE 4–79 Water Transparency in Lake Erie During September 14–22, 1965

Pinsak, 1968

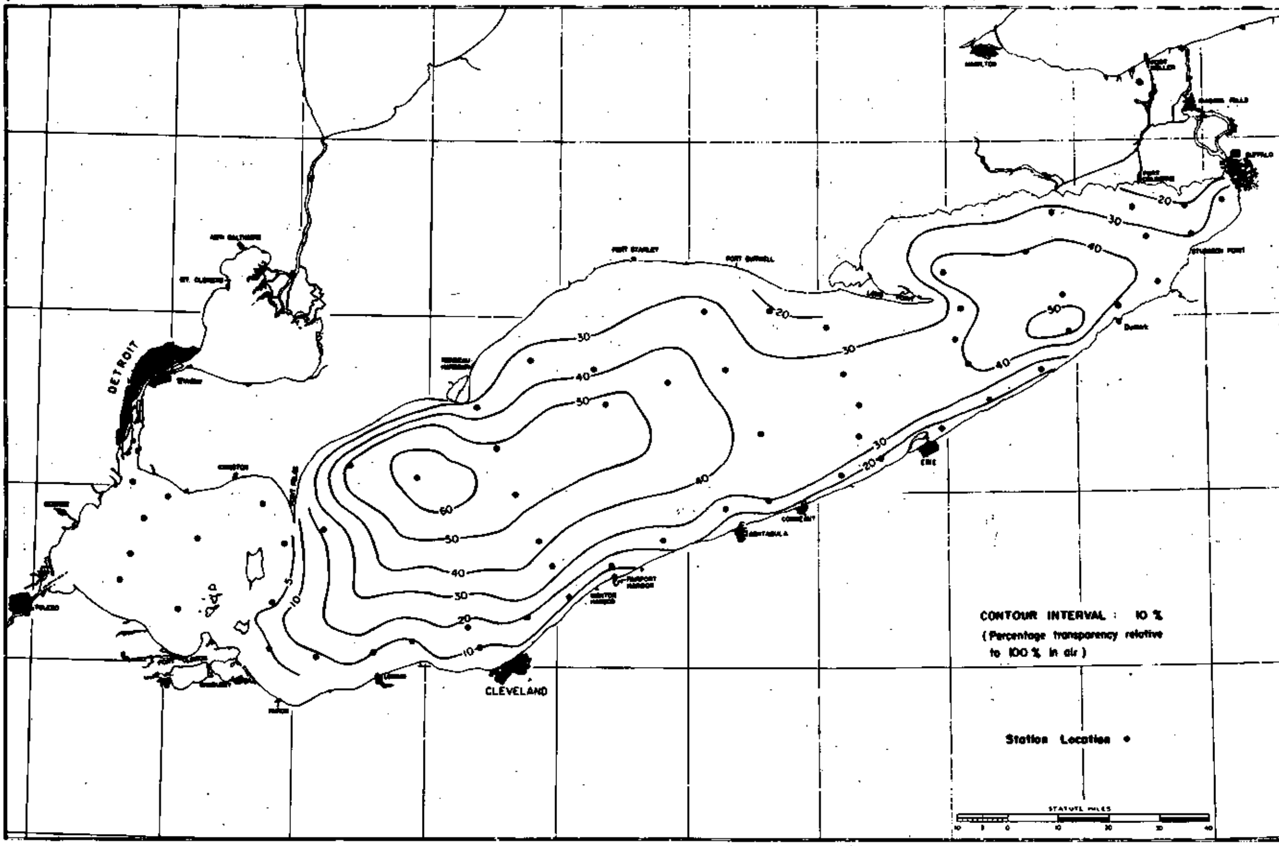

FIGURE 4–80 Water Transparency in Lake Erie During October 11–26, 1965 Pinsak, 1968

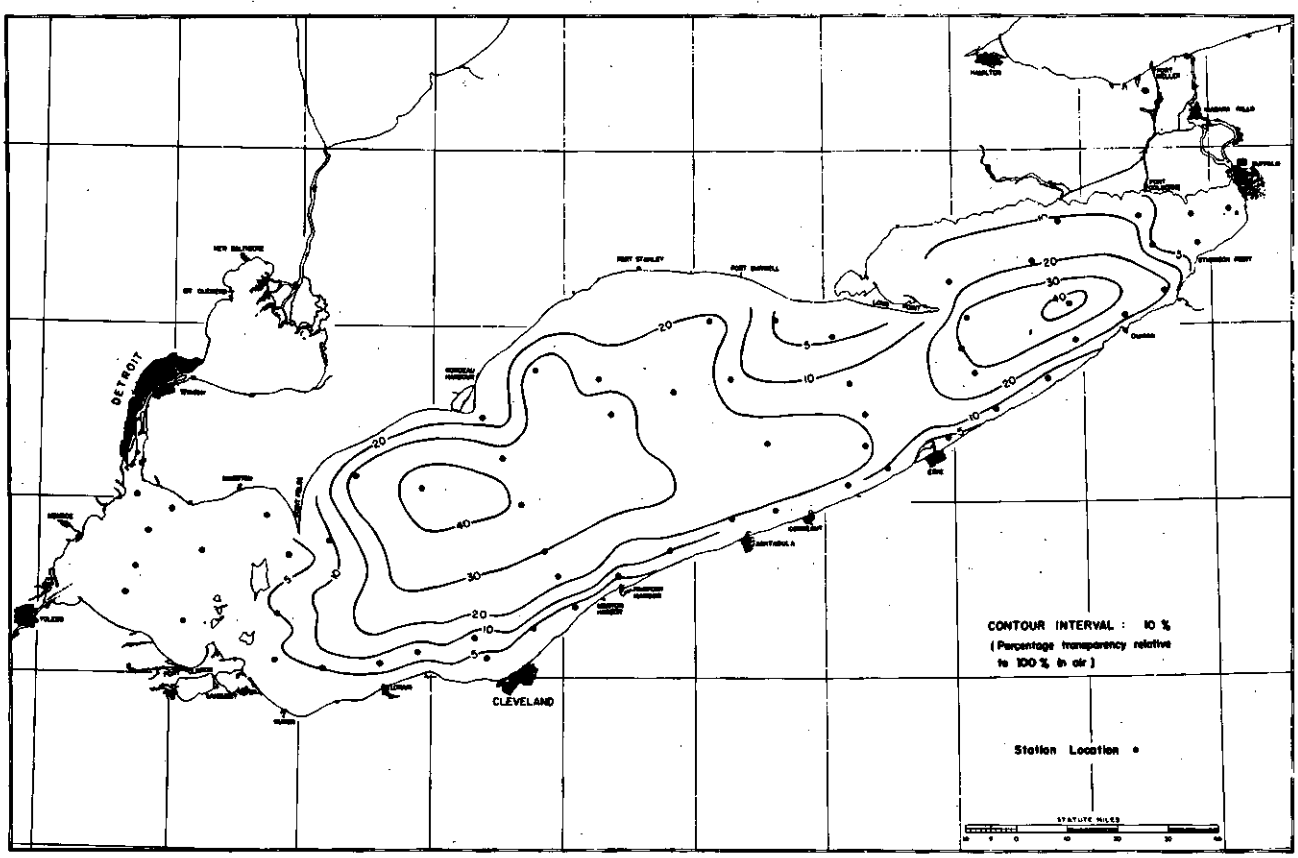

FIGURE 4–81 Water Transparency in Lake Erie During October 26 to November 9, 1965 Pinsak, 1968

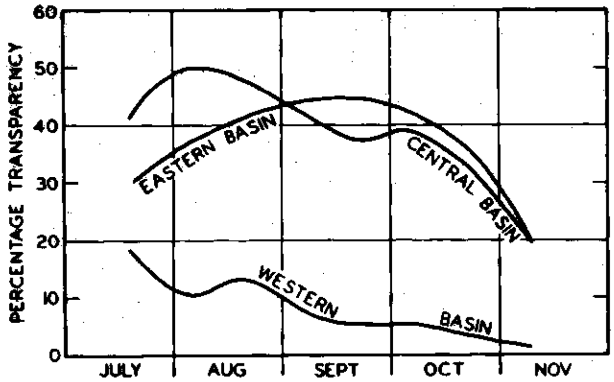

FIGURE 4–82 Average Water Transparency in Lake Erie During 1965

Pinsak, 1968

the transparency for specific time periods could then be related to recurring seasonal variations (Figures 4–76 through 4–81). The low transparency observed in the western basin agrees with findings of earlier investigators. Highest transparency in July (Figure 4–76) agrees with Chandler's[132] 1939 to 1940 observations. A dense algal bloom in September in the western basin could not be detected by the transparency meter (Figure 4–79) as the turbidity was high enough to mask the contribution by the algal bloom (Pinsak[615]). Several of the cruises (Figures 4–76, 4–77, and 4–78) indicated relatively high transparency water in the offshore central basin area between Avon Point and Ashtabula, Ohio, as observed by Beeton[51] in 1959–60. This phenomenon could be observed any time the lake was stratified and a northerly wind moved offshore water against the shore.

Each of the three basins have different characteristics relating to physiography. However, there is a general decrease in transparency within all three from July into November (Figure 4–82). Pinsak[615] concluded that the low western basin transparency is due to tributary influx, shallow water, the nature of the organic mud bottom, and the fact that the bulk of the sediment remains in the western basin. Seasonal increase of suspended material is 40 percent in the western basin and 60 percent in the central and eastern basins. Masses of high transparency water are moved primarily by wind stress within the central and eastern basins and may mask or distort the effect of tributary influx. A direct correlation was found between transparency and temperature with the least transparency occurring below the thermocline and above the sediment-water interface. Stratification of suspended material persists in the hypolimnion over extended periods indicating minimal circulation and is more complex in structure than is indicated by the temperature, whereas the structure in the epilimnion varies greatly. Profiles made possible by the *in situ* device facilitate the detection of features produced by tributary influx and wave effects.

Canada Centre for Inland Waters measured transparency of Lake Erie surface water during 1970 (Figures 4–83 through 4–86). Although Jackson Turbidity Units (J.T.U.) are not compatible with other units of measurement, patterns can be compared. Low turbidity occurred in the eastern basin and deepwater areas of the central basin in April (Figure 4–83). Turbidity was highest in the shallow western basin and nearshore areas, especially in proximity to tributary influx. The lake was the least turbid in late July (Figure 4–84). Turbidity increased in the fall (Figure 4–85) especially in the western basin and along the shoreline, and continued to increase into December (Figure 4–86), especially in the western basin and along the southern shore.

Although both the techniques used to measure transparency and the scope of these observations have varied, the most significant point common to all of the studies is the fact that similar physical phenomena have been noted on a seasonal basis indicating that physical characteristics of Lake Erie have not changed significantly during the past 40 year period.

3.8.7 Lake Ontario

Lake Ontario, like Lake Erie, contains relatively high concentrations of suspended and dissolved solids. As a result, the shorter wavelengths are attenuated more and the greatest light penetration (Beeton[50]) is in the long wavelength range (Figure 4–55).

Canada Centre for Inland Waters examined surface turbidity in Lake Ontario during 1970. In the spring turbidity around the periphery of the lake was high compared to open water portions because of the associated turbulence and runoff (Figure 4–87). The highest turbidity of 10.0 J.T.U. was observed off the mouth of the Genesee River at Rochester, New York. Surface turbidity generally decreased in summer, but then increased in late August in midlake to the 2.0 J.T.U. range (Figure 4–88) due probably to plankton concentrations. By mid-September (Figure 4–89) turbidity was

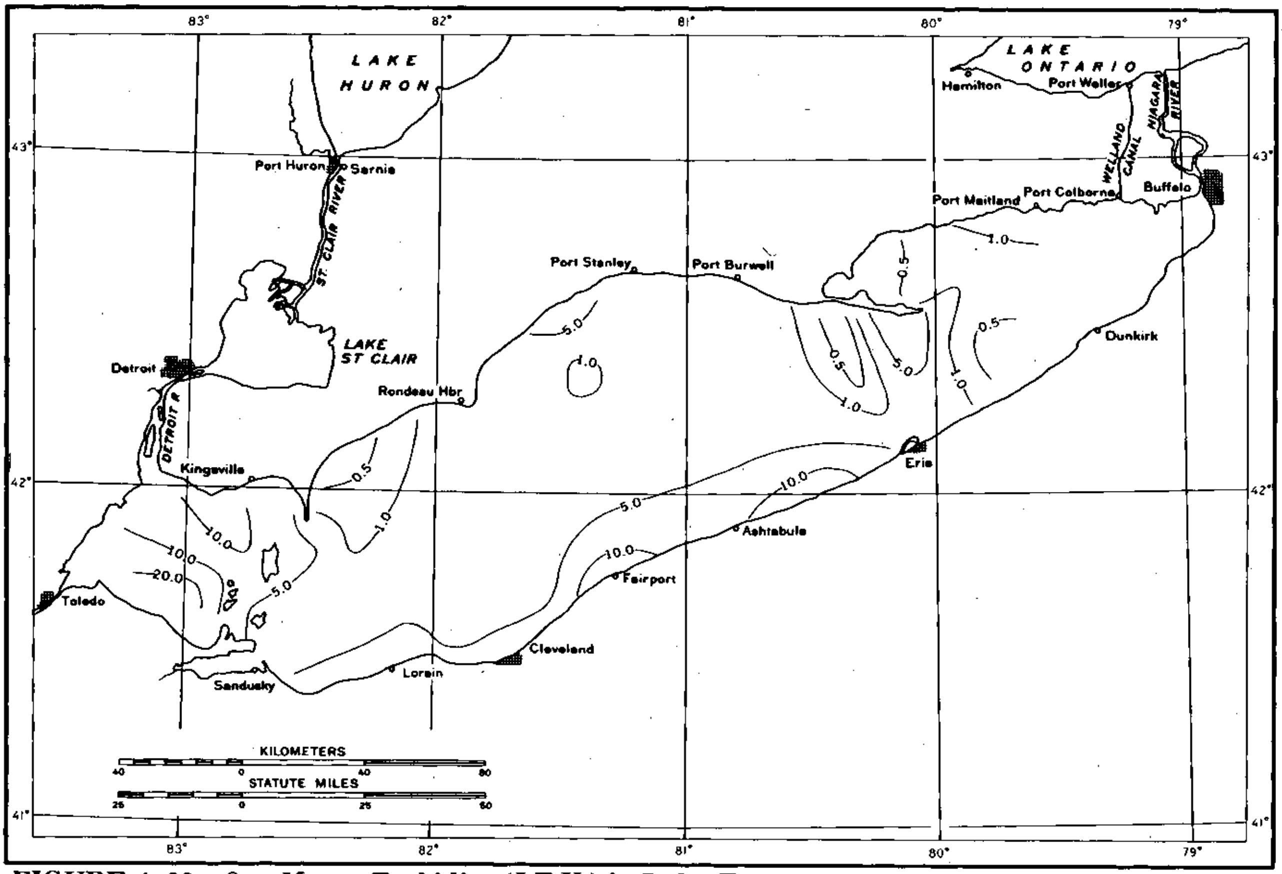

FIGURE 4–83 One Meter Turbidity (J.T.U.) in Lake Erie; April 6–11, 1970

Canada Centre for Inland Waters, 1970

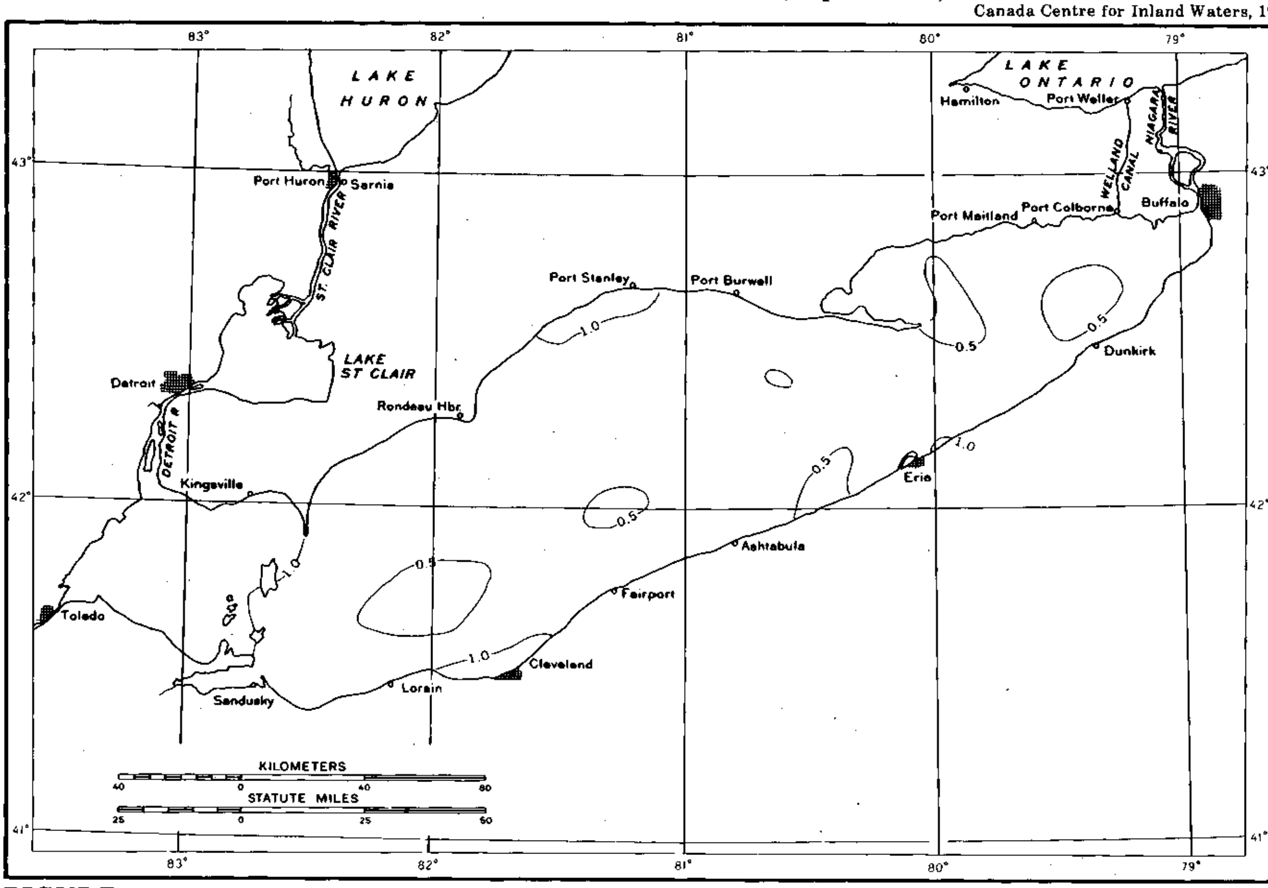

FIGURE 4–84 One Meter Turbidity (J.T.U.) in Lake Erie; July 27 to August 2, 1970

Canada Centre for Inland Waters, 1970

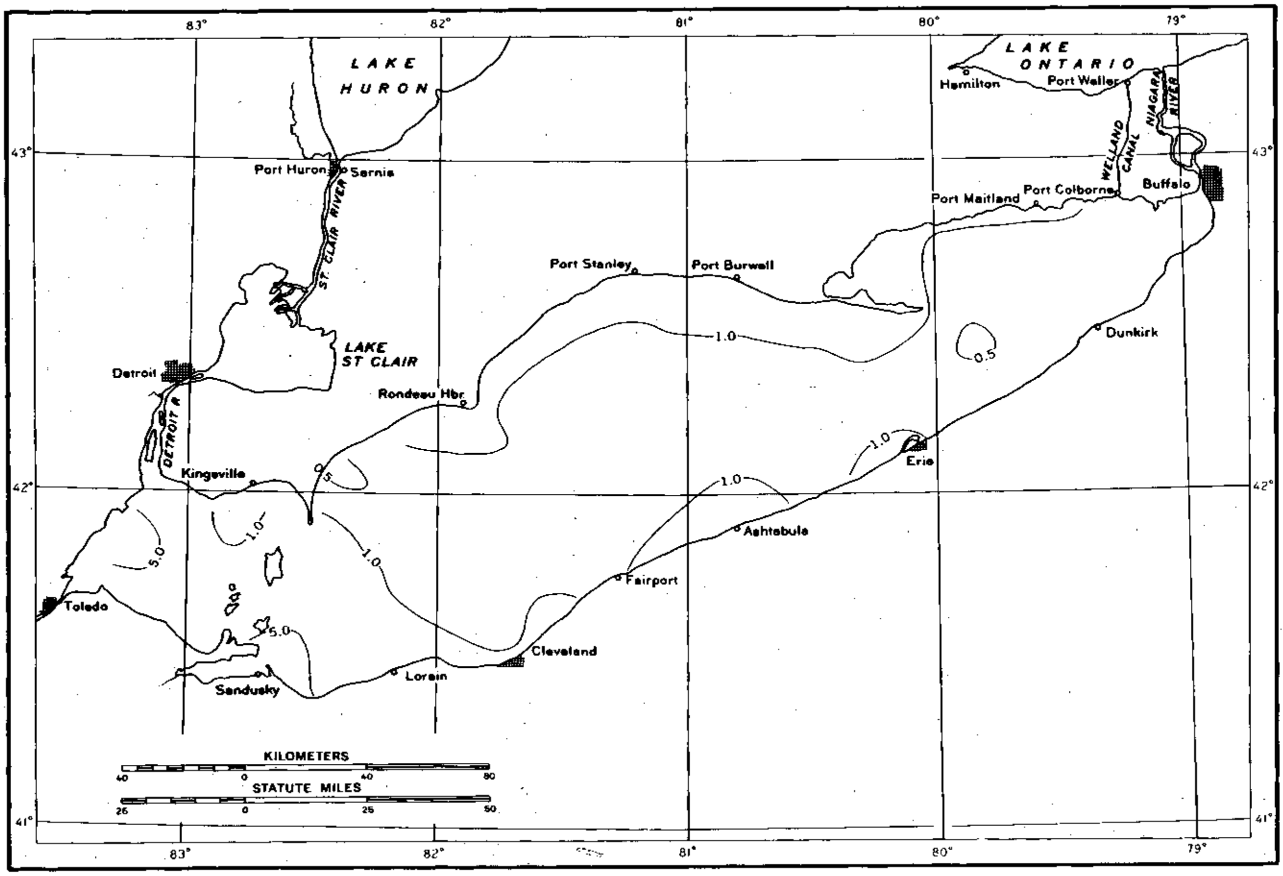

FIGURE 4–85 One Meter Turbidity (J.T.U.) in Lake Erie; October 20–25, 1970

Canada Centre for Inland Waters, 1970

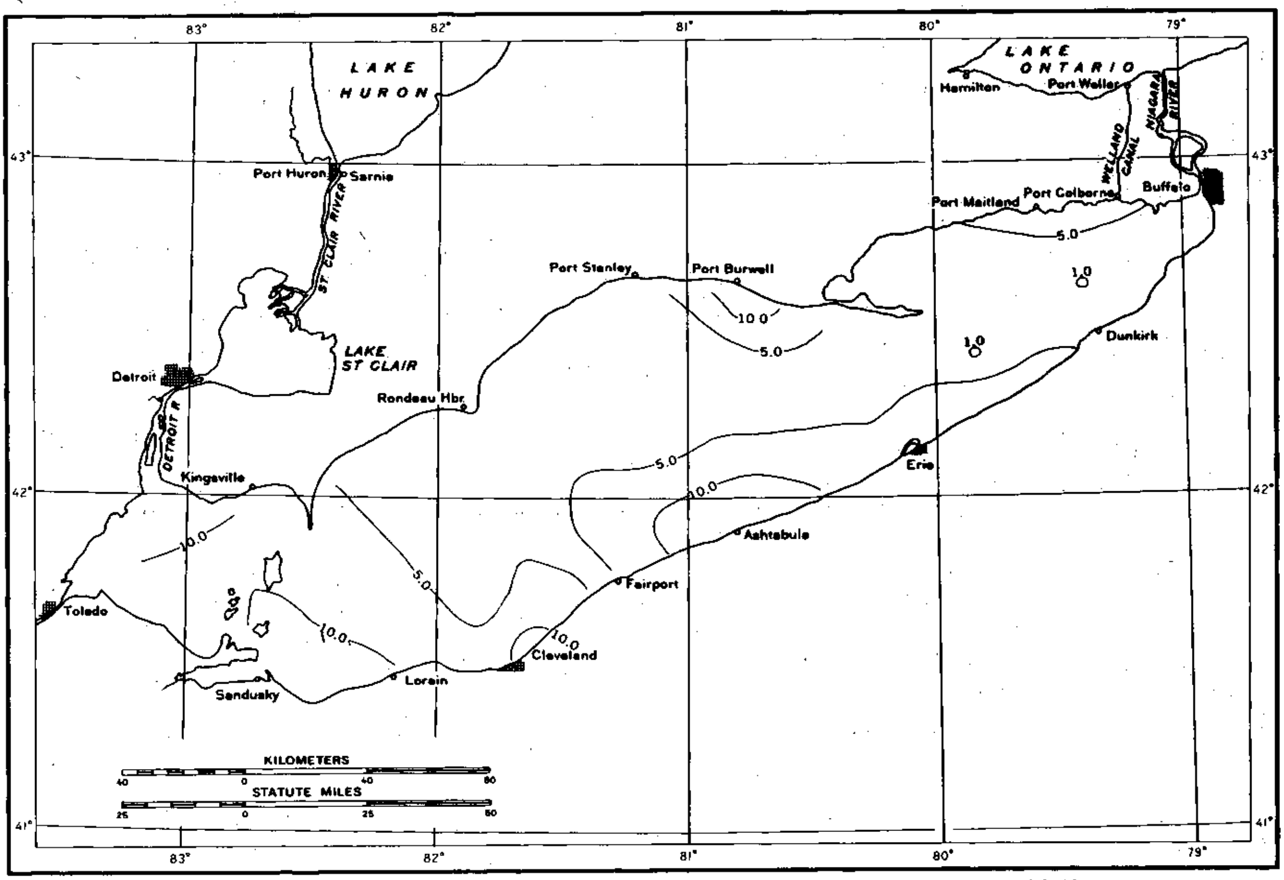

FIGURE 4–86 One Meter Turbidity (J.T.U.) in Lake Erie; December 13–18, 1970

Canada Centre for Inland Waters, 1970

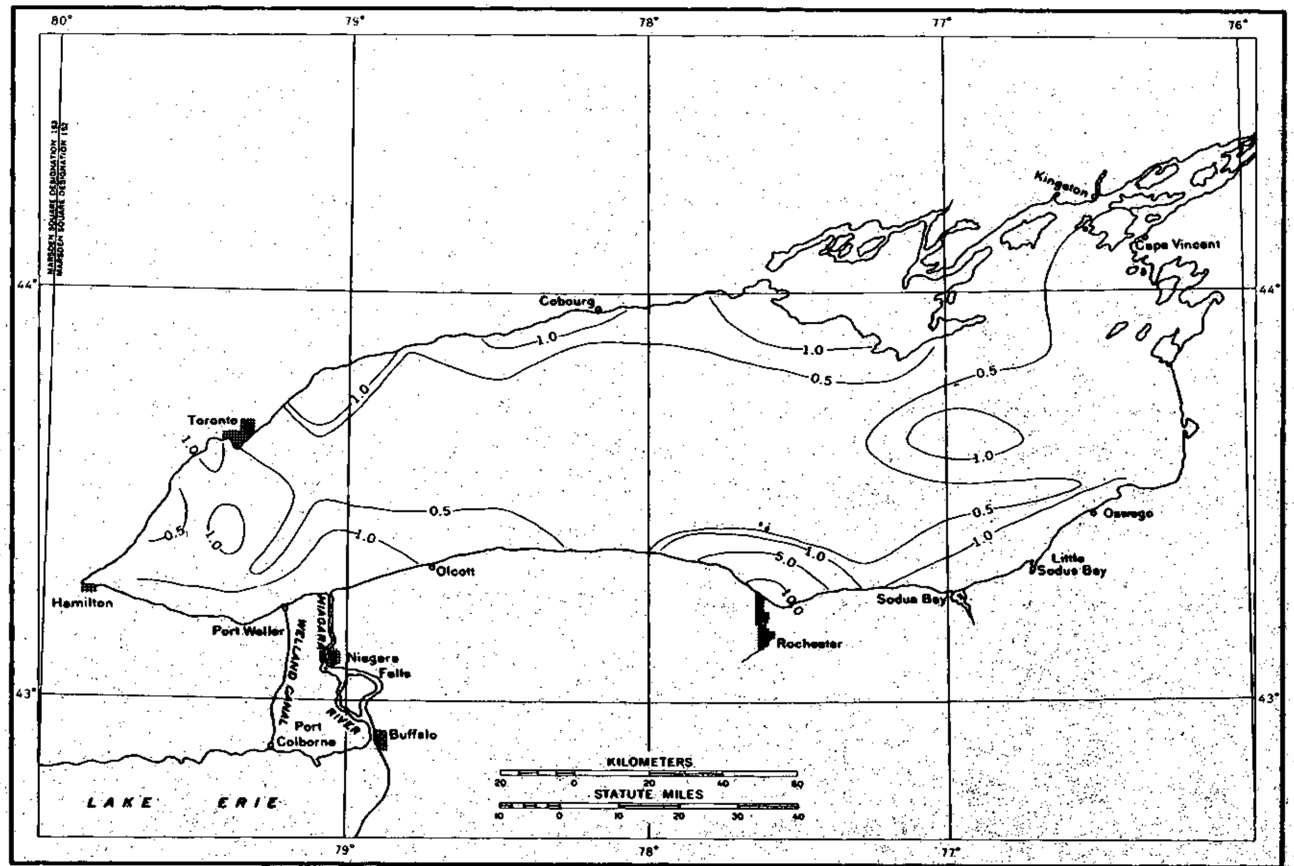

FIGURE 4–87 One Meter Turbidity (J.T.U.) in Lake Ontario; March 31 to April 5, 1970
Canada Centre for Inland Waters, 1970

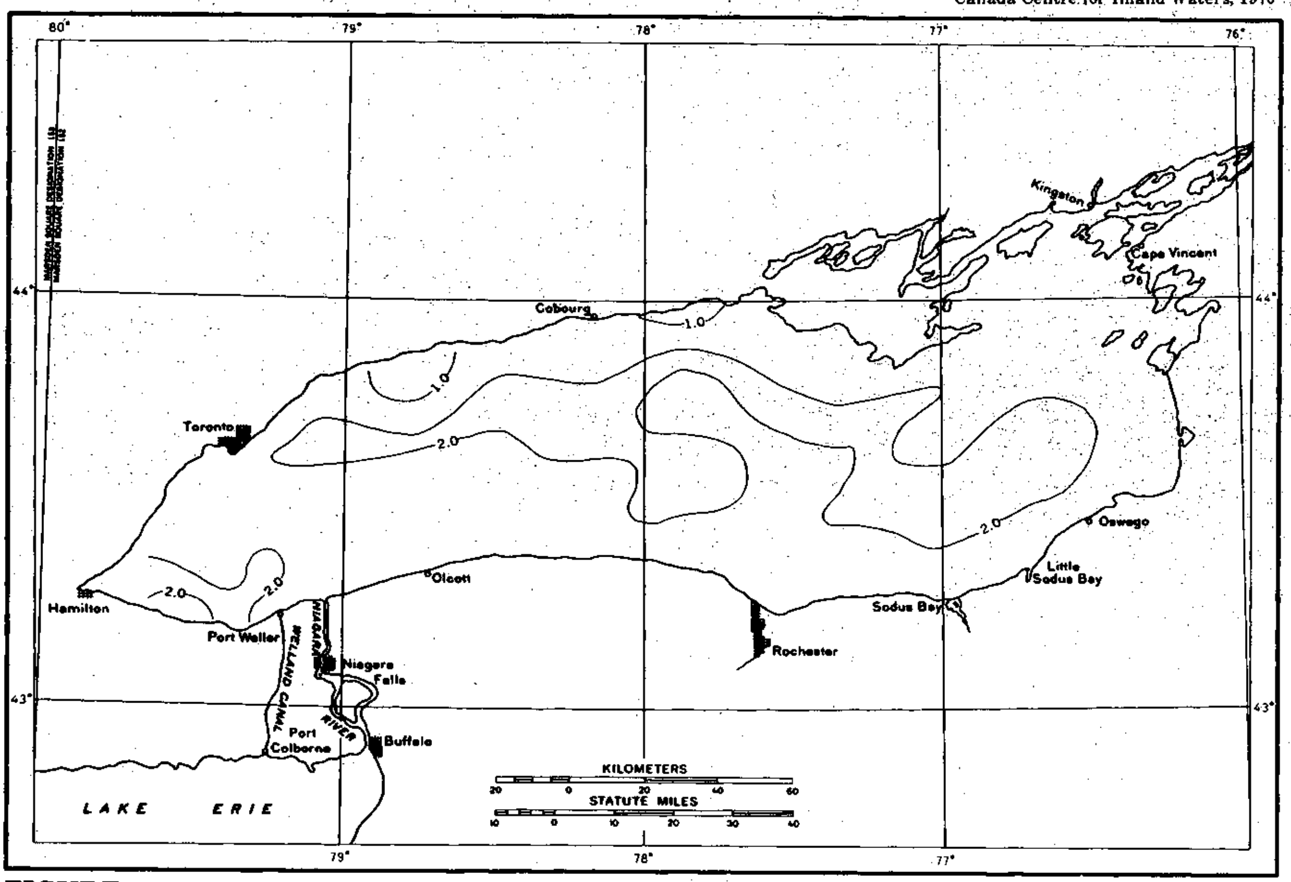

FIGURE 4–88 One Meter Turbidity (J.T.U.) in Lake Ontario; August 17–21, 1970
Canada Centre for Inland Waters, 1970

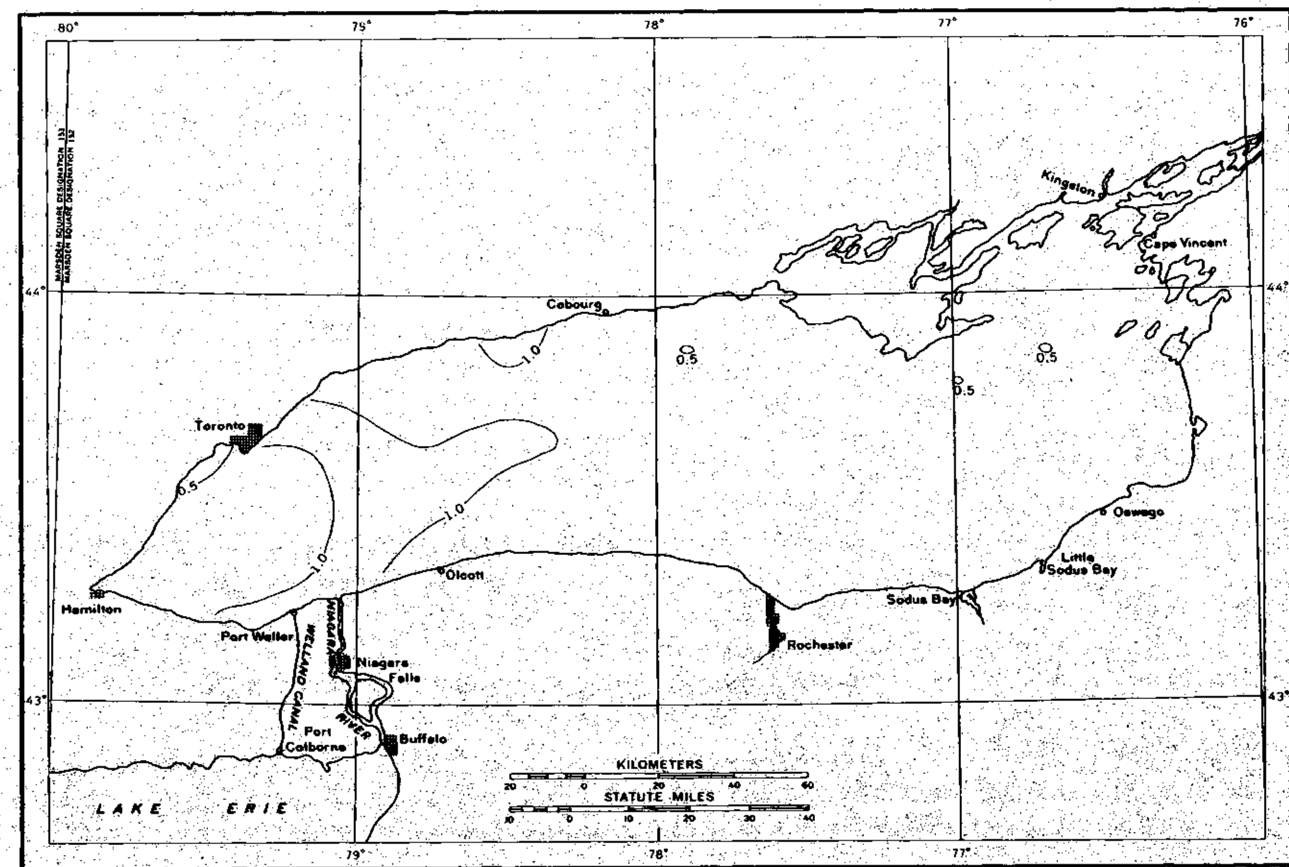

FIGURE 4–89 One Meter Turbidity (J.T.U.) in Lake Ontario; September 14–19, 1970
Canada Centre for Inland Waters, 1970

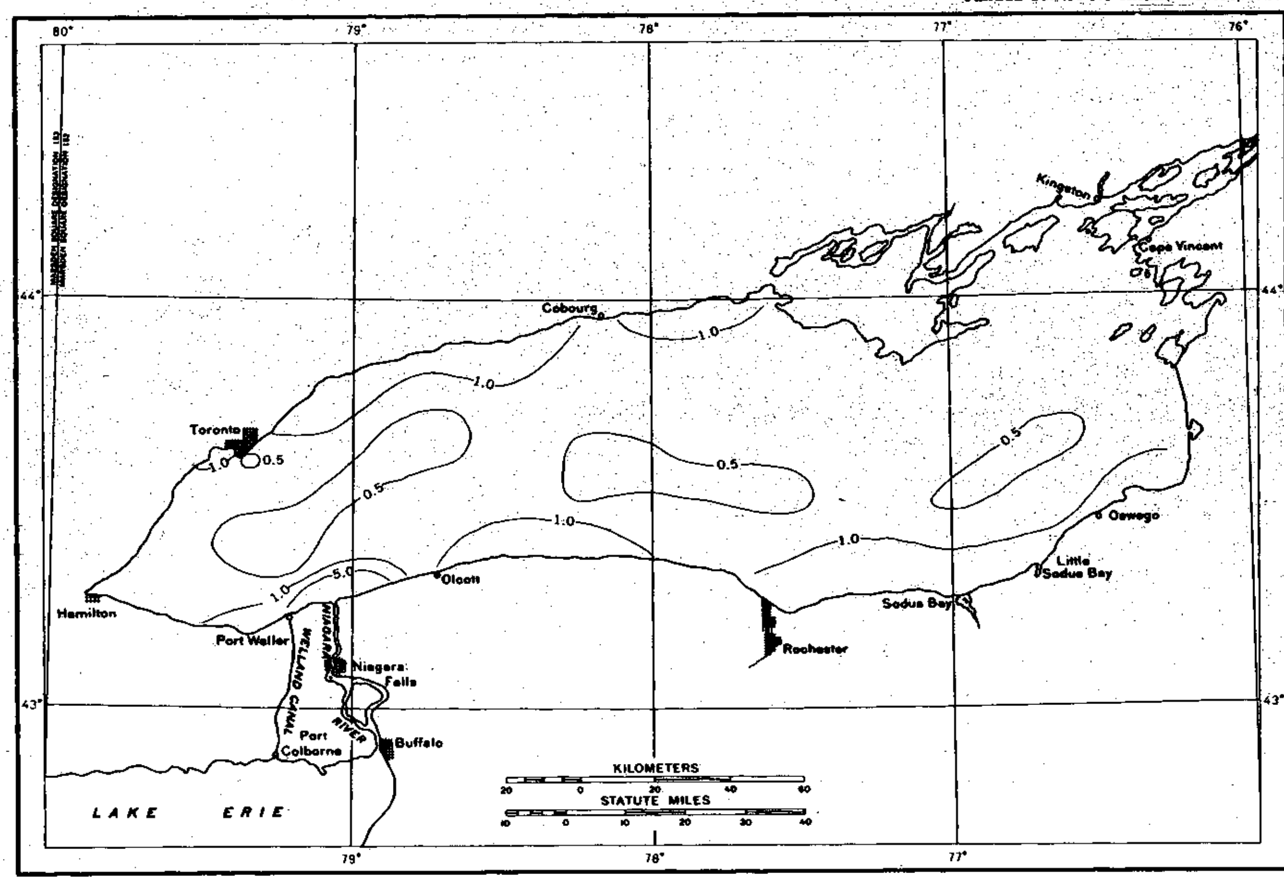

FIGURE 4–90 One Meter Turbidity (J.T.U.) in Lake Ontario; December 7–12, 1970
Canada Centre for Inland Waters, 1970

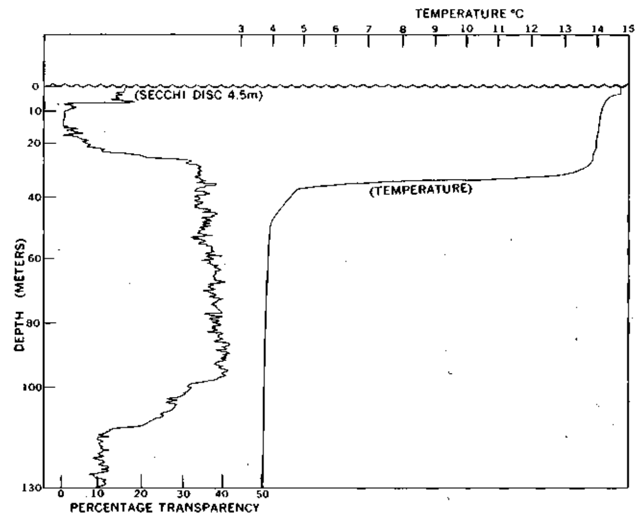

FIGURE 4–91 Temperature Transparency Relationship in Eastern Lake Ontario; October 30, 1970

Lake Survey Center, NOAA

less than 1.0 J.T.U. except for the obvious influx in the western quarter of the lake. During early December (Figure 4–90) after the lake had become isothermal and with the increased fall runoff, nearshore turbidity had increased with most of the nearshore areas greater than 1.0 J.T.U. The effect of the Niagara River is pronounced at this time with turbidity greater than 5.0 J.T.U. off the mouth.

An accurate definition of turbidity must come from examination to depth rather than at the surface. The transparency profile is basically related to temperature structure but is influenced by other factors as well. Structure is pronounced in Lake Ontario in late October (Figure 4–91). Low transparency near the surface was observed at this time over large areas of the lake. The Secchi disc transparency was 4.5 meters, disappearing just above a zone of much lower turbidiy. Transparency was then rather uniform and high from just above the thermocline to 95 meters where a zone of turbid water was lying above the bottom. As previously noted, the *in situ* meter defines struc-

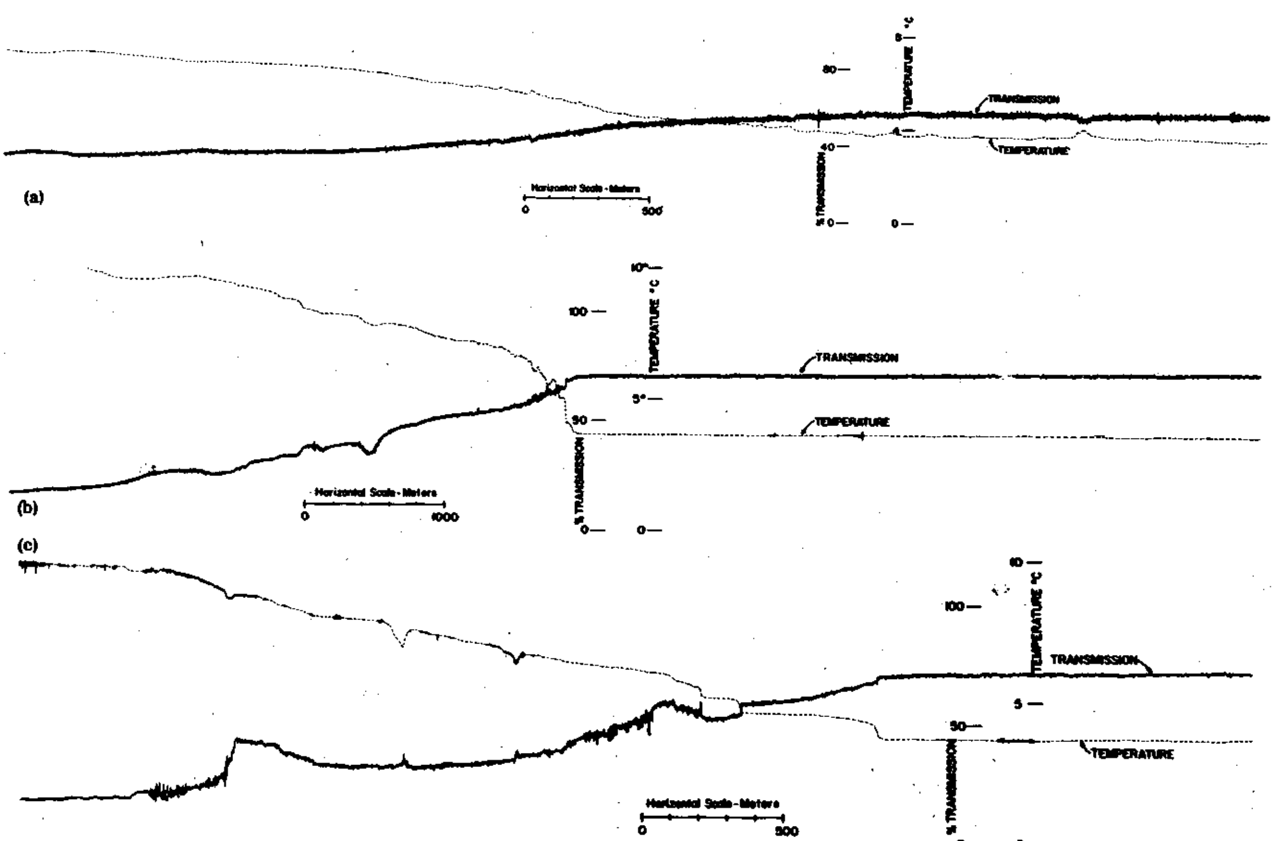

FIGURE 4–92 Three Characteristic Records of Temperature-Percent Light Transmission on Crossing the 4°C Surface Isotherm in Lake Ontario

Rodgers, 1968

tures that are not detectable on the temperature curve.

Rodgers[671] observed an inverse relationship between temperature and transparency in the region of the thermal bar. Low temperature open-lake water, less than 4°C, had high transparency, while on the shore side of the thermal bar the warm water trapped the suspended material (Figure 4–92). The low transparency was attributed to the growth of organic materials in the warmer water. Rodgers noted that a towed transmissometer may be a highly useful tool in identifying water masses.

3.9 Summary and Recommendations

The thermal regime of the Great Lakes varies on a regular basis and is fundamentally the same throughout the total geographic extent. Differences in thermal structure can be attributed to differences in heat input into the lakes and differences in total heat storage based on volume. Winds produce anomalies such as tilting of the thermocline and consequent upwelling and downwelling, and more or less intense mixing of the surface layer. Zones of downwelling along the east shores are a result of the predominant westerly wind. However, all these variations are only local and short-term irregularities superimposed on the basic thermal regime. The major control on this regime is the amount of incoming energy. The pattern remains the same; only magnitude varies in response to change in heat input. Convection or turbulent mixing is the major mechanism that distributes heat through the lake and it is controlled largely by variations in the basic physical properties of the water. Winds are the basic mixing mechanism but turbulent transport created by physical differences related to water temperature is responsible for the overall thermal structure.

During the period just prior to isothermal mixing in a lake, the total heat in a water column varies only with the vertical distribution of heat in the column. Thus, the intensity of mixing that occurs is directly related to the amount of heat in the epilimnion and the ratio of the volume of the epilimnion to that of the hypolimnion just prior to the development of the isothermal phase. Because the epilimnion is generally warmer than the hypolimnion in the Great Lakes, hypolimnetic water will not become stagnant over a long period, but rather can be expected to mix completely at least once a year.

Recent emphasis in the Great Lakes has been on study of the mechanics of thermal plumes and total lake energy budgets, yet the climatic effect of heated water influx into the lakes is largely unknown. At the present time, information is not adequate to define in quantitative terms the meteorological consequences of the large amounts of heat energy and water vapor that are released into the atmosphere from large cooling towers.

A survey of the heated water influx throughout the entire Great Lakes Basin would be in order as a first step in quantifying management problems with respect to both the receiving water body and the receiving air body. Only after thermal discharges are measured and classified on a regional basis can intelligent and effective regional planning of waste thermal energy disposal begin.

A primary factor affecting the ecological balance of the Great Lakes is transparency. This property has a basic relationship with suspended material, light penetration, and nutrients. Transparency is also a major aesthetic consideration. The physical properties of water provide the control. During periods of stratification, circulation and movement of that fraction of the particulate material capable of being held in suspension is restricted largely to the epilimnion, with the consequent effect of bypassing the classical sedimentation process. This fraction is composed primarily of organic material, which makes it even more significant when one considers that organic material is regarded as the prime factor in lake eutrophication.

Transparency of the lakes is not uniform nor is it stable. Fluctuations may be short-term, catastrophic, seasonal, or annual and are both areal and vertical. The physiography of a lake basin, depth and depth variations, bottom types, character and extent of influx, exposure to wind fields, and thermal structure all cause variations in transparency. Natural changes adhere to a basic annual cycle with short-term effects superimposed. The effects of all the controlling variables are more or less predictable in time and space. Investigations that are limited in duration and area studied or that consider effects without analyzing causes may appear to be random or may lead to erroneous management recommendations. Definitions of the annual cycles in a lake are necessary adjuncts to shorter-term programs because they form a baseline on which to superimpose the segments. Factors that control physical properties should be better defined, and the proper time and space perspectives of problem areas should be determined before development of any reasonable comprehensive management plan.

Section 4

HYDROMETEOROLOGY: CLIMATE AND HYDROLOGY OF THE GREAT LAKES

Jan A. Derecki

4.1 Introduction

4.1.1 Description and Scope

The climate of the Great Lakes Region is determined by the general westerly atmospheric circulation, the latitude, and the local modifying influence of the lakes. Due to the lake effect, the regional climate alternates between continental and semi-marine. The semi-marine climate is more consistent contiguous to the lakes, but with favorable meterological conditions, it may penetrate deeply inland. The Great Lakes climate and hydrology are closely related. Variations in mean lake levels, and consequently lake outflows, are controlled by the imbalance between precipitation and evaporation.

The Great Lakes drainage basin is discussed in other appendixes and a brief summary of the climatic and hydrologic elements of the drainage basin is given in Section 1 of this appendix. The major storm tracks affecting the Great Lakes Region are indicated in Figure 4–13. Distributions of mean annual values for air temperature, precipitation, runoff, and water losses over the land areas of the Basin, showing latitudinal and lake-effect variations, are indicated in Figures 4–15, 17, 19, and 20, respectively. The average monthly means, highs, and lows of overland air temperature for the individual lake basins and for the total Great Lakes Basin are shown in Figure 4–16.

4.1.2 Lake Effect

With a total water volume of 22,813 km³ (5,473 cu. mi.) stored in the lakes, varying from 484 km³ in Lake Erie to 12,234 km³ in Lake Superior, the Great Lakes have a tremendous heat storage capacity. Through air-water interaction, the lakes influence the climate over them and over adjacent land areas. Because of the lake effect, air temperatures are moderated, winds and humidities are increased, and precipitation patterns are modified. Although these phenomena have been recognized for decades, it is only in recent years that intensive programs have been undertaken to determine the more exact nature and magnitudes of these processes.

The Great Lakes moderate temperatures of the overlying air masses and surrounding land areas by acting as heat sinks or sources. The process of heat exchange between the lakes and atmosphere is both seasonal and diurnal. During spring and summer, the lakes are generally colder than air above and have a cooling effect on the atmosphere. During fall and winter, the lakes are generally warmer than the atmosphere and serve as a heat source. However, during the winter months, the ice cover reduces the lake effect.

A daily pattern of heat exchange is superimposed upon the seasonal pattern. This daily pattern is produced by land-water temperature differences. Because lakes are more efficient than land areas in storing heat, lake temperatures have a tendency to remain stable, while land temperatures undergo daily variations that are more in line with the air temperatures. When the land is warmer than water, the relatively warmer air over adjacent land areas tends to rise and is replaced by colder, heavier air from the lakes. When the land is colder, the process is reversed. This

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process of heat exchange produces light winds, which are known as lake breezes. The offshore and onshore lake breezes are illustrated in Figure 4–14. The direction of lake breezes is governed by the land-water temperature differences and is independent of the general atmospheric circulation. However, lake breezes occur only during relatively calm weather and affect a limited air mass along the shoreline, rarely extending more than several kilometers (2–3 miles) inland. The moderation of temperatures by the lakes affects regional agriculture by reducing frost hazards in the early spring and in the fall, thus lengthening the growing season, especially in coastal areas. Examples of this effect are the cherry orchards of the Door Peninsula in Wisconsin and the Grand Traverse Bay area in Michigan, and the vineyards of the western Lake Erie islands in Ohio.

Because lake breezes have a limited range and require special conditions, the lake effect on winds is minor. A much more important effect is the considerable increase in geostrophic wind speed over the lakes. This increase is caused by reduced frictional resistance to air movement over the relatively smooth water surface, and by the difference in atmospheric stability created by air-water temperature differences. Recent studies indicate that the increase in overwater wind speed varies from approximately 15 percent in midsummer to as much as 100 percent in late fall and early winter. The average annual increase is approximately 60 percent.

The Great Lakes also cause an increase in overwater humidity by releasing large quantities of moisture through evaporation. On an annual basis the humidity over the lakes averages 10 percent to 15 percent higher than that over the land. Seasonal changes in humidity over the lake compared to that over land vary from a decrease of approximately 10 percent due to overwater condensation in the late spring, to an increase of approximately 10 percent in the summer, 15 percent in the fall, and 30 percent in the winter.

The Great Lakes also influence the distribution of cloud cover and precipitation. Modification of precipitation patterns due to lake effect is caused by the changes in atmospheric stability in combination with prevailing wind direction and topographic effects. During summer, the air undergoes overland warming before passing over the lakes. The warm air over relatively cold water results in the development of stable atmospheric conditions, which discourage formation of air-mass showers and thunderstorms. During winter, the conditions are reversed, and the cold, inland air passing over relatively warm water becomes less stable and picks up moisture, which encourages snow flurries. As the winter air masses move over the lakes, the moisture that accumulates in the air produces heavy snowfalls on the lee sides of the lakes, due to orographic effects of the land mass. The fact is well documented that heavy snowbelt areas result from the lake effect. These areas include Houghton on Lake Superior, Owen Sound on Lake Huron, Buffalo on Lake Erie, and Oswego on Lake Ontario.

4.1.3 Measurement Networks

Basic meteorological data in the Great Lakes Basin are available from regular observation networks operated by the National Weather Service and the Canadian Meteorological Service. The networks consist of a limited number of first order stations that provide hourly observations for air temperature, precipitation (total and snow), wind speed and direction, humidity, and duration of sunshine and cloud cover. More numerous cooperative stations provide daily observations for air temperature and/or precipitation. Certain more specialized stations collect additional data on solar radiation, radiosonde information, weather radar, and pan evaporation. Other regularly observed data useful in Great Lakes climatology include water temperatures recorded by municipalities at their water intake structures and by Federal agencies at selected lake perimeter locations.

In addition to the regular networks, more sophisticated data are collected periodically or seasonally for research on lake climatology. These include special precipitation networks, established and operated on lake islands and adjacent shorelines; synoptic surveys conducted by research vessels that take observations for the whole range of hydrometeorologic parameters; lake towers that give measurements with vertical profiles for selected parameters for air-water interaction studies; aerial surveys by conventional aircraft for ice reconnaissance and water surface temperatures, using infrared and airborne radiation thermometer techniques; and weather satellites that provide useful information for the investigation of cloud and ice cover on the lakes.

Hydrologic data on the Great Lakes Basin are compiled and published by several agencies. Records of tributary streamflow to the lakes are available from the U.S. Geological Survey and the Canada Centre for Inland Waters, Department of the Environment, Canada. The extent of gaged area increased substantially in the late 1930s, giving coverage to approximately 50 percent of the Basin. At present approximately 64 percent of the Basin is gaged; gaged areas for Lakes Superior, Michigan, Huron, Erie, and Ontario basins represent approximately 53, 71, 66, 67, and 63 percent of their respective basins. In addition to surface water data, these agencies and the Geological Survey of Canada publish observation well records providing information on ground-water conditions. However, the network of observation wells useful in determining ground-water flow to the lakes is extremely limited.

The Great Lakes levels and outflows are available from the Lake Survey Center. Lake levels are determined from a network of water level gages maintained by the Lake Survey in the United States and the Fisheries and Marine Service, Department of the Environment, in Canada. Flows in the connecting channels are determined by the Lake Survey from appropriate water level gage ratings based on periodic current meter flow measurements.

4.2 Radiation

4.2.1 Total Radiation Spectrum

Total radiation received at the surface of the earth consists of shortwave radiation coming directly from the sun or scattered downward, and longwave radiation, emitted from the atmosphere. Portions of the incoming radiation in both short and long wavelengths are reflected and additional longwave radiation is emitted to the atmosphere. The main radiation exchange processes taking place within the terrestrial system (space-atmosphere-earth) are illustrated in Figure 4–93, presenting annual radiation balance, which is based largely on information provided by London.[503] The net effect of shortwave radiation is the solar heating of the earth, while longwave radiation results in cooling.

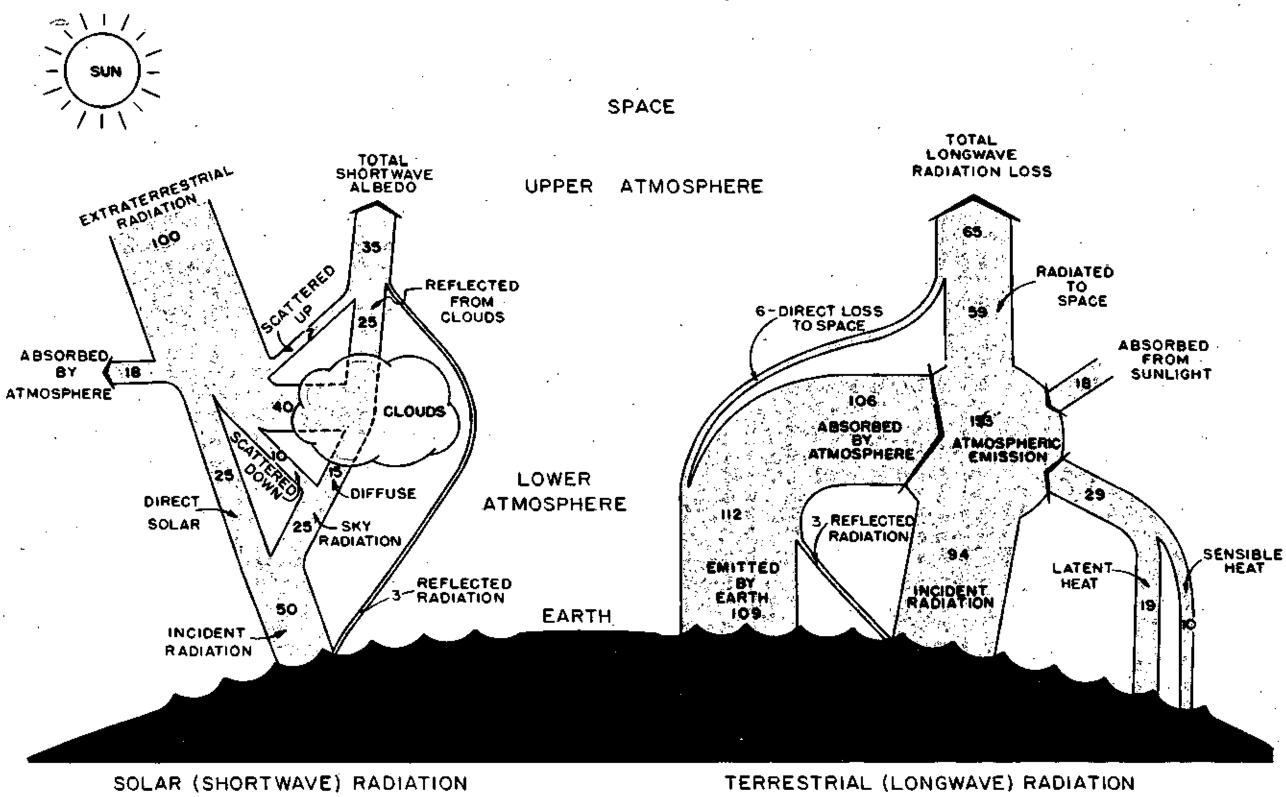

FIGURE 4–93 Annual Atmospheric Heat Budget. Shows percentage distribution of radiation components for northern hemisphere.

After London, 1957

There is some duplication of names used for the same radiation components. Shortwave or global radiation is generally referred to as solar radiation and both names are used interchangeably in this report. Insolation is incident or incoming solar radiation. Similarly, terrestrial radiation is used synonymously with longwave radiation, while longwave radiation from the atmosphere is called atmospheric radiation.

A regular network for measuring shortwave radiation has been established but only few of these are in the Great Lakes Region. A regular network for total radiation measurements (shortwave and longwave) has not been established, since there are only a limited number of radiometers in operation at various research installations. Available information indicates that the average monthly all-wave incident radiation in the Great Lakes Region varies from a winter low of approximately 400 langleys per day (ly/day) in December to a summer high of approximately 1400 ly/day in June or July.

4.2.2 Solar Radiation

Solar radiation is reduced by the atmosphere before reaching the earth's surface. Attenuation of the extraterrestrial solar radiation is caused by scattering, reflection, and absorption by gas molecules, water vapor, clouds, and suspended dust particles (Figure 4–93). As a result of the attenuation, the incoming shortwave radiation on a horizontal surface arrives partly as direct solar radiation and partly as sky radiation (scattered downward by atmosphere and diffused through the clouds). Sky radiation is a high percentage of the total incident radiation during low declination of the sun and on overcast days.

Part of the incoming solar radiation is reflected from the receiving surface (clouds and earth) back to the atmosphere, the amount of reflection depending on the surface albedo or the ratio of reflected to incident radiation. Albedo values for a water surface depend on the solar altitude (angle of the sun above the horizon), cloud cover, and the roughness of the water surface, but for many practical purposes these factors can be assumed to be constant for daily or longer periods. During the Lake Hefner study, Anderson[16] developed empirical curves, which interpret water surface albedo as a function of sun altitude for various cloud cover conditions. Based on results of that study, Kohler and Parmele[464] recommended an average daily albedo for water surface of 6 percent. The relatively low albedo for open water conditions increases drastically with ice and snow cover. Bolsenga[76] gives albedo values for various types of ice common on the Great Lakes. These values range from 10 percent for clear ice to 46 percent for snow ice, both free of snow cover. The presence of partial or complete snow cover on the ice can significantly increase these values.

There is a limited network of regular stations that measure incident solar radiation in the Great Lakes Region. The average monthly values from these stations are shown in Figure 4–94. Periods of record for the stations vary from 10 to 50 years. Based on records from the radiation network, the average monthly incoming solar radiation in the Great Lakes Basin varies from a low of approximately 100 ly/day in December (winter solstice) to a high of approximately 550 ly/day in June and/or July (near the summer solstice), with an average annual value of about 320 ly/day. The average monthly extremes for reflected solar radiation from the lakes represent from 6 to 33 ly/day (6 percent water surface albedo).

Beginning in the last decade, direct overwater measurements of solar radiation were included in the synoptic surveys of the Great Lakes conducted by several research organizations. These measurements are generally limited to the navigation season (April-December), are not continuous, and are somewhat biased towards fair weather conditions, but nevertheless they represent actual conditions over the lakes and provide a basis for comparison of the overwater and overland radiation. Richards and Loewen[653] conducted a preliminary study of this type, which shows that incident solar radiation over the lakes is greater than that recorded on adjacent land stations during summer and smaller during winter months. This confirms the physical concepts of the lake effect. Their study is limited to four years of data during the April-December periods and shows that overwater radiation at the beginning and end of the period amounts to 90 percent of the overland radiation. The overwater radiation increases gradually during spring and summer to an average high of approximately 140 percent of the overland radiation in the late summer, then it decreases rapidly in the fall.

Other recent studies of solar radiation on the Great Lakes include determination of the radiation balance for Lake Ontario (Bruce and Rodgers[108] and Rodgers and Anderson[675]). Determination of the total atmospheric water

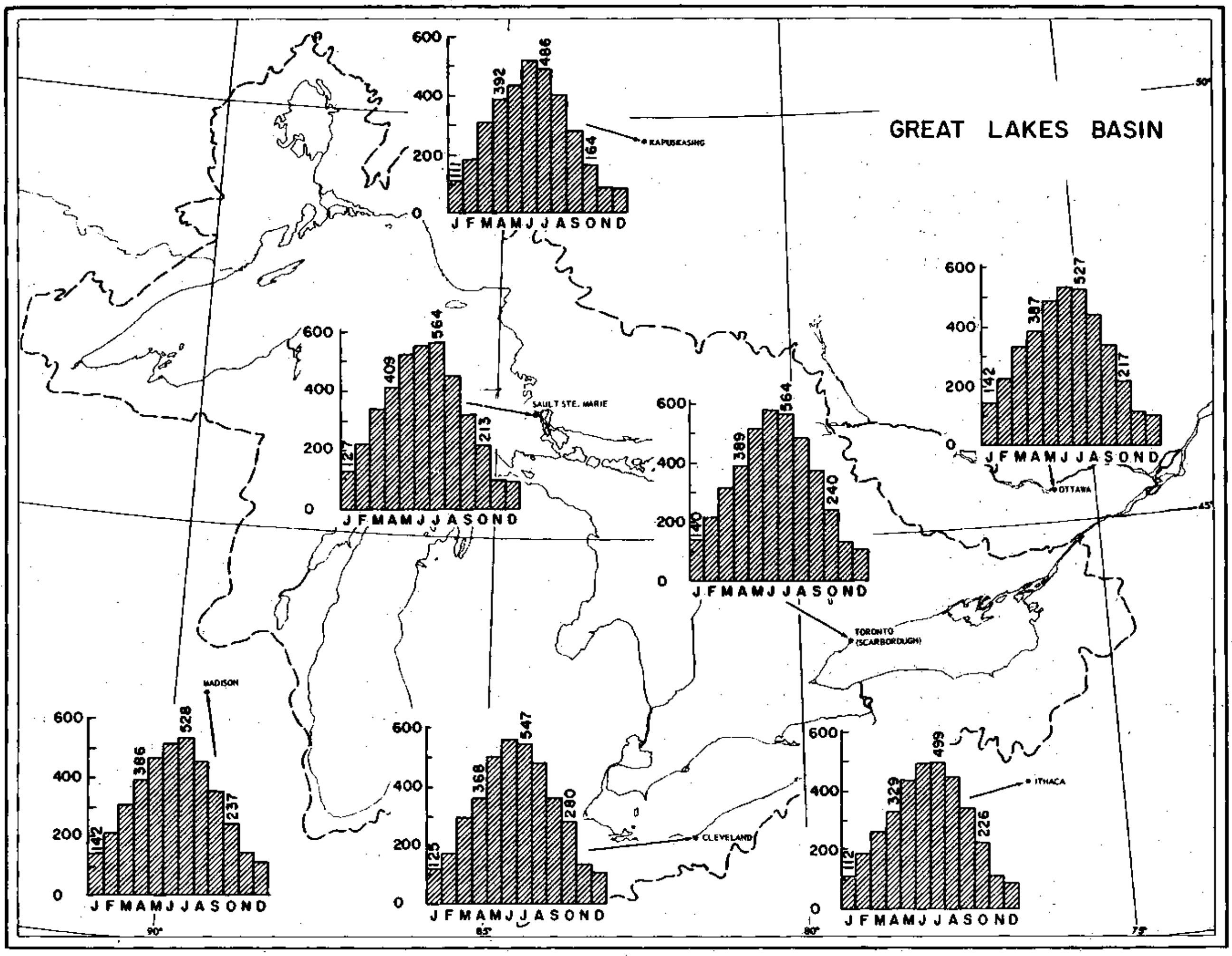

FIGURE 4–94 Average Daily Solar Radiation (Langleys) in the Great Lakes Basin

From Phillips, 1969

vapor over the Great Lakes Basin and derivation of a relationship between atmospheric water vapor and surface dew point (Bolsenga[74,77]) could contribute to parameterization of the solar radiation term. This might compensate for the lack of recording stations in the lakes.

4.2.3 Terrestrial Radiation

Terrestrial radiation over a body of water (or over land) consists of the incident atmospheric radiation, reflected atmospheric radiation, radiation emitted by the water body, and energy released through the processes of evaporation, condensation, and precipitation (latent heat), and turbulent heat transfer (sensible heat). The net result of the incident, reflected, and emitted radiation components is the net back radiation, a longwave radiation loss to the atmosphere (Figure 4–83). The net back radiation is primarily a function of the temperature of the water surface, which controls emitted radiation, and the water vapor content of the air, which controls atmospheric radiation. Other factors that affect the net back radiation include the emissivity of water (relative power of a surface to emit heat by radiation), which reduces emitted radiation below that of black body (an ideal surface that emits maximum radiation); the reflectivity of water, which controls reflected atmospheric radiation; and the concentration of carbon dioxide and ozone in the atmosphere, which are minor contributors to the atmospheric radiation. The reflectivity of a water surface for atmospheric radiation is 3 percent (Anderson[16]), only about half as much as for the solar radiation.

The earth and the atmosphere can absorb and emit more than 100 percent of radiation, exceeding the original input from the sun. This is possible because of the so-called greenhouse effect of the atmosphere. By blocking terrestrial radiation (very small direct loss to space), the atmosphere forces the earth surface temperature to rise above the value that would occur in the absence of the atmosphere, which in turn produces upward vertical transfer of both latent and sensible heat.

Terrestrial radiation may be determined indirectly from the total (all-wave) and solar (shortwave) radiation measurements, but all-wave measurements are too sparse for this purpose. Atmospheric radiation may also be computed utilizing various radiation indices (temperature, percent of sunshine or cloud cover, vapor pressure). Anderson and Baker[15] present a method of computing incident terrestrial radiation under all atmospheric conditions from observations of surface air temperature, vapor pressure, and incident solar radiation. Emitted radiation is determined from water surface temperatures. Based on available information, estimates of terrestrial radiation for the Great Lakes are as follows: monthly incident atmospheric radiation varies from a winter low of approximately 300 ly/day in December to a summer high of approximately 800 ly/day in June or July; reflected atmospheric radiation for these months represents 9 to 24 ly/day (3 percent reflectivity); monthly emitted radiation from the lakes varies from a low of approximately 400 ly/day during winter to a high of 900 ly/day during summer; monthly net back radiation (longwave radiation loss) is roughly 100 ly/day throughout the year (Figure 4–100).

4.3 Winds

4.3.1 Lake Perimeter Winds

Winds are a critical factor of lake climate because they provide energy for lake waves, constitute a principal force for driving lake currents and shifting of ice cover, and through air movement provide means for the regulation of thermal budget over the lakes and adjacent land areas by heat dissipation and transfer. In the Great Lakes Region the global atmospheric circulation with prevailing westerly winds is of particular importance on the lower lakes where it coincides with the longitudinal axes of the lakes, exposing the full lengths of the lakes to the winds and the lee shores to the maximum lake effect.

Because of the lake effect on adjacent land areas, wind data from stations located around the perimeter of the lakes are of particular interest to the Great Lakes. Since more representative data were not available, these data have often been used in past studies as overwater winds, frequently without adjustment for anemometer height or the increase in wind speed over the lakes. Average monthly perimeter wind speeds for the Great Lakes are given in Table 4–7. The average annual perimeter wind speed generally increases from north to south, from approximately 4.5 m/s (10 mph) to 5.0 m/s (11 mph). Average monthly wind speeds increase from the summer low of 3.5 m/s to 4.0 m/s (8–9 mph) to the winter high of 4.5 m/s to 5.5 m/s (10–12 mph).

A summary of wind direction for selected stations around the lakes and the St. Lawrence River is presented in Figure 4–12. The wind roses in this figure show wind direction frequencies for the months of February, May, August, and November, indicative of the four seasonal periods.

Actual wind conditions on the lakes and further inland vary somewhat from those indicated by shore stations, which are affected to a varying degree by the lakes and lake-land interaction. The perimeter weather stations are located at some distance inland, and may generally be unaffected by lake breezes, but the stations located on the lee sides of the lakes are certainly affected by the lakes during winds from the prevailing wind directions.

The long east-west axis of Lake Superior is divided by the Keweenaw Peninsula, which separates the lake into two basins where winds are frequently of opposite direction. On the western end of the lake (Duluth) the winds are predominantly from the west and northwest during cold months and from the east and northeast during the warm months. On the eastern end of the lake (Sault Ste. Marie) there are predominantly easterly winds in the cold months and westerly winds during warm months. In the middle section of the lake (Marquette) predominant winds are from the northern and southern quadrants. The mean monthly wind speed at these stations varies from 3 m/s (7 mph) in the summer to 6 m/s (14 mph) in the winter (for average perimeter wind speeds for the whole lake see Table 4–7). The maximum recorded wind velocity was 41

TABLE 4–7 Average Perimeter Wind Speeds for the Great Lakes (m/s)

	Lake				
Period	Superior	Michigan	Huron	Erie	Ontario
January	4.6	5.4	4.8	5.5	5.0
February	4.5	5.3	4.4	5.5	5.0
March	4.6	5.5	4.6	5.5	5.0
April	4.8	5.5	4.6	5.4	4.8
May	4.6	5.0	4.2	4.7	4.3
June	4.0	4.3	3.7	4.2	3.9
July	3.8	3.8	3.6	3.8	3.8
August	3.8	3.8	3.5	3.8	3.6
September	4.1	4.3	4.0	4.1	3.8
October	4.4	4.9	4.3	4.4	4.0
November	4.6	5.4	4.8	5.2	4.6
December	4.5	5.3	4.8	5.3	4.8
Annual	4.4	4.9	4.3	4.8	4.4

Values are based on mean data published in 1969 for the following stations:
Superior: Sault Ste. Marie, Marquette, Duluth, and Thunder Bay.
Michigan: Milwaukee, Muskegon, and Green Bay.
Huron: Alpena, Gore Bay, and Wiarton.
Erie: Toledo, Cleveland, Buffalo, and London.
Ontario: Rochester, Syracuse, Trenton, and Toronto.

m/s (91 mph) from the south at Marquette in May, 1934.

Around Lake Michigan the predominant wind direction is from the western quadrant, perpendicular to the long axis of the lake. Because of the north-south lake orientation, the highest seas generally coincide with strong northerly and southerly winds. Prevailing winds from these directions are reported at some locations, in contrast to the general predominant westerly direction. The variation in prevailing winds is evident in northern Lake Michigan where winds in Traverse City come from the south during fall, while Green Bay, on the opposite (western) shore, is assailed by westerly winds. Around the southern portion of the lake prevailing winds in the spring at Milwaukee are from the north, while at Chicago they are from the southwest. The mean monthly wind speed at these stations varies from 3m/s to 6 m/s (7–14 mph), which is similar to Lake Superior, but the annual wind speed around Lake Michigan is higher. The highest wind velocity recorded on all the Great Lakes, 49 m/s (109 mph) from the southwest, occurred at Green Bay in May 1950.

Winds on Lake Huron may be equally effective on the sea state from all directions due to the lake configuration. There is considerable variation in wind direction around the lake, but in general, prevailing winds are from the western quadrant. In some locations prevailing winds shift seasonally to the south during fall (Wiarton, Ontario), and a large percentage of winds along the western shore come from the eastern quadrant during warmer months, as indicated at Alpena and Bay City (Saginaw River Light) in Michigan. The range of mean monthly wind speed at these stations varies from the summer low of 4 m/s (8 mph) to the winter high of 6 m/s (13 mph). The highest velocity recorded was 27 m/s (61 mph) from the southwest at Alpena in November 1940.

The highest monthly wind speeds around the Great Lakes occur on Lake Erie, which also has the largest range between the monthly values of wind speed. The mean monthly wind speed at stations located around the lake varies from 4 m/s to 8 m/s (8–18 mph). These winds are predominantly from the western quadrant with a prevailing direction from the southwest, which coincides roughly with the long axis of the lake. This fact, along with the relative shallowness of the lake, makes Lake Erie highly susceptible to large-scale water level motions, especially at the eastern and western extremes of the lake. Because of the prevailing wind direction, lake effect on the lee shores is quite pronounced and the monthly wind speeds at Buffalo are normally somewhat higher than at other stations around the lake. Prevailing winds at some locations are from the eastern quadrant, and in the middle section of the lake (Cleveland), prevailing winds during warmer months shift to the north and south directions. The maximum velocity recorded was 41 m/s (91 mph) from the southwest at Buffalo in January 1950.

The predominant wind direction around Lake Ontario is similar to that of Lake Erie, with prevailing winds during most months from the southwest (Rochester, Trenton), which approaches the direction of the long axis of the lake. During winter months the predominant wind direction shifts to the west. On the northwestern end of the lake (Toronto) winds frequently prevail from the west, and at times from the north. The mean monthly wind speed at these stations varies from 3 m/s to 6 m/s (7–13 mph). The highest wind velocity recorded was 33 m/s (73 mph) from the west at Rochester in January 1950. The prevailing winds along the St. Lawrence River are parallel to the river, primarily from the southwest and secondarily from the northeast.

4.3.2 Overwater Winds

Overwater winds differ from overland

winds, both daily and seasonally, because of differences in air stability conditions and frictional resistance. Daily variation is caused mainly by diurnal heating and cooling, which are more pronounced over land areas than over water and result in larger daily wind variations over land than over water. Seasonal variation is caused by the winter heating and summer cooling effects of the lakes. The lakes offer less resistance to wind movement, resulting in considerably higher overwater wind speeds regardless of the season.

The highest wind speeds (one-minute wind gusts) on the Great Lakes, reported from anemometer-equipped vessels since 1940, are listed for each lake as follows: Lake Superior, 42 m/s (93 mph) from the northwest in June 1950; Lake Michigan, 30 m/s (67 mph) from the west-southwest in November 1955; Lake Huron, 49 m/s (109 mph) from the west-northwest in August 1965; Lake Erie, 38 m/s (85 mph) from the north-northwest in June 1963; Lake Ontario, 26 m/s (57 mph) from the west-northwest in November 1964. These velocities were observed during the navigation season and are based largely on observations taken four times daily during synoptic hours (0100, 0700, 1300, and 1900 hours, EST). Higher wind speeds may have occurred during winter months and at times other than synoptic hours. Most of the shipboard wind directions listed by the National Weather Service verify the predominantly westerly wind direction indicated by the perimeter stations.

The first intensive effort to determine overwater winds utilized various ships-of-opportunity programs, which were conducted periodically and consisted initially of commercial vessels making wind observations four times daily. The data collection program has now been expanded to off-shore towers, buoys, research vessels, and research stations located on small islands in the Great Lakes. Because of practical limitations imposed on measurement of wind data for prolonged periods of time over the lakes, the primary aim of wind measurement programs was to determine the relationship between overland and overwater winds. Several studies of this type have been conducted, relating shore data with observations from ships and islands located on the Great Lakes (Hunt,[397,398] Lemire,[492] Bruce and Rodgers,[108] and Richards et al.[649]).

The ratios of wind speed over water to wind speed over land vary diurnally and seasonally, and are a function mainly of the stability of the air. For unstable atmospheric conditions, with water temperature much higher than air, lake-land wind ratios are about two, and for stable atmospheric conditions, with air much warmer than water, wind speed ratio values are near one; for the adiabatic or neutral stability conditions values are intermediate. Hunt's investigation was conducted mainly for Lake Erie during navigation season (April–November), with results grouped into the spring and fall periods. Bruce and Rodgers[108] prepared a similar study for Lake Ontario. Their investigation was extended by Lemire[492] who included data from some of the other Great Lakes and derived monthly wind speed ratios for the spring, summer, and fall months (March–October). Richards[648] extended these ratios for the winter months using partial results determined by Lemire and extrapolation based on the air-water temperature difference, along with limited wind observations on Lake Ontario. The variation of wind speed ratios determined in these studies is shown in Table 4–8. Monthly ratios vary from 1.2 to 2.1, with low values during summer and high during winter, and an overall annual average of about 1.7.

The effects of overwater fetch (length of open water) on lake winds, besides atmospheric stability, were studied by Richards et al.,[649] who utilized wind data collected during synoptic surveys on Lakes Erie and Ontario. Their analysis included five stability ranges (from very unstable to very stable), four wind speed classes (3 m/s to 8 m/s), and five fetch ranges (10 km to 65 km). They found that the lake-land wind ratio increases with the atmospheric instability, but the increase is most pronounced in light winds. Under very unstable atmospheric conditions (large negative air temperature-water temperature difference, $T_A - T_W$) the wind ratio increases gradually from 1.4 for strong winds to 3.0 for light winds, with a 2.2 value for all winds. Under very stable atmospheric conditions (large positive $T_A - T_W$ difference) the wind ratio increases gradually from 0.8 for strong winds to 1.4 for light winds, with a value of 0.9 for all winds. Thus, under very stable conditions the lakes may reduce the wind speed, especially in strong winds. The effect of overwater fetch was not as pronounced and somewhat erratic. Under unstable atmospheric conditions the wind speed ratio increases with the overwater fetch, but only for lengths smaller than 50 km (25 nautical miles). Under stable atmospheric conditions the relationship between wind ratios and overwater fetch was highly erratic. Summarized results of this study are listed together with other wind studies in Table 4–8.

TABLE 4–8 Lake-Land Wind Speed Ratios for the Great Lakes

Hunt (1958)		Lamire (1961)		Richards, Dragert, McIntyre (1966)	
Period	Ratio	Period	Ratio	Stability Range $T_A - T_W$ (°C)	Ratio
		January	1.96[1]		
		February	1.94[1]		
		March	1.88		
		April	1.81		
Spring	1.35	May	1.71	≥ -12.6	2.24
		June	1.31	-12.5 to - 4.1	1.88
		July	1.16	- 4.0 to 4.0	1.44
		August	1.39	4.1 to 12.5	1.06
Fall	1.82	September	1.78	≥ 12.6	0.92
		October	1.99		
		November	2.09[1]		
		December	1.98[1]		
Navigation Season	1.58		1.63		
Annual			1.75		1.51

[1]Values for winter months were extended by Richards (1964) through extrapolation.

4.4 Air Temperature

4.4.1 Lake Perimeter Temperature

Temperature is one of the principal indicators of climate and exerts a large influence on other climatic elements, such as precipitation and evaporation. The vast water expanses of the Great Lakes moderate air temperature over the lakes, which in turn has a moderating effect on adjacent land areas. An indication of the lake effect on shoreline temperatures is given in Figure 4–95 prepared by Pond,[622] which compares mean hourly air temperatures for March, June, and September at Douglas Point, located on the eastern shores of Lake Huron, to those at Paisley climatological station, some 20 km (12 miles) inland. During late winter (March), the lakeshore station is consistently warmer by 2°C to 4°C (3–7°F) than the inland station. This effect changes gradually during spring to the summer effect, providing daytime cooling of the lakeshore station by as much as 4°C (7°F) and nighttime warming by 2°C (3°F) in June. In the early fall the effect reverses again and the lakeshore station is consistently warmer throughout the day.

Because of the lake effect and lack of direct overwater measurements for any longer period of time, various investigators used data from perimeter stations to estimate air temperature over the lakes. The average monthly and annual air temperatures for the individual lakes, based on perimeter data for the 1931–69 period, are listed in Table 4–9. Average annual temperatures vary from 4°C (39°F) on Lake Superior to 9°C (48°F) on Lake Erie, with intermediate values on other lakes. Average monthly temperature extremes also occur on Lakes Superior and Erie, and vary from monthly lows of approximately −11°C and −4°C (13 and 26°F) in January to monthly highs of about 18°C and 22°C (65 and 71°F) in July, on the two lakes, respectively.

The air temperature decreases as latitude increases, being lowest for Lake Superior and highest for Lake Erie. Disregarding minor local variations, the average annual temperature on Lake Superior varies from 1°C (34°F) along the extreme northern shore to 5°C (41°F) along the southern shoreline (see Figure 4–15). Distribution of average annual temperature on Lake Michigan varies from approximately 6°C (43°F) in the north to 10°C (50°F) in the south. On Lake Huron, the average annual temperature increases southward from 5°C to

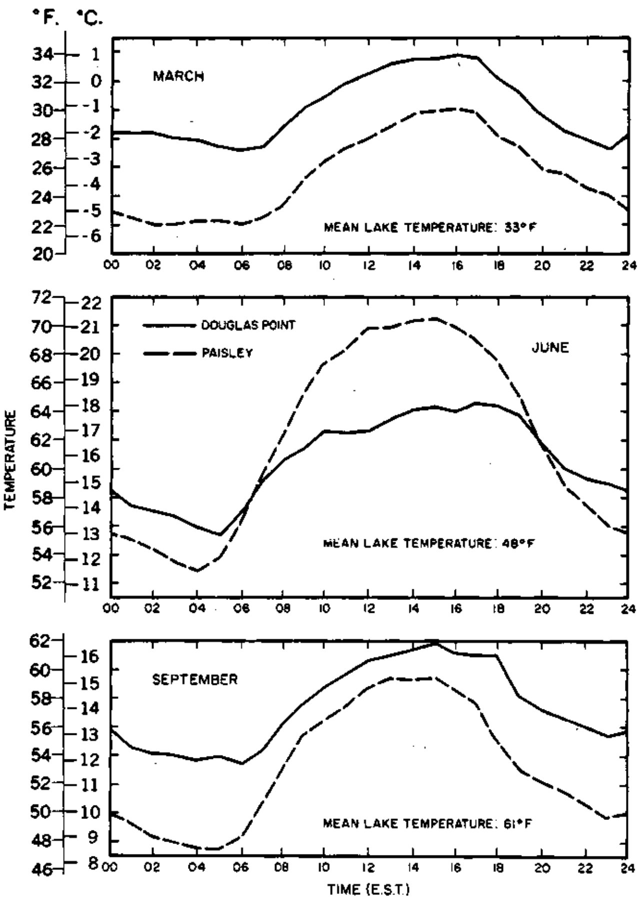

FIGURE 4–95 Mean Hourly Temperatures for Douglas Point and Paisley, Lake Huron, for the Months of March, June, and September, 1962
From Pond, 1964

8°C (41 to 47°F). The annual temperature on Lake Erie increases from a low of 8°C (47°F) along the northeastern shore to a high of 11°C (52°F) along the southwestern shoreline. On Lake Ontario, the annual air temperature increases from 7°C to 9°C (45 to 48°F) between the northern and southern shores.

It should be noted that the air temperatures discussed above are based on lake perimeter stations and may be different from those representing mid-lake conditions. Some difference in these temperatures is introduced by the land effect, which takes place not only at shore stations but also in the shallow coastal waters. Furthermore, most first order perimeter stations used to derive temperature estimates are located some distance inland, where the land effect is more pronounced. Nevertheless, because of data limitations, air temperatures from the perimeter stations around the lakes are generally used as representative values for the average conditions on the lakes (Hunt,[395] Powers et al.,[624] Snyder,[751] Rodgers and Anderson,[675] Derecki,[214] and Richards[648]).

4.4.2 Overwater Temperature

The difference between air temperature over lake and land areas in the Great Lakes Basin has been studied by several investigators. In describing the climate of South Bass Island in western Lake Erie, Verber[848] compared island records (Put-in-Bay) with perimeter and inland stations and concluded that the mean mid-summer temperature (July) decreases gradually from Put-in-Bay to perimeter stations (Sandusky and Toledo) and to inland stations (Tiffin and Bucyrus) located within 80 km (50 miles) south of the lake. He attributes the higher overlake temperatures to the increased solar radiation due to less precipitation and cloud cover over the lake. During mid-winter (January) the reverse is true, because the portion of Lake Erie around the island region is shallow and normally freezes over and is largely ice covered, thus reducing the lake effect. Although Put-in-Bay has the highest mean July temperature and the lowest mean January temperature of the five stations, its average monthly range during the year is the smallest, because thermal stability over the lake acts as a damper against sudden heating or cooling. The aver-

TABLE 4–9 Average Perimeter Air Temperature for the Great Lakes, 1931–1969 (Degrees Centigrade)

Period	Lake				
	Superior	Michigan	Huron	Erie	Ontario
January	-11.2	- 6.4	- 7.4	- 3.8	- 5.2
February	-10.4	- 5.6	- 8.0	- 3.7	- 5.2
March	- 4.7	- 0.4	- 3.5	0.9	- 0.1
April	3.1	6.8	4.1	7.4	6.8
May	9.2	12.7	10.2	13.6	13.1
June	14.6	18.4	15.8	19.2	18.7
July	18.1	21.3	18.9	21.8	21.4
August	17.4	20.4	18.7	20.9	20.3
September	13.0	16.4	14.2	17.2	16.4
October	7.2	10.3	8.7	11.1	10.2
November	- 0.7	2.8	2.0	4.3	3.8
December	- 7.7	- 3.6	- 4.2	- 1.7	- 2.8
Annual	4.0	7.8	5.8	8.9	8.1

Values are based on data for the following stations:
Superior: Sault Ste. Marie, Marquette, Duluth, and Thunder Bay.
Michigan: Milwaukee, Muskegon, and Green Bay.
Huron: Alpena, Gore Bay, and Wiarton.
Erie: Toledo, Cleveland, Buffalo, and London.
Ontario: Rochester, Syracuse, Trenton, and Toronto.

age monthly maximum-minimum temperature range increases gradually inland from approximately 8°C (14°F) at Put-in-Bay to approximately 12°C (22°F) at Bucyrus, and the frost-free season decreases gradually inland from more than 200 days to approximately 150 days. Also, the hottest days in July show higher temperatures on mainland stations than at Put-in-Bay. During the winter an ice cover around the island region, usually forming in January and lasting through February, acts as an insulator between the warm water and cold air, producing enough change in the normal temperature pattern to make February colder than January. On exceptional occasions when the lake is free of ice during these two months, temperature was approximately 3°C (5°F) higher.

Summer temperature conditions for western Lake Erie may be assumed to be indicative of temperature modification by the other Great Lakes, although mid-lake modification is undoubtedly more pronounced since the island itself produces some effect. Winter conditions, on the other hand, may not be comparable because other lakes have much greater depths and different ice-cover conditions. In a comparison of summer data for Fort William and Caribou Island (175 miles away) made in connection with a synoptic survey of Lake Superior, Anderson and Rodgers[14] show that air temperature on the island is much more stable than and differs considerably from that at Fort William, on the perimeter of the lake. They state that measurements from the island are extremely valuable since they represent an entirely maritime situation, which is caused by modification of low level air masses by the lake. However, there are only a few island stations measuring air temperatures on the lakes and most are operated only during the navigation season.

Measurement of air temperature on lake towers or buoys, and synoptic surveys by vessels initiated in the late 1950s, provide more reliable data by eliminating possible island effects. Based on synoptic survey data collected by the research vessel *Porte Dauphine* on Lake Ontario, Bruce and Rodgers[108] observed that air temperatures at 3 m (10 ft) above the water surface are much closer to water surface temperatures than to land temperatures at the lake perimeter (mean of temperatures at Toronto and Rochester). Rodgers and Anderson,[675] utilizing these data in the energy budget study of Lake Ontario, made similar observations and showed that air temperature over water in June is about 6°C (10°F) higher than water surface temperature, while air temperature at Toronto displays a different pattern and is on the average approximately 17°C (30°F) higher than water temperature. These figures are based on only three days of data from a single cruise, and their magnitudes may not be valid for longer periods. Rodgers and Anderson[675] state that there are insufficient data to provide a reliable conversion of land station temperatures to the overwater air temperatures. At present, with approximately a decade of data available, this difficulty has been overcome but the conversion factors have not been developed. There are no published reports presenting overwater temperatures on the lakes, other than data reports for the individual surveys.

4.5 Water Temperature

4.5.1 Water Surface Temperature

The oldest sources of water surface temperature data in the Great Lakes are the records obtained at various marine structures, such as docks, breakwaters, and lighthouses. These stations were later replaced by the somewhat more sophisticated sites offered by the intake structures of the water treatment plants located around the lakes. Water temperature at the intake stations is obtained in the coastal waters, a few hundred to a few thousand meters off shore, and at depths of 3 to 15 meters (10 to 50 feet) below the surface. These data obviously do not represent the temperature at the surface and require adjustments for open lake conditions. Initially, open lake measurements were made by commercial vessels along their navigation routes, and more recently by research vessels engaged in synoptic surveys of the lakes. The latest development in measuring surface water temperatures involves the use of airborne infrared thermometers. The use of airborne radiation thermometers permits fast and regular observations of surface temperatures over large areas. Information on surface temperatures is also provided by satellite imagery, but in the present state of art this information cannot be used for quantitative temperature determination.

Among the earlier studies of the water surface temperatures in the Great Lakes were those by Freeman[271] and by Horton and Grunsky.[376] In both studies water temperature records from daily observations at various harbor locations for the 1874–86 period

TABLE 4–10 Comparison of Great Lakes Water Surface Temperature (Degrees Centigrade)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Lake Superior													
Lake Survey (1944) 1904-43[1]	0	0	0	1	3	4	8	12	11	8	5	1	4
Millar (1952) 1935-39	-	-	-	-	2	4	7	13	12	9	6	-	-
Richards & Irbe (1969) 1959-68	2	0	0	1	2	4	7	12	12	9	6	4	4
Lake Michigan													
Lake Survey (1944) 1904-43[1]	0	0	1	4	7	12	17	18	16	11	7	2	8
Millar (1952) 1935-41	-	-	-	-	5	11	16	21	18	12	8	-	-
Lake Huron													
Lake Survey (1944) 1904-43[1]	0	0	1	3	6	12	18	19	17	12	7	2	8
Millar (1952) 1935-41	-	-	-	-	4	9	18	20	16	12	7	-	-
Richards & Irbe (1969) 1959-68	3	2	1	1	4	8	15	18	16	12	8	6	8
Lake Erie													
Lake Survey (1944) 1904-43[1]	0	0	3	6	9	18	22	22	21	14	7	1	10
Millar (1952) 1937-41	-	-	-	-	10	17	21	23	19	15	9	-	-
Richards & Irbe (1969) 1950-68	1	1	1	3	9	17	21	22	19	15	9	4	10
Lake Ontario													
Lake Survey (1944) 1904-43[1]	0	0	2	5	9	14	18	19	17	13	7	1	9
Millar (1952) 1936-46	3	2	2	3	6	12	19	21	18	13	7	4	9
Richards & Irbe (1969) 1950-68	3	2	2	3	6	12	19	21	18	13	7	4	9

[1]Period shown for Lake Survey study indicates extreme limits and not actual length of data.

were used as basic data. Monthly temperatures for the individual lakes were derived by applying correction factors for time of observations and some adjustment for open lake conditions.

The U.S. Lake Survey[825] compiled monthly water surface temperatures for each lake from temperature data collected at various locations by the field parties from 1904 through 1943. Derived values differ somewhat from those given by Freeman and are considerably different from Horton and Grunsky's values.

Probably the best known and most often used Great Lakes water surface temperatures are those determined by Millar.[543] Millar's study is based on the data obtained from continuous recordings of water temperature taken by thermographs installed on the condenser intakes of steamships. Data collection covers the 1935–46 period for Lake Ontario and the 1935–41 period for all other lakes. Millar developed temperature distributions on each lake by months and derived average monthly values for each lake. Due to restricted navigation, winter temperatures for lakes other than Ontario were either not available or gave insufficient coverage to derive reliable monthly means. Many investigators in recent years have used Millar's temperatures, most frequently to adjust surface temperatures derived for various periods from the water intakes or other sources. Studies of this type include Hunt,[395] Snyder,[751] Rodgers and Anderson,[675] and Richards and Rodgers.[654]

Determinations of Great Lakes water surface temperatures, limited to a single lake, were made by several investigators. Church[142,143,144] analyzed water temperatures for Lake Michigan, based on bathythermograph observations obtained during 1941–44 period. He showed that irregularities in the water temperature distribution are the result of strong winds and upwelling, both of which act to lower the water temperature at the surface. Another presentation of Lake Michigan temperatures for the summer months is given by Ayers et al.[29] Their values are based on synoptic surveys conducted in 1955. Ayers et al.[28] also determined water temperatures for Lake Huron from a similar survey conducted on that lake in 1954. The last two studies are summarized by Ayers.[25] Monthly water temperatures on Lake Erie are given by Powers et al.[624] who present a comparison of long-term water intake records to offshore cruise data.

The most recent determination of water surface temperatures was made by Richards and Irbe.[651] Their study covers the 1950–68 period for Lakes Erie and Ontario, and the 1959–68 period for Lakes Huron and Superior. Monthly temperatures determined for each year on the individual lakes were based on available information from airborne radiation thermometer surveys, ship observations, water intake stations, and subjective adjustments of mean lake temperatures based on mean air temperatures from shoreline stations. The subjective adjustments of mean water temperatures were used primarily during winter months for lakes lacking sufficient temperature measurements.

A comparison of the Great Lakes mean water surface temperatures (Table 4–10) shows that surface temperatures vary with latitude and depth of the lakes. The average annual surface temperatures vary from 4°C (40°F) for Lake Superior, the northernmost and deepest lake, to 10°C (50°F) for Lake Erie, the southernmost and shallowest lake. Average annual surface temperatures on the other lakes, with intermediate latitudes and depths, amount to 8°C (46°F) for Lakes Michigan and Huron and 9°C (48°F) for Lake Ontario. The average monthly surface temperatures vary from the winter lows of 0°C (32°F) on Lake Superior and 2°C (36°F) on Lake Ontario to the summer highs of 13°C (55°F) on Lake Superior and 23°C (73°F) on Lake Erie.

4.5.2 Temperature at Depth

Many of the studies mentioned in the preceding discussion on water surface temperature also deal with the vertical temperature distribution in the Great Lakes. Church[142,143] showed that the annual temperature of Lake Michigan undergoes four basic seasonal cycles with distinct characteristics, namely, the spring warming, summer stationary, autumn cooling, and winter stationary. Because of different latitudes and depths, the timing and duration in the lakes of these cycles are not synchronous, but all lakes display these four basic seasonal periods. Occurrence of the periods is governed by the lake temperature-water density relationship.

The seasonal changes of thermal structure in large deep lakes of mid-latitudes, such as the Great Lakes, are shown graphically in Figure 4–96, and discussed in Section 6. As the warming season progresses, the top layers of water absorb heat from the atmosphere, becoming progressively warmer, and through conduction of heat downward and mixing induced by winds, the warm layer becomes deeper. The warm upper water (epilimnion) is separated from the cold deeper water (hypolimnion) by the thermocline. The epilimnion is less dense and literally floats on top of the hypolimnion. In the early stages of development, the thermocline is rather weak and is easily broken down by wind action, which readily mixes the thin surface layer of heated water with colder water below, thus

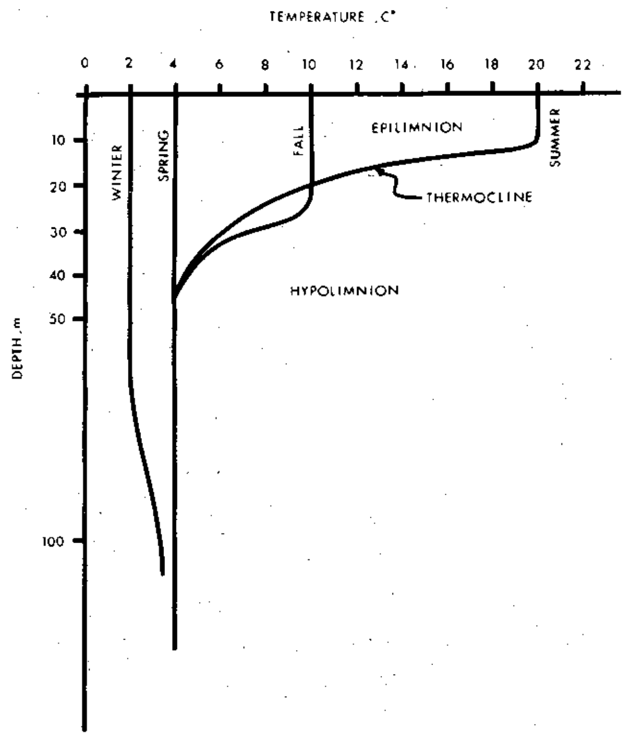

FIGURE 4–96 Seasonal Changes in the Thermal Structure of a Large, Deep Lake of Mid-latitudes

producing further development and deepening of the thermocline. As the thermocline approaches its maximum depth, the mixing becomes progressively less. The final deepening occurs during summer storms with relatively little activity during calmer periods.

The summer stationary period is characterized by nearly stationary lake surface temperatures in their maximum range. At the beginning of this period the thermocline descends to its maximum depth, where it remains relatively stable. The establishment of a strong thermocline at constant depth indicates that there is only a negligible transfer of heat by conduction, either above or below the thermocline. Anderson and Rodgers[14] showed that the maximum depth of the thermocline during this period of peak heat content is about 15 m (50 ft) in all the Great Lakes, in spite of marked difference in their transparency, configuration, size, orientation, and latitude.

Lake cooling begins in the fall, with substantial net loss of heat resulting from the interaction of cooling and heating processes, such as radiation, evaporation, conduction, precipitation, and condensation. In the fully developed cooling period of late fall, with water surface temperature substantially above that of maximum density, cooling of the homogeneous surface layer proceeds rapidly, since only this layer is affected due to stability of the thermocline. At the same time, with the increased frequency of storms in this season the upper layer becomes deeper as well. As the cooling continues, temperature of the upper layer approaches that of maximum density, the thermocline becomes less stable, and the wind-stirring may be complete from top to bottom with the destruction of the thermocline. Church[142] indicates this critical temperature of the homogeneous surface layer to be 6°C (43°F) or slightly above. In the advanced stages of cooling, depth exerts an important control on temperatures in the lakes. With the loss of the thermocline the entire column of water becomes isothermal and further cooling at the surface proceeds slowly because the entire water column loses heat.

During the winter stationary period the lake waters are again at less than maximum density, but in this case the surface is colder than 4°C. In coastal areas and lakes with shallower depths temperatures are generally isothermal vertically. In deep waters an inverse stratification develops, with colder epilimnion and slightly warmer hypolimnion. This stratification is not as pronounced as during the summer, because the downward mixing process is aided by strong winds and convection produced by daytime heating during winter. Water temperature in the entire column or the deep upper layer, whichever the case, approaches freezing point on the lakes with extensive ice cover, and stays at about 2°C (36°F) on the lakes which are largely free of ice. Because great depths are affected, water temperature changes during this period are naturally slow. Thus, Lake Erie with its shallow depths freezes sooner and more often than Lake Superior, which because of its great depths is capable of sustaining tremendous heat losses. By the same token, ice breakup on Lake Erie is much faster.

Since each lake consists of a whole range of depths, which generally increase from shallow coastal waters to a maximum depth in mid-lake, each lake contains water masses with distinct thermal structures characteristic of their depth, particularly during warming and cooling periods. In the beginning stages of the spring warming period the shallow waters along the shore warm up much faster than mid-lake areas, producing large horizontal temperature gradients near the boundary between the warm and cold surface temperatures. The coastal waters are well above 4°C at the surface and vertically stratified, while those in mid-lake are less than 4°C and uniform in temperature from top to bottom in depths as great as 180 m (600 ft) (Church[142] and Rodgers[672]). The most extensive investigation of this phenomenon, named the thermal bar, was made on Lake Ontario by Rodgers.[673] As the warming season progresses the thermal bar zone moves lakeward from the shores and eventually disappears. During the fall cooling period the process is repeated, with the cold temperatures moving offshore towards the center of the lake.

In the above discussion of seasonal temperature changes within a column of water, no consideration was given to any movement of water into or out of the column due to the normal lake currents. Actually, water temperatures and currents in a lake are closely related. Any lake is subject to water movement resulting from the inflow-outflow balance and the general water circulation induced by winds and geostrophic forces. Thus, once established, a thermocline seldom stays still, but fluctuates in a wave-like motion (Section 6). Rodgers[672] states that the thermocline moves up and down through a distance of 10 to 20 m (30 to 60 ft), with wavelengths of tens of kilometers. He also states that these internal waves are seldom evident to the casual observer and their detection requires continuous observation of temperatures at one or more locations within the lake.

Periodically, strong winds blowing steadily from one direction may tilt the thermocline, deepening the epilimnion on the downwind shore and reducing its depth on the upwind shore. Prolonged strong winds pile up warm surface water and produce sinking on the downwind shore, while at the same time they remove warm surface water and produce corresponding upwelling of cold water from deeper layers on the upwind shore. Upwelling occurs frequently on the northwest shoreline of Lake Ontario and the west shores of Lake Michigan. Tilting of the thermocline can be observed from the water temperature records of municipal water intakes located on the opposite shores of the lake.

4.5.3 Air-Water Temperature Relationship

The difference between air and water surface temperatures is the primary indicator of the atmospheric stability over the lakes. When the air is warmer than the water sur-

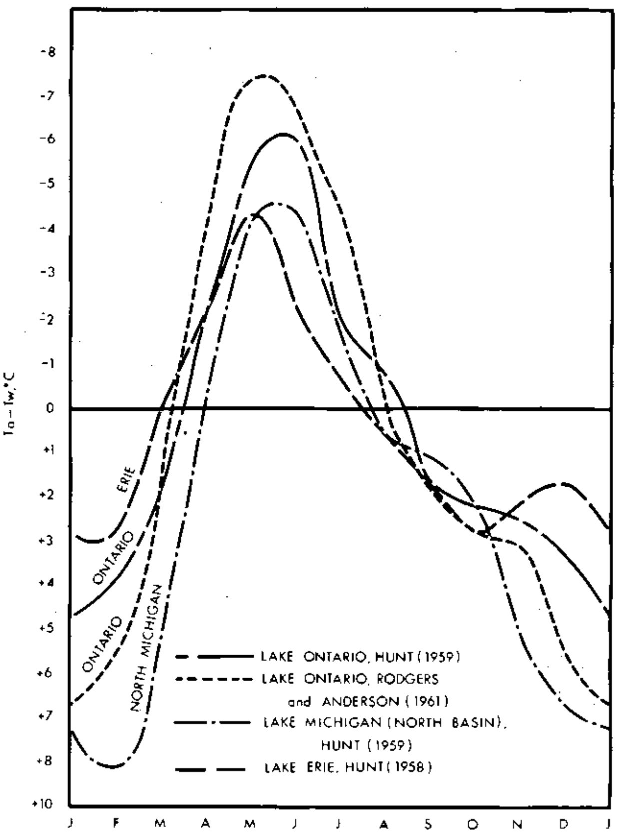

FIGURE 4–97 The Relationship of Air-Water Temperature Differences in the Great Lakes

face, the air will tend to be stable. Conversely, when the air is cooler than the water surface, the air will tend to be unstable. Thus, other things being equal, the greater the positive difference between the air and water surface temperatures, the more stable the atmosphere and smaller the opportunity for the occurrence of overwater precipitation, high winds, and evaporation. On the other hand, the greater the negative difference between the air and water surface temperatures, the more unstable the atmosphere and greater the opportunity for the occurrence of the above climatic processes.

Atmospheric stability over the Great Lakes varies appreciably during the year. The air is normally warmer than the water surface during spring and colder for a somewhat longer period in fall (Figure 4–97). Because of the shortcomings in data used for air-water temperature differences, their magnitude may not be representative of the actual mid-lake conditions, and considerable variation in the magnitude shown at times for the same lake seems to indicate this deficiency. For Lake Ontario, Hunt[395] used mean values from three perimeter stations (Toronto, Oswego, and Trenton) for the 1937–56 period to obtain average air temperature over the lake. Water surface temperatures for this lake were obtained by adjusting values given by Freeman,[271] U.S. Lake Survey,[825] and Millar.[543] In the same study, for the northern Lake Michigan air temperature, Hunt used St. James and Beaver Island data from 1911 to 1956; water surface temperatures were obtained from records in the vicinity of Beaver Island from unstated sources. In a study on Lake Erie, Hunt[398] used the water surface temperatures given by Freeman, U.S. Lake Survey, and Millar, and the normal air temperatures from four perimeter stations (Detroit, Cleveland, Erie, and Toledo). In a second study for Lake Ontario, Rodgers and Anderson[675] used Millar's water surface temperatures and normal air temperatures from Toronto and Rochester.

In all cases except Lake Michigan, air temperature over the lakes was determined from perimeter stations and may be considerably different than at mid-lake, as pointed out by Rodgers and Anderson in their study. Because land area is more sensitive to both heating and cooling, these air temperatures obtained at perimeter stations would tend to intensify the extreme conditions, being higher than at mid-lake during summer and lower during winter periods. Air temperature data for Lake Michigan represent conditions over an island and may be more representative. The water surface temperatures, except those by Millar, were also determined mostly from perimeter stations and would tend to have the same deficiencies, but probably not to the same degree. Thus, the air-water relationships shown probably over-accentuate the magnitudes between these temperatures.

The monthly values of air-water temperature difference indicate that there are four periods of prevailing atmospheric conditions over the Great Lakes. Duration and timing of these periods vary for different lakes, depending primarily on latitude. Generally, the air is normally warmer than water during spring months of April, May, and June (also July in northern areas), and the atmospheric conditions are stable. During mid-summer months of July and August the air and water temperatures are approximately the same, thus indifferent or adiabatic (occurring without loss or gain of heat) equilibrium conditions exist in the atmosphere. From early fall to mid-winter months (September through February) the air is normally colder than water and the atmosphere is unstable. However, during winter months the presence of ice and snow cover has a significant modifying effect on the air-water temperature relationship. Finally, during late winter in March (also April in northern areas) the air and water temperatures are again about the same, and the adiabatic equilibrium conditions prevail. The adiabatic equilibrium conditions occur during relatively short, transitory periods and variation in the atmospheric conditions during these two periods may be considerable. In contrast, the spring stable conditions and the fall unstable conditions present long, well-established periods.

4.6 Humidity

4.6.1 Lake Perimeter Humidity

The influence of the lakes produces higher and more stable humidity in the Great Lakes area than at similar latitudes in the mid-continent. Since warmer atmosphere is capable of holding more water vapor, the amount of water vapor present in the atmosphere varies constantly with temperature and availability of moisture. However, this discussion is concerned with the relative humidity or the ratio between the actual vapor pressure and the saturation vapor pressure at the same temperature. Since all lakes provide large quantities of moisture through evaporation, the upper Great Lakes with lower temperatures and corresponding lower dew points attain somewhat higher values of relative humidity. Prevailing winds and lake breezes are important factors in raising or lowering humidity values on land areas adjacent to the lakes.

Humidity measurements on lake perimeters are provided by the first order meteorological stations located around the lakes. Humidity values at these stations are generally published for the four daily synoptic hours (1:00 and 7:00, a.m. and p.m.), but hourly values are also available. Data from these stations are the sole source of continuous humidity records for extended periods of time. Because of the lake effect on adjacent land areas, various investigators have utilized these data to obtain estimates of humidity over the lakes by averaging records from several perimeter stations. Some of the more recent studies also employed correction factors to adjust these estimates to overlake conditions. The correction factors were derived from infrequent overwater measurements, similar to those used for winds, and are discussed later.

TABLE 4-11 Average Perimeter Humidity for the Great Lakes (Percent)

	Lake				
Period	Superior	Michigan	Huron	Erie	Ontario
January	77	76	81	77	78
February	76	73	79	77	77
March	74	73	76	74	74
April	69	69	73	70	69
May	68	66	70	69	68
June	72	69	74	70	70
July	74	71	74	71	68
August	76	74	77	74	72
September	79	76	78	75	74
October	76	73	79	75	74
November	78	76	83	78	78
December	79	78	83	79	78
Annual	75	73	77	74	73

Values are based on mean data published in 1969 for the following stations:
Superior: Sault Ste. Marie, Marquette, Duluth, and Thunder Bay.
Michigan: Milwaukee, Muskegon, and Green Bay.
Huron: Alpena, Gore Bay, and Wiarton.
Erie: Toledo, Cleveland, Buffalo, and London.
Ontario: Rochester, Syracuse, Trenton, and Toronto.

An estimate of the average monthly and annual humidity values for the individual Great Lakes, based on data from perimeter stations, is given in Table 4-11. The perimeter humidity for all lakes increases from a low of approximately 70 percent in the spring to a high of approximately 80 percent during the late fall. Average annual humidity varies from 73 percent for Lake Michigan to 78 percent for Lake Huron, with intermediate values for other lakes.

Examination of records for the individual stations around the lakes indicates a daily variation and a general northward increase in humidity. Based on four observations a day, highest humidity normally occurs late at night and during early morning hours (1:00 and 7:00 a.m. readings), while lowest humidity occurs in the early afternoon (1:00 p.m. reading). At most stations average annual relative humidity values for the night and morning readings range between 75 and 85 percent, with the maximum values occurring during summer. The afternoon readings range between 60 and 70 percent, and are lowest in the spring and summer. At most locations average daily range in humidity is from 5 to 10 percent during winter and from 15 to 20 percent during summer.

4.6.2 Overwater Humidity

The humidity records from perimeter stations contain both lake and land effects and

TABLE 4–12 Lake-Land Humidity Ratios for the Great Lakes

Period	Richards & Fortin (1962) 1959-1961	Jackson (1963) 1959-1962
January	1.33	1.25
February	1.30	1.24
March	1.21	1.22
April	1.14	1.04
May	.86	.89
June	.94	.94
July	1.09	1.10
August	1.09	1.10
September	1.11	1.09
October	1.15	1.14
November	1.15	1.13
December	1.31	1.28
Annual	1.14	1.12

are not necessarily representative of the extensive water areas included in the Great Lakes. The major controlling factor of humidity is the air temperature, and temperatures over lake and land areas differ. Overwater humidity data are obtained either from direct overwater measurements, which are available only on an intermittent basis, or from empirical relationships derived from those measurements. Such relationships combine many of the differences between overwater and overland conditions into a single correction factor, a lake-land humidity ratio (Richards and Fortin,[650] Jackson[420]). The monthly humidity ratios derived in these studies are shown in Table 4–12. They indicate that on an annual basis overwater humidity is some 10 to 15 percent higher than overland humidity at perimeter stations. During spring, overwater humidity is approximately 10 percent lower than perimeter humidity, but during the rest of the year overwater humidity is higher, with a maximum difference of approximately 30 percent in the winter.

The average daily variation of the humidity ratios presented in the studies shows high humidity ratios during the night and low ratios during daytime hours. The nighttime maximum occurs generally between 1:00 and 4:00 a.m. and the daytime minimum occurs around noon. Richards and Fortin, based on four daily observations, indicate lowest humidity ratios at 1:00 p.m., while Jackson, using eight daily observations, shows the lowest ratio at 10:00 a.m. Inspection of their diurnal variation curves shows that the difference in time is related to the number of daily observations, and indicates that four observations a day are not sufficient to obtain the daily humidity distribution.

TABLE 4–13 Average Perimeter Precipitation for the Great Lakes, 1937–1969 (cm)

Period	Lake: Superior	Michigan	Huron	Erie	Ontario
January	5.5	4.8	6.7	6.5	6.8
February	4.1	3.9	5.3	5.7	6.4
March	4.4	5.0	5.3	6.9	6.5
April	6.0	7.3	6.5	8.5	7.2
May	7.6	7.6	7.0	8.2	7.5
June	9.0	8.6	7.2	8.3	6.3
July	7.2	7.5	6.7	7.7	7.2
August	8.7	7.7	7.5	8.1	7.4
September	8.6	8.4	8.2	7.1	7.0
October	6.4	6.2	6.9	6.8	6.9
November	6.8	6.3	7.7	7.4	7.5
December	5.5	4.8	7.3	6.5	7.0
Annual	79.8	78.1	82.3	87.7	83.7

Note: Based on data assembled by the Lake Survey Center, NOAA.

4.7 Precipitation

4.7.1 Lake Perimeter Precipitation

Precipitation includes all forms of moisture deposited on the earth surface from the atmosphere. The principal forms of precipitation include rain, hail, sleet, and snow, all of which are readily measurable. Of particular interest in the Great Lakes Basin is the precipitation measured at lake perimeters. Investigations of precipitation distribution indicate that perimeter stations show marked variation from precipitation further inland, and since direct overwater measurements are generally not available, it is assumed that perimeter observations are sufficiently representative of overwater conditions (e.g., Freeman[271]).

Estimates for the average monthly and annual precipitation on individual lakes during the 1937–69 period are shown in Table 4–13. The annual precipitation varies from 78 cm (30.8 inches) for Lake Michigan to 88 cm (34.5 inches) for Lake Erie, with an overall average for all the lakes of 81 cm (32.0 inches). Annual precipitation increases from north to south and from west to east. The southward increase in precipitation is climatic, since warmer atmosphere is capable of sustaining more moisture, while the eastward increase is caused by the lake effect, since additional moisture is supplied to the atmosphere by the lakes as

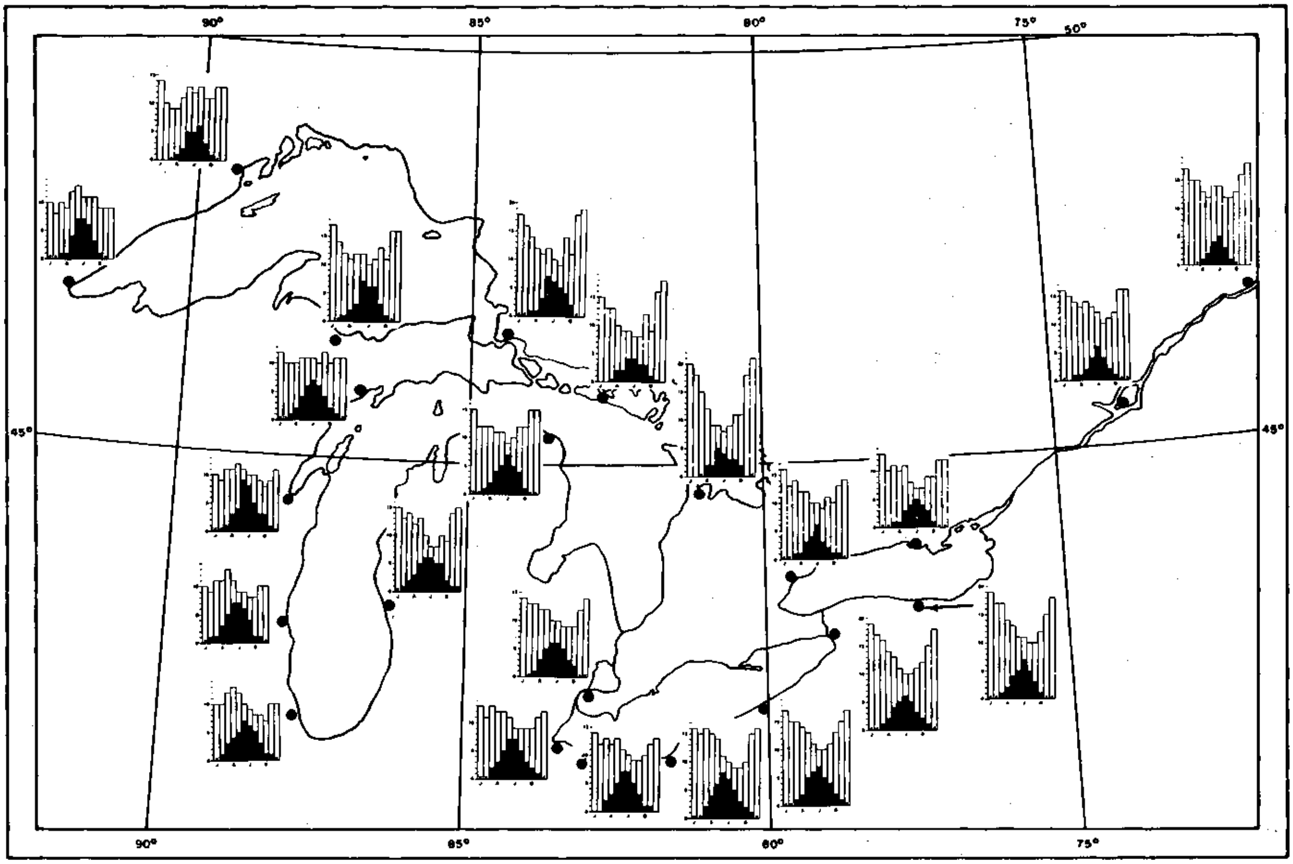

FIGURE 4–98 Mean Monthly Number of Days with Measurable Precipitation (open bars) and Thunderstorms (shaded) in the Great Lakes Basin

From U.S. Weather Bureau, 1959

they are exposed to the prevailing westerly winds.

The seasonal precipitation pattern shows well-distributed and abundant precipitation throughout the year, although a larger portion of the annual supply falls during the summer months, a characteristic of continental climates. The relatively high summer rainfall is especially pronounced on the western and northern lakes. The average monthly precipitation increases from a winter low of 4 cm to 5 cm (1.6 to 2.0 inches) in the upper lakes and 6 cm to 7 cm (2.4 to 2.8 inches) on the lower lakes to a summer high of 8 cm to 9 cm (3.1 to 3.5 inches) on all lakes.

The mean number of days per month with measurable precipitation at perimeter stations increases from the windward to the lee sides of the lakes, and also increases generally from summer to winter months. Exceptions to this seasonal distribution occur along the western and northern shores of Lakes Michigan and Superior. The number of days with measurable precipitation and thunderstorms at perimeter stations is shown in Figure 4–98. Highest thunderstorm frequencies occur along the western shore of Lake Michigan and the southern shore of Lake Erie.

During the winter months precipitation in the Great Lakes Basin is largely in the form of snow. In the northern areas it generally consists of snowfall exclusively, with permanent snow cover throughout the winter. In the southern areas precipitation alternates between snowfall and rainfall, with intermittent snow cover on the ground.

4.7.2 Overwater Precipitation

Observations have indicated that large bodies of water, such as the Great Lakes, modify the atmosphere above them, including precipitation patterns. One theory explaining the reduction of overwater precipitation in the summer is that the water cools the air above it.

However, precipitation measurements on the islands fail to confirm this in all cases. Horton and Grunsky[376] and Verber[848] suggested that reduced overwater precipitation in the summer may be due to less thunderstorm activity. This results from the cooling effect of the lakes, which produces a more stable atmosphere over the water than over surrounding land areas. Byers and Braham[117] made a similar observation about Lake Michigan and added that in the winter the warming effect of the lakes encourages greater precipitation on the lee shore than on the windward shore. Pearson,[599] from a study of precipitation observations by radar, found that the formation of air-mass showers over Lake Michigan in the summer was inhibited.

The elements affecting overwater precipitation in the winter are less definite. It is apparent that the warming effect of the lakes encourages snow flurries, but whether the precipitation is less, equal to, or more than that falling on the adjacent shorelines is a matter of controversy. Light precipitation belts on windward sides and heavy precipitation belts on the lee sides of the lakes are well established, but the quantities recorded at these locations do not necessarily yield representative overwater precipitation. The observed heavy snowfall on the lee shores of the lakes might be confined to the lake perimeters and would then represent an accumulation of precipitation resulting from the lake-land interaction. The elevation of the air mass as it moves from the water to the land surface, coupled with the air movement from the warm water to the cold land during winter, combine to cause more precipitation on the lee shores. This may apply to the islands as well. Winter measurements are also less accurate because snow is more sensitive to wind, increasing the effects of exposure, so the gages do not adequately measure winter precipitation. Freezing of the lakes complicates the process further.

Recognizing the shortcomings of perimeter observations for estimating overwater precipitation, several investigators derived relationships of overwater to perimeter precipitation, utilizing data from islands to represent overwater conditions. However, island data may not be reliable for this purpose, and results of the studies are often contradictory.

Based on records from Beaver Island in the Lake Michigan and North Bass Island in Lake Erie, Horton and Grunsky[376] concluded that precipitation on the lakes was lower than at perimeter stations. They calculated seasonal lake-land precipitation ratios, which indicate that precipitation on Lakes Superior, Michigan, and Huron (Beaver Island) averages 93 percent of that measured at shore stations during winter months, and 94 percent during summer months. For Lakes Erie (North Bass Island) and St. Clair their overwater precipitation amounts to 84 percent of perimeter precipitation for winter and 85 percent for summer months. However, Day[205] suggests that the differences in island and shore precipitation are due to wind reduction of precipitation gage catch at the more exposed island sites, rather than any real deficit in precipitation on the lakes.

To study overwater precipitation a storage-type precipitation network was established in 1952 on a number of islands in northern Lake Michigan by the U.S. Lake Survey and the U.S. Weather Bureau. Based on twice-a-year precipitation records from this network and monthly records from Beaver Island and adjacent shore stations, Hunt[395] concluded that annual overwater precipitation on Lakes Michigan and Ontario averages 79 percent of that measured at perimeter stations, with monthly values varying from 60 percent in August to 91 percent in November. Hunt assumed precipitation at the smallest, exposed island to be true overwater precipitation. Kohler[461] questioned that assumption and indicated that the relative catch of the island gages is highly correlated with windiness, and that virtually all the differences in precipitation catches could be explained by relative windiness at the gage sites. In another precipitation study of the northern Lake Michigan island network, Kresge, Blust, and Ropes[476] agreed with Kohler and used the higher measured amounts at both island and land gages as true overwater and shore precipitation and corrected the other gage records for gage exposure. The annual overwater precipitation was about the same (102 percent) as precipitation from shore stations. Seasonally, overwater precipitation ranged from 3 to 10 percent less than perimeter precipitation in the summer, depending on the offshore and onshore winds, respectively; and 9 percent more in the winter.

In a Lake Michigan precipitation study based on records from the Four-Mile Crib in the southern tip of the lake and land gages in the Chicago area, Changnon[137] determined a lake-land precipitation relationship similar to that derived by Hunt. Changnon's lake-land precipitation ratios show monthly variations ranging from 78 percent in October to 95 per-

TABLE 4–14 Lake-Land Precipitation Ratios for Lake Michigan and Lake Erie

	Lake Michigan				Lake Erie
Period	Hunt (1959a) 25 years 1911–56	Changnon (1961) 11 years 1945–56	Kresge, Et al. (1963) 30 years 1906–62	Upchurch[1] (1970) 6 years 1963–68	Derecki (1964) 13 years 1920–46
January	.88	.95	1.13	1.39	.95
February	.85	.86	1.13	2.26	.89
March	.81	.84	1.07	1.05	1.03
April	.78	.81	1.01	.89	1.04
May	.75	.87	.96	.83	1.07
June	.73	.79	.93	.49	.92
July	.69	.82	.90	.70	1.04
August	.60	.87	.91	.64	1.03
September	.74	.83	.98	1.10	.95
October	.89	.78	1.05	.96	.89
November	.91	.79	1.10	1.62	1.02
December	.89	.89	1.13	1.32	1.03
Winter (Nov-Apr)	.85	.86	1.09	1.42	.99
Summer (May-Oct)	.73	.83	.96	.79	.98
Annual	.79	.84	1.02	1.10	.99

[1]Upchurch ratios are based on inland stations located 160 km west of the lake (this appendix).

cent in January, with an annual average of 84 percent.

The lake-land precipitation ratios calculated for Lake Erie (Derecki[214]) show considerable monthly variations, without a definite seasonal trend. Overwater precipitation was based on records from Pelee, South Bass (Put-in-Bay), and Catawba Islands, and land precipitation on records from surrounding perimeter stations. The resultant annual ratio was 99 percent with monthly ratios that varied from 89 percent in February and October to 107 percent in May.

In 1963 the U.S. Lake Survey, in cooperation with the U.S. Weather Bureau, modified their existing precipitation network in northern Lake Michigan by replacing the storage-type gages, which were read twice a year, with precipitation recorders producing hourly readings. Similar gage networks were established in western Lake Erie in 1964 and eastern Lake Ontario in 1969. Using recorded data from Lake Michigan islands and land stations located some 160 km (100 miles) west of the lake (Figure 4–18), Upchurch[808] derived lake-land ratios which vary from 49 percent in June to 226 percent in February, with an annual average of 110 percent.

The monthly precipitation ratios derived in the above studies are tabulated in Table 4–14. Monthly ratios given by Hunt[395] and by Kresge et al.[476] represent values from smoothed annual graphs, while those of others are arithmetic averages for the number of years used in their derivations. The Upchurch data are not comparable directly with other data in the table, because Upchurch used remote inland gages while all others used lake perimeter gages. The inland stations, however, indicate more correctly the lake effects on precipitation distribution throughout the year.

4.7.3 Weather Radar

Present methods of measuring precipitation have many shortcomings, such as use of point measurements to represent an area, variations in gage catch, accuracy, effects of windiness and exposure on the catch, and access or installation difficulties in remote areas on large bodies of water. A potentially powerful tool for eliminating some of these problems and obtaining more truly representative precipitation data may be the use of weather radar. Weather radar is applicable to both land and water areas, but it is of particular interest for large lakes because of gage installation and access difficulties.

The use of weather radar for obtaining quantitative precipitation data requires climatological analysis of photographed precipitation echo patterns. The process involves use of a grid overlay on radar photographs, counting echo occurrences, and correlating with measured precipitation. Current use of radar precipitation observations, although promising, is not advanced sufficiently to provide usable, quantitative data. Poor performance is attributed mainly to weak radar equipment, which displays a decrease of echo occurrences per volume of rainfall outward from the radar location, thus limiting the effective range (Bruce and Rodgers[108]). More powerful radar equipment is required. Further developments in radar technology in combination with high-speed computers may provide an ideal answer to the overwater precipitation measurement problem.

4.8 Evaporation

4.8.1 Determination of Evaporation

Evaporation from the lakes is the loss of water from the lake surface to the atmosphere in the form of water vapor. Considering lake and land areas of the Great Lakes Basin, two-thirds of the water supplied by precipitation is lost by evaporation. Evaporation losses from the water surface of the lakes, where the supply of moisture is continuous, are substantially higher than from the land and amount to approximately three-quarters of the overwater precipitation. Thus, it is readily apparent that evaporation has a great effect on the availability of water and on the heat budget of the lakes, since evaporation is basically a cooling process.

There is no direct method to measure evaporation from large water bodies. Since the actual evaporation losses are dependent directly on meteorological factors, it is possible to develop methods that use hydrologic and meteorologic data and permit determination of evaporation losses from the lakes with acceptable accuracy. These methods include water budget, mass transfer, energy budget, evaporation-pan observations, atmospheric humidity budget, and momentum transfer. The first four of these methods have been used to compute evaporation from the Great Lakes.

The water budget method consists of solving the water budget or mass-balance equation, described at the end of this section, for the unknown evaporation component. All other major components of the water budget necessary to compute evaporation from the Great Lakes are either measured directly or can be estimated from related measurements. This is the only direct method of computing evaporation estimates and has been used in various studies to provide control for other methods, which require determination of empirical constants. Evaporation, as determined by the water budget method, is a residual of several large factors and includes the errors of these factors, which may affect the computed evaporation values considerably. Care must be exercised to reduce these errors to a minimum by using all available data and considering the effects of the lakes on some of them, such as on overwater precipitation.

The mass transfer method of computing evaporation is a modified application of Dalton's law, where evaporation is considered to be a function of the wind speed and the difference between the vapor pressure of saturated air at the water surface and the vapor pressure of the air above. A summary of the theoretical development of the mass transfer method and a review of the equations developed by various investigators is given by Anderson et al.[17] The more promising of these equations were tested by Marciano and Harbeck.[512] The problem in applying this method to the Great Lakes is that climatological data for any appreciable period of time are almost exclusively restricted to the perimeter land stations, which may be and often are not representative of open-lake conditions. Variations in air stability that affect both wind and vapor pressure are essentially diurnal in character over land and seasonal over water. The required adjustments for perimeter data, or lake-land ratios for wind and humidity have been made in recent years and are being improved as more overwater data are collected. Thus, the mass transfer method of computing evaporation from the Great Lakes holds great promise for the future. Its primary advantage is the elimination of the main objections of the water budget method, namely, uncertainties with respect to ground water and dependence of computed evaporation on large factors, such as inflow and outflow from the lakes.

The energy budget method requires determination of the energy exchange between a body of water and the atmosphere, which includes such factors as the net solar and atmospheric radiation, conduction of sensible heat to the atmosphere, energy utilized by evaporation, net advective energy, and energy storage within the body of water, disregarding some minor heat sources or sinks (chemical, biological, exchange with bottom sediments). The water loss is determined from the related energy or heat loss by evaporation. Detailed discussion of various terms comprising the energy budget and its practical application is presented by Anderson.[16] However, in the Great Lakes this method has been used infrequently because of the difficulty in obtaining data on energy components.

A convenient and inexpensive method of obtaining evaporation estimates, although frequently questioned on theoretical grounds, is that of evaporation-pan observations, which utilize observed water losses from evaporation pans and experimentally determined pan-to-lake relationships. The ratios of pan evaporation to lake evaporation, or pan coefficients, vary depending on pan characteristics. An extensive investigation of the relationships between pan and lake evaporation was reported by Kohler et al.[462]

4.8.2 Evaporation from Lakes

To compute evaporation from the Great Lakes various investigators have used one or more of the four methods described above. The water budget and mass transfer methods were used most frequently. There are only two known studies which utilize the energy budget approach. The evaporation-pan observation method has also been used infrequently. Results obtained by various investigators often differ considerably, especially for shorter, monthly periods. Some of this variation is natural, reflecting variability of evaporation between the various periods of record involved, but some of it, especially in extreme cases, is due to computation procedures and inaccuracies of basic data. More recent determinations use better basic data and should be more accurate.

Among the earliest methods used to determine evaporation from the Great Lakes is that of evaporation-pan observations. Henry[341] concluded that the ratio of evaporation from floating pans to land pans was approximately 0.5 and used this ratio to estimate lake evaporation. Hickman[355] described experiments in which water temperature in the pan was maintained at the lake surface water temperature, and the pan-lake ratio or pan coefficient was assumed to be 1.0. The latest estimates of evaporation from the lakes by this method (U.S. Weather Bureau[828]) give pan coefficients ranging from approximately 0.75 in the southern areas of the Basin to 0.80 in the northern areas. The above studies give annual evaporation estimates, without breakdown into seasonal or monthly amounts.

The water budget is one of the traditional methods of determining lake evaporation (Russell,[692] Freeman,[271] Pettis,[605] Hunt,[395] Brunk,[111] and Derecki[213,214]). In some studies (Hunt, Derecki) precipitation from perimeter stations was adjusted by lake-land ratios to represent overwater conditions. Others used unadjusted perimeter precipitation. Later studies showed that Hunt's reduction was probably too extreme, resulting in somewhat lower evaporation than indicated by most of the other recent studies for Lake Ontario. Because Lakes Michigan-Huron have a common outlet (St. Clair River), water budget determinations for these lakes can be made only for both lakes as a single unit.

Probably the first mass transfer determination of Great Lakes evaporation is that given by Freeman[271] who used a relatively simple formula similar to those used in all subsequent Great Lakes mass transfer studies. Other evaporation studies, mostly of Lake Ontario, which employed mass transfer methods are those by Horton and Grunsky,[376] Hunt,[395] Kohler,[461] Snyder,[751] Bruce and Rodgers,[108] Richards,[648] Richards and Rodgers,[654] and Richards and Irbe.[651] Richards[648] modified the mass transfer equation by introducing monthly wind and humidity ratios for adjusting data obtained from land stations. In previous studies wind data from perimeter stations were being adjusted to overwater winds based on seasonal periods. Because of data limitations, most studies mentioned above employed inconsistent periods of record to determine various factors of the mass transfer equation. In some of them, the average evaporation values are based on only a few years of record, which is much too short to establish reliable long-term trends. The first mass transfer determination of evaporation with consistent periods of record for all factors was made for Lake Ontario by Richards and Rodgers.[654] This study was extended to include other lakes bordering on Canada by Richards and Irbe.[651]

Evaporation studies by the energy budget method conducted on the Great Lakes are limited to Lake Ontario (Bruce and Rodgers,[108] and Rodgers and Anderson[675]). The results of these studies are practically identical. The authors concede that their estimates are high due to inaccuracies of data used, and they discuss the possible errors. Continuing research on interaction between the atmosphere and lake surface should enable more direct evaluation of the energy exchange factors, reduce their dependence on empirical relationships, and improve the accuracy of evaporation estimates determined by the energy budget method.

Evaporation from the Great Lakes varies with latitude and depth. The warmer, lower latitudes provide greater evaporation opportunity, and the lake depths govern heat storage capacity. The influence of lake depths is mainly seasonal. Deeper lakes warm and cool more slowly, retarding the seasonal low and high evaporation losses. The depths of the Great Lakes coincide with latitude; Lake Superior is deepest (410 m) and Lake Erie is the shallowest (65 m), while the centrally located lakes have approximately similar intermediate depths (230 to 280 m). Thus, evaporation from the lakes increases from north to south, being lowest for Lake Superior and highest for Lake Erie. The centrally located lakes, Michigan, Huron, and Ontario, have intermediate evaporation rates.

The average evaporation values for individual lakes, obtained in some of the better known or more recent studies mentioned in the preceding paragraphs, are listed in Table 4–15. The table also shows the methods used, the source, and the periods of record, although, for methods other than water budget and the last

TABLE 4–15 Comparison of Great Lakes Evaporation (Centimeters)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
LAKE SUPERIOR													
WATER BUDGET													
Freeman (1926) 1921-25	8.9	7.9	6.6	5.8	0.3	0.3	1.5	-0.3	3.3	5.3	7.9	9.7	57.2
Derecki (1965) 1939-59	8.9	6.6	5.8	-0.8	-1.0	-1.0	-0.5	2.8	5.8	6.9	9.7	9.7	52.8
MASS TRANSFER													
Freeman (1926) 1900-24	9.1	8.4	6.9	2.5	0.0	0.0	0.0	3.0	4.3	7.1	6.9	8.1	56.4
Snyder (1960) 1921-50	7.6	6.4	4.8	1.8	-1.8	-5.8	-7.4	-0.5	5.6	6.4	6.9	8.4	32.3
Richards & Irbe (1969) 1959-68	11.7	9.1	5.8	1.5	1.0	-3.6	-8.1	-4.1	3.3	6.4	10.4	12.2	45.7
LAKE MICHIGAN													
MASS TRANSFER													
Freeman (1926) 1900-24	7.6	7.1	4.1	2.3	1.5	1.8	7.9	9.9	9.1	8.6	6.6	6.6	73.2
Snyder (1960) 1921-50	7.6	6.6	4.1	1.0	-2.3	-3.0	3.0	7.9	9.9	8.6	6.9	7.6	57.9
LAKES MICHIGAN-HURON													
WATER BUDGET													
Freeman (1926) 1915-24	8.4	2.8	4.3	3.6	-0.3	-0.3	0.5	4.8	9.7	10.4	10.2	10.7	64.8
LAKE HURON													
MASS TRANSFER													
Freeman (1926) 1900-24	7.9	7.9	5.1	2.0	2.0	2.5	7.9	10.2	9.1	7.1	6.1	7.1	74.9
Snyder (1960) 1921-50	7.9	6.9	4.3	1.3	-1.5	-2.8	3.3	8.3	9.9	8.1	6.9	8.4	61.2
Richards & Irbe (1969) 1959-68	11.9	8.9	4.6	-0.8	0.0	-2.0	0.5	5.1	8.6	11.4	11.7	11.7	71.6
LAKE ERIE													
WATER BUDGET													
Freeman (1926) 1951-24	4.6	2.8	12.7	-3.8	0.0	0.8	4.8	11.4	13.7	15.0	12.2	9.1	83.3
Derecki (1964) 1937-59	5.3	1.5	1.5	0.0	1.0	2.8	9.4	13.7	16.0	13.7	12.2	7.1	84.3
MASS TRANSFER													
Freeman (1926) 1900-24	6.4	6.6	2.8	3.6	1.9	7.4	17.0	18.3	16.0	13.5	7.1	6.1	106.4
Snyder (1960) 1921-50	6.6	5.1	2.5	1.3	2.0	4.6	9.4	12.2	12.7	10.9	9.7	8.9	85.9
Richards & Irbe (1969) 1950-68	5.6	4.1	1.3	-3.0	5.8	7.6	7.1	11.2	14.2	15.7	13.7	7.6	90.9
LAKE ONTARIO													
WATER BUDGET													
Hunt (1959a) 1934-53	6.1	3.0	1.8	1.0	0.5	-0.5	2.8	7.9	9.7	11.4	10.4	9.7	63.8
Morton & Rosenberg (1959) 1934-52	8.1	5.8	2.0	2.0	1.3	0.5	4.6	10.2	10.7	11.7	11.4	11.2	79.5
MASS TRANSFER													
Freeman (1926) 1900-24	6.6	6.6	4.1	2.5	0.8	2.8	9.4	13.0	11.7	10.9	6.1	6.1	80.5
Hunt (1959a) 1937-52	7.1	5.6	5.6	2.0	0.0	0.3	4.8	6.4	9.7	8.1	7.1	6.1	62.7
Snyder (1960) 1921-50	7.9	6.9	4.3	1.5	-1.5	0.3	5.8	10.2	10.7	9.4	6.6	7.6	69.6
Richards & Irbe (1969) 1950-68	9.7	7.4	4.3	-1.8	1.0	0.3	4.8	8.1	10.9	9.1	8.9	8.9	71.6
ENERGY BUDGET													
Rogers & Anderson (1961) 1958-60	12.4	8.9	5.1	0.5	-1.8	0.0	11.7	8.9	10.2	9.4	10.9	10.7	86.9

NOTE: Energy budget and mass transfer studies (except Richards & Irbe, 1969) used variable periods of record for various factors involved.

mass transfer study (Richards and Irbe,[651]) these periods are only approximations. Results of most studies show reasonable agreement between different computations.

The average long-term seasonal variation of evaporation from the Great Lakes is shown in Figure 4–99, presented as smoothed graphs based on studies indicated in Table 4–15. Lakes Michigan and Huron are included in a single graph, because of common water budget computations and limited determinations by other methods. The available information indicates that the evaporation from these lakes is similar and compares with that of Lake Ontario. In view of the latitude and depth distributions of these three lakes, this similarity appears to be quite reasonable.

The long-term average annual evaporation from the Great Lakes amounts approximately to 65 cm (25 cm (25 in.) The following are estimates of annual evaporation for the individual lakes: Superior, 55 cm (21 in.); Michigan-Huron, 65 cm (26 in.); Erie, 85 cm (33 in.); and Ontario, 70 cm (28 in.). These estimates were based on several studies and should be considered as indicators of the long-term average value. During individual years annual evaporation may vary considerably from the long-term values listed above.

Seasonally the low evaporation normally occurs in the spring, when the water temperature is close to or even below the dew point temperature of the air. These low evaporation rates vary from slight evaporation to condensation. With rising water temperatures evaporation increases until it reaches the high

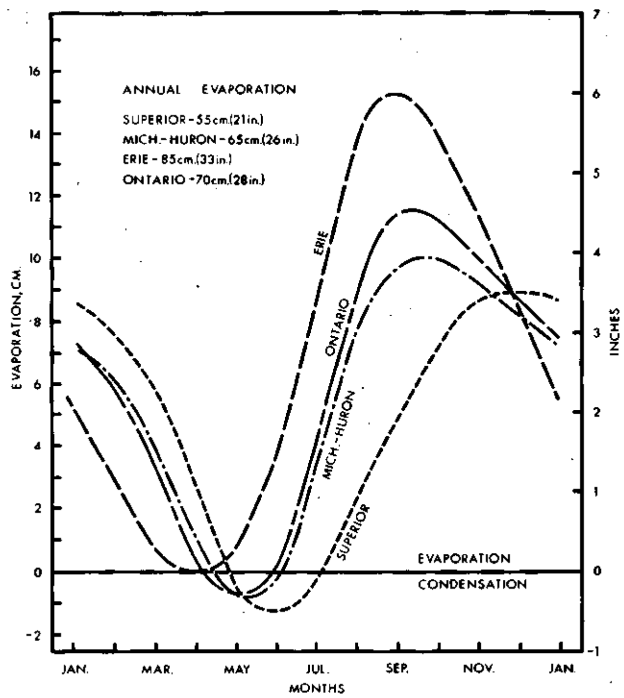

FIGURE 4-99 Evaporation from the Great Lakes. The smoothed lines are based on several studies from 1926-1969.

evaporation season, which for most lakes is in the fall, when the water temperature is considerably above the dew point temperature of the air. Because of its great depth and tremendous heat storage capacity, highest evaporation from Lake Superior occurs in the late fall and early winter period. The long-term average values of the highest monthly evaporation vary from approximately 9 cm (3.5 in.) for Lake Superior to 15 cm (6.0 in.) for Lake Erie. These high evaporation rates, coupled with low air temperatures, cause rapid dissipation of heat from the water surface. With the sharply falling water temperatures, evaporation begins to decrease.

4.9 Runoff from Drainage Basin

4.9.1 Surface Runoff

Water enters the lakes from the drainage basin mainly through the tributary streams. When rainfall exceeds the infiltration capacity of the soil the excess water reaches the tributary streams either as direct surface runoff or as interflow. Interflow is defined as that water which percolates through the soil above the phreatic or permanently saturated ground-water zone. Although interflow reaches the streams with more delay than direct surface runoff, the two are difficult to distinguish, and together are referred to as surface runoff. The infiltration capacity of soils varies widely depending upon precipitation factors such as intensity, duration, and type of precipitation, and soil factors such as antecedent soil moisture, type of soil, shape and slope of the basin, and vegetation. During winter months, the ground is usually frozen, and interflow is reduced to the periods of ground thaws, but surface runoff still occurs during intermittent snowmelts. Basin hydrology is considered in Appendix 2, *Surface Water Hydrology*.

Water which infiltrates into the soil is transmitted downward to the ground-water table and becomes a part of the ground-water reservoir. Ground-water flow is discussed later in this section.

The storage of water on the drainage basin in whatever form, be it ground water, channel storage, or snowpack, is a fundamental hydrologic factor of runoff delay. Natural regulation by upland lakes and artificial regulation by man-made reservoirs and control structures are also common in the basins of all the Great Lakes. Lake regulation delays, prolongs, and diminishes the peak runoff by storing water during periods of high runoff.

Runoff is measured at gaging stations on many of the tributary streams and together with measured flows in connecting rivers is the most accurate data in the hydrologic cycle. Unlike measurements of other components, which sample only points within an area, gaged runoff effectively integrates the entire area about the point of measurement. However, runoff data contain some uncertainties, but these are considered to be random. Errors may be introduced in the measurement of runoff, particularly during winter months due to ice effects, and by extrapolating the gaged runoff to the nearby ungaged areas to obtain coverage for the entire drainage basin.

Routine computations of the total average surface runoff to the lakes are not made by any agency associated with the Great Lakes, but runoff estimates have been made in the course of hydrologic studies. The values of runoff presented in this report were obtained by direct areal extrapolation of the available gaged streamflow records to the nearby ungaged areas, and summation of the total runoff amounts from individual basins of the tributary streams within each lake basin, which in turn were combined to obtain total runoff from

TABLE 4–16 Runoff-Precipitation Ratios, 1937–1969

Period	Lake: Superior	Michigan	Huron	Erie	Ontario
January	.49	.47	.43	.55	.55
February	.50	.66	.48	.68	.55
March	.61	.62	.75	.86	.95
April	1.01	.61	.93	.63	1.13
May	.85	.42	.67	.35	.60
June	.46	.26	.37	.19	.34
July	.36	.24	.27	.12	.20
August	.26	.18	.18	.08	.15
September	.28	.18	.16	.08	.16
October	.40	.28	.28	.13	.25
November	.44	.32	.33	.20	.34
December	.52	.44	.43	.40	.48
Annual	.52	.39	.44	.35	.48

TABLE 4–17 Average Runoff into the Great Lakes, 1937–1969

Period	Runoff in cm depth on lake surface: Superior[1]	Michigan	Huron	Erie[2]	Ontario
January	3.4	4.3	5.5	8.2	13.2
February	2.9	5.1	5.2	8.9	12.5
March	3.8	6.4	8.4	14.1	22.8
April	8.6	9.2	12.7	12.8	30.3
May	9.8	7.2	10.2	7.2	17.7
June	6.5	5.2	6.1	4.2	9.2
July	4.5	3.9	4.2	2.4	5.7
August	3.6	3.1	3.0	1.5	4.4
September	3.6	3.2	3.0	1.3	4.6
October	3.7	3.7	4.1	2.0	6.5
November	4.2	4.1	5.3	3.3	9.8
December	3.7	4.2	6.0	5.9	12.8
Annual	58.3	59.6	73.7	71.8	149.5

[1] Includes diversions into Lake Superior (about 5cm/yr – 140 m^3/s). See DIVERSIONS.
[2] Excluding drainage area of Lake St. Clair.

the entire drainage area of the Great Lakes. Similar methods were employed in previous studies (Freeman,[271] Horton and Grunsky,[376] Pettis,[605] Hunt[395]). Results obtained by various investigators generally differ somewhat because of different periods of record and varying coverage of the gaged tributary area, which increases steadily. Peak runoff to all the lakes usually occurs in the early spring as a result of melting snow augmented by rainfall and lack of growing vegetation. The low point usually occurs in the late summer.

To facilitate comparison with other components of the hydrologic cycle, such as precipitation or evaporation, runoff values are frequently given in units of depth over respective areas, and this practice is retained in this report. Runoff distribution on the drainage basin is shown in Figure 4–19. Comparison of runoff with the corresponding overland precipitation for both monthly and annual periods, expressed as runoff-precipitation ratios, is shown in Table 4–16. These ratios indicate that average annual runoff during the period from 1937 to 1969 represents from 35 to 49 percent of the overland precipitation, while average monthly runoffs vary from a high of 113 percent in the spring to a low of 8 percent during the summer. The substantial differences in the retention of precipitation on the basins of the individual lakes are due primarily to higher evapotranspiration losses in the south, but other factors such as infiltration capacity of soils, forest cover, land cultivation, and urbanization, also affect the relationship between runoff and precipitation. Although precipitation on Lake Erie is among the highest and is comparable with that of Lake Ontario, runoff into Lake Erie is low because of the high water losses by evapotranspiration. Similarly, the Lake Superior basin, with the lowest precipitation, has a high runoff because of the reduced water losses in the north. High runoff in the spring accounts for 30 to 40 percent of the annual amount.

The importance of surface runoff to the hydrology of the Great Lakes depends not only on the absolute magnitude of flow but also on the relative magnitude of runoff with respect to surface area of each lake. Runoff represents one-third to one-half of the overland precipitation and is almost equal to overwater precipitation on all the lakes except Ontario, where runoff is almost twice as high. The average runoff values for monthly and annual periods, expressed in centimeter depth on the lake surface, are listed in Table 4–17. Average annual runoff during the 33-year period (1937–69) varied from 58 cm (23 in.) for Lake Superior to 150 cm (59 in.) for Lake Ontario, 60 cm for Lake Michigan, 74 cm for Lake Huron and 72 cm for Lake Erie. The annual value for Lake Superior includes approximately 5 cm (2 in.) from the Ogoki and Long Lake Diversions, which are channeled and measured in the tributary streams, while Lake Erie runoff excludes streamflow tributary to Lake St. Clair, since it is measured in the Detroit River and thus becomes part of the inflow to that lake. The average monthly runoff varied from a high of 30 cm (12 in.) during April on Lake Ontario to a low of 1.3 cm (0.5 in.) during September on Lake Erie.

4.9.2 Underground Flow

Underground flow from ground water

reaches the lakes by percolation, either directly through the lake bottom or through tributary streams. Since most streams in the Great Lakes Basin derive their base flow from ground water, the underground flow reaching the lakes through tributary streams is measured and considered with the surface runoff. Thus, direct contribution from ground water to the lakes is of primary interest to the lake hydrology. Depending on the geohydrologic characteristics of the system and the water levels in lakes, the underground flow could be either into or out of the lakes.

There is very little information on the underground flow in the Great Lakes Basin, particularly on direct ground-water supplies, and knowledge in this field should be expanded. The evaluation of direct underground flow requires ground-water profiles, which can be derived from a network of observation wells located around the lakes. There is only a handful of wells located within 15 km (10 mi.) of the lakes, and wells located further inland may be poor indicators of ground-water flow. In addition to lake perimeters, special attention should also be concentrated on any areas where, because of geologic structure, ground-water divides may be significantly different from topographic divides.

There are many geological studies of ground-water conditions for specific areas of the Basin. However, these studies cover relatively small areas (one section of a lake basin) and are not related directly to the underground flow into or out of the lakes. They are approached from the geological point of view and consider areal geology, water use, economics of water development, and the usual ground-water data obtained from observation wells, pumping tests, and chemical analysis. Thus, they reveal only limited information, which is not readily adaptable to large areas encompassing one or more lake basins. Large area hydrologic studies dealing with ground water are more important for the underground flow aspect. Because of the varying geologic and climatic conditions over such large areas, estimation of the underground flow into any one lake is very difficult, and ground-water data are not sufficient to determine this flow by direct methods.

In most hydrologic studies underground flow was considered negligible and assumed to be zero (Freeman,[271] Horton and Grunsky,[376] Hunt,[395] Morton and Rosenberg,[561] Derecki[214]). Horton and Grunsky state that there is a marginal belt around the perimeters of Lakes Michigan and Huron, from which water reaches the lakes mainly through ground water and not through surface streams. They also state that there are numerous instances of watershed leakage from one drainage basin to another and probably from the higher-lying drainage basins directly into the lakes. Based on these considerations, they concluded that the summer runoff to the lakes estimated from measured streamflow may be less than the actual runoff by an amount exceeding 13 cm (5 in.) on the lakes, but in their study they assumed the underground flow to be zero. Hunt acknowledges a possibility of a considerable underground flow between Lakes Erie and Ontario, due to the very large potential head between them. He investigated this matter and concluded that there is no appreciable ground-water flow into Lake Ontario, and that what flow might exist is probably steady throughout the year.

In some hydrologic studies underground flow was estimated by various forms of water budget computations. Russell[692] estimated monthly amounts of water entering the lakes from underground sources, which resulted in the annual values 65 cm (25 in.) on Lake Superior, 83 cm (33 in.) on Lakes Michigan-Huron, 51 cm (20 in.) on Lake Erie, and 130 cm (51 in.) on Lake Ontario. However, Russell did not distinguish between ground-water flow into streams and ground-water flow directly into lakes, so values listed above include base flow of streams. Pettis[605] estimated direct underground flow into the upper lakes as 42 cm (16 in.) to Lake Superior and 58 cm (23 in.) to Lakes Michigan-Huron. Pettis also states that a considerable part of a large underground water body in the northern part of the State of Ohio has a definite motion towards Lake Erie.

In contrast to the high underground flow claimed by the above investigators, Bergstrom and Hanson[62] computed inflow to Lakes Michigan-Huron from the ground-water sources to be approximately 0.5 cm (0.2 in.). They suggest that the actual discharge along the shore could be several times that given above, but the amount would still be relatively small, and probably less than the error inherent in extrapolation of runoff, lake evaporation, and precipitation. Snyder[751] indicates that there are underground outflows from Lake Superior and Lakes Michigan-Huron that amount to approximately 22 cm (9 in.) and 5 cm (2 in.) on these lakes, respectively. He also suggests that there are underground inflows to Lakes Erie and Ontario of approximately 19 cm (8 in.) and 8 cm (3 in.), respectively. Snyder bases his indicated groundwater flow on the differences in evaporation estimates computed by mass transfer and water budget methods.

Widely divergent opinions on the amount and direction of underground flow to the Great Lakes leave the subject in a state of controversy. For example, Pettis[605] claims the underground inflow to Lake Superior is 42 cm on lake surface per year and Snyder[751] indicates an outflow from the same lake of approximately 22 cm. It is apparent from the cautious wording and the conflicts that exist in the preceding studies that the estimates are little more than conjectures.

4.10 Lake Inflow and Outflow

4.10.1 Inflow

The inflow to any of the Great Lakes is the quantity of water supplied by the lake above, modified by the local inflow to the connecting river. Local inflow is usually less than one-half percent of the total flow and generally is disregarded in computing lake outflows and the corresponding inflows to the lakes below. However, the Lake Huron outflow and Lake Erie inflow normally differ by approximately 2 percent and occasionally the difference is much higher. Therefore, flow at the head of St. Clair River is used to determine outflow from Lakes Michigan-Huron, while the flow of the Detroit River is used to obtain inflow to Lake Erie. The importance of inflow to the lakes increases progressively in descending order through the lakes. The smaller lower lakes are affected by these flows to a much greater extent than the upper lakes. Inflow to Lakes Michigan-Huron is of the same order of magnitude as the overwater precipitation, but in Lakes Erie and Ontario, it is an order of magnitude greater. During the period of hydrologic study, 1937–69, the average annual inflow was equivalent to 60 cm (24 in.) for Lakes Michigan-Huron, 640 cm (250 in.) for Lake Erie, and 927 cm (365 in.) for Lake Ontario. The variation in the annual inflow during this time had a range of approximately 40 cm (15 in.) for Lakes Michigan-Huron, and approximately 240 cm (95 in.) for Lakes Erie and Ontario. Thus, in the lower lakes the variation in the annual inflow is three times greater than the average annual overwater precipitation. Because of the magnitude and fluctuation of the inflows to the lower lakes, accuracy of inflow is extremely important in studies of the hydrologic cycle.

4.10.2 Outflow

The outflow of each of the Great Lakes is the quantity of water flowing from a given lake through its natural outflow river and through man-made outlets. As a factor in the hydrologic cycle of the lakes the outflow of any lake, including that through man-made diversions, represents the water yield of the entire basin above the point of outflow measurement.

The outflow from Lake Superior through the St. Marys River has been artificially controlled since 1922 by a gated dam structure, which allows diversions for the generation of power. Release of water through the control structure and for the generation of power is made in accordance with a regulation plan, designed to maintain the level of Lake Superior within specified limits.

The outflow from Lakes Michigan-Huron through the St. Clair and Detroit Rivers, which together with Lake St. Clair constitute the natural outlet of these lakes, is controlled largely by the level of Lake Huron at the head of the St. Clair River and the level of Lake Erie at the mouth of the Detroit River. No man-made control of this flow exists, except for the fixed remedial control provided by the dikes constructed in the lower Detroit River to compensate for the effects of deepening the navigation channels in that river. These compensating controls do not regulate lake levels. However, they are designed to provide the same net discharge capacity in the rivers as existed before the improvements, so that the levels upstream are maintained. The navigation improvements in the St. Clair River, including some works recently completed, cause a lowering of the levels of Lakes Michigan-Huron, and remedial works are being evaluated. In the winter period ice normally slightly reduces the open water flow of the St. Clair and Detroit Rivers.

The outflow from Lake Erie through the Niagara River is controlled largely by the level of Lake Erie at the head of the river and the level of the Chippawa-Grass Island Pool above Niagara Falls. If the diversions of water from the Chippawa-Grass Island Pool for the generation of power are not compensated for, they can lower the levels of Lake Erie. However, a submerged weir was constructed during the period 1942–47 at the downstream end

TABLE 4–18 Average Flows in Connecting Rivers of the Great Lakes, 1937–1969 (m^3/s)

Period	St. Marys	St. Clair	Detroit	Niagara	St. Lawrence
January	1,980	4,420	4,620	5,240	6,230
February	1,980	4,250	4,420	5,240	6,230
March	1,940	4,810	4,960	5,320	6,400
April	2,020	5,130	5,270	5,640	6,830
May	2,180	5,240	5,350	5,920	7,020
June	2,310	5,350	5,410	5,950	7,190
July	2,450	5,410	5,490	5,830	7,140
August	2,570	5,440	5,490	5,720	7,000
September	2,550	5,380	5,440	5,580	6,770
October	2,510	5,320	5,380	5,470	6,570
November	2,430	5,270	5,300	5,470	6,460
December	2,110	5,130	5,240	5,470	6,460
Annual	2,250	5,100	5,200	5,570	6,690

of the pool, as the initial phase of the remedial works designed in part to counteract this effect. Presently, a gated control structure extending partially into the river from the Canadian shore provides compensation for the power diversion, which was increased by the 1950 treaty between the United States and Canada. This second control structure is located downstream and runs parallel to the weir.

The outflow from Lake Ontario through the St. Lawrence River since 1958 has been largely controlled by the release of water through the Iroquois Dam near Iroquois, Ontario. Beginning in April 1960 the release of water has been made in accordance with a regulation plan, which provides for weekly flow changes throughout the year. Thus, Lake Ontario levels are fully regulated and are independent of any channel changes or diversions. Prior to the construction of the Iroquois Dam in 1958, the Galop Rapids, a short distance downstream from Ogdensburg, New York, constituted a natural weir, the flow over which was controlled substantially by the level of Lake Ontario.

The average monthly and annual flows of the outflow rivers for the 1937–69 period are listed in Table 4–18. Prior to 1957 the flows of the St. Clair River were based on published records of combined St. Clair-Detroit River flows, since the flows in both rivers were considered to be essentially equal. During the period of study, annual flow from the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence Rivers averaged 2,250 m^3/s, 5,100 m^3/s, 5,210 m^3/s, 5,580 m^3/s, and 6,680 m^3/s (79, 180, 184, 197, and 236 thousand cfs), respectively. Low flows occur in the winter and high flows in the summer, with a progressive delay of the summer highs in the upstream rivers.

The range in the average monthly flows was approximately 700 m^3/s (25,000 cfs) for the St. Marys and Niagara Rivers, and 1,300 m^3/s (45,000 cfs) for the other rivers. The difference between the high and low annual flows during the 33-year period varied from approximately 1,400 m^3/s (50,000 cfs) on the St. Marys River to 2,000 m^3/s (70,000 cfs) on the Detroit River. The relatively large variations in flow of the St. Clair and Detroit Rivers, in comparison with other rivers, are due primarily to ice retardation of winter flows.

The importance of outflow to lake hydrology increases progressively with downstream lakes. The average annual outflows (river flows and diversions), expressed in units depth on the lake surface, represent 86 cm (34 in.) on Lake Superior, 139 cm (55 in.) on Lakes Michigan-Huron, 706 cm (278 in.) on Lake Erie and 1,077 cm (424 in.) on Lake Ontario. Variation in the annual outflow during the period of study had a range of approximately 50 cm (20 in.) for Lakes Superior and Michigan-Huron, 190 cm (75 in.) for Lake Erie, and 300 cm (120 in.) for Lake Ontario.

Numerous studies of the connecting river flows have been made. These studies have analyzed the effects on flow equations of regimen changes, formation of ice, weed retardation, and water temperatures. Detailed discussion of outflows is given in Appendix 11, *Levels and Flows*. Flow equations and the means of revising them when channel changes occur, and turbine ratings used to compute flows through power structures are generally well established. As a result, data on the flows in the connecting rivers of the Great Lakes are considered to have a greater accuracy than for any other hydrologic factor, except the change in lake storage.

4.10.3 Diversions

Water diversions in the Great Lakes Basin may be broadly divided into two types: outside diversions, which take water into or out of the system; and inside diversions, which retain water entirely within the system. Diversions of water into the Basin have the effect of raising water levels of the lake into which the diverted water is discharged and the levels of the lakes downstream through which the diverted water must pass on its way to the sea. Diversions of water from the Basin have the converse effect on the levels of the lakes at and downstream from the point of diversion. Diversions from one point to another within the

Basin may have no effect on the lake levels if within the same lake basin; or, if not compensated for, diversions may lower the levels of the lake upstream and temporarily raise the levels downstream. The temporary rise in levels downstream is due to increased discharge rates while the levels of the lake above drop to adjust to the larger outlet capacity due to the diversion. The rate of adjustment in lake levels decreases exponentially with time, and the period of adjustment depends on the size of the lake involved and the capacity of its outlet. For example, Lakes Michigan-Huron reach 90 percent adjustment in approximately seven years and Lake Erie in less than one year (Bajorunas[35a]).

There are five major diversions in the Great Lakes Basin (Figure 4–1): the Ogoki and Long Lake Projects divert water into Lake Superior; the Chicago Sanitary and Ship Canal diverts water out of Lake Michigan; and the Welland Canal and the New York State Barge Canal divert water from Lake Erie and Niagara River into Lake Ontario. All other diversions presently in existence on the St. Marys, Niagara, and St. Lawrence Rivers divert water from one point to another within the same river and with remedial structures have no effect on lake water supplies and lake levels.

The Ogoki and Long Lake Projects divert water into Lake Superior from the Albany River drainage basin in the Hudson Bay watershed. The Ogoki diversion diverts water from the Ogoki River into the Nipigon River. The Long Lake diversion diverts water from Long Lake at the head of the Kenogami River to the Aguasabon River. These diversions have increased the supply of water to Lake Superior by an average rate of approximately 142 m^3/s (5,000 cfs), which is equivalent to approximately 5 cm (2 in.) on the lake surface per year.

The Chicago Sanitary and Ship Canal, along with the Calumet Sag Canal, a branch which connects with Lake Michigan south of Chicago, diverts water from Lake Michigan through the Des Plaines and Illinois Rivers to the Mississippi River. This diversion, commonly referred to as the Chicago diversion, represents the amount of water diverted from Lake Michigan for navigation purposes and for domestic use by the City of Chicago. The total diversion from the lake at Chicago amounts to 88 m^3/s (3,100 cfs), which represents an annual amount of water exceeding 2 cm (about 1 in.) on the surface of Lakes Michigan-Huron. The net effect of all three outside diversions, the inputs to Lake Superior and the output from Lake Michigan, is to increase the supplies to Lake Michigan-Huron and the downstream lakes by approximately 54 m^3/s (1,900 cfs).

The diversion of water through the Welland Canal, from Lake Erie at Port Colborne to Lake Ontario at Port Weller, includes water used in the DeCew Falls power plant, which amounts to most of this diversion, plus diversions for navigation purposes. The total Welland Canal diversion amounts to approximately 198 m^3/s (7,000 cfs), which is equivalent to approximately 25 cm (10 in.) on the Lake Erie surface per year.

The New York State Barge Canal withdraws water from the Niagara River at Tonawanda, New York, for navigation purposes, but the water diverted into the canal is returned to Lake Ontario at Oswego, New York. The Barge Canal diverts approximately 31 m^3/s (1,100 cfs) during the navigation season. Since 1956 there has been no diversion during winter months.

The average monthly and annual flows during the period of study, 1937–69, for the major diversions described above are listed in Table 4–19. Annual values listed in the table are somewhat different from the normal values presented in the discussion because of periodic variations from the normal.

4.11 Lake Level Fluctuations

4.11.1 Lake Levels

The elevations of the water surface of the Great Lakes are tied to the mean sea level at Father Point, Quebec, on the Gulf of St. Lawrence. This plane of reference, established especially for the Great Lakes in 1955, is called the International Great Lakes Datum. The average monthly and annual lake levels for the 33-year period, 1937–69, are given in Table 4–20. These levels are based on mean lake level tabulations published by the Lake Survey, and represent records from master gages, each lake having a single master gage located at a strategic point. Approximate water surface elevations of the lakes are 183 m (601 ft.) for Lake Superior; 176 m (578 ft.) for Lakes Michigan-Huron; 174 m (570 ft.) for Lake Erie; and 75 m (245 ft.) for Lake Ontario.

Of primary interest in lake hydrology are the variations of lake levels caused by the changing volume of water in the lakes. These

TABLE 4-19 Major Diversions in the Great Lakes Basin, 1937–1969 (Cubic Meters per Second)

Period	Ogoki Project into L. Superior 1943-69[1]	Long Lake Project into L. Superior 1939-69[2]	Chicago Diversion out of L. Michigan 1937-69[3]	Welland Canal from L. Erie to L. Ontario 1937-69[4]	N. Y. State Barge Canal from Niagara R. to L. Ontario 1937-69[5]
January	94	35	90	160	9
February	75	35	88	162	9
March	65	29	85	162	4
April	67	28	95	170	22
May	148	54	99	177	31
June	216	65	107	178	31
July	152	48	110	172	31
August	121	39	114	181	31
September	111	34	105	180	31
October	105	33	91	182	31
November	120	36	85	181	31
December	111	35	98	170	16
Annual Average	115	39	97	173	23

[1] Period of record starts in July 1943. Since 1945 total amount of Ogoki and Long Lake diversions has averaged 142 m^3/s (5,000 cfs).
[2] Period of record starts in July 1939.
[3] Since 1938 total diversion (navigation plus domestic pumpage) has averaged 88 m^3/s (3,100 cfs). However, higher flows were authorized on two occasions by the U. S. Supreme Court.
[4] Since 1950 total diversion (navigation and hydropower) has averaged 198 m^3/s (7,000 cfs).
[5] Since 1929 during navigation season this diversion has amounted to 31 m^3/s (1,100 cfs). Since 1956 there has been no diversion during winter months.

volumetric changes are generally referred to as lake level fluctuations and apply to the entire lake. They involve time periods of sufficient duration to allow absorption of any local short-period variations, so that entire water surface can be assumed to be level. The local short-period variations, classified as water level disturbances, do not involve volumetric changes but displacement of water level caused primarily by winds and variations in barometric pressure. Water level disturbances are discussed in Section 6, while detailed discussion of lake levels is given in Appendix 11, *Levels and Flows*.

The water level fluctuations represent storage or depletion of water in the lakes. Seasonal fluctuations undergo a relatively regular cycle; high levels usually occur in the summer and low in the winter.

TABLE 4-20 Average Levels of the Great Lakes, IGLD (1955), 1937–1969 (Meters)

Period	Superior at Marquette	Michigan-Huron at Harbor Beach	Erie at Cleveland	Ontario at Oswego
January	183.00	176.01	173.66	74.40
February	182.93	176.01	173.68	74.42
March	182.89	176.02	173.76	74.50
April	182.92	176.09	173.92	74.71
May	183.04	176.19	174.03	74.85
June	183.13	172.26	174.07	74.92
July	183.20	176.32	174.06	74.88
August	183.23	176.30	174.00	74.77
September	183.23	176.25	173.90	74.64
October	183.20	176.19	173.79	74.51
November	183.15	176.13	173.70	74.44
December	183.08	176.08	173.68	74.42
Annual	183.08	176.15	173.85	74.62

4.11.2 Change in Storage

The change in storage on the lakes for any

TABLE 4–21 Average Change in Storage on the Great Lakes, 1937–1969 (Centimeters)

Period	Superior[1]	Michigan-Huron[2]	Erie[3]	Ontario[4]
January	-6.7	-2.1	0.6	0.9
February	-5.2	0.0	2.4	3.4
March	-2.1	4.0	14.0	15.2
April	9.1	11.3	15.5	21.3
May	11.3	8.2	6.4	11.0
June	8.8	6.7	1.8	0.3
July	4.0	0.9	-4.3	-7.6
August	1.8	-3.4	-8.5	-12.8
September	-1.8	-5.8	-10.7	-13.4
October	-4.9	-6.7	-9.4	-10.7
November	-5.8	-4.6	-4.9	-4.3
December	-8.5	-5.8	0.0	-1.8
Annual	0.0	2.7	2.9	1.5

Note: Change in storage determined from 10-day means (5 at end and 5 at beginning of following month) by averaging records from the following gages:

[1] Thunder Bay, Duluth, Michipicoten, Marquette, and Pt. Iroquois.
[2] Milwaukee, Ludington, Mackinaw City, Harbor Beach, Thessalon, and Goderich.
[3] Cleveland and Port Stanley.
[4] Oswego, Kingston, Cobourg, Toronto, Port Weller, and Rochester.

given period is determined from the change in lake levels. Mean lake levels for several days are used for the determination of beginning-of-period levels. This minimizes the effect of external forces such as winds or barometric pressure. The mean level of a lake at any given time is determined by averaging recorded levels of several gages, situated at points around the lakes in a pattern selected to provide good approximation of the whole lake level.

In recent years, the gage patterns used for determination of lake storage have been coordinated by the Lake Survey and Canadian agencies to provide consistent values in both countries. These gage patterns consist of five gages for Lake Superior, six gages for Lakes Michigan-Huron and Ontario, and two gages for Lake Erie. Each determination is based on ten days of recorded levels (five at the end of one month and five at the beginning of the next month). This determination period is rather long for the beginning-of-month levels. In other determinations four (two plus two) or two (one plus one) days were normally used. The most recent determination is based on two days of recorded levels (one at end and one at beginning of month), employing more gages weighted by the Thiesson polygon method to reduce possible effects of short-term water level disturbances (Quinn,[635a] Quinn and Todd[635b]).

The coordinated average change in storage for monthly and annual periods on each lake during the 1937–69 period is shown in Table 4–21. Since the change in lake storage is primarily a seasonal phenomenon, the long-term annual values should be small due to balancing of rising and falling lake levels, as indicated in the table. The average seasonal change in storage varies with latitude. The lower lakes have rising lake levels during winter and spring, and falling lake levels during summer and fall. This distribution is delayed by approximately one month on Lakes Michigan-Huron and by a full season (3 months) on Lake Superior. The highest average monthly rise was approximately 11 cm on Lakes Superior and Michigan-Huron, 16 cm on Lake Erie, and 21 cm on Lake Ontario; the highest average monthly decline was approximately 8 cm for Lake Superior, 7 cm for Lakes Michigan-Huron, 11 cm for Lake Erie, and 13 cm for Lake Ontario. During individual years the variation in annual and monthly change in lake storage may be considerable. In extreme cases this range may exceed several times the highest average monthly change in storage on each lake.

The change in storage discussed above includes volumetric changes, which are affected by water density variations. A mass of water expands or contracts as it is heated or cooled. The amount of expansion or contraction depends on the change in temperature and depth to which this change becomes effective (thermocline depth). Investigations of the thermal expansion of water in the Great Lakes indicate that thermal expansion is insignificant and may be disregarded (Hunt,[395] Derecki[214]).

4.12 Heat Budget

The interaction of the various climatic and hydrologic elements results in heating and cooling processes within the lakes. Some processes take place at the lake surface and are transmitted through the water body while others produce heat changes by mixing of the water masses. Meteorological factors such as radiation, air temperature, precipitation, and evaporation affect surface temperature, while winds contribute to the deepening of the surface layer. Hydrologic factors such as runoff, inflow, and outflow cause temperature changes by horizontal movement of water mass.

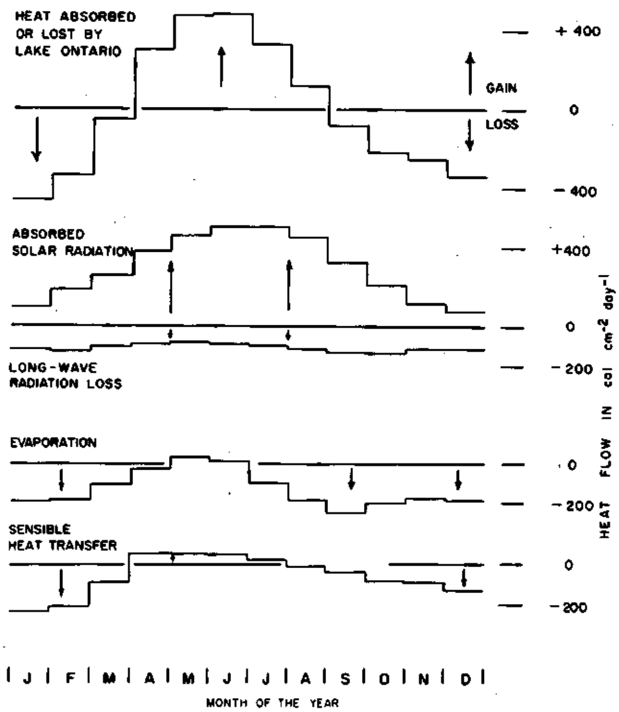

FIGURE 4–100 The Heat Budget of Lake Ontario

From Rodgers, 1969

The heating and cooling processes are summarized in the heat budget of the lakes, which represents the amount of energy gained or lost by the lakes during various temperature changes. There are five basic energy or heat processes affecting the Great Lakes. The four major processes include energy produced by radiation, sensible heat transfer to or from the atmosphere, heat loss by evaporation, and energy storage within the lake. A fifth process of net advected energy may be important locally, especially at the mouths of the inflow rivers and near the effluents of sewage disposal or cooling water from power plants. However, this process has very little effect on the total heat content of the lakes because such inflows with substantial difference in temperatures are relatively small. The energy exchange may be expressed by the equation:

$$O_s + Q_v = Q_b + Q_h + Q_e + Q_t$$

where Q_s = net solar radiation (incident minus reflected)

Q_v = net advected energy (heat due to water input minus output and snow melt)

Q_b = net terrestrial radiation (emitted minus atmospheric)

Q_h = conduction of sensible heat to or from the atmosphere

Q_e = energy utilized by evaporation

Q_t = energy storage within the body of water.

The heat budget for Lake Ontario, the only lake for which such determination has been made (Rodgers and Anderson,[675] Bruce and Rodgers,[108] and Rodgers[672]), is presented in Figure 4–100. The largest energy change is produced by the absorption and loss of heat by the lake water mass; the lake gains heat during spring and summer months and loses heat in the fall and winter. The radiation processes produce both gain and loss of heat; the lake absorbs heat from solar radiation and loses heat through the longwave radiation exchange between water surface and atmosphere. Evaporation cools the water surface and produces heat loss, except during spring when slight condensation produces small heat gain. The transfer of sensible heat to the atmosphere results from the air-water temperature differences; the lake surface is cooler than air and gains heat in the spring and summer, and the process is reversed in the fall and winter. The net effect of all these processes is to produce heat gain during the spring-summer period and heat loss during fall and winter months.

The heat budgets for the other lakes would follow generally similar patterns, although the amounts of energy contained in various processes would differ depending on the hydrometeorological conditions on each lake. The accuracy of heat budget presented for Lake Ontario may be sufficient to indicate general trends for various energy processes, but evaporation studies show that accuracy should be improved for successful application to the solution of practical problems. This was one of the objectives of the International Field Year for the Great Lakes, an intensive field observation program conducted on Lake Ontario in 1972.

4.13 Water Budget

4.13.1 Water Budget Computations

The water budget of the Great Lakes is an accounting of all incoming and outgoing water, such as inflow and outflow by the rivers, supply from and storage in the ground, overwater precipitation, evaporation, and varia-

TABLE 4–22 Average Water Budget, 1937–1969 (Centimeters)

Lake	Water Supply P	R	I	Water Loss O	E	Storage ΔS	Balance Needed B
Superior	80	58	0	86	55	0	-3
Michigan-Huron	80	67	60	139	65	3	0
Erie	88	72	640	706	85	3	6
Ontario	84	150	927	1,077	70	2	12

$P + R + I - O - E - \Delta S = \pm B$

P = precipitation on the lake surface
R = runoff from drainage area (surface and underground)
I = inflow from the upstream lakes
O = outflow to the lake below
E = evaporation from the lake surface
ΔS = change in storage of water in the lake
B = balance needed

NOTE: Diversions are included in runoff, inflow, or outflow, where applicable.
Evaporation values are the long-term estimates, not necessarily applicable to this 33-year period.

tion of water storage in the lakes. These water budget factors are interrelated in the hydrologic cycle, which is composed of a perpetual sequence of events governing the depletion and replenishment of water in the Basin. The Great Lakes water budget may be expressed by the equation:

$$P + R + I = O + E \pm \Delta S$$

where P = precipitation on the lake surface
R = runoff from drainage area (surface and underground)
I = inflow from the upstream lakes
O = outflow to the lake below
E = evaporation from the lake surface
ΔS = change in storage of water in the lake (plus if storage increases, minus if decreases)

In practical applications the water budget equation may be modified by eliminating all factors that are negligible or not applicable to individual lakes (e.g., inflow for Lake Superior). Factors other than those listed may also be included. For example, runoff and ground water may be treated separately, and diversions may be included as a separate factor.

The average annual water budget for the 1937–69 period is shown in Table 4–22, which contains groupings of water supply, water losses, lake storage, and algebraic accumulation of these factors for each lake. The differences needed for balancing of the major factors represent a combination of any possible ground-water flow and cumulative errors in estimating other factors. For most lakes these differences are quite small for the average annual values, and are well within the limits of error. The largest difference, for Lake Ontario, is approximately equal to 15 percent of precipitation or evaporation, 8 percent of runoff, or 1 percent of inflow or outflow. For shorter monthly periods and for individual years, the percent differences should increase significantly, because the effect of compensating reduction of random errors would be smaller.

Further studies pertaining to the water budget of the Great Lakes should be directed towards elimination of existing gaps in present knowledge, improvement of data collection networks, comparability of measurement accuracies for various factors, development and implementation of new measurement methods, and closer coordination of these efforts in both countries.

4.13.2 Importance of Water Budget

Lake levels and outflows of the Great Lakes effectively integrate all other components of the water budget and are of primary interest to lake users. However, growth of the population and economy of the area has resulted in an increase in and diversification of demands for lake water, and the competition for its use is increasing rapidly. Use of the lakes for navigation, water power, municipal and industrial water supplies, sanitation, irrigation, fish and wildlife, recreation, and other riparian interests frequently results in conflicting demands, some of which are detrimental to water quality. To provide optimum utilization and preservation of the lakes, a thorough understanding of the entire hydrologic cycle of the system is necessary.

The importance of the water budget to lake water resources has been recognized in many studies and investigations (e.g., Freeman,[271] Horton and Grunsky,[376] U.S. Congress-Senate[817,821]). Knowledge of the magnitudes and variations of the individual water budget components is needed for the improvement of forecasts of lake levels and outflows, for the refinement of lake regulation plans, and for determination of the effects of diversions into and out of the system. Because of the vastness of the Great Lakes, changes in lake levels take place rather slowly and advanced information on the expected stages is of great interest to navigation, hydropower, and for shore protection. For Lakes Superior and Ontario, the only lakes presently regulated, accurate forecasts are even more important to permit planning for the most beneficial operation of the regulating structures.

Section 5

GREAT LAKES ICE COVER

Donald R. Rondy

5.1 Introduction

The Great Lakes are located directly on a path of major storm systems (Figure 4–13) which generate a variety of weather patterns. Air temperature is the most important factor affecting ice formation. The temperature range across the Great Lakes Basin is illustrated by a comparison of the January monthly mean temperature at Cleveland and Duluth. At Cleveland, Ohio, on the south shore of Lake Erie, the January mean temperature is −2.5°C (27.5°F), and at Duluth, Minnesota, on Lake Superior, it is −12.9°C (8.8°F), a difference of more than 10°C. These wide differences in temperature also account for variations in the severity and the length of the winter season which in turn determine the length of the ice cover period. The winter period, which is related to the ice season, is generally considered to begin when the daily average air temperature first drops to 0°C and lasts until it again rises above freezing. This period is different for each lake and varies from 82 days at Cleveland to 150 days at Duluth. For comparison, the mean number of days during which minimum temperatures are 0°C and below varies from 119 days at Cleveland to 191 days at Duluth. The mean date of the first 0°C temperatures in the autumn also has a considerable range and varies from September 24 at Duluth to November 2 at Cleveland. In the spring the average date of last 0°C temperature varies from April 21 at Cleveland to May 22 at Duluth. Although the period of daily average temperatures below freezing is as long as 150 days at Duluth, the ice season is considerably shorter. It usually begins in late December and continues until early April with the actual length of season changing from lake to lake.

5.2 Lake Ice Genesis

The winter or ice season on the Great Lakes can be classified into three phases: cooling phase, ice formation phase, and breakup or fragmentation phase.

5.2.1 Cooling

Many factors determine the severity of an ice season and among the most important are the amount of thermal energy stored in the mass of water and the rate at which convective mixing takes place. At the end of the summer the lakes are fairly well stratified and usually contain a well-developed thermocline. As the air temperature drops below the water temperature, the fall cooling phase begins. The cold air in contact with the water cools the water and the density differences due to thermal stratification are reduced, thus allowing wind-induced mixing to penetrate deeper and deeper into the water mass. When the water column is isothermal at 4°C (39°F), density differences are so slight that wind-generated turbulence and convective mixing keep the water column fairly well mixed and isothermal. This fall turnover ceases at temperatures below 4°C. As the water temperature continues to fall stratification again occurs which limits deep mixing by wind action. Heat loss at this time affects only the thin, top layer of water and consequently this surface is much more responsive to temperature fluctuations.

During a cooling period a large lake of substantial depth is warmer than the air. This causes currents of warmed air to rise from the lake surface and allows cold air to move onto

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the lake from shore. The result is that the shallow offshore waters are cooled more rapidly than the central lake areas. If the air temperatures are not low enough and the heat lost by direct radiation is not great enough to remove the heat faster than it is conducted upward through the water column, then the central lake area may never reach the freezing point. The heat storage capacity of the lake then becomes a function of its area and depth and the position of the thermocline reflects the amount of stored heat. These two factors determine when the lake will become isothermal and ultimately when an ice cover will form.

5.2.2 Ice Formation

After the surface water of the lake has cooled to the freezing point and the latent heat of fusion, i.e., heat required to melt or freeze a unit mass of ice without a change in temperature, has been given up, crystallization begins. Ice begins to form along the shore and ice needles branch out over the water surface. The ice needles spread until the nearshore surface is covered with a thin ice layer. The extent of this ice layer depends on existing meteorological conditions. The ice needles extend rapidly over the surface if the water is supercooled (a liquid cooled beyond its nominal freezing point). If it is not supercooled, the ice layer gradually grows out from shore until the surface has become covered. The supercooling of water is possible if the lake is undisturbed, but if wind and current cause agitation, it is almost impossible to cool the water much below 0°C. Another factor that tends to limit supercooling is the latent heat of fusion. When the supercooled water freezes it releases 80 calories of latent heat per gram. This release of heat raises the temperature of the surrounding water and rapidly brings it to 0°C. The quantity of supercooled water on the lakes must therefore be quite small. As the stored heat passes up the water column and through the ice by conduction, the ice gradually becomes thicker.

The building of an ice cover is a very complex procedure and many hydrometeorological factors influence its formation. However, ice formation, and ice thickening in particular, is controlled mostly by air temperature. The removal of heat from the ice surface by conduction, radiation, evaporation, and the presence of snow is also very important in the ice formation phase.

There are two general types of ice cover that are formed on the Great Lakes. The first is the ice formed by the rapid freezing of surface water in the absence of wind and snow. This is a smooth homogeneous cover called sheet ice and is the strongest and purest form of lake ice. The second is a form made of fused individual ice pieces. This type of cover is produced by the breaking up and refreezing of thin or newly formed sheet ice. Snowfall on the lake surface during initial ice formation also contributes to this type of ice cover. The ice formed by these two conditions, fusing and snowfall, is generally referred to as agglomeratic ice.

The agglomeratic ice has a more complex character than sheet ice. It generally contains ice of various ages combined with snow masses that have been welded together by new lake ice. This ice is usually formed when weather allows the breakup of a thin, young ice sheet. The broken, drifting ice is forced together, becomes fragmented again, is reconsolidated by wind and wave action, and then refreezes during the next cold spell. During the ice season there may be many freeze-breakup cycles and snowfalls, each of which add to the intricacy of the agglomeratic ice. When a heavy snow falls on the lake surface and the water is not warm enough to melt it, it forms a water-saturated snow blanket. This snow blanket is broken up by waves and forms snow or slush balls or snow-slush pans, which, upon freezing, are included in the ice cover. The pans are generally circular in shape and have raised rims due to contact with one another.

In the development of the ice cover the same ice structure often reappears consistently in the same location, particularly in bays and protected areas where shoreline configuration is a dominant factor in exposure to wind stresses.

Any appreciable accretion of ice cover on the lakes first occurs in the sheltered bays and harbors and in a narrow fringe along the shoreline. Parallel ridges of shore ice are usually found alongshore as the ice fringe develops. The parallel ridges are usually referred to as ice foot formations and are the result of freezing spray from the surf zone and consolidation of drift ice and slush. The ice foot mass builds on the perimeter of large bodies of water that remain ice-free far into the winter season.

Once the ice cover is established, it thickens through accretion from below. By this process the ice thickens at the ice-water interface and the rate of ice growth is determined by the temperature gradient through the ice. Exam-

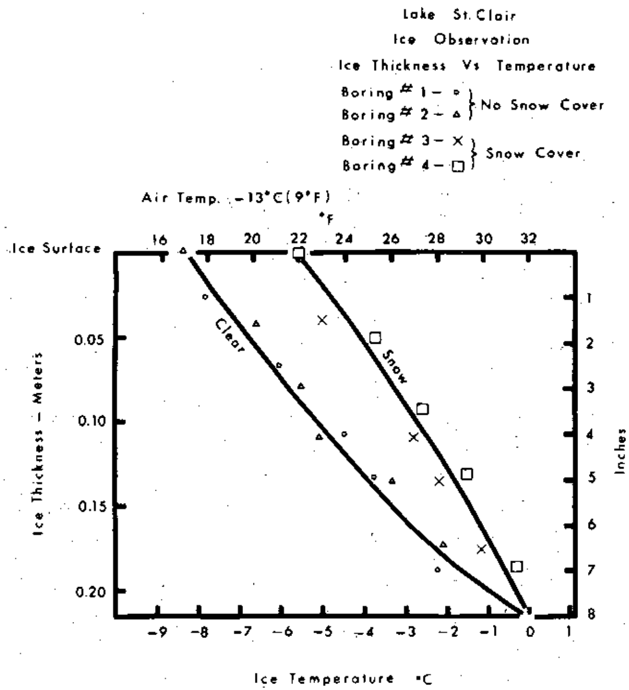

FIGURE 4–101 Temperature Profile Through a 20 cm Ice Cover on Lake St. Clair. Samples taken at 8:00 pm, February 2, 1965. Air temperature was −13°C (9°F).

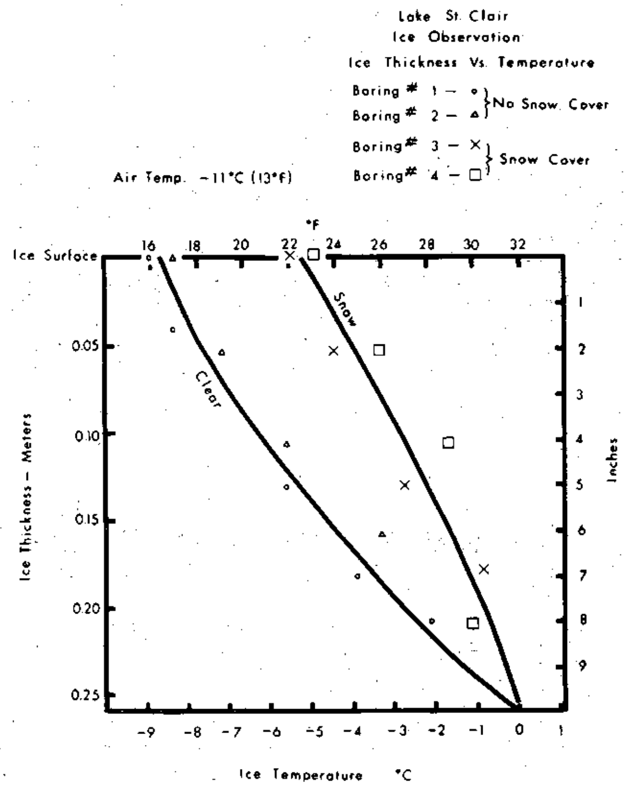

FIGURE 4–102 Temperature Profile Through a 25 cm Ice Cover on Lake St. Clair. Samples taken at 8:15 pm, February 4, 1965. Air temperature was −11°C (13°F).

ples of this temperature gradient (Figures 4–101 and 4–102) indicate a temperature difference between the ice-water interface and the ice-air boundary on snow-free ice of approximately 8°C. The insulating effect of the snow cover is illustrated by the increase of the ice surface temperature under only a few inches of snow. The temperature difference through snow-covered ice was reduced to approximately 5°C. Ice forms a protective shield against wave action and tends to reduce heat loss to the atmosphere. By limiting the quantity of heat lost from the water mass, protection is also given to temperature-sensitive biota. During the period of ice cover, water temperatures range from 0°C at the ice-water interface to nearly 4°C at the deep-lake bottom.

Another factor that affects ice thickness, in addition to air temperature, is snowfall. This factor is particularly important in the Great Lakes Region where the mean annual snowfall varies from 91 cm to 254 cm. Annual accumulation of snowfall during severe winters is more than doubled on the south and east shores of Lake Superior, the southeastern end of Lake Erie, and the eastern end of Lake Ontario. Extensive snowfall in these areas is the result of lake effect, orographic influence, and prevailing winds. The snowfall factor affects the ice cover in two basic ways. First, it controls the thickness of the ice cover by acting as an insulator between the air and ice surface and effectively reduces the temperature gradient through the ice. Secondly, the weight of the snow cover depresses the ice, causing fractures and cracks that allow water from below, which is under pressure, to flow to the ice surface and flood and wet the overlaying snow. When this water and wet snow freeze, a whitish ice mass, which is generally called snow ice, is formed. In areas of large snow accumulation snow ice is a major part of the structure of both sheet ice and agglomeratic ice types.

The stages of ice formation are defined by a series of terms, many of which have been borrowed from sea-ice terminology. The more frequently used terms for the various stages of the ice cycle include:

(1) New ice is a general term for newly formed ice which includes frazil, slush, ice rind, and pancake.

(2) Frazil ice is fine platelets of ice suspended in the water. This is the first stage of freezing and gives an opaque appearance to the water surface.

(3) Slush is water-saturated snow floating as a viscous mass on the water surface after a heavy snowfall.

(4) Ice rind is a thin, elastic crust of ice formed by the freezing of slush or frazil on a quiet surface. Ice rind is easily broken by wind or waves.

(5) Pancake ice is circular pieces of newly formed ice, from .5 m to 3 m in diameter, with raised rims caused by the pieces striking together due to wind and wave action.

(6) Fast ice is ice that is generally contained in the location where it was originally formed. It may attain a considerable thickness and is found attached to shore or held in place by islands, shoals, or structures.

(7) An ice foot is narrow ice fringe that is attached to and parallels the shore. It is unmoved by low, winter water levels and remains after the fast ice has gone.

(8) Pack ice is a general term used to include areas of ice other than fast ice. It is divided by size, age, arrangement, and concentration. This term includes ice fields, ice floe, cake, and brash.

(a) An ice field is a collection of floes that exceed 5 nautical miles.

(b) An ice floe is a basic term usually used for a single piece of pack ice.

(c) A cake is ice fragments up to 11 m across.

(d) A brash is small ice fragments up to 2 m across.

(9) The melt stage incorporates the last stage of the ice cycle during which melting occurs. The melt stage includes puddles, thaw holes, and rotten ice.

(a) Puddles are an accumulation of melt water on the ice due to melting snow and/or ice.

(b) A thaw hole is a circular open hole in the ice that is a further development of puddles.

(c) Rotten ice is an advanced stage of disintegration of any ice type where the ice has become honeycombed in the course of melting.

5.2.3 Breakup

The effect of the spring warming trend is to fragment and melt the ice cover. In general the melting process takes place at the expense of the heat of the surrounding water, but it can also result from the direct absorbtion of solar radiation in the vicinity and contact with warm air. When the air temperature rises above freezing, the snow cover and upper portions of the ice sheet are melted first, causing pools or puddles of melt water to form. A unique feature of these melt water puddles is that when they are refrozen, they turn a brilliant sky-blue color. The blue color has been attributed to the scattering of light by the slight differences in the concentration of the ice molecules. The deeper the blue color, the purer the ice. Any impurities in the ice can perceptibly alter the color.

Continued warm weather causes melting along the crystal boundaries forming a loosely bound ice mass. Lake ice crystals are generally in a pronounced columnar structure. Lake ice in this stage of melting is generally called candle ice. A unique feature of this ice type is that the slightest blow from almost any object will cause it to break into the characteristically long columnar crystals.

Solar radiation is the principal source of heat gained by the ice cover. The albedo of the surface, expressed as a ratio of reflected to incident radiation, determines the quantity of radiation absorbed. Bolsenga[76] (Table 4–23) found that snow-covered ice has a total albedo of 67 percent, slush ice 41 percent, and clear lake ice 10 percent. The higher albedo of snow-covered ice emphasizes the insulating effect of snow cover. In this case it shields the underlying lake ice from solar radiation. There is usually more rapid melting along the shore of the lakes because the darker, sediment-contaminated shore materials absorb a greater amount of solar radiation because of their reduced albedo.

The water over the ice has a much higher ability to absorb heat from solar radiation, which is critical to the melting ice cover. As pools of water collect on the ice and open water appears in the cracks and leads between the floes, the effect of solar radiation becomes greater. Radiant heat energy also has the ability to penetrate to the interior of the ice mass and cause selective internal melting. With the melting along shore and the seasonal spring rise of water levels, it is possible for the ice cover to sever any shore restraints and become a free floating body. In this free floating condition it is highly susceptible to wind and waves acting in the open water areas. The action induced by wind and current breaks up the ice cover and mixes it with warm subsurface water, which aids in the melting and ultimate removal of the ice.

TABLE 4–23 Albedo of Ice Types with Solar Altitudes and Cloud Conditions

Ice Types	Albedo (%)	Solar Altitude (degrees)	Cloud Cover
Clear Lake Ice	10	37	Clear
Refrozen Pancake	31	32	40% Altocumulus
Slush	41	38	100% Cirrostratus
Brash (snow between blocks)	41	40	100% Cirrus & Cirrostratus
Snow Ice	46	32	50% Cirrus & Cirrostratus
Snow Covered Ice	67	41	100% Cirrostratus

SOURCE: Bolsenga, 1968.

5.3 Ice Hazards

An important aspect of the ice season and of the breakup period in particular is the potential destructive ability of the ice cover. Both the lake ice cover and the ice in the connecting channels and tributary streams can be destructive, but each has its own unique effect.

Because of the large, ice covered areas on the Great Lakes, the thermal expansion and contraction of the ice sheet during the season can be considerable. As the air temperature drops the ice sheet contracts, developing cracks which fill with water and refreeze. When the temperature again begins to rise, the warming of the ice surface causes the ice sheet to expand and to generate considerable pressure. This pressure is relieved in two ways: the ice sheet fractures and forms cracks and thrust lines where one floe overrides another and creates a thrust or pressure ridge along the line of fracture; or pressure is relieved by a linear movement of the ice sheet. This linear movement causes a shoreward shift of the ice that can cause considerable damage to shoreline structures and facilities.

During the breakup period, vast fields of drift ice can be moved shoreward under wind pressure and have been known to move hundreds of feet inland and literally bury shore installations. As the shoreward moving ice encounters obstructions, it disintegrates, forming heaps and piles of broken and crushed ice that sometimes reach heights of 7 m or more and occur in widely scattered areas. There appear to be three prerequisites to the ice pile formation: an extensive area of drift ice that is well into the candling stage of melting; a gently sloping beach with a relatively smooth bottom; and a very strong wind.

Another aspect of the thaw and breakup period on the Great Lakes is the flooding potential of tributary streams and the formation of ice jams and ice dams in the connecting channels. The southern lakes, Erie and Ontario in particular, tend to cause flooding of their tributary rivers and streams. The potential for flooding exists when a number of conditions have been met. There must be an extensive ice cover on the lake at the river mouth, the tributary must be ice covered, and there must be an unseasonably warm period to start the breakup and ice movement. The warm weather causes runoff into the streams, raising their levels and accelerating the breakup and movement of the stream ice cover. The ice drifts downstream but is prevented from moving out into the lake by the lake ice. The drifting river ice is stopped and begins to accumulate in an upstream direction where it could possibly form jams. There appears to be a critical flow velocity where the drift ice will be forced under the established ice cover and travel downstream until stopped by flow conditions and/or obstructions. When the drift ice is stopped, ice dams begin to build at narrows and constrictions in the channel. These ice dams retard flow and flooding results. The flooding conditions are usually relieved by water pressure destroying the ice dams.

Ice bridges at the entrances to the connecting channels and rivers of the Great Lakes must be continually observed for possible ice dam formations. Ice dams at these points can create hydraulic pressure that becomes dangerous to downstream facilities, particularly if the hydraulic pressure is released in a short time period. The failure of the ice dam and its resulting surge, together with the ice it carries downstream can cause considerable damage. There are a number of areas on the Great Lakes where potential danger from ice jams and ice dams exists. The most critical area is in Lake Huron at the entrance to the St. Clair River and at the lower end of the river in the vicinity of Algonac, Michigan. The head of the Detroit River in Lake St. Clair and the island area in the lower river are also trouble spots. Another area that has special problems because of its location, is the Niagara River Gorge below the falls. One other area that is a potential trouble spot is the Sugar Island area of the St. Marys River. Longer and longer navigation seasons keep the river ice broken up and the drift ice becomes a flooding threat because it is likely to form ice jams. With most of the danger and damage potential occurring during breakup, this phase of the ice season is as important as the cooling or ice formation stages.

5.4 Extension of the Navigation Season

One other important aspect of the early ice season on the Great Lakes is the effect on commercial navigation. In the past the shipping season usually came to an end about the middle of November and did not begin again until late March or mid-April. There have been recent successful attempts to extend the shipping season on the Great Lakes, particularly through the St. Marys River and the Straits of Mackinac.

Once closed by ice, some ports are not again opened to shipping until early May. Few commercial vessels travel the lakes year-round. Automobile and railroad ferries cross Lake Michigan throughout the year and a few oil tankers, with Coast Guard assistance, travel the length of the lake. The Straits of Mackinac are crossed by a railroad ferry in a year-long operation and there is some shipping between the ports of Toledo and Detroit through most of the winter. However, many areas create difficulties for navigation and require ice breaking operations in the spring before lake commerce can begin. The most difficult of these areas are the St. Marys River and Whitefish Bay. Other critical areas include the Straits of Mackinac and the island area of northern Lake Michigan and the lower St. Clair River-Lake St. Clair-Detroit River waterway. An early ice cover on Lake St. Clair causes jamming in the channels above the lake and drift ice in the Detroit River causes problems in the island area of the lower river. The extreme eastern end of Lake Erie is another problem area. The prevailing winds and currents concentrate drift ice in this area and tend to seal off Buffalo Harbor from shipping until late in the spring.

A number of government agencies are currently working on environmental problems related to the extended season. They are examining these external influences in order to identify the immediate problems and to determine the long-term effects.

The extension of the navigation season is by no means an easy task and successful operations are presently dependent on Coast Guard ice breaker activities. As economies, equipment, and cargoes that can more easily withstand the rigors of winter shipping are introduced, the navigation season will be extended. The problem of winter navigation can be divided into three general parts; harbor facilities, ship design, and winter navigation.

5.4.1 Harbor Facilities

The majority of lake shipping is engaged in bulk trade which require changes in operational techniques and the winterization or modification of loading-unloading equipment in order to adapt it for the extended navigation season. The cargo itself may have to change its form to enable winter shipments to be made. The production of taconite pellets from low grade iron ore is an example of a form change that lends itself well to winter shipment. The problem of harbor icing must be controlled or eliminated so that vessels can move freely to and from their berths and loading docks.

5.4.2 Ship Design

Because of the bulk trade, Great Lakes ships are purposely designed to handle the most cargo at the least expense. They are long, low, narrow beamed, or shallow draft, and have a blunt bow. The bow configuration in conjunction with the driving power does not lend itself to passages through heavy ice. Many ocean-going cargo vessels now enter the Great Lakes and these ships with their ocean travel hulls are somewhat better suited for winter operations. If winter-long navigation becomes a reality, modification of the lake vessels will be a necessity. One additional problem to be solved is that of superstructure icing. This icing adds many hundreds of tons to vessel weight and reduces the stability factor in the open lake. The increased load of the ice could also cause problems in the shallow connecting channels.

5.4.3 Winter Navigation

Many of the navigation aids are removed for the winter, making vessels dependent on only the remaining year-round aids. This causes navigation problems that become critical in the narrow, restricted connecting channels. Extreme caution is also necessary when traversing extensive ice fields to insure that any shifting of the field does not move the ship over shoal areas.

5.5 Ice Removal and Control

Much information is available on methods to control or remove ice cover. There are two basic techniques: breaking and melting of ice.

5.5.1 Breaking

Breaking is usually accomplished by ships with ice breaking capability and to a limited extent by explosives. These are brute force techniques but are valuable under particular circumstances. The use of ice breakers to control ice and aid navigation is presently the most practical for great distances and large areas. Explosives, although useful in special situations, are generally undesirable and have a harmful effect on the ecosystem.

5.5.2 Melting

The technique of melting can be divided into two separate classes: melting at the surface through the use of chemicals and dust; and melting from the bottom of the ice sheet utilizing bubbler systems and thermal check valves.

The use of chemicals to melt ice and snow is not generally used on lake or river ice cover, but dusting has been used to reduce albedo and to conduct heat (solar energy) to the ice or snow cover. Materials used in dusting include coal dust, cinders, fly ash, and sand. Successful materials are those that for the most part are inert, but their effect on the environment should be thoroughly evaluated. Dusting is best carried out from aircraft because of the large areas involved and the relatively inaccessible locations. Weather conditions are the deciding factor when choosing the optimum time to dust. Dusting is most effective when air temperatures are near freezing or higher. Periods of high temperatures and signs of natural breakup are good indicators of prime dusting time. In areas where late heavy snowfalls are not unusual, a second application of dusting material is often necessary. Dusting acts to reduce an ice cover by surficial and internal melting. Surficial melting is caused by the absorption of solar radiation by the dust particles which create melt puddles. These puddles in turn absorb radiation and cause the ice surface to become pitted. Internal melting proceeds as the dust particles melt down into the ice cover creating many needle-like tubes of water which cause the ice to become honeycombed. The absorption of heat and the resulting melting loosens the ice crystal bond and speeds the breakup of the ice cover.

Melting from the bottom of an ice sheet is usually accomplished through the use of a bubbler system or a thermal check valve. Both systems are used to increase the movement of heat from the bottom regions of a body of water to the surface. These two systems cause vertical currents to transport the warmer deep waters to the surface. The bubbler uses small air bubbles rising to the surface to start these vertical currents in motion and the check valve relies on differential temperatures to promote the same action. The bubbles and vertical currents obviously stop at the ice surface, but the momemtum of the vertical currents is transferred to the horizontal direction spreading radially and symetrically at the surface. The water surface at the ice-water interface must be, by necessity, at 0°C (32°F) and when the vertical currents reach the ice surface they sweep away the cold water and replace it with the warm water from below. This method, then, leads to a large effective ice melting rate.

5.6 Ice Cover

The location of the Great Lakes in the temperate zone together with their great water volume insures that the freezing period is not long enough nor severe enough to cause a lakewide, solid, stable ice cover to form. Unlike Arctic regions, the ice cover on the lakes does not remain from year to year, but it is formed, accumulated, broken up, and melted in a single season.

A simple sequence of ice formation rarely occurs on the lakes because of the variable weather conditions that prevail during the winter months. Extremely low air temperatures may occur for a number of days allowing an extensive, but thin, ice cover to form. The

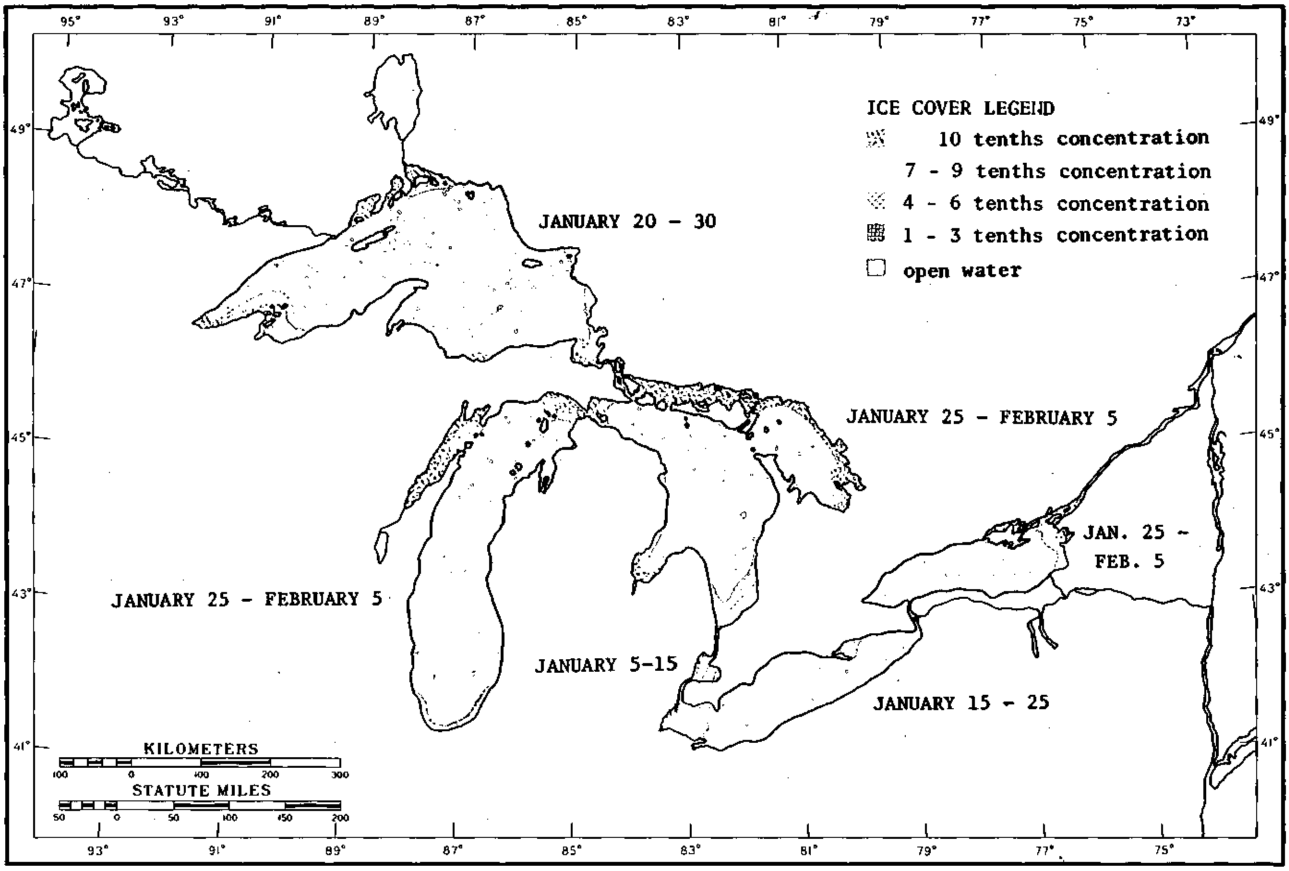

FIGURE 4–103 Patterns of Early Ice Cover on the Great Lakes, with Average Dates

cold spell may be followed by warm weather and strong winds, and consequently the thin ice cover is broken up and concentrated on a lee shore or melted in the lake by upwelling warm water. The effects of winds, currents, and upwelling upon the ice cover causes its areal extent and distribution to change rapidly. Large lake-surface areas also influence the ice cover by causing it to react to water level fluctuations. Water level changes tend to keep the ice in a fluid state and make it more susceptible to wind and current action.

Ice cover on the Great Lakes is made up of ice of various ages and types, but it acts as a homogenous ice sheet as long as air temperatures remain below freezing. Long fetches across the lakes allow the wind and wave forces to attain considerable strength and cause the ice cover to undergo almost constant changes. As the ice cover moves and changes, it rafts and forms ridges that in some areas reach a height of 7 m to 8 m and are grounded on the bottom 9 m to 14 m below the surface.

Lake-ice thickness normally varies from a few centimers to a meter or more in protected areas. A lake-ice thickness of 1.27 m was reported in the Duluth area of Lake Superior. As the ice cover forms in shallow protected bays, and builds out from shore, wind and wave action break it up. The broken ice is reconsolidated to form floes and fields that move out into the lake and sometimes cover as much as 90 percent of the surface area. Figures 4–103, 4–104, and 4–105 illustrate typical patterns of ice distribution, accretion, and breakup across the Great Lakes Basin. The dates of various stages of the ice season are also indicated.

Ice cover on the Great Lakes is affected by many hydrometeorological factors, but each lake has its own characteristics that affect ice formation and distribution.

5.6.1 Lake Superior

This lake, the largest and deepest of the Great Lakes, has an extremely large heat storage capacity. Winds, waves, and currents

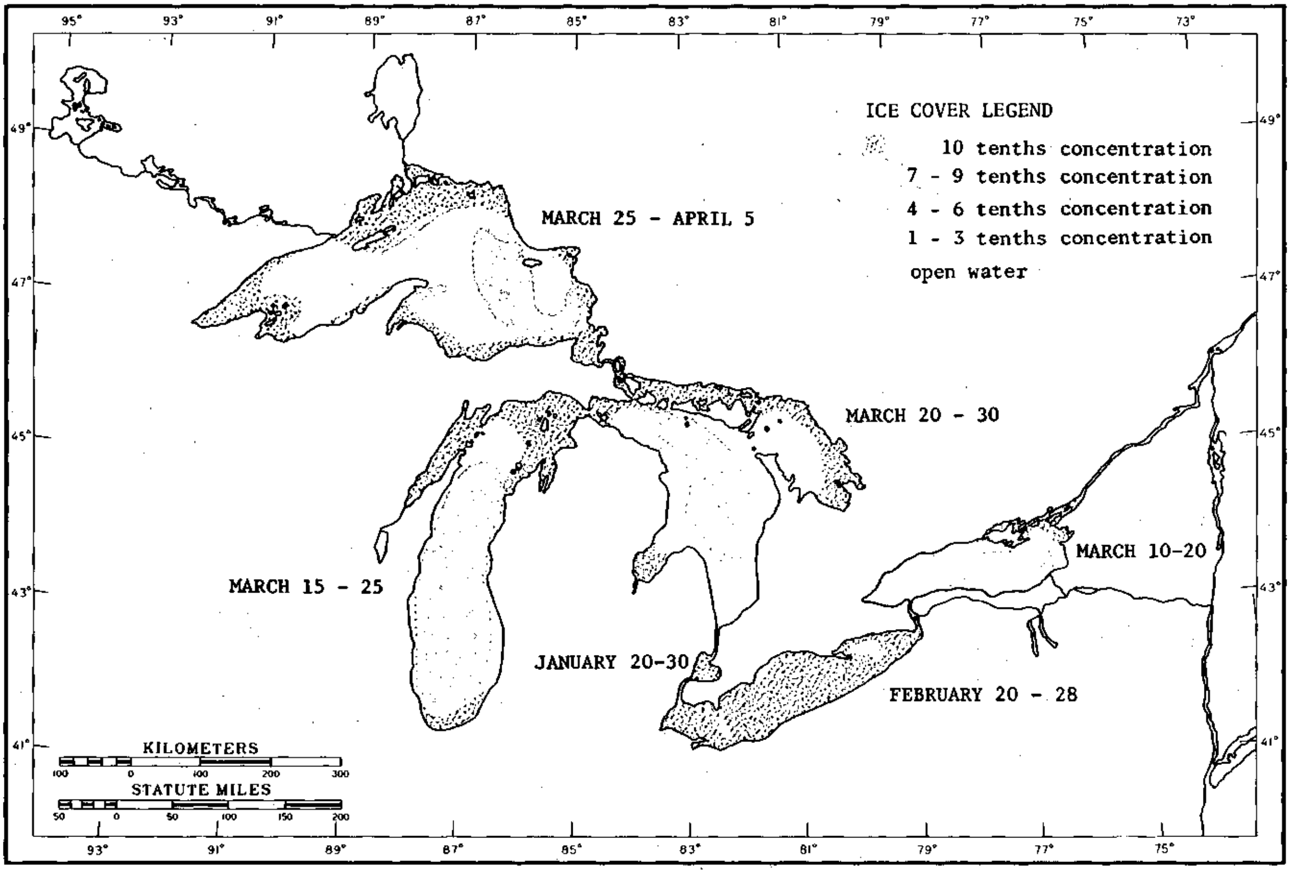

FIGURE 4–104 Maximum Ice Cover Distribution on the Great Lakes, with Average Dates

acting together with the stored heat energy have a more pronounced effect on the ice cover than on any other lake. Upwelling currents change the extent and distribution of ice, and cause melting wherever they come in contact with the ice cover even though air temperatures are below freezing.

Under normal climatic conditions the period of ice formation begins in January and continues to maximum accumulation in the last week of March. The areas other than harbors that have the first extensive ice formation are the bays along the north shore, the Apostle Islands area, and the lower St. Marys River. Ice cover progresses until the shallows along the lake perimeter are covered. In some areas the perimeter cover extends many miles out into the lake. That area of the lake located between Stannard Rock and Caribou Island in the eastern basin is generally ice free except for isolated areas of drift ice. The dates of the greatest areal extent of ice cover will, in general, vary from March 25 along the south shore to April 5 along the north shore. The northern location and the ice season duration, approximately 150 days, gives Lake Superior the greatest ice cover of all the Great Lakes. Ice thickness in excess of 1 m in the harbors along the north shore is common.

The composition of the ice cover ranges from fast, thick, winter ice and areas of consolidated young ice, rind, and pancake, to vast areas of pack ice. The pack ice is made up of fields and floes of drifting brash and cake. Normally the ice covers 60 percent of the surface area and during seasons of severe cold has been estimated to cover 95 percent of the lake surface. This vast ice surface covers approximately 77,000 km² (30,000 mi²). The ice thickness, surface area, and ice season length make the disposition of ice cover on Lake Superior the most similar to ice cover in the Arctic regions.

5.6.2 Lake Michigan

Lake Michigan, because of its north-south orientation and 480 km (300 mi) length, may have ice formation and deterioration happening simultaneously. For example, the March

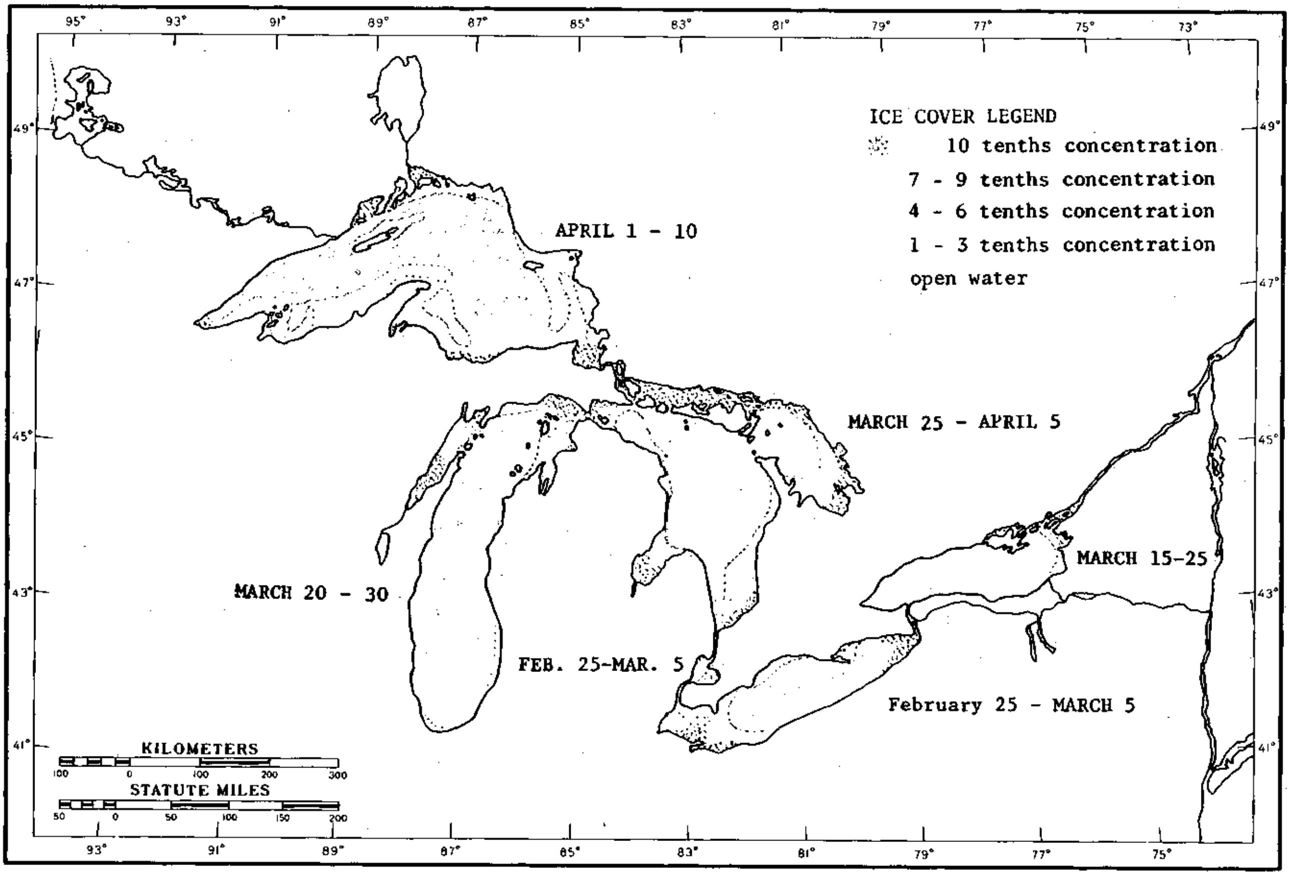

FIGURE 4-105 Ice Cover Breakup on the Great Lakes, with Average Dates

monthly mean air temperature ranges from 2.5°C (36.5°F) at Benton Harbor, Michigan in the south to −3.2°C (26.2°F) at Escanaba, Michigan in the north. With this temperature range it is evident that ice can be melting in the south and forming in the north.

The period of extensive ice formation begins about the last week of January and continues until around the third week of March. Under normal conditions the greatest extent of ice cover occurs between March 15 and March 25 and covers 40 percent of the lake surface. The first ice formation is in Green Bay and Little Bay de Noc, located in the northwest portion of the lake. These areas are protected from the warming effect of the deep lake and are the first to cool and produce an ice cover. As the ice season progresses, the Straits of Mackinac and the shallow areas north of Beaver Island begin to collect an ice cover. The ice forms and accumulates in a southerly direction with a relatively rapid buildup along the Fox Islands and a slower growth rate around the southern perimeter. The circular surface current patterns of the southern basin distribute drifting floes along the shore, and even during a mild season, the drift ice is consolidated and can extend from shore out into the lake a distance of 16 km to 24 km. The distribution of ice, particularly pack ice, is primarily governed by wind and current patterns.

The ice thickness on Lake Michigan varies considerably and generally ranges from 20 cm to 25 cm at Chicago Harbor to more than 76 cm in Little Bay de Noc. The Straits and island area usually present formidable ice ridges, some having depths as great as 9 m, which become hazardous for shipping during breakup. Many harbors along the Michigan shore are closed to shipping for short periods of time because of concentrations of drift ice at their entrances. This drift ice is sometimes consolidated to a depth of over 2 m and can be penetrated by only the most powerful vessels.

5.6.3 Lake Huron

The orientation and patterns of ice formation on Lake Huron are quite similar to those of Lake Michigan, however, the temperature differences between the north and south are not as great. Average March temperatures vary from approximately 1°C (34°F) at Port Huron on the southern end of the lake to −3.4°C (25.9°F) at Mackinaw City on the Straits. Lake Huron also has large areas that are protected from deep lake currents. These areas are the North Channel, which is one of the first areas to become ice covered, and Georgian Bay, which tends to react to ice formation as an individual lake. Georgian Bay has the characteristic accumulation of shore ice and ice cover in the bays and harbors. As the winter progresses the growth of the ice cover extends towards the middle areas. Lake Huron proper has three areas that form and accumulate extensive ice cover early in the season: the Straits in the north, Saginaw Bay, and the southern basin in the Port Huron area.

During a normal ice season, 60 percent of the lake becomes ice covered during the period March 20 to March 30. At the time of greatest ice cover fast ice covers the Straits area eastward to Bois Blanc Island, Thunder Bay at Alpena, Michigan, and Saginaw Bay out to Charity Island. The southern basin, because of the water current patterns, collects large amounts of drifting ice that may become heavily concentrated at the entrance to the St. Clair River near Port Huron. The remainder of the lake usually contains extensive areas of drifting floes, brash, and cake with the deep central area remaining almost ice free. The lake clears rapidly of ice in the spring and usually by April 5 only the North Channel, the Straits of Mackinac, and Saginaw Bay contain any extensive ice cover.

5.6.4 Lake St. Clair

Lake St. Clair usually is not included in the Great Lakes system, but its strategic location between the St. Clair and Detroit Rivers makes it important. This lake has an average depth of only 3.4 m with the deepest points located in the dredged shipping channels. The depth and small surface area of Lake St. Clair cause it to react quickly to wind conditions and air temperature changes. The prevailing winds, currents, and inflow from the various channels of the St. Clair River affect the ice cover and its distribution to a considerable degree.

Early ice formation generally occurs in Anchor Bay, along the St. Clair Shores area and on the east side of the lake in the Mitchell Bay area. Ice cover accumulates much faster in the eastern half of the lake and, because of winds and currents, the western side of the lake is the last to become ice covered. At breakup the western side is the first area to be cleared of ice. The lake becomes ice covered early in the season, generally during the last of January, however, it has become completely covered in early January a number of times. During the period of greatest ice cover, the distribution varies from thick, fast ice in the bays and protected areas to heavy, consolidated floes of brash and cake in the mid-lake shipping channel. The head of the Detroit River is usually ice free the entire season except for minor jamming when drift ice becomes concentrated in the area. An early ice cover on Lake St. Clair also poses a potential navigation problem for commercial shipping because the vessels must stay within the narrow dredged channel in the lake.

The breakup period of the Lake St. Clair ice cover is relatively short. As breakup progresses, winds and currents move the drifting ice to the entrance to the Detroit River where strong river currents move it out of the lake and downstream. The lake is usually ice free in early March.

5.6.5 Lake Erie

Lake Erie reacts rapidly to seasonal temperature changes, and due to its shallow depth, it is the most thermally unstable of the Great Lakes. Because of the rapid response to air temperatures the lake can accumulate a considerable ice cover in a short period of time. Lake Erie develops the most extensive ice cover of any of the Great Lakes; however, because of its thermal instability, the development of the ice cover from year to year is highly variable.

Lake Erie first produces an extensive ice cover in the shallow, western basin and in the Long Point Bay area to the east. The ice cover begins to accumulate in early January and is usually at its maximum by the last week of February.

This lake in the Great Lakes system is subjected to temperatures that fluctuate from above to below freezing during the winter months, and these fluctuations have a considerable effect upon the ice cover. In mid-January daily average air temperatures at Cleveland, for example, have been recorded as high as 10°C (50°F). These high temperatures soften the ice and the induced stresses due to thermal expansion are relieved mostly by fracturing. The fractures and expansion cracks make the ice cover more susceptible to the action of wind, currents, and waves. Under the influence of currents and winds the ice cover shifts causing rafting and pressure ridges to form. Pelee Passage on the western end of the lake, the south shore from Fairport, Ohio, to Sturgeon Point, New York, and the vicinity of Buffalo are areas of the lake where extensive rafting and pressure ridges are generated. During a winter season with normal temperatures it is possible for the lake to become 95 to 100 percent ice covered.

The ice cover during the period of greatest extent is made up of various ice types and concentrations. The western basin contains heavy winter ice which, because of the blocking effect of the islands, tends to stay in place for the season. The area of the lake located between Sandusky, Ohio, and Erie, Pennsylvania, generally contains vast floes and fields of pack ice of differing concentrations. Quite often there are bands of lesser concentrations and even open water along the north shore of this central area. The eastern basin usually contains large, extensive areas of consolidated floes that are concentrated by the prevailing winds and currents. There have been winters where winds from the west have caused a water setup that tilted the lake surface and caused a difference in water levels between Buffalo and Toledo of more than 4 m. The effect upon the ice cover of this wind and wind-caused setup is to break up and clear the central areas of ice and concentrate it along the south and east shores. Most of the lake becomes ice free shortly after breakup which occurs at the end of February or the beginning of March. The broken drifting ice is concentrated by winds and currents in the eastern end of the lake and may remain in the Buffalo area until early May.

5.6.6 Lake Ontario

Lake Ontario has the smallest surface area of all the Great Lakes, but it has a mean depth that is second only to Lake Superior. The combination of small surface area and great depth gives this lake a very large heat-storage capacity causing it to respond slowly to changing air temperatures. This response to climatic change is reflected in the amount of ice cover produced, which is less than the amount produced in any of the other Great Lakes.

Any extensive ice cover formation does not appear until late January and is confined mostly to the east end of the lake. Under normal conditions the greatest extent of ice cover occurs near the middle of March and occupies 15 percent of the lake surface. During the period of maximum ice cover, the ice is concentrated mostly in the northeast portion of the lake at the entrance to the St. Lawrence River. The ice cover is generally composed of fast ice which extends from Henderson Bay to Prince Edward Bay. Adjacent to the fast ice edge are large areas of drift ice that generally extend from Lakeport on the Canadian side to Mexico Bay on the eastern shore. Throughout the season shore ice accumulates and then breaks loose and drifts off. A large ice run in the Niagara River can discharge large quantities of ice into Lake Ontario. The ice collects around the river mouth and at times the coverage can be extensive.

The prevailing winds and currents tend to confine and concentrate the ice cover at the northeastern end of the lake and at the approaches to the St. Lawrence River. The lake is generally ice free early in April except for isolated drift ice and ice in some protected bays.

5.7 Summary

The location of the Great Lakes system is in an area of varied winter weather patterns and temperature differences. Monthly mean temperature differences of 10°C or more across the Great Lakes are not uncommon. The number of days with minimum temperatures below freezing varies from 119 days at Cleveland, Ohio, on the south shore of Lake Erie, to 191 days at Duluth, Minnesota, on western Lake Superior. The period of ice cover is considerably shorter than this and in general begins in late December and continues until early April, with the actual length changing from lake to lake.

The ice season is classified into three general phases: cooling phase, ice formation phase, and breakup or fragmentation phase. The cooling phase begins when the air temperature drops below that of the water. As the water is cooled and wind-induced mixing penetrates deep into the water mass, the water approaches isothermal conditions. When the water mass reaches highest density at 4°C (39°F) further cooling causes the surface-water layers to become stratified and prevent deep mixing.

The heat-storage capacity of the lake is a function of its area and depth, and the position of the thermocline reflects the amount of stored heat. These factors determine when the lake becomes isothermal and, ultimately, when an ice cover forms.

The ice formation phase begins when the water surface has cooled to the freezing point and the latent heat of fusion has been given up. Ice forms along the shore and ice needles branch out over the water surface. The extent of the first ice cover depends upon existing meteorological conditions, but ice formation and thickening are controlled mostly by air temperature.

Two general ice types are formed on the Great Lakes. One is a smooth homogeneous cover formed by rapid freezing in the absence of wind and snow and is called sheet ice. The other is made up of snow and various ice types fused together and is referred to as agglomeratic ice.

The ice cover forms a protective shield against wind waves and their mixing action and retards heat loss to the atmosphere. The retardation of heat flow also gives a certain protection to vegetation and fish life. The temperature gradient under the ice cover ranges from 0°C at the ice-water interface to 4°C at the deep lake bottom (Figure 4–96).

The breakup or fragmentation phase of the ice season begins with the spring warming trend. The breakup is a complex procedure that causes fragmentation and melting of the ice cover.

The melting process takes place at the expense of the heat of the surrounding water, from absorption of solar radiation, and from contact with the warm air. The absorption of heat causes melting along the crystal boundaries. This forms a loosely bound ice mass that is generally referred to as candled ice.

When melt water collects on the ice and open water appears, the effect of solar radiation becomes more pronounced. In fragmenting, the ice sheet is first reduced to vast fields of drift ice then to smaller floes and finally to brash and cake which is quickly melted by wind-induced upwelling.

The shoreward movement of the ice sheet is always a potential danger to facilities during both formation and breakup. It can also cause flooding due to ice dam formation in tributary streams and connecting rivers.

Commercial navigation on the Great Lakes is also affected by the ice cover. In past years the navigation season usually ended in mid-November and did not begin again until March or April. More recently the navigation season has been extended through January and has been quite successful. Early spring navigation is difficult because of ice conditions, and many areas require ice breaking operations before commerce can begin. Problems encountered during winter navigation can be divided into three categories: harbor facilities, ship design, and navigation.

Basically there are two techniques for the control or removal of the ice cover. The techniques are classed as breaking and melting. Breaking is usually accomplished through the use of ice-breaking ships and, to some extent, explosives. Ice breaker operations, however, are still the mainstay of winter and early spring navigation. Of the techniques used in melting the ice cover, dusting and bubbling have received the most attention. The principle of dusting is to reduce the surface albedo and to conduct solar energy to the ice or snow cover. Successful materials used in dusting include coal dust, cinders, fly ash, and sand. Dusting is most effective when air temperatures are near 0°C or higher. The bubbling technique releases bubbles from a perforated pipe located in deep water. As the bubbles rise they generate vertical currents which transport the warm deep waters to the surface. This action sweeps away the cold surface waters and replaces them with warm water from below. This method can be used to prevent ice formation or to control the extent of the ice cover.

The winter period in the Great Lakes area is not long nor severe enough to cause a lakewide, solid, stable ice cover to form. The ice cover on the Great Lakes is a combination of various ages and types of ice but acts as a homogeneous ice sheet as long as air temperatures remain below freezing.

Each of the lakes has its own hydrometeorological factors and characteristics that cause ice thickness to vary from a few centimeters to a meter or more. These characteristics also influence the areal ice coverage which during a normal winter varies from 15 percent on the surface of Lake Ontario, 40 percent on Lake Michigan, 60 percent on Lakes Superior and Huron, and up to 95 percent on Lake Erie.

Section 6

WATER MOTION

Paul C. Liu, Gerald S. Miller, and James H. Saylor

6.1 Surface Motion

6.1.1 Introduction

Water motions at the lake surface are generally designated under the broad term "waves." There are, however, a number of diversified physical processes that can be categorized as surface motion of the Great Lakes. These processes include wind-generated surface waves, free and forced lake oscillations, and short- and long-term lake level variations.

Surface motions are important to at least three operating interests in the Great Lakes: navigation, shore protection, and hydroelectric power development. A knowledge of surface-wave characteristics is essential in establishing design criteria for lake vessels, harbor breakwaters, and offshore structures. Wave action is the primary agent responsible for shore erosion and is a factor in deposition of material in navigation channels. The need for safe and economical navigation routes for vessels requires development of wave climate charts. Long-period waves such as seiches and storm surges affect the safe operation in harbors and embayments, and long-term lake level fluctuations play a significant role in navigation, water supply, and power storage capacity.

Although interest in surface phenomena in the Great Lakes was shown as early as the seventeenth century (Bajorunas[36]), only during the past twenty years have efforts been made to acquire a more detailed understanding of the surface motions. One reason for the increased interest was the unusually high lake stages in the early 1950s. In the following years a number of notable surface motions, which caused severe damages, intensified the demand for further studies. One example occurred in June 1954 when an unexpected surge of water along the Chicago shoreline of Lake Michigan drowned seven people (Harris[314]). In November 1966, during an early winter storm, the *SS Daniel J. Morrell*, a 177 m (580 ft) ore carrier, northbound on Lake Huron, was broken in half and sunk. The waves which caused this disaster were reported to have grown rapidly to more than 6 m (20 ft) under an extremely variable wind from northwest through northeast with gusts more than 28 m/s (92 ft/s) (Swope[780]).

The study of surface motions in the Great Lakes has much in common with similar studies in the oceans; therefore advances in oceanography have stimulated many relevant studies on the Great Lakes. The lakes represent a compromise between open ocean and laboratory models and provide a favorable place for exploratory or definitive experiments. The Great Lakes are ideal for the study of wind-wave generation, growth, and decay, since the fetch can be well defined, the scaling problem is relatively simple, and little swell activity exists.

6.1.2 Classification of Surface Motion

The various motions at the lake surface can be classified in a number of ways. Bajorunas[36] defined two general classes. One class concerns long-term variations assuming a level water surface; the other class includes those processes that occur while the volume of water in the lake remains constant. The predominant number of surface motion studies fall into the latter class.

Fluctuations of the lake surface contain

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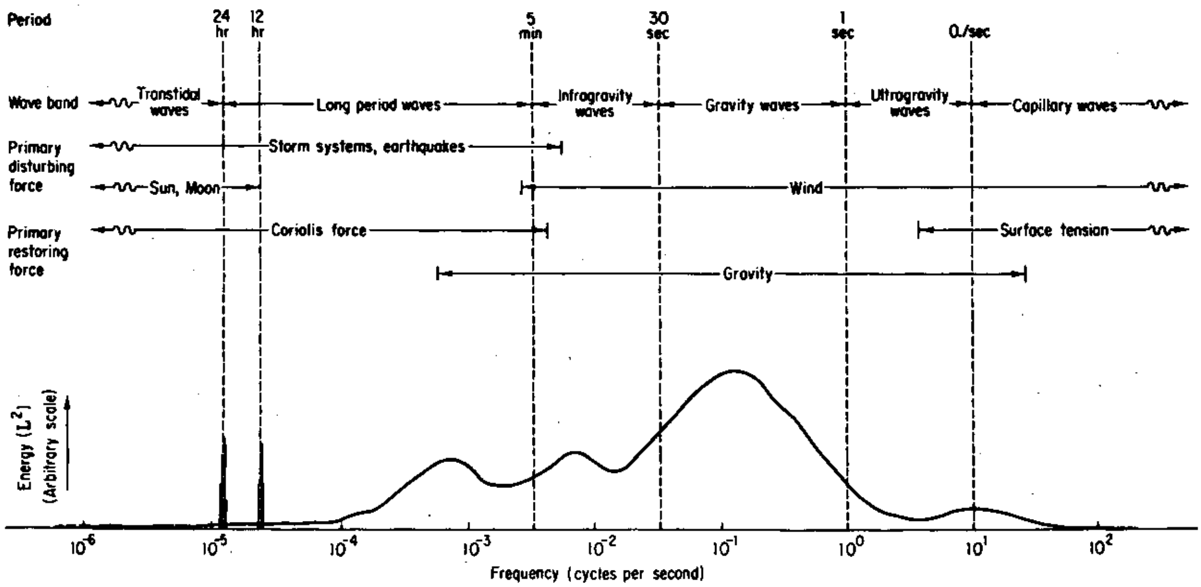

FIGURE 4–106 Schematic Representation of the Energy Contained in the Various Lake Surface Motions

From Kinsman, 1965

short periodicities of a few seconds as well as longer periods. One useful classification of surface motions frequently used in oceanic studies is by period, the time it takes for two successive crests (or troughs) to pass the observer. Figure 4–106 presents a schematic representation of this classification. In the figure, the relative energy contained in various surface motions are plotted with respect to their corresponding wave periods (Kinsman[458]).

Surface motions with the shortest periods are capillary waves or ripples that are controlled mainly by the surface tension of the water. The ripples have very short wavelengths and appear as fine corrugations on the slope of longer waves. Compared with other processes, capillary waves and ultragravity waves with periods less than 1 second play a less significant role in lake surface motion.

Waves with periods between 1 and 30 seconds are known as gravity waves. The band of wind-generated gravity waves (Figure 4–106) contains more wave energy than any other band. Gravity waves in the oceans generally occur in two states, wind waves and swell. Wind waves, generated by wind, are characterized by an extremely random, turbulent form and have periods of 1 to 10 seconds. Wind waves degenerate into swell as they travel from the generating area to a relatively calm region. Swells have longer periods, and are more regular in shape than wind waves. In the Great Lakes where the generating area generally covers the whole lake swells rarely occur.

Waves with periods between 30 seconds and 5 minutes are classified as infragravity waves. The class includes long swell, surf beats, and nearshore water level oscillations. Although these infragravity waves were first recognized in shallow water in ocean-wave studies more than twenty years ago, their presence has not yet been explained satisfactorily (Munk[567]).

Long-period waves, including seiches, surges, wind tides, and astronomical tides, have periods of 5 minutes to 24 hours. With the exception of astronomical tides, the long-period waves are primarily generated by meteorological forces. A storm wind and an intense barometric pressure gradient can produce a variety of disturbances at the lake surface. Numerous studies have been conducted on the theoretical and empirical features of these long-period waves in the Great Lakes.

The astronomical or true tide is caused by the gravitational attraction of the moon and sun acting upon the water mass of the lakes. The true tides recorded on the Great Lakes have a mean range of 0.03 m (Table 4–24), a very small value in comparison to the more pronounced fluctuations of the lake surface in response to meteorological factors. Astronomical tides are therefore generally considered to be negligible in the Great Lakes.

TABLE 4–24 Mean Ranges of True Tide Recorded on the Great Lakes

Reference	Lake	Station	Mean Range
Graham (1860)	Michigan	Chicago	0.045 m
Harris (1907)	Michigan	Chicago & Milwaukee	0.043 m
Dohler (1964)	Erie	Port Colborne	0.030 m
Dohler (1964)	Erie	Kingsville	0.043 m
Dohler (1964)	Ontario	Toronto	0.018 m
Dohler (1964)	Ontario	Kingston	0.012 m
Dohler (1964)	Huron	Port Huron	0.012 m
Dohler (1964)	Superior	Sault Ste. Marie	0.030 m

All the above surface motions occur with no volumetric changes in the lakes. For those processes with periods greater than 24 hours, the volume of water in the lakes can no longer be considered as constant. The volumetric variations for longer time periods result from cyclical climatological changes. These long-term lake level variations, including annual, seasonal, and monthly fluctuations, are of interest in controlling and regulating the lakes, in correlating lake surface with climate changes, and in predicting future lake behaviors.

Currents at the lake surface, which are not necessarily of periodic nature, are also of interest in the study of Great Lakes surface motions. These currents are usually wind-generated and tend to follow certain seasonal circulation patterns. Most available studies on surface currents have endeavored to assess these patterns.

6.1.2.1 Surface Wind Waves

The most evident and most common surface waves in the lakes are those generated by wind. However, there are few studies of wind waves in the Great Lakes. The present discussion therefore draws from a combination of Great Lakes and oceanic-wave studies.

The study of surface wind waves, as the study of other sciences, has been pursued empirically and theoretically. An empirical study attempts to establish wind and wave relationships from observed data. A theoretical study endeavors to develop a quantitative understanding of wave generation and growth which can be verified by empirical data. The use of these two methods for investigating waves goes back to the 19th century. Stevenson in 1850 formulated an empirical relationship between wave height and wind fetch from observations at several British lakes. A theoretical model of wave growth, known as the Kelvin-Helmholtz model, was developed between 1868 and 1874. Reviews of these early investigations of wind waves along with more recent developments can be found in many publications (Sverdrup, et al.,[774] DeFant,[208] Kinsman,[458] and Phillips[607]).

The increased interest in wave studies in recent years was stimulated by the need to forecast ocean waves during the 1940s. Sverdrup and Munk[775] developed one of the earliest forecasting methods. Their method was revised by Bretschneider[87,88] and evolved into the well-known Sverdrup-Munk-Bretschneider (SMB) method. By applying this method, Saville[704,705] hindcasted waves for Lakes Michigan, Erie, and Ontario for the period 1948 to 1950 using synoptic weather charts. A similar work for Lakes Michigan, Huron, and Superior for the period of 1965 to 1967 was conducted by Cole and Hilfiker.[156a] In the absence of more realistic data, these hindcast wave data represent an immediate source of Great Lakes wave information.

A major advance in the study of wind waves, the introduction of the wave spectrum concept, has emerged from the concurrent studies of Darbyshire,[186] and Neumann.[575] A widely used spectrum method of wave forecasting, the PNJ method, was further developed by Pierson, Neumann, and James.[611] Originally derived from statistical analysis of stochastic signals, the wave spectrum concept is based on the assumption that the random sea surface at any instant can be considered as the sum of many sinusoidal waves having different lengths, heights, and directions. Figures 4–107 and 4–108 present two well-known illustrations of this concept. In Figure 4–107, each layer represents a series of sine waves and the sea surface is the result of all these layers superimposed together. In Figure 4–108, a typical wave record is resolved into 14 different sine waves. The wave spectrum shown in the upper part of the figure gives the description of the wave energy distribution in terms of wave frequency. This spectral description thus presents a general and useful characterization of the surface wind waves. The basic wave parameters, wave height and period, can be determined from the wave spectrum.

The realization of the advantage and importance of spectral representation of wind waves has led to numerous attempts to formulate a spectral equation. Such an equation is essential in developing a computerized numerical scheme for forecasting waves. As wave spectra are of a directional nature, it is customary to represent a directional spectrum, $S(\omega,\Theta)$, as the product of a scalar or one-

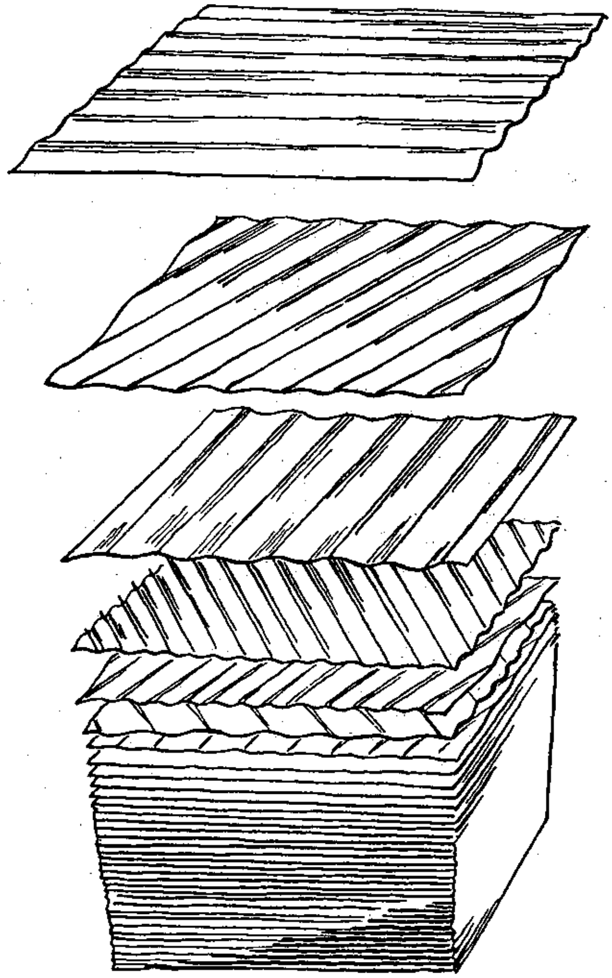

FIGURE 4–107 Sea Resulting from a Number of Superimposed Sinusoidal Wave Trains
From Bascom, 1964

dimensional spectrum, $S(\omega)$, and a directional wave-spreading function, $D\omega(\Theta)$; thus

$$S(\omega,\Theta) = S(\omega)D_{\omega}(\Theta) \qquad (1)$$

where the wave-spreading function at radian frequency, ω, satisfies the condition

$$\int_0^{2\pi} D_{\omega}(\Theta) = d\Theta = 1 \qquad (2)$$

As empirical data on directional spectrums are extremely meager, formulations of $D_{\omega}(\Theta)$ are scarce. Most of the effort has been directed toward deriving $S(\omega)$ from application of the curve-fitting process to the available data. Two major spectral equations developed by Bretschneider[88a] and Pierson and Moskowitz[610] are of the form:

$$S(\omega) = p\omega^{-5} \exp\left[q\omega^{-4}\right] \qquad (3)$$

where p and q are dimensional parameters dependent on the wind field. Bretschneider's

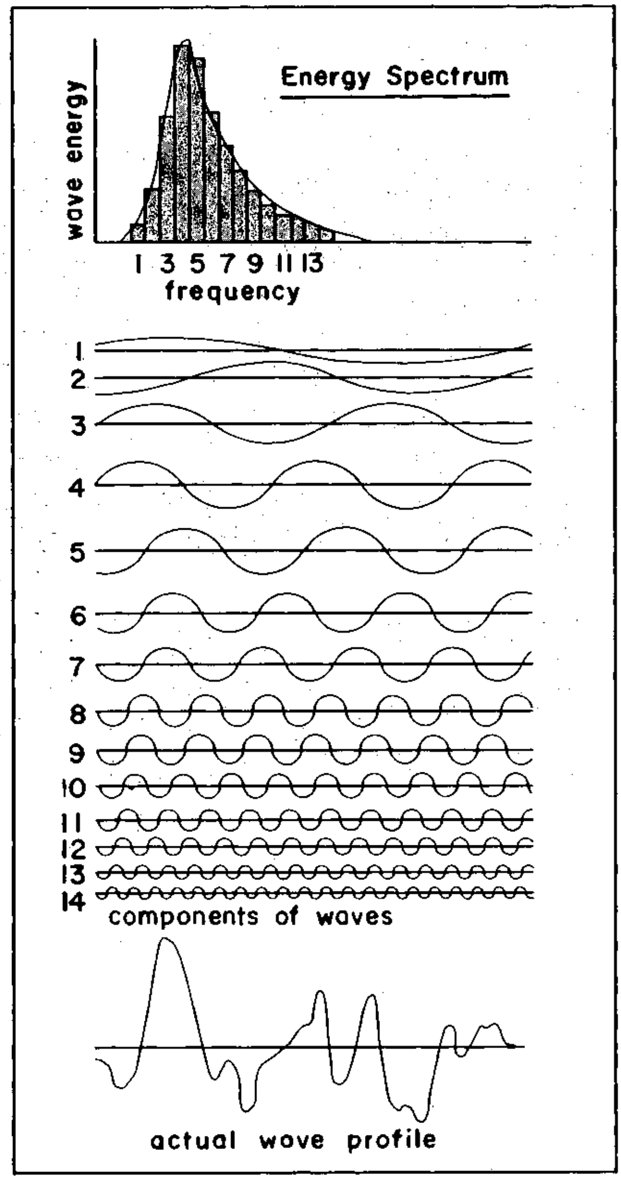

FIGURE 4–108 A Typical Wave Energy Spectrum and the Corresponding Wave Profile
After King, 1959

equation was obtained from an analytic function for the joint probability distribution of wave heights and periods. The equation requires a specific height and period statistic to determine the spectrum. Pierson and Moskowitz's equation, derived for fully developed seas using the similarity theory of Kitaigorodski,[458a] requires only knowledge of the wind speed to estimate p and q. In connection with a study of Great Lakes wind waves, Liu[501] developed an empirical spectral equation for fetch-limited deep-water wind waves

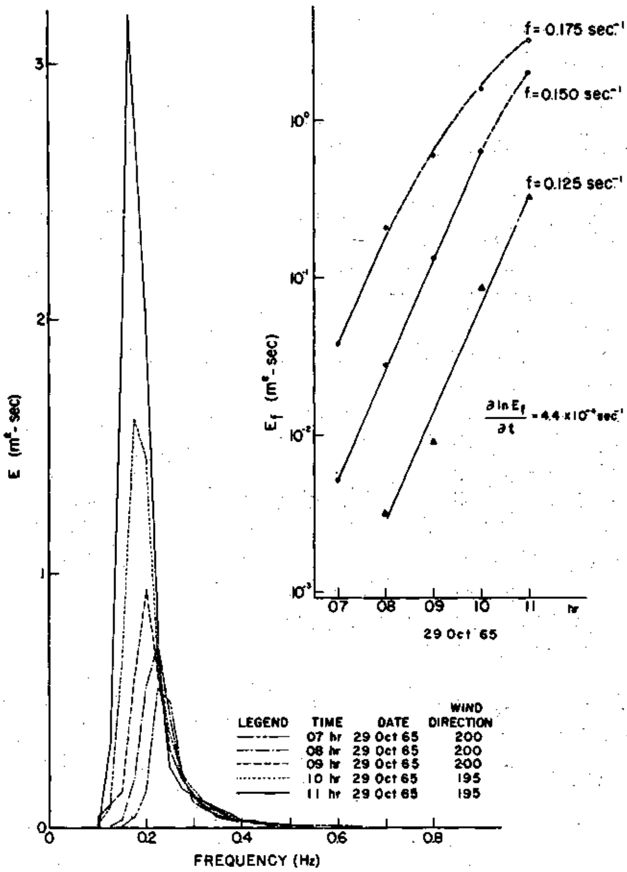

FIGURE 4-109 An Episode of Spectral Growth in Lake Michigan

$$S(\omega) = (0.4g^2/F_o^{1/4}\omega^5) \exp.\left[-5.5\text{x}10^3(g/U_*F_o^{1/3}\omega)^4\right] \qquad (4)$$

where g is the acceleration due to gravity, $F_o = gF/U_*^2$ is the dimensionless fetch parameter with respect to fetch, F, and friction wind velocity is U_*. The data used in deriving equation 4 were recorded at a tower near Muskegon, Michigan, during the fall of 1967 (Liu[501]) and from previously published laboratory and oceanic observations (Liu[501]). For wind fields with sufficient duration, the equation produces reasonably good results in estimating actual wave spectra. Figure 4-109 shows a set of spectral growth patterns with respect to fetch computed using equation 4 for a wind speed of 20 m/s at the 10 m level.

The application of equation 4 requires knowledge of fetch F, and friction wind velocity U_*. Since U_* is not as readily available a parameter as wind speed U_{10}, Liu[501] used an approximate relation of $U_* = U_{10}\,(U_{10}\,2/gF)^{1/3}$ With a known fetch in m, and U_* in m/s, the significant wave height, H_s, in m, and wave period, T_m, corresponding to maximum wave energy, in seconds, T_m can be obtained from the following relations:

$$H_s = \frac{1.74 \times 10^{-2}}{g} F_o^{13/24} U_*^2 \qquad (5)$$

$$T_m = \frac{0.73}{g} F_o^{1/3} U_* \qquad (6)$$

During the International Field Year for the Great Lakes 1972, Lake Survey Center measured directional wave spectra in Lake Ontario and developed the spreading function, $D_\omega(\Theta)$, in order to estimate the full spectrum, $S(\omega, \Theta)$, for more generalized application.

While empirical correlations between wind and wave parameters can be obtained from actual observations and measurements, the problem of determining how the energy in the wind is transferred to the waves still remains. Several conjectured mechanisms characterize the present state of wind wave theory. Significant progress in theoretical wind wave development came in the late 1950s when the resonance and shear flow instability models were developed by Phillips[608] and Miles,[541] respectively. Both models deal with the central question of pressure distribution on the water surface under the action of an invariably turbulent wind. Phillips' theory indicated that the pressure fluctuations produced in turbulent air are advected across the water surface by the wind. Thus, waves can be initiated on a smooth water surface by resonance between pressure fluctuations in the air and free modes of oscillation of the water surface. Miles' theory, on the other hand, was formulated on the assumption that momentum and energy are transferred from the wind to the existing waves by the instability of the mean shear flow in the air. These two models are complementary as the resonance mechanism provides for initial wave generation, while the shear flow mechanism provides for the maintenance and growth of the waves. Phillips[607] and Miles[542] have reformulated the mechanisms to provide a combined Phillips-Miles model. Numerous laboratory and field experiments indicate that the model underestimates the actual wave growth by one order of magnitude. The study of Lake Michigan wind waves by Liu[500] was no exception.

Further development of the wind wave theory is required for the determination and estimation of the energy transfer due to nonlinear interactions. Hasselmann[325] discusses the theoretical derivations of the various processes on nonlinear interactions. The results, however, are complicated, and some processes are poorly understood. Future advances in the theory of wind waves depend largely on the further understanding of the physical environment, which in turn depends on additional observations. Available data for the Great Lakes are far from adequate. Extensive measurements, including all the meteorological factors and the directional spectrum of waves, are needed. Only extensive exploratory and definitive measurements will verify, revise, and enhance the necessary theoretical developments.

6.1.2.2 Long-Period Waves

The long-period waves, sometimes called long waves, are those oscillations in lake level that have periods of a few minutes to a few hours. Three kinds of long-period waves are of importance in the Great Lakes. They are surges, wind tides, and seiches. The three terms, which represent three different surface motion processes, are sometimes incorrectly used. In the present discussion, surges refer to forced lake-level oscillations that result from atmospheric pressure gradients combined with strong winds; wind tides are forced oscillations that result from wind only; and seiches are the free oscillations of the lake surface that continue after the external forces that caused the initial oscillation have ceased to act.

The first of the many studies of Great Lakes long-period waves were done by Denison[210] who studied the effects of wind and pressure on Lake Ontario. However, the majority of literature has appeared since 1950. The Lake Michigan surge of June 26, 1954, was studied extensively by Freeman and Bates,[272] Ewing et al.,[251] Harris,[314] and Platzman.[617] Jelesnianski[425] and Donn[221] studied other surges in Lake Michigan. Platzman[617] developed a numerical method which has been applied to surge prediction in the southern basin of Lake Michigan (Irish,[415] and Hughes[390]). A regression model for surge prediction was applied to Lake Erie by Harris and Angelo.[317] Wind tides, which are particularly prominent on Lake Erie, have been studied by Keulegan,[452] Harris,[316] Gillies,[287] Hunt,[397] Verber,[852] Irish and Platzman,[416] and Platzman.[616] Studies of seiches in the Great Lakes were conducted by Harris,[316] Hunt and Bajorunas,[399] Verber,[852] Housley,[384] Platzman and Rao,[618] Rockwell,[670] and Simpson and Anderson.[740,741] Studies of long-period waves using spectral analysis were done by Platzman and Rao,[620] Mortimer,[559] and Miller.[544] Systematic reviews of knowledge of long-period waves up to the early sixties were presented by Bajorunas,[36] and Mortimer.[557]

The theoretical aspect of these studies is generally based on the linearized, vertically integreated hydrodynamic equations which take the form

$$\frac{\partial(hu)}{\partial t} - fhv = -gh\frac{\partial\eta}{\partial x} - \frac{h}{\int_\omega}\frac{\partial\rho\alpha}{\partial x} + \frac{1}{\int_\omega}(Y_{xs} - Y_{xb}) \qquad (7)$$

$$\frac{\partial(hv)}{\partial t} - fhu = -gh\frac{\partial\eta}{\partial y} - \frac{h}{\int_\omega}\frac{\partial\rho\alpha}{\partial y} + \frac{1}{\int_\omega}(Y_{ys} - Y_{yb}) \qquad (8)$$

$$\frac{\partial\eta}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = c \qquad (9)$$

where x and y are horizontal rectangular coordinates; u and v are corresponding velocity components; $\int_\omega$ is the water density; $\rho\partial$ is the atmospheric pressure, h is the depth of the lake, g is the acceleration due to gravity; Y_{xs}, Y_{ys} and Y_{xb}, Y_{yb} are the components of surface wind and bottom stresses; f is the Coriolis parameter, where $f = 2\ \Omega \sin \phi$, with ϕ as the latitude and Ω the earth's angular speed; and η is the height of the free water surface above the mean lake level.

Equations 7, 8, and 9 are basic equations applicable to all of the long-period wave processes. Several assumptions have been made in deriving these equations. The amplitude of the long waves has been assumed to be small compared to the depth of the lake, and the horizontal scale of the waves is assumed to be large compared with the lake depth thereby justifying the neglect of nonhydrostatic pressure forces and nonlinear acceleration terms. Furthermore, the lakes are assumed to be incompressible and homogeneous, hence density variations are neglected. The latter assumption is generally untrue because the Great Lakes do develop thermal stratification. However, long-period waves at the lake surface are primarily transient external waves, and density variations play a relatively minor role. In most studies the Coriolis forces in equations 7 and 8 are neglected.

Even with all of these assumptions as well as the linearization, equations 7, 8, and 9 are still not readily applicable because the atmospheric pressure gradient, wind stress fields, and bottom stresses have yet to be determined. At the present only empirical approximations are available for these parameters. Much additional work will be needed before the linearized theory can be effectively operative.

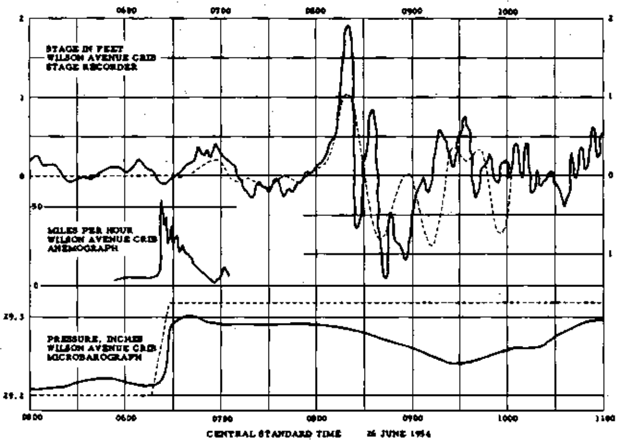

FIGURE 4–110 Lake Level, Wind, and Atmospheric Pressure Records at Wilson Avenue Crib, Chicago, Illinois; June 26, 1954. The broken curve of level shows the results of numerical computation for a squall-line speed of 54 knots; the broken curve of pressure gives the corresponding pressure rise assumed in the calculation.

From Platzman, 1958

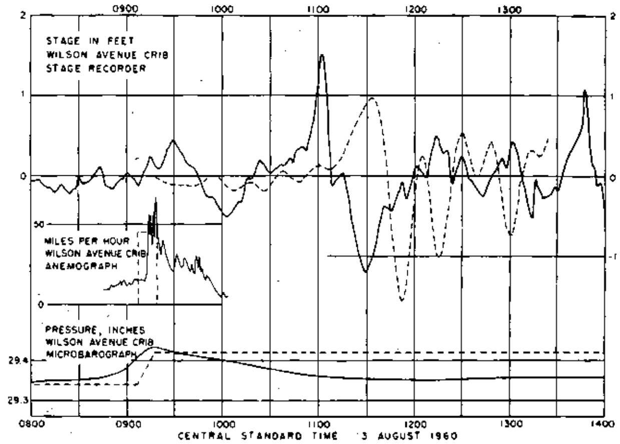

FIGURE 4–111 Lake Level, Wind, and Atmospheric Pressure Records at Wilson Avenue Crib; August 3, 1960. The broken curves of lake level, wind, and pressure show the results of numerical computation for a squall line moving at 54 knots and at 115°.

From Irish, 1965

6.1.2.3 Surges

A surge is a sudden, usually unexpected, rise in lake level associated with a rapid change in atmospheric pressure, a pressure jump, and a storm wind. The main purpose of studying surges is, therefore, two-fold: to explain the physical characteristics of the phenomenon; and, through prediction of dangerous high waters, to warn a threatened lakeshore or harbor area.

Studies of surges in the Great Lakes, especially the one in Lake Michigan on June 26, 1954, by Ewing et al.,[251] Freeman and Bates,[272] Harris,[314] and Donn,[221] have shown conclusively that this surge was produced by an intense, fast-moving squall line passing over the lake. A mid-lake disturbance was produced by the resonant coupling of the pressure gradient and wind stress that accompanied the squall line with gravity waves on the lake. While maximum energy transfer occurs when the atmospheric disturbance and the gravity waves are at nearly equal speeds, Harris[314] concluded that "the orientation of the pressure jump will be equally or more important than the speed" when the topography of the lake bottom, as well as shoaling and reflection effects, are taken into account.

Platzman[617] made an important contribution to surge prediction studies using equations 7, 8, and 9, but neglected the Coriolis force and bottom stress, and employed finite difference methods to solve the equations numerically. The squall line was assumed to be bounded by two parallel lines, between which the pressure changed linearly. As a first approximation, wind stress was neglected. The squall line was further assumed to move with a constant speed and without change of shape. Figure 4–110 shows the results of predicted and measured water levels at the Wilson Avenue Crib, Chicago, Illinois, on June 26, 1954. The predicted time of arrival of the peak surge agreed closely with the measurements. The magnitude of the predicted surge, however, was 40 percent lower than measured. Irish[415] applied the same method to predict the surge that occurred on August 3, 1960, in southern Lake Michigan. The results at the Wilson Avenue Crib (Figure 4–111) failed to predict the early arrival of the peak surge, which was again about 40 percent low.

Applying one-dimensional analysis to equations 7, 8, and 9 and assuming that bottom friction is proportional to some weighted sum of the surface stress and the mean current velocity, Harris[315] developed a regressional prediction model that is dependent on the knowledge of past surge records. Harris and Angelo[317] applied this model to the recorded storm surges in Lake Erie with reasonably good results. This model cannot, however, lead to an operational prediction system, as it requires an unpracticably large amount of data based on precisely similar observational practice.

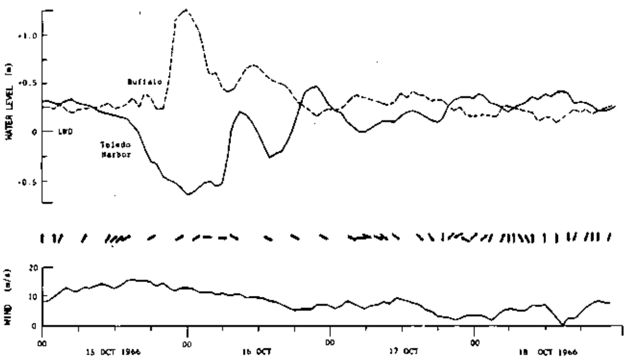

FIGURE 4–112 Wind Tide and Set-up on Lake Erie, Along with Wind Speed and Direction, Recorded near Toledo Harbor Light. The arrows indicate wind direction from its source.
From Miller, 1969

6.1.2.4 Wind Tides

Wind tides are generally considered to be synonymous with storm surges. While the term storm surge is usually used for oceanic studies, the term wind tide is used on lakes. Bajorunas[36] gave two criteria to distinguish between the surges discussed in the previous section and wind tides: wave length and duration of buildup time. Wind tides always have a single wave with a length double that of the fetch in the wind direction, while surges have waves of shorter lengths. A wind tide takes hours to reach equilibrium, while surges only need a few minutes to build up. The amount of rise in water level produced during a wind tide is known as wind set-up. The difference between the Buffalo and Toledo water levels in Lake Erie during October 15–18, 1966, is an example of wind tide and wind set-up (Figure 4–112).

In the simplest case of a wind tide with constant wind speed and direction and constant lake depth, the inclination of the lake surface can be obtained from equation 10,

$$\frac{\partial \eta}{\partial x} = \frac{\Upsilon_{xs} \quad \Upsilon_{xb}}{\int_{\omega} g\,(h+\eta)} \qquad (10)$$

where Υ_{xs} and Υ_{xb} are acting in opposite directions and the depth h is replaced by $h+\eta$ to consider greater wave amplitudes. As mentioned earlier, the stresses in equations 7, 8, and 9 are not clearly understood, so empirical approximations are used to determine the wind set-up. Hunt[397] studied the dependence of wind stress upon wind speed and thermal stability of the atmospheric boundary layer, and derived working relations applicable to Lake Erie data.

Because of the west-southwest to east-northeast orientation, Lake Erie is particularly vulnerable to the wind tide excitation by prevailing southwesterly winds (Figure 4–7). Irish and Platzman[416] studied extreme wind tides on Lake Erie for the 20-year period 1940 to 1959 and found that a set-up in excess of 3 m (9.8 ft) can be expected once every 2 years. The largest recorded wind set-up on Lake Erie was 4.2 m (13.8 ft). While attempting to identify those meteorological conditions associated with wind tides, Irish and Platzman[416] found that the resonant coupling involved in the energy transfer from atmosphere to lake surface does not contribute significantly to set-up magnitude. This suppression of the resonance was later theoretically corroborated by Platzman.[616]

There are no wind tide studies available for lakes other than Erie at present. Bajorunas[36] estimated that, for a given wind, the set-ups excited on Lakes Michigan and Huron are 25 percent of the magnitude of Lake Erie set-up, and those on Lakes Superior and Ontario are only 17 percent.

6.1.2.5 Seiches

A wind tide will persist as long as the wind stress is sufficient to maintain the water gradient. As the wind stress decreases, the stable surface of the wind tide cannot be sustained, and a seiche results. Seiches are long, free oscillations with periods determined by the geometry and the depth of the lake as well as the mode of the standing wave. Figure 4–112 shows a seiche following the Lake Erie wind tide of October 16, 1966. After the initial water level disturbance which was due to a strong southwest wind, the wind speed subsided and the wind direction switched to northeast, while the fluctuations of water levels at both ends of the lake continued.

One of the frequently studied aspects of seiches in the Great Lakes is the longitudinal free oscillations. This can be attained observationally by spectral analysis of water level records and theoretically by numerical integration of the hydrodynamical equations. For a long channel of uniform width and variable depth, the linearized, one-dimensional equations can be obtained from equations 7 and 9 by neglecting the earth's rotation and the external forces, which give

$$\frac{\partial (hu)}{\partial t} + gh\,\frac{\partial \eta}{\partial x} = 0 \qquad (11)$$

TABLE 4–25 Lake Superior Seiche Periods in Hours

Mode	Computed Rockwell (1966)	Observed Housley (1962)	Observed Fee (1969)	Observed Miller (1970)
1	7.19	8.20	8.10	8.80
2	4.30	4.10	4.90	3.80
3	3.29	2.70	3.80	1.90
4	2.84	----	----	----
5	2.24	----	----	----

TABLE 4–26 Lake Michigan Seiche Periods in Hours

Mode	Computed Mortimer (1965)	Computed Rockwell (1966) Closed	Computed Rockwell (1966) Open	Observed Mortimer (1965)
1	9.08	9.09	8.83	9.00
2	4.90	4.92	4.87	5.20
3	3.57	3.58	3.53	5.70
4	2.88	2.91	2.85	3.10
5	2.40	2.42	2.37	2.50

TABLE 4–27 Lake Huron Seiche Periods in Hours

Mode	Computed Endros (1908)	Computed Rockwell Closed	Computed Rockwell Open
1	6.12	6.71	6.49
2	--	4.80	4.57
3	--	3.18	3.13
4	--	2.66	2.60
5	--	2.26	2.24

$$\frac{\partial(hu)}{\partial t} + \frac{\partial \eta}{\partial t} = 0 \qquad (12)$$

Upon the cross differentiation, the continuity equation can be written as

$$\frac{\partial}{\partial x}\left[h\frac{\partial \eta}{\partial x}\right] - \frac{1}{g}\frac{\partial^2 \eta}{\partial t^2} = 0 \qquad (13)$$

If harmonic oscillations for free surfaces are assumed, which is appropriate for a closed basin, write

$$\eta(x_1 t) = R_e\left[\eta(x)\exp(i\, z\pi\, ft)\right] \qquad (14)$$

TABLE 4–28 Lake Erie Seiche Periods in Hours

Mode	Computed Platzman et al., (1965)	Computed Hendrickson (1968) One-dim.	Computed Hendrickson (1968) Two-dim.	Observed Platzman et al., (1965)
1	14.08	13.92	14.37	14.38
2	8.92	8.56	8.41	9.14
3	5.70	5.70	5.53	5.93
4	4.11	4.14	4.03	4.15
5	3.69	----	3.62	----

TABLE 4–29 Lake Ontario Seiche Periods in Hours

Mode	Computed Rockwell (1966)	Computed Simpson, et al., (1964)	Observed Hamblin (1968)
1	4.91	5.41	5.40
2	2.97	2.48	2.38
3	2.15	----	----
4	1.63	----	----
5	1.29	----	----

where f is the oscillation frequency, and equation 15 can be given in terms of the independent variable x by

$$\frac{d}{dx}\left[h\frac{dn}{dx}\right] + \frac{(2\pi f)^2}{g} M\eta = 0 \qquad (15)$$

The normal modes of oscillation can then be obtained by applying the finite difference method to equation 15 together with the configuration of the lakes.

Tables 4–25 through 4–29 summarize the available information on the first five modes of longitudinal free oscillations for each of the Great Lakes. Fair agreement has been obtained between observed and computed periods and among different investigators. Only computed periods are available for Lake Huron (Rockwell[670]).

Platzman and Rao[620] examined the effect of neglecting earth rotation and frictional forces in arriving at equations 11 and 12, and found no significant effect on the period of any longitudinal mode. Similar conclusions were also obtained by Miles and Ball[542a] in a theoretical study of a circular lake with a parabolic bottom shape. Both of the authors infer that earth rotation transforms the lowest longitudinal mode into an amphidromic wave, i.e., the high water rotates about the lake in a counterclockwise direction. This amphidromic nature, however, was not detected in analyses of data from Lake Michigan (Mortimer[559]), and Lake Ontario (Hamblin[309]).

Hendrickson[340] attempted a two-dimensional study of Lake Erie free oscillation by solving

$$\frac{\partial}{\partial x}\left[h\frac{\partial}{\partial x}\right] + \frac{\partial \eta}{\partial y}\left[h\frac{\partial \eta}{\partial y}\right] + \frac{(2\pi f)^2}{g}\eta = 0 \qquad (16)$$

which is the two-dimensional equation analogous to equation 15. The results offered some insight into the two-dimensional characteristics of the lake's oscillation. The effect of earth's rotation remains unexplored. The first five modes computed from equation 16 (Table 4–28) are in fairly close agreement with the one-dimensional results.

6.1.3 Long-Term Variation of Lake Levels

Long-term variation of lake levels refers to the volumetric changes of the lakes wherein the water surface is assumed to be level. Lake level rises with increasing volume and falls with decreasing volume. The main factors that affect these variations are precipitation, evaporation, runoff, as well as other man-made and geological changes. Brunk,[110,112] Laidly,[480] Richards,[646,647] and Verber[852] discussed the various effects of these factors over the Great Lakes levels.

In general, the most regular variation in lake levels is the annual cycle (Figures 4–24, 4–26, 4–29, 4–31). This cycle varies from low water in the late winter to high water in midsummer. Amplitude of the cycle differs from lake to lake and varies from year to year. The following discussion given by Richards[647] offers a clear and concise description of this phenomenon:

> Rising water levels come in the spring and early summer: (i) after the snow-melt and spring floods, (ii) when precipitation is at its greatest, (iii) when ground-water levels are highest, and (iv) evaporation rates are lowest (due to the low water temperature). By contrast, falling water levels come in the fall and winter: (i) when evaporation rates are highest, (ii) when ground-water levels are lowest, (iii) when precipitation is at its lightest, and (iv) when most of the winter's precipitation on the watershed is locked up by snow.

One of the unresolved questions lies in the detection of long-term periodicities of Great Lakes levels. For years efforts have been made to identify a pattern of long-term variations. Cycles of seven, eleven, and ninety years have been postulated (Verber[852]) but there is also strong doubt by some as to the existence of long-term periodicities. Laidly[480] and Liu[500] found evidence of the existence of an eight-year cycle from spectral and auto-correlation analyses. If such a long-term cycle could be ascertained, development of accurate long-term lake level predictions would be more assured. The effects of the hydrologic cycle on lake storage, and hence levels, were discussed in Section 4.

6.1.4 Currents at the Lake Surface

Discussion so far has concentrated on periodic surface motions. Aperiodic motions, notably currents, are also induced at the lake surface. The study of surface currents in the Great Lakes has been confined to determination of seasonal or persistent circulation patterns. The classical drift bottle study of Harrington,[313] for warm months as reproduced by Millar[543] (Figure 4–113), is still one of the most complete and comprehensive studies of surface currents in the Great Lakes. Ayers, et al.[28] and Johnson[432,433] studied surface currents in Lakes Michigan and Huron and found that seasonal patterns are generally similar to Harrington's earlier study. A concise review was given by Hough.[380]

As the seasonal surface currents are mostly related to, and maintained by the prevailing wind over the lakes, the wind also produces wind-drift currents at the lake surface. The direction of the wind-drift current in the Great Lakes is approximately 30° to 45° to the right of the wind due to the Coriolis force. The evidence of this directional relationship between wind and wind-drift currents was illustrated by Ayers[27] in a drift bottle study. Dynamics of wind-drift currents, as explained by the Ekman theory, have been studied extensively in the ocean (Sverdrup et al.,[774] Neumann and Pierson[576]).

Another kind of lake surface current of interest is the wave-drift current. Wave-drift currents are formed from the unclosed orbital motion of water particles during the passage of waves. This unclosed orbit traverses an open curve that induces gradual advancement of the water particles with the passage of each wave and thus results in a net current in the direction of wave propagation. As discussed previously, the energy transfer from wind to water is intricate and not fully understood; the presence of wave-drift currents further complicates the boundary condition. No measurements are available concerning the wave-drift currents in the Great Lakes.

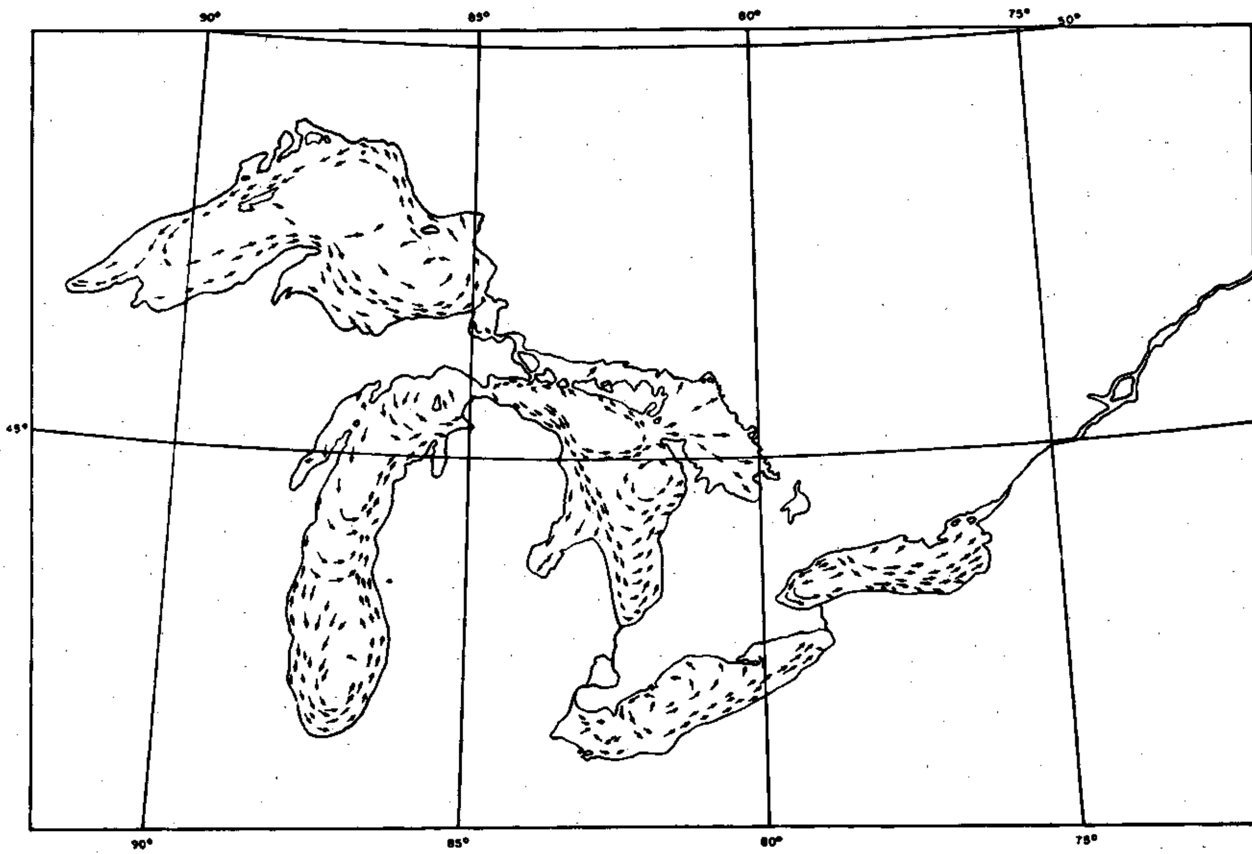

FIGURE 4–113 Surface Currents of the Great Lakes

After Harrington, 1895

6.2 Internal Water Motion

6.2.1 Thermally Driven Circulation

An idealized summary of the annual cycle of water density distribution in deep lakes involves development and decay of thermally differentiated layers or strata. Rodgers[671,674] showed that the heating of surface water in spring was not uniformly distributed across the surface of Lake Ontario. Instead, he found that warm water forms initially in the shallow depths along shore and spreads gradually toward the deeper parts of the lake basin (Figure 4–114). The boundary between warm, less dense inshore water and cold, still isothermal lake water was marked by intense horizontal temperature gradients and also color differences. Deeping and lakeward growth of the shore-bound warm water was found to be associated with the development of a thermocline behind the advancing warm front. Rodgers termed this early stage in thermocline development the "thermal bar." A similar process occurs in fall, with water in the shallow, coastal zone cooling more rapidly than water in the deep, central parts of the lake. The formation of ice in shallow coastal waters while the central portions of the lakes are ice free is further evidence of this phenomenon.

The importance of differential heating of surface lake water to the present discussion is the existence of thermally driven lake water circulation, which is much more complicated than the simple convective overturns discussed previously. The thermally driven circulations were modeled theoretically by Huang.[387] The most general of Huang's circulation patterns applies to the lengthy intervals of summer heating and winter cooling during which the water density at the lake surface is greatest over the deep basins and decreases monotonically as the water depth decreases toward the coasts. The horizontal circulation pattern during these intervals consists of counterclockwise currents encircling the deep basins. These are geostrophic currents representing a blance between horizontal pressure and Coriolis forces. A similar,

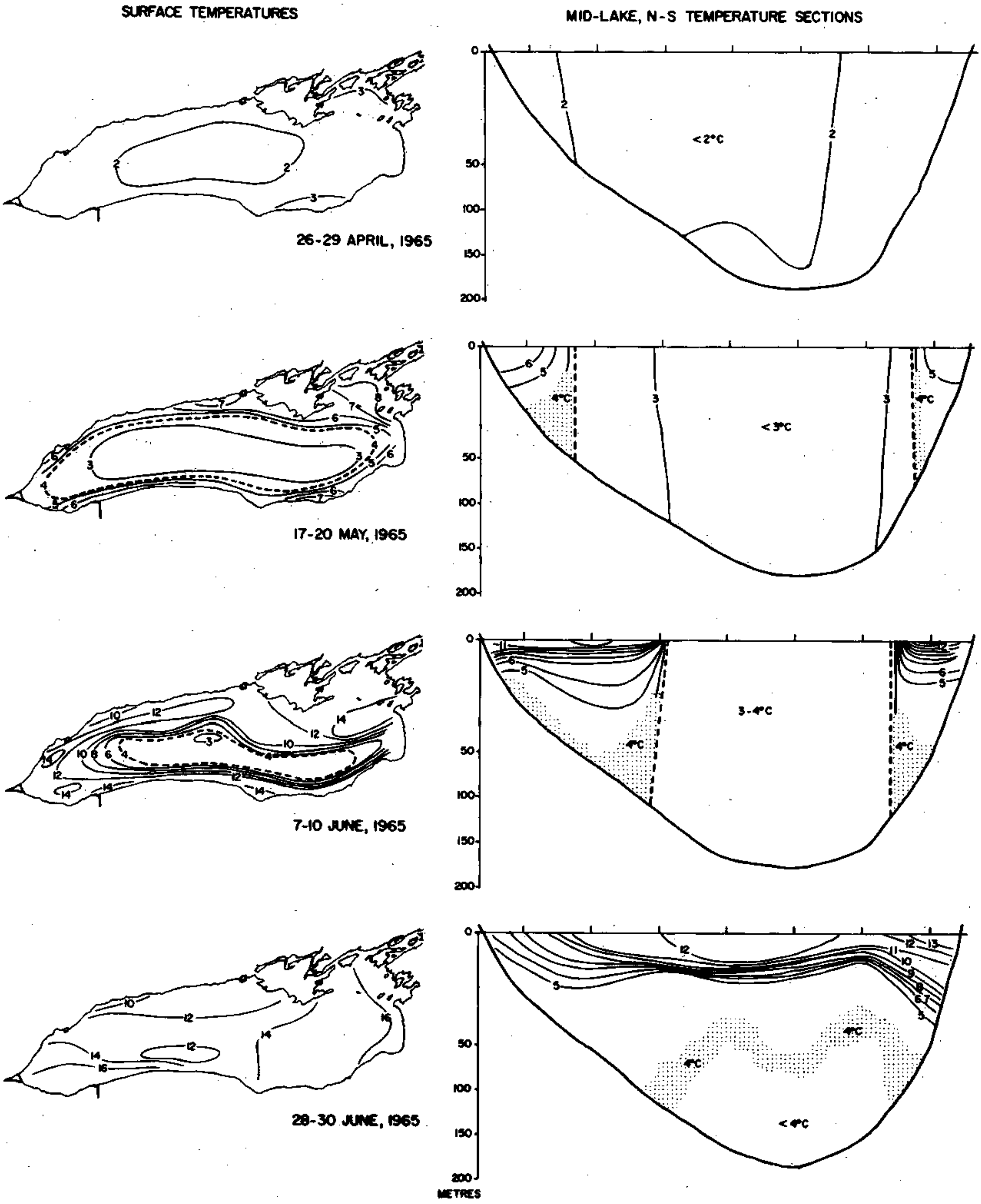

FIGURE 4–114 Development of the Thermal Bar from Winter to Full Summer Stratification. Shading indicates areas of maximum density.

From Rodgers, 1966

but clockwise, circulation pattern results from early spring heating and early fall cooling, when the surface water density is least over the deep basins and increases monotonically as the water depth decreases. These intervals are much shorter in duration than the intervals during which counterclockwise circulation prevail. Counterclockwise circulation is associated with divergence (upwelling) along the coasts and convergence (sinking) over the deep basins, while clockwise circulation exhibits convergence along the coasts and divergence over the basins. Huang also studied the circulation associated with the condition of intense horizontal thermal gradients separating coastal and offshore waters. The current patterns in this case are more complex, but they represent relatively short-lived phenomena in the annual cycle of lakes. Huang demonstrated a close correlation between the computed thermally driven current patterns and the observed currents in Lake Michigan. The circulation pattern during a long season of strong density stratification, which is characterized by an almost isothermal, warm epilimnion overlying an isothermal hypolimnion of near maximum water density has not been modeled using only thermal considerations.

6.2.2 Wind-Driven Circulations During the Density-Stratified Season

Circulations driven by wind stress on the water surface are superimposed on thermally driven currents. The wind stress is approximately proportional to the square of the wind speed and the stress is transmitted through the water column by friction. The effect of the wind stress is to drive a net transport at some angle to the right of the wind direction in the northern hemisphere. In homogeneous deep water, Ekman (in Sverdrup, et al.[774]) showed that surface currents were directed 45° to the right of the wind stress if the effects of the earth's rotation are taken into account and if the eddy viscosity is independent of depth. With increasing depth the angle of the current flow to the right of the wind stress increases in a regular fashion, so that at some depth termed the "depth of frictional resistance," the flow is exactly opposite the wind stress. At this level the current speed is approximately 1/23 that at the surface, and the net transport of water in depths above this level is directed 90° to the right of the wind stress. In shallow water and in water that is density stratified, the net transport is directed at some lesser angle to the right of the wind stress. During conditions of low wind stress, wind-driven circulations cause small perturbations in the thermal currents driven by differential heating or cooling of the lake surface. Sustained periods of high wind stress thoroughly mix the surface layers, destroying the horizontal temperature gradients and creating a configuration that approximates a two-layer model.

With establishment of the summer density stratification, the direct effects of wind-driven mixing and circulation are confined to the upper layer (Figure 4–115). When a homogeneous upper layer is formed, stability will be great at its lower boundary; there the eddy viscosity is small and further increase in the thickness of the homogeneous epilimnion is impeded, although the thickness may be much less than that of the layer in which a wind current should normally develop. Further increase in epilimnion thickness due to mixing across the density discontinuity at the thermocline must be very slow. There are no available estimates of the time required for the wind current to penetrate to the depth that it would have reached in homogeneous water.

If the wind decays, heating at the surface may again decrease the surface water density, but as soon as the wind starts to blow, a new homogeneous layer is formed. With light winds this may result in the formation of a new layer at the surface, so that two thermoclines and three homogeneous layers are observed. More typically, however, the wind mixes the entire epilimnion and a new homogeneous density is attained. This process increases the density difference between the two layers and further retards mixing across the thermocline. Therefore the most stable stratification is achieved in late summer just before the start of fall cooling of the surface.

With wind currents confined to the upper layer, the epilimnetic water mass is transported at some angle to the right of the wind stress. This fact is of considerable importance because the transport of the surface layers by wind plays a prominent part in the generation and maintenance of lake current. Boundary conditions and converging or diverging wind systems must cause in certain regions an accumulation of less dense epilimnetic waters and in other regions an upwelling of denser hypolimnetic waters from subsurface depths. The wind currents cause an altered distribution of mass and therefore an altered distribu-

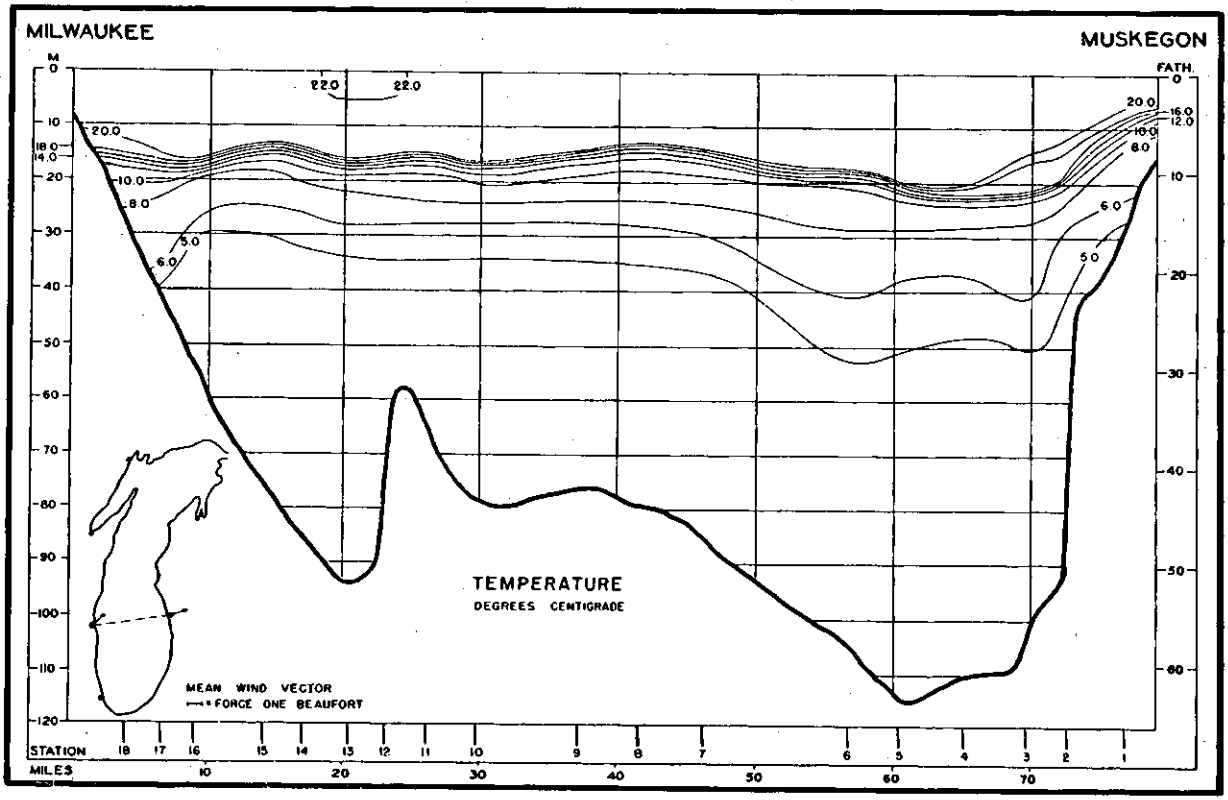

FIGURE 4–115 Distribution of Temperature (°C) in Lake Michigan; August 15, 1942. Observed from a ferry, Milwaukee-Muskegon transection.

From Church, 1945

tion of pressure, which can exist only in the presence of certain relative currents.

The coasts of the lakes impede wind transport resulting in the pileup of warm epilimnetic water along the coast toward which the wind current flows. Since all motion at the shore must be parallel to the coastline, a convergence must be present offshore causing sinking and an accumulation of the less dense epilimnetic water. A divergence must occur off the opposite coast, where the surface water is transported offshore, which results in upwelling of cold, denser water from the subsurface layer. Observations show that the regions of intense upwelling and sinking are restricted to relatively narrow strips that parallel the coasts of the Great Lakes (Mortimer[558]), while vertical excursions of the thermocline are much less over the deeper portions of the lake basins. The altered density distribution must be associated with relative currents that exhibit a balance between horizontal pressure and Coriolis forces. Since the pressure gradients are most intense in the coastal strips and directed essentially normal to the coastline, wind currents in the epilimnion generate secondary geostrophic currents flowing parallel to the coast. The normal wind currents are closely associated with the prevailing wind patterns over the lakes and lead to semi-permanent, intense geostrophic currents along the lake coasts. These currents have been called "coastal jets" by Csanady[171a] and others. The normal current patterns may be quickly altered by changes in wind intensity and direction. Ayers et al.[29] described modifications of the Lake Michigan circulation due to intervals of sustained northerly winds that interrupt the prevailing southwesterly air flow. In spite of the fact that the semi-permanent, baroclinic coastal currents are conspicuous features of lake circulation and are closely associated with wind-driven convergence and divergence of lake water, the internal structure of these currents is extremely complex and varies greatly from day to day. This complexity is shown dramatically in the closely spaced observations made by Csanady and Pade.[173]

The relatively small dimensions of the lake basins in comparison with the dimensions of weather systems means that the effects of the lake coasts are much more important in causing accumulations or depletions of epilimnetic waters than are the effects of converging or diverging wind systems. Therefore, it is not surprising that there has been much interest in determining the response of lake models to uniform wind stresses acting on the lake surface. For application to the density-stratified season, a two-layer model is a most reasonable configuration for investigation.

6.2.3 Wind-Driven Circulations During the Homogeneous Season

During conditions of homogeneous lake water the wind currents penetrate much deeper than when the water column is stratified. Ekman derived an empirical relation for the "depth of frictional resistance"; it is

$$D = 7.6\ W\ (\sin \phi)^{-1/2} \qquad (17)$$

where D is the frictional resistance depth in meters, W is the wind speed in meters per second, and ϕ is the latitude. For moderate wind speeds the wind currents penetrate considerably deeper than 20 or 30 meters, which is an average depth for the upper layer during summer stratification. Strong winds with speeds of 10 meters per second or greater occur frequently on the lakes during late fall and winter, and during such intervals the wind currents must extend to bottom depths. In homogeneous water one would expect a more fully-developed Ekman wind-drift layer, with the water transport directed at right angles to the wind stress. Continuity requires a second Ekman layer along the bottom of the lake, with flow opposite to that of the surface layer. Observations of these Ekman layers have not been reported. The deep penetration of wind currents in homogeneous water promotes effective mixing of the entire water column. The effectiveness of wind stirring results in cooling of all lake water below the temperature of maximum water density in winter, and in warming above this temperature in spring before the process is retarded by density stratification.

In the deeper parts of the lake basins, one would anticipate that the current speeds will be greater during homogeneous lake water conditions than during conditions of density stratification. Observations supporting this idea were reported by Verber.[849] However, during the density-stratified season, large amplitude internal waves occur at the density discontinuity and these internal waves cause currents flowing in both the upper and lower layers. In spite of these additional currents in summer, the winter isothermal water is characterized by stronger deep currents.

The stress of the wind acting on the lake surface and variations in atmospheric pressure tilt the water surface. Return flow near the lake bottom is retarded as the wind currents are driven into shallow water near the coasts, so that the wind tilt most likely does not consist of a uniform slope between the downwind and upwind coasts, but instead the gradients of height are largest in narrow strips paralleling the coasts. The gradients of pressure thus established must be associated with absolute currents representing a balance between Coriolis and horizontal pressure forces. These geostrophic currents thus tend to preserve the wind-generated current patterns even after the wind decays. The resulting current patterns would therefore exhibit most intense and persistent currents in narrow strips parallel to the shore, with less intense circulations characterizing the conformal currents necessary in the interior lake regions.

Winter circulation responds more quickly to changes in the wind stress than does summer circulation, since only minor redistribution of the water mass is required in homogeneous water to adjust to the newly applied stress. In contrast, adjustment to the applied wind stress in summer requires extensive shifting of the upper layer water mass. In either case, the newly applied stress must first destroy the geostrophic currents associated with earlier wind patterns that persist following wind decay. Circulation during the density-stratified season is, for these reasons, more persistent and closely related to the prevailing winds, while circulations during the unstratified seasons are shorter-lived and more closely related to the existing wind. In this connection, it should also be remembered that the wind speeds are generally greater on the lakes during the season when the water mass is not density stratified and that this fact plays an important role in maintaining homogeneous conditions. A part of the difference in wind speeds results from the stable stratification in the air over the lakes in summer, when the water surface is relatively cool; and the unstable stratification of the air over the water during winter, when the lake surface is relatively warm.

In summary, the stress of the wind blowing across the water surface is the principal source of energy driving lake circulation. Secondary, absolute, geostrophic currents are generated by stress tilting of the lake surface. These secondary currents represent a balance between Coriolis and horizontal pressure forces. In addition, during the season of density stratification, relative geostrophic currents are generated by wind stress tilting of the thermocline surface and by accumulations or depletions of upper layer water. Geostrophic currents persist following decay of the wind stress, and lead to persistent circulation patterns. Wind-induced currents are modified by thermally driven circulation that results from differential heating or cooling of the surface waters. Thermally driven circulation may be a dominant force in shaping current patterns during the spring and fall periods of rapid surface heating and cooling.

6.2.4 Internal Waves

Wind and other forces acting on the surfaces of the Great Lakes generate surface waves with a wide range of periods as explained earlier in this section. These wave periods vary from less than one second for capillary waves to many hours for oscillations involving an entire lake surface. The characteristics of waves which occur on the surface of a lake are essentially independent of the lake's internal density structure, and their maximum vertical displacement occurs at the water surface. Waves for which the vertical displacement decreases exponentially with depth are termed short waves, while waves for which the vertical displacement decreases linearly with depth, being zero at the bottom, are termed long waves.

Internal waves may occur in stratified water within which the density varies with depth. Internal waves are characterized by having their greatest vertical displacements at the density discontinuity or at some intermediate depth where the amplitude can greatly exceed the amplitudes of waves on the free surface. Internal wave theories were first developed for stratified fluids consisting of two homogeneous layers and later extended to the general case of progressive internal waves in heterogeneous water.

In a system consisting of two layers of infinite thickness, the lower layer of density ρ and the upper layer of density ρ', waves at the interface surface between the two layers will have a phase velocity c as given by

$$c^2 = \frac{gL}{2\pi} \frac{\rho-\rho'}{\rho+\rho} \qquad (18)$$

where L is the wave length and g is the gravitational constant. These are short waves because the two layers are of infinite thickness, so the wave length L is always negligible in comparison. If ρ' is the density of air and ρ the density of water, the equation gives the phase speeds of ordinary short (deep water) surface waves, since ρ' is very small relative to ρ. Surface waves can therefore be thought of as internal waves on the air-water interface. Short internal waves at the interface between two layers of water propagate much more slowly than surface waves of the same wavelength, since in the lakes (or oceans) ρ' is always very nearly equal to ρ.

If the density stratification of a fluid is stable, a parcel of the fluid displaced from its density varies from that of the surrounding fluid. In returning to its equilibrium level, the parcel will acquire momentum which causes it to overshoot the equilibrium position and therefore to oscillate in periodic manner about the level from which it was displaced. The frequency of the oscillation depends upon the intensity of stratification. Such oscillations are normally referred to as "stability oscillations" or as Brunt-Väisälä waves. The Brunt-Väisälä frequency (N) is approximately

$$N^2 = (g/\rho)\, \partial\rho/\partial z \qquad (19)$$

where ρ is the displaced fluid density, $\partial\rho/\partial z$ is the vertical gradient of density (the assumption being made that the density varies only with depth), and g is the gravitational constant. The maximum vertical density gradient determines the maximum frequency of the stability oscillations. This represents a theoretical high-frequency limit for short internal waves.

Observations of Brunt-Väisälä waves in Lake Michigan were reported by Mortimer, et al.[560] They found that the maximum frequency of the observed waves closely approximates the theoretical frequency limit estimated from the density profile. These waves should always be present when the lake waters are stratified; their almost universal occurrence in stratified ocean waters has been well documented.

The origin of Brunt-Väisälä waves is not fully understood; however, any mechanism capable of displacing parcels of a stably stratified fluid would tend to originate them. Unstable shear flows at the thermocline surface are a possible source.

Long (shallow water) internal waves are also possible at the interface between two water layers of differing density. Internal long waves are analogous to long waves which occur on the air-water interface. If two-layer stratification is considered and effect of the earth's rotation is neglected, the phase velocities for surface and internal long waves are obtained from the equations

$$c_1^2 = g\,(h+h') \qquad (20)$$

$$c_2^2 = \frac{ghh'}{h+h'}\,\frac{\rho-\rho'}{\rho} \qquad (21)$$

where c_1 is the surface (air-water interface) wave speed, c_2 the internal wave speed, h the layer depth, and the primes refer to the upper layer. Surface long waves in the Great Lakes have received considerable attention from numerous investigators. These waves consist of surges, seiches, and tides in the usual terminology. Internal long waves (long refers to the description of those waves whose wavelengths are large compared to the total depth h+h') have received much less attention, with knowledge of their characteristics being acquired in only recent years. These waves have been studied most thoroughly in Lake Michigan, but a few scattered observations in the other Great Lakes indicate that the wave characteristics are similar in all of the lakes.

Consider solutions of the linear, shallow-water wave problem in an infinitely long rectangular channel which rotates counterclockwise (as in the northern hemisphere) about a vertical axis. The choice of a model configuration is somewhat arbitrary, but a good case can be made for considering an infinite channel. The channel contains water that is density stratified in a two-layer configuration. Solving the long-wave equations in such a model configuration gives two classes of possible time-periodic waves, Kelvin and Poincaré waves (Figure 4–116). These linear (normal mode) waves can occur at both the water surface and at the internal density discontinuity. The speed of wave propagation at the surface is much faster than at the internal density boundary, and the surface waves are analogous to the longitudinal (Kelvin) and transverse (Poincaré) seiches, which are the long-wave normal modes in a closed basin that does not rotate about a vertical axis. Although Kelvin and Poincaré waves are derived from consideration of an infinite channel model, these wave forms approximate the observed wave forms in Lake Michigan (Mortimer[557,558]).

If walls are inserted across the channel to form a closed rectangular basin of large length-to-width ratio, a good approximation of the shape of Lake Michigan can be attained if the length of the basin is five or six times greater than its width. Exact analytic solutions that satisfy the boundary conditions are not possible with present techniques, but solutions that nearly satisfy the boundary conditions can be built for this situation by superimposing an infinite number of standing Kelvin and Poincaré waves (Lauwerier[488]). For example, the longest period surface seiche of Lake Michigan takes the form of a standing Kelvin wave, with the wave crest rotating in a counterclockwise manner around the perimeter of the lake.

Internal Kelvin waves are essentially edge waves, with amplitudes that decay exponentially away from the coast and are negligible more than four or five kilometers offshore. Only internal Kelvin waves propagating northward along the eastern coast of Lake Michigan have been observed; southward travelling waves along the western shore have not been detected.

Extensive studies of internal waves and water currents were conducted by the U.S. Public Health Service during 1963 and 1964 (Verber[851]). An important result of these investigations was the discovery that a large amount of the internal wave energy is concentrated in waves that have frequencies very near the local inertial frequency (2 sin ϕ revolutions per day, where ϕ is the latitude). Waves with frequencies near the inertial frequency were so dominant during the density-stratified season that many of the current meters moored in the open lake recorded little other than inertial period, clockwise rotations of current velocities. Internal Poincaré waves have frequencies (σ) given by the relation

$$\sigma^2 = f^2 + c_2^2\,(l^2 + k^2) \qquad (22)$$

where f is the inertial frequency (about 10^{-4} radians per second in Lake Michigan), c_2 is the internal wave speed given previously (equation 21), and l and k are transverse and longitudinal wave-numbers of the internal oscillations, respectively. For conditions representative of maximum density stratification which occurs in late summer, the internal wave speed is about one-half meter per second. Long-wavelength internal Poincaré waves therefore have frequencies which are very near the local inertial frequency. Mortimer[558] demonstrated that the inertial period oscillations of lake thermoclines are indeed as-

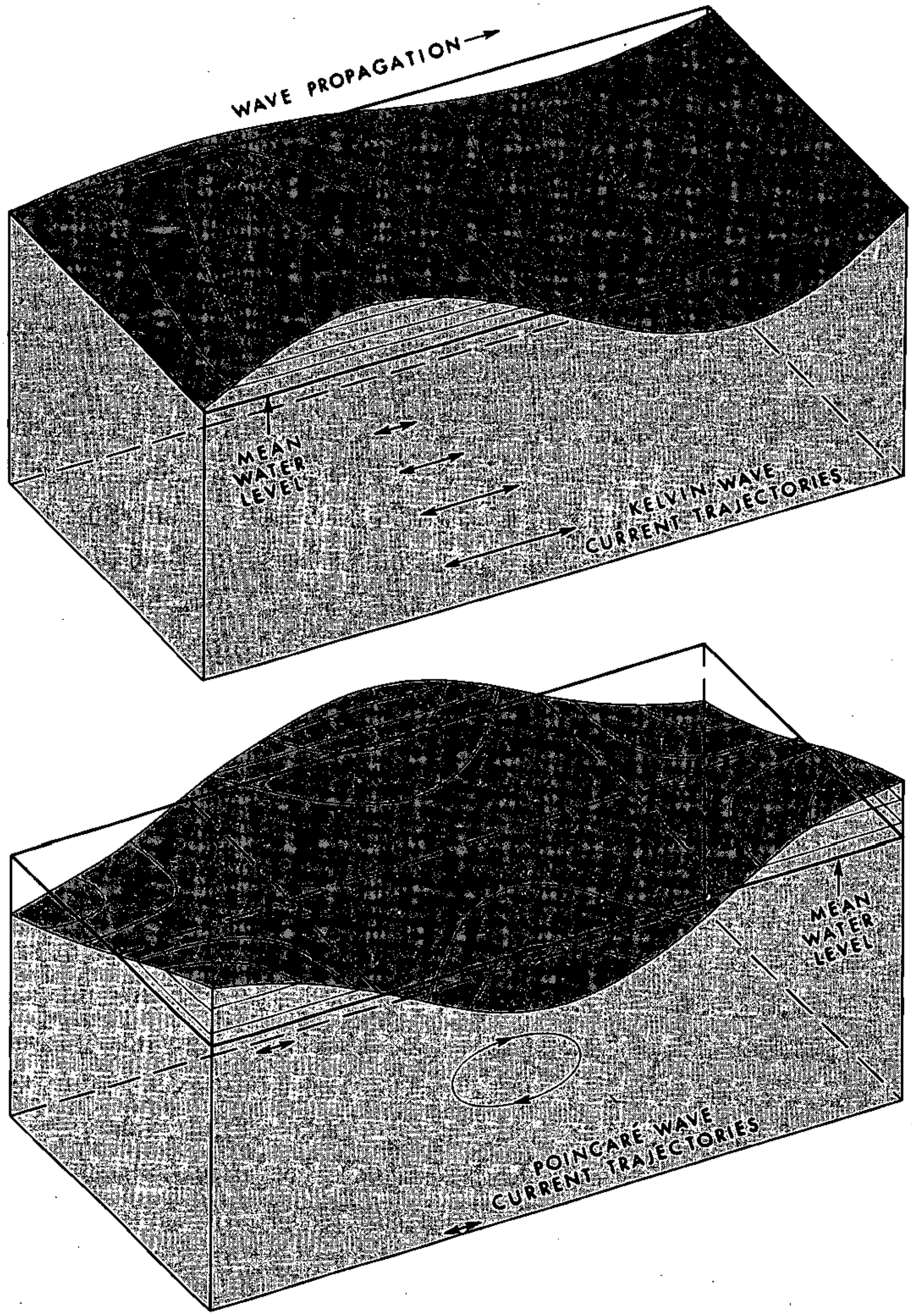

FIGURE 4–116 Kelvin and Poincaré Waves in an Infinitely Long Rectangular Channel that Rotates Counterclockwise about a Vertical Axis, as in the Northern Hemisphere

sociated with long internal Poincaré waves, with modes of odd transverse wave-numbers, $l = \pi/L$, $l = 3\pi/L$ and so on, where L is the width of the channel dominating the wave structure. He suggested that the waves may be generated by wind stress tilting of the thermocline surface, which, after the wind calms, oscillates in a superposition of the various normal modes. Odd transverse wave-numbers would be favored because the stress depresses the thermocline on the downwind coast of the lake, and elevates it on the other coast.

However, there are several characteristics of internal Poincaré waves that are not well explained by Mortimer's generation theory. In the first place, each interval of high wind stress should initiate a new internal wave regime, since it is unlikely that the applied stress would be in phase with the existing internal waves. This is not shown by the observations, since internal waves of near inertial frequency can be traced without interruption in periodicity for very long duration, sometimes for several weeks or months (Malone[510]). Also, for long waves propagating on the surface of a two-layer configuration, the motions in the two layers are in phase, with the slip between layers being small (though not zero). Internal waves, on the other hand, propagate with the motions in each layer exactly out of phase. The internal waves should therefore dissipate much more rapidly due to internal friction than surface waves, but the observations imply just the opposite, with surface waves decaying in just a few days while the internal waves persist much longer. It might be argued that there are no frictional losses as the two water layers flow in opposition to each other, but this argument is not supported by observations. On the contrary, a velocity shear between layers is an often-discussed mechanism for the generation of the short wavelength stability oscillations considered previously. In this connection, it is also important to remember that the interface between layers is not as sharply defined as it is in a system such as oil floating on water. The interface is diffuse, being represented by a thermocline with a thickness on the order of five or ten meters in which the temperature gradient is often nearly constant.

Considering the effects of the non-linear terms in the equations governing shallow-water motions in an infinite channel, Saylor[710] showed that the relatively rapid decay of surface wave amplitudes may result from causes other than frictional dissipation. Quadratic non-linear terms in the governing equations admit the possibility of resonant interactions between three waves. In such a resonant trio of waves, the wave energy is exchanged comparatively freely between the waves in a periodic fashion, although the period of the energy exchange is considerably longer than the period of any individual wave in the resonant triad. The non-linear analysis shows that all of the longitudinal surface modes of oscillation are coupled together in such a resonant manner, so that any particular oscillation which is set in motion with an initially finite amplitude is unstable. It interacts in a resonant manner with all other possible longitudinal long waves and its energy is transferred to these other oscillations. Thus, if a particular finite-amplitude wave is generated, for example, by the decay of a wind set-up, the individual wave may not be discernible in records of water surface elevation for more than a few complete oscillations, but this does not necessarily imply that the wave energy has been dissipated by friction. More likely, a considerable portion of the wave energy has been transferred throughout the entire spectrum of possible longitudinal, shallow-water waves. Mortimer's[559] spectral analyses of water surface elevations confirmed the existence of the first eight longitudinal modes in Lake Michigan, with energy distributed in the modes in a regular pattern. The external forces setting the oscillations in motion are usually configured such that the initial wave energy is concentrated in the modes with very small wave-numbers. In this connection, estimates of bottom friction coefficients in the Great Lakes, which have been based on the rate of amplitude decay of finite-amplitude oscillations when their occurrence is discernible throughout several periods of oscillation, are probably unreliable.

Non-linear analysis also shows that the surface, longitudinal waves can be resonantly coupled with internal Poincaré waves, but only with internal waves of odd transverse wave-numbers. The intensity of the interactions decreases as the transverse wavelength decreases. Frequencies of the internal waves predicted from non-linear theory thus are in close agreement with the observational data (Mortimer[558]). It is also important to note that resonances are not possible between three internal Poincaré waves of near inertial frequency, so that following excitation, these internal waves propagate independently of each other. All internal Kelvin waves, on the other hand, interact resonantly with each other in the same manner as do the surface waves, so that in comparison with internal Poincaré waves, the internal Kelvin waves are relatively unstable. Thus, the Kelvin waves are short-lived phenomena, while the Poincaré waves are very stable.

Resonance with internal Poincaré waves requires that the difference between the wave frequencies of two surface waves approximate the inertial frequency. This condition is satisfied by at least several pairs of adjacent wave-number, longitudinal surface oscillations in Lake Michigan. Identification of the pair (or pairs) of surface waves involved in the interactions requires knowledge of the longitudinal wavelengths of the internal waves, and these wavelengths are not known at present.

The investigations of non-linear wave resonance utilize an infinitely long, rectangular channel model of a Great Lake that rotates counterclockwise about a vertical axis (as in the northern hemisphere). The wave forms derived from solution of the linear, shallow-water wave equations in such a model configuration closely resemble the observed wave forms in Lake Michigan, even though the lake is essentially a closed basin and longitudinal wavelengths are confined to a discrete set of possible oscillations. In such studies the shape of the model basin appears to play a significant role as indicated by the investigations of Csanady[172] and Birchfield,[67] who studied the response of a circular model of a Great Lake to a suddenly imposed wind stress. In a circular basin model, with parameters that are appropriate to Lake Huron, the Kelvin wave response cannot occur at the water surface. All surface waves are Poincaré waves that do not seem to adequately describe the lake's surface oscillations. In addition, solution of the initial value problem in a two-layered circular basin does not predict large amplitude internal Poincaré waves of near inertial frequency at the density discontinuity. However, the solution does predict a large, quasi-static response of the thermocline surface to the applied wind stress. Maximum thermocline displacements are confined to narrow coastal strips about 4.5 kilometers in width. Similar quasi-static responses are derived by considering the effects of a suddenly imposed wind stress on a two-layered, infinite channel model; and, in this case also, the amplitudes of the internal Poincaré waves of near inertial frequency are much smaller than those observed.

In summary, internal waves always exist in the Great Lakes during conditions of vertical water density stratification. Short internal waves have frequencies clustered about the frequency of stability oscillations, which depends solely on the local vertical gradient of water density. Long internal waves, which are large in amplitude and long-lived, have frequencies clustered about the local inertial frequency. Although the properties of internal waves have been observed principally in Lake Michigan, the few observations reported from the other Great Lakes show sufficient similarities to indicate that the same mechanisms are operable in all.

6.2.5 Turbulence and Diffusion

Laminar flow connotes a state in which layers of fluid move in an orderly manner such that random local fluctuations of velocity do not occur. The physical properties of water at rest or in laminar flow are described in terms of parameters such as dynamic viscosity, diffusivity, and conductivity, but rarely are these parameters applicable to motions in lakes or oceans. The molecules of a fluid move at random and an exchange of molecules takes place between layers. Therefore, an exchange of heat occurs if the molecules of adjacent layers are of different temperatures; diffusion takes place if the dissolved substances vary in concentration in space; an exchange of momentum occurs if layers differ in velocity. The rates of transfer depend upon the local gradients of temperature, concentration, and velocity, and upon the coefficients of thermal conductivity, diffusivity, and viscosity, respectively. These physical characteristics of the fluid depend upon temperature, concentration, and pressure and can be determined experimentally.

Turbulence prevails and a random motion of water parcels is superimposed on the mean flow in lakes or oceans. The character of the turbulence depends upon many factors, such as the mean velocity, the velocity gradients, and the properties of the boundary surfaces. In turbulent flow, the exchange of properties between adjacent layers is not limited to the interchange of molecules, but instead fluid parcels of various dimensions are exchanged between layers, carrying with them their characteristic properties. In this sense, an instantaneous picture of fluid velocity or of other parameters would present a most complicated pattern as evidenced by the complex patterns measured with instruments designed to record the turbulent fluctuations. Most instruments, however, are designed to measure the mean properties, such as current velocities or water temperature averaged over several minutes or hours. Since it is impossible to measure instantaneous water currents and temperatures in space, it follows that gradients cannot be determined and there is, therefore, no basis to apply the coefficients of thermal conductivity, diffusivity, and viscosity as measured in the laboratory to processes in the lakes. If only the average gradients can be measured, another approach must be made to describe the lake processes.

For the case of laminar flow the coefficient of viscosity, ν, is defined by the relation

$$\tau_s = \nu \, dv/dn \tag{23}$$

where τ_s is the shearing stress exerted on a surface of the unit area, and dv/dn is the shear velocity normal to this surface. For the case of turbulent flow, a coefficient of eddy viscosity, A, is defined in a similar manner:

$$\tau_s = A \, d\bar{v}/dn \tag{24}$$

where now $d\bar{v}/dn$ represents the shear of the mean velocities normal to the surface. The numerical value of eddy viscosity depends upon the intensity of the mass exchange between layers, and the intensity of exchange depends upon such factors as the mean velocities, the velocity gradients, and the character of boundary surfaces. This numerical value also depends on how the "average" velocities are determined, i.e., upon the spatial distribution of the observations and upon the lengths of time to which the averages refer. The definition of eddy viscosity is based on the concept that parcels that leave one layer carry to the adjacent layer the average momentum of the layer they just left. Momentum of a parcel is transferred to the adjacent layer so that the parcels obtain the mean velocity of their new surroundings before again changing layers. Thus, eddy viscosity is an expression representing the transfer of momentum. This transfer is increased by turbulence, as evidenced by the fact that the eddy viscosity is many times greater than the molecular viscosity measured in the laboratory.

Eddy viscosity can be determined only by examination of its effects on the mean motion of the water. It is convenient to distinguish between two types of turbulence, vertical and lateral. Vertical eddy viscosity results from the comparatively slight random motions in a vertical plane, while lateral eddy viscosity results from the exchange of water masses due to the existence of large-scale horizontal eddies. Observations have shown that lateral eddy viscosity is normally several orders of magnitude greater than vertical eddy viscosity.

The distinction between vertical and lateral turbulence in the lakes becomes particularly significant when the lake waters are density stratified, because the stratification affects the two types of turbulence in a different manner. With stable density stratification, random vertical motion is impeded. Parcels displaced upward are heavier than the surrounding water mass and tend to sink to their original level, while parcels displaced downward are lighter and tend to rise. Thus, work must be expended against gravity for a water parcel to change levels, and the vertical turbulence is greatly reduced. At the thermocline vertical turbulence may be almost entirely suppressed, and the eddy viscosity is very small. Stratification effects on lateral turbulence are negligible because the lateral motions take place along surfaces of equal density.

The same reasoning is applicable to thermal conductivity and to diffusivity. The momentum transfer between layers results from an exchange of mass, and the rate of exchange is expressed in terms of the eddy viscosity. Therefore, when dealing with eddy conductivity and eddy diffusivity, it is reasonable to assume that the rate of heat or solute transfer is also proportional to the mass transfer, as well as to the gradient of the property being transferred. This is normally expressed by setting the coefficients of eddy conductivity and diffusivity equal to rA, where, for conductivity, r is a factor which depends upon the specific heat of the liquid and upon the manner in which the heat is transferred to its surroundings and A is the coefficient of eddy viscosity. In unstratified water, the mechanism is usually pictured as one in which the transferred parcel breaks down into smaller and smaller elements, and where the heat is ultimately transferred by molecular conduction. In this case the momentum and heat of the displaced parcel are eventually evened off to those properties in its new environment, and the factor r is simply equal to the specific heat of the fluid (for water, r is nearly one). In the case of stable stratification, the heat of the displaced parcel may not be equalized with its new surroundings as rapidly as the momentum is transferred by collision, so that the coefficient r is considerably less than the fluid's specific heat. Observations of eddy viscosity and conductivity have confirmed that this is the case. Similar reasoning applies to the eddy diffusivity,

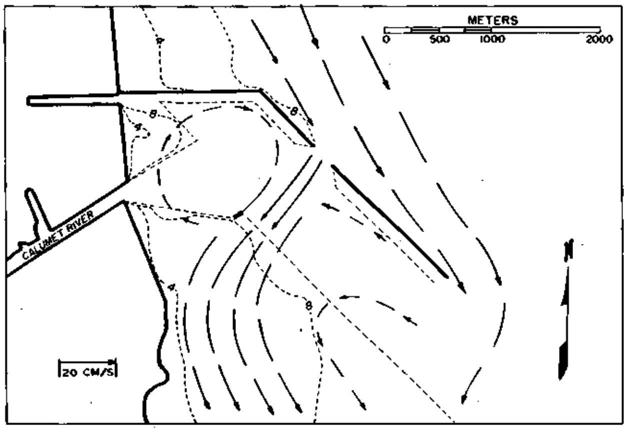

FIGURE 4–117 Current Pattern at Calumet Harbor, Lake Michigan, During a High-Speed North or Northeast Wind

From Saylor, 1964

and under normal conditions the diffusivity is the same as the conductivity. Lateral eddy conductivity and diffusivity are unaffected by stratification, and in water they equal the eddy viscosity.

Eddy diffusivity has received the most attention in Great Lakes investigations, since diffusion plays as important role in the dispersal of contaminants introduced into the lakes, mainly along the coasts. Stratification effects are pronounced, and the Great Lakes are good model oceans for studies of the mixing coefficients.

6.3 Water Movement in Harbors

6.3.1 Introduction

Knowledge of the circulation patterns in embayments of the Great Lakes provides a basis for controlling currents adverse to navigation, predicting sedimentation patterns, determining flushing rates, and selecting locations for water intakes and waste outfalls. Currents detrimental to navigation have long been recognized and steps to alleviate such currents have been implemented either in harbor design or through modification to existing harbors. With the marked increase in industrial, human, and vessel waste discharged into or near many commercial and recreational harbors, a pollution hazard has developed and determination of the flushing rates of contaminants is an additional important consideration in harbor design. Flushing rates depend on factors that vary with harbor configuration, width of the opening, tributary influx, and location in the lake system.

Harbors are designed with the prime purpose of reducing waves and currents within the harbor to some acceptable level. Navigation and water quality interests are frequently at odds because barriers must be constructed to minimize adverse currents and waves in harbor areas. This frequently results in reduced flushing rates and, hence, a sharp drop in water quality within the harbor confines. Calumet Harbor on Lake Michigan is one example. Strong northeasterly storm winds generate intense currents that flow southward through the gap between breakwaters, thus causing navigation problems (Figure 4–117). Although closing the gap would eliminate adverse currents, closure would also reduce flushing of the harbor (Saylor[711]).

In order to optimize navigational safety and water quality, a complete knowledge of local and open lake currents and the changes in currents and sedimentation patterns due to coastal structures is necessary before mathematical models that relate currents to their causative forces and harbor geometry can be derived. Resulting design criteria will bring about improved utilization, decrease costly maintenance, increase safety to navigation, and improve water quality.

During the last several years, circulation patterns in selected harbors on Lakes Erie, Huron, Michigan, and Superior have been studied in an attempt to relate observed circulation to the main causative forces. The harbors vary greatly in design, size, and exposure to current-generating forces, and hence applying results from one harbor to another is usually difficult. Little theoretical work has been done, and the present state of knowledge is still in the descriptive stage.

This review describes the main causative forces that are pertinent to circulation development, the circulation patterns and flushing characteristics of selected harbors and embayments, and those conclusions and recommendations that can be drawn from these investigations.

6.3.2 Current-Generating Forces

There are four primary forces that cause currents in harbors: wind stress, which includes pure wind drift and wave-induced currents; water-level oscillations; density currents; and tributary inflow. The first three phenomena have been discussed in terms of open lake characteristics in the preceding subsections so only their presence in and effect on the harbor and embayment environment will be discussed.

6.3.2.1 Wind-Driven Currents

The transfer of momentum from wind to water at the air-water interface and the friction between moving layers within the water produce pure wind-driven currents. Although the momentum transfer mechanism is not fully understood, the ratio of the current speed to wind speed has been empirically determined to be approximately 0.03 for winds to 15 m/s (34 mph) (Keulegan[452]).

According to the Ekman theory, in a deep homogeneous ocean the surface currents are directed 45° to the right of the surface stress and the mass transport is directed at right angles to the stress. Currents in shallow water are directed at a lesser angle. On Lake Michigan, Saylor[711] found that currents outside the nearshore area are directed 15° to the right of the wind.

Saylor[709] observed that during onshore or offshore winds, surface movement in the coastal waters is in the direction of the wind stress, mid-depth currents are nearly parallel to the shoreline, and continuity is maintained by return flow near the bottom. Strong onshore winds generate a boundary region near the shore in which the currents at all depths flow parallel to the shoreline. This boundary region increases in width with increasing wind speed. When the wind parallels the shoreline, the nearshore current speed is greatest, and the current direction may be uniform from surface to bottom.

The ability of winds to generate surface currents inside a harbor is impaired by the very limited fetch. However, the wind is often of sufficient strength to drive the surface water out of the harbor, and continuity is maintained by inflow near the bottom.

6.3.2.2 Wave-Induced Currents

As the wind blows over the water surface, a portion of the energy transmitted to the water is manifested in the form of waves. Water particles do not traverse a closed path, but instead follow an open orbit. This orbital motion results in a mass transport in the direction of wave propagation. Along a shore, the amount of water transported shoreward by waves must be compensated by a hydraulic current flowing lakeward. Thus the mass transport caused solely by waves is relatively low compared with other processes.

Waves approaching a shoreline at an angle undergo changes in velocity, height, length, and direction. As the waves impinge on the shallow nearshore area, they are refracted and tend to conform to the bottom contours. However, the waves usually break at a slight angle to the shore resulting in a longshore component of motion commonly known as littoral or longshore currents. These currents are effective in moving masses of water and sediment along the shore. Although numerous attempts to theoretically predict longshore current velocities have been made, there is still no adequate solution (Galvin[281]).

6.3.2.3 General Nearshore Current Features

Nearshore currents play a major role in determining circulation patterns in many Great Lakes harbors. Saylor[707,711] noted several general features of the nearshore current structure at all locations on the Great Lakes where nearshore currents have been measured:

(1) Wind-driven currents are generally of higher speed during onshore winds than during offshore winds, illustrating the effect of sheltering by the coast and of limited overwater fetch.

(2) At a fixed depth below the surface the current speed increases with increasing distance from shore because of the effects of bottom friction in shallow water.

(3) During periods of strong wind, a well-defined variation of current speed with depth exists, with the highest speeds observed at or near the surface due to wind stress and lowest speeds near the bottom.

(4) During periods of strong winds parallel to the shore, the ratio of the surface current to that of wind speeds is close to the 0.03 value determined by Keulegan.[452]

Saylor[709] observed that for winds of 6 m/s (13 mph) or greater, full response of the nearshore currents to the applied wind stress is generally achieved in one hour or less. The rate of decay of coastal currents after cessation of strong winds varies with location and is apparently closely related to the open-lake circulation and the lake depth. As a case in point, Saylor[708] observed that near Little Lake Harbor westerly and northwesterly winds over eastern Lake Superior generate strong eastward-flowing coastal currents that reach steady state conditions in approximately two hours. After cessation of the winds, the current persists for days with only a slight decrease in speed after the first day. This eastward-flowing nearshore current pattern coincides with the dominant current pattern in the open lake in this region (Harrington,[313] Ragotzkie[636]). Near Harbor Beach, Lake Huron, strong southward-flowing currents, in response to strong north winds, decay very rapidly after cessation of the wind. This southerly flow is opposite to the prevailing current pattern in this part of the lake (Harrington,[313] Ayers et al.[28]). Saylor[709] also noted that nearshore currents in Lake Erie decay rapidly, probably due to the shallowness of the lake.

Nearshore currents are an important natural flushing agent in harbors of the Great Lakes. Therefore, harbor circulation studies must include not only measurements of nearshore currents, but also a knowledge of open-lake circulation and its effect on current-decay rates. Open-lake currents and their temporal and spatial variation are not well documented. A comprehensive long-term program of continuous measurements of all influencing parameters is necessary to adequately describe and predict open-lake circulation.

6.3.2.4 Water-Level Fluctuations

Although astronomical tides in the Great Lakes are small, temporal changes in mean water level in the form of wind tides, surges, and seiches are effective current-generating mechanisms. These short-term water-level changes in the lakes are defined and characterized in preceding subsections.

Currents due to seiches are at maximum across the nodal section. At the node, water movement is entirely horizontal and continuity requires that the water flow through the nodal section to compensate for the change in water volume passing from one end of the lake to the other. If the water depth is much less than the wave length, the maximum velocity through the nodal section can be estimated by

$$V = (gh)^{1/2} H/h \qquad (25)$$

where V is the velocity, $(gh)^{1/2}$ is the wave velocity, H is the seiche amplitude, and h is the water depth. For example, Platzman and Rao[620] found that, for the first seich mode in

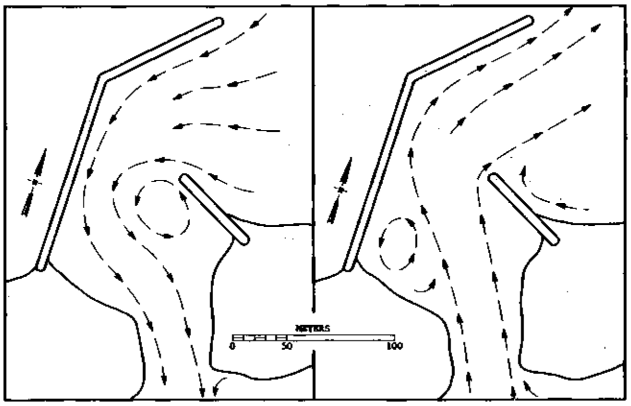

FIGURE 4–118 Trajectories of Inflow and Outflow Currents at Little Lake Harbor with Negligible Current in Lake Superior

From Saylor, 1966

Lake Erie, there is a mean current of about 15 cm/sec (0.5 fps) per foot of amplitude at Buffalo, increasing to 21 cm/sec (0.7 fps) through constricted areas. Conneaut Harbor, Lake Erie, located near the nodal areas for both the uninodal and binodal longitudinal seiches, experiences strong reversing seiche currents across the harbor entrance. When the seiche currents are added to the wind-generated surface currents and longshore currents due to waves, the cross-entrance currents can become detrimental to navigation (Hunt and Bajorunas[399]).

Although the narrow, restricted openings into many harbors provide protection from waves, periodic temporal changes in water level result in large hydraulic heads that fill and empty the harbors and cause strong, reversing currents through the harbor entrances. These water level effects are, of course, most pronounced in harbors located near antinodes, the point where the vertical water-level change is a maximum. Housley[384] reported that hazardous currents in the entrance channels of Duluth-Superior Harbor are caused by flows into and out of the harbor in response to several modes of the longitudinal seiche of Lake Superior. Saylor[708] measured inflow and outflow through the channel to Little Lake Harbor, Lake Superior, after an extended period of light offshore winds and negligible lake currents. The circulation patterns, which result from seiching action, are shown in Figure 4–118. Similarly, Toledo Harbor, located at the western end of Lake Erie, experiences highly variable currents, due in part to large water level fluctuations that frequent this shallow lake. Figure 4–119 is an

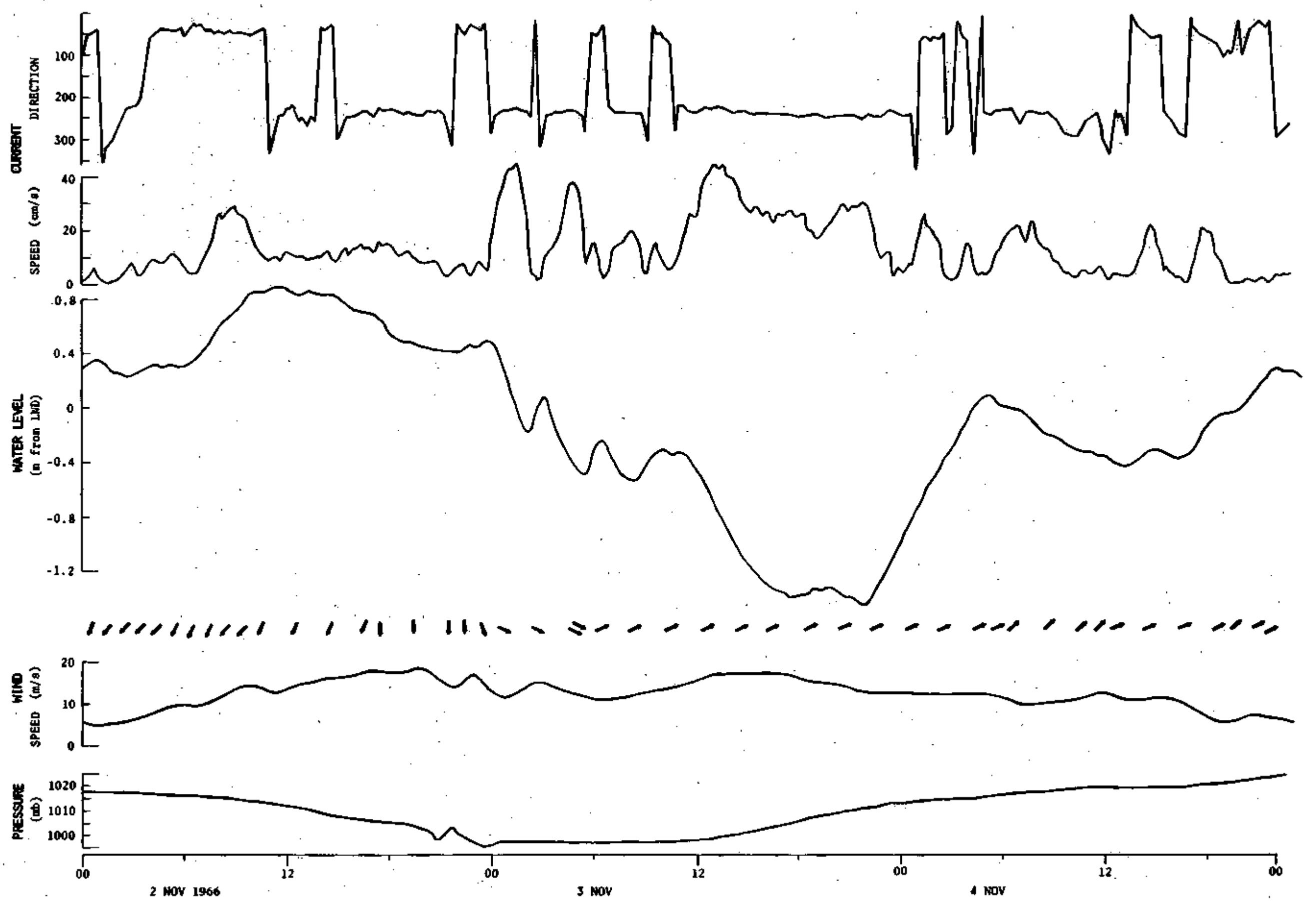

FIGURE 4–119 Current Velocities Resulting from Changes in Water Level and the Associated Wind Speed and Direction, and Atmospheric Pressure for Toledo Harbor, Ohio. The arrows indicate wind direction from its source.

From Miller, 1969

example of the current direction and speed associated with a positive wind tide (increased water level) followed by a large negative wind tide, and finally seiches (Miller[544]). Harbor current velocities during wind tides or meteorological disturbances are highly unpredictable and it is only after the initial disturbance decays into seiches that the currents become quasi-tidal.

A small harbor responds rapidly to water level fluctuations. For example, Little Lake Harbor, Lake Superior, responds fully to oscillations with periods of 15 minutes or longer (Saylor[709]). In addition to the easily recognizable first several modes of a lake seiche, oscillations with periods ranging from 15 minutes to two hours persist in many harbors. In Racine Harbor and Muskegon Harbor on Lake Michigan, Saylor[711] observed 10- and 12-minute period water level oscillations, but fluctuations with periods of less than 20 minutes were absent offshore.

Because of the rapid response of the harbor, the velocities of the reversing currents are controlled mainly by these shorter-period oscillations. For example, Saylor[709] observed that reversing currents speeds of 0.6 m/sec (2 fps) were associated with oscillations of one-hour period and 0.1 m (0.3 ft) height in Little Lake Harbor. Using the above observations and past water-level records, current speeds up to 2 m/sec (6.6 fps) are possible through the entrance to Little Lake Harbor. An explanation of these shorter-period oscillations is not clear. In the case of Little Lake Harbor, Saylor[708] concluded that these short-period waves are normal modes of the lake surface since once a particular period of oscillation is excited, it persists for some time.

No oscillatory motion toward and away from the shore due to standing waves transverse to the shoreline was observed (Saylor[708]) indicating that water level fluctuations have little effect on nearshore currents.

A combination of seiche-induced reversing currents through a harbor entrance and nearshore current flow across the entrance provide a good natural flushing mechanism. During each seiche cycle, a quantity of water flows out of the harbor, is carried away by the nearshore current, and replaced by lake water during the inflow portion of the cycle.

Harbors may also possess resonant oscillations. When a periodic excitation is applied at one of the free or natural periods of the harbor, the motion will increase to an amplitude determined by the damping of the system. This phenomenon is termed resonance. Free oscillations will result if the harbor is considered to be open ended with a reflecting boundary at the other end, and if the length of the basin is such that the wave travel time is an odd-integer multiple of one-quarter of the wave period (Sverdrup, et al.[774]). The resonant periods can be approximated by Merian's formula for open-ended basins,

$$T = 4L/n\sqrt{gd} \qquad (26)$$

where L is the length of the basin, n is the mode, g is acceleration due to gravity, and d is the water depth. Since the harbor areas are small, the resonant period of the fundamental mode lasts a few minutes.

In a resonant basin oscillation, all the incoming wave energy is concentrated in one standing wave system with resulting buildup of large amplitude vertical and horizontal water movements at the antinodes and nodes. This horizontal motion verifies the importance of seiches in harbors. For example, a two-minute period wave 10 cm (0.3 ft) in height would cause a 2 m (4 ft) horizontal movement with an average velocity of about 3 cm/s (0.1 fps). Sources of these harbor disturbances may be winds piling up water at the coast, longer-period lake seiches, reflection of wind waves, or meteorological disturbances. Raichlen[639] reviewed recent advances in harbor resonance theory.

Harris[316] studied water level records from many Great Lakes harbor sites and observed short-period oscillations with the following characteristics:

(1) All harbors in the same area tend to become excited at approximately the same time.

(2) The characteristic period appears to be different in each harbor.

(3) The harbor disturbances may occur as much as an hour or two before or after the apparently associated atmospheric disturbance passes the harbor.

(4) Harbor disturbances may occur when no atmospheric disturbance passes the immediate area of the harbor.

Saylor[708] also found that large amplitude, short-period oscillations at Little Lake Harbor were often uncorrelated with local weather.

The last two characteristics imply that the energy of the disturbance may be communicated to the lake at some distance from the harbor and transmitted to the harbor in the form of a water level disturbance in the lake. From these observations, Harris theorized that atmospheric disturbances give rise to a wide spectrum of disturbances on the open lake and, by resonance, selected periods are amplified within a harbor. If this hypothesis is correct, forecasting short-period disturbances, and therefore currents, will not be feasible since the records show that, though there is some connection between meteorological fluctuations and lake-level fluctuations, the relation is not simple or direct.

6.3.2.5 Density Differences

Density differences in the harbor areas are mainly due to inflow from tributaries that have different temperatures or chemical compositions than the receiving water, and also to local heating and chemical loading. The differences in density result in stratification. In stratified water, the exchange of fluid across the region of greatest density change (thermocline or chemocline) is inhibited. Current directions in the two layers may be opposite, hence, the dispersion of wastes can be controlled to a limited extent in time by adjusting the height of outfalls so that wastes are discharged into the stratum that will most suitably disperse or assimilate the waste.

Saylor[711] observed two distinct harbor circulation patterns in Muskegon Outer Harbor, Lake Michigan, depending on the presence or absence of stratification. During spring the temperature of the Muskegon River water is as much as 8°C (14°F) warmer than the receiving water, and the river outflow through the harbor is thus confined to the upper layer. The colder, more dense lake water flows into the harbor and circulates in eddies at either side of the harbor. The degree of cold water intrusion depends on the magnitude of the outflowing current. Summer and fall water temperatures are more nearly the same, and during offshore or light onshore winds, the circulation is governed by the northward-flowing nearshore current. Saylor[711] also observed

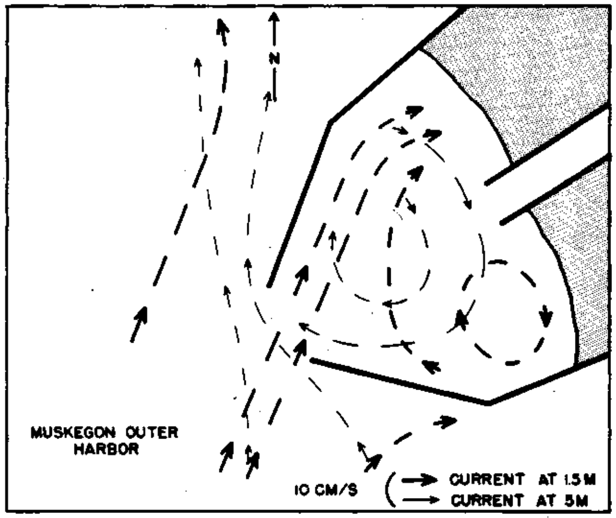

FIGURE 4–120 Current Patterns in Muskegon Outer Harbor, Michigan, During a Southwesterly Storm

From Saylor, 1964

that during intense southwest storms, an appreciable surface current flows into the northern half of the harbor due to wind stress and waves (Figure 4–120). The lower-layer return current flows out through the harbor entrance almost at right angles to the incoming surface current.

6.4 Embayments

Circulation studies in embayments have usually been included only as a part of larger lake circulation programs. Because of their sheltered water, shallow depths, and surrounding dense population, embayments, like harbors, have water quality problems. The Rochester Embayment is one example. Many of the same current-generating forces and their complex interactions active in harbors also pertain to embayments. Water level measurements taken within an embayment tend to be complex. Because sloping beaches are good reflectors for waves and due to concavities in coastlines, a portion of the energy entering an embayment may become trapped. Repeated reflections result in complex standing waves which may achieve resonance. Hence, a harbor located in an embayment has additional oscillations due to the embayment boundaries. This adds to the total complexity of describing long-period waves in specific locations.

Several embayments have been referenced in studies of circulation and pollution, but extensive studies are as yet lacking. From three separate one-day lakewide surveys, Ayers et al.[28] found two patterns of circulation in Saginaw Bay. In late June, there is surface inflow along the north side, and the prevailing west winds combined with the Coriolis force tend to deflect the outflow onto the southern shore. During the later summer months, the entire surface moves out of the bay with a compensating bottom inflow. Beeton and Hooper,[56] treating the bay as a typical estuary and using the Saginaw River water as a tracer, determined that it would take 113 days for a one-day accumulation of river water to move through the bay during peak river discharge, and 186 days with annual average river flow.

From an investigation in Chequamegon Bay, an elongated bay on Lake Superior, Ragotzkie et al.[638] concluded that when the bay is thermally stratified, the physical patterns are analogous to the patterns in a moderately stratified estuary, with the aperiodic offshore winds replacing the astronomical tide as the predominant flushing mechanism. Water level oscillations cause inflow and outflow in the bay, and when combined with horizontal currents across the mouth of the bay, they provide an additional natural flushing action.

If the embayments of the Great Lakes do behave in a similar fashion to estuaries, then the principles derived for estuaries are applicable, at least during times of thermal stratification.

6.5 Analytical Methods

Circulation patterns in harbors are determined by the breakwater configuration, and the strength and direction of tributary and coastal flow resulting from the complex interactions of various current components. The strength and direction of coastal flow is difficult to model mathematically because of the number of variables necessary to adequately describe the functional relationships.

Saylor[707] used two methods to hindcast the direction of coastal flow at Harbor Beach, Lake Huron, from wind and observed harbor circulation data: the first method utilized data taken directly from the wind rose; the second method consisted of examining the wind track drawn from four-hour-average wind vectors. The wind rose showed that, for the period sampled, 80 percent of the winds were from directions that cause northward-flowing

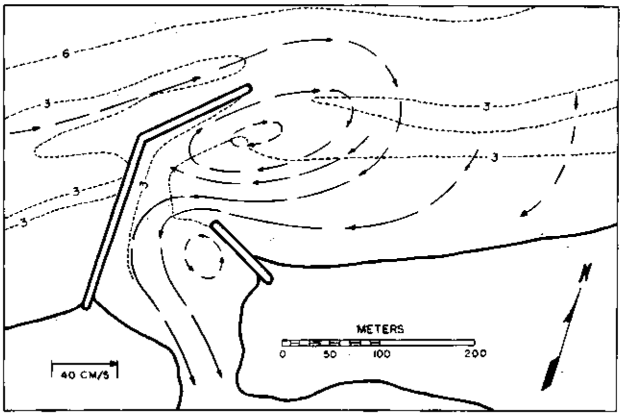

FIGURE 4–121 Circulation Model During a Westerly Storm and Inflow at Little Lake Harbor, Lake Superior

From Saylor, 1966

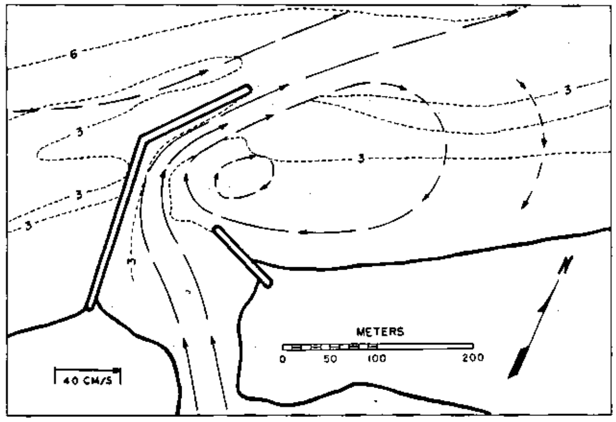

FIGURE 4–122 Circulation Model During a Westerly Storm and Outflow at Little Lake Harbor, Lake Superior

From Saylor, 1966

nearshore currents or the winds were not sufficiently strong to change the current pattern. Hence, the ratio of northward harbor circulation to southward circulation was 4 to 1. Using the observed relationship of current flow through the harbor to wind speed, duration, and direction, the second method yielded a hindcasted circulation for each four-hour interval. Taking into account the approximate one-hour lag between wind shift and response, this method produced a ratio of northward to southward harbor circulation of 2.8 to 9. The difference in the ratios computed from the two methods was attributed to the high percentage of northerly winds over 9 m/sec (20 mph). Since the wind-track technique takes wind speed into consideration, Saylor considered it to be more representative of actual conditions.

Knowledge of the circulation patterns generated by coastal currents from either direction gives valuable information about the proper placement of intakes and outfalls. For example, Saylor[707] states that, from the observed circulation patterns and the computed ratio, the power plant located near Harbor Beach can expect to recirculate a portion of its own discharge and a portion of another company's effluent approximately 75 percent of the time.

6.6 Tributary Inflow

Numerous Great Lakes harbors are located at the mouths of tributaries, and the net lakeward flux due to inflow provides an important natural flushing mechanism. Because a mean state of volume equilibrium must be maintained, the amount of water that passes out of the harbor during any period must equal the inflow from the river during the same period. The current speed due to discharge can then be given by

$$V = Q/A \tag{27}$$

where V is the current speed, Q is the river discharge, and A is the cross-sectional area.

Outflow from most tributaries varies seasonally with maximum discharge during spring runoff and during high precipitation periods. During these times, river inflow dominates the harbor circulation regime by forcing a continuous outflow through the harbor openings. For the greater part of the year, tributary discharge is nominal and other forces dominate the current regime, although inflow still results in a small, net outflow component.

6.7 Composite Currents and Flushing Characteristics

Currents at any location, particularly in harbors of the Great Lakes, nearly always consist of a complex mixture of different current-generating forces. The effect of these forces is seen in Little Lake Harbor by comparing circulation patterns due to water level oscillations only, as discussed earlier (Figure 4–119), with patterns obtained when nearshore currents were also present (Figures 4–121 and 4–122). Strong eastward-flowing currents along the shore are driven by the dominant west and northwest winds. The small harbor size permits a rapid response to

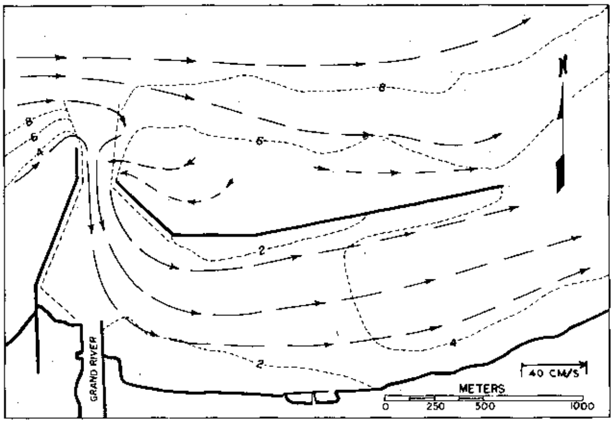

FIGURE 4–123 Current Pattern at Fairport Harbor, Lake Erie, During High-Speed West or West-Southwest Wind

From Saylor, 1964

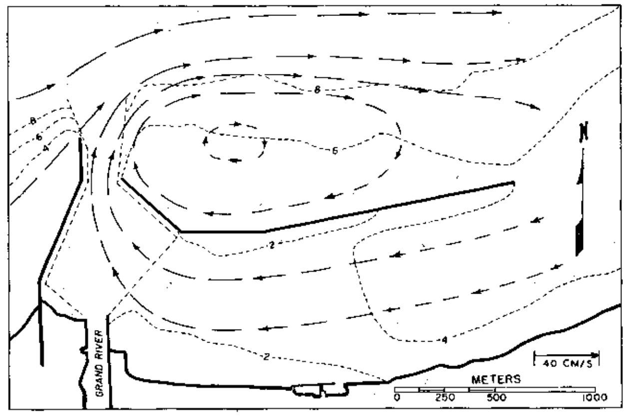

FIGURE 4–124 Current Pattern at Fairport Harbor, Lake Erie, with Eastward Flowing Nearshore Currents, after Cessation of High-Speed Wind

From Saylor, 1964

water level oscillations with periods of 15 minutes or longer. Currents due to water level oscillations combined with the effects of the nearshore currents, create an eddy to the east of the west breakwater.

Because of man-made fills on either side of the channel, Toledo Harbor is not affected by longshore currents as are many of the other Great Lakes harbors. However, large amplitude, temporal water level fluctuations are frequent in Lake Erie. The reversing-type currents created by these oscillations are modified by inflow from the Maumee River. The river inflow prolongs the ebb portion of the seiche-current cycle and enhances the current speed. During the flood portion of the cycle the opposite occurs. When river discharge becomes great, the reversing characteristics of seiche currents may disappear entirely.

Wind stress usually does not produce appreciable currents within harbors because of limited fetches. However, wind stress and/or density differences can result in oppositely directed currents in some Great Lakes harbors. On one occasion in Toledo Harbor, for example, the surface current was lakeward at 15 cm/sec in response to a 7 m/sec wind while at the 4.5 m depth the flow was upstream at 10 cm/sec. Although the wind-driven current is confined to the upper layer, it may constitute an important flushing mechanism.

Fairport Harbor, Lake Erie, does not experience inflowing and outflowing currents caused by water level oscillations because of the nearly unrestricted communication with Lake Erie (Saylor[711]). However, reversing currents flowing parallel to the shoreline are created by longitudinal seiches in the lake and changing wind directions. Eastward-flowing nearshore currents, due mainly to the prevailing westerly winds, dominate in this region of Lake Erie. Because of the relatively long fetch and shallow water in the outer harbor, direct wind stress produces an eastward-flowing current in the outer harbor that is compensated for by inflow through the navigation channel (Figure 4–123). Upon cessation of the strong westerly winds, the current in the harbor reverses and flows westward in the outer harbor, then out through the entrance (Figure 4–124), and an eddy forms lakeward of the east breakwater. Northeasterly winds produce a pattern similar to that shown in Figure 4–124. The circulation patterns show that Fairport Harbor has a rapid flushing time under most wind conditions because of the harbor design and the interaction of nearshore and wind-drift currents.

Calumet Harbor, Lake Michigan, also has unrestricted communication with Lake Michigan. Unlike Fairport Harbor, the inner harbor area has very poor flushing characteristics. The prevailing circulation is controlled by the clockwise current pattern in southern Lake Michigan. The currents, flowing northward along the shore, do not penetrate the harbor but flow around the end of the breakwater and continue north (Figure 4–125). The inner harbor is practically stagnant; the only flushing mechanism is the slow reversing currents through the breakwater opening.

Unfortunately, many of the harbors on the Great Lakes are located in natural enclosures

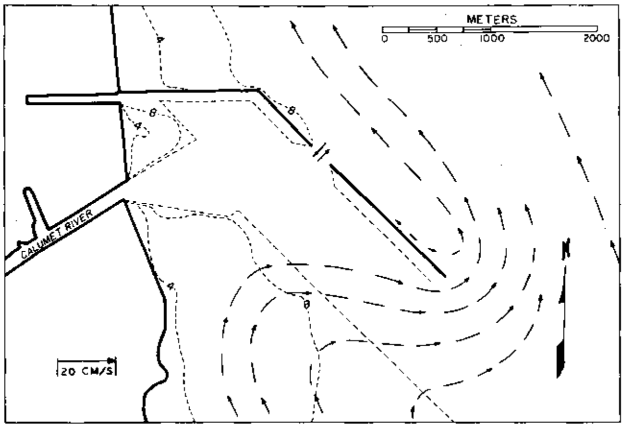

FIGURE 4–125 Current Pattern at Calumet Harbor, Lake Michigan, During Prevailing Wind and Nearshore Current Conditions

From Saylor, 1964

with only small openings to the lake. If these harbors have negligible flushing by tributary drainage, physical factors do not play a large role in dilution, dispersion, or removal of pollutants, and stagnant water results. Wheatley Harbor on Lake Erie is an example of a small harbor with such problems (Steggles and Thon[759]).

Water level disturbances, their height and period, cannot be routinely predicted with sufficient accuracy to determine current velocity. However, if nearshore currents are negligible and water level changes and tributary discharge can be considered the primary causative forces, such as in Toledo Harbor, then another approach can be taken. Since the rate of change in water level, rather than height alone, is responsible for strong currents, Miller[544] used the rate of water level change and the current speed to obtain a current velocity equation for Toledo Harbor:

$$V = 6 + 100\,Q/A - 8\Delta h \qquad (28)$$

where V is the mid-channel current velocity (cm/sec), Q is the river discharge (m^3/sec), A is the cross-sectional area (m^2), and Δh is the water level change (cm) at the Toledo Harbor gage during a 15-minute interval. A one-hour, moving-average technique to filter out high frequency variations and a factor necessary to convert from the near-channel edge, where the measurements were taken, to mid-channel speeds were used. The large scatter in the rate of water level change with respect to current speed, the empirical correction factor for mid-channel conditions, and the omission of wind-stress effects, may contribute to possible inaccuracies.

Quantitative functions relating current-generating forces to current velocities and patterns are obviously lacking. The difficulty in obtaining comprehensive relationships is compounded by a lack of knowledge about the generation, propagation, and decay of the individual forces responsible for current formation.

6.8 Summary and Conclusions

Investigations of harbor circulation patterns conducted in the Great Lakes have identified the primary causative forces as direct (pure wind drift) and indirect (wave induced) wind stress, water level oscillations, tributary discharge, and density differences.

Nearshore currents, consisting of both pure wind drift and wave-produced longshore currents, exhibit several features common to many locations investigated:

(1) The wind-driven currents are generally stronger during onshore winds than during offshore winds, and the currents attain a maximum velocity, about 3 percent of the wind speed, when the direction parallels the shore.

(2) At a fixed depth, the current speed increases with increasing distance from shore.

(3) During strong winds, the highest current speeds are found at the surface and near the bottom.

(4) The current near the coast parallels the shoreline.

(5) Full response of the coastal currents to an applied wind stress is generally achieved in one hour or less.

(6) The decay time of nearshore currents is a function of the prevailing current patterns in the open lake and of the water depth. Nearshore currents are an effective flushing mechanism for many Great Lakes harbors.

In harbors with restricted openings, water level fluctuations cause a filling and emptying of the harbor, and create significant currents through harbor entrances, particularly those harbors located near an antinode. Long-wave climate varies from locale to locale. Short-period disturbances (5 minutes to 2 hours), for which an adequate physical explanation is lacking, have been observed at several locations. Open lake disturbances can cause resonance within a harbor when certain conditions are met.

Tributary inflow through harbors is an effective natural flushing mechanism, especially during high runoff and precipitation periods. Continuity requires that the amount of inflow be compensated by an equal outflow. Because discharge from most tributaries is highly variable, the flushing rates are not consistent.

Water density differences in harbors are usually created by water of a different temperature than the lake water flowing into the harbor and by heating of the shallow nearshore areas. The resulting stratification determines circulation patterns.

Flushing rates depend on factors that vary with harbor dimensions, configuration, and location. Many harbors are located in natural protected areas with only a small opening to the lake where the physical forces are negligible; hence the water is quite stagnant.

Analytical techniques have seen limited application. The difficulty in deriving analytical methods is partly mathematical and partly in the complexity and multiplicity of the causative phenomena and the temporal and spatial variations of the phenomena.

Definition of circulation patterns in harbors and embayments requires monitoring of many parameters for a complete analysis. Advances in the area of localized circulation necessitates a knowledge of lake circulation, diffusion and mixing, wind- and wave-induced nearshore currents, water level oscillations, and density differences. Future research should concentrate on developing workable mathematical models of the important physical processes and verifying these findings by means of the observed circulation. Prediction of circulation patterns, flushing times, and sediment transport directions will aid in elimination of adverse currents and improve water quality through efficient flushing.

Section 7

CHEMICAL CHARACTERISTICS OF THE GREAT LAKES

Sam B. Upchurch

7.1 Introduction

Temporal and spatial changes in water chemistry, regional distribution of chemical constituents, and general sources of chemical loading are discussed in this section. Sources and sinks for chemical constitutents are related to buffering by both inorganic equilibria and organic assimilation. A conceptual model relates inorganic and organic chemical loads in the lakes to chemical weathering in the drainage basins, known chemical loads, and chemical equilibria. A simple chemical budget relates water chemistry in each lake to the entire Great Lakes system, and assists in the evaluation of the consequences of discharging effluents into the lakes.

7.2 Types of Chemical Loads

Chemical influx into a lake from an adjacent drainage basin can be characterized by the following scheme:

(1) natural contributions
- (a) inorganic runoff
- (b) organic runoff
- (c) precipitation and atmospheric fallout
- (d) ground water

(2) cultural contributions
- (a) agricultural runoff
  - (i) inorganic
  - (ii) organic
- (b) municipal-industrial discharge
  - (i) inorganic
  - (ii) organic
- (c) precipitation and atmospheric fallout
- (d) ground water

7.2.1 Natural Contributions

Natural contributions include those constituents that are evolved by the weathering of naturally occurring soils and bedrock, and are combined with organic solutes and solids derived from and by biota of the drainage basin. These constituents are transported to the lakes by surface runoff, precipitation, and ground water.

The weathering of soils and rock is essentially a titration process (Garrels and Mackenzie[284]) where

$$CO_2 + H_20 + \text{soil or rock mineral} = \text{dissolved ions} + \text{degraded minerals} + HCO_3^- \quad (29)$$

The amount of bicarbonate (HCO_3^-) in natural water is, therefore, a measure of the amount of weathering. The completeness of the reaction depends on the nature and abundance of the reactants and products, the temperature, and the residence time of the water at the weathering site. Under appropriate conditions the nature of the products from weathering of a known rock or soil can be predicted. The following are common sources and their weathering products:

(1) basic igneous and metamorphic rocks and associated soils—K^+, Na^+, Ca^{+2}, Mg^{+2}, Fe^{+2}, Fe^{+3}, Cl^-, HCO_3^-, SO_4^{-2}, SO_4^{-2}, H_4SiO_4, SiO_2 quartz, minor degraded clay minerals

(2) acid igneous and metamorphic rocks and associated soils—K^+, Na^+, Ca^{+2}, HCO_3^-, H_4SiO_4, SiO_2 quartz, degraded clay minerals

(3) shales and clay-rich soils—K^+, Na^+, Mg^{+2}, Ca^{+2}, HCO_3^-, SO_4^{-2}, H_4SiO_4, degraded clay minerals

(4) limestone, dolomite, and associated soils—Ca^{+2}, Mg^{+2}, HCO_3^-, SO_4^{-2}, minor degraded clay minerals.

Other inorganic constitutents also occur in natural runoff, but are quantitatively of less importance. For example, phosphate released to the water by weathering is removed from

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the water by the biota and cycled through the ecosystem.

Organic constituents in natural runoff are poorly understood. They consist of animal wastes, dissolved and particulate humic substances produced by decomposition of plant material, and particulate plant and animal debris. Lange[484] showed that fulvic acid, a humic substance, is capable of stimulating growth of blue-green algae. Jernelov,[431] Meknonina,[531] and Cline et al.[152] have shown that humic substances may be of great importance in the mobilization and transport of trace metals. Other organic constituents in natural runoff are less common, because they are also removed from the system through metabolic and photochemical reactions.

7.2.2 Cultural Contributions

Cultural contributions consist of chemicals that are either indirectly washed or discharged directly into the lakes. Agricultural wastes consist of inorganic (e.g., phosphates, nitrates, ammonia, lime) and organic (e.g., organic fertilizers, pesticides, animal wastes) constituents that are washed from drainage areas into streams and lakes. Municipal-industrial discharge consists of a complex array of wastes that include industrial waste, municipal sewage, inputs from commercial and recreational boating, fallout from the atmosphere, and storm-sewer discharge. The constituents that are discharged into the lakes are many and varied. However, a few of current concern are plant nutrients; toxic metals; hydrocarbons, including petroleum products, pesticides, and phenol; and oxidizable organics that deplete oxygen from the system.

Cultural inputs do not relate to rock or soil type. These inputs are a function of land use and activity. Fortunately, major sources of cultural input have been identified, so their impact on the system can be evaluated.

Precipitation carries airborne natural and cultural constituents that may be present as aerosols, dust, or gases. Ground water also serves as a natural and cultural source of chemicals to lakes. The salt and anhydrite/gypsum beds under the Michigan structural basin (see Section 1) contribute an unknown amount of sodium, calcium, chloride, and sulfate to the lakes. As deep well injection and waste disposal become more prevalent, cultural loads through ground water will increase.

7.3 Sampling Methods

Several sampling problems are unique to the Great Lakes. Because of the high level of urbanization adjacent to the lakes, detailed data on the distribution of constituents are required. The size of the lakes makes synchronous sampling throughout a lake logistically impossible, unless permanent instrument platforms are employed. An approximation of the static, synchronous view of a lake is usually made by occupying sampling sites scattered throughout a lake over a period of days or weeks. These views, erroneously called synoptic surveys, are subject to considerable error due to short-term climatic stresses, wind set-ups, flood discharge, winter ice cover, and diurnal and longer-term variation in biochemical uptake and release. The reader, therefore, is cautioned that the synoptic surveys presented in this and other reports reflect transient conditions that do not occur synchronously, and should be considered to represent the average condition of the lake rather than the condition at a specific time.

The water column is not homogeneous, especially during periods of stratification and/or flood discharge. Consequently, one should be aware of the vertical position of samples and, if average lake values are given, the number of samples at each site and the vertical distribution of those samples.

Much of the data used to show historical trends in the composition of the waters of the Great Lakes are taken from analyses at nearshore stations and public water intakes (Beeton[48]). These data may reflect higher concentrations than actually exist in the open lake because they were collected near sources of pollution or in areas isolated from the open lake by coastal currents, physical barriers, or thermal barriers.

Analytic techniques are varied and are subject to rapid technological advances. Older data may not be comparable to more recent data because of changes in methodology. The accuracy and precision of all data vary with sampling technique and analytical method. A discussion of analytic techniques and their accuracies is given in *Standard Methods* (American Public Health Association et al.[10]).

This review of Great Lakes chemistry assumes that similar data can be correlated and that, although synoptic surveys do not show actual lake conditions, they do show sources and kinds of chemical constituents and their general distribution patterns.

7.4 Chemical Water Quality Criteria

All of the Great Lakes States have established water quality criteria for the Great Lakes based on designated uses that include domestic water supply, fish and wildlife, recreation, and industrial water supply. Most have adopted the U.S. Department of Health, Education, and Welfare[829] Public Health Service standards for drinking water with certain modifications. The Public Health Service standards and the States' standards for Great Lakes open water are given in Table 4–30. Rigor of the standards depends on the designated use, the natural quality of the water body, and the need for specific controls. The criteria applied to the open lakes are based on the quality required to minimize the costs of treatment, to prevent consumption of toxic or harmful constituents, and to control locally important inhibitors to water quality. Where specific legislation was not needed, the States opted for the Public Health Service standards in conjunction with the general criteria to limit deleterious or harmful, unspecified constituents.

Constituents cited in the water quality standards are silver (Ag), alkalinity, arsenic (As), boron (B), barium (Ba), carbon chloroform extract, cadmium (Cd), chloride (Cl^-), hexavalent chromium (Cr^{+6}), copper (Cu), dissolved solids, dissolved oxygen (DO), fluoride (F^-), filterable iron (Fe soluble), hardness, cyanide (CN^-), herbicides (including 2,4–D; 2,4,5–T; and 2,4,5–TP), methylene blue active substances (MBAS), filterable manganese (Mn soluble), ammonia (NH_3), nitrate and nitrite (NO_3^- and NO_2^-), oil, phosphorus (P), a number of pesticides, hydrogen ion (expressed as pH), phenol, radioactivity, selenium (Se), sulfate (SO_4^{-2}), turbidity, uranyl ion (UO_3^-), and zinc (Zn). The sources of information on specific and general State water quality standards are the Minnesota Water Pollution Control Commission,[548] Wisconsin Department of Resource Development,[907] Michigan Water Resources Commission,[540] Illinois Sanitary Water Board,[405] Stream Pollution Control Board of the State of Indiana,[766] Water Pollution Control Board of the State of Ohio,[870] Pennsylvania Sanitary Water Board,[601] and New York Department of Health.[577]

Water quality standards for the harbors and embayments of the Great Lakes and for the upland lakes of the Great Lakes Basin are discussed in Appendix 7, *Water Quality*, and in the references cited above.

7.5 Chemical Associations

Inputs into the Great Lakes differ, depending on the lithology of the bedrock and soil and on cultural development in each drainage basin. Correlation analysis of several years of chemical data from the Raquette River of New York (Table 4–31) shows the relationship of the constituents of a natural stream that drains a Precambrian igneous and metamorphic terrane. The Raquette River has little cultural development in its basin. Positive correlations with flow volume suggest that the contained load is a product of natural weathering, and increased runoff is accompanied by flushing of the constituents derived from the drainage basin. Calcium, potassium, sodium, pH, silica, and bicarbonate are positively correlated, indicating that they are derived from dissolution of silicate minerals. The negative correlation between pH and chloride indicates that hydrochloric acid or some compound containing hydrogen ions and chloride may be added to the river as an unnatural constituent. The negative correlation between pH and iron is explained as an equilibrium phenomenon involving the solution of iron compounds at low pH (see Subsection 7.5.11). NO_3^-, Cl^-, SO_4^{-2}, and HCO_3^- are positively correlated with each other and with all cations except iron. The strengths of the correlation coefficients indicate that calcium and magnesium, sodium and potassium, and pH and bicarbonate are closely related and can be considered as groups.

The Maumee River drains a limestone-dolomite terrane that is characterized by heavy agricultural and industrial use. A correlation analysis (Table 4–32) of several years of water quality data indicates several interesting associations. High sodium and chloride correlation are due to the use of salt. Strong positive correlations between specific conductance, a measure of the total dissolved solid load, and nitrate, sulfate, and chloride indicate that they are more important as balancing agents in an industrial-agricultural regime than in a natural regime where bicarbonate balances the cations.

Groups and systems to be discussed are:

(1) dissolved solids
(2) chloride
(3) carbonate system
(4) oxygen system
(5) phosphorus system
(6) nitrogen system
(7) organic carbon compounds
(8) calcium and magnesium
(9) sulfur system
(10) silicon system

Continued on Page 157

TABLE 4–30 Water Quality Standards for Great Lakes Open Water[1]

Parameter	USPHS[2]	Minn.[3]	Wis.[3]	Mich.[3]	Ill.[3]	Ind.[3]	Ohio	Pa.	N.Y.[3]
Ag	0.05	---	---	---	---	---	0.05	---	---
Alkalinity	30-400 or 500[4]	---	---	---	---	---	---	---	---
As	0.05	0.01	---	---	---	---	0.05	---	---
B	1.0	---	---	---	---	---	---	---	---
Ba	1.0	1.0	---	---	---	---	1.0	---	---
Carbon Chloro- form Extract	0.15	0.2	---	---	---	---	---	---	---
Cd	0.01	0.01	---	---	---	---	0.01	---	---
Cl^-	250	50	---	MA[5]: 50 (MA = 10 where present Cl^- <10	AA[5]: Year Conc. 1970 9 1980 10 1990 11 2000 12 SDV[5]: 15 through 1970	AA: Year Conc. 1970 9 1980 10 1990 11 2000 12 SDV: 15 through 1970	---	---	---
Cr^{+6}	0.05	Trace	---	Normally not detectable SV[5]: 0.05	---	---	0.05	---	---
Cu	1.0	Trace	---	---	---	---	---	---	---
Dissolved Solids	500	500	MA: 500 SV: 700	200	AA: Year Conc. 1970 165 1980 172 1990 179 2000 186 SDV: 200 through 1970	AA: Year Conc. 1970 165 1980 172 1990 179 2000 186 SDV: 200 through 1970	MA: 500 SV: 750	MA: 500 SV: 750	---
Dissolved Oxygen	MA: ≥4.0 SV: ≥3.0	≥7 1 Oct. to 31 May ≥5 other times	>80% of saturation SV: ≥5 No change >1	Present at all times in quantities to prevent nuisance. Cold water, intolerant fish: >6 Warm water, intolerant fish: >4 and DA: 5	AA: >90% of saturation SV: >80% of saturation	AA: >90% of saturation SV: >80% of saturation	≥5.0 during at least 16 hours of any 24-hour period SV: ≥3.0	MDV: >5.0 SV: >4.0	Trout Waters ≥5.0 Non-Trout waters ≥4.0
F^-	0.8 - 1.7[4]	1.5	---	---	AA: 1.0 SDV: 1.3	AA: 1.0 SDV: 1.3	2.0	---	---
$Fe_{soluble}$	0.3	0.3	---	---	AA: 0.15 SDV: 0.30	AA: 0.15 SDV: 0.30	---	0.3	---
Hardness	≤300 to 500[5]	50	---	---	---	---	---	---	---
CN^-	0.20	Trace	---	Normally not detectable SV: 0.2	SDV: 0.025	SDV: 0.025	0.2	---	---
Herbicides	0.1	---	---	---	---	---	---	---	---
MBAS	0.5	0.5	---	---	AA: 0.02 SDV: 0.05	AA: 0.02 SDV: 0.05	---	0.5	---
$MN_{soluble}$	0.05	0.05	---	---	---	---	---	---	---
NH_3	0.05 (as N)	Trace	---	---	AA: 0.02 (as N) SDV: 0.05 (as N)	AA: 0.02 (as N) SDV: 0.05 (as N)	---	---	---
NO_3^- & NO_2^-	10 (as N)	45	---	---	0.4 (Total N)	0.4 (Total N)	---	---	---
Oil	Virtually absent	Trace	---	No visible film, no globules	Substantially free of visi- ble, floating oil	Substantially free of visi- ble, floating oil	---	---	---
P	Should not lead to nuisance algae or coagulation problems	---	---	---	AA: 0.03 SDV: 0.04 (as PO_4)	AA: 0.03 SDV: 0.04 (as PO_4)	---	---	---

TABLE 4–30(continued) Water Quality Standards for Great Lakes Open Water[1]

Parameter	USPHS[2]	Minn.[3]	Wis.[3]	Mich.[3]	Ill.[3]	Ind.[3]	Ohio	Pa.	N.Y.[3]
Pb	0.05	0.05	---	---	---	---	0.05	---	---
Pesticides[6]									
pH	6.0 - 8.5	6.5 - 8.5	6.0 - 9.0	6.5 - 8.8 no change >0.5	AA: 8.1 - 8.4 DA: 7.7 - 9.0	AA: 8.1 - 8.4 DA: 7.7 - 9.0	DA: 6.5 - 8.5 SV: 5.0 - 9.0	7.0 - 9.0	6.5 - 8.5
Phenols	0.001	Trace	---	MA: 0.002 SV: 0.005	AA: 0.001 SDV: 0.003	AA: 0.001 SDV: 0.003	---	---	0.005
Radioactivity (pc/l):									
Gross	1000	---	---	1000	---	---	1000	---	---
Ra_{226}	3	---	---	---	---	---	---	---	---
Sr_{90}	10	---	---	---	---	---	---	---	---
Se	0.01	0.01	---	---	---	---	0.01	---	---
SO_4^{-2}	250	250	---	---	AA: Year Conc. 1970 24 1980 26 1990 28 2000 30 SDV: 50 through 1970	AA: Year Conc. 1970 24 1980 26 1990 28 2000 30 SDV: 50 through 1970	---	---	---
Turbidity	---	5	---	No objectionable, unnatural turbidity	None of other than natural origin that will cause substantial visible contrast with natural appearance of water	None of other than natural origin that will cause substantial visible contrast with natural appearance of water	---	---	---
UO_3^-	5	---	---	---	---	---	---	---	---
Zn	5	5	---	---	---	---	---	---	---
Designated Uses	Drinking Water	Domestic Consumption Fisheries & Recreation Industrial Consumption	Fisheries & Recreation Municipal Water Supply Shipping Industrial Consumption Waste Assimilation	Domestic Water Supply Industrial Water Supply Recreation Fish, Wildlife & other Aquatic Life Agricultural and Commercial	Public Water Supply Industrial Water Supply Commercial and Sport Fishing Recreation	Municipal Water Supply Industrial Water Supply Recreation Warm-Water Fisheries	Public Water Supply Industrial Water Supply Aquatic Life Recreation	Aquatic Life Water Supply Recreation Navigation Waste Assimilation	Ontario Domestic Consumption Bathing Agriculture Ontario & Erie Recreation Boating Fishing Industrial Consumption Transportation Sewage Disposal Industrial Waste Disposal

[1]Maximum allowable concentrations in mg/l, unless otherwise designated.
[2]United States Public Health Service.
[3]Unless otherwise stated, the open lake water within this State shall conform to the Drinking Water Standards of the U.S. Public Health Service (1962). The USPHS standards are given at the head of each column.
[4]Depends on local, natural water concentrations.
[5]AA = Annual Average; MA = Monthly Average; SDV = Single Daily Value; SV = Single Value at Any Time; DA = Daily Average
[6]Only the USPHS has pesticide standards which are: Aldrin, 0.017; Chlordane, 0.003; DDT, 0.042; Dieldrin, 0.017; Endrin, 0.001; Heptachlor, 0.018; Heptachlor epoxide, 0.018; Lindane, 0.056; Methoxychlor, 0.035; Org. Phos. + Carbamates, 0.1; and Toxaphene, 0.005.

TABLE 4–30(continued) Water Quality Standards for Great Lakes Open Water[1]

		General Standards (where adopted)
Minnesota	(1)	No untreated sewage or treated sewage with pathogenic organisms shall be discharged.
	(2)	No discharge that will create nuisance conditions, including floating solids, scum, oil, discoloration, odor, gas evolution, sludge, slime, or algae.
Wisconsin	(1)	Substances that yield objectionable deposits shall not be present in quantities that will cause nuisance conditions.
	(2)	Floating debris, oil, scum, or other material shall not be present in such amounts as to cause a nuisance.
	(3)	Materials producing color, odor, taste, or unsightliness shall not be present in such quantities as to cause a nuisance.
	(4)	No substance will be present in quantities harmful or toxic to human, animal, plant, or aquatic life.
Michigan	(1)	Toxicants should not exceed 1/10 of 96 hour TL_m from continuous flow bioassay.
	(2)	Material producing objectionable turbidity, color, deposits, or injury to human, fish, wildlife, or aquatic life may not be present in quantities sufficient to create a nuisance.
	(3)	Nutrients originating from cultural sources shall not cause growths of algae, weeds, or slimes that are injurious to the designated use.
Ohio	(1)	Shall be free of substances attributable to municipal, industrial, or other discharges that will settle to form putrescent or other objectionable sludge deposits; that will produce color, odor, or other conditions in such degree as to create nuisance; or that will singly or in combination with other chemicals, be toxic or harmful to human, animal, plant, or aquatic life.
	(2)	Shall be free of unsightly or deleterious floating debris, scum, oil, and other floating materials attributable to man.
	(3)	Toxic substances will be less than or equal to 1/10 of the 48 hour TL_m, unless otherwise limited.
Pennsylvania	(1)	Shall be free of substances attributable to municipal, industrial, or other waste discharges in concentration or amounts sufficient to be inimical or harmful to water uses to be protected or to be harmful to human, animal, plant, or aquatic life, including, but not limited to, oil, scum, and other floating materials; toxicants; and substances that cause odor, taste, or discoloration.
New York	(1)	Any water receiving sewage, industrial wastes, or other waste discharges shall not be impaired for best use of water in any other class by reason of such wastes.
	(2)	No readily visible floating or settleable solids or sludge deposits attributable to sewage, industrial wastes, or other wastes.
	(3)	All sewage or waste effluents will be disinfected.
	(4)	No wastes that, alone or in combination, produce odor, color, oil, or other deleterious conditions will be present in quantities sufficient to cause nuisance.
	(5)	No toxic or other deleterious wastes will be present in such quantities as to be injurious to fish life or be unsuitable or unsafe for drinking water, or unsuitable for any other best usage as designated.

TABLE 4–31 Linear Correlation Matrix for Flow and Chemical Composition, Raquette River at Raymondville, New York

	1	2	3	4	5	6	7	8	9	10	11	12	13	
Parameter	Flow	SiO_2	Fe_{Total}	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	HCO_3^-	SO_4^{-2}	Cl^-	NO_3^-	Spec. Cond.	pH	
Units	m^3/s	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	μmohs	--	
Mean	107	8.25	.226	16.9	6.01	2.50	.85	71.9	9.37	1.43	1.01	141.	6.9	
Standard Deviation	37.1	2.74	9.74	8.34	3.38	.74	.28	42.7	1.98	0.03	0.300	64.8	.3	
	1.0		$\underline{-0.53}$[1]	$\underline{0.54}$	$\underline{0.65}$		0.45	$\underline{0.58}$		-0.41		$\underline{0.56}$	$\underline{0.62}$	1
		.100				$\underline{.057}$	0.40		0.40	$\underline{0.59}$				2
			1.00										-0.43[2]	3
				1.00	$\underline{0.96}$	$\underline{0.70}$	$\underline{0.63}$	$\underline{1.00}$				$\underline{0.99}$	0.44	4
					1.00	$\underline{0.64}$	$\underline{0.73}$	$\underline{0.97}$				$\underline{0.97}$	0.49	5
						1.00	$\underline{0.49}$	$\underline{0.71}$			0.43	$\underline{0.72}$		6
							1.00	$\underline{0.65}$				$\underline{0.70}$		7
								1.00	$\underline{0.30}$[2]		$\underline{0.38}$[2]	0.99	$\underline{0.40}$[2]	8
									1.00	0.46	$\underline{-0.60}$	0.36[2]		9
										1.00			0.41	10
											1.00	0.38[2]		11
												1.00	0.42	12
													1.00	13

[1]Underlined values are significant at P = 99%, others at P = 95%

[2]Determined for n = 48, all other pairs determined for n = 26

SOURCE: Upchurch, 1972

TABLE 4–32 Linear Correlation Matrix for Flow and Chemical Composition, Maumee River at Toledo Harbor, Ohio

	1	2	3	4	5	6	7	8	9	
Parameter	Flow	Na^+	HCO_3^-	SO_4^{-2}	Cl^-	NO_3^-	PO_4^{-3}	Spec. Cond.	pH	
Units	m^3/s	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	--	
Mean	109.	23.7	153.	83.5	34.2	13.0	1.23	536.	7.4	
Standard Deviation	8.55	6.75	37.0	24.9	8.17	11.3	1.36	105.	.4	
	1.00					0.56[1]				1
		1.00			0.91					2
			1.00	0.82		0.43		0.85	0.37	3
				1.00	0.36	0.72		0.97	0.36	4
					1.00			0.46		5
						1.00	0.36	0.67	0.54	6
							1.00			7
								1.00	0.42	8
									1.00	9

[1]Underlined coefficients are significant at P = 99%, others at P = 95%

n = 45

SOURCE: Upchurch, 1972

(11) iron and manganese
(12) trace elements
(13) radionuclides

Several of these groups are important because they affect water quality and the chemical loads in the Great Lakes.

Loading from the tributaries of the Great Lakes is highly variable (Upchurch[807]). Streams that drain areas of igneous and metamorphic bedrock generally carry lower chemical loads than streams from shale and limestone-dolomite terranes, because weathering rates of silicate minerals are slower than those of calcite and dolomite and because igneous and metamorphic terranes in the Great Lakes Basin are generally less habitable owing to poor drainage. Figures 4–126 and 4–127 show the temporal distribution of selected constituents in the Raquette River at Raymondville, New York, for water year 1960–61 and in the Maumee River at Toledo Harbor for water year 1966–67. The chemical loads are so variable with time that average compositions cannot characterize the stresses placed on the environment.

7.5.1 Dissolved Solids

Knowledge of the total load of dissolved material in a water body is useful in identifying the degree to which natural weathering and cultural inputs affect water chemistry. Dissolved solids characterize the total load derived from dissolution of minerals in the tributary drainage basins, bottom sediments, plus cultural input from municipal, industrial, and rural waste discharge. Therefore, dissolved solids serve as a useful index for monitoring the progress of lake aging.

Average dissolved solid concentrations of the Great Lakes are shown in Table 4–33. The present concentrations are below the standards set by the Great Lakes States (Table 4–30). However, the averages are close enough to the standards that individual values most probably exceed the standards at times.

Dissolved solid loads in all of the lakes except Lake Superior have increased over the period of record (Figure 4–128), indicating progressively greater influx of dissolved constituents. Extrapolation of the historical

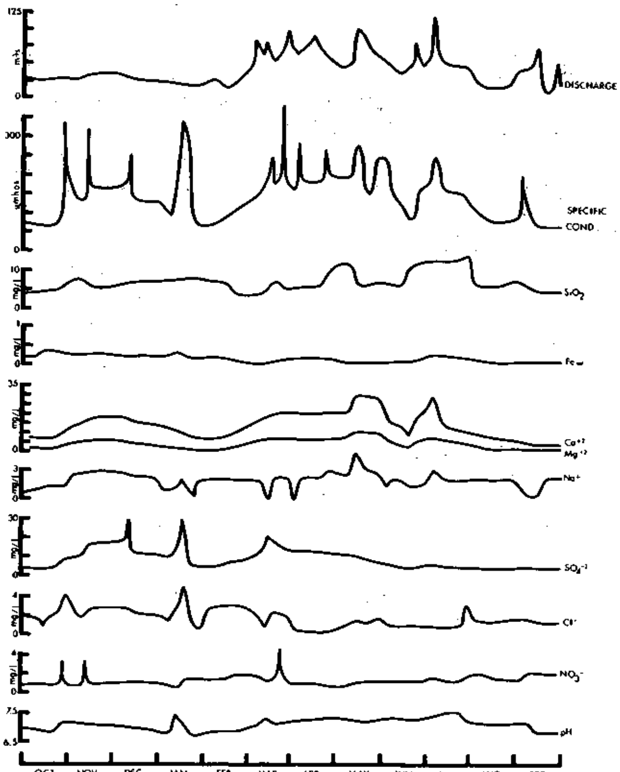


FIGURE 4–126 Seasonal Distribution of Discharge and Chemical Composition of the Raquette River at Raymondville, New York; Water Year 1960–61

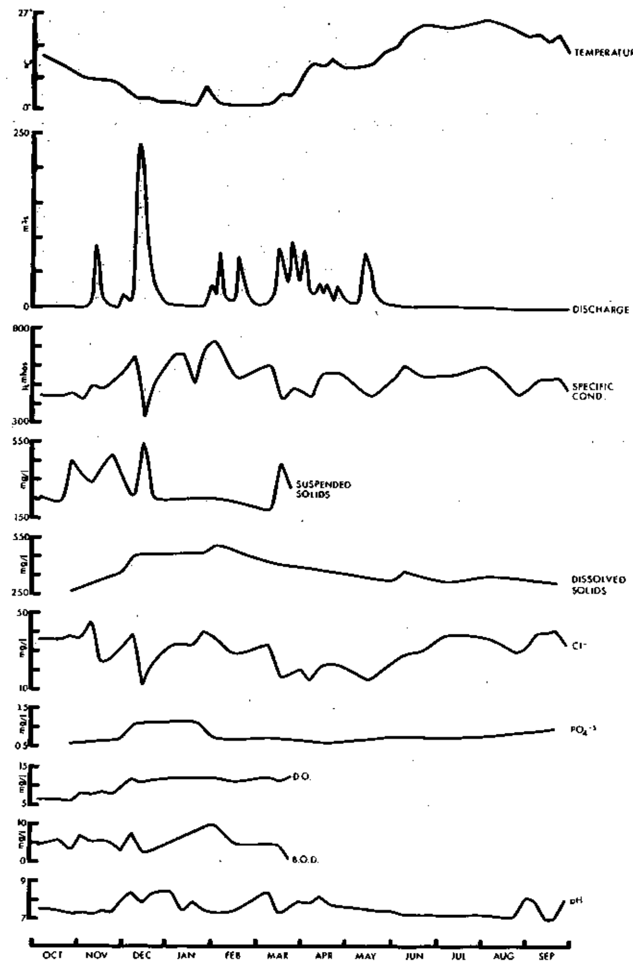


FIGURE 4–127 Seasonal Distribution of Discharge, Temperature, and Chemical Composition of the Maumee River at Toledo Harbor, Ohio; Water Year 1966–67

trends for the lakes indicates rapid increases in dissolved solid concentrations with average compositions exceeding the standards by the year 2000 if no action is taken.

Specific conductance is a measure of the ability of water to conduct an electrical current. Since ionic constituents serve as electrical conductors, specific conductance as a measure of the total ionic strength (Figure 4–129) is also an index of dissolved ion content in water. Efficiency of the solution as a conductor varies with the nature of the ions present. In areas where natural weathering predominates, bicarbonate, the major anionic product of the weathering process, and the cations sodium, potassium, calcium, and magnesium, contribute to the conductivity. Cations in cultural effluents require an anionic constituent to maintain electrical neutrality in the solution. Anions in the solution are augmented by bicarbonate through equilibrium with the atmosphere or other sources in order to maintain electrical neutrality. The concentration of total dissolved solids may be estimated by multiplying the specific conductance in μmhos/cm by a factor that varies from 0.5 to 0.9 (see Section 3), depending on the ionic strength of contained constituents. The relationship between conductivity or ionic strength and dissolved solids makes this easily measured characteristic useful in limnological studies. Specific conductance of Lake Superior is low (Figure 4–130). The major sources of dissolved material are Duluth and the St. Louis River drainage basin, Marathon and the Black and Pic River drainage basins, Marquette, and the Thunder Bay drainage basin. The most obvious variations in surface distribution of dissolved material are the movement of material lakeward from Duluth, the zone of high conductance that extends southward from Thunder Bay, the plume extending eastward from Marquette. The great volume of Lake

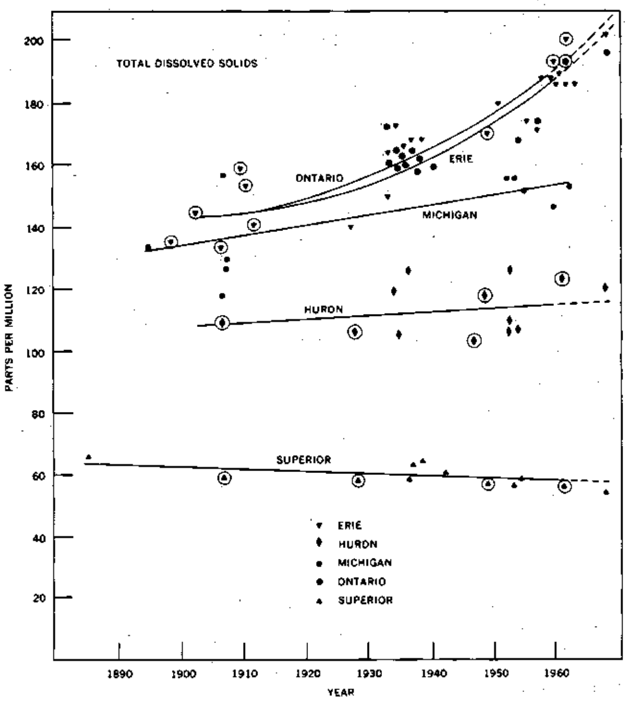


FIGURE 4–128 Changes in Total Dissolved Solids in the Great Lakes. Circled points are the average of 12 or more determinations. Solid lines are Beeton's; dashed lines are extensions of Weiler and Chawla's data.

After Beeton, 1965; Weiler and Chawla, 1969; Kramer, 1964

Superior provides much assimilative capacity; the volume of dissolved solids is so low that diffusion is not altered during periods of stratification.

The conductivity data of Beeton and Moffett[58] in Lake Michigan (Figure 4–131), indicate that the Chicago-Gary area is the major source of dissolved solids in that lake. Average inshore dissolved solid concentration in 1962–63 was 175 mg/l (86–810 mg/l range) and the offshore concentration was 155 mg/l (100–240

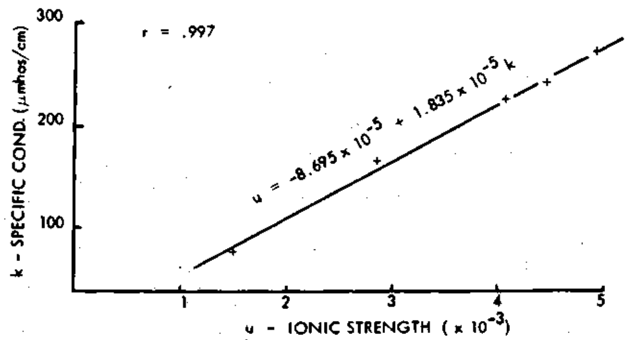


FIGURE 4–129 Ionic Strength-Specific Conductance Relationship for the Great Lakes. Data averages (x) are given for each lake. From left to right the lakes are: Superior, Huron, Michigan, Ontario, and Erie.

From Beeton and Chandler, 1963; Kramer, 1964

FIGURE 4–130 Representative Distribution of Dissolved Solids in Lake Superior Surface Water Through the Measure of Specific Conductance (μmhos)

Data from Lake Survey Center (NOS–NOAA) cruises 7/18–8/8/68 and 7/27–8/9/69

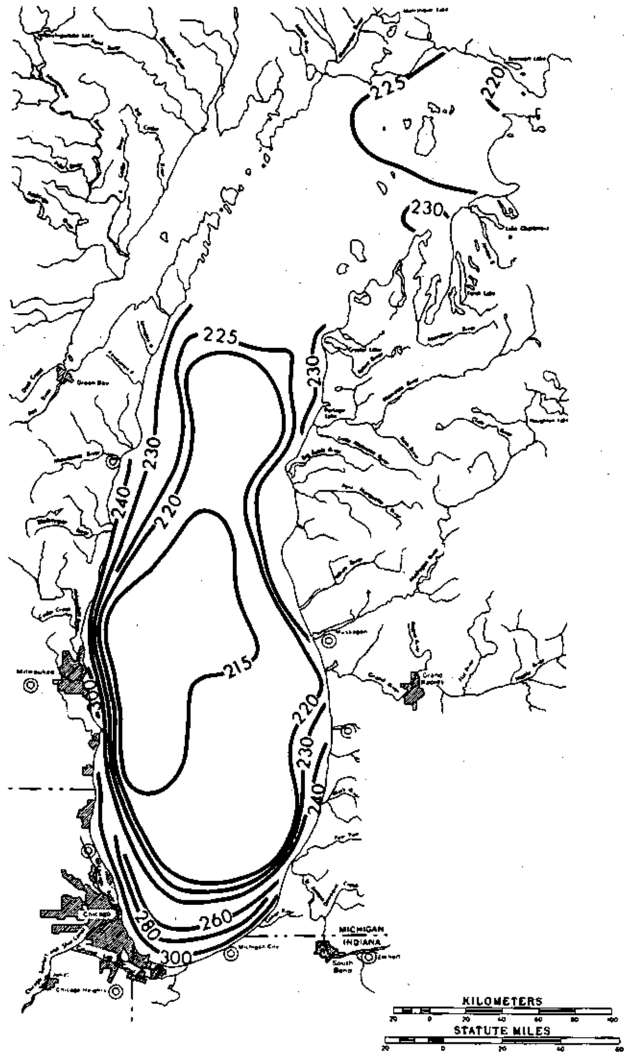


FIGURE 4–131 Representative Distribution of Dissolved Solids in Lake Michigan Surface Water Through the Measure of Specific Conductance (µmhos)

Data from Beeton and Moffett, 1964

FIGURE 4–132 Representative Distribution of Dissolved Solids in Lake Huron Surface Water Through the Measure of Specific Conductance (µmhos)

Data from Lake Survey Center (NOS–NOAA) cruise 8/2–8/17/66

mg/l range) (Federal Water Pollution Control Administration[835]). Green Bay (Figure 4–135) and Traverse Bay have average dissolved solids concentration of 183 mg/l (132–179 mg/l range) and 190 mg/l (105–745 mg/l range), respectively. Both bays locally affect loading in Lake Michigan. These effects are related to lake circulation near the bays.

Lake Huron shows the influence of the relatively high conductivity water from Lake Michigan and low conductivity water from Lake Superior (Figure 4–132). The major sources of dissolved solids in Lake Huron are Saginaw Bay, and to a lesser extent Thunder Bay and Georgian Bay. The cross section in Figure 4–132 suggests that water with slightly higher conductivity can be found along the bottom on the eastern side of the Lake Huron basin, but the lake was stratified during that time. The chemical gradient may be attributed to influx of water with a slightly higher dissolved solid load from Georgian Bay or to downwelling along the eastern shore. Saginaw Bay (Figure 4–136) constitutes a major source of dissolved material (Allen;[7] Beeton et al.[59]) with high concentrations along the shores of the bay.

Lake Erie has the highest dissolved solids content of any of the lakes (Table 4–33). The major sources of dissolved material are the Detroit River, Toledo and the Maumee River

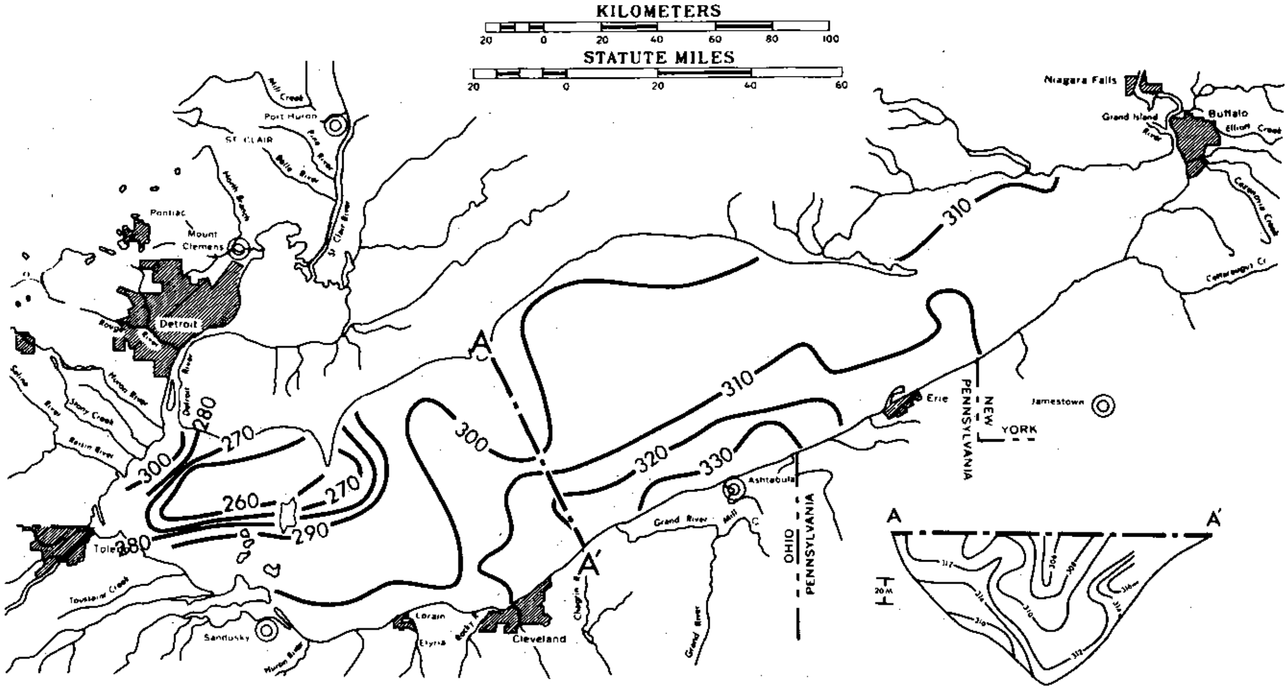


FIGURE 4–133 Representative Distribution of Dissolved Solids in Lake Erie Surface Water Through the Measure of Specific Conductance (μmhos)

Data from Lake Survey Center (NOS–NOAA) cruise 8/9–9/20/65

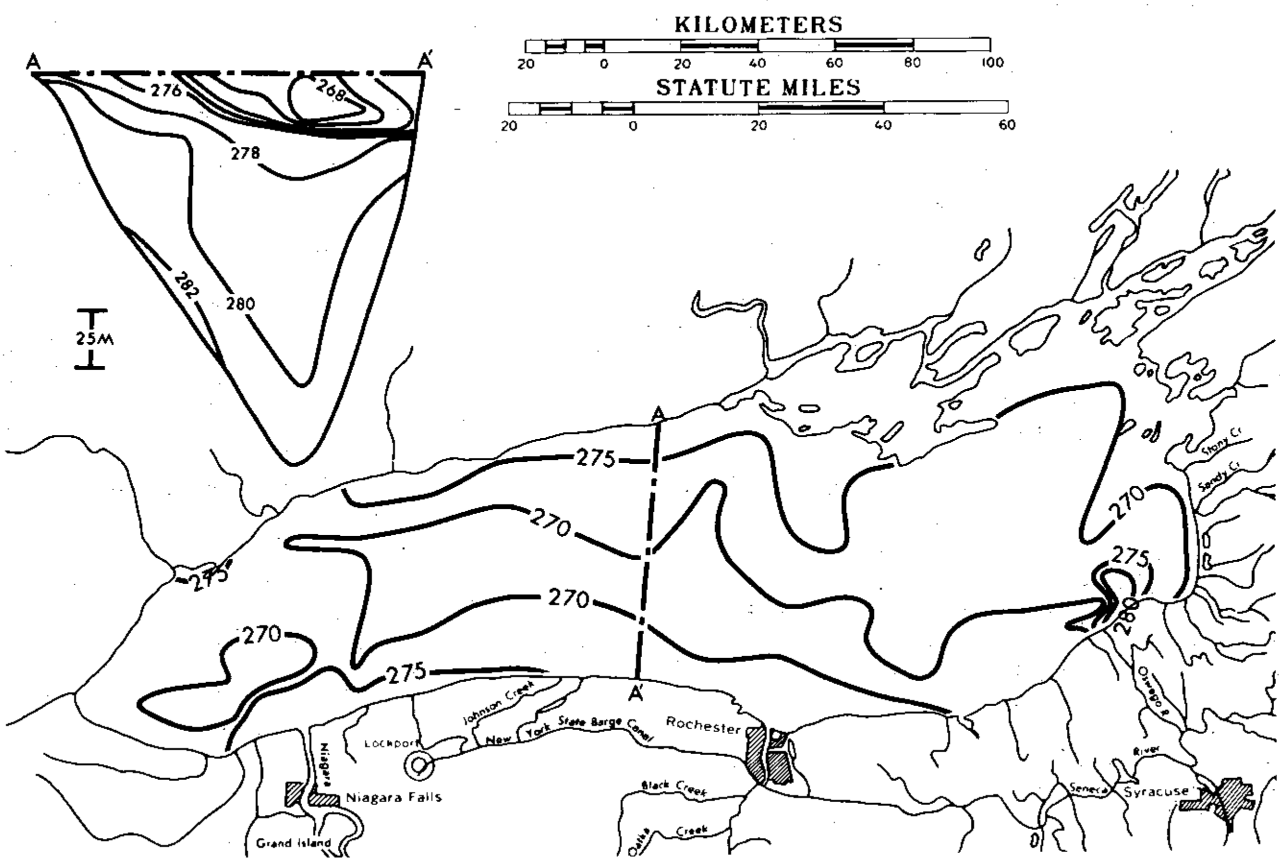


FIGURE 4–134 Representative Distribution of Dissolved Solids in Lake Ontario Surface Water Through the Measure of Specific Conductance (μmhos)

Data from Canada Centre for Inland Waters (1969) cruise 8/2–8/7/66

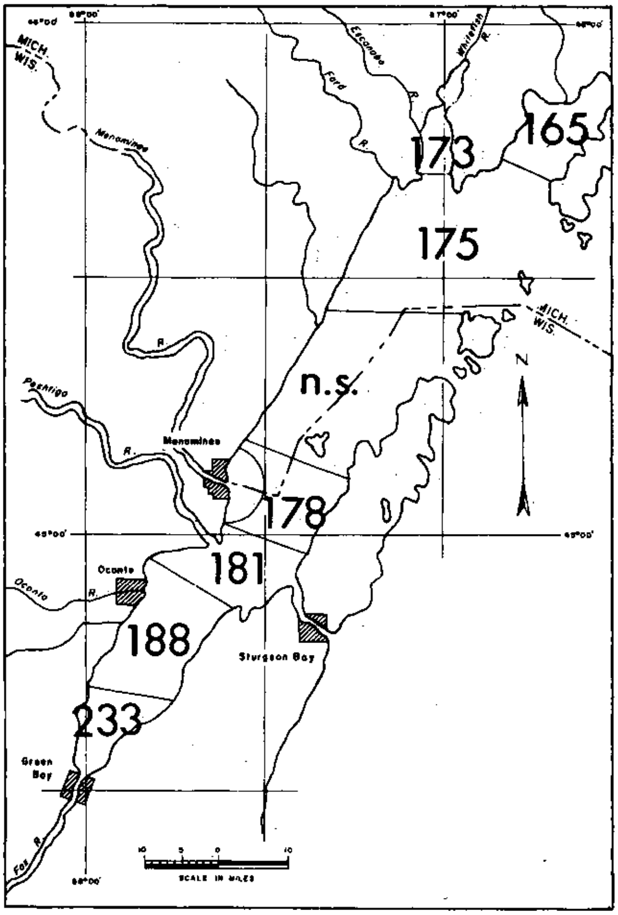


FIGURE 4–135 Mean Dissolved Solids Concentration (mg/l) in Green Bay, Lake Michigan; 1963. The letters n.s. mean not sampled.
From Federal Water Pollution Control Administration, 1968c

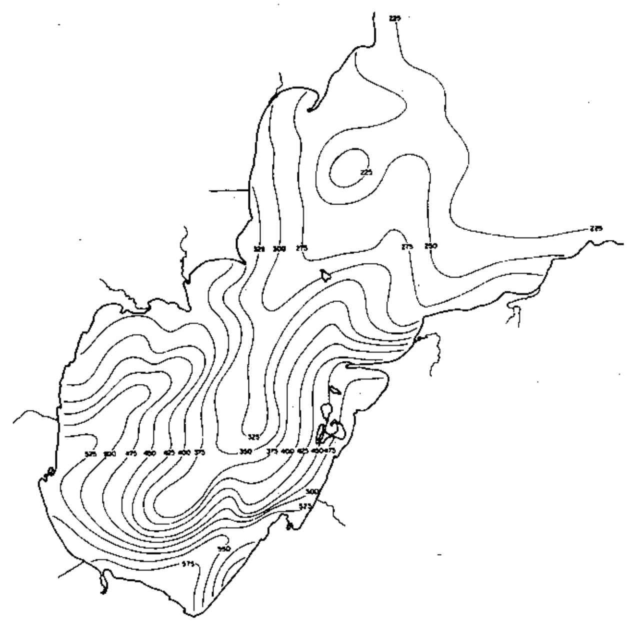


FIGURE 4–136 Conductivity (μmhos) of Saginaw Bay Water (at 18°C) on August 10, 1956
From Beeton et al., 1967

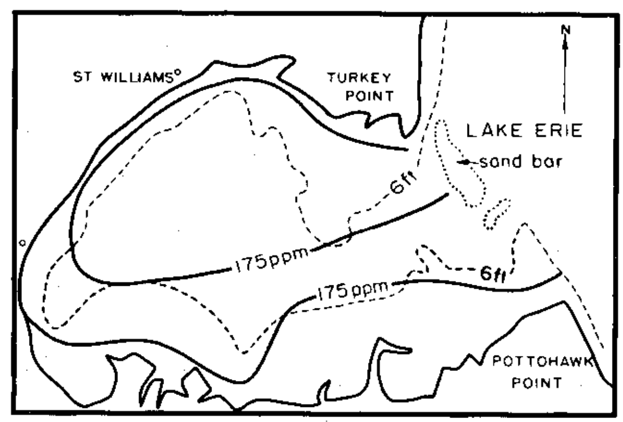


FIGURE 4–137 Dissolved Solids in Inner Long Point Bay, Ontario
From Berst and McCrimmon, 1966

basin, the Grand River basin of Ohio, the Cleveland area and Cuyahoga River basin, and that portion of Ontario between Long Point and Port Colborne. The highest conductivity water occurs inshore (Figure 4–133). Conductivity and dissolved solids distribution in Lake Erie have been summarized by many studies, including those by Kramer,[468] Anderson and Rodgers,[13] Federal Water Pollution Control Administration,[834] and Weiler and Chawla.[876] Numerous studies have been done on harbors and smaller embayments in Lake Erie. Berst and McCrimmon[65] described the dissolved solids in Inner Long Point Bay, Ontario (Figure 4–137). Other such studies are reviewed in Subsection 7.7, Great Lakes Harbors.

Dissolved solid load is high in Lake Ontario because this lake receives most of its water from Lake Erie. Important sources that can be identified are the Niagara River, Oswego and the Oswego River, Toronto, and the northern shore of the lake from Port Whitby eastward (Figure 4–134).

7.5.2 Chloride

Chloride (Cl^-) is the only commonly occurring aqueous constituent in freshwater systems that can be considered conservative. Conservative constituents do not combine with other aqueous or solid phases and are not

TABLE 4–33 Average Concentrations of Major Ions in the Great Lakes

	Ontario[1]	Erie[1]	Huron[1]	Michigan[2]	Superior[1]
Ca (mg/l)	40	37	28	32	13
Mg (mg/l)	8	8	7	10	3
Na (mg/l)	13	12	3	3	1
K (mg/l)	1	1	1	1	1
SO_4 (mg/l)	29	26	17	16	4
Cl (mg/l)	28	25	6	6	1
HCO_3 (mg/l)	113	113	96	130	51
F (mg/l)	0.12	0.11	0.07	0.1	0.32
Alkalinity (mg/l)	93	92	79	113	52
Dissolved Solids (mg/l)	194	198	118	150	52
pH	7.9	8.1	8.0	8.0	7.8

[1]From Weiler and Chawla, 1969.
[2]From Kramer, 1964.

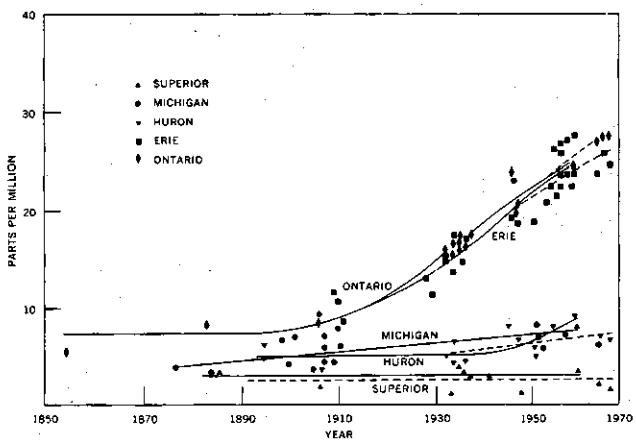


FIGURE 4–138 Changes in Chloride Concentration in the Great Lakes. Solid lines represent Beeton's data fit; dashed lines are revisions by Weiler and Chawla.
Data from Kramer, 1964; Beeton, 1965; Weiler and Chawla, 1969

removed from the system by chemical precipitation, absorption or adsorption on mineral surfaces, metabolic processes, or chelating. Consequently, chloride is used as an index of chemical loading and buildup, and as an indicator for the location of sources and sinks of nonconservative material. Chloride originates from many sources, including street salting, oil field brines, chloride compounds used by industry, additives to cleaning compounds, atmospheric aerosols, and natural weathering of minerals.

Because of ease of determination and the conservative nature of chloride, it has been extensively used in the Great Lakes as an index of pollution (Tiffany and Winchester,[801] Tiffany et al.[802]) and to demonstrate the temporal distribution of chemical loading (Beeton,[48] Ownbey and Willeke,[594] Ownbey and Kee,[593] Weiler and Chawla,[877] O'Connor and Mueller,[583] Upchurch and Robb[810]). Chloride ions can be fixed by exchange processes on clay minerals (Grim[304]), so chloride is not absolutely conservative. However, ion exchange reactions involving chloride do not appear to be quantitatively important; thus, lakewide balances of chloride are valid. Figure 4–138 shows the increase in chloride concentration in the Great Lakes during the past 100 years. Lake Superior has shown no historical buildup in chloride. Chloride has increased slightly in Lakes Michigan and Huron and greatly in Lakes Ontario and Erie since about 1910. Effects of chloride loading on lake composition are discussed in Subsection 7.8.

Chloride levels are extremely low in Lake Superior (Table 4–33), although high chloride mine waters are released to the lake at several places. Spain et al.[755] and Spain and Andrews[754] found a mean chloride concentration of 177 mg/l in Torch Lake, a lake that receives mine drainage and is a tributary to Lake Su-

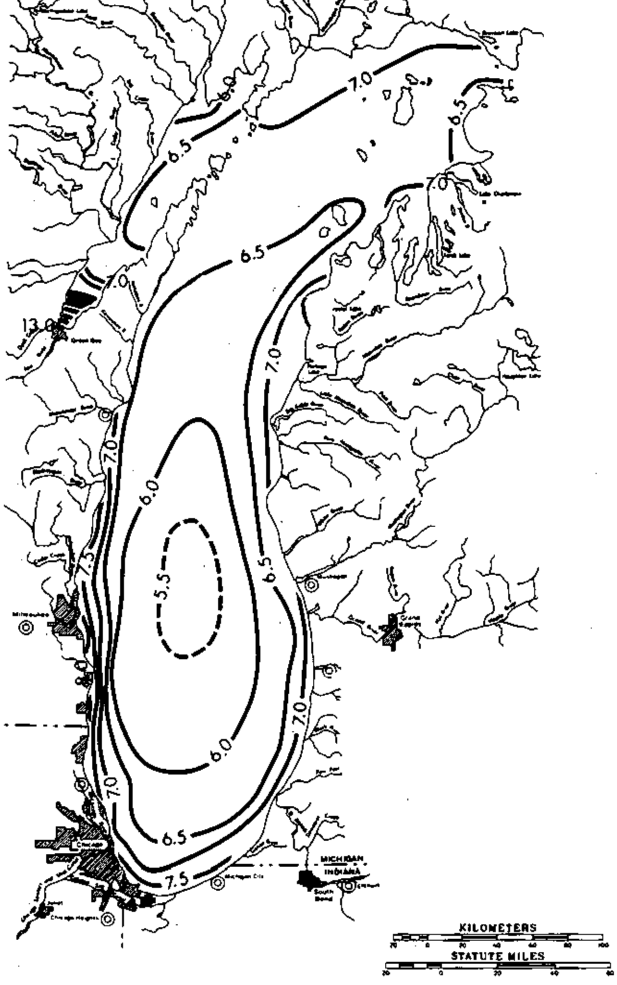


FIGURE 4–139 Representative Distribution of Chlorides (mg/l) in Lake Michigan Surface Water

Data from Beeton and Moffett, 1964

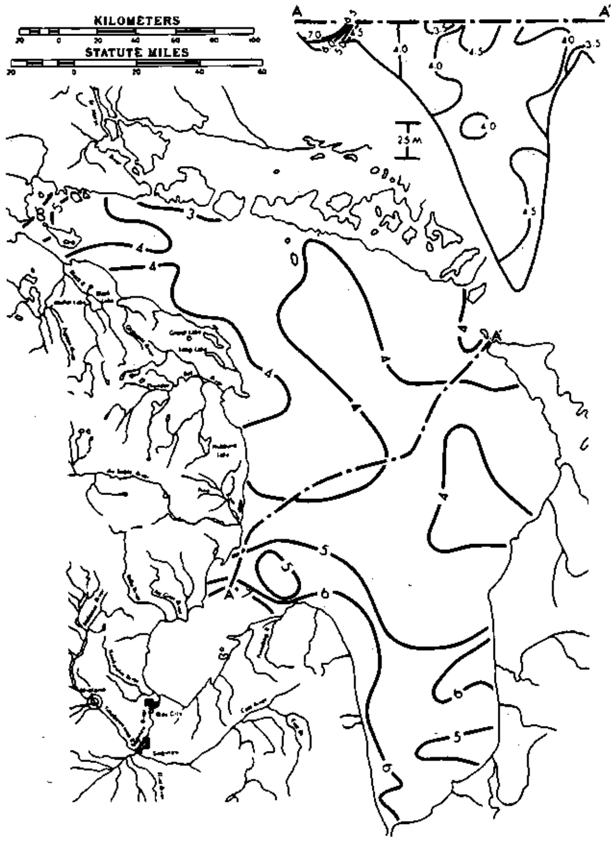


FIGURE 4–140 Representative Distribution of Chlorides (mg/l) in Lake Huron Surface Water

Data from Lake Survey Center (NOS-NOAA) cruise 8/2–8/17/66

perior. In Portage Lake, a part of the Keweenaw Waterway, Spain and his colleagues used chloride and natural fluorescence as tracers and were able to identify water contributions from Lake Superior, Torch Lake, and the tributaries to Portage Lake. The runoff cycle is a major factor in the rate of chloride influx.

A chloride loading problem is rapidly developing in Lake Michigan (Ownbey and Willeke[594]). Among the sources of chloride that can be identified from areal distribution (Figure 4–139) are Green Bay, Milwaukee, Chicago-Gary, and the reaches from Benton Harbor to Muskegon and from Little Sable Point to Frankfort. The Manistee River and Lake Manistee (Childs[141]), where concentrations up to several hundred milligrams per liter occur, are major problem areas. Ground water near Lake Michigan at Manistee also poses a chloride threat with up to 2000 mg/l. Ludington has also been identified as a source of chloride loading. The Federal Water Pollution Control Administration[835] indicates minor chloride influx into Lake Michigan from Green Bay and Traverse Bay. The average chloride concentration in the immediate vicinity of Green Bay, Wisconsin, in the summer of 1964 was 13 mg/l. A major shortcoming of chloride studies is illustrated in these reports for Green Bay and Traverse Bay: unless a continuous source of chloride is present, summer chloride concentrations represent minimum level. In the Great Lakes Basin street salting is a major contribution that is added only in the winter.

Lake Huron chloride loadings are dominated by inflow from Lake Michigan and Saginaw Bay (Figure 4–140). Other possible sources are at Goderich and Grand Bend, Ontario. Chloride in Saginaw Bay (Figure 4–143)

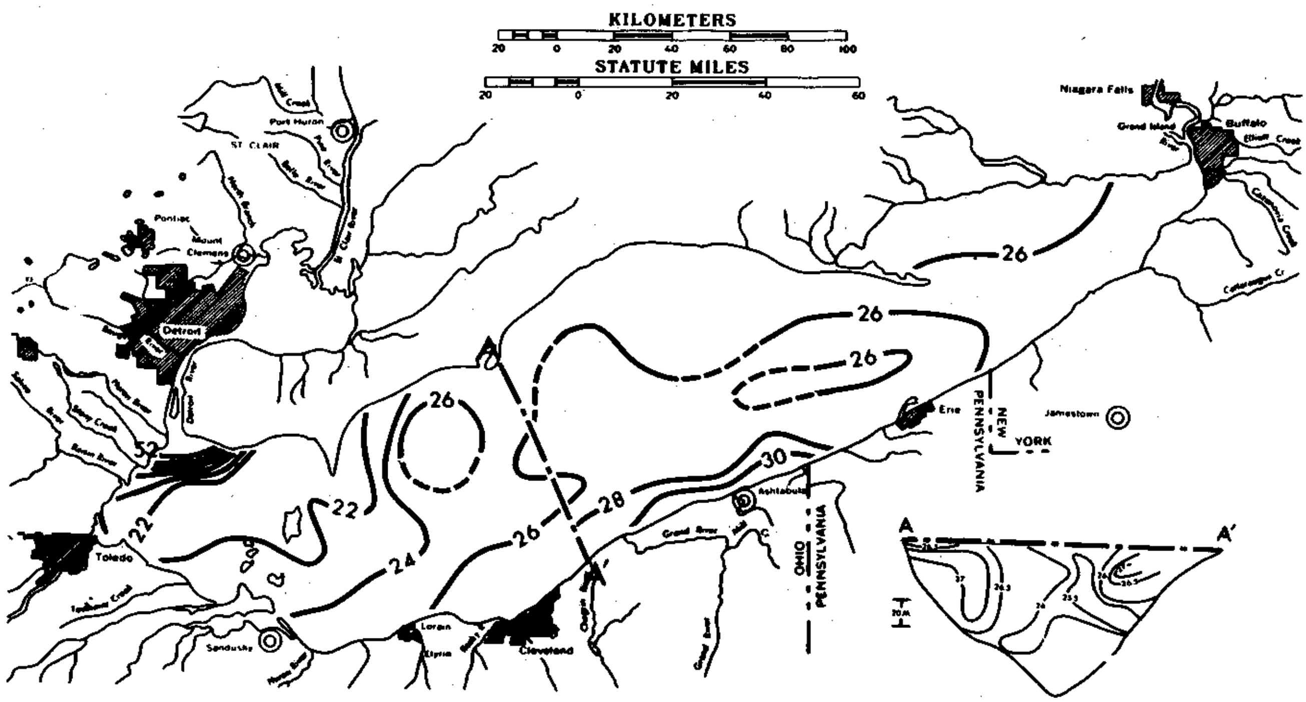


FIGURE 4–141 Representative Distribution of Chlorides (mg/l) in Lake Erie Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

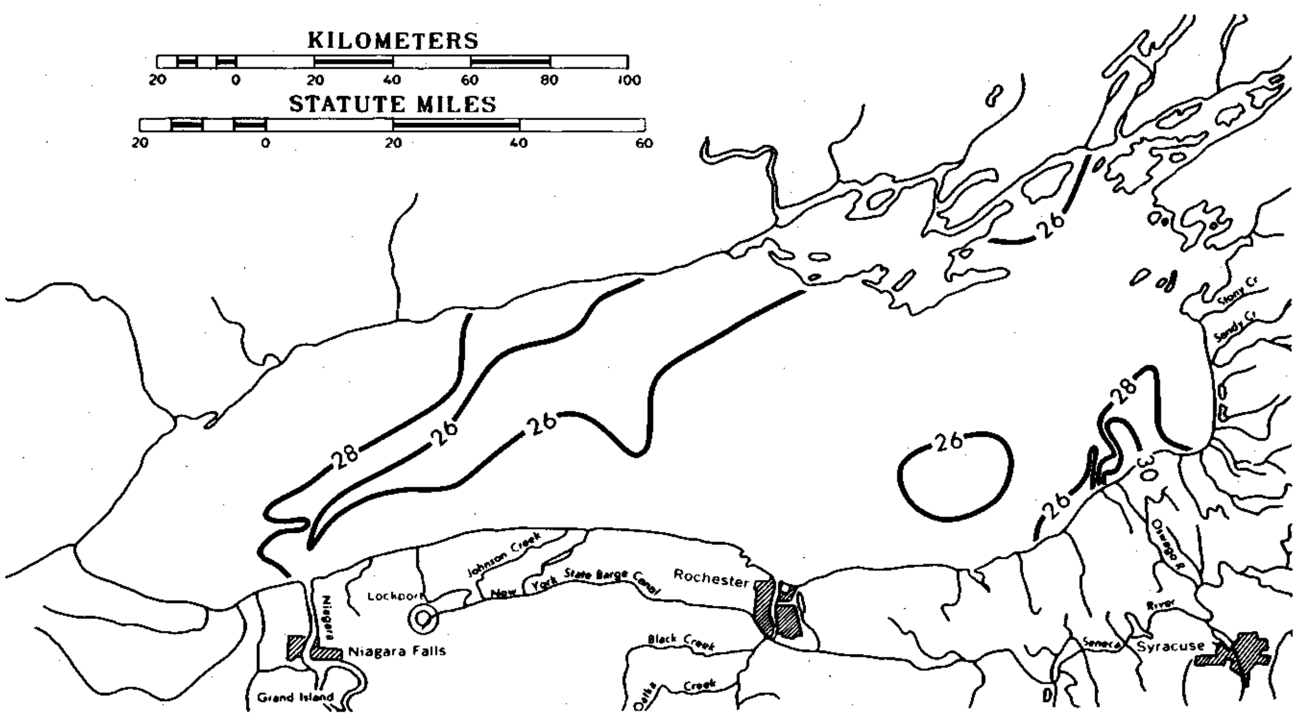


FIGURE 4–142 Representative Distribution of Chlorides (mg/l) in Lake Ontario Surface Water
Data from Canada Centre for Inland Waters (1969) cruise 8/2–8/7/66

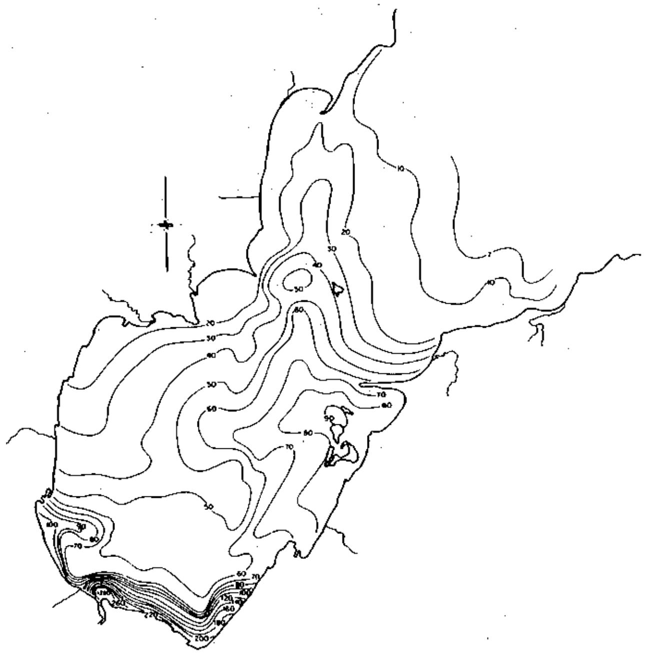


FIGURE 4–143 Chloride Distribution (mg/l) in Saginaw Bay on June 21 and 22, 1956
From Beeton et al., 1967

is derived from the brine fields in the watershed of the Saginaw River and from the Midland, Bay City, and Saginaw urban complex. This high chloride water is diluted with Lake Huron water in Saginaw Bay but maintains its identity along the western coast of Lake Huron to the St. Clair River.

Because the volume of Lake Erie is low and the industrial-urban development is high, chloride concentration is relatively high. The Detroit River is a major source of chloride in Lake Erie (Figure 4–141). Other significant sources are Toledo and the Maumee River, Cleveland, the Grand River, and the industrial region from Lorain, Ohio, to Erie, Pennsylvania.

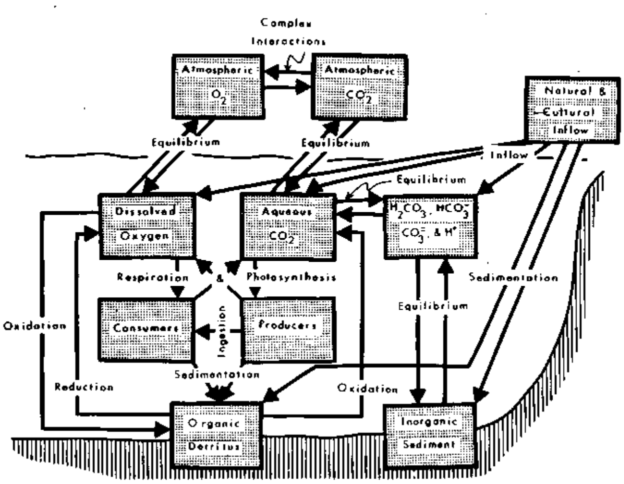


FIGURE 4–144 Simplified Oxygen-Carbon Cycle in a Lake

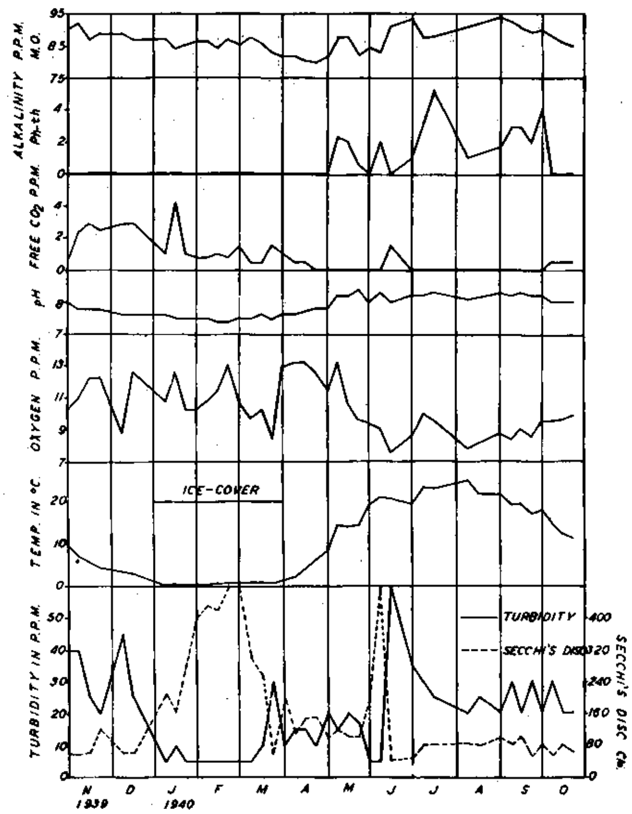


FIGURE 4–145 Methyl Orange Alkalinity, Phenolphthalein (ph–th) Alkalinity, Free Carbon Dioxide, pH, Dissolved Oxygen, Temperature, and Turbidity Values in the Upper Meter of Water in the Bass Island Area of Western Lake Erie. Secchi disc readings are in centimeters.
From Chandler, 1942

Lake Ontario reflects the loading from Lake Erie and contributions from Toronto-Hamilton, Ontario, and it receives mean concentrations of about 160 mg/l from the Oswego and Genesee Rivers in New York (Figure 4–142). Subsection 7.8 contains additional chloride loading data.

7.5.3 Carbonate System

The system that includes the interaction of water and carbon dioxide is one of the most important chemical life-support systems. Carbon dioxide, a required ingredient for photosynthetic activity, is present in the lakes in varying amounts. Sources of carbon dioxide are exchange with the atmosphere, oxidation of organic material, respiration, and mineral weathering.

Carbon dioxide is highly soluble in water and forms several aqueous compounds. The following aqueous reactions involve exchange with atmospheric carbon dioxide:

$$CO_2 + H_2O = H_2CO_3 \quad (30)$$

$$H_2CO_3 = H^+ + HCO_3^- \quad (31)$$

$$HCO_3^- = H^+ + CO_3^{-2} \quad (32)$$

Equilibrium relationships within the system are controlled by water temperature, pressure, atmospheric carbon dioxide pressure, and association with reactive solids such as the mineral calcite ($CaCO_3$).

It is simple to measure pH, the negative logarithm of hydrogen ion activity, and pH anomalies can be used to identify imbalances in the carbonate system. However, pH by itself cannot be used as an indicator of the viability of the life-support system. Alkalinity (essentially H_2CO_3, HCO_3^- or bicarbonate, and CO_3^{-2}) is also needed.

Bicarbonate is the dominant naturally occurring anion in the lakes because chemical weathering of naturally occurring substances often includes carbonic acid (H_2CO_3) as a titrant:

$$H_2CO_3 + \text{mineral} = HCO_3^- + \text{degraded mineral} + \text{dissolved ions} \quad (33)$$

Bicarbonate concentration is reflected in conductivity, dissolved solids, and hardness. In limestone and dolomite terranes aqueous reaction with CO_2 causes the pH and hardness to increase, reducing the wetting ability of cleansers and causing boiler scale after evaporation. In pollution studies, pH, bicarbonate, hardness, and alkalinity are used to identify areas where highly reactive substances are being released. Reequilibration with the atmosphere, with aqueous carbonate species, and with reactive sediment, and dispersion produce rapid assimilation of effluents with undesirable carbonate loads.

The carbonate cycle in the Great Lakes is part of a complex biochemical system (Figure 4–144) that is characterized by equilibrium relationships with other chemical constituents and is vital to plant and animal life. Much of the bottom sediment can act as a buffer on the carbonate system. The most abundant carbonate buffering mineral is calcite ($CaCO_3$), which limits pH fluctuations by precipitation or dissolution. The dissolution and/or precipitation of calcite and the carbonate buffering process is discussed in Subsection 7.5.8.

Many of the organisms in the lakes that are considered aesthetically or economically important have low tolerances to pH fluctuations. For example, fish production appears best within a pH range of 6.5 to 8.4 (Rudolfs[687]) and plankton production is optimal between 7.5 and 8.4 (Chandler[131]). Because of the nature of the equilibria within the carbonate system, high or low pH may cause imbalances in other constiuents vital to aquatic life and water quality.

Because carbon dioxide is a plant nutrient, simple equilibrium relationships between elements of the carbonate system rarely hold in natural waters (Verduin,[856] Sechriest[727]). Verduin showed that the rate of photosynthesis per unit plant volume was essentially the same during winter and summer. However, because of the differences in standing crop, carbon dioxide fixation averaged 68 μmoles absorbed per liter of water per day at 23°C decreasing to 10 μmoles at 0°C. Carbon dioxide equilibration with the atmosphere is negligible compared with changes in the water column, thus necessitating a near balance between CO_2 production by respiration and CO_2 metabolism by photosynthetic autotrophs. Disruption of this balance may be a factor in the accelerated eutrophication occurring in the Great Lakes. Kuentzel[478] and Tang and Bhagat[785] suggested that increased contribution of biogenic CO_2 from respiration of the organisms that degrade sewage (Subsection 7.5.4) may now be the limiting factor in eutrophication. Chandler[133] described the temporal variation of alkalinity, pH, and oxygen (Figure 4–145) over the span of a year 1939–40). His data show the interaction of oxygen and the carbonates. During the winter months mixing and oxygenation occur, alkalinity and pH are relatively low, and free CO_2 is high. During the summer, with increased temperature and stratification, oxygen is reduced, and pH and alkalinity increase.

The distribution of pH in the lakes indicates sources of abnormal acid or basic waste discharge and the degree of equilibration of the carbon system with the atmosphere and sediment. Lake Huron and the lower lakes have increasingly higher pH, which probably represents equilibration with the carbonate minerals present in the lake sediments. Sources of acid discharge in Lake Superior (Figure 4–146) are along the Minnesota shore, the Thunder Cape area of Ontario, Batchawana Bay, and the region near Black River, Michigan. All of

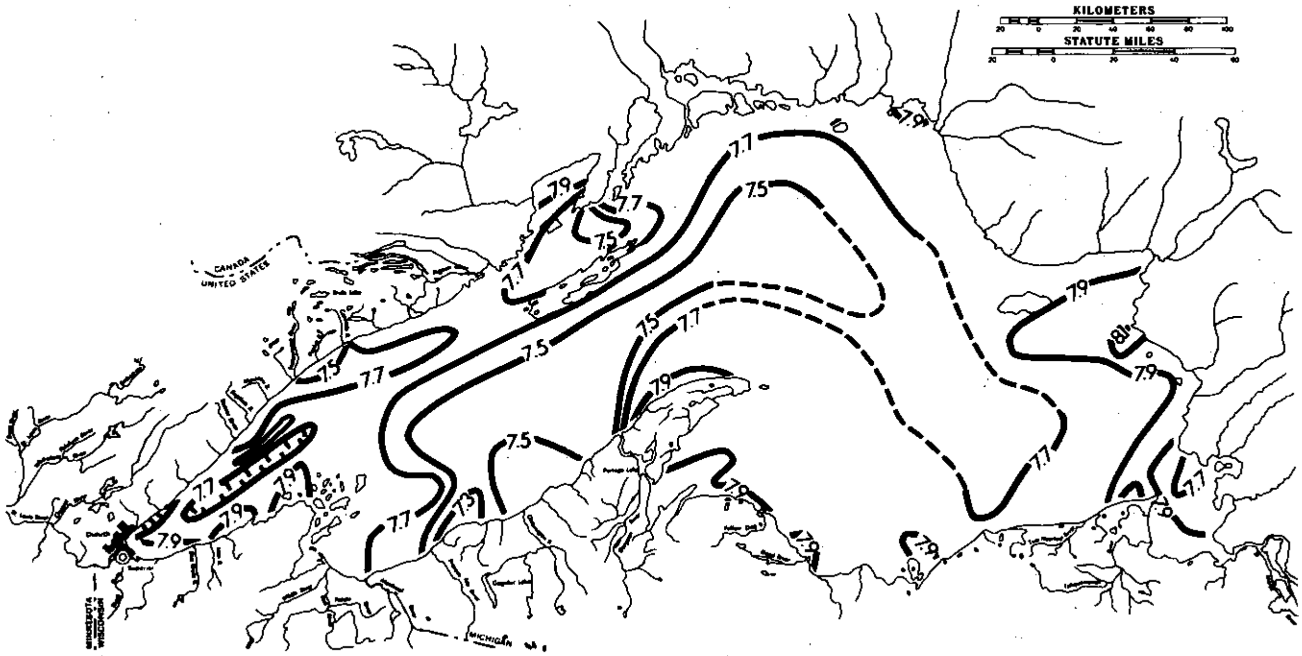


FIGURE 4–146 Representative Distribution of pH in Lake Superior Surface Water
Data from Lake Survey Center (NOS–NOAA) cruises 7/18–8/8/68 and 7/27–8/9/69

FIGURE 4–147 Representative Distribution of pH in Lake Huron Surface Water
Data from Lake Survey Center (NOS-NOAA) cruise 8/2–8/17/66

these areas are characterized by mining activity and the low pH may reflect acid mine water. During the synoptic survey represented in Figure 4–147, Lake Huron was thermally stratified. A distinct chemocline existed, with higher pH water in the epilimnion. The higher pH above the chemocline indicates that the water in the epilimnion is more nearly in equilibrium with the atmosphere and carbonate minerals than that of the hypolimnion. Lake Michigan data are insufficient for determination of the areal distribution of pH. In Lake Erie pH show the effects of increased equilibration with the atmosphere and carbonate minerals (Figure 4–148). High pH in the vicinity of Cleveland suggests an influx of basic constituents. The principal areas of lower pH water in Lake Ontario (Figure 4–149) are near Oswego, the Toronto-Hamilton coast, and the area around Oshawa, Ontario. Part of the difference in pH between surface and bottom water observed in the lakes is due to atmospheric interaction. However, Hartley et al.[322] show that high pH water on the surface of the western basin of Lake Erie is a result of additions near the mouth of the Detroit River (Figure 4–150). Due to the buffering capacity of natural waters, pH is not useful for identification of pollution sources. The primary use of pH is in determining reaction paths in systems that are dependent on pH.

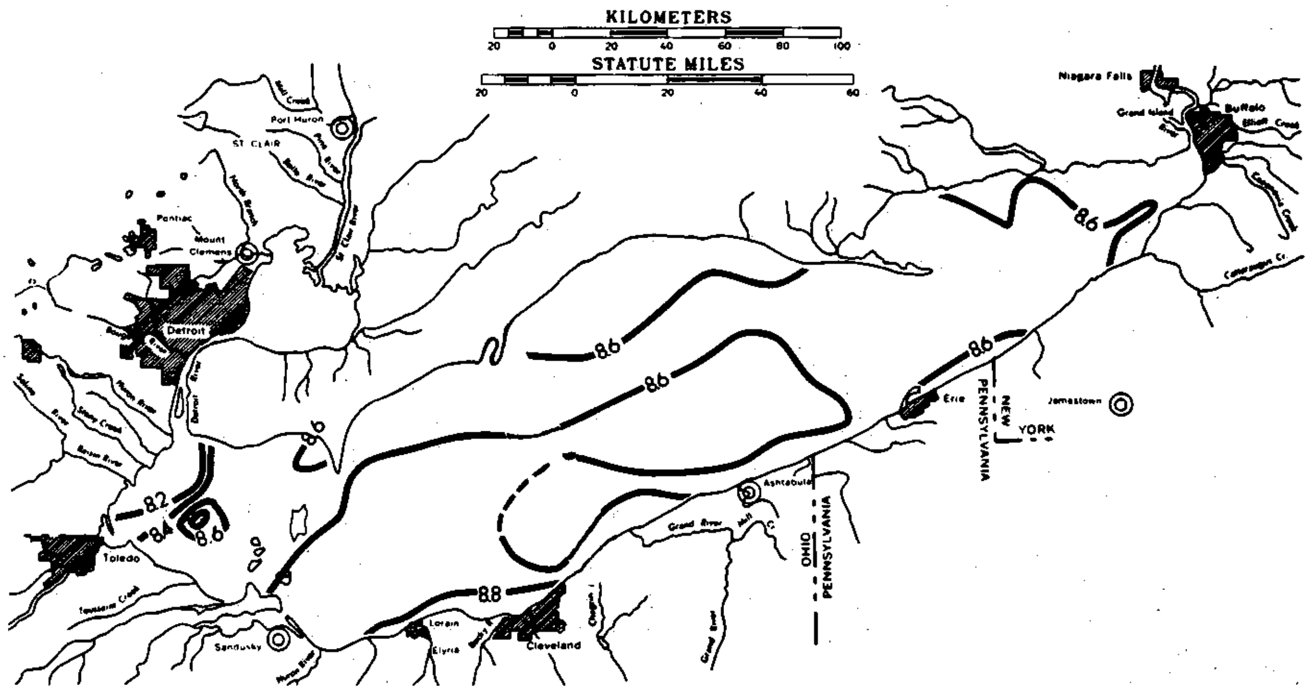


FIGURE 4–148 Representative Distribution of pH in Lake Erie Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

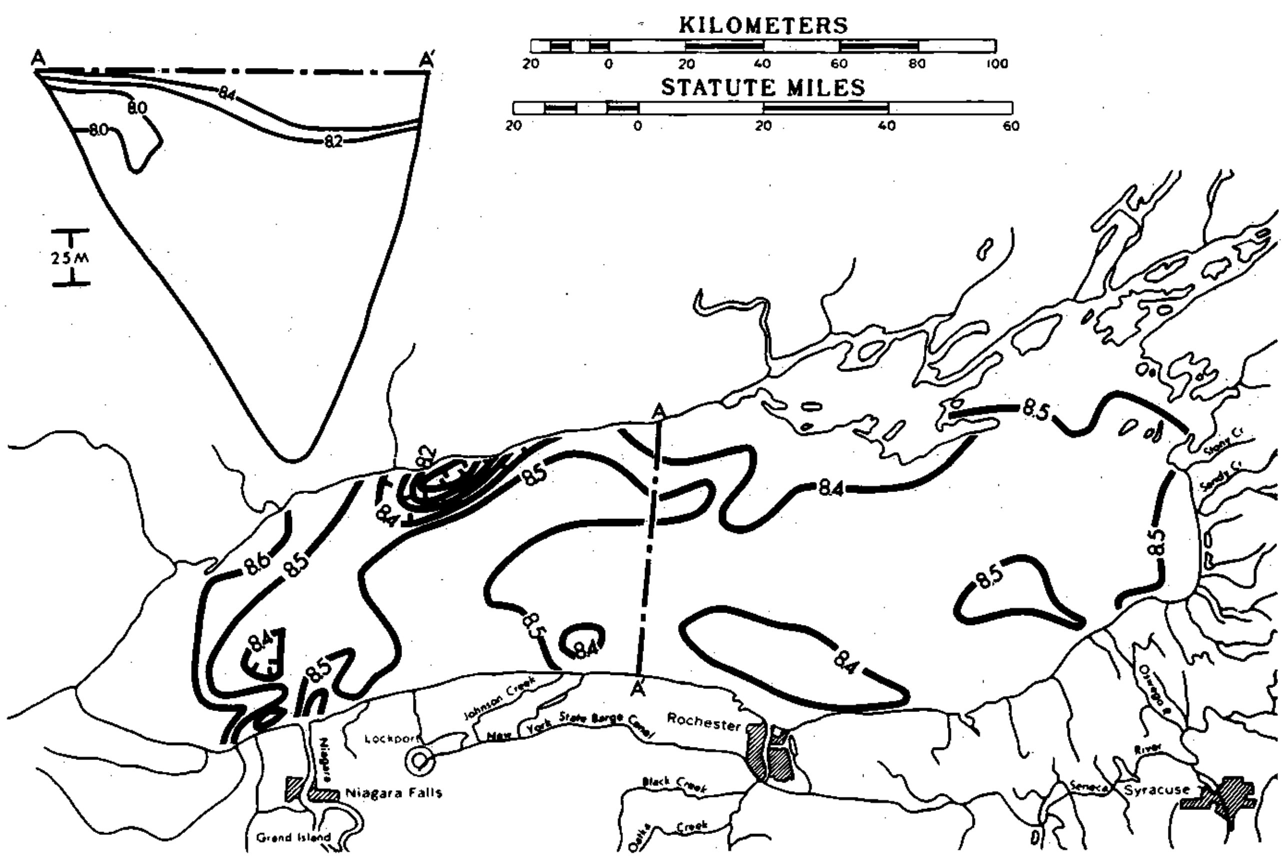


FIGURE 4–149 Representative Distribution of pH in Lake Ontario Surface Water
Data from Canada Centre for Inland Waters (1969) cruise 8/2–8/7/66

Alkalinity is more useful than pH because it represents the products of reactions involving hydrogen ions and CO_2. Alkalinity of the lakes (Figures 4–151 through 154) increases downstream suggesting equilibration with carbonate minerals. High alkalinity indicates possible influx of material with a high carbonate content. Kramer[472] discussed the tendency toward carbonate, silicate, and phosphate equilibria downstream in the lakes and showed that Lake Erie is nearest to equilibrium of the five Great Lakes (Figure 4–155). Distribution of alkalinity supports Kramer's conclusion.

7.5.4 Oxygen System and Redox Potential

Dissolved oxygen is required for the metabolic activity of most aquatic organisms. The solubility of oxygen in water is low and is dependent upon pressure and temperature. Oxygen is more soluble in cold water than warm, so hypolimnetic water normally serves as an oxygen reservoir. Oxygen replenishment is dependent on exchange with the atmosphere and on photosynthetic activity (Figure 4–144). Therefore, deep water is oxygenated only when the lakes are unstratified. In the summer the hypolimnion deoxygenates in varying degrees relative to biological and biochemical demands. Bacteria and oxidizable organic constituents are more efficient at removing oxygen from water than most macro-organisms, so the introduction of sewage or other easily oxidized material encourages development of oxidizing bacterial populations, increases dissolved oxygen demand, and accelerates oxygen depletion in relation to volume of the hypolimnion. Tolerances to low oxygen levels vary, but most Great Lakes fauna cannot tolerate extremely low levels.

Five characteristics are commonly used to describe the oxygen system:

(1) Dissolved oxygen concentration is a measure of the amount of elemental oxygen in the system.

(2) Oxygen activity is a measure of the free oxygen available for metabolic activity and does not include complexes or combined forms of oxygen.

(3) Percent saturation of oxygen is more meaningful than oxygen activity or dissolved oxygen concentration because the solubility of oxygen in water is a function of water temperature, the partial pressure of oxygen in air, and the mineral content of the water. By measuring percent saturation the oxygen level is related to the total amount of oxygen that can be contained by the water at a specific temperature, air pressure, and ionic strength. Percent saturation and oxygen activity are indices of the capability of a water mass to support a well-balanced aquatic community.

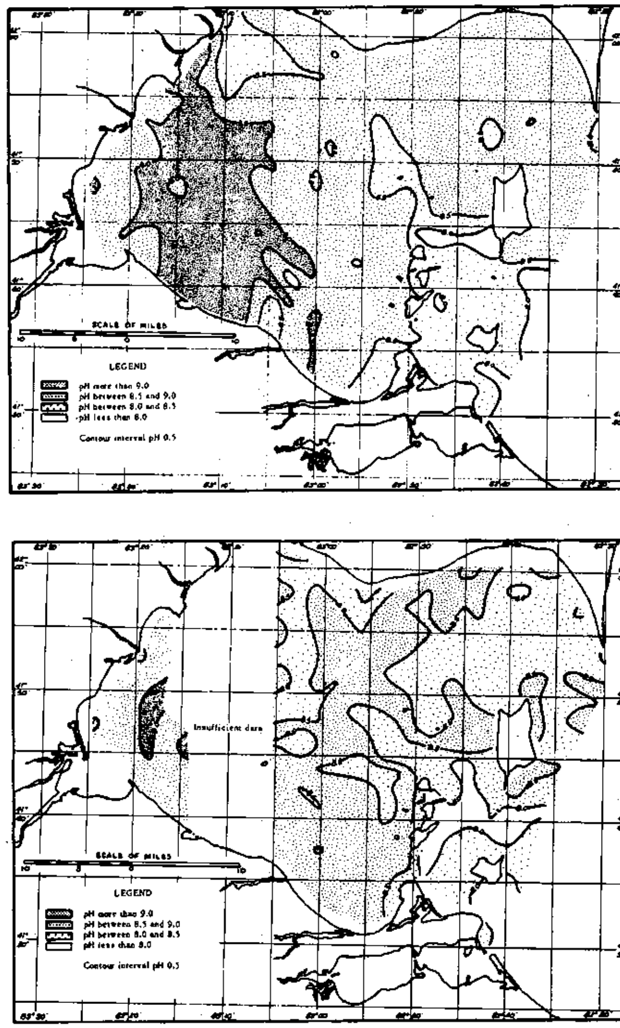


FIGURE 4–150 Hydrogen Ion Concentration (pH) of Surface (upper figure) and Bottom (lower figure) Water in Western Lake Erie on June 23, 1963

From Hartley et al., 1966

(4) Biochemical oxygen demand (BOD) is a measure of the removal of oxygen from water by organic material. This oxygen removal is accomplished by four mechanisms:

(a) oxidation of carbonaceous material
(b) oxidation of nitrogen compounds
(c) oxidation of sulfur compounds
(d) oxidation of easily oxidized inorganic compounds

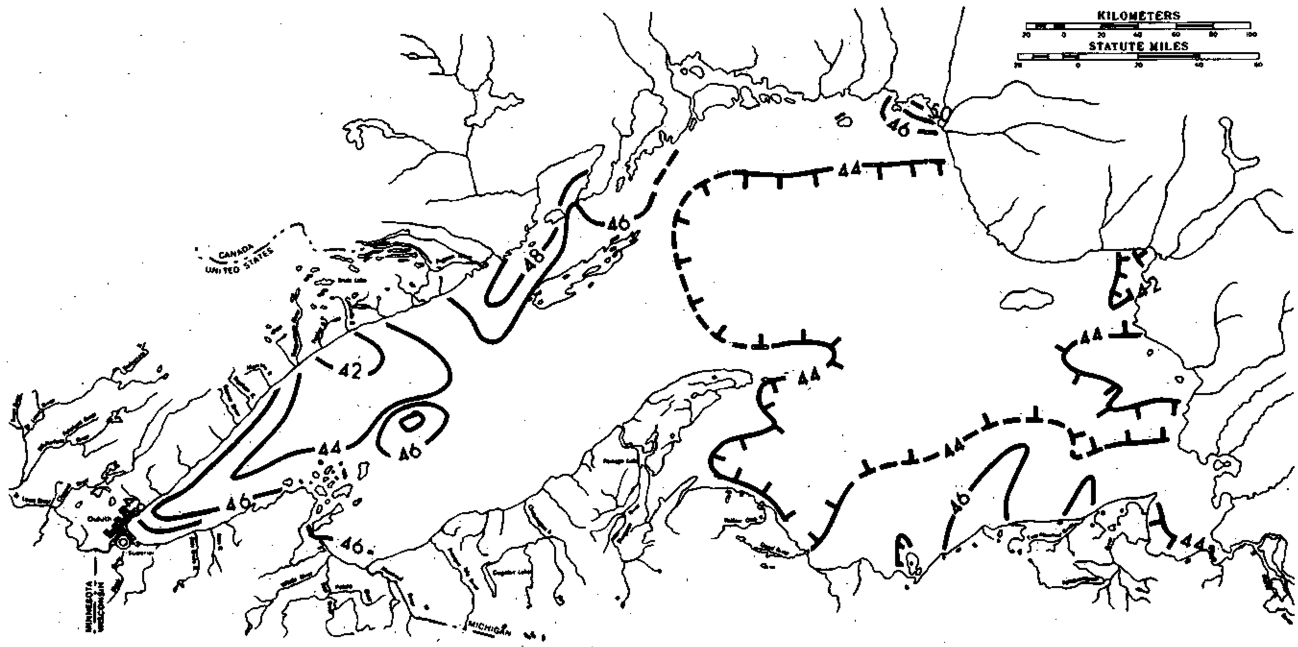


FIGURE 4–151 Representative Distribution of Alkalinity (mg/l) in Lake Superior Surface Water
Data from Lake Survey Center (NOS–NOAA) cruises 7/18–8/8/68 and 7/27–8/9/69

FIGURE 4–152 Representative Distribution of Alkalinity (mg/l) in Lake Huron Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 8/2–8/17/66

In polluted water the first three mechanisms are most important. BOD as such is not a pollutant, but oxygen is used up by this process that could otherwise be available to macroorganisms. Therefore, high BOD, if it is not complemented by oxygen replenishment, can cause harm by disruption of the food chain and deterioration of the normal ecosystem.

(5) Chemical oxygen demand is a measurement, expressed in terms of the oxygen equivalent, of the material that can be oxidized by a strong chemical oxidant. It differs from BOD in that BOD is a measure of the amount of organic material that can be oxidized while COD is a measure of the total amount of material that can be oxidized.

A useful concept for relating dissolved oxygen to BOD is the oxygen sag curve (Bartsch and Ingram[42]). In a stream, which is linear as compared to a lake, and with known rate and flow characteristics, the relationship of BOD and available dissolved oxygen can be computed mathematically. If BOD exceeds the oxygen replenishment rate, deoxygenation occurs (Figure 4–156) and the biota suffers. Survival of the biota depends on magnitude of BOD and the time required to reoxygenate the water. The same processes that operate in streams operate in the lakes, but are much more difficult to characterize in a lake. Factors that affect BOD in a lake include depth and stratification, atmospheric pressure, water movement, turbulence, temperature,

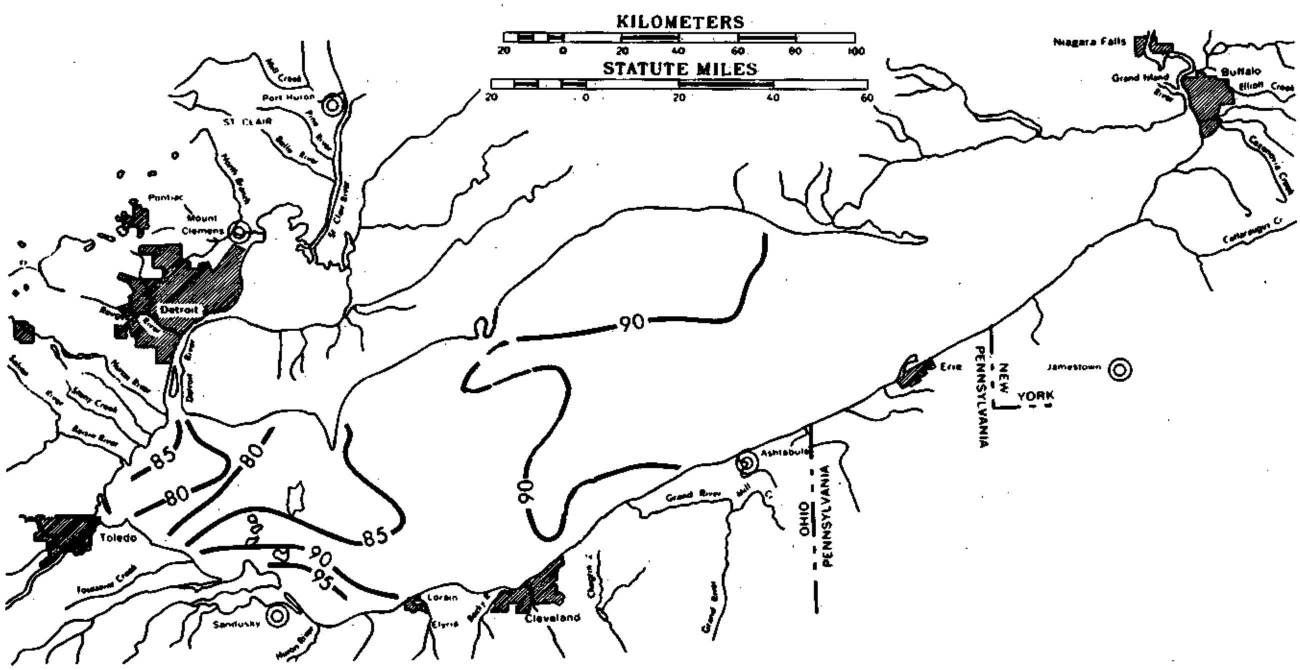


FIGURE 4–153 Representative Distribution of Alkalinity (mg/l) in Lake Erie Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

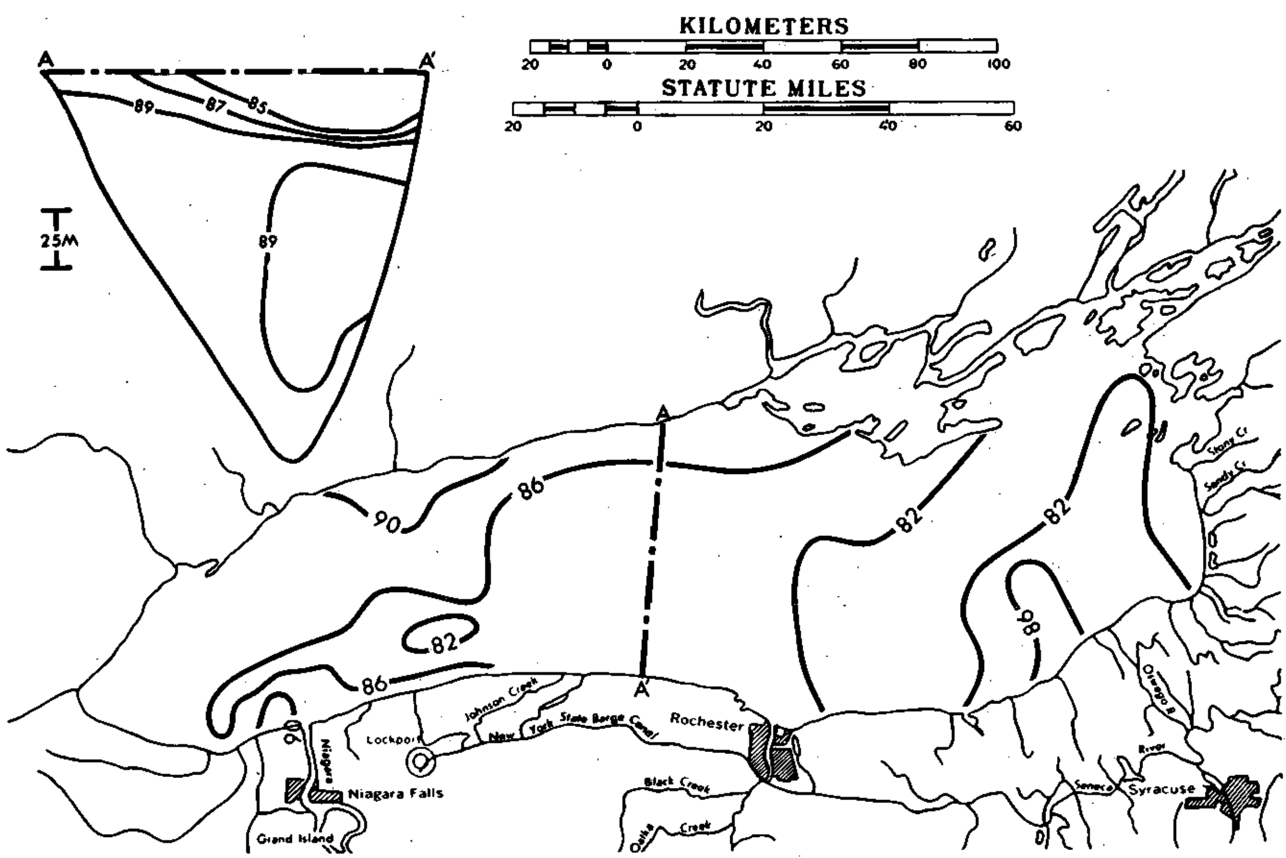


FIGURE 4–154 Representative Distribution of Alkalinity (mg/l) in Lake Ontario Surface Water
Data from Canada Centre for Inland Waters (1969) cruise 8/2–8/7/66

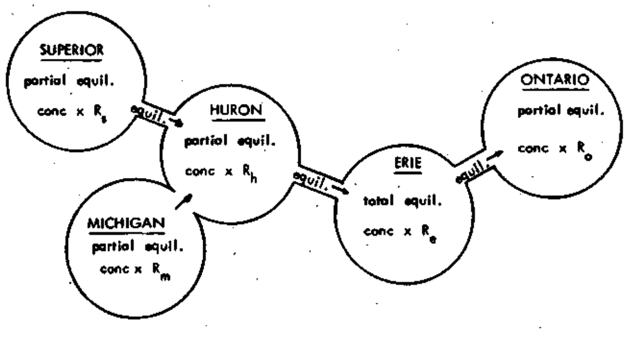


FIGURE 4–155 Development, Chemical Equilibrium, and Inheritance of Concentrations in each of the Great Lakes. The "R" refers to the ratio of total evaporation per area per time to precipitation per area per time.

From Kramer, 1964

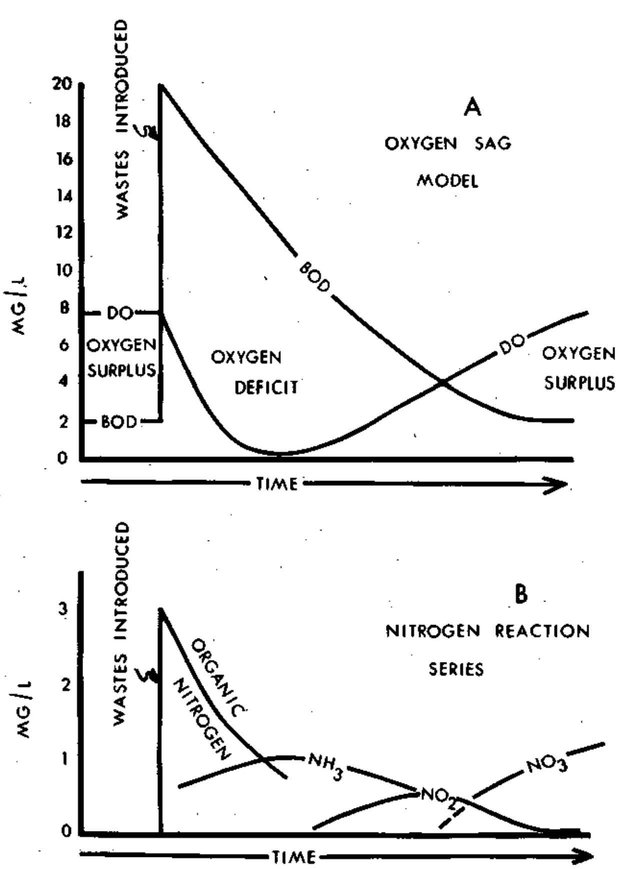


FIGURE 4–156 Theoretical Sequences of Reactions Showing Oxygen Sag (A) and Nitrogen Reaction (B) upon Introduction of Organic Wastes

light penetration and nutrient supply to the photosynthetic autotrophs, and quantity of introduced wastes. Sediment permeability and organic content control the depth below the sediment-water interface to which the oxygen demand is effective. Thorstenson and Mackenzie[797] studied migration of pore-water chemicals in the sediments of Harrington Sound, Bermuda, and concluded that annual exchange with the overlying water may take place to depths as great as 1 m into the sediment. BOD is retarded by low temperatures, so the maximum oxygen demand occurs in warm water, such as harbors, shallow embayments, and shallow portions of the lakes. In the process of biogenic oxidation, CO_2 (which is required for photosynthetic activity) is produced. Excessive algal production is an indication of an excessive rate of eutrophication. Thus, BOD may be directly linked to eutrophication (Kuentzel;[478,478a] Tang and Bhagat[785]), although upland lakes would be more susceptible than the Great Lakes.

The oxidation-reduction or redox potential (Eh) is used to determine the potential of an environment to oxidize or reduce material. Oxidation is a loss of electrons (e.g., $Fe^{2} \rightarrow Fe^{3}$) and reduction is a gain of electrons, so the oxidation-reduction potential measures the direction that electrons flow between a water sample and a reference hydrogen electrode. If the Eh is negative, compounds will be reduced, while positive Eh indicates a tendency to oxidation. In inorganic systems the free energies of the reactions determine the Eh. If organic activity is present, then the metabolic process controls Eh. For example, certain bacteria have the ability to oxidize organic wastes at the expense of other oxidation-reduction reactions in the system, and the environment becomes a reducing environment. Oxygen availability is a major factor in controlling Eh. Other factors that govern Eh are free energies of reaction, metabolic activity, and pH of the system, so Eh represents a combination of inorganic and metabolic reactions.

The importance of Eh is evident when the interaction of tributary and lake water in a polluted harbor is considered. If compounds that are easily oxidized (e.g., sulfites, organic sewage) are introduced, the bacterial and inorganic oxidation of these compounds forces reduction of compounds with lower oxidation potentials. The subsequent consumption of oxygen at a higher rate than reaeration hinders complete oxidation of the materials that are easily oxidized. The wastes that are not oxidized in the confined area of the harbor remain as potential sites for oxygen consumption and electron removal until buried or transported to a less restricted area. The resulting waste, which has a negative Eh, causes

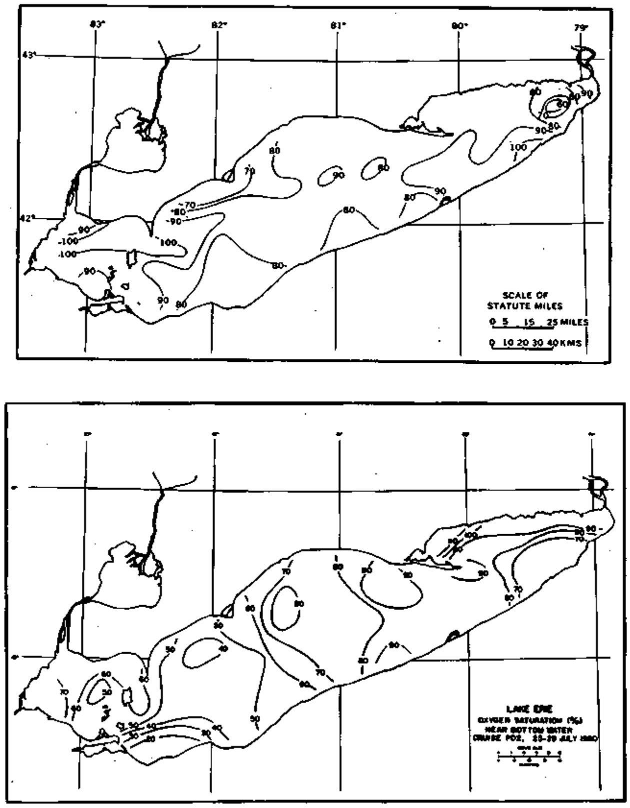


FIGURE 4–157 Surface (upper figure) and Bottom (lower figure) Percent Oxygen Saturation in Lake Erie on July 25 to 29, 1960. Dots indicate sampling stations.
From Anderson and Rodgers, 1966

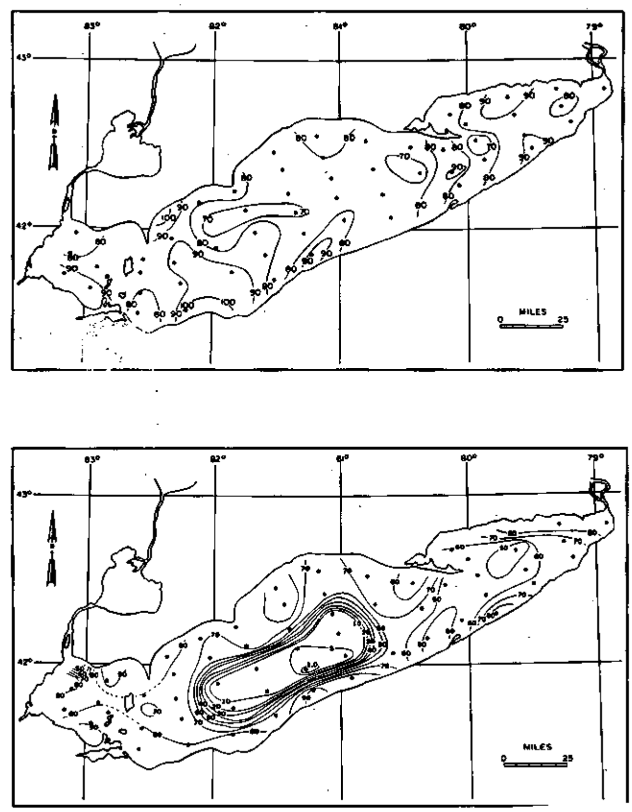


FIGURE 4–158 Surface (upper figure) and Near Bottom Water (lower figure) Percent Oxygen Saturation in Lake Erie on September 26 to 30, 1960
From Anderson and Rodgers, 1964

problems such as methane and acetylene gas production, and bottom and water quality degradation if transported into cleaner environments.

Oxygen in Great Lakes water has been thoroughly studied and regions of oxygen depletion have been identified. The only major open lake region in the Great Lakes where oxygen depletion is known to be critical is in the central basin of Lake Erie (Figure 4–157). Carr[124] and Carr et al.[126] concluded that intermittent low oxygen levels have been present in the central basin since the late 1920s. The low oxygen levels occur during periods of stratification when BOD in the low volume hypolimnion exceeds available oxygen. Materials balance studies of BOD material entering Lake Erie indicate that the oxygen demand in the lake exceeds the BOD of this material. The annual organic waste load into Lake Erie has a BOD equivalent to 82 million kilograms (180 million pounds) of oxygen whereas a recent period of oxygen depletion had an estimated deficit of 122 million kilograms (270 million pounds) of oxygen (Commoner[161]). Therefore cultural inputs alone cannot account for the annual oxygen deficit. The answer lies in the accumulation and decay of material that is not consumed or decomposed in the water column and in turn increases BOD and oxygen consumption. Anderson and Rodgers[13] show the deoxygenation dramatically (Figure 4–158). Thermal stratification leads to rapid oxygen depletion near the bottom of Lake Erie because volume of the hypolimnion is small, and the oxygen cannot be effectively replenished. An additional impact of low oxygen is the release of nutrients that had been previously removed from the system by sediment interaction. The release of nutrients accelerates algal production and further deoxygenation, thus creating a cyclical flux of materials that can become self-sustaining.

The other Great Lakes have not had deoxygenation problems as yet because supplies of oxygen in their hypolimnions greatly exceed demand. Continued release of BOD materials and nutrients in the other

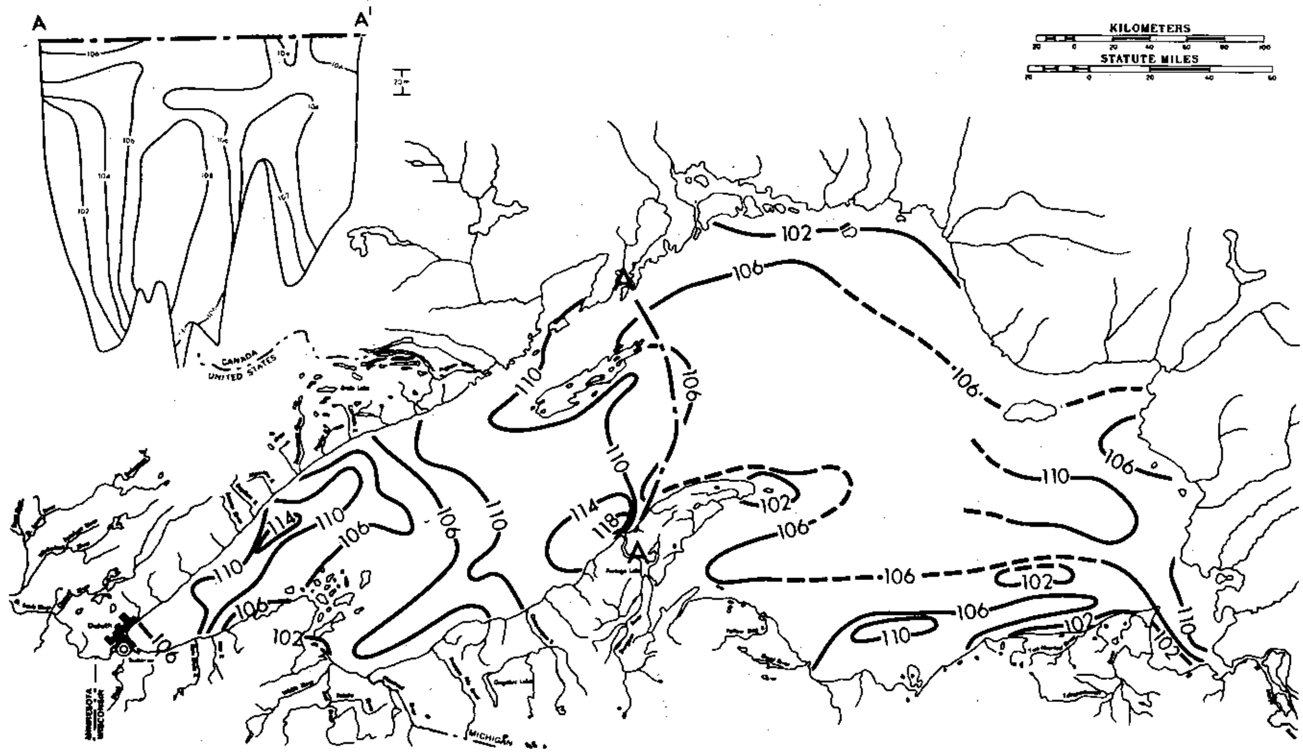


FIGURE 4–159 Representative Oxygen Concentrations (percent saturation) in Lake Superior Surface Water

Lake Survey Center (NOS–NOAA)

lakes could cause problems similar to those in Lake Erie in the future.

Oxygen depletion is also a problem in a few of the Great Lakes embayments (Figures 4–159 through 163). Oxygen depletion occurs at the southern end of Green Bay where circulation is restricted. A 1963 survey by the FWPCA[835] showed an average DO saturation of 52 percent in the southern part of Green Bay. The minimum recorded saturation during 1963 was zero (Figure 4–164). None of the other major embayments have serious oxygen depletion problems.

BOD data are not available for all of the Great Lakes and their embayments. Studies have largely been restricted to harbors and sewage outfalls. The FWPCA[833,834] made a reconnaissance in 1963 and 1967–68 of Lake Erie BOD and COD levels along a longitudinal traverse of the lake (Table 4–34). The COD data are of particular interest because they indicate significant changes in the load of oxidizable material in the lake. In the central basin, water COD increased 20 percent and sediment demand decreased 25 percent. In the eastern basin water COD and sediment COD increased by 10 percent and 70 percent, respectively. Although these changes may reflect natural environmental variations or inadequate sampling, they indicate the rapidity with which the system can develop oxygen demands, if conditions are appropriate. The extreme difference in oxygen demand of water and sediment due to the concentration of organic debris by sedimentation is also illustrated.

Biochemical oxygen demand is highly variable in the other Great Lakes as well as in Lake Erie. Lake Superior BOD is extremely low (Figure 4–165). However, Duluth, Silver Bay, Grand Marais, Thunder Bay, Marathon, Michipicoten, the Tahquamenon River, and the Apostle Islands are regions of local high BOD loadings. Data for Lake Michigan are insufficient for a map showing regional BOD distribution. The average BOD of inshore water for Lake Michigan in 1962–63 (FWPCA[835]) was 1.4 mg/l, with a maximum of 8.6 mg/l. BOD levels in Traverse Bay on Lake Michigan for the same period range from 0.6 mg/l to 1.7 mg/l, with an average of 1.2 mg/l. No data are available for Green Bay. Highest BOD values in Lake Erie occur in the Detroit River, Toledo Harbor-Maumee River, the middle of the central basin off Cleveland, Erie Harbor, Dunkirk Harbor, and the head of the Niagara River (Figure 4–166). The concentra-

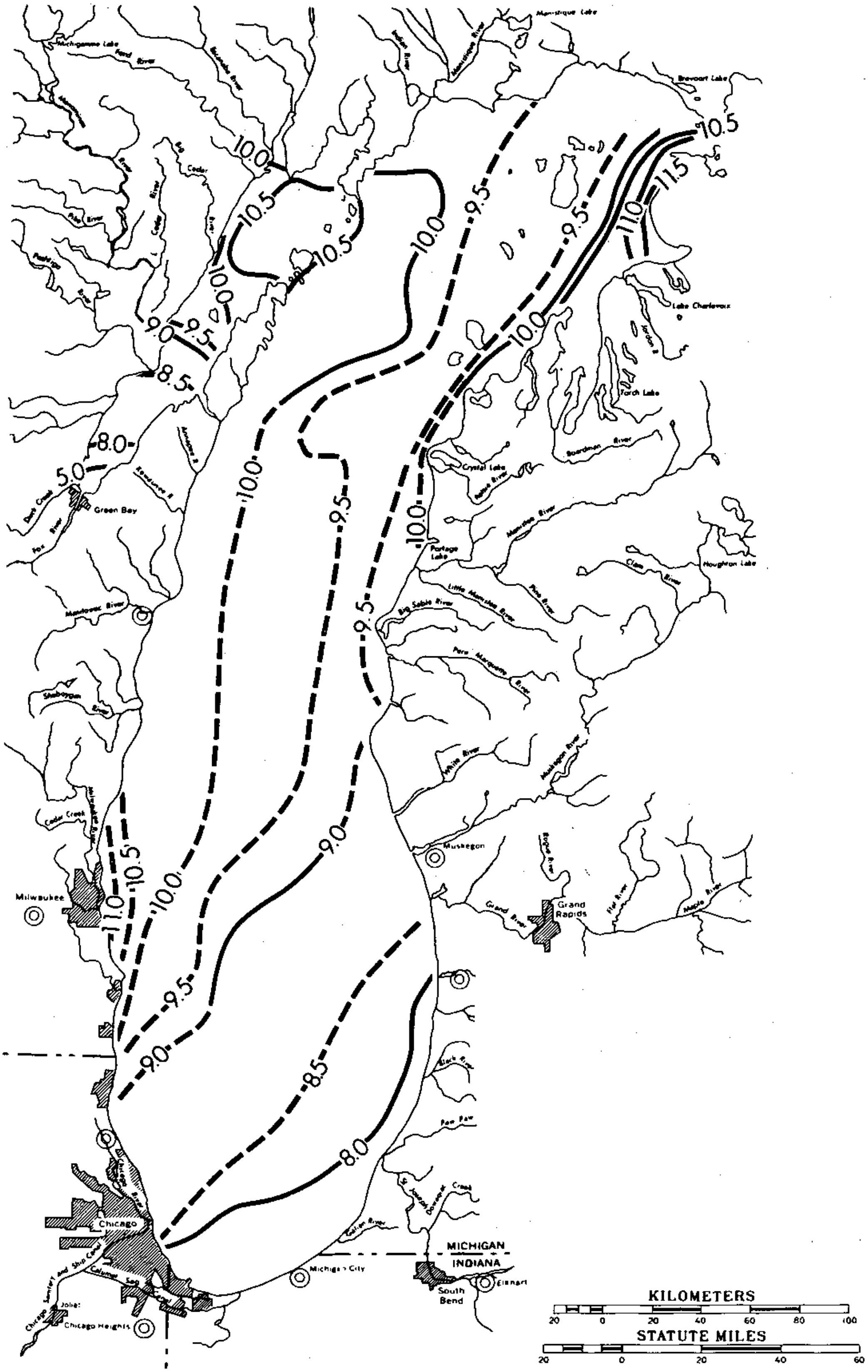


FIGURE 4–160 Representative Oxygen Concentrations (mg/l) in Lake Michigan Surface Water

Data from Beeton and Moffett, 1964

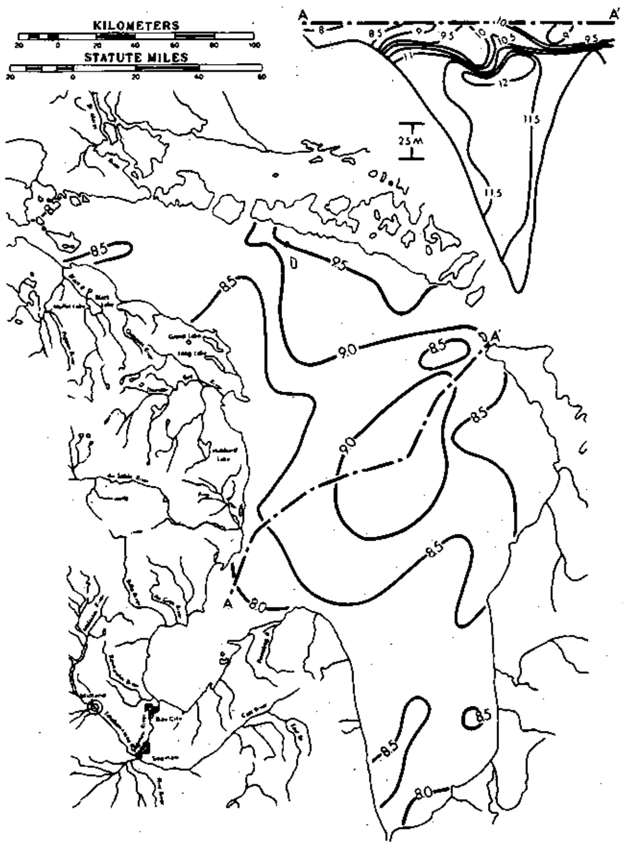


FIGURE 4–161 Representative Oxygen Concentrations (mg/l) in Lake Huron Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 8/2–8/17/66

tion of high BOD materials in the central basin is a major factor in the severe deoxygenation in that region. The BOD of Lake Ontario sediments is essentially as high as that of Lake Erie sediments (Figure 4–167). Volume of water in the hypolimnion prevents regional deoxygenation. Lake Ontario sources of BOD are the Toronto-Hamilton area, the Niagara River, and the region near Sodus Bay, New York.

Eh data from the lakes are as scarce as BOD data. A large number of observations have been made in harbors and restricted areas but only Lakes Superior, Huron, and Erie have synoptic data for an entire lake (Figures 4–168 through 4–170). Negative Eh values are infrequent in Lakes Superior and Huron. They occur primarily near harbors and are indicative of municipal waste loading and possibly mine drainage. Lake Erie had extensive areas of negative Eh during the synoptic survey represented in Figure 4–170. The extensive negative Eh values in the sediment correspond with high organic loads and indicate the areal extent of the pollution problem.

7.5.5 Phosphorus System

Nutrients required by green algae include B, C, Ca, Cl, Co, Cu, Fe, H, K, Mg, Mn, Mo, N, Na, O, P, S, Si, V, Zn, and certain vitamins. Phosphorus is most often the controlling nu-

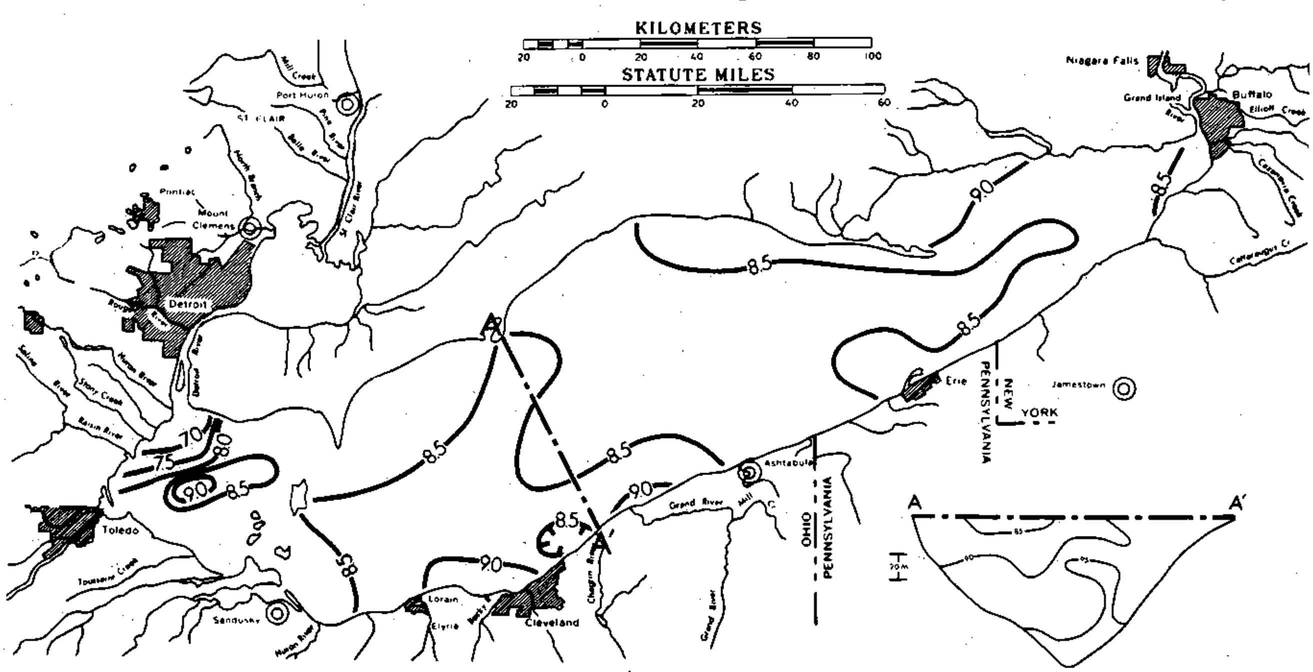


FIGURE 4–162 Representative Oxygen Concentrations (mg/l) in Lake Erie Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

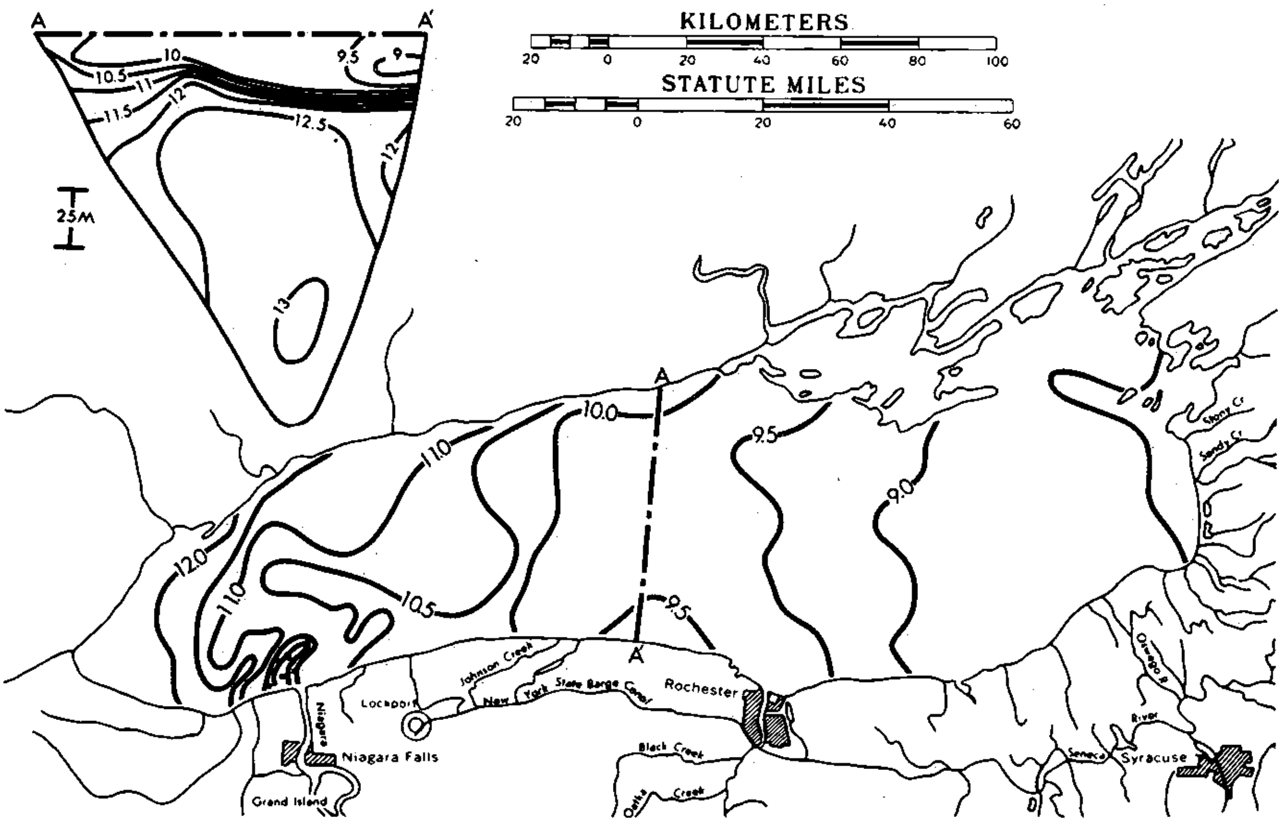


FIGURE 4–163 Representative Oxygen Concentrations (mg/l) in Lake Ontario Surface Water
Data from Canada Centre for Inland Waters (1969) cruise 8/2-8/7/66

TABLE 4–34 Lake Erie BOD and COD Values

	Water			Sediment			
	Average	Maximum	Minimum	Average	Maximum	Minimum	Year
		(mg/1)			(mg/g)		
BOD							
Total Lake	1.10	---	---	---	---	---	1967-68
Western Basin	1.7	4.1	0.4	1.6	2.9	0.9	1967-68
Central Basin	1.0	2.7	0.0	1.9	3.1	1.0	1967-68
Eastern Basin	1.2	2.5	0.2	1.9	3.1	1.0	1967-68
COD							
Total Lake	7.36	---	---	---	---	---	1967-68
	8.53	---	---	---	---	---	1967-68
Western Basin	10.4	29.0	1.1	63.5	96.0	6.0	1963-64
	9.8	18.9	5.5	66.1	85.8	39.1	1967-68
Central Basin	7.1	16.0	3.1	55.7	91.0	3.0	1963-64
	8.6	11.9	5.2	41.0	78.9	7.9	1967-68
Eastern Basin	7.4	27.0	4.7	27.8	79.0	1.0	1963-64
	8.2	11.0	6.1	48.1	77.0	33.3	1967-68

SOURCE: Federal Water Pollution Control Administration, 1968e

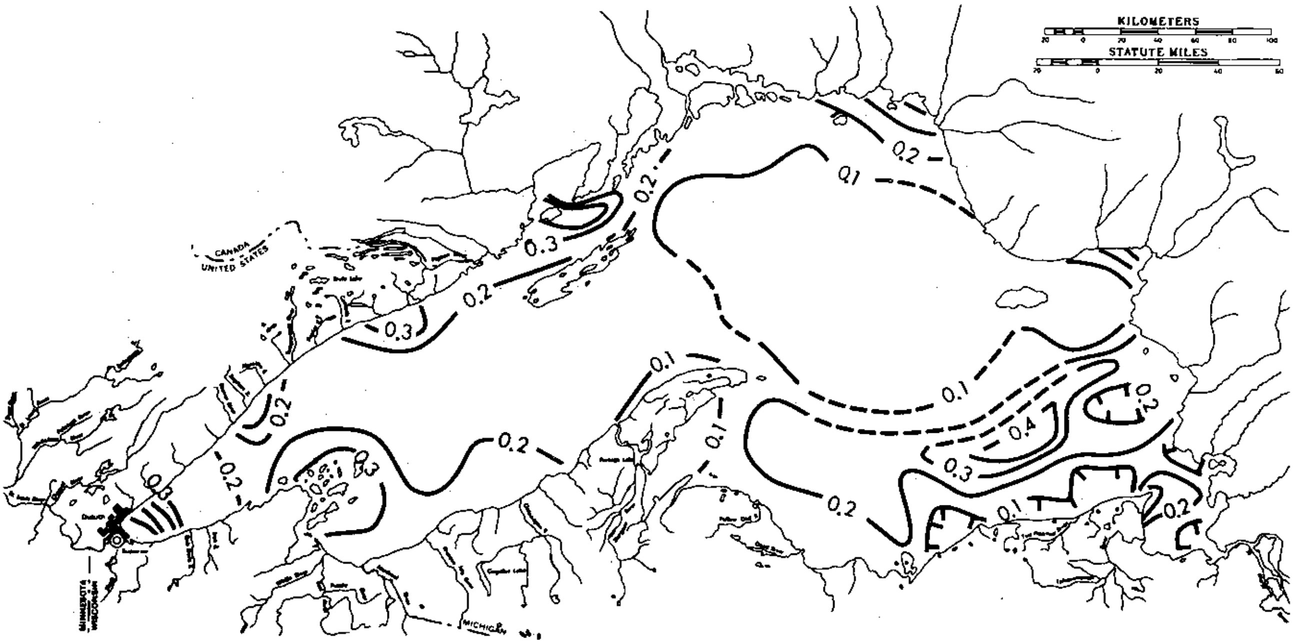


FIGURE 4–165 Representative Distribution of BOD (mg/l) in the Bottom Sediments of Lake Superior

Data from Lake Survey Center (NOS–NOAA) averages of data from May to November, 1968 and 1969

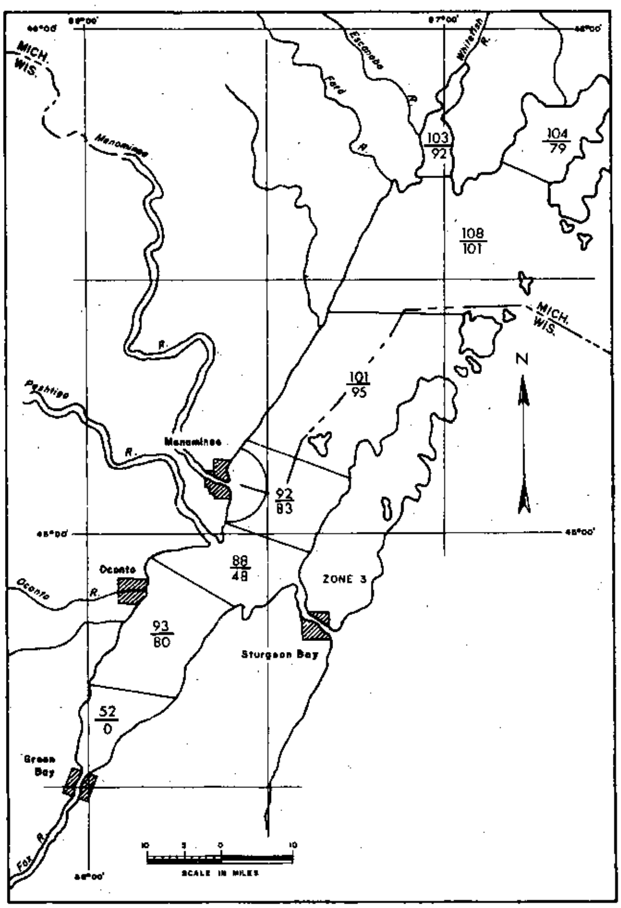


FIGURE 4–164 Mean (upper number) and minimum (lower number) Percent Oxygen Saturation in Green Bay, Lake Michigan, During 1963

Data from Federal Water Pollution Control Administration, 1968c

trient in the production of phytoplankton. The only natural source of phosphorus is limited weathering of phosphatic minerals in the drainage basin. Therefore, in juvenile undisturbed ecosystems phosphorus compounds are scarce and the growth of plants and animals is limited by the phosphorus availability. Consequently, phosphorus compounds would be immediately assimilated by plants as they became available through weathering (Figure 4–171). After phosphorus is in the food chain a portion of it is conserved and recycled from producer to consumer to decomposer to producer. Consequently, considerable recycling of phosphorus takes place in the biotic community.

If there is no limitation on algal production by nutrients or other factors, then increased primary production and nuisance algal blooms result. Overproduction of algae leads to increased turbidity, increased oxygen demand when the algae decompose, loss of valuable consumers such as predacious fish, and consequent degradation of over-all water quality. Increased productivity is a natural phenomenon in the eutrophication cycle and is usually visually evident in upland lakes. The use of phosphatic fertilizers and phosphate-rich detergents has obviated the limitation of phosphate on primary productivity and has accelerated eutrophication in many lakes and rivers. Control of the eutrophication process necessitates knowledge of the effects of nutrients on algal production. If phosphorus is the

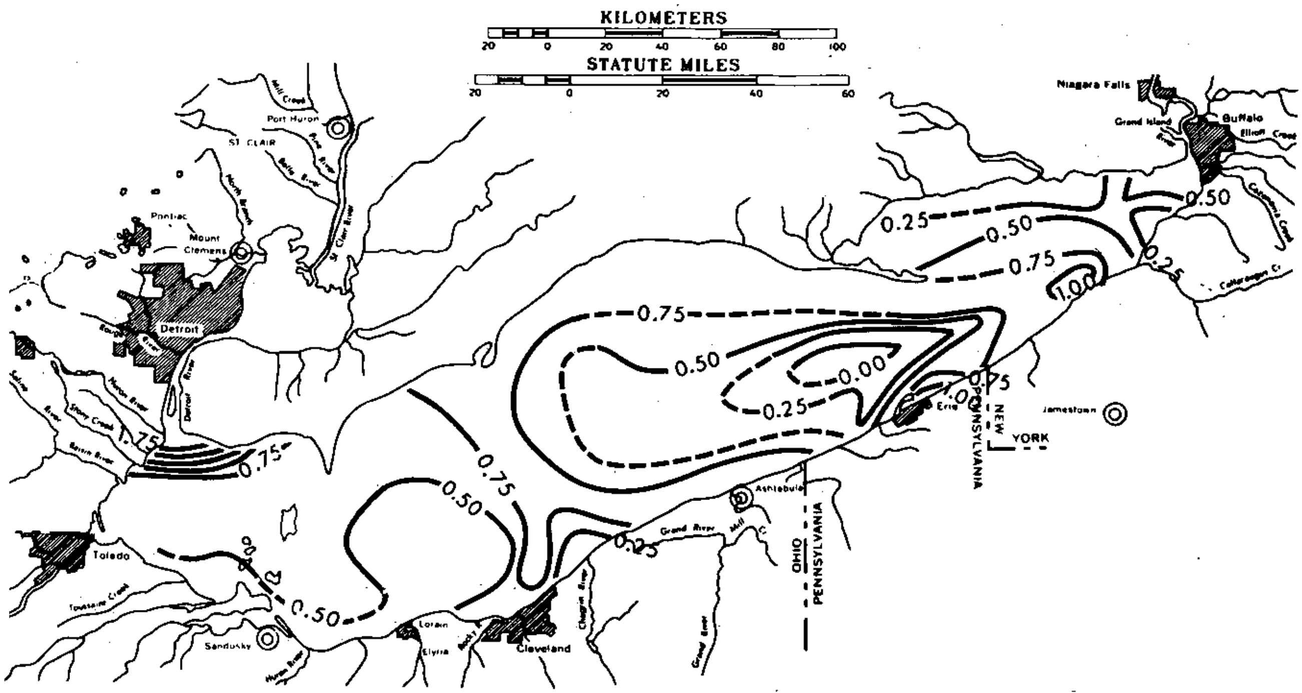


FIGURE 4–166 Representative Distribution of BOD (mg/l) in the Bottom Sediments of Lake Erie
Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

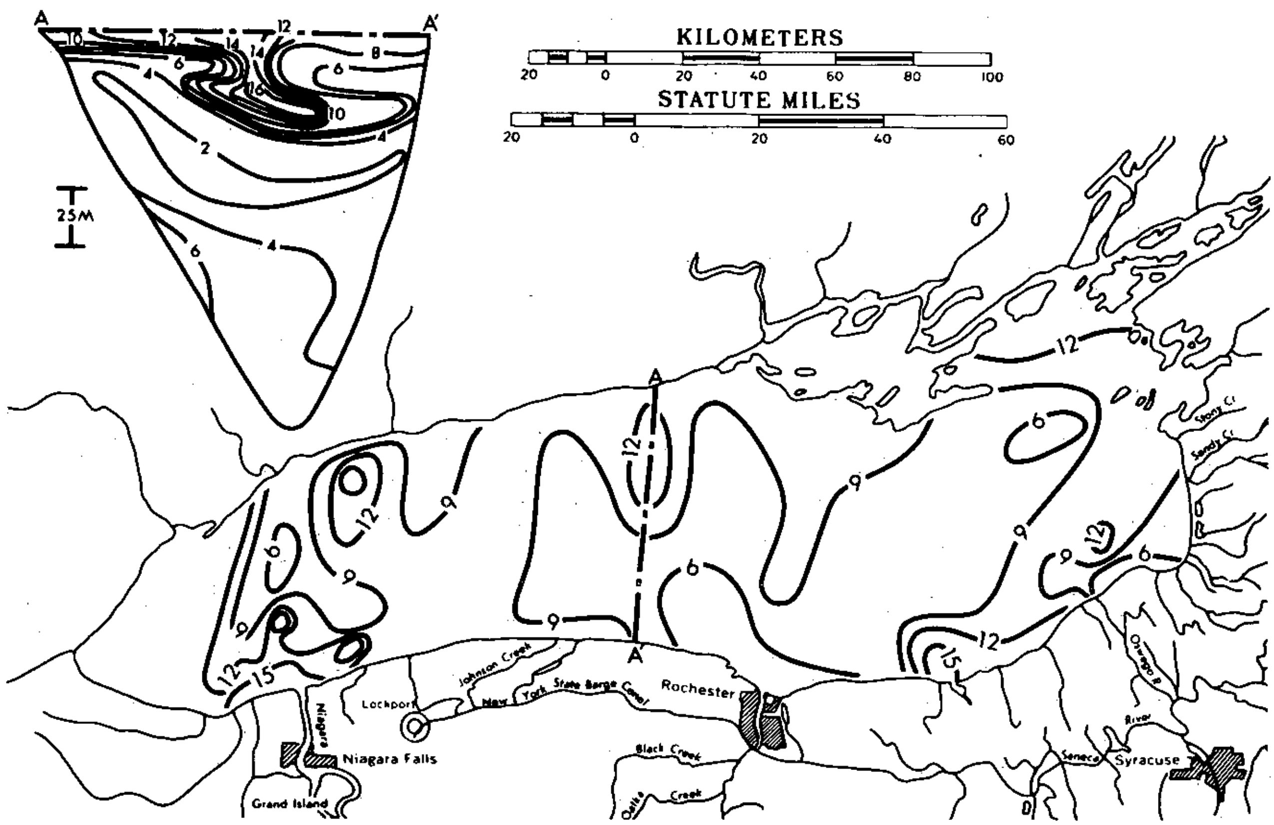


FIGURE 4–167 Representative Distribution of BOD ($x10^{-1}$mg/l) in the Bottom Sediments of Lake Ontario

Data from Canada Centre for Inland Waters (1969) cruise 8/2–8/7/66

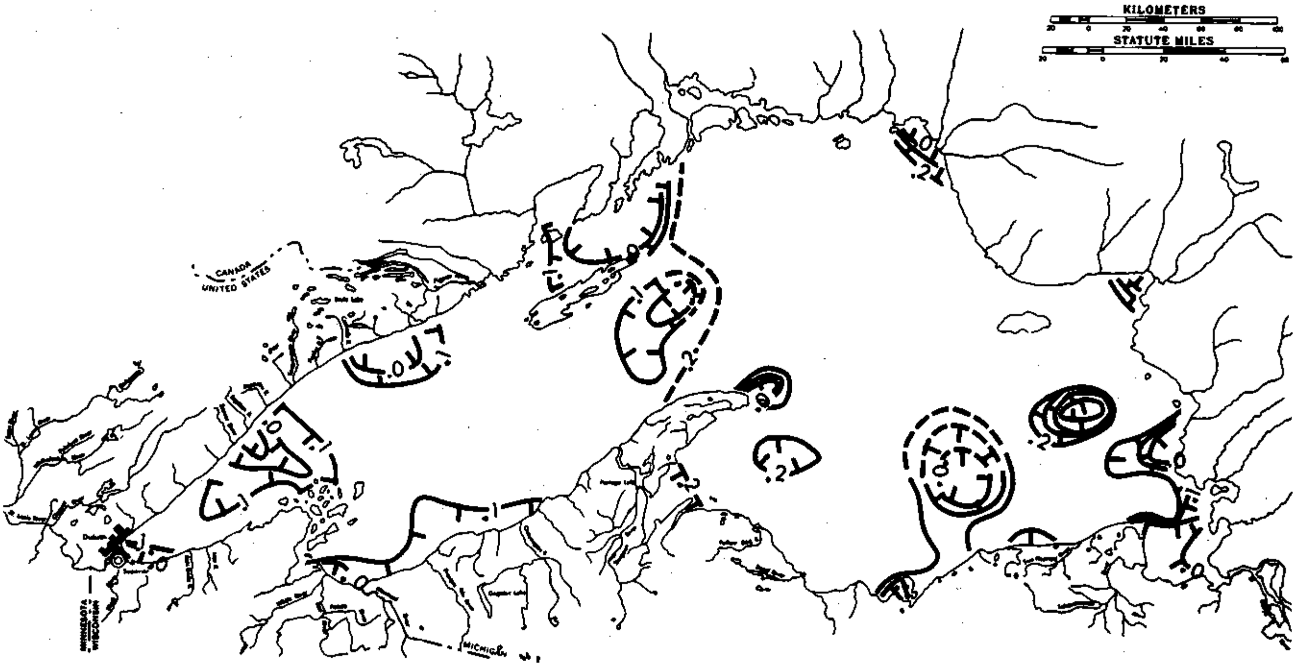


FIGURE 4–168 Representative Distribution of Eh (mv) in the Bottom Sediments of Lake Superior
Data from Lake Survey Center (NOS–NOAA) cruises 7/18–8/8/68 and 7/27–8/9/69

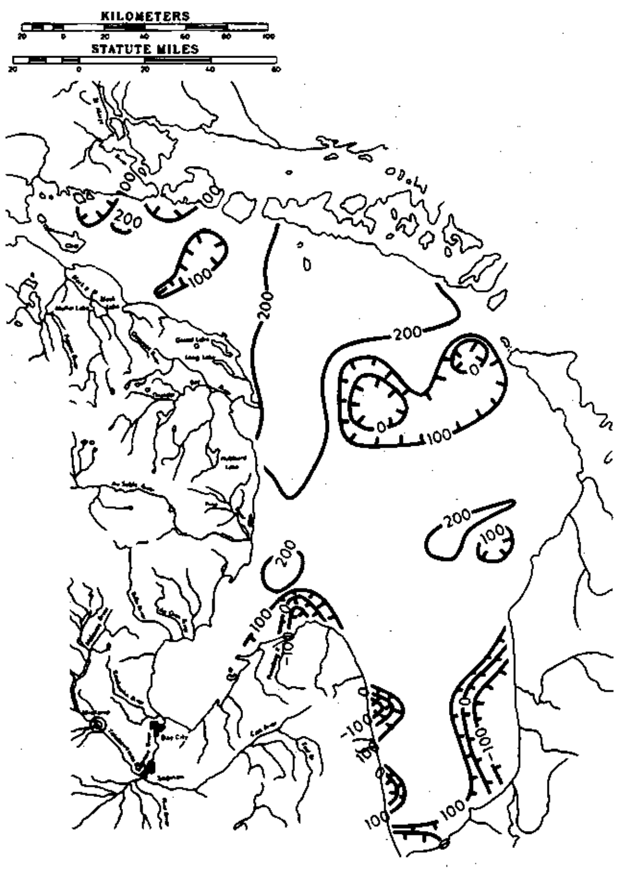


FIGURE 4–169 Representative Distribution of Eh (x10^{4}mv) in the Bottom Sediments of Lake Huron
Data from Lake Survey Center (NOS–NOAA) cruise 8/2–8/17/66

limiting nutrient, then this knowledge must include the phosphorus cycle (Figure 4–171), methods of reducing phosphate wastage in agriculture and domestic consumption, and methods of removing the excess phosphatic material already present in a lake.

The Water Quality Committee on Nutrients in Water[871] has summarized the sources and forms of phosphorus. The natural sources of phosphorus are the relatively insoluble apatite minerals, especially hydroxyapatite ($Ca_{10}(OH)_2(PO_4)_6$), fluorapatite ($Ca_{10}F_2(CO_4)_6$) and a few other relatively rare minerals. These minerals are slowly weathered, providing a small but steady supply of phosphorus to surface waters. Soluble orthophosphate and condensed or complex phosphates are added to the surface water by man and by other living organisms.

In water, phosphorus occurs as orthophosphate (PO_4^{-3}, HPO_4^{-2}, $H_2PO_4^{-1}$, H_3PO_4), inorganic complex or linear condensed phosphates (pyrophosphate—$P_2O_7^{-4}$, $HP_2O_7^{-3}$, $H_2P_2O_7^{-2}$, $H_3P_2O_7^{-1}$, $H_4P_2O_7$; tripolyphosphate—$P_3O_{10}^{-5}$, $HP_3O_{10}^{-4}$, $H_2P_3O_{10}^{-3}$, $H_3P_3O_{10}^{-2}$, $H_4P_3O_{10}^{-1}$, $H_5P_3O_{10}$), inorganic-ring condensed phosphate (trimetaphosphate—$P_3O_9^{-3}$, $HP_3O_9^{-2}$, tetrametaphosphate—$P_4O_{12}^{-4}$, $HP_4O_{12}^{-3}$, organic orthophosphates (sugar phosphate esters—glucose–6–phosphate, fructose–6–phosphate; deoxyribonucleic acid; phospholipids; inositol phosphates), phosphoamines (creatine phosphate, phosphoproteins), and organic con-

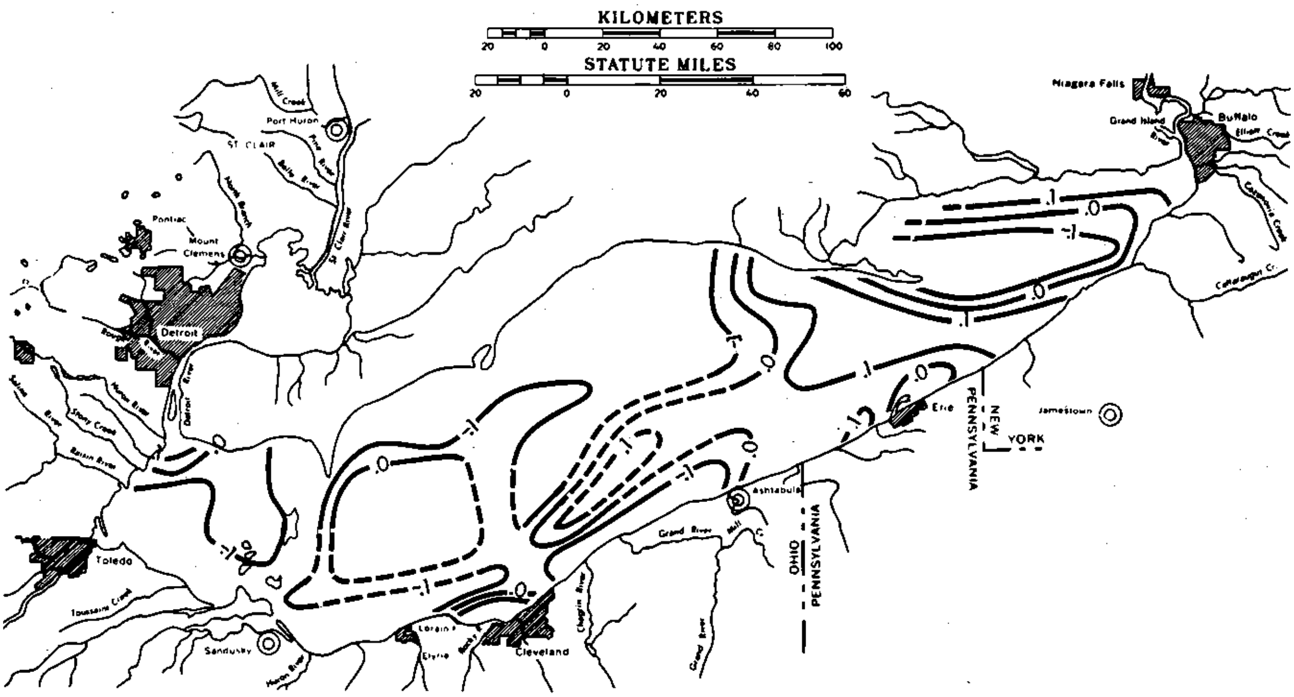


FIGURE 4-170 **Representative Distribution of Eh (mv) in the Bottom Sediments of Lake Erie**
Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

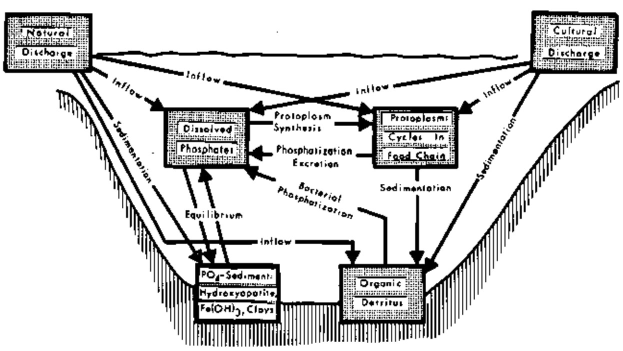


FIGURE 4–171 Simplified Phosphorus Cycle in a Lake

densed phosphates (adenosine-5-triphosphate; coenzyme A) (Water Quality Committee on Nutrients in Water[871]).

Phosphorus occurs in the lakes most commonly as orthophosphate and polyphosphates. Other phosphorus compounds, such as the condensed phosphates, hexametaphosphate, and tripolyphosphate from detergents, are rapidly hydrolized to orthophosphate in waste treatment plants and in natural waters (Shannon and Lee;[728] Heinke[336]). Orthophosphate, soluble phosphorus, and total phosphorus are most often reported in the literature on the Great Lakes. Juday, et al.[441] introduced the terms total and soluble (ortho-) phosphate; total phosphate includes soluble as well as all particulate phosphorus compounds. The difference between total soluble and soluble orthophosphate is designated organic phosphorus and is primarily polyphosphate. Orthophosphate is the form most readily utilized by plants and is a measure of the phosphorus available for primary production. Total phosphorus reflects the total load of phosphorus in the water body, which is important when considering the introduction of wastes to the water. The form that phosphate takes in water is pH dependent. The most important forms occurring in pH range 5 to 9, which would include Great Lakes waters, are $H_2PO_4^{-1}$ and HPO_4^{-2} (Water Quality Committee on Nutrients in Water[871]).

One of the most important properties of many inorganic and organic phosphorus compounds is the ability to form complexes and chelates with cations. It is for this reason that phosphates are added to detergents and water softening chemicals, where they are intended to complex calcium and magnesium. Conditions are appropriate for the formation of complexes in natural waters. However, little work has been done to determine the impact of such complexes on the mobility of metals such as calcium, magnesium, iron, and trace metals in natural waters.

Phosphate is removed from lake water by four major processes:

(1) sedimentation of organic detritus
(2) adsorption by ferric hydroxide ($Fe(OH)_3$)
(3) ion exchange on clays
(4) precipitation of hydroxyapatite.

Sedimentation of organic debris was discussed in Subsection 7.5.4. It entails overproduction of organic materials which die and settle to the bottom. Unless decomposed, the organic detritus retains the phosphorus metabolized in growth. The adsorption of phosphate on ferric hydroxide gel is discussed in Subsection 7.5.11. If Eh is positive and oxygen is present, ferric hydroxide precipitates and adsorbs phosphate. A drop in dissolved oxygen and a negative Eh causes release of phosphate to the water, and hence, nutrient enrichment. Grim[304] discussed the anion exchange capacities of clays with respect to phosphate. The importance of anion exchange on clays needs to be better understood as it may be of great impact in the Great Lakes. If the concentrations of calcium and orthophosphate are high enough, inorganic phosphatic minerals, such as hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) may precipitate (Subsection 7.5.8). Regardless of the mechanism by which phosphorus is removed from a lake, Hynes and Greib[404] and Gumerman[307] have shown that an equilibrium condition exists between water and sediment, and reduction of soluble phosphate input to a lake will be accompanied by a concomitant release of soluble phosphate from the sediment. This is likely to extend the effects of excess nutrient loading for some years after loading from the drainage basins has been abated. The degree of phosphate release from sediment depends on texture, bioturbulence, sediment chemistry, and sedimentation rates (Thorstenson and Mackenzie[797]).

Assimilative capacity of a large lake relates to the volume of water available for dilution of an effluent. Consequently, the assimilative capacity of the Great Lakes is large. Lake depth is a significant factor when the waters are enriched by nutrients because a large portion of the volume of a shallow lake is available for photosynthetic activity and accelerated eutrophication (Figure 4–172). The ranges given in Figure 4–172 for Lake Norrviken and Lake Mendota represent the ranges in historical data for those lakes and are typical of most lakes with similar characteristics that receive cultural wastes. Using Vollenweider's[864] criteria for trophism in lakes, Lake Erie is presently eutrophic and Lake Ontario is mesotrophic. The possible trends in trophism of

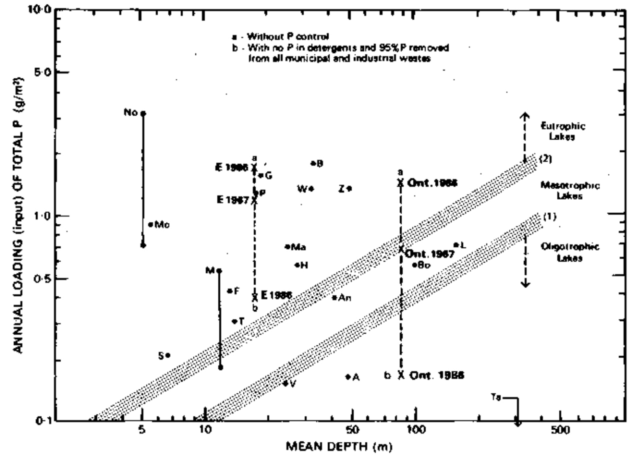


FIGURE 4–172 State of Eutrophication for a Number of Lakes in Europe and North America. Lakes represented include Aegerisee, Switzerland (A); Lake Annecy, France (An); Baldeggersee, Switzerland (B); Lake Constance, Austria, Germany, Switzerland (Bo); Lake Fures, Denmark (F); Greifensee, Switzerland (G); Hallwilersee, Switzerland (H); Lake Geneva, France, Switzerland (L); Lake Mendota, U.S.A. (M); Lake Malaren, Sweden (Ma); Moses Lake, U.S.A. (Mo); Lake Norrviken, Sweden (No); Pfaffikersee, Switzerland (P); Lake Sebasticook, U.S.A. (S); Turlersee, Switzerland (T); Lake Tahoe, U.S.A. (Ta); Lake Vanern, Sweden (V); Lake Washington, U.S.A. (W); Zurichsee, Switzerland (Z); Lake Erie (E); and Lake Ontario (Ont).

Modified from Vollenweider, 1968; reproduced by IJC, 1969

Lakes Erie and Ontario with and without phosphate loading control, as suggested by the International Joint Commission,[408] are also shown in Figure 4–172.

With continued phosphate loading, disruption of the ecosystem by overproduction of algae becomes a cyclic phenomenon. Introduction of phosphorus stimulates algal growth. Occurrence of an algal bloom increases turbidity, and light availability then becomes a limiting factor to further algal production (Azad and Borchardt[3]). Turbidity during periods of high runoff is also a limiting factor (Curl[174]). After consumption of available phosphate or loss of light, production decreases and the algae die and decompose. Those algae that decompose near the surface release phosphorus to the system. The deposited organic material creates a high BOD that deoxygenates the water. If deoxygenation is sufficient, the phosphate adsorbed on ferric hydroxide sediment is released along with the phosphate from the decomposition of algae. Release of phosphate

FIGURE 4–173 Representative Distribution of Phosphate ($x10^{-3}$mg/l) in Lake Michigan Surface Water

Data from Beeton and Moffett, 1964

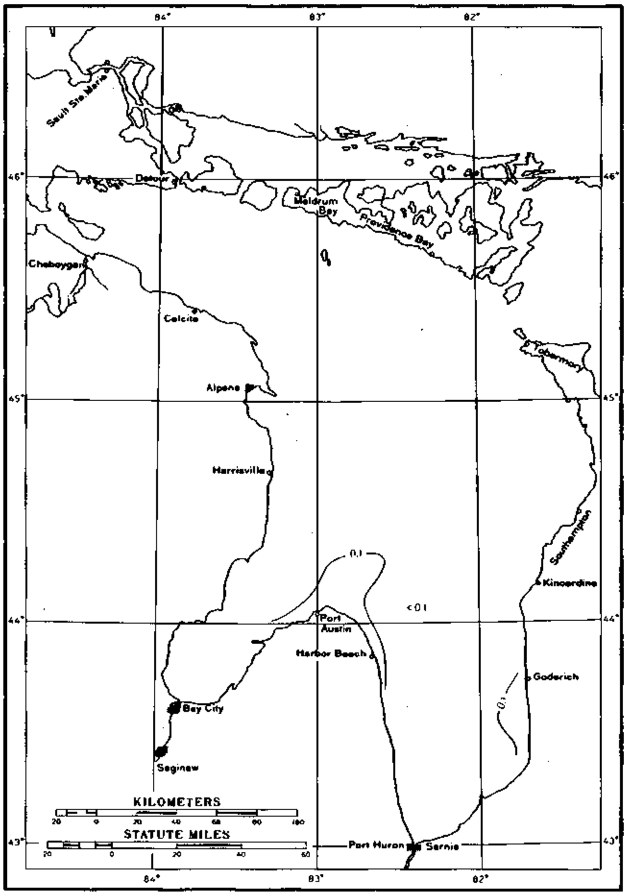


FIGURE 4–174 Representative Distribution of Phosphate (mg/l) in Lake Huron Surface Water

Data from Lake Survey Center (NOS–NOAA) cruise 8/2–8/17/66

for algal decomposition and sediment equilibria may induce a new cycle of algal production. Subsequent algal blooms depend upon the interplay of nutrient release and solar radiation, which is a function of depth, season, and turbidity.

The only way to stop the phosphate-algae cycle is to stop phosphate input to the lakes. Natural regulation has been effective in some regions where swamps and bogs occurring at the mouths of phosphate-enriched tributaries trap sediments and nutrients before they reach the lake. The filling of swamps such as has taken place in the Maumee drainage basin reduces the impact of natural regulation.

With increased use of phosphate and loss of natural regulation, improved waste treatment management, reduction of phosphorus utilization, and legislation to protect the lakes from excess phosphorus loading must be provided to reduce phosphorus input. The International Joint Commission[408] and various interest groups in the Lake Erie basin have recommended from 80 percent to complete removal of phosphate from sewage wastes by tertiary treatment. A ban on detergents with phosphatic surfactants has been effected in some areas, although there is danger that other, more toxic surfactant or chelating agents that can mobilize heavy metals may replace phosphate. Canada and several local governments in the United States have already initiated programs to rid detergents of phosphate, and such legislation is pending in several States. Kuentzel[478] questioned the efficacy of phosphorus control as a mechanism to combat eutrophication in the Great Lakes on the basis that phosphorus storage and release from the sediment may reduce effectiveness of phosphorus control.

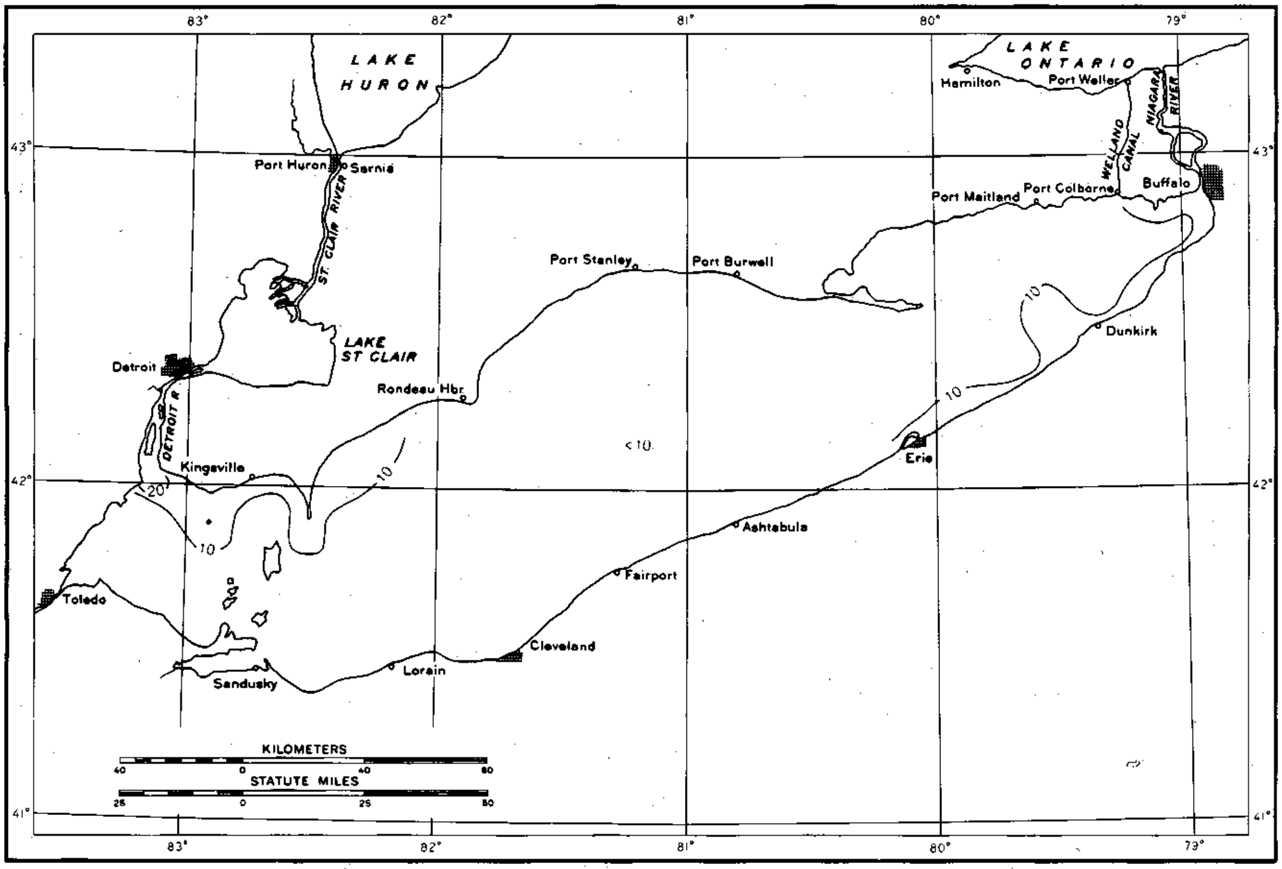


FIGURE 4–175 Weighted Average Distribution of Phosphate ($\times 10^{-3}$mg/l) in Lake Erie Surface Water

Data from Lake Survey Center (NOS–NOAA) cruise 5/25–6/14/67

Phosphorus release from sediment certainly occurs. However, the technology to control phosphorus is well advanced and, in the absence of other proven control alternatives, waste treatment control is currently the best and most cost-effective treatment alternative.

The major sources of phosphate in the Great Lakes are the metropolitan areas (Figures 4–173 through 176). The rapid hydrolysis of phosphate from detergents and assimilation of phosphate by the biota and sediment cause phosphate concentrations to decline rapidly away from their sources. Consequently, it is only in restricted embayments and areas of overloading of phosphate that significant phosphate concentrations occur. Notable regions of phosphate overloading are near Chicago, Green Bay, Saginaw Bay, Detroit, Toledo, Long Point, Buffalo and the Niagara River outlet, Toronto, Cobourg, and Oswego. The majority of these sources are urban areas, rather than agricultural. If the main sources of phosphate are urban, then sewage treatment and nonphosphatic detergents may be feasible solutions to the phosphate problem. However, all known sources of nutrients should be assessed.

Lakes Erie and Ontario are subject to the greatest stress from phosphate input. Sutherland, et al.[770] and Kramer[469] have shown that phosphate concentrations are periodically high enough to approach saturation with respect to hydroxyapatite. Figure 4–177 shows the log ratio of equilibrium product for hydroxyapatite to actual ion product with positive numbers indicating supersaturation. Western Lake Erie is supersaturated and other regions near urbanized areas approach saturation. No authigenic hydroxyapatite has yet been found in the lakes. Snow and Thompson[750] compared the saturation of Lake Erie with respect to hydroxyapatite to plankton abundance and found increasing plankton concentration with increase in hydroxyapatite saturation. From these data it appears that algal production and adsorption

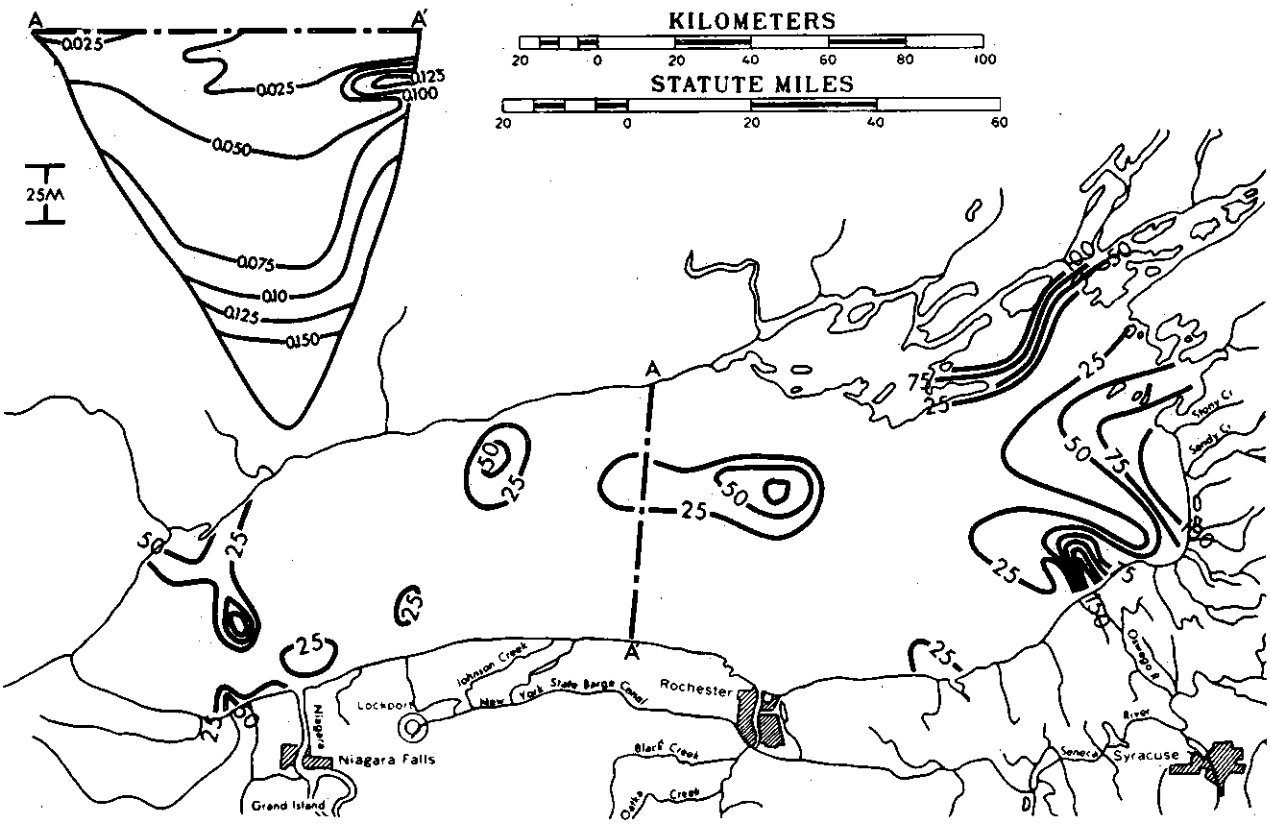


FIGURE 4–176 Representative Distribution of Phosphate ($x10^{-3}mg/l$) in Lake Ontario Surface Water. Map and cross section contour interval are different.

Data from Canada Centre for Inland Waters (1969) cruise 8/2–8/7/66

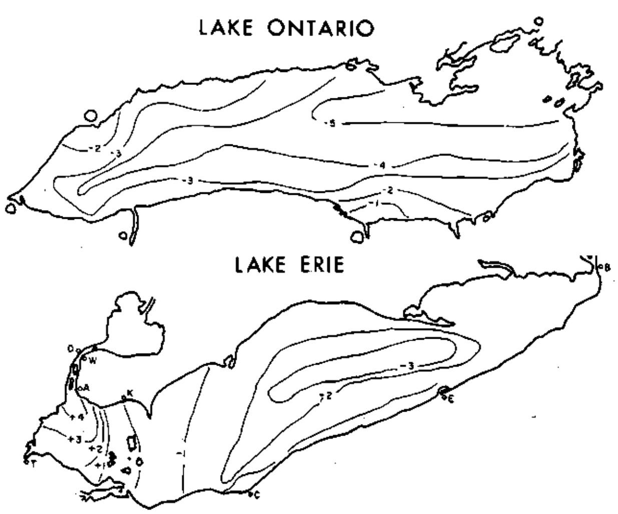


FIGURE 4–177 Degree of Saturation of Surface Water of Lake Erie (top) and Lake Ontario (bottom) with Respect to Hydroxyapatite for August 22–26, 1966. Positive values represent supersaturations; negative values represent undersaturated conditions. Numbers are $\log_{10}$ (equilibrium product/ion product).

From Kramer, 1967b

on ferric hydroxide and not hydroxyapatite equilibria may be the mechanism by which phosphorus is removed from water in Lake Erie.

7.5.6 Nitrogen System

Nitrogen is a nutrient that, in excess quantities and with no other nutrient limitation, stimulates aquatic growth and accelerates eutrophication. The atmosphere is approximately 80 percent nitrogen. This source is generally not used directly by aquatic organisms but serves as a potential source of nitrogen in the natural system through bacterial or algal conversion to nitrogen compounds (Figure 4–178). Nitrogen is readily available and is therefore not a limiting factor for organic growth in unpolluted systems. The use of nitrate (NO_3^{-1}), nitrite (NO_2^{-1}), and ammonia (NH_4^{+1}) compounds in agriculture, industry, and domestic activity has increased the influx of nitrogen into the Great Lakes. When combined with increased loadings of

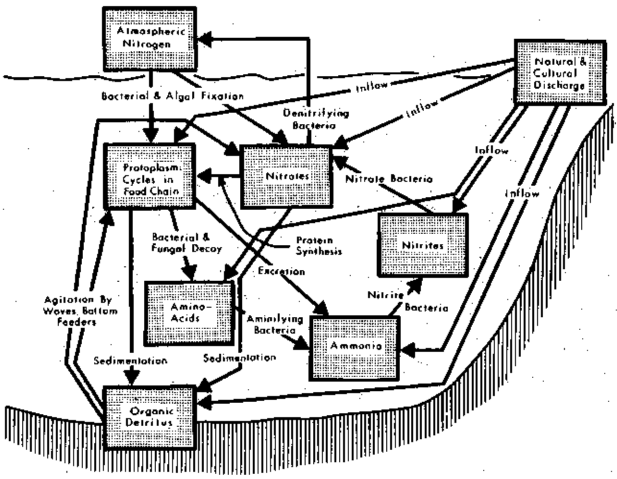


FIGURE 4–178 Simplified Nitrogen Cycle in a Lake. See Figure 4–217 for amplification of the general rule in the nitrogen cycle.

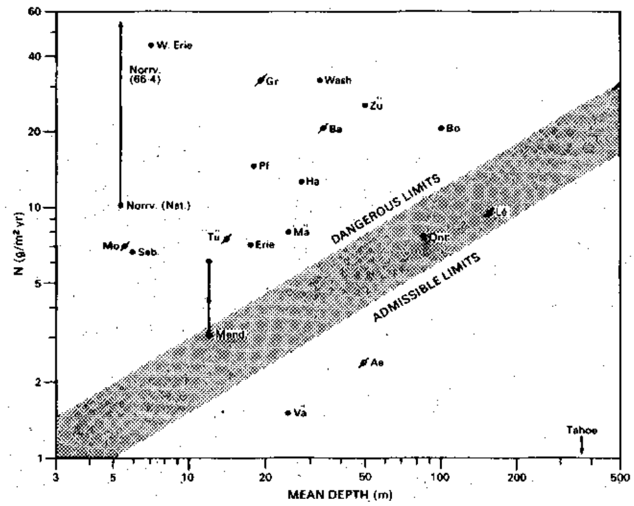


FIGURE 4–179 Nitrogen Loading Versus Mean Depth for Various Lakes in Europe and North America. The dots with slanted lines refer only to inorganic nitrogen. Lakes represented include Aegerisee, Switzerland (Ae); Baldeggersee, Switzerland (Ba); Lake Constance, Austria, Germany, Switzerland (Bo); Western Lake Erie (W. Erie); Lake Erie (Erie); Lake Geneva, France, Switzerland (Le); Greifensee, Switzerland (Gr); Hallwilersee, Switzerland (Ha); Lake Malaren, Sweden (Ma); Lake Mendota, U.S.A. (Mend); Moses Lake, U.S.A. (Mo); Lake Norrviken, Sweden (Norrv); Lake Ontario, U.S.A. (Ont); Pfaffikersee, Switzerland (Pf); Lake Sebasticook, U.S.A. (Seb); Lake Tahoe, U.S.A. (Tahoe); Turlursee, Switzerland (Tu); Lake Vanern, Sweden (Va); Lake Washington, U.S.A. (Wash); and Zurichsee, Switzerland (Zu).

From Vollenweider, 1968

phosphorus and other nutrients, increased nitrogen influx accelerates the trophic development.

The nitrogen cycle (Figure 4–178) is complex. Bacteria and phytoplankton fix most of the nitrogen as protoplasm. Decay and excretion yield amino acids, ammonia, and nitrites. Bacteria and fungi are responsible for the amino acid-ammonia-nitrite-nitrate conversions (Figure 4–156). Exchange with the atmosphere, influx of nitrogenous material from shore, assimilation by the biota, and loss of nitrogenous material through sedimentation and outflow regulate the lake nitrogen budget. Because of sedimentation of organic debris, nitrogen accumulates in the lake system. To characterize the relative importance of the various states of the nitrogen cycle, analyses for nitrogen compounds may include albuminoid (proteinaceous) nitrogen; organic nitrogen including proteins, amino acids, polypeptides, and others; ammonia (NH_3); nitrate (NO_3^{-1}), nitrite (NO_2^{-1}); and molecular nitrogen (N_2). The conversion of reduced to oxidized nitrogen compounds is rapid in the Great Lakes and the process is analogous in many ways to oxygen sag in streams (Figure 4–156). When a reduced form of nitrogen, either organic nitrogen, ammonia, or nitrite, is introduced to the receiving water, oxidation takes place. The conversion from organic nitrogen to ammonia to nitrite to nitrate may be made either inorganically or biologically by nitrifying bacteria. The roles of bacteria and phytoplankton in the nitrogen cycle are discussed in Section 8.

Since the relative volume of water in the photic zone is critical to the rate of lake aging, the relation of nitrogen loading and mean depth (Figure 4–179), as noted by Vollenweider,[864] becomes significant in trophic development. Shallow lakes have less water available for dilution of nitrogen compounds and their photic zone for plant production is a larger percentage of the total volume.

Greeson[301] summarized the minimum nitrogen requirements for algal growth and reproduction from the literature. The described minimum requirements range from trace quantities to 5.3 mg/l. Water quality standards for Great Lakes water reflect these indefinite limits. Few States have adopted numerical limits for inflow water, but instead require that no nutrient be discharged in great enough quantity to cause nuisance conditions and that the Public Health Service Drinking Water Standards be met. Because nitrogen

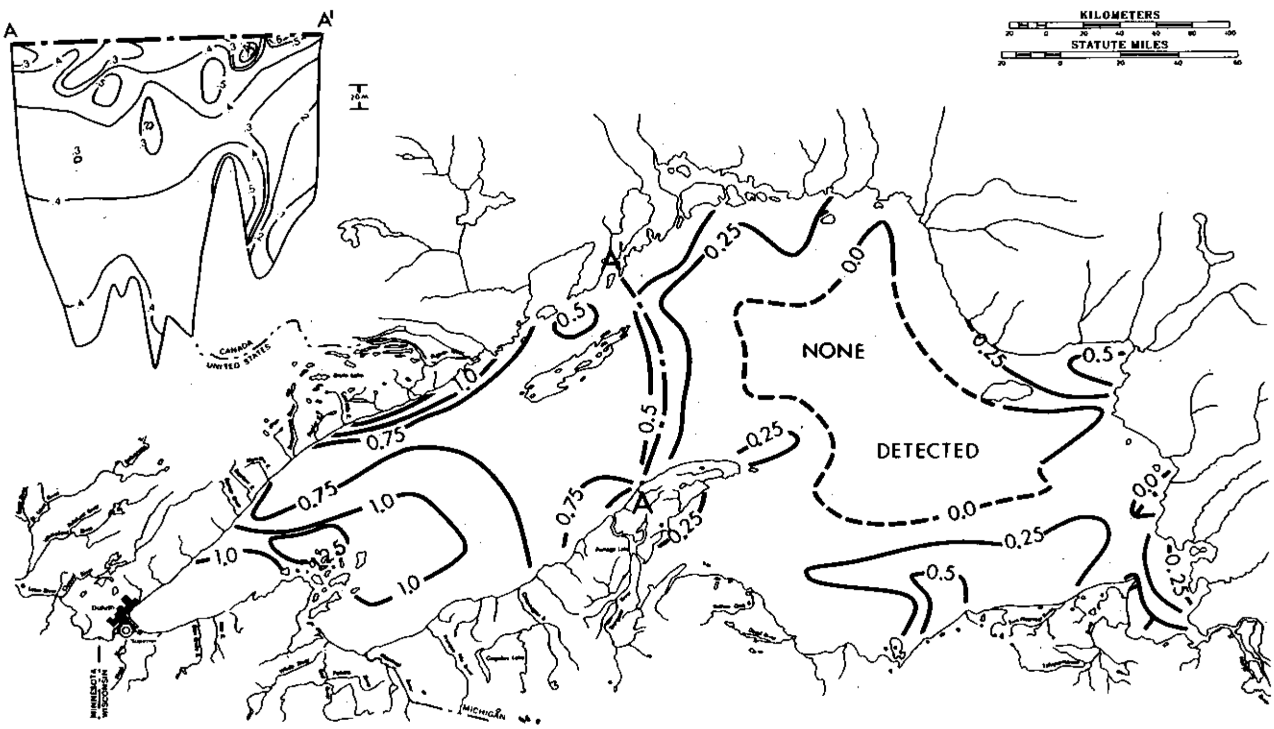


FIGURE 4-180 Representative Distribution of Nitrogen, as Nitrate (mg/l), in Lake Superior Surface Water

Data from Lake Survey Center (NOS-NOAA) cruises 7/18-8/8/68 and 7/27-8/7/69

sources are difficult to control (e.g., nitrogen is available from the atmosphere), it is generally felt that control efforts should be directed to other nutrients such as phosphorus. For example, the International Joint Commission[408] suggests that phosphorus rather than nitrogen input be controlled because, among other reasons, "appreciable quantities of readily assimilable nitrogen compounds (nitrates and ammonia) are delivered directly to the lakes in precipitation . . ." and ". . . during time of nitrate deficiency in surface waters some blue-green algae can utilize N_2 derived from the atmosphere as a source of nitrogen." In Lake Erie and southern Lake Michigan where quantities of phosphorus are stored in the sediments, release of phosphorus from the sediment may reduce the immediate benefits of phosphorus control. Therefore, even limited control of nitrogen from agricultural and industrial sources may be a deterrent to algal production.

The process of atmospheric nitrogen fixation has been extensively studied in Lake Mendota, Wisconsin, and Pymatuning Reservoir and Sanctuary Lake, Pennsylvania, using the stable isotope N^{15}, (Dugdale et al.[229] and Dugdale and Dugdale[228]). Their studies showed that measurable fixation occurs and that, depending on phytoplankton abundance and light penetration, fixation rates can be high. Dugdale and Dugdale also noted that the presence of combined inorganic nitrogen (NO_3^{-1} and NH_4^{+1}) inhibited atmospheric nitrogen fixation. If this is true, then reduction of nitrogen inputs into the Great Lakes could be offset by atmospheric fixation. However, the presence of phosphate and micronutrients stimulates nitrogen fixation (Dugdale and Dugdale[228] and Goering and Neess[290]). So it is possible that control of phosphorus input and other nutrients could limit the extent to which atmospheric nitrogen can be fixed, and the total nitrogen budget might then be reduced by control of nitrogen loss from the drainage basins. In a study of contributions of nitrogen to Lake Ontario from several drainage basins in the vicinity of Toronto, Ontario, Neil et al.[573] concluded that, with the exception of March and April when runoff is greatest, urban contributions of nitrogen exceed rural by approximately 10 to 1 (34,000 lbs N/mi²/yr for rural sources). The urban effluent can be treated, and Neil et al.[573] estimated that, for the Toronto area, 87 percent of nitrogen influx into Lake Ontario can be removed by sewage treatment.

Nitrogen is assimilated rapidly in the Great

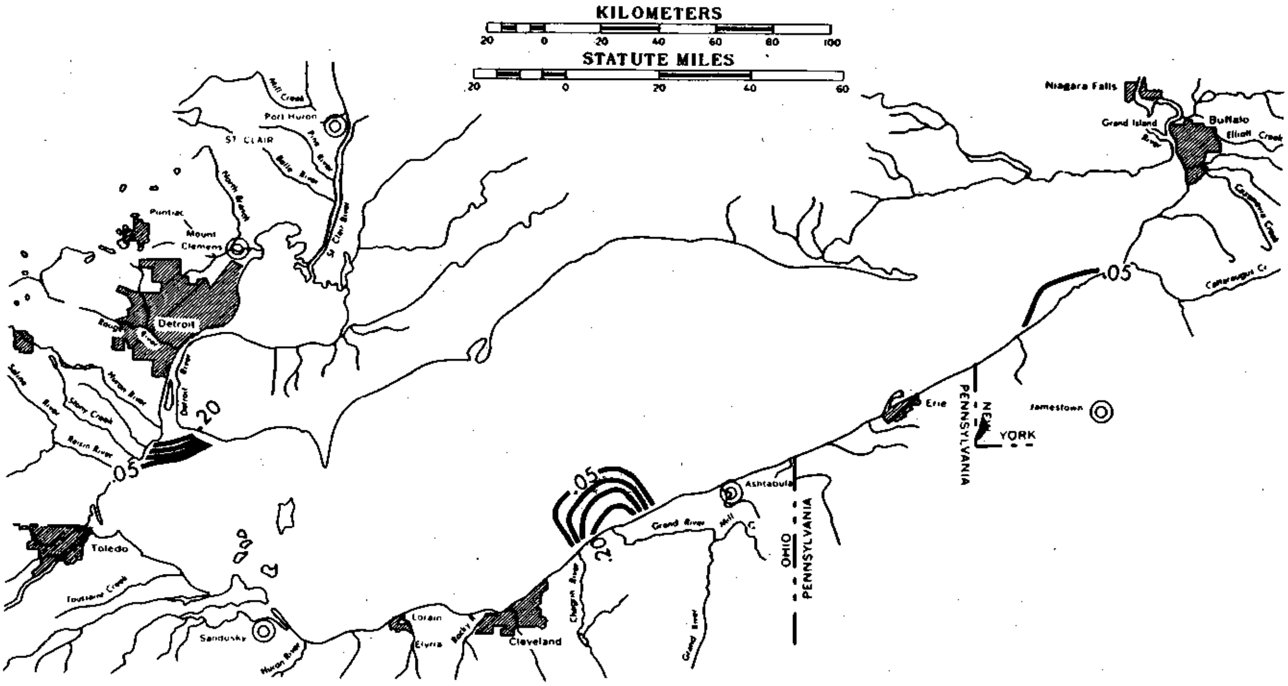


FIGURE 4–181 Representative Distribution of Nitrogen, as Nitrate (mg/l), in Lake Erie Surface Water

Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

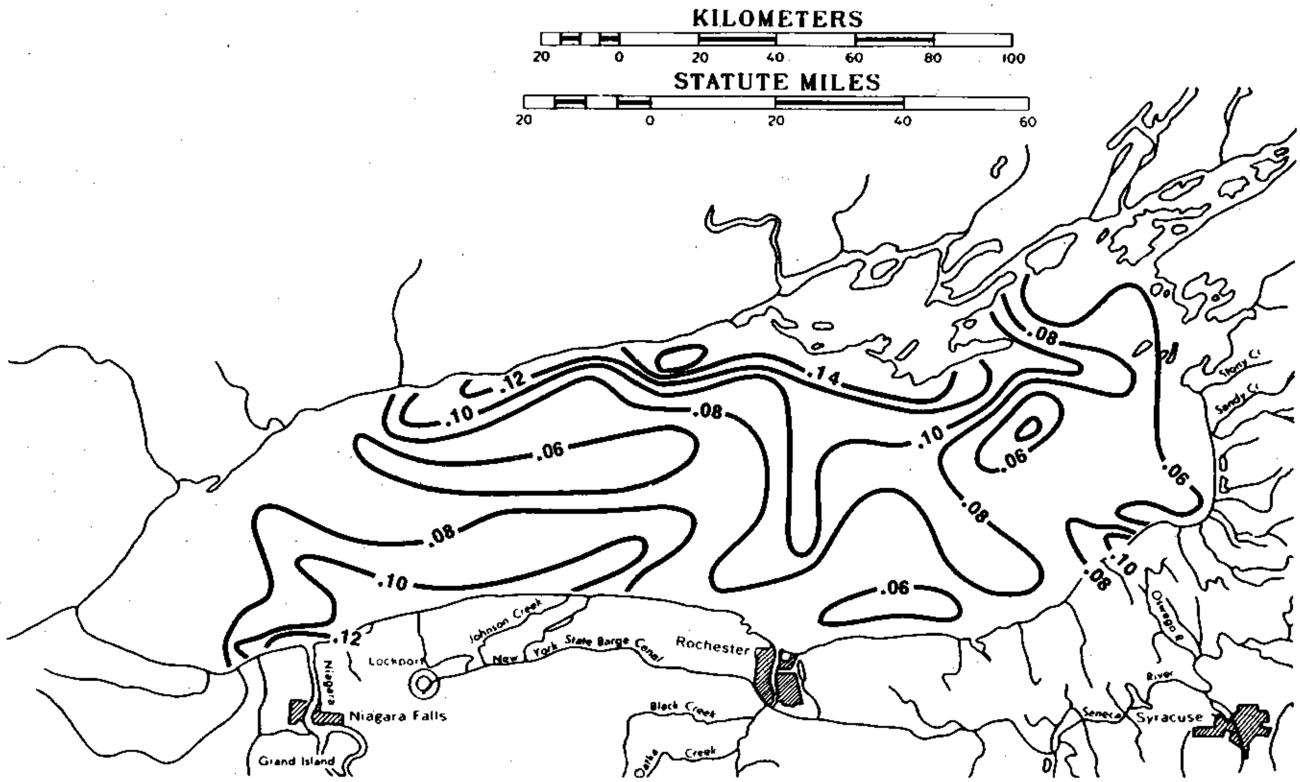


FIGURE 4–182 Representative Distribution of Nitrogen, as Nitrate ($x10^3$mg/l), in Lake Ontario Surface Water

Data from Canada Centre for Inland Waters (1969) cruise 8/2–8/7/66

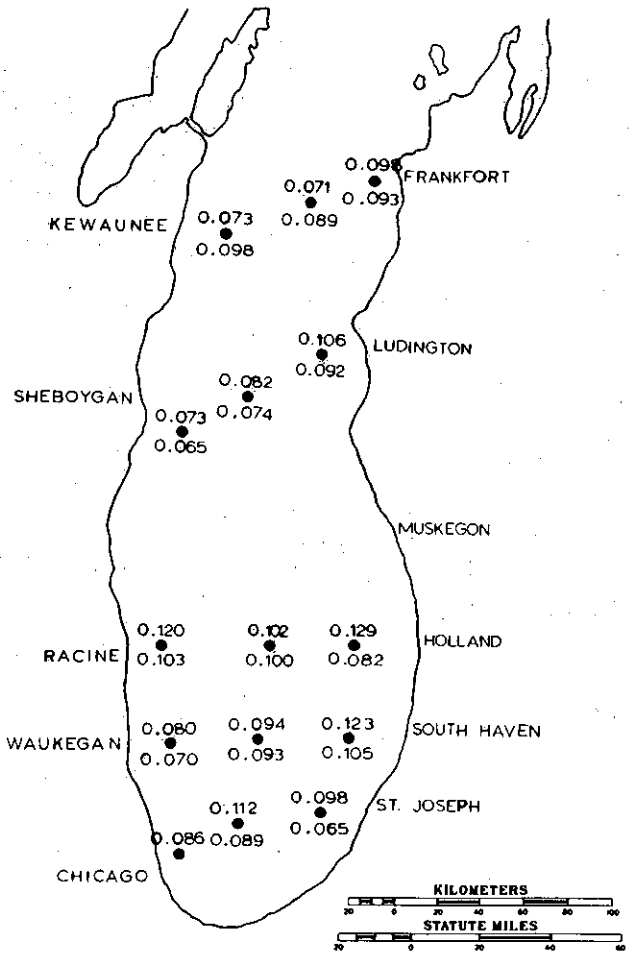


FIGURE 4–183 Average Concentration of Organic Nitrogen in Lake Michigan. Upper number represents the concentration (mg/l) in the upper 20 meters; lower number represents the concentration below a depth of 20 m.
From Robertson and Powers, 1968

Lakes; therefore, steep concentration gradients occur in the vicinity of nitrogen sources (Figures 4–180 through 182). Nitrogen may be chemically stratified in the lakes. Lower values above the chemocline, which corresponds with the thermocline, may reflect uptake by phytoplankton; or the higher concentrations below the chemocline may indicate release of nitrogen by decomposition of nitrogenous organic debris. Robertson and Powers[667] and Howard et al.[385] support the observation that algal production causes the low nitrate concentrations above the chemocline. Nitrogen fixation by blue-green algae (Howard et al.[385]) occurs at least from June through November in Lake Erie during periods of wide variation in turbidity, temperature, nutrients, and solar radiation. Robertson and Powers studied organic nitrogen components in Lake Michigan (Figure 4–183) during 1964, and found slightly higher concentration in the upper layers, especially during the summer and fall. Since organic nitrogen excludes ammonia, nitrates, and nitrites, it is reasonable that higher organic nitrogen in the photic zone represents biosynthesis.

7.5.7 Organic Carbon Compounds

The subsections describing carbonate and oxygen cycles pointed to the significance that organic carbon compounds may have on the ecosystem. High BOD creates competition with the biota for oxygen. In the presence of metabolic activity many organic carbon compounds are metastable, and as they oxidize, they contribute to the oxygen demand of a system. Some organic carbon compounds are toxic (pesticides, phenols, detergents) or physically destructive and unsightly (petroleum products, crude oil). The organic carbon compounds that are of environmental concern at present or may require investigation and action in the future include pesticides, polychlorinated biphenyls (PCBs), phenols, detergents, petroleum, organic gases, organic acids, and cyanide. The ecological importance of these eight classes of organic-carbon compounds and the distribution of total organic carbon are reviewed below. Many of these substances are considered to be deleterious to the aquatic environment and water quality standards have been adopted for a few of them (Table 4–30). Other substances are poorly understood and require research before their impact on the Great Lakes environment will be understood.

7.5.7.1 Pesticides

Perhaps more than any other organic pollutants, the pesticides (insecticides, herbicides, fungicides, defoliants, algicides) threaten the success of the ecosystem, including man. Many of the commonly used pesticides are not readily degraded in natural environments. They tend to persist and are distributed over wide areas by water and wind. Primary producers assimilate the toxicants and, as the producers are consumed by organisms higher in the food chain, the toxicants are passed on and may be concentrated by a process called "biological magnification" (Woodwell;[916] Peterle[602]). Many species concentrate toxicants in fatty (lipid) tissues. It is possible for lethal concentrations to accumulate in those tissues, and, when the lipid material is assimilated in the absence of external food, death may occur (Federal Water Pollution Control Administration[831]). The concentration of toxicants by biological magnification is especially evident in fish and shore birds. For example, fish kills (Federal Water Pollution Control Administration[830]) and gull fatalities (Hickey et al.[354]) have been directly related to pesticide buildup in tissues. In 1969, 34,000 Lake Michigan coho salmon were confiscated by the U.S. Food and Drug Administration because DDT residues from 13 ppm to 19 ppm were considered unsafe (International Joint Commission[408]). Some animals assimilate toxicants that inhibit reproduction. Decreases in nesting success in certain shore birds have been directly attributed to DDT (Hickey et al.;[354] Wurster and Wingate[920]). High pesticide levels reduce calcium metabolism and affect hormone production, which result in fragile egg shells and non-viable eggs. Predators, including man, can consume organisms that concentrate toxicants and receive a debilitating or lethal dose. Wurster[919] and Menzel et al.[532] observed that DDT and other chlorinated hydrocarbons reduce the photosynthetic activity of some species of marine phytoplankton, especially when cell concentrations are low. If this phenomenon is widespread in the Great Lakes, large segments of the food chain could be disrupted. In fact, Wurster suggests that selective destruction of the food chain may partially explain the emergence of normally uncommon phytoplankton species, and the accompanying nuisance algal blooms of eutrophic lakes.

The tolerance of organisms to toxic compounds cannot be defined specifically. For example, the potential dangers of toxication from pesticides increases with temperature. Consequently, toxicant loading limits must account for differences in the physical system during summer and winter. The tolerance of each organism differs, and to evaluate the effects of toxicant release on the aquatic ecosystem, all taxa in the system should be considered. Little is known about the synergistic effects of pesticides and other chemical constituents. To be meaningful, toxicant loading limits must account for synergism, and this requires studies of the tolerances of taxa in the climate and chemical environment of the receiving water. Needless to say, this is an enormous task in the discipline where little data exist.

The water quality criteria for pesticides (Table 4–30), used in the Great Lakes Basin are poorly defined, and consist of restrictions on use of certain pesticides and adherence to the drinking water standards of the U.S. Public Health Service.[829] A convenient measure used in some States is the median tolerance limit (TL_m). This is the dose required to kill 50 percent of individuals of a given species within a given time, usually 48 to 96 hours. To allow a margin of error, water quality criteria are usually set at .1 of the TL_m of a particular fish species. Tables 4–35 and 4–36 show the TL_m values for selected aquatic organisms treated with pesticides. Certain of the pesticides are extremely toxic. For example, only 3 μg/l of aldrin, 10 μg/l of chlordane, 9 μg/l of DDD, 2.1 μg/l of DDT, or 18 μg/l of lindane (benzene hexachloride) reach the TL_m for rainbow trout, which is a relatively resistant species. Chlorinated hydrocarbon pesticides are degraded slowly (Table 4–36), and when in animal tissue the pesticides can reach toxic levels by intake exceeding metabolism and excretion. Therefore, even though TL_m values are not approached. toxicity may be induced.

Several processes degrade the persistent pesticides; photolysis is known to induce degradation of DDT under certain conditions (Plimmer et al.[621]). The ecological consequences of the photo-oxidation products of chlorinated hydrocarbons are unknown, and they may contribute to the stresses on the ecosystem that are now attributed to the hard pesticide.

Several mechanisms can remove hard (non-biodegradable) pesticides from the water column in addition to assimilation by the biota. For example, sodium humate increases the solubility of DDT in water as much as twenty times, and humic acid, which is essentially insoluble in water can sorb appreciable amounts of 2,4,5–T (Wershaw et al.[882]). Using sediment from several upland lakes in Wisconsin, Lotse et al.[505] showed that lindane is adsorbed by sediment. The amount of uptake depends on the type of insecticide, pH, temperature, clay content, and organic content. Hartung and Klinger[323] found a significant correlation between sedimented oil and DDT in the Detroit River that suggests that oil residues in sediment may cause partitioning and removal of chlorinated pesticides from water. The above studies indicate that pesticides are potentially available to the water column and biota by desorption or by sediment ingestion by bottom feeders. Consequently, the removal problems discussed in Subsection 7.5.5 may

TABLE 4–35 48-hour Median Tolerance Limits[1] of Selected Fish and Cladocerans to Selected Pesticides in Water

Pesticide	Cladoceran	TL_m(μg/l)	Fish	TL_m(μg/l)
INSECTICIDES				
Abate	---	--	Brook trout	1,500
Aldrin	*Daphnia pulex*	28	Rainbow trout	3
Benzene hexachloride (lindane)	*Daphnia pulex*	460	Rainbow trout	18
Carbaryl (sevin)	*Daphnia pulex*	6.4	Brown trout	1,500
Carbophenothion (trithion)	*Daphnia magna*	0.009	Bluegill	225
Chlordane	*Simocephalus serrulatus*	20	Rainbow trout	10
DDD (TDE)	*Daphnia pulex*	3.2	Rainbow trout	9
DDT	*Daphnia pulex*	0.36	Bass	2.1
Dieldrin	*Daphnia pulex*	240	Bluegill	3.4
Dichlorvos (DDVP)	*Daphnia pulex*	0.07	Bluegill	700
Endrin	*Daphnia pulex*	20	Bluegill	0.2
Heptachlor	*Daphnia pulex*	42	Rainbow trout	9
Malathion	*Daphnia pulex*	1.8	Brook trout	19.5
Parathion	*Daphnia pulex*	0.4	Bluegill	47
Rotenone	*Daphnia pulex*	10	Bluegill	22
Toxaphene	*Daphnia pulex*	15	Rainbow trout	2.8
HERBICIDES, FUNGICIDES, DEFOLIANTS, & ALGICIDES				
Aquathol	---	--	Bluegill	257
Copper Sulfate	---	--	Bluegill	150
2,4-D, PGBEE	*Daphnia pulex*	3,200	Rainbow trout	960
2,4-D, BEE	---	--	Bluegill	2,100
2,4-D, isopropyl	---	--	Bluegill	800
2,4-D, butyl ester	---	--	Bluegill	1,300
2,4-D, butyl + isopropyl ester	---	--	Bluegill	1,500
Dalapon	*Daphnia magna*	6,000	---	-- [2]
Diquat	---	--	Rainbow trout	12,300
Endothal, copper	---	--	Rainbow trout	290
Endothal, dimethylamine	---	--	Rainbow trout	1,150
Hydrothol 191	---	--	Rainbow trout	690
Silvex, PGBEE	*Daphnia pulex*	2,000	Rainbow trout	650
Silvex, isoctyl	---	--	Bluegill	1,400
Silvex, BEE	---	--	Bluegill	1,200
Sodium arsenite	*Simocephalus serrulatus*	1,400	Rainbow trout	36,500

[1]48-hour TL_m, static bioassay, micrograms per liter. Data from Federal Water Pollution Control Administration (1968a).
[2]Very low toxicity

apply to hard pesticides. Cessation of inputs into Great Lakes water may not be reflected by rapid decreases in the amount of pesticides in the biota because of the reserves of pesticides stored in sediment and organic complexes.

Several studies in the Great Lakes suggest that detoxification of hard pesticides by bacteria and algae may be an important process in ridding the lakes of hard pesticides. Leshniowsky et al.[494] described the removal of aldrin from Lake Erie water by flocculent bac-

TABLE 4–36 Effects of Six Chlorinated Pesticides on Some Beneficial Water Uses

Pesticide	Fish and other aquatic life	Stock and wildlife watering	Domestic water supplies
Aldrin	Fish - 96 hr. TL_m 0.00013 - 0.05 mg/l *Chironomus* larvae - 8 hr. 0.023 mg/l Lymnaeid snails - 24 hr. 4.8 mg/l	Rats - LD_{50}, 39 - 66.8 mg/kg Birds - LD_{50}, Appx. 4-14 mg/kg Sheep and Cattle - 0.5 lb/acre on alfalfa, no reaction	Man - LD_{50}, 5 g/70 kg Acute and chronic effects
Lindane (Gamman BHC)	Fish - threshold 0.01 - 0.02 mg/l, -20 hr TL_{100}, 0.5 mg/l Plankton - inhibited growth 5 mg/l	Rats - LD_{50}, 600 mg/kg Birds - LD_{50}, 60-400 mg/kg	Man - LD_{100}, 0.6 g/kg Bad taste and odor - 20 μg/l (persists 2 years)
DDT	Fish - toxic dose 0.001 - 5 mg/l *Daphnia* - 64 hr TL_m 0.001 mg/l *Chironomus* larvae - 0.001 mg/l	Rats - LD_{50}, 250 mg/kg Chickens - LD_{50}, 1,300 mg/kg Birds - LD_{50}, 300 - 500 mg/kg	Man - LD_{100}, 30 g/70 kg Taste and odor (MPC) 0.2 mg/l
Dieldrin	Fish - 96 hr. TL_m 0.008 - 0.04 mg/l *Chironomus* larvae - 8 hr. TLm 0.007 mg/l *Daphnia* - 50 hr. immobilization 0.330 mg/l	Rats - LD_{50}, 37-87 mg/kg Squirrels, rabbits, woodchucks exhibited toxicity to small dosages Birds - LD_{50}, 35-50 mg/kg	Man - LD_{50}, 5 g/70 kg
Endrin	Fish - 96 hr. TL_m 0.0006 - 4.2 mg/l, highly toxic *Daphnia* - 50 hr. immobilization 0.352 mg/l	Rats - LD_{50}, 7.3 - 48 mg/kg Dogs - 6 weeks LD_{100}, 10 mg/kg Rabbits - LD_{50}, 7 - 10 mg/kg Birds - LD_{50}, 5 - 15 mg/kg	Non-persistent
Heptachlor (Refined chlordane)	Fish - 96 hr. TL_m 0.019 - 0.230 mg/l *Daphnia* - 50 hr. immobilization 0.058 mg/l	Rats - LD_{50}, 90 mg/kg Birds - LD_{50}, 125 - 400 mg/kg	Moderately persistent

SOURCE: Pressman (1963), reproduced in Johnson et al., (1967).

teria. These bacteria, either *Flavobaterium* or *Protaminobacter* and *Bacillus*, form flocs that are capable of adsorbing and concentrating aldrin. The resulting sediment can serve as a reservoir for pesticide release at some future time. Algae are known to detoxify certain chlorinated hydrocarbons, especially lindane. The Great Lakes algae, *Chlorella* and *Chamydomonas*, were shown to metabolize lindane in the laboratory (Sweeney[777]). He suggested that algal metabolization may account for the relatively low levels of lindane as compared to other pesticides in the Great Lakes.

At present only Michigan and Pennsylvania control pesticide usage in the United States portion of the Great Lakes Basin. These controls, and similar ones in Ontario, limit the types of pesticides used, but do not exclude all persistent pesticides. Since runoff is a major source of pesticides in the lakes, basinwide controls must be established. Significant amounts of chlorinated hydrocarbon pesticides are also entrained by winds during crop spraying and are carried hundreds of miles before being deposited by rainfall or aeolian sedimentation (Frost[277]). Basinwide legislation may not suffice to totally control this type of pesticide input into the Great Lakes, so Federal action is necessary. Care must also be taken that the alternatives selected do not sanction pesticides that are as harmful as chlorinated hydrocarbons. For example, many of the substitutes for DDT are organophosphates, which are toxic to mammals and many lower animals.

Pesticide levels in the Great Lakes are low (Table 4–37). Since pesticides are widely used in the Great Lakes Basin, it appears that a combination of dilution, sediment interaction, biological flocculation or detoxification (Leshniowsky et al.;[494] Sweeney[777]), and biotic assimilation account for these low levels.

The Green Bay drainage area is a fruit growing region, so chlorinated hydrocarbon pes-

TABLE 4–37 Chlorinated Hydrocarbon Pesticide Concentrations in the Great Lakes (mg/l)

Location	Dieldrin	Endrin	DDT	DDE	DDD	Aldrin	Hepta-chlor	Hepta-chlor Epoxide	BHC	Year of Determination & Reference
St. Lawrence R.,	0.003	P	ND	P	ND	ND	ND	ND	ND	(A)
Massena, N. Y.	ND	ND	ND	ND	0.010	ND	0.031	0.017	ND	(B)
Lake Erie,	ND	ND	ND	ND	ND	ND	ND	ND	ND	(A)
Buffalo, N. Y.	ND	ND	ND	ND	ND	ND	ND	0.002	ND	(B)
Maumee R.,	ND	ND	0.087	0.015	ND	P	P	ND	ND	(A)
Toledo, O.	0.023	ND	ND	ND	ND	ND	ND	ND	ND	(B)
Detroit R.,	ND	ND	ND	ND	ND	P	ND	ND	ND	(A)
Detroit, Mich.	0.018	ND	ND	0.008	ND	ND	0.015	P	ND	(B)
St. Clair R.,	ND	ND	ND	P	ND	ND	P	ND	ND	(A)
Port Huron, Mich.	ND	ND	ND	ND	ND	ND	ND	ND	ND	(B)
Lake Michigan	0.007	0.006	P	ND	ND	ND	ND	ND	ND	(A)
Milwaukee, Wisc.	0.003	ND	ND	ND	ND	ND	ND	ND	ND	(B)
Lake Superior	P	ND	P	P	ND	ND	ND	ND	ND	(A)
Duluth, Minn.	ND	ND	ND	ND	ND	ND	ND	ND	ND	(B)

P=Presumed present, based on inconclusive chromatographic evidence
ND=None detected
(A)=Data collected in 1964, by Weaver, et al., (1965)
(B)=Data collected in 1965, by Breidenback, et al., (1967)

TABLE 4–38 Pesticide Residues in Whole Fish from Lake Erie, 1965–1967

Species	Number of fish	Number of analyses	Method[1]	Pesticide concentration mg/kg fresh weight: Dieldrin	o,p-DDT	p,p-DDD	p,p-DDE	p,p-DDT	p,p-DDE p,p±DDT	Total DDS[2]
Alewife	27	6	H	--	.13	.69	.32	.44	.76	1.59
		6	S	.14	--	--	--	--	.99	----
American smelt	8	1	H	--	.22	.19	.27	.60	.87	1.28
		1	S	.04	--	--	--	--	.72	----
		1	E	--	--	--	--	--	--	.84
Brown bullhead	7	1	H	--	.00	.11	.06	.04	.10	.21
		1	S	.00	--	--	--	--	.18	----
		1	E	--	--	--	--	--	--	.34
Emerald shiner	6	2	H	--	.15	.75	.44	.21	.65	1.55
		1	S	--	--	--	--	--	.03	----
Gizzard shad	9	2	H	--	.02	.26	.08	.17	.26	.53
		2	S	.08	--	--	--	--	.30	----
Freshwater drum	12	2	H	--	.12	.42	.22	.25	.48	1.01
		2	S	.04	--	--	--	--	.32	----
		2	E	--	--	--	--	--	--	.54
Goldfish	2	1	E	--	--	--	--	--	--	.70
Spottail shiner	9	3	E	--	--	--	--	--	--	.25
Stonecat	2	1	E	--	--	--	--	--	--	.28
Walleye	47	5	H	--	.12	.61	.40	.38	.79	1.52
		5	S	.09	--	--	--	--	1.75	----
		27	E	--	--	--	--	--	--	1.01
White bass	3	1	H	--	.23	.22	.50	.94	1.44	1.89
		1	S	.04	--	--	--	--	1.32	----
White sucker	3	1	H	--	.00	.11	.10	.16	.26	.37
		1	S	.02	--	--	--	--	.19	----
Yellow perch	212	4	H	--	.06	.32	.28	.38	.65	1.03
		4	S	.05	--	--	--	--	.57	----
		22	E	--	--	--	--	--	--	.75

[1] H-homogenized; S - saponification; E - ether extraction
[2] DDD + DDE + DDT

SOURCE: International Joint Commission, 1969b, Vol. 2, p. 115

ticides are commonly found in the aquatic environment of this area. Biological magnification is easily demonstrated here and the consequences of pesticide loading are already evident. Johnson et al.[435] estimated that in 1962, 134,279 pounds of chlorinated hydrocarbons were used in the Green Bay watershed. The primary pesticides used were DDT and derivatives (87 percent), aldrin (9 percent), and dieldrin (2 percent). Hickey and Keith[353] and Hickey et al.[354] found high levels of pesticides in Green Bay and adjacent Lake Michigan sediment in 1963 and 1964. Even deep water mud contained an average 0.014 mg/l of DDT, DDE, and DDD (wet weight basis). In the same area biological magnification was indicated by higher levels in the biota. For example, the crustacean *Pontoporeia affinis* contained 0.41 mg/l; oldsquaw ducks contained 0.44 mg/l, and whitefish contained 0.54 mg/l. Clearly, there is a concentration of pesticides in the biota over water or sediment levels. Other organisms that contained hard pesticides include alewives (3.3 to 4.2 mg/l), whole chubs (4.5 mg/l), whitefish muscle tissue (5.6 mg/l), and gulls (20.8 mg/l in brain, 98.8 mg/l in breast muscle, and 2441 mg/l in body fat). Mortalities of shore birds as a result of the high pesticide levels are well documented in the Lake Michigan area. Keith[444] concluded that chlorinated pesticides were responsible for fatalities of adult and juvenile gulls and egg non-viability in the Green Bay area. The buildup of pesticide levels in the food chain in the Green Bay area is evident. Examination of pesticide levels in fish from Lake Erie from 1965 to 1967 by the Bureau of Commercial Fisheries and Michigan State University (International Joint Commission[408]) (Table 4–38) support the concept of biological magnification. The Ontario Water Resources Commission (OWRC) (International Joint Commission[408]) analyses of fish from Lake Erie and Lake Ontario are similar to those in Table 4–38 and show significant concentration of pesticides in fish. The OWRC data are of special interest because they show, to a limited degree, in which tissues DDE is concentrated. Mean DDE concentrations in Lake Erie fish ranged from 0.03 mg/kg in the ovaries of a yellow perch from the western basin to 4.70 mg/kg in the ovaries of a yellow perch from the eastern basin. In most cases DDE was 3 to 10 times as concentrated in the gonads as compared to muscle tissue. Lake Erie fish generally contained less than 1 mg/kg DDE. Similar data were taken by the OWRC in Lake Ontario where DDE levels usually ran less than 2 mg/kg. Maximum and minimum values obtained in Lake Ontario were 0.03 mg/kg DDE in the muscle of a female black crappie and 68.90 mg/kg DDE in the testes of a male northern pike.

The Great Lakes Fishery Commission summarized DDT levels in the Great Lakes fish as follows (International Joint Commission[408]):

1. Great Lakes fishes contain significant quantities of DDT residues as high as 10.4 mg/kg in chubs (*Coregonus hoyi*); even higher concentrations have been observed by OWRC in the testes of a male northern pike in Lake Ontario.
2. DDT levels in Lake Michigan fish are two to five times higher than in fish from other Great Lakes.
3. DDT levels in eggs and fry of rainbow trout and Coho salmon from Lake Michigan are similarly two to five times higher than in eggs and fry of these species from Lake Superior and Oregon.
4. Death of 700,000 Coho fry hatched from eggs produced by Lake Michigan Coho displayed the same characteristics as did the death of fry exposed to lethal DDT levels; fry produced from eggs taken from Lake Superior and Oregon Coho did not suffer unusual losses during development.
5. Moribund fry from Lake Michigan Coho had significantly higher DDT levels than surviving fry from Lake Michigan.

7.5.7.2 Polychlorinated Biphenyls (PCBs)

PCBs are a series of compounds formed by substituting chlorine atoms for one or more hydrogen atoms on the biphenyl molecule. They have low vapor pressures, low water solubility (maximum solubility is approximately 0.2 mg/l at atomospheric temperatures), high dielectric constants, and are miscible with most organic solvents. Consequently, PCBs are used as coolant-insulation fluids in transformers; ballasts for fluorescent fixtures; plasticizers in polyvinyl chloride films and wire coatings; additives to high temperature oils, hydraulic fluids, and lubricants; additives to epoxy paints; protective coatings for wood, metal, and concrete; additives in carbonless reproducing paper; and for impregnation of fiber insulation in wiring (Gustafson[308]).

PCBs were first discovered in the environment in Sweden in 1966 and in the United States in 1967. They are widespread and are known to occur in the food chain, water, and sediment. Like the hard pesticides, PCBs are persistent and are subject to biological magnification. They are toxic if taken in sufficient doses and chronic toxicity can occur after accumulation over a period of time. Acute toxicity is approximately the same as with other chlorinated aromatic compounds and the degree to which organisms are affected varies. Gustafson[308] (1970) found that acute PCB toxicity is a minor problem. PCBs are only slightly toxic to fish, while certain aquatic invertebrates are somewhat more sensitive (shellfish, oysters, and shrimp) or insensitive (insects). Chronic toxicity is a problem, however. By biological magnification and retention in the food chain, PCBs can reach fatal or debilitating levels in most consumer organisms. In this respect, PCBs are similar to DDT.

Unlike DDT, PCBs have only recently been found worldwide at dangerous levels. This is primarily because they are not intentionally applied in large quantities over wide areas like DDT. PCBs occur in industrial wastes, and are accidentally introduced to streams and lakes in small quantities. Although remote areas are not subject to PCB loading, wind and water transport have made PCBs nearly ubiquitous.

PCBs have been identified in the Great Lakes (Gustafson[308]). However, lack of data precludes evaluation of the extent of PCB loading and potential danger to the ecosystem. Immediate action should be taken to determine the PCB content of the Great Lakes sediment, water, and biota; toxicities to the biota; and sources of PCBs.

7.5.7.3 Phenol and Phenolic Compounds

Phenols and associated compounds can occur as natural or cultural imputs in the Great Lakes system. Phenols are hydroxy derivatives of benzene, produced naturally in minor quantities by algae, but are introduced into the system primarily as industrial waste products from oil refineries, coke plants, plastics plants, and some other chemical plants. Phenols have several deleterious effects on water quality. Concentrations of 0.001 to 0.1 mg/l impart an unpleasant odor and taste to water that is difficult to eliminate by standard water treatment. Phenols and phenolic compounds impart odors and tastes to fish flesh at concentrations as low as 0.001 mg/l (Federal Water Pollution Control Administration[832]), and may cause extensive internal damage to fish subjected to these low concentrations (Mitrovic et al.[549]). They are toxic at concentrations of 0.1 to 10 mg/l.

Phenol retention in the Great Lakes presents little problem because phenols are biodegradable and degrade rapidly away from the source (Figure 4–184). However, biodegradation results in nuisance algae and slime growths (Federal Water Pollution Control Administration[831]), high oxygen demands, and a generally detrimental effect on the chemical system (Federal Water Pollution Control Administration[831]).

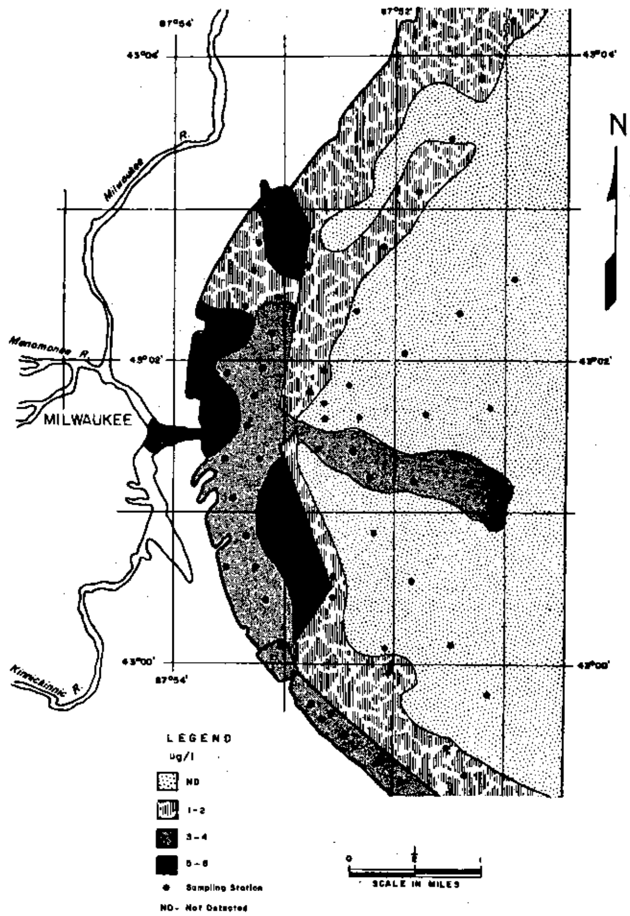


FIGURE 4–184 Phenol Distribution near Milwaukee Harbor, Wisconsin
Data from Federal Water Pollution Control Administration, 1968c

The mean phenol concentration in inshore Lake Michigan in 1962–63 was 2 μg/l (range 0–32 μg/l) (Federal Water Pollution Control Administration[835]). Mean concentration in southern Green Bay reached 21 μg/l and in northern Green Bay phenols were not detectable during June-July, 1963. Phenol determinations in the other lakes are restricted to harbor areas.

7.5.7.4 Detergents

Detergents have become extremely important as water pollutants because of their wide usage. As mentioned in the subsection on phosphates, detergents often contain phosphatic compounds that serve as nutrients in the aquatic ecosystem. They can cause un-

TABLE 4–39 Effect of Alkyl-aryl Sulfonate, including ABS, on Aquatic Organisms

Organisms	Concentration[1]	Time	Effect
Trout	5.0	26 to 30 hours	Death
	3.7	24 hours	TL_m
	5.0	---	Gill pathology
Bluegills	4.2	24 hours	TL_m
	3.7	48 hours	TL_m
	0.86	---	Safe
	16.0	30 days	TL_m
	5.6	90 days	Gill damage
	17.0	96 hours	TL_m
Fathead minnow	2.3	---	Reduced spawning
Fathead minnow fry	13.0	96 hours	TL_m
	11.3	96 hours	TL_m
	3.1	7 days	TL_m
Pumpkinseed sunfish	9.8	3 months	Gill damage
Salmon	5.6	3 days	Mortality
Yellow bullheads	1.0	10 days	Histopathology
Emerald shiner	7.4	96 hours	TL_m
Bluntnose minnow	7.7	96 hours	TL_m
Stoneroller	8.9	96 hours	TL_m
Silver jaw	9.2	96 hours	TL_m
Rosefin	9.5	96 hours	TL_m
Common shiner	17.0	96 hours	TL_m
Carp	18.0	96 hours	TL_m
Black bullhead	22.0	96 hours	TL_m
"Fish"	6.5	---	Minimum lethality
Trout sperm	10.0	---	Damage
Daphnia	5.0	96 hours	TL_m
	20.0	24 hours	TL_m
	7.5	96 hours	TL_m
Lirceus fontinalis	10.0	14 days	6.7 percent survival (hard water)
Crangonyx setodactylus	10.0	14 days	0 percent survival (hard water)
Stenonema ares	8.0	10 days	20 to 33 percent survival
	16.0	10 days	0 percent survival
Stenonema heterotarsale	8.0	10 days	40 percent survival
	16.0	10 days	0 percent survival
Isonychia bicolor	8.0	9 days	0 percent survival
Hydropsychidae (mostly *cheumatopsyche*)	16.0	12 days	37 to 43 percent survival
	32.0	12 days	20 percent survival
Orconectes rusticus	16.0	9 days	100 percent survival
	32.0	9 days	0 percent survival
Goniobasis livenscens	16.0	12 days	40 to 80 percent survival
	32.0	12 days	0 percent survival
Snail	18.0	96 hours	TL_m
	24.0	96 hours	TL_m
Chlorella	3.6	---	Slight growth reduction
Nitzchia linearis	5.8	---	50 percent reduction in growth
Navicula seminulum	23.0	---	50 percent growth reduction in soft water

[1]mg/l

SOURCE: Federal Water Pollution Control Administration, (1968a).

sightly scums and suds that reduce light penetration and thus modify the energy budget of a lake. They are toxic to aquatic organisms if present in sufficient quantities.

Alkyl benzene sulfonate (ABS) has been a widely used non-biodegradable detergent. Consequently, its toxic effects (Table 4–39) are promulgated over wide areas and are persistent. Although an extensive literature exists on ABS and its effects on the environment, little is known of its behavior in an aquatic system. For example, water hardness, temperature, and pH are known to affect the behavior of ABS, but the extent of that effect is unknown. ABS in concert with other toxicants is known to have a synergistic effect of unknown extent. The Federal Water Pollution Control Administration[831] has recommended a limit of one-seventh of the 48 hour TL_m for ABS, with short periods (less than 24 hours) of 1 mg/l allowable.

In 1965 U.S. detergent manufacturers ceased production of hard detergents using the ABS surfactant. The present primary surfactants are linear alkylate sulfonates (LAS), which are biodegradable. LAS compounds are two to four times more toxic than ABS (Federal Water Pollution Control Administration[832]) until they become degraded. There is little information on LAS effects upon the ecosystem. The Federal Water Pollution Control Administration[831] summarized much of the existing median toxic limit data for LAS on freshwater fish, and recommended that the concentration of LAS should not exceed 0.2 mg/l or one-seventh of the 48 TL_m for a given fish population. Dugan[226] found that LAS had a synergistic effect when combined with chlorinated pesticides. Low oxygen levels are also known to increase the toxicity of LAS (Federal Water Pollution Control Administration[831]).

LAS and ABS surfactants are not normally separated in water quality studies, but are combined and reported as methylene blue active substances (MBAS), a name derived from the standard test for surfactants (American Public Health Association et al.[10]).

MBAS data in the open lakes are sparse. The Federal Water Pollution Control Administration[835] monitored MBAS in the harbors and tributaries of Lake Michigan in 1963–64. Traverse Bay was the only embayment examined and none of the open lake was sampled for MBAS. In Traverse Bay MBAS averaged 0.03 mg/l (range 0.01 mg/l to 0.06 mg/l), as compared with an average MBAS of 0.03 mg/l (range 0.02 mg/l to 0.05 mg/l) in the adjacent portions of Lake Michigan. ABS in Lake Erie in 1963–64 was 0.067 mg/l in the western basin, 0.065 mg/l in the central basin and 0.065 mg/l in the eastern basin (Federal Water Pollution Control Administration[833]). The samples in Lake Erie ranged from 0.01 mg/l to 0.20 mg/l. Since ABS detergents have not been used since 1965, these data should represent maximum values and the present ABS content in Lake Erie should be less.

The transition to biodegradable detergents will reduce the toxic effects of detergents. However, biodegradability does not mean that the detergent-derived problems in the Great Lakes will be obviated. As long as phosphates, ammonia, or any other nutrient remains in the detergent the more critical problems of eutrophication will be present.

Phosphates are added to detergents to soften water by combining with calcium and other ions, to disperse and suspend particulate matter, and to augment the cleaning action of the detergents. Alternatives include nitrilotriacetic acid (NTA), organic polyelectrolytes, and sodium citrate. Although most tests indicate that NTA is benign, Epstein[244] warns that under heavy load, low temperature, low oxygen, and/or low sewage bacteria conditions NTA may not completely degrade, and the intermediate products in the breakdown to nitrate and nitrite may be toxic. Furthermore, he warns that NTA is a metal-chelating agent, which means that NTA could complex toxic metals from a sewer system or the sediment and cause toxic conditions in the water. This may be a particular problem in the Great Lakes where known toxic metals (e.g., mercury, copper, zinc) are bound in the sediments. NTA and all other substitutes to phosphates in detergents should be, therefore, carefully considered in light of Great Lakes chemistry before use is initiated.

7.5.7.5 Petroleum

Crude oil is injurious to the environment in several ways. Most oil products are biodegradable and biodegradation exerts a considerable oxygen demand. When incorporated with sediment, petroleum products accelerate loss of oxygen. In fact, the natural occurrence of petroliferous rock has contributed to the eutropication of Lake Erie since that lake was formed. The bottom of the lake contains sediment derived in part from a petroliferous shale bedrock (Section 1), the oxidation of which creates an oxygen demand regardless of cultural additions of the system.

Most petroleum products are less dense than water and remain at the water surface. Floating oil hinders exchange of gases between the water and atmosphere, and leave unsightly slicks on the surface. The slicks of oil and oil derivatives foul neustonic organisms and waterfowl. If large quantities of oil are present, mass mortalities result (Hunt[393]). Plants may also be affected by coating of petroleum products, which decreases interaction with the atmosphere.

The lighter fractions of petroleum cause potentially serious problems because of extreme toxicity, high vapor pressure, and low viscosity. For example, gasoline is commonly spilled in lakes and rivers. It is not viscous, so it rapidly spreads into an invisible layer on the water surface. The high vapor pressure causes the more volatile fractions to enter the atmosphere leaving a residue of heavier fractions and additives, such as the highly toxic tetraethyl lead. Neustonic organisms ingest the gasoline products on the surface and the soluble fractions are ingested by the entire aquatic biota.

Petroleum products are removed from the aquatic system by oxidation, metabolization, and sedimentation. Oxidation of the lighter fractions of crude oil leaves a tarry residue that adheres to surfaces and mars beaches. Brown and Tischer[107] found the microbial breakdown is a significant mechanism for degrading petroleum products under aerobic and anaerobic conditions. In Brown the Tisher's experiments oil removal was most rapid under aerobic conditions in the presence of nitrogen and phosphorus enrichment. Fish were subjected to the soluble byproducts of the microbial breakdown of petroleum and the results suggest that the products are more toxic to fish than the original oil. The heavier fractions and oxidized products of petroleum settle to the bottom and become part of the sediment. Oil-enriched sediment is unsuitable for a normal benthic biota as it forms a poor substrate for larval development, attachment or burrowing of animals, and attachment of rooted plants. The petroleum may have a high BOD that competes with the biota, as well as degrading the substrate. As mentioned in Subsection 7.5.7.1, oil in the sediment is known to partition and concentrate DDT.

Oils enter the lakes from a variety of sources. They flow into the lakes from untreated industrial discharge, urban runoff, and fuel and lubricants on vessels. The most significant sources are oil spills from coastal installations, tankers, and oil wells. It would be impossible to list the spills that occur each year in the Great Lakes. However, an active petroleum industry in the Great Lakes Basin has led to many spill occurrences, including storage tank losses, tanker hold pumping, loading and discharging accidents, and wellhead losses (Federal Water Pollution Control Administration;[836] International Joint Commission[407,408,409]).

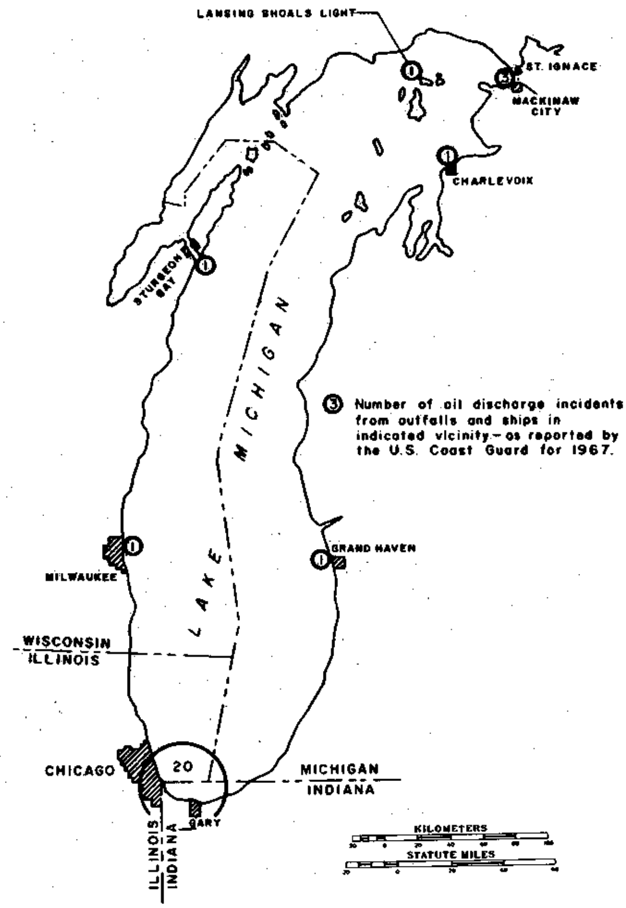


FIGURE 4–185 Number and Distribution of Oil Spills in Lake Michigan in 1967
U.S. Coast Guard and Federal Water Pollution Control Admin., 1968b

Twenty-eight oil spills were reported on Lake Michigan during 1967 (Figure 4–185). The Chicago-Gary region is responsible for most of these because of the petroleum refineries and heavy industry in the area. Enforcement practices have reduced the incidence of such spills.

A potential source of oil spills is the drilling operations in the open lake. Offshore wells are currently operating in Ontario waters off

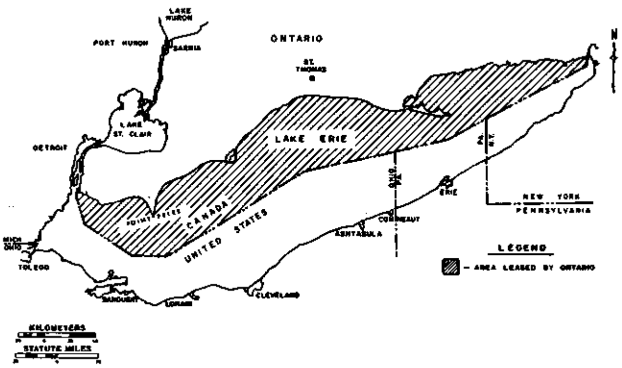


FIGURE 4–186 Acreage Leased in Lake Erie for Oil and Gas Drilling
Modified from International Joint Commission, 1969b

Lake Erie. By 1968 there were more than 250 producing gas wells but no oil wells in these waters. Very few wells have been drilled on the United States side of Lake Erie, and none are currently producing. Exploration in the U.S. is currently prohibited. Figure 4–186 shows the leased acreage in Lake Erie for oil and gas exploration (International Joint Commission[408]). Since there is little oil present, well-head oil spills appear to present little hazard. Future oil exploration could change the situation.

Adequate legislation exists to enable enforcement of the laws against oil spillage. However, detection devices and methods are inadequate. Chemical tracers may be a solution to the problem of detecting unobserved oil spills and identifying the source of the pollution. Johnson et al.[436] related various analytical methods in an effort to identify the source of one oil slick on southern Lake Michigan. Their experiments indicate the difficulty encountered in oil spill detection and enforcement. The International Joint Commission[408] has outlined the current structural and institutional methods for control of oil spills in the Great Lakes.

A special problem concerning oil derivatives, in addition to other pollutants, is the disposal of dredged spoil from industrialized harbors and rivers. Until 1969 open lake disposal was a common practice. The Army Corps of Engineers, Buffalo District[811] in conjunction with the Federal Water Pollution Control Administration, studied the effects of open lake spoil disposal on water and bottom quality. Pursuant to their findings, alternative disposal methods (e.g., disposal on land, disposal in diked areas) have been chosen where needed to preserve lake quality.

7.5.7.6 Organic Gases

Organic gases are not a serious problem in the open Great Lakes. However, in restricted areas, such as harbors, oxidation of organic debris may lead to the evolution of flammable, toxic, noxious gases such as methane and acetylene. These gases have become local problems in the Cuyahoga River, Indiana Harbor, and other confined areas. Cessation of influx of oxidizable organics will reduce the problem of organic gas evolution.

7.5.7.7 Organic Acids

Organic acids are a normal result of decay in the woods and swamps of the Great Lakes Basin. The most often used classification of the organic acids includes humic acid (alkali-soluble, acid-insoluble fraction of humus), fulvic acid (alkali-soluble, acid-soluble humus fraction), hymatomelanic acid (alcohol-soluble humic acid fraction), and humin (alkali insoluble fraction) (Stevenson and Butler[761]). Little is known about the structure and importance of these natural organic acids (Wershaw et al.[883]). Humic substances are highly variable in composition and molecular weight. Under normal conditions humic and fulvic acids do not present a problem in the Great Lakes. However, upland lakes may be severely affected by acid inputs from adjacent swamps and bogs.

Under conditions of loading of pollutants, such as pesticides, phosphates, and nitrates, humic and fulvic acids may have a synergistic or retarding effect on those pollutants. Humic and fulvic acids are known to serve as buffers, ion exchangers, surfactants, sorbents, and chelating agents (Konova[465]).

Wershaw et al.[882] showed that presence of sodium humate solubilizes DDT and that humic acid strongly sorbs 2, 4, 5–T. Lange[484] showed that fulvic acid can stimulate growth of blue-green algae by chelating iron. Recently is has been shown that organic acids are important agents in the complexing of heavy metals (e.g., mercury, copper) and that the presence of organic acids may account for the mobilization of these metals as either solid or soluble complexes, and may provide direct pathways for toxic materials to enter the food chain (Cline et al.;[152] Cline[151]).

Other organic acids that have been identified from either natural or cultural sources include mono-carboxylic acids (e.g., formic, acetic, stearic, lactic, acrylic), dicarboxylic acids (e.g., oxalic, malonic, succinic), and urea. Little is known of the toxicities of these constituents of their impact on the aquatic environment.

Control of the naturally occurring organic acids is impractical. Since their only apparent ill effects are in conjunction with known pollutants, control of those pollutants appears to be a logical solution. The ecological impact of acids from industrial, agricultural, and municipal wastes should be studied to determine if elimination of these acids is necessary.

7.5.7.8 Cyanide

Cyanides (CN^-) are common industrial chemicals. They have been studied extensively in order to establish water quality standards (Table 4–30). However, little is actually known of the impact of cyanides on the aquatic biota (Federal Water Pollution Control Administration[831]). Doudoroff et al.[223] showed that the complexes of cyanide that were most toxic to fish are HCN and a few heavy metal (e.g., Ag) cyanide complexes. Because cyanic acid (HCN) is an important toxicant, the availability of hydrogen ions (pH) is a controlling factor in cyanide toxicity. Cyanides are also known to be toxic to diatoms (Federal Water Pollution Control Administration[831]).

7.5.7.9 Organic Carbon

Organic carbon is an indicator of the amount of carbon present in a water mass and includes the carbon compounds produced by biotic production and introduced by man. There are several ways of determining organic carbon, and they vary in efficiency. The water quality standards (Table 4–30) are based on carbon chloroform extract (CCE). CCE does not give the total organic carbon concentration, as it is insensitive to certain compounds, such as synthetic detergents. More sensitive techniques are used to monitor total organic carbon for productivity-pollution load studies. The use of organic carbon as a measure of productivity is discussed in Section 8.

Very few studies have been concerned with organic carbon in the water or sediment of the Great Lakes. Robertson and Powers[666] summarized the organic matter dissolved in the water column of all five lakes, based on a relatively few, shallow samples. The mean and range of dissolved organic matter in the Great Lakes are shown in Table 4–40. As dissolved organic matter is a measure of productivity and organic chemical loading, the sequence of increasing organic matter from Lake Superior to Lake Ontario reflects the accelerated aging and increased waste loading in the lower lakes. According to Robertson and Powers, the higher concentration in shallow water results from metabolic activity in the photic zone.

TABLE 4–40 Dissolved and Particulate Organic Matter in Great Lakes Water (mg/l)

	Dissolved		Particulate	
	Mean	Range	Mean	Range
0–25 m depth				
Lake Superior	2.62	2.22–2.98	0.42	0.28–0.50
Lake Huron	2.71	2.52–2.91	0.71	0.61–1.00
Lake Michigan	4.91	3.24–5.81	1.12	1.05–1.18
Lake Erie	---[1]	5.82–6.01	---[2]	0.41–3.80
Lake Ontario	6.13	5.85–6.53	1.41	1.09–1.68
>25 m depth				
Lake Superior	2.25	1.77–2.65	0.30	0.20–0.40
Lake Huron	2.72	2.41–2.83	0.98	0.71–1.31
Lake Michigan	4.61	4.51–4.77	1.15	0.97–1.33
Lake Erie	---[2]		---[2]	
Lake Ontario	---[2]		---[2]	

[1]Insufficient sample set
[2]Not determined

SOURCE: Robertson and Powers, (1967).

Particulate organic matter in the sediment and water column is a primary source of natural dissolved organic carbon. According to Robertson and Powers'[666] summarization of the distribution of particulate organic matter in the Great Lakes (Table 4–40), particulate matter shows essentially the same trends as dissolved organic matter in the water column. Determination of organic carbon and chlorophyll in sediment is somewhat more revealing than in the water column because sources of organic contribution can often be identified. Organic carbon in the sediment is closely correlated with depth and sediment texture (Powers and Robertson[627]) (Figure 4–187). Deeper water contains finer textured sediment and more organic carbon. Consequently, mean organic carbon determinations for a region are erroneous unless weighted by areal extent, depth, and texture. Organic carbon in Lake Ontario sediment ranges from 0.5 percent nearshore to 4.0 percent offshore (Lewis and McNeeley[497]). Kick[453] and Kemp and Lewis[449] found essentially the same concentrations in Lake Erie, and Powers and Robertson[627] found ranges from 0.05 percent inshore to 3.5 percent offshore in Lakes Michigan and Huron (Figure 4–187). Organic content does not increase with depth in Lake

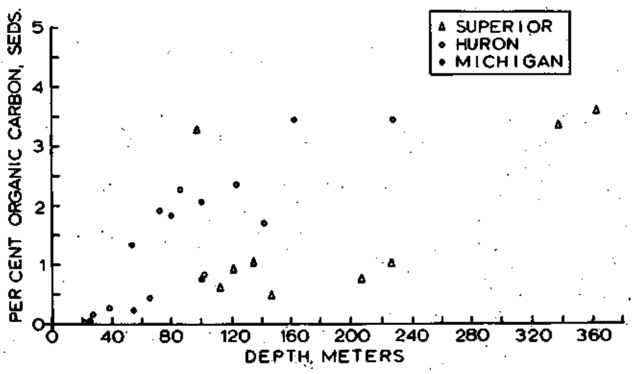


FIGURE 4-187 Distribution of Sedimentary Organic Carbon Versus Depth in Lakes Superior, Michigan and Huron

From Powers and Robertson, 1967

Superior because of lower productivity. Whereas organic carbon cannot be attributed to a particular source material, chlorophyll can be attributed to primary production. Kemp and Lewis[449] found that total chlorophyll concentration in Lake Erie ranged from 0 ppm to 29.3 ppm (dry weight) and in Lake Ontario ranged from 0.5 to 21.7 ppm. On the same basis pheophytin (a chlorophyll degradation product) ranged from 0.7 ppm to 120.2 ppm in Lake Erie and 16.0 ppm to 191.5 ppm in Lake Ontario. Based on an estimated 60,000 ppm chlorophyll and pheophytin in living organic matter (phytoplankton) and a range of from 680 ppm to 4030 ppm chlorophyll and pheophytin in organic sediment, Kemp and Lewis estimated a minimum of 93 percent degradation in lake sediment. They also concluded from other evidence that chlorophylls are essentially degraded by the time they reach the lake bottom and pheophytins are 93 percent to 100 percent decomposed before deposition. Clearly, degradation of organic matter is a rapid process and can contribute many dissolved organic constitutents to the lakes.

7.5.8 Calcium and Magnesium

Calcium and magnesium are important in the Great Lakes because of their effect on water hardness, scale formation, and the carbonate cycle. H_2CO_3, HCO_3^-, and CO_3^{-2} (indicators of alkalinity), and Ca^{+2} and Mg^{+2} are the most abundant chemical constituents in Great Lakes water (Table 4-32), representing 70 percent of the total ionic strength in Lakes Erie and Ontario and 90 percent in Lake Superior (Kramer[472]). Calcium and magnesium are widespread and readily available in the Great Lakes Basin. Bedrock and overlying sediment in the Great Lakes Region, outside of the Canadian Shield, are composed of high proportions of the mineral calcite ($CaCO_3$) and dolomite ($Ca, Mg(CO_3)_2$) (Section 1). Dissolution of calcite and dolomite occurs through interaction with acid solutions, such as rainwater, by reactions such as:

$$CO_2 + H_2O = H_2CO_3 \qquad (34)$$

$$H_2CO_3 + CaCO_3 = Ca^{++} + 2HCO_3^- \qquad (35)$$

$$2H_2CO_3 + Ca,Mg(CO_3)_2 = Ca^{++} + Mg^{++} + 4HCO_3^- \qquad (36)$$

Other sources of Ca^{+2} and Mg^{+2} in the Great Lakes Basin are chemical weathering of feldspars and ferromagnesian silicate minerals in, or derived from, the igneous and metamorphic rocks of the Canadian Shield, and ground-water dissolution of gypsum and anhydrite in the strata of the Michigan structural basin. The latter source is of significantly less regional importance than dissolution of minerals on the surface.

Hardness, normally a measure of the amount of calcium and magnesium present in water, affects the wetting capabilities of soap or detergent solutions by combining with the soap to form a less soluble compound. If a calcium-magnesium-rich solution is concentrated by evaporation of water, the solubility product of calcite may be exceeded and a calcium carbonate scale that is deleterious to cooling systems and boilers will form. Water hardness has been related to plant growth, particularly in upland lakes. In lakes where the water is relatively soft there is a likelihood that phytoplankton will be the major assimilator of nutrients, while in hard water filamentous algae and higher plants will consume nutrients and become a problem (Hooper et al.[375]).

Calcite and dolomite form an important buffering system in the Great Lakes. By means of the dissolution reactions and the carbonate reaction, acid discharge into the lakes is neutralized, CO_2 is stabilized, and pH is fixed (Kramer[472]). Under certain conditions of temperature, CO_2 pressure, and calcium and magnesium concentration, saturation with respect to calcite and dolomite is approached in the Great Lakes (Figures 4-188 and 4-189). Saturation with respect to the carbonate minerals is especially prevalent in the lower lakes (Figure 4-155) where calcium and magnesium concentrations are compounded by inflow from upper lakes and from tributaries in terranes characterized by calcite and dolomite.

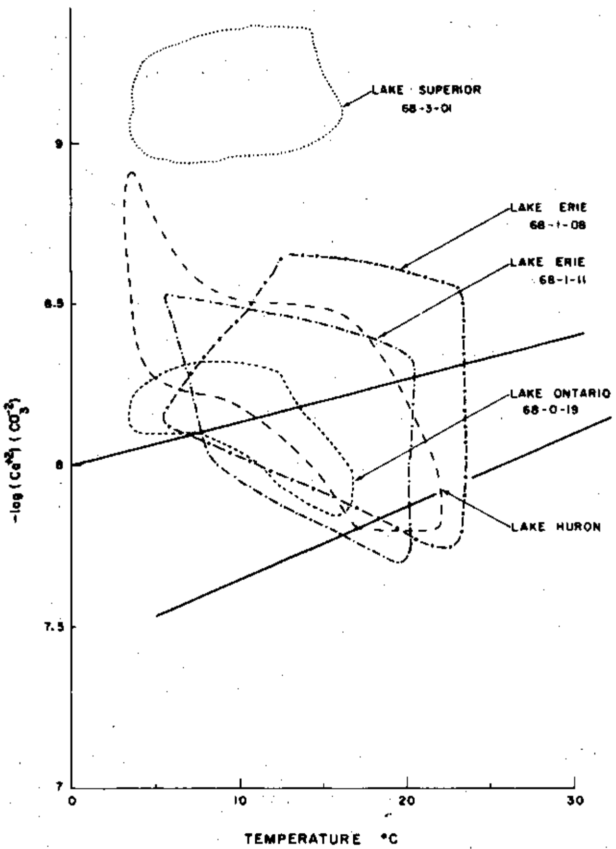


FIGURE 4–188 Ion Product Diagram for Calcite as a Function of Temperature in the Great Lakes. Areas outlined by dashed lines bound lake water analyses; solid lines represent solubility of calcite (upper) and aragonite (lower).
From Weiler and Chawla, 1969

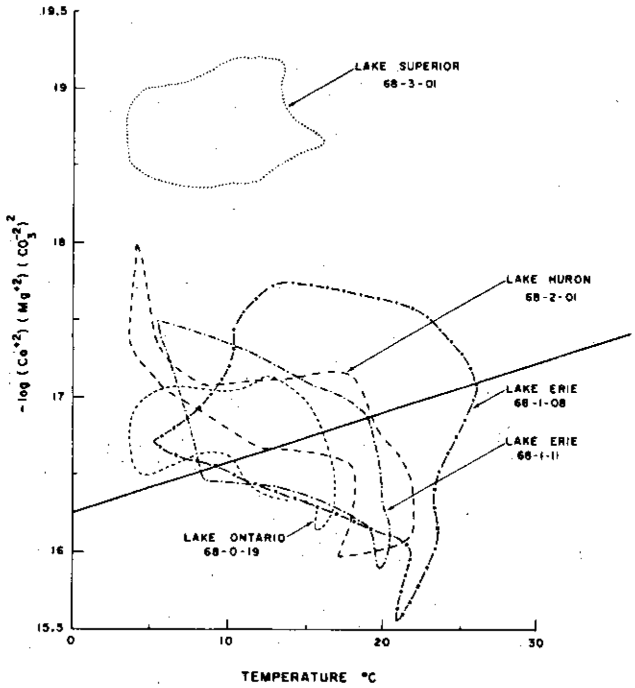


FIGURE 4–189 Ion Product Diagram for Dolomite as a Function of Temperature in the Great Lakes. Areas outlined by dashed lines bound lake water analyses; solid line represents solubility of dolomite (upper) and aragonite (lower).
From Weiler and Chawla, 1969

Other buffering mechanisms that can remove or contribute calcium and magnesium to the lakes are reactions with phosphates, ion exchange with clays, metabolic activity, and complexing with organic acids. Calcium may combine with phosphate (Subsection 7.5.5) to form the mineral hydroxyapatite, according to the reaction

$$Ca^{+2} + 6PO_4^{-3} + 2OH^- = Ca\,(PO_4)_6(OH)_2 \qquad (37)$$

Calcium and magnesium are the most common divalent cations found in exchange positions on clay (Grim[304]). In the limited regions of the Great Lakes where clays with high exchange capacities are found, ion exchange may be an important process for removing calcium and magnesium. Organisms use small amounts of calcium in production of hard parts, such as shells, carapaces, and bones; and plants use magnesium in chlorophyll production. Hoffman and Ehrlich[365,366] have shown that divalent cations, particularly calcium, can be complexed by natural organic acids. These calcium complexes may account for the apparent saturation and supersaturation with respect to calcite and hydroxyapatite in regions where these minerals do not appear to be forming.

The patterns of calcium and magnesium loading in the Great Lakes reflect the contrast in bedrock lithology and land use. Figure 4–190 indicates that Lakes Superior, Huron, and Michigan are essentially at steady-state conditions, where inflow of calcium equals outflow. A steady-state concentration in these lakes indicates that cultural inputs are negligible, whereas Lakes Erie and Ontario show increases in loads in the last sixty years (which correspond to the increase of agricultural activity in the two lake basins). High calcium concentrations occur in tributaries that drain agricultural areas, and low concentrations occur in the tributaries in undeveloped basins. Steepness of the chemical gradients away from the river mouths is governed by the rate of calcium-magnesium loading, diffusion rates, and the assimilative capacity of the lake. Lake Superior has a high assimilative

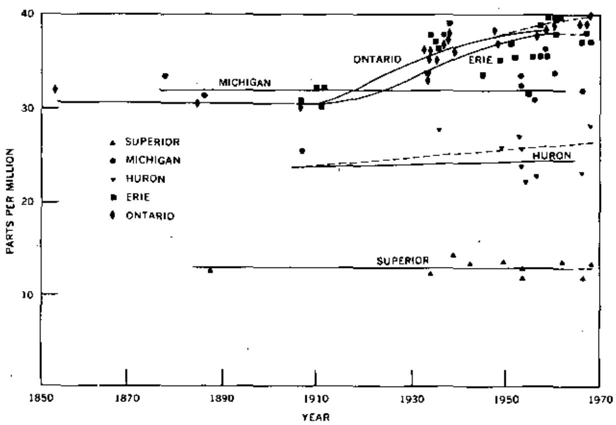


FIGURE 4–190 Historical Calcium Concentration Trends (mg/l) in the Great Lakes. Solid lines represent Beeton's suggested trends; dashed lines are after Weiler and Chawla.
From Beeton, 1965; Kramer, 1964; Weiler and Chawla, 1969

capacity because of its volume and a low calcium concentration (Figure 4–191) because loading from the undeveloped Canadian Shield is minimal. In contrast, Lake Erie has little assimilative capacity and is in an area of high calcium loading (Figure 4–192). Consequently, input into Lake Superior appears as restricted areas of high concentration, and in Lake Erie input appears as broad regions of high concentration.

7.5.9 Sulfur System

The many organic and inorganic sulfur compounds in a lake system can exist in either an oxidized or reduced form, depending on the availability of oxygen and the Eh of the system or on organisms that govern the state of the sulfur compounds by metabolic activity. In an oxidizing environment most of the inorganic sulfur occurs as sulfate ions (SO_4^{-2}). In anaerobic environments hydrogen sulfide (H_2S) is the prevalent inorganic sulfur compound. Most organic sulfur is combined as proteins or amino acids. Other sulfur compounds that are locally important, especially near sources of cultural input, are sulfuric acid (H_2SO_4) and its dissociation products, sulfites (SO_3^{-2}), and sulfonates (complex hydrocarbons with HSO_3^- radicals derived from detergents).

Sulfur compounds enter the lakes from several sources: atmospheric precipitation; ground water and surface runoff from regions that have sulfur-containing minerals in bedrock or soil; industrial wastes, including those from oil refineries, tanneries, paper and pulp mills, plastics plants, and other chemical plants; and domestic sewage.

The three most detrimental sulfur compounds in industrial and domestic wastes are H_2S, SO_3^{-2}, and sulfonated detergents. Hydrogen sulfide is very soluble in water and imparts the familiar "rotten egg" odor commonly associated with polluted water and with

FIGURE 4–191 Representative Distribution of Calcium (mg/l) in Lake Superior Surface Water
Data from Lake Survey Center (NOS–NOAA) cruises 7/18–8/8/68 and 7/27–8/7/69

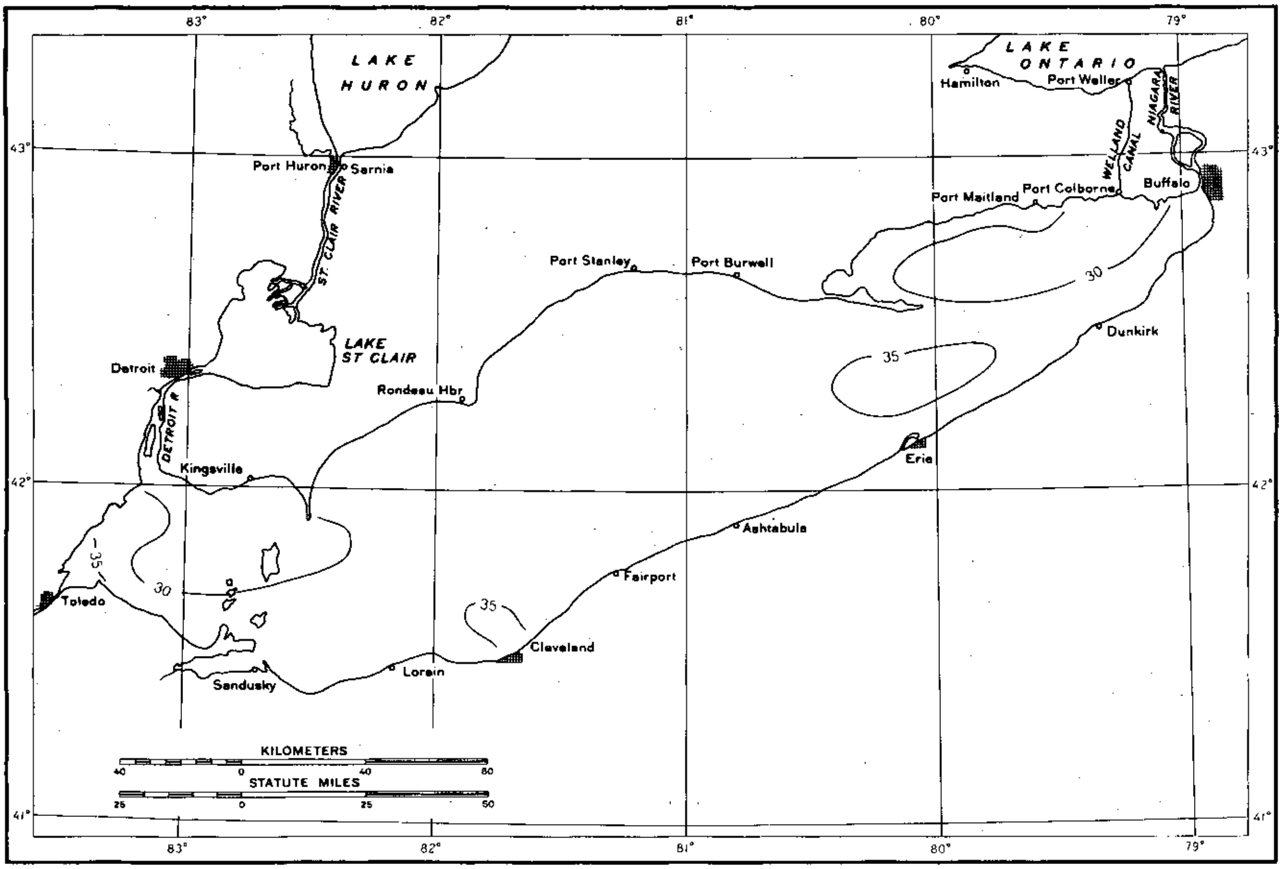


FIGURE 4–192 Representative Distribution of Calcium (mg/l) in Lake Erie Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 9/8–9/20/65

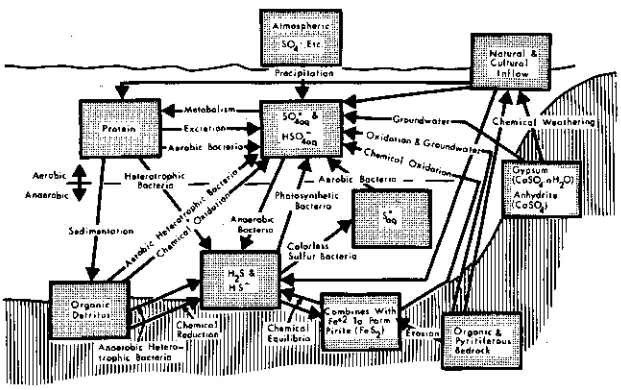


FIGURE 4–193 Simplified Sulfur Cycle in a Lake

springs containing significant H_2S. Hydrogen sulfide is not only disagreeable in taste and odor but is known to be as toxic as hydrogen cyanide and several times as toxic as carbon monoxide to many taxa. Concentrations of 1.0 mg/l to 25.0 mg/l of H_2S are lethal to many fish in a period of 1 to 3 days (Federal Water Pollution Control Administration[831]). H_2S in an aerobic environment causes high BOD and COD levels that are also destructive to the biota. Sulfites are usually associated with paper and pulp mills. They are equally as toxic as H_2S and cause high oxygen demands. Sulfonated detergents are deterimental because the detergents persist and are found where the other problem sulfur compounds do not. Sulfur is a minor nutrient for organic production and may be involved in the growth of nuisance algae in polluted systems.

The sulfur cycle (Figure 4–193) is propagated by two mechanisms that work in concert. In environments that are depleted in oxygen by BOD and COD from heterotrophic bacteria and chemical oxidation, H_2S is formed by bacterial reduction of oxidized sulfur compounds in the water column and organic sediment. Where oxygen is abundant, reduced forms of sulfur are oxidized by bacteria. Because bacteria that oxidize reduced sulfur compounds are ubiquitous, any influx of reduced sulfur (e.g., H_2S, SO_3^{-2}) creates a high BOD. Unless anaerobic conditions exist, H_2S will not persist, but will be rapidly oxidized. H_2S

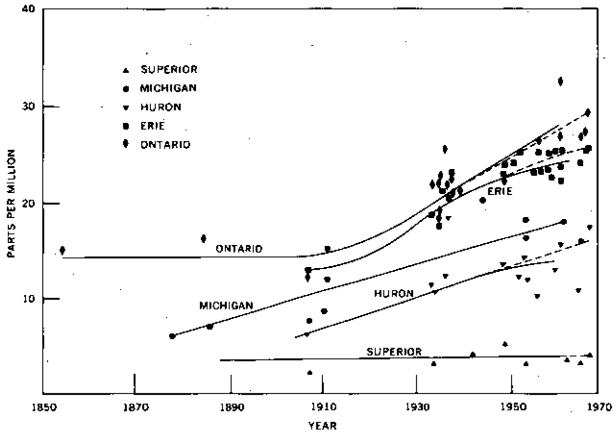


FIGURE 4–194 Changes in the Sulphate Concentration (mg/l) in the Great Lakes. Solid lines represent Beeton's suggested trends; dashed lines represent Weiler and Chawla's suggested trends.

From Beeton, 1965; Kramer, 1964; and Weiler and Chawla, 1969

is a problem, however, in some harbors and in portions of Lake Erie where DO is occasionally depleted. In silt-and clay-rich sediment the permeability often is low enough to maintain local reducing conditions in the vicinity of decomposing organic debris, even though the overlying water mass is aerobic.

Strata that contain gypsum, anhydrite, pyrite, and organic compounds are included in Figure 4–193 because they may represent locally important sources of sulfur compounds in the Great Lakes. Gypsum and anhydrite are mined from Silurian and Devonian strata in the Michigan structural basin so losses to the lakes from the mines may be of local importance. All of the lakes, except Lake Superior, lie in topographic basins containing shale. The shale is highly organic, so there is a natural source of BOD sulfur compounds in the lake bottoms.

Since sulfur is a minor nutrient and is stored in proteins, trapped in sediment as H_2S, and cycled through the food chain by bacteria, the natural storage capacity of a large lake system for sulfur is enormous. However, the net assimilative capacity of the Great Lakes system in recent years has been insufficient to buffer out all of the sulfate added to the system, and sulfate concentrations are rising (Figure 4–194).

The areal distribution of sulfate in the lakes (Figures 4–195 through 197) is similar to that of calcium. Regions of high sulfate concentrations nearshore have distinct gradients into open lake water. Enriched sulfate in several of the Great Lakes embayments appears to represent the influence of industrial waste discharge. For example, Green Bay has a sulfate concentration ranging from 9.5 mg/l to 26 mg/l and an average concentration of 19 mg/l, which is well above the Lake Michigan average. Traverse Bay has an average concentration of 18 mg/l and a range of 12 mg/l to 22 mg/l (Federal Water Pollution Control Administration[835]). Similarly Saginaw Bay reflects high loadings (Beeton et al.[59]). The chemical gradients out of the embayments are distinct, indicating that loading is greater than flushing capacity.

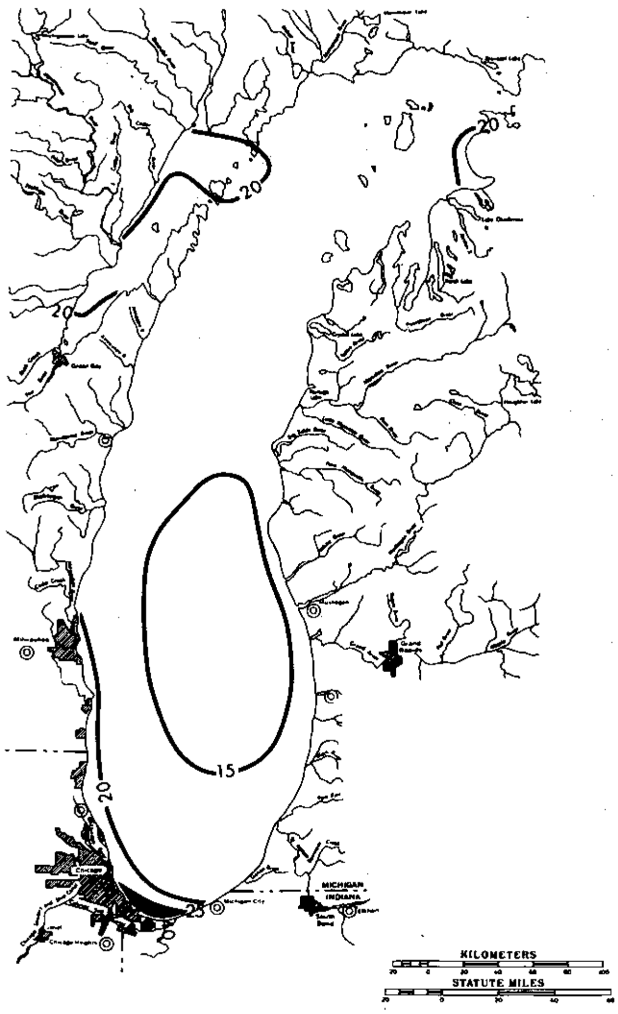


FIGURE 4–195 Representative Distribution of Sulfate (mg/l) in Lake Michigan Surface Water

Data from Beeton and Moffett, 1964

7.5.10 Silica System

Silica is important in the Great Lakes for

FIGURE 4–196 Representative Distribution of Sulfate (mg/l) in Lake Huron Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 8/2–8/17/66

three reasons: it is a nutrient that is consumed by diatoms for construction of hard parts, it is a good index of chemical weathering in terranes where silicate rocks abound, and it may react with other constituents to form silicate minerals in lake sediment.

Silica has been shown to be a significant nutrient in stimulating the productivity of phytoplankton in experiments using Lake Michigan water (Schelske and Stoermer[717]). Increased carbon fixation and increased diatom counts result when small quantities of SiO_2 are added to lake water, even in the absence of other nutrient additives. The abundance of diatoms (Section 8) and frequency of diatom blooms suggests that they act as significant buffers in removing silica from lake water.

The inorganic reactions involving silicate minerals are known to serve as sources and possible sinks of silica and cations such as Na^+, K^+, Ca^{+2}, Mg^{+2}, and Al^{+3}. The products and reactants in weathering or precipitation of a silicate mineral can be predicted by the following:

$$CO_2 + H_2O + \text{silicate mineral} = \text{dissolved ions} + \text{degraded silicate minerals} + HCO_3^- \quad (38)$$

The products and reactants of some of the possible weathering reactions in the Great Lakes are listed in Table 4–41. Many of the most common cations, sedimentary minerals, and bicarbonates are released in the reactions.

The silicate reactions, like other inorganic reactions, are equilibrium relationships. Therefore, the rate of reaction and the path that the reaction takes are governed by the residence time of water in the vicinity of a mineral, the composition and crystal structure of the mineral, temperature, and water composition.

Most of the reactions that produce the minerals commonly found in sediments occur in a stepwise fashion. For example orthoclase (Table 4–41) is thermodynamically unstable in Great Lakes water. Orthoclase will slowly react to form muscovite, potassium, silica (H_4SiO_4), and bicarbonate. If circulation is poor, the reaction cannot proceed past the orthoclase-muscovite phase until all of the orthoclase is consumed. If circulation is possible, then both orthoclase and muscovite are metastable and the next step in the reaction series, the formation of kaolinite (see Table 4–41) with the release of potassium, silica, and bicarbonate may occur. A convenient manner for representing the silicate reactions is by the activity diagram (Garrels and Christ;[283] Helgeson;[337] Helgeson, Garrels, and Mackenzie;[339] Helgeson, Brown, and Leeper[338]). In activity diagrams the phase boundaries in an aqueous system are related to concentrations of the principal components that are dissolved in the water at a specified temperature. Quartz, water, and certain other constituents are presumed to be in excess and aluminum is assumed to be conserved. Figure 4–198 shows the phase boundaries and lake water concentration fields for the activity ratios of potassium to hydrogen and sodium to hydrogen versus silica (Kramer[470]). Lake water is generally saturated with respect to gibbsite in the winter and kaolinite in the summer, and sediment interstitial water is saturated with respect to kaolinite. Consequently, those silicate minerals that are unstable with respect to kaolinite in Great Lakes waters will tend to react with the water to produce kaolinite ions. The destruction of metastable silicates may not occur in either lake or interstitial water because reaction kinetics are too slow, organic

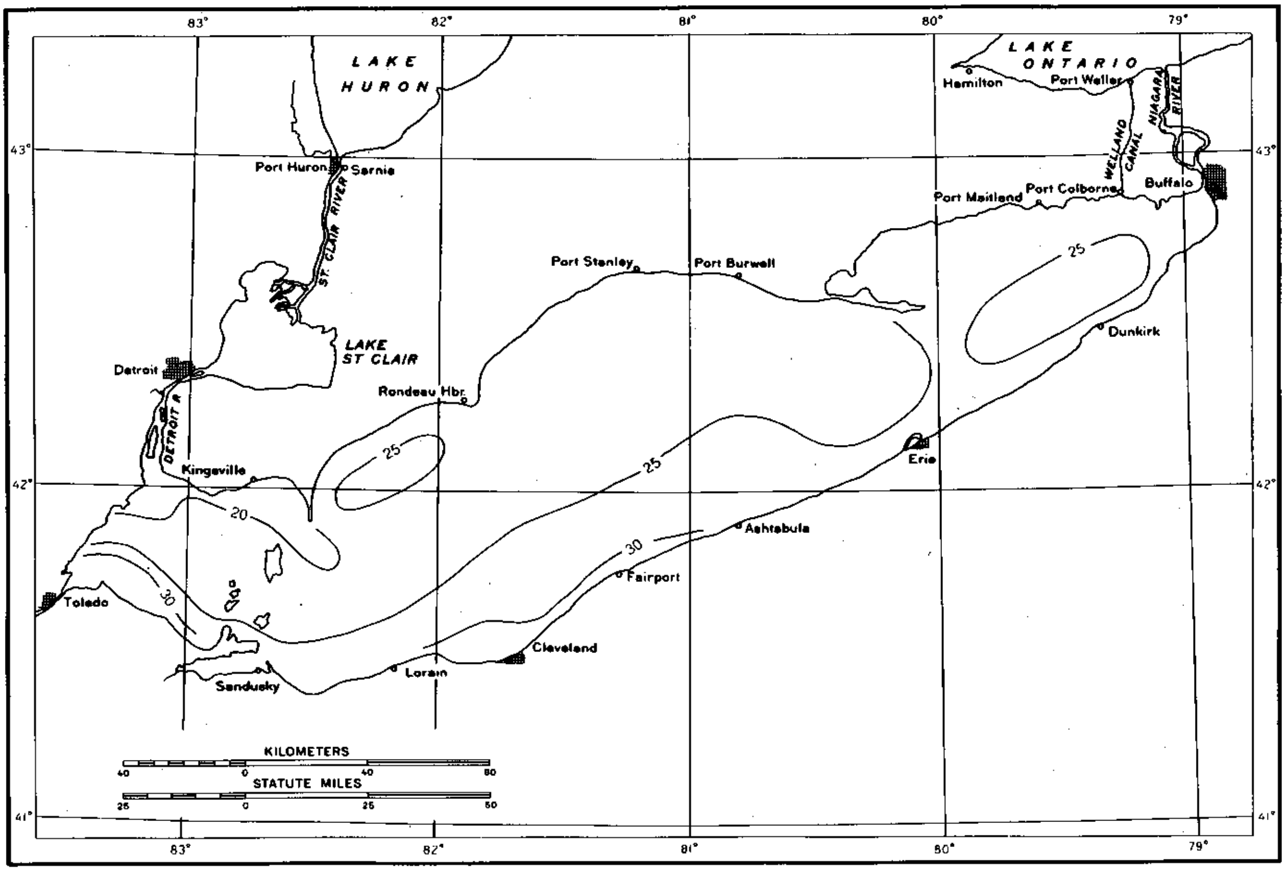


FIGURE 4–197 Weighted Average Distribution of Sulfate (mg/l) in Lake Erie
Data from Lake Survey Center (NOS–NOAA) cruise 5/25–6/14/67

coatings may protect the mineral (Chave[139]), or precipitation of a thin shell of the stable mineral may protect the metastable mineral from further reactions (Upchurch[808]).

The stable silicate minerals in Great Lakes waters are primarily the clay materials, kaolinite, muscovite (illite), and montmorillonite (Section 7). Many clay minerals have the property of being able to sorb or desorb organic and inorganic ions either by ion exchange through stoichiometric reactions or by simple sorption (Grim[304]). Common cations that can be retained by clay minerals are Ca^{+2}, Mg^{+2}, H^{+}, K^{+}, NH^{+4}, and Na^{+}. Common anions are SO_4^{-2}, Cl^{-}, PO_4^{-3}, and NO_3^{-}. The relative ease with which the clay mineral adsorbs or desorbs an ion depends on the exchange capacity, ions present at the ion exchange sites, ions present in the water, and temperature. Clay minerals also serve as ion-exchange sites for heavy metals. Ion exchange between hydrogen and potassium ions occurs in clays in Lake Erie (Kramer[468]). Other exchange reactions are discussed in Subsections 7.5.5 and 7.5.8.

Kramer[471] conducted a study of the stabilities of silicate minerals in Lakes Onaping (an Ontario lake in granitic terrane), Huron, and Erie. He found that in Lake Onaping the stable minerals are kaolinite, orthoclase, albite, and illite. For Lake Huron, he found the stable silicate minerals to be Na- and Ca-montmorillonite, albite, chlorite, and amorphous silica; and in Lake Erie he found the stable silicate minerals to be muscovite, orthoclase, Ca-montmorillonite, and kaolinite. Calcium from dissolution of carbonate minerals in the drainage basins and lake sediment is incorporated in the sediment minerals of Lakes Huron and Erie, this producing the calcium clay minerals. From the above data Kramer concluded that the silicate system is an active buffering mechanism in the Great Lakes.

Because silica is derived primarily by weathering of silicate minerals in the Great Lakes watersheds, the major sources are agricultural and mining regions where relatively unweathered materials are continually exposed and erosion is widespread. In Lake Superior (Figure 4–199) silica is derived from

TABLE 4–41 Major Silicate Mineral Weathering Products

Reactant (with H_2O and CO_2)	Products
Actinolite - $Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2$	Chlorite, Ca^{+2}, Mg^{+2}, $Fe^{+2,+3}$, H_4SiO_4, HCO_3^-
Albite - $NaAlSi_3O_8$	Sodium Montmorillonite, Na^+, HCO_3^-, H_4SiO_4
Anorthite - $CaAl_2Si_2O_8$	Calcium Montmorillonite, Ca^{+2}, HCO_3^-, H_4SiO_4
Augite - $(Ca, Mg, Fe, Al)_2(Si, Al)_2O_6$	Chlorite, Ca^{+2}, Mg^{+2}, $Fe^{+2,+3}$, Al^{+3}, HCO_3^-, H_4SiO_4
Biotite - $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	Kaolinite, K^+, Mg^{+2}, $Fe^{+2,+3}$, H_4SiO_4, HCO_3^-
Chlorite - $(Mg,Fe)(Al,Fe)_2Si_3O_{10}(OH)_8$	Montmorillonite, Mg^{+2}, $Fe^{+2,+3}$, H_4SiO_4, HCO_3^-
Gibbsite - $Al(OH)_3$	Al^{+3}, HCO_3^-
Kaolinite - $Al_2Si_2O_5(OH)_4$	Gibbsite, H_4SiO_4, HCO_3^-
Montmorillonite - $(Na,Ca)(Al_{2.33}Si_{3.67}O_{10})(OH)_2$	Kaolinite, Na^+, Ca^{+2}, H_4SiO_4, HCO_3^-
Muscovite - $KAl_3Si_3O_{10}(OH)_2$	Kaolinite, K^+, H_4SiO_4, HCO_3^-
Orthoclase - $KAlSi_3O_8$	Muscovite, K^+, H_4SiO_4, HCO_3^-
Quartz - SiO_2	H_4SiO_4

mining areas such as the Keweenaw Peninsula, Michipicoten Bay, and the Minnesota shore. From the cross section it appears that silica is released from the sediment to the water column by dissolution of metastable silicate minerals. In Lake Huron (Figure 4–200) the influence of influx of high silica water from Lake Superior and from the agricultural and mining areas in the Saginaw Bay drainage basin is obvious.

7.5.11 Iron and Manganese

Iron and manganese compounds are important in the Great Lakes for the following reasons:

(1) Their sensitivity to chemical changes and reduction-oxidation reactions makes them buffers, in pH, Eh, and oxygen systems.

(2) Iron compounds serve as sites of nutrient removal and/or release.

(3) Small quantities of iron and manganese are micronutrients required for plant and animal growth.

(4) Large quantities of iron amd manganese are toxic to plants and animals.

(5) High concentrations of iron and manganese impart taste and color to water.

(6) Manganese in the form of ferromanganese nodules may be present in mineable quantities in some lakes.

Iron and manganese in minor amounts are widespread in the Great Lakes Basin. Both elements occur in reduced (Fe^{+2}, Mn^{+3}) and oxidized (Fe^{+3}, Mn^{+4}) forms in the Great Lakes. The transitions in oxidation states are reversible and may occur inorganically or organically.

Iron and manganese are derived from weathering of ferromagnesian silicate and oxide minerals in igneous and metamorphic terranes (Subsection 7.5.10), and from pyrite, manganese, oxides, and iron-containing carbonate rocks in sedimentary terranes. The rocks of the Canadian Shield contain abundant mineral sources of iron and manganese, including some, such as the iron ranges of Minnesota, Wisconsin, and Michigan, that may cause local, unnatural influx into the

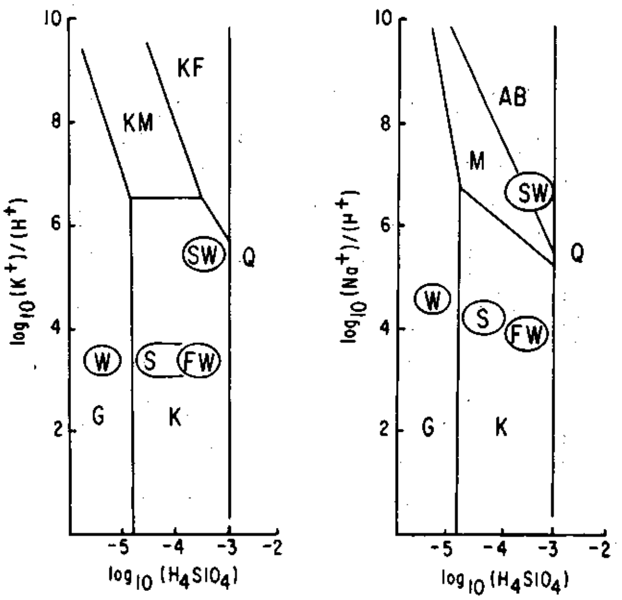


FIGURE 4–198 Activity Diagrams Showing Stability Fields of Great Lakes Water in Contact with Common Sediment Minerals. W, S, FW, and SW represent winter lake water; summer lake water; interstitial, fresh sediment water; and interstitial, marine sediment water, respectively. Mineral stability fields include gibbsite (G), kaolinite (K), amorphous silica (Q), K-mica (KM), K-feldspar (KF), montmorillonite (M), and albite (AB).

From Kramer, 1967a

lakes. Ground water has also been suggested as an important source of iron and manganese in the Basin (Rossmann and Callender[682]).

Oxygen availability and Eh govern the oxidation state of both iron and manganese (Hutchinson;[402] Ruttner;[693] Garrels and Christ[283]). For example, in deoxygenated water Fe^{+3} is reduced to Fe^{+2}, which combines with HCO_3^- by the reaction

$$Fe^{+2} + 2HCO_3^- = Fe(HCO_3)_2 \qquad (39)$$

The ferrous bicarbonate is a soluble species that commonly occurs in the hypolimnion when deoxygenation and abundant CO_2 production coincide. If a lake is well mixed or oxygen demand is insuffcent to drive the hypolimnion oxygen content to zero, ferrous bicarbonate and other ferrous iron species are rapidly oxidized to the ferric state by reactions such as

$$4Fe(HCO_3)_2 + 2H_2O + O_2 = 4Fe(OH)_2 + 8CO_2 \qquad (40)$$

The ferric hydroxide is insoluble and forms a chemical precipitate. Manganese is reduced more easily and oxidized with more difficulty than iron, but behaves in an essentially similar manner. Soluble iron and manganese can be present only in the absence of oxygen and presence of CO_2. In well oxygenated lakes iron is removed from the water column to the sediment.

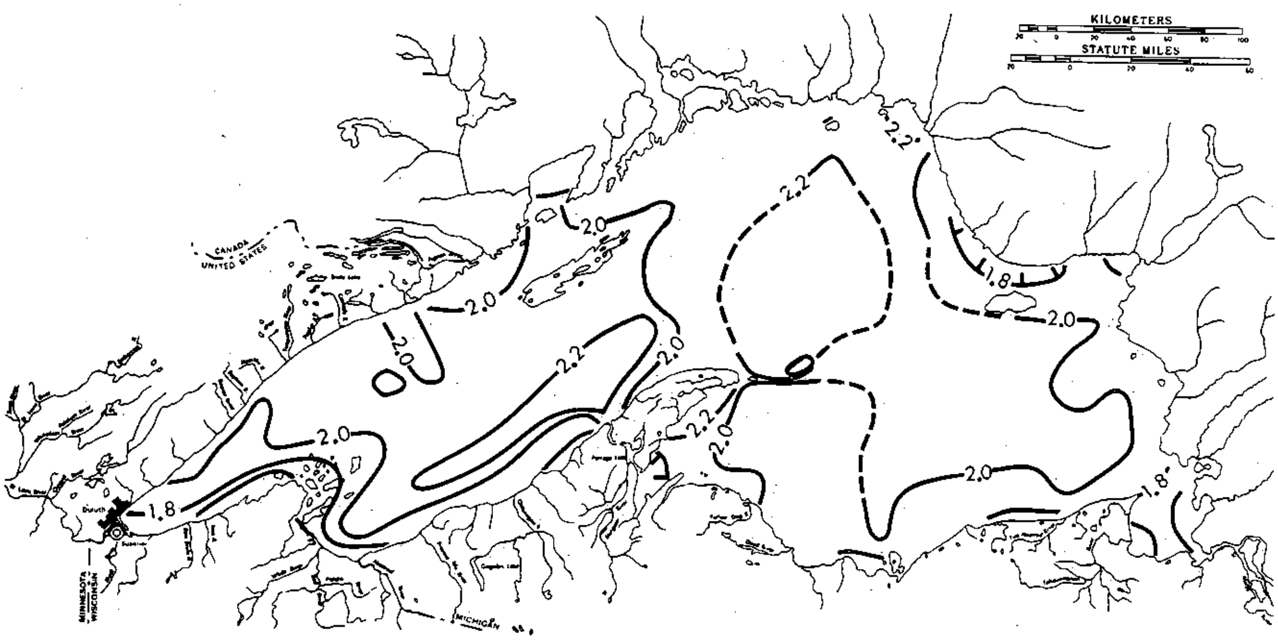


FIGURE 4–199 Representative Distribution of Silica (mg/l) in Lake Superior Surface Water

Data from Lake Survey Center (NOS–NOAA) cruises 7/18–8/8/68 and 7/27–8/9/69

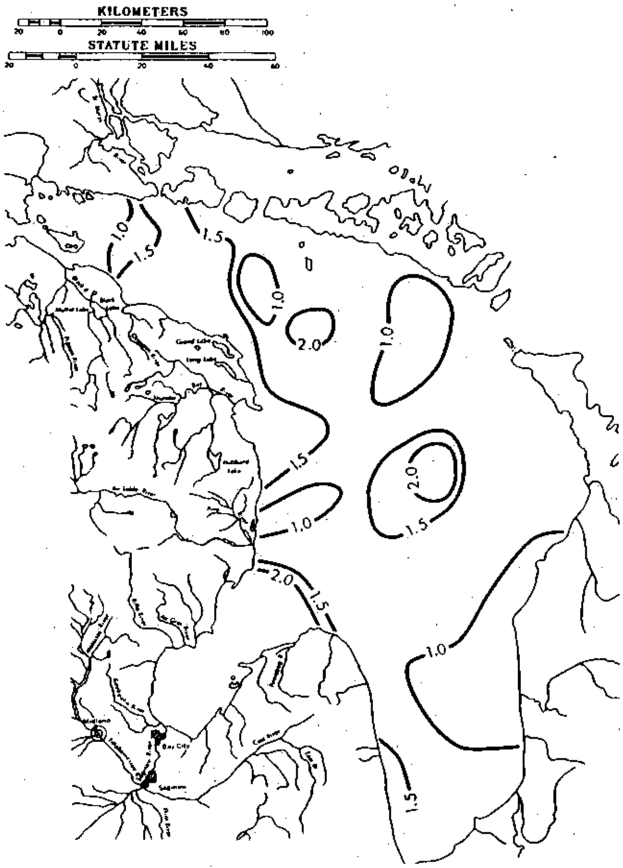


FIGURE 4–200 Representative Distribution of Silica (mg/l) in Lake Huron Surface Water
Data from Lake Survey Center (NOS–NOAA) cruise 8/2–8/17/66

Eh and pH have profound effects on the solubility and oxidation state of both iron and manganese. Figure 4–201 shows the Eh- and pH-controlled stability fields of those iron and manganese compounds that may occur in the Great Lakes, and the limits of naturally occurring interstitial and lake water for Lake Michigan (Rossmann and Callender[682]). At 25°C, pH must be less than zero for reduction of either iron or manganese. Because of the buffering capacity of calcite and dolomite, which occur in excess in the lakes, it is unlikely that the pH can go below 7 and that dissolution of iron and manganese can occur. However, in the vicinity of acid waste discharge, influx of high BOD waste, or oxidation of other organics, local dissolution may occur.

In oxygenated water ferric iron compounds can act as buffering mechanisms for phosphates. If pH is greater than 7 and phosphate is present, then ferric phosphate, $Fe_2(PO_4)_3$, can precipitate. Ferric iron can also form ferric hydroxide which gels and adsorbs phosphate. Mortimer[556] concluded that deoxygenation in the hypolimnion leads to release of phosphorus. The phosphate adsorbed on ferric hydroxide gel is released to the environment by changing the equilibrium relationship as a consequence of reduced phosphate loads, regardless of the oxygen level (Ruttner[693]). The extent to which these two processes of phosphate buffering occur in the Great Lakes is unknown. It is evident that the processes operate in western and central Lake Erie. Curl[174] described phosphate buffering in western Lake Erie and attributed at least a portion of the uptake to interaction with ferric iron compounds.

Other buffering mechanisms that involve iron compounds include reactions with humic substances, reactions with H_2S, metabolic uptake, and reduction of nitrate to nitrite. Humic substances can form humate colloids with iron, which are insoluble and exist in the presence of oxygen (Oden[584] in Ruttner;[693] Schnitzer[723]).

In the presence of sulfide, which may be generated during the decay of organic material, and at an alkaline pH, Fe^{+2} is known to be fixed in sediment as pyrite (FeS_2) or other ferrous sulfide minerals.

Iron and manganese are necessary for growth of plants and animals (Hewitt[351]). Plants especially require iron to aid in chlorophyll production (Welch[879]). Certain bacteria have the ability to oxidize inorganic iron compounds. Since iron and manganese are necessary for plant and baterial growth, those organisms represent potentially significant sinks for the two metals.

In large quantities both metals are toxic. Iron should be present in quantities between 0.2 mg/l and 2 mg/l for maximal algal production. If iron exceeds 5 mg/l it is toxic to algae and other organisms (Welch[879]). Manganese toxicities have been identified at 0.5 mg/l, although 2 mg/l can be tolerated by most aquatic plants (Federal Water Pollution Control Administration[831]).

Manganese nodules were discovered in Green Bay and Lake Michigan in 1968 (Rossmann and Callender[682,683]). The nodules range from 1 percent to 25 percent manganese with an average of 10 percent (Moore[552]). These deposits may prove to be economically important. The nodules are poorly structured hydrated oxides and hydrates (Rossmann and Callender[682]). The nodules are authigenic, and it is postulated that they form at the sediment-water interface from ground water that contains iron and manganese derived from weathering of ferromanganese minerals if Eh, pH, sedi-

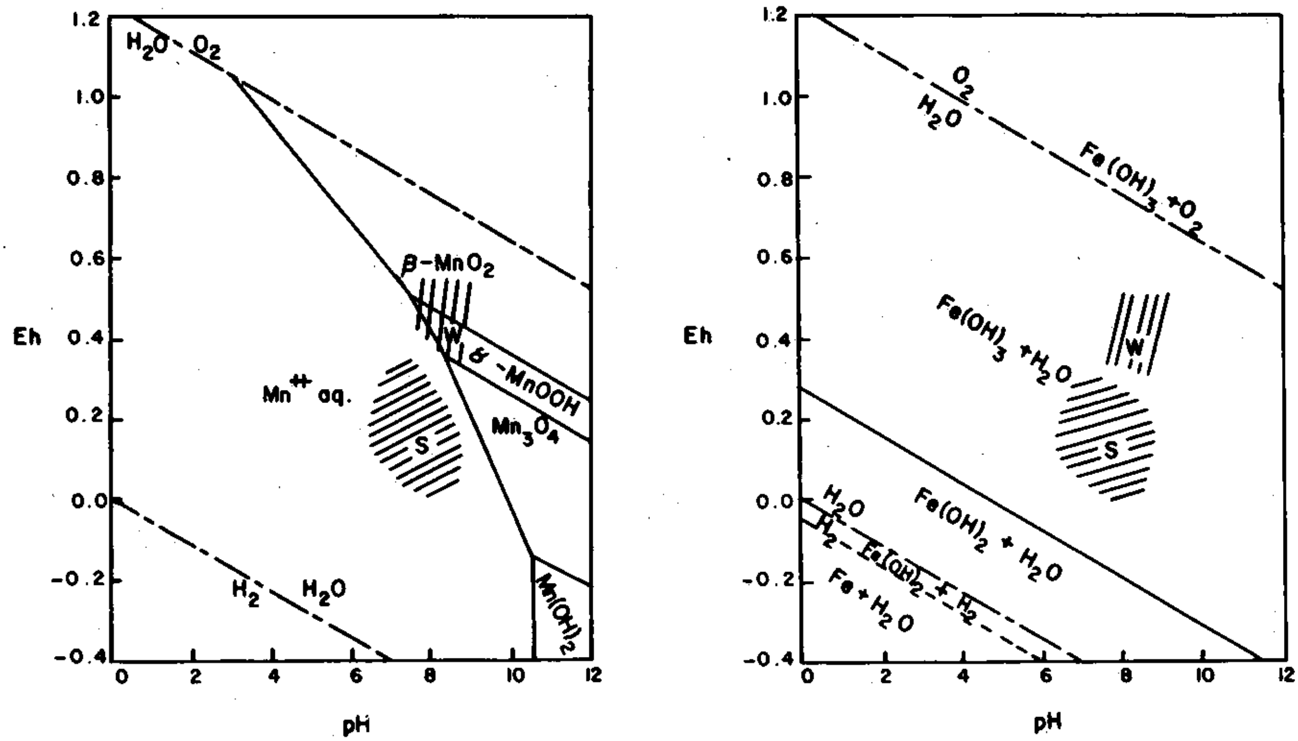


FIGURE 4–201 Eh-pH Diagrams Showing the Comparative Stabilities of Manganese and Iron Compounds at 25°C and 1 atm Total Pressure. W represents lake water; S represents sediment water.

From Rossman and Callender, 1969

ment type, and DO are appropriate. Cline and Upchurch[153] suggest that manganese can be released from organic complexes by burial, decay, and sediment dewatering. The released metals may then be free to migrate upward to the sediment-water interface. Figure 4–201 shows the stability fields for the minerals in question. Ferric hydroxide is stable in both the sediment and water. Thus, ferric hydroxide precipitates throughout the sediment and is not concentrated at any one horizon. On the other hand, aqueous manganese (Mn^{+2}) is stable in the sediment. At the sediment-water interface Mn^{+2} is no longer stable and the ferric hydroxide and hydrated oxides of manganese precipitate as nodules from the upward moving ground water. Subsequent to the reports of nodules in Lake Michigan and Green Bay, manganese crusts and nodule-like forms have been found in Oneida Lake (Dean[206]), Lake Ontario (Cronan[170]), and Lake Tomahawk, Wisconsin (Bowser and Travis[80]). Average iron and manganese concentrations for Great Lakes waters are shown in Table 4–42.

The hydroxides and organic gels that form in the presence of iron and manganese may color water an unsightly brown and reduce light penetration. The gels are not a widespread color or turbidity problem in the Great Lakes at present. However, Cleveland, with one of its water intakes in the hypolimnion of the central basin of Lake Erie, has problems at present and the gels are problems in some of the upland lakes, especially the dystrophic ones.

7.5.12 Trace Elements

The trace elements and their compounds are important for many reasons. Most of the metals are toxic if present in sufficient quantity and all of the elements can be used to identify sources of natural and cultural influx. Examples of the application of the use of trace element content in sediment to identify sources of those elements include the work of Ruch et al.,[686] Shimp et al.,[735] Kennedy et al.,[450] Shimp et al.,[735a] and Shimp and Leland[734] in southern Lake Michigan. They found a multiplicity of trace elements and compounds, most notably Hg, Cu, Pb, Cd, and As, and that there is a definite increase in concentration within the

TABLE 4–42 Trace Elements in the Great Lakes Water (µg/l)

Element	Lake Superior Median	Lake Superior Range	Lake Huron Median	Lake Huron Range	Lake Erie Median	Lake Erie Range	Lake Ontario Median	Lake Ontario Range
Zn	27	9– 80	33	10–110	11	0–290	71	18–115
Cu	12	4–230	3	2– 13	7	4– 58	60	5–175
Pb	2.2	1– 7	2.7	2– 7	2.8	1– 12	3.3	2– 7
Fe	8	3–230	22	3–400	48	3–460	8	4–500
Ni	2	0– 9	4	2– 15	3	2– 30	5.6	2– 16
Cr	1	0– 18	1.6	0– 19	1.6	0– 14	0.7	0– 12
Mn	<1	0– 1	<1	0–100	<1	0– 20	<1	0– 44
Sr	32.5	30– 70	119	100–175	173	130–200	188	180–200

SOURCE: Weiler and Chawla, (1969).

TABLE 4–43 Mean and Coefficient of Variation of Trace-Metal Input into Lake Michigan from Selected Michigan Rivers

	St. Joseph mean	St. Joseph coeff.	Kalamazoo mean	Kalamazoo coeff.	Grand mean	Grand coeff.	Muskegon mean	Muskegon coeff.	Pere Marquette mean	Pere Marquette coeff.	Manistee mean	Manistee coeff.	Boardman mean	Boardman coeff.
Conductivity (µmho/cm)	506.0	0.1	582.8	0.0	686.6	0.0	335.8	0.1	436.5	0.1	713.7	0.1	351.5	0.0
Calcium (mg/l)	67.1	0.1	75.3	0.0	76.7	0.1	41.4	0.1	59.7	0.1	80.4	0.3	43.0	0.2
Iron (µg/l)	24.4	0.5	46.6	0.6	33.8	0.3	37.1	0.7	30.3	0.7	38.8	0.3	20.4	0.5
Copper (µg/l)	4.2	0.2	2.8	0.1	10.4	0.8	3.1	0.2	1.7	0.2	2.4	0.1	1.9	0.1
Nickel (µg/l)	17.5	0.6	17.0	0.4	41.0	0.5	8.0	0.2	7.5	0.3	8.4	0.1	2.8	1.0
Chromium (µg/l)	2.1	0.4	2.1	0.2	22.4	1.1	4.5	0.6	1.6	0.7	2.1	0.3	0.9	0.1
Zinc (µg/l)	6.9	0.8	4.8	0.5	10.8	1.0	4.6	0.5	4.1	0.4	2.2	0.3	2.2	0.0
Manganese (µg/l)	5.1	0.3	30.8	1.0	17.8	0.9	7.1	1.5	9.1	0.7	7.6	0.7	8.6	0.2
Strontium (µg/l)	104.9	0.3	134.1	0.2	226.6	0.3	123.0	0.2	270.7	0.4	582.8	0.1	61.0	0.4

SOURCE: Robbins, et al., 1972.
NOTE: Mean of 5 observations from February to September, 1971.

upper few centimeters of sediment which is associated with organic carbon. This increase in concentration was attributed to recent cultural contributions through surface runoff and the atmosphere. Cline and Upchurch[153] suggested that the buildup in metals at the sediment-water interface may be the result of decomposition of organic complexing agents which induces release of metals to the interstitial water and upward migration of the decomposition products and associated metals.

The mode of mobilization and transfer of trace elements in aquatic systems is highly variable and subject to debate at the present time. Robbins et al.[662] found measurable amounts of iron, copper, nickel, chromium, and zinc in Lake Michigan tributary water (Table 4–43). The metal concentrations represent the material transported as soluble, organic complexes, or as inorganic ions. Robbins and Callender[661] examined the fate of trace metals contributed to Lake Michigan from the Grand River offshore of Grand Haven, Michigan (Table 4–44), and found a maximum metal concentration at approximately 19 km (12 mi) offshore, the zone of maximum sediment thickness. In Rochester Harbor, New York (Orzek et al.[592]), and in various Michigan lake sediments (Cline and Upchurch[153]), it was found that organic complexes are significantly more important than inorganic sediment or interstitial water as mobilization, transport,

TABLE 4–44 Bottom Sediment Concentration of a Series of Trace Metals Contributed to Lake Michigan from the Grand River, Grand Haven, Michigan

	Offshore Distance (Miles)								
Element	3.0	8.0	10.0	12.0	13.0	16.0	18.0	21.0	25.0
Al[1]	3.0	3.9	4.9	4.8	5.0	5.3	4.1	5.5	5.1
V (μg/g)	44.2	71.5	81.2	85.9	86.9	89.2	59.4	104.1	83.9
Ti[2]	3.7	5.7	4.2	6.8	9.6	3.2	2.7	5.0	4.2
Ca[1]	5.6	6.1	5.9	5.7	5.1	5.7	4.1	5.4	6.3
Mg[1]	2.5	4.5	3.0	3.9	3.0	4.3	2.7	2.2	5.1
Na (mg/g)	2.6	2.3	2.6	2.4	2.7	2.4	1.8	2.0	2.5
Mn (mg/g)	0.5	0.7	1.2	1.3	0.9	1.2	1.3	1.5	1.2
Zn (μg/g)	480	558	610	698	682	668	622	656	618
Cu (μg/g)	72	82	94	114	108	108	106	114	120
Ni (μg/g)	130	186	150	248	164	124	134	148	134
Cr (μg/g)	212	200	200	236	232	214	216	200	184

[1]weight %

[2]arbitrary units

SOURCE: Robbins and Callender, 1972.

and sedimentation media. The trace elements of current or predictable concern are discussed individually.

7.5.12.1 Arsenic (As)

Arsenic is widely used in pesticides (Federal Water Pollution Control Administration[831]) and detergents (Angino et al.[21]). Consequently, arsenic is present in small quantities throughout the Great Lakes Basin. It occurs naturally in the Canadian Shield and is recovered in the nickel mines of the Sudbury, Ontario, region. Little is known about the toxicities of arsenic compounds to Great Lakes taxa. However, certain deleterious effects are well known from studies in other environments. Arsenicals, which are used in pesticides, are toxic to aquatic organisms at levels over 1 mg/l. Arsenous oxide (As_2O_3) and aqueous equivalents ($As(OH)_3$, H_3AsO_3, $H_2AsO_3^-$) are toxic to fish when present at levels higher than approximately 2 mg/l, and to some plants at levels higher than 1 mg/l (Federal Water Pollution Control Administration[831]). Arsenic compounds are not known to be essential to growth. When ingested in low concentrations, arsenic is known to accumulate by biological magnification. Arsenic is concentrated in kidneys, liver, and tissues of the gastro-intestinal trace and is carcinogenic (U.S. Department of Health, Education, and Welfare[829]). Because of the process of biological magnification, utmost precautions should be taken to insure that arsenic loads do not reach toxic levels.

Little work has been done on the distribution of arsenic in the Great Lakes. Ruch et al.[686] found arsenic concentrations in cores from southern Lake Michigan that range from 5 ppm to 30 ppm. Areas of high concentration are near Benton Harbor and Grand Haven, Michigan, and near Waukegan, Illinois. The arsenic is concentrated in the uppermost portions of the sediment column and are positively correlated with organic carbon content. Ruch et al.[686] supposed that the arsenic comes from pesticide and detergent use in the drainage basin.

7.5.12.2 Barium (Ba)

Barium is not, nor is it likely to become, a problem in the Great Lakes. Water quality standards for drinking water (Table 4–30) include barium because it is a muscle stimulant and is highly toxic if ingested as a soluble compound (Federal Water Pollution Control Administration[831]). The solubility of some simple barium salts (e.g., $BaSO_4$, $BaCO_3$) is increased by the presence of iron and magnesium, which may cause local, abnormal concentrations of barium.

7.5.12.3 Boron (B)

Boron is presently not a serious contaminant of Great Lakes waters. It is essential to plant growth in quantities less than 1 mg/l. Excess boron in water can be toxic to some plants and can affect the central nervous system of certain animals. Borates are used in detergents and cleaning compounds, so they are introduced into the environment. As such, they may present a future hazard to water use in the Great Lakes Basin.

7.5.12.4 Bromide (Br^-)

Bromide is not present in sufficient quantities in the Great Lakes to present a hazard. Bromide is conservative in the Great Lakes system and is used as an index of chemical loading (Tiffany et al.,[802] Tiffany and Winchester[801]). Average total bromide concentrations for the Great Lakes and connecting channels are Lake Superior, 13 μg/l; Lake Michigan, 11 μg/l; Lake Huron, 21 μg/l; St. Clair River, ~ 24 μg/l; Lake St. Clair, 50 μg/l; Detroit River, ~24 μg/l; Lake Erie, 31 μg/l; and Lake Ontario, 47 μg/l.

7.5.12.5 Cadmium (Cd)

Cadmium is utilized by several industries in the Great Lakes Basin. Electroplating processes, combination of cadmium in metal alloys, and cadmium contamination in zinc processing and galvanizing are possible sources of cadmium contamination. Cadmium loss to the environment through corrosion of zinc water pipes is thought to be a major source of danger to man and the environment (Schroeder[724]). The metal is extremely toxic to man and has been studied primarily in the human context (U.S. Department of Health, Education, and Welfare[829]). Little is known about cadmium in the aquatic environment. It is known to accumulate in tissue and so reach higher concentrations than in the surrounding water. Mount[564] reported concentrations of up to 100 mg/g (dry weight) of cadmium in living bluegills, which suggests that a potential hazard exists to man if cadmium enters the aquatic environment.

There are only scattered data on cadmium in the Great Lakes. In the sediment of southern Lake Michigan cadmium ranged from 5 ppm to 19 ppm with a mean of 11 ppm (Shimp et al.[735]). Weiler and Chawla[876] could not detect cadmium in Lake Erie water.

7.5.12.6 Chromium (Cr)

Chromium is utilized in the metal industries for alloy and plating purposes. The hexavalent form, which usually occurs as chromate, CrO_4^{-2}, is an efficient oxidizing agent and is used as a cleanser. Hexavalent chromium is the most toxic form of chromium (U.S. Department of Health, Education, and Welfare[829]), and is known to be carcinogenic when inhaled and toxic to fish and algae in small doses. Chromium is concentrated in trout and salmon and so is potentially dangerous.

The average and range of chromium concentrations for Great Lakes water are shown in Table 4–42. The mean concentration in southern Lake Michigan sediment is 53 ppm with a range of 30 ppm to 92 ppm (Shimp et al.[735]). Orzek et al.[592] found chromium in sediment in Rochester Harbor, New York, that was concentrated in the organic fraction. Total chromium ranged from 1.6 μg/l to 19 μg/l whereas organic chromium compounds ranged from 0.07 mg/g to 1.37 mg/g calculated on the total mass of organic material present. Ingestion of these chromium-organic complexes could present a severe hazard.

7.5.12.7 Copper (Cu)

Copper is a micronutrient needed by most organisms. The Public Health Service drinking water standards (Table 4–30) (U.S. Department of Health, Education, and Welfare[829]), are based on the quantity that imparts an unpleasant taste to water. Copper is toxic to fish and plants (Table 4–35) in small quantities and has been used as an algicide. Jordan et al.[438] reported toxicity in some algae at concentrations as low as 0.1 mg/l, with *Cladophora* toxicity at 0.5 mg/l. Close control in using copper compounds as algicides must be exercised in order to avoid damage to the fauna.

Copper content in the Great Lakes is derived from two apparent sources. Lake Superior has a high copper content (Table 4–42) relative to Lakes Huron and Michigan, and according to Weiler and Chawla,[877] the copper content is highest west of the Keweenaw Peninsula. It appears that a part of the high Lake Superior copper loadings can be attributed to copper deposits and mines in the drainage basin. With the exception of the western basin, Lake Erie also has low copper concentrations. Copper decreases eastward in Lake Ontario, also. The western halves of Lakes Superior, Erie, and Ontario are more populated, suggesting a major input from urban areas. The eastward declines in copper concentration suggest that organisms and sediment are partitioning and/or assimilating some of the copper. Copper is known to be metabolized, adsorbed on clays, and chelated by natural organic acids (Cline and Upchurch[153]). Shimp et al.[735] described two cores from southern Lake Michigan in which copper is concentrated in the upper few centimeters of sediment with an average of 37 ppm and a range of 21 ppm to 109 ppm. The relationship of copper with organics in Rochester Harbor, New York (Orzek et al.[592]) is the same as for chromium.

7.5.12.8 Fluoride (F^-)

Fluorides are not a problem in the Great Lakes. They are derived in trace quantities from weathering and from pesticides, and are added in small quantities to public water supplies and dentrifrices as a tooth-decay preventative. Fluorides are not important constituents in industrial or cultural wastes. Most plants resist fluoride assimilation and prevent harmful amounts of fluorides from entering the food chain. Fluorides can be toxic to fish in concentrations higher than 1.5 mg/l (Federal Water Pollution Control Administration[831]). Average fluoride values for the Great Lakes are given in Table 4–33.

7.5.12.9 Iodine (I)

Iodine is a micronutrient needed for growth of some plants and animals. It has been used in the Great Lakes as a tracer for estimating chemical loading (Tiffany et al.,[802] Tiffany and Winchester[801]). Winchester[903] concluded that the differences in iodine concentration and compounds between the Great Lakes and the oceans may create a stress on anadromous fish introduced into the lakes. Smith[747] suggested that alewife die-offs may result from thyroid deficiencies induced by low iodine concentrations in the lakes. Average iodine levels in the Great Lakes are Lake Superior, 1.1 μg/l; Lake Huron, 1.3 μg/l; Lake Michigan, 0.9 μg/l; Lake St. Clair, 2 μg/l; Lake Erie, 1.7 μg/l; and Lake Ontario, 2.9 μg/l.

7.5.12.10 Lead (Pb)

Lead is a potentially dangerous pollutant that is discharged into the Great Lakes from mine wastes and industrial outfall, and introduced from the atmosphere as a result of combustion of leaded gasolines. Concentration of lead occurs in aquatic organisms, especially in calcareous tissues and hard parts. Little information is available regarding tolerance levels for aquatic organisms, although toxicity has been reported for concentrations as low as 1 mg/l (Federal Water Pollution Control Administration[831]). There are no data to show what proportion of lead in the Great Lakes comes from the atmosphere but it can be assumed that reduction in the use of tetraethyl lead in gasolines will reduce the lead load in the lakes.

The average concentrations of lead in the Great Lakes are shown in Table 4–42. The uniformity in concentration suggests that atmospheric contributions, which are ubiquitous, may be more important than local contributions from cities and tributaries. Lead is concentrated in the upper few centimeters of southern Lake Michigan sediment (Shimp et al.[735]) with an average of 27 ppm and a range from 16 ppm to 90 ppm. The data of Shimp et al. support atmospheric transport as a prime source of lead in the Great Lakes system by the spatially uniform and relatively high concentration at the sediment-water interface.

7.5.12.11 Mercury (Hg)

A few years ago a discussion of mercury would have been relegated to a brief warning similar to those for arsenic and cadmium in this appendix. It is now known that mercury contamination of aquatic organisms occurs in the Great Lakes and that a potential hazard to man results from that contamination. Chlor-alkali plants, pulp and paper mills, electrical industries, and other minor uses by the public and industry are sources of mercury in the Great Lakes.

Recognition of the dangers of methylmercury came about after two occurrences of poisoning in Japan in 1950 and 1956 and after significant bird mortalities in Sweden (Turney[806]). It took nine years before the source of the poisoning was identified and eighteen years after the first outbreak before the industry responsible admitted its involvement. The poisoning was induced by eating fish and shellfish contaminated by methylmercury discharged by a vinylchloride and acetaldehyde plant. In Sweden methylmercury was used as a fungicidal seed coating from the early 1940s to 1965. Birds that ate treated seeds had low survival rates and the bird population decreased rapidly. After cessation of seed treatment with methlymercury the bird population began to recover. It is through Swedish research that biological magnification in the food chain, high mercury levels in fish, and industrial sources of mercury were identified.

The chlor-alkali plants at Sarnia, Ontario, and at Wyandotte, Michigan, were losing up to 65 pounds (Branch[83]) and 20 pounds (Turney[806]), respectively, of metallic mercury per day to the St. Clair and Detroit Rivers. Both of these companies operated under the commonly held assumption that, unlike methylmercury, metallic mercury is essentially inert and harmless in the aquatic environment. When it was discovered in 1969 that the metallic mercury was not inert, action was taken both by the State and Provincial water resource agencies and by the industries to cease release of mercury.

Little is known of the process by which metallic mercury is converted to methylmercury in the aquatic environment. Two mechanisms have been suggested (Turney[806]). Soluble mercury compounds, such as mercuric chloride, which is known to have been discharged at one plant, may be assimilated through fish gills. An alternative or parallel process is that fish obtain the mercury through biological magnification through the food chain. According to Turney, predators, such as walleye and bass, show the highest mercury contamination, a fact which supports the food chain theory. The conversion of metallic mercury to methylmercury may take place through bacterial action in the sediment (Wood et al.,[912] Jensen[429]). A third possible mechanism for the mobilization of mercury is through chelation with humic substances (Subsection 7.5.7.9, Organic Carbon). Meknonina[531] has shown that humic substances can complex mercury in soils. Cline et al.[152] have shown that the humic substances in the St. Clair River can complex mercury and that the complex forms a precipitate. The precipitate appears to be fulvic acid and it contains approximately 45 percent mercury by weight. The precipitate has a specific gravity of approximately 2 g/cm^3, which is about the specific gravity of most sediment minerals. The organic-mercury precipitate would, therefore, be easily transported in streams without detection since samples for chemical analysis are usually filtered to remove sediment and biotic material, and could be readily ingested by bottom feeders and primary consumers. Once ingested the mercury could be methylated *in vivo*. Glew and Hames[289] have shown that the solubility of metallic mercury at 25°C in distilled water is 0.06 mg/l. If the mercuric ion is complexed by humic substances, there is no limit to the amount of mercury that can be made available to the biota through ingestion of the complex. Regardless of the mechanism, methylmercury has contaminated the fish and sediment of Lake Michigan, the St. Clair River, Lake St. Clair, the Detroit River, and Lake Erie.

Mercury concentrations in fish have been reported as being well above the 0.5 mg/l action level set by the U.S. Food and Drug Administration. Sediment from just below the Sarnia plant contained up to 2000 mg/l mercury (dry weight) and from just below the Wyandotte plant contained up to 84 mg/l mercury (dry weight) (Turney[806]). Sediment in Lake St. Clair contains much less mercury with maximum reported levels of 1.3 mg/l off the mouth of the St. Clair delta (Branch[83]). There is no detectable mercury reported from the water of the St. Clair-Detroit River system, and consequently mercury is not currently a drinking water hazard, and is a hazard to the public only when consumed through fish (Purdy[633]).

Mercury content in Lake Michigan sediments has also been found to be rather high. Kennedy et al.[450] analyzed 132 cores from the southern basin and found 0.1 ppm to 0.4 ppm of mercury in the upper sediment layers in the deep parts of the basin and off Benton Harbor and Grand Haven, Michigan. Natural background concentrations, based on the cores, range from 0.03 ppm to 0.06 ppm. They also noted a direct positive correlation between mercury content and organic carbon and sulfur.

The mercury pollution problem dramatizes the lack of understanding of the chemical, physical, and biological processes that operate in the aquatic environment. Failure to promptly identify problems, exchange information, and set standards led to an environmental crisis in the Great Lakes Region. Other potential problems exist and could be obviated with foresight in planning, management, and research.

7.5.12.12 Potassium (K)

Potassium is a micronutrient required for plant and animal growth. It is derived from

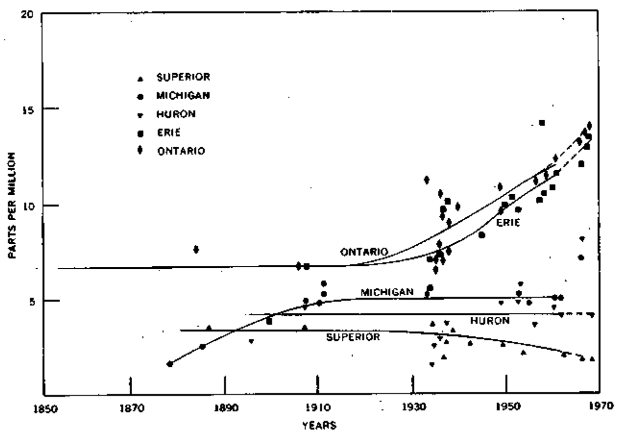


FIGURE 4–202 Changes in Sodium and Potassium Concentration in the Great Lakes. Solid lines represent Beeton's suggested trends; dashed lines represent Weiler and Chawla's.
From Beeton, 1965; Weiler and Chawla, 1969

weathering of minerals such as orthoclase feldspar (Table 4–41), chemical wastes, atmospheric contributions from marine aerosols, and contributions to the atmosphere and surface water from dust containing minor amounts of potassium minerals. The only currently recognized importance of potassium in the Great Lakes is in the dissolution and precipitation of potassium silicate minerals in sediment (Subsection 7.5.10, Silica System). Figure 4–198 shows the silicate stability fields of water in the Great Lakes and indicates that dissolution of potassium silicates is likely. Potassium may be removed from the system by ion exchange on clays.

7.5.12.13 Silver (Ag)

Little is known about the effects of silver on the aquatic environment. Silver is limited in drinking water (Table 4–30) because, in sufficient doses, it concentrates in the skin, eyes, and mucous membranes, and causes a permanent blue discoloration. Silver is thought to be concentrated in aquatic plants and is known to be toxic to both plants and animals if levels are high enough. Silver compounds are, therefore, used in disinfectants in some water uses.

7.5.12.14 Sodium (Na)

Sodium is derived in the same manner as potassium. A major source of sodium in the Great Lakes is street salting and the industrial use of brines derived from the Silurian salt in the Michigan structural basin. A discussion of the mechanisms that may remove sodium from the environment is given in Subsection 7.5.10, Silica System. Like potassium, sodium silicates do not appear to be thermodynamically stable in Great Lakes water or sediment (Figure 4–198). Ion exchange on clays may account for removal of some sodium from the lake system. However, the concentration of sodium in the lakes is increasing at the present time (Figure 4–202).

7.5.12.15 Selenium (Se)

Selenium is a micronutrient required by all living things. Certain plants are able to accumulate selenium from the soil or water without apparent effect. However, animals have low tolerance to selenium and can be seriously harmed by ingesting the selenium concentrated in plants. The majority of information on selenium toxicity comes from studies on agricultural problems (Federal Water Pollution Control Administration[831]). Selenium should be investigated in the aquatic environment as well. There are few systematic data on selenium in the Great Lakes.

7.5.12.16 Uranyl Ion (UO_2^{-2})

Even though it is radioactive, the primary reason for inclusion of uranyl ion in the drinking water standards is that the uranyl ion has an unpleasant taste and color, and can be injurious to the kidneys (Federal Water Pollution Control Administration[831]). Little is known of its effect on the aquatic environment. There are no systematic data on uranyl loads in the Great Lakes.

7.5.12.17 Zinc (Zn)

The primary sources of zinc in the Great Lakes Region are similar to those of cadmium, which commonly occurs as an impurity in zinc. Zinc has little adverse effect on man, other than imparting an unpleasant taste and appearance in water. In small doses zinc is utilized in human metabolic activity (U.S. Department of Health, Education, and Welfare[829]). Excessively high concentrations can cause temporary gastric distress. Zinc is toxic to fish and algae. As is the case with many heavy metals, the toxicity of zinc is dependent on pH and calcium-magnesium concentration (Mount[563]), and a single standard for the concentration of the metal is not valid. The effects of zinc on various fish and algal species have been reviewed by the Federal Water Pollution Control Administration.[831]

Zinc concentrations in the Great Lakes are shown in Table 4–41. As is the case with copper, zinc concentrations are highest in the western ends of Lakes Superior and Erie, reflecting local inputs from urban regions. The concentration decreases from north to south in Lake Huron, and from west to east in Lake Ontario (Weiler and Chawla[877]). Shimp et al.,[735] found a mean zinc concentration of 84 ppm and a range of 42 ppm to 179 ppm in sediment from southern Lake Michigan. Orzek et al.[592] observed preferential uptake of zinc by organic molecules in nearshore sediments of Lake Ontario at Rochester, New York.

7.5.12.18 Summary

Some of the known toxic elements that may presently be threatening the aquatic environment have been discussed. However, other metals may also be threatening the aquatic environment without our knowledge. For example, Schroeder[724] has warned that beryllium and antimony are threatening man, and the same may be true of the lake system. Most, if not all, of the heavy metals are toxic in some form and have the property of being stored and concentrated in plant and animal tissue and in sediments. Consequently, it is necessary that not only water quality analyses but sediment and biota quality analyses be made to protect man from consumption of toxic materials. Bioassays and tolerance limit studies must be made for Great Lakes taxa under Great Lakes conditions in order to set standards that will protect the aquatic community from further damage.

7.6 Radionuclides

Radionuclides are better controlled and understood than other potential pollutants because of the widespread interest that was generated after technological awareness of the hazards of radioactive substances had developed. Consequently, legislation, monitoring methods and precautions against hazards have kept pace with the need. Because of the ease of monitoring radioisotopes and the extensive data base developed since the advent of nuclear power in the early 1940s, radioisotopes have become a tool used to trace the behavior of stable elements, toxic heavy metals, and hard pesticides. The study of radionuclide effects on the environment and biota represents, with a few exceptions, a notable contrast to the crisis ecology currently practiced in the United States.

Through monitoring of radioactive waste dispersion the process of concentration in organic tissue and biological magnification first became apparent (Woodwell[916]). The sources of radioisotopes in the environment are presently limited and little new material is added each year. Possible cultural sources are fallout from atmospheric nuclear blasts, disposal of reactor wastes, and other accidental losses from reactors and research activities. Although atmospheric nuclear tests and waste disposal have been curtailed, there is sufficient radioactive material left in the environment from these practices to cause some concern. Radioisotopes are dispersed through atmospheric and water circulation. The isotopes are assimilated by lower organisms and thus begin the progression up the food chain, being concentrated each step of the way. If radionuclide concentrations reach sufficiently high levels, the radioactivity causes tissue damage, reproductive failure, and death. Although many isotopes can cause damage and may be present in the environment, three have caused the most concern because they behave in a manner similar to nutrients and therefore, are highly susceptible to retention and biological magnification. Strontium–90 (^{90}Sr) is a fission product that commonly occurs in fallout. It emits beta radiation that can impair the ability of bone marrow to produce blood cells. Strontium behaves in a fashion similar to calcium and is, therefore, fixed in bone, shell, and plant tissue. Cesium–137 (^{137}Cs) is a gamma ray-emitting fission product that behaves like potassium. Iodine–131 (^{131}I), another gamma ray source, is concentrated in the thyroid gland along with stable iodine (^{127}I). Because of the inherent hazard of other radioisotopes, such as radium–226 (Table 4–30), the standards for drinking water and food consumption are

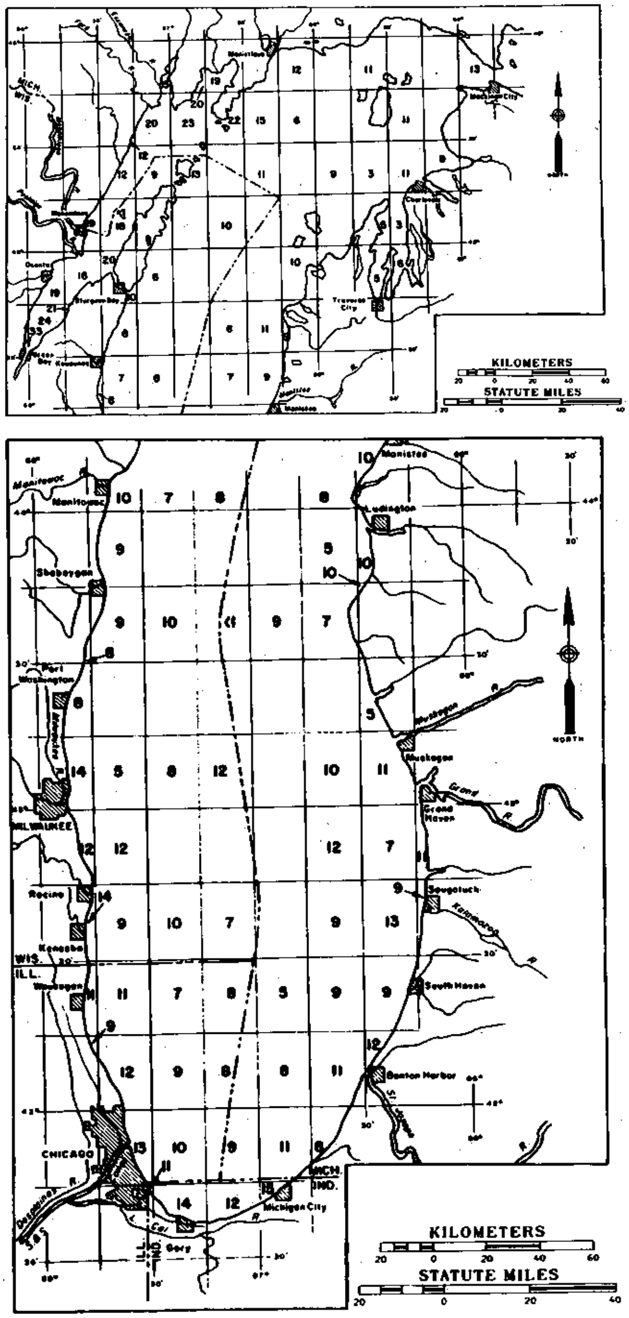


FIGURE 4–203 Gross Beta Radioactivity (pc/g) in Lake Michigan Water. Values represent averages of data taken in 15′ quadrangles.
From Risley, 1965

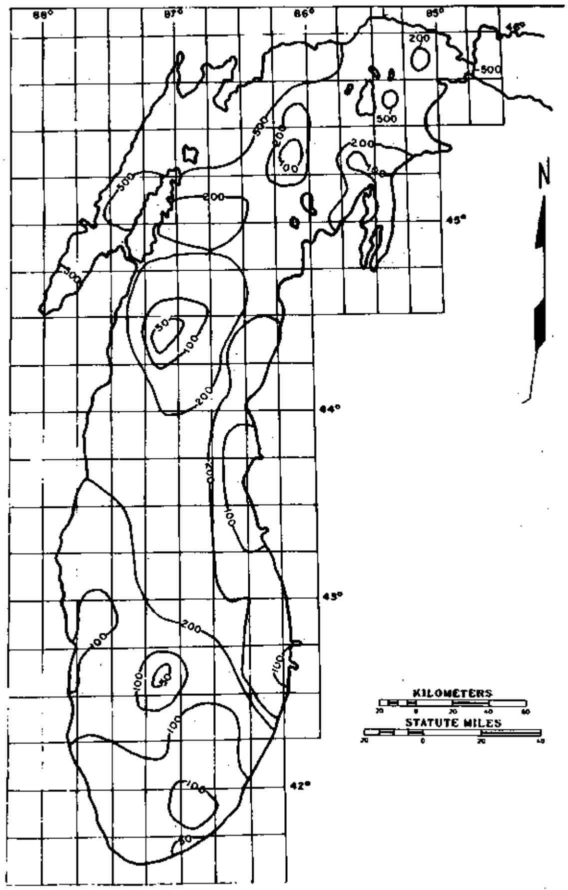


FIGURE 4–204 Gross Beta Radioactivity (pc/g) of Lake Michigan Bottom Sediments
From Risley and Abbott, 1966

highly responsive to recommendations of the national and international radiological research groups (Federal Water Pollution Control Administration[831]).

Radioactivity levels have been systematically studied in Lake Michigan (Risley;[658,659] Risley and Abbott[660]) and Lake Erie (Risley and Abbott[660]). The distributions of average gross beta radioactivity, sediment gross beta radioactivity, and plankton gross beta radioactivity in Lake Michigan water are shown in Figures 4–203 through 4–205. From the three distributions, an order of concentration is evident, where

$$\frac{\text{radiation}}{\text{water}} << \frac{\text{radiation}}{\text{sediment}} < \frac{\text{radiation}}{\text{plankton}}$$

The concentration of nuclides in the food chain is clearly shown. At the concentrations reported none of the radioactivity levels pose a health hazard.

Total alpha radioactivity is greatest on the Michigan side of Lake Michigan. Risley[659] attributed this to natural alpha radioactivity. Average beta radioactivity is highest off Chicago, near the mouth of the Milwaukee River, at the Racine channel, near the St. Joseph

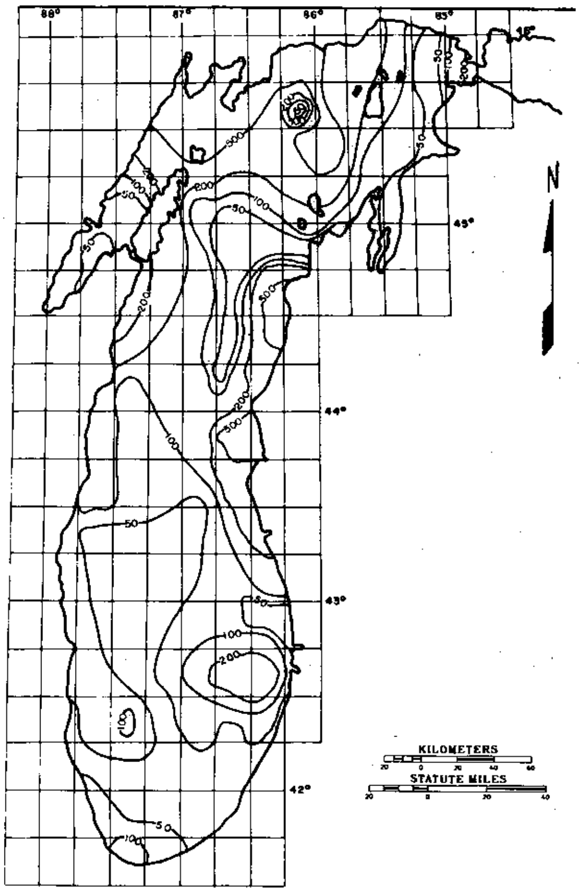


FIGURE 4–205 Gross Beta Radioactivity (pc/g) of Lake Michigan Plankton
From Risley and Abbott, 1966

River mouth, southwest of the Holland channel, in Green Bay, and at Mackinaw City. Slightly higher than background counts were indicated west of the Big Rock Point nuclear power plant at Charlevoix, Michigan. Generally, gross beta counts were higher nearshore than in the open lake.

Radionuclides are also concentrated in Lake Erie plankton, but are not found in the sediment and water (Figures 4–206 through 208). The radioactivity levels in Lake Erie are similar to those of Lake Michigan, although variation of counts between samples from Lake Erie is less (Risley and Abbott[660]). In both the Lake Michigan and Lake Erie investigations it was noted that radioactivity levels were highest in tributary streams during spring flooding.

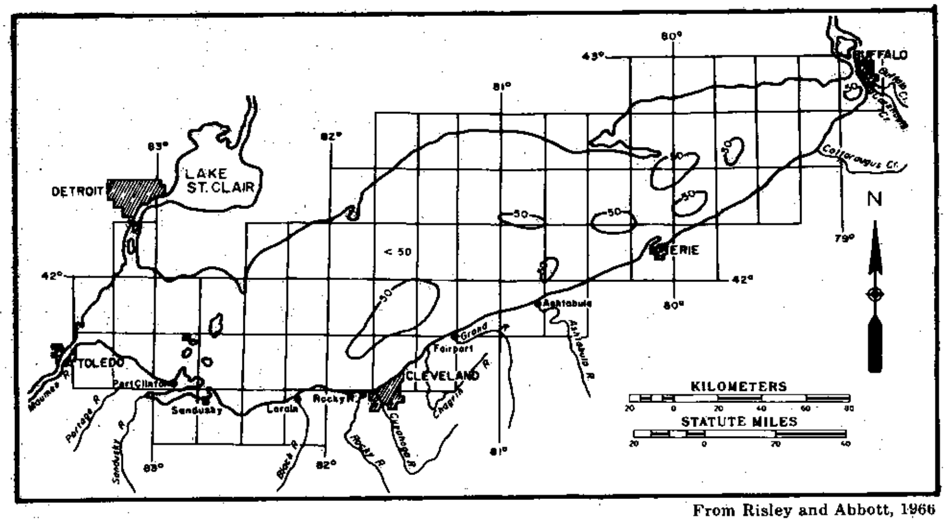
7.7 Great Lakes Harbors

The harbors of the Great Lakes pose a water quality and economic problem. Because of the economic benefits obtained from water transportation, it is advantageous to maintain harbors for use by shipping and industrial interests. The associated heavy industrialization and harbor development has led to severe pollution in many of the harbors. Solid material interferes with navigation by filling the harbor and introduction of deleterious chemical constituents interferes with industrial water use. Transfer of water and sediment out of the

TABLE 4–45 Chemical Parameters as a Measure of Pollution of Sediments

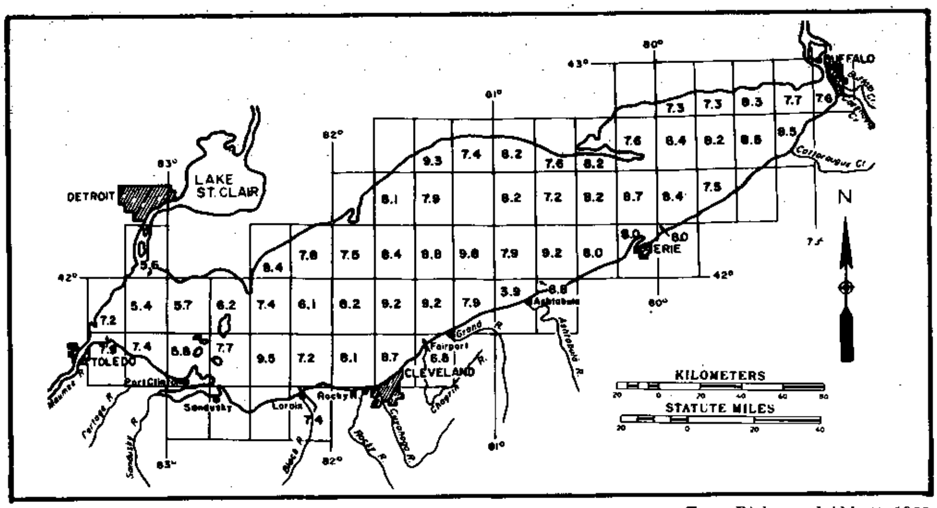
Parameter	Degree of Pollution			No. of Samples	Errors[2]
	Light[1]	Moderate[1]	Heavy[1]		
Ammonia (N)	0–25	25–75	over 75	53	19%
COD	0–40,000	40,000–120,000	over 120,000	28	18%
Total Iron	0–8,000	8,000–13,000	over 13,000	67	19%
Lead	0–40	40–60	over 60	21	14%
Oil & Grease	0–1,000	1,000–2,000	over 2,000	78	13%
Phenol	0–0.26	0.26–0.60	over 0.60	55	29%
Total Phosphorus	0–100	100–300	over 300	79	20%
Sulfide	0–20	20–60	over 60	21	14%
Volatile Solids	1–5%	5–8%	over 8%	78	15%
Zinc	0–90	90–200	over 200	21	19%

[1] All values in mg/kg (dry) unless otherwise indicated
[2] An error is defined as an overall rating that falls outside of its range for a particular parameter, e.g., a station with a "light" rating falling in the "moderate" range for a particular parameter.
Source: U.S. Army Corps of Engineers, Buffalo District, 1969.



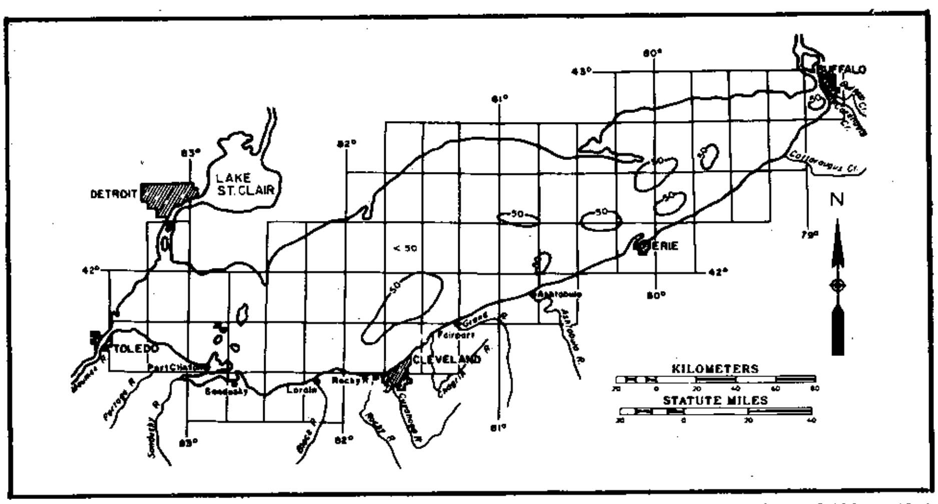
From Risley and Abbott, 1966

FIGURE 4–206 Lake Erie Dissolved Solids Gross Beta Radioactivity (pc/g)



From Risley and Abbott, 1966

FIGURE 4–207 Lake Erie Plankton Gross Beta Radioactivity (pc/g)



From Risley and Abbott, 1966

FIGURE 4–208 Lake Erie Sediment Gross Beta Radioactivity (pc/g)

TABLE 4–46 Classification of Pollution of Harbor Sediments

LAKE SUPERIOR

UNPOLLUTED

Michigan

Big Bay Harbor
Black River
Grand Traverse
Keweenaw Waterway
Lac LaBelle Harbor
Little Lake
Ontonagon Harbor
Presque Isle Harbor
Whitefish Point Harbor

Wisconsin

Cornucopia
Port Wing
Saxon Harbor

POLLUTED

Minnesota & Wisconsin

Duluth-Superior Harbor

LAKE MICHIGAN

UNPOLLUTED

Michigan

Charlevoix Harbor
Frankfort (outer habor)
Grand Haven (harbor)
Holland Harbor (entrance channel)
Ludington Harbor
Manistee Harbor
Manistique Harbor
Muskegon Harbor
Pentwater Harbor
Portage Lake Harbor
Saugatuck Harbor
South Haven (outer harbor)
St. Joseph Harbor (outer channel)
White Lake Harbor

Wisconsin

Green Bay Harbor (outer channel)
Manitowoc (outer harbor)
Oconto Harbor
Pennsaukee Harbor
Port Washington Harbor
Racine Harbor
Sturgeon Bay Ship Canal (approach channel)
Two Rivers Harbor (outer channel)

Illinois

Waukegan (outer harbor)

LAKE MICHIGAN

POLLUTED

Michigan

Frankfort (inner harbor)
Grand Haven (river)
Holland Harbor (inner channel)
New Buffalo Harbor
South Haven (turning basin)
St. Joseph Harbor (inner channel)

Wisconsin

Green Bay Harbor (inner channel)
Kenosha Harbor
Kewaunee Harbor
Manitowoc Harbor (river)
Menominee Harbor
Milwaukee Harbor
Sheboygan Harbor
Sturgeon Bay Ship Canal (canal)
Two Rivers Harbor (inner channel)

Indiana

Indiana Harbor
Michigan City Harbor

Illinois

Waukegan (inner harbor)

Indiana & Illinois

Calumet River & Harbor

LAKE HURON and Connecting Channels

UNPOLLUTED

Michigan

Alpena
Au Sable Harbor
Lake St. Clair
Les Cheneaux Island Channels
Sebewaing River
Cheboygan (except turning basin)
St. Clair River
St. Marys River

POLLUTED

Michigan

Detroit River
Harbor Beach Harbor
Rouge River
Saginaw Harbor

LAKE HURON and Connecting Channels

POLLUTED

Michigan

Cheboygan (turning basin)

LAKE ERIE

UNPOLLUTED

Michigan

Bolles Harbor
Monroe Harbor (outer channel)

Ohio

Rocky River Harbor

New York

Dunkirk Harbor

POLLUTED

Michigan

Monroe Harbor (inner channel)

Ohio

Ashtabula Harbor
Cleveland Harbor
Conneaut Harbor
Fairport Harbor
Huron Harbor
Lorain Harbor
Sandusky Harbor
Toledo Harbor

New York

Buffalo Harbor
Black Rock Channel
Tonawanda Harbor
Little River Harbor

Pennsylvania

Erie Harbor

LAKE ONTARIO

UNPOLLUTED

New York

Great Sodus Bay Harbor
Little Sodus Bay Harbor

POLLUTED

New York

Oswego Harbor
Rochester Harbor

SOURCE: U.S. Army Corps of Engineers, Buffalo District, 1969.

harbor by stream discharge, by flushing, and by dredging leads to degradation of the lakes. Some of the potentially harmful materials contained in harbor sediments include biodegradable organic matter (BOD); oil and grease; nutrients; fine-grained, slow-to-settle sediment; pathogenic bacteria; and potentially toxic levels of trace metals (U.S. Army Corps of Engineers, Buffalo District;[811] Orzek et al.[592]).

During 1967 a survey of Great Lakes harbor water and sediment quality was made by the U.S. Army Corps of Engineers, Buffalo District, and Federal Water Quality Administration to evaluate the impact of dredging and open lake spoil disposal on lake water and bottom quality. Unless otherwise cited, the data and classification scheme used in this subsection are extracted from the reports of the Corps of Engineers study. The water quality standards established for harbors and nearshore areas are discussed in Appendix 7, *Water Quality*.

It is evident from the review of toxic and potentially toxic materials that the sediment in grossly polluted harbors represents a locally important source for lake and harbor contamination. In such cases more stringent water quality standards will not prevent the harbor from being a source of pollution until the sediment is either covered to an extent that exchange with the water is impossible, removed by dredging, or removed by normal flushing.

Great Lakes harbors can be classified on the basis of the chemical quality of the water and sediment (Table 4–45). The criteria selected for the classification scheme represent the most common constituents that are likely to degrade the lake as a result of natural or man-caused influx. The classification is based on analyses of samples taken from Lake Michigan harbors in which pollution levels were identified subjectively. The scheme has not been applied outside of the harbors studied by the Federal Water Quality Administration, as described in the Buffalo District report. The classification scheme does relate the pollutants to precisely definable parameters. The Federal Water Quality Administration has identified all harbors in the Great Lakes as either polluted or unpolluted (Table 4–46) but the basis for this classification is subjective and insensitive to pollutants that cannot be easily detected.

Based on bioassays of sediment from selected harbors (Gannon and Beeton[282]) a five-fold classification was established that is applicable to the effects of disposal of dredge material in the open lake and to the habitability of the harbor bottom (Figure 4–209). The five categories range from one, where the sediment is clean, nontoxic and stimulates algal growth, to five, where the sediment is toxic and algal growth is limited. This subject is further discussed in Section 8.

A combination of the classification schemes developed for the Buffalo District study by the Federal Water Quality Administration and the University of Wisconsin should aid in accurate assessment of harbor conditions, and point toward action needed to clean up the harbors. Unfortunately, neither of the two schemes has yet been applied and subjective evaluations still prevail. The problem has economic significance because open lake disposal of "polluted" dredge spoil is not allowed.

Flushing of harbors still causes pollution in the lakes through direct exchange of water and interaction with the sediment in the harbor. Any of a large number of harbors can be used as an example. Cleveland Harbor, Ohio, situated at the mouth of the Cuyahoga River, receives waste sources including both treated and untreated industrial and municipal effluents. Much of the waste material is removed from the river before it enters the lake by precipitation with or adsorption on metal oxides and metal-organic complexes. By these processes an estimated 96 percent of the iron, 86 percent of the phosphates, and 44 percent of total solids are removed from the river before it flows into the lake (Figure 4–210). The organic material in the river creates a high oxygen demand that deoxygenates the lower river which could lead to release of the iron and phosphates that have been precipitated from the system.

Due to the extreme loading from sources on the Cuyahoga River, sediments in the lower river and the harbor contain high concentrations of organic and nutrient constituents (Table 4–47). Comparison of Figure 4–210 and Table 4–47 shows that constituent concentrations decrease gradually in the river to within a mile of the outer harbor. Near the outer harbor sediment quality shows a marked improvement. Sediment from the Cuyahoga River is toxic to all taxa (Class 5 sediment, Figure 4–209). Experiments with outer harbor sediment have shown that the sediment does not affect benthic fauna, is toxic to zooplankton, and stimulates algal growth (Class 3 or 4, Figure 4–209).

Toledo Harbor, Ohio, at the mouth of the Maumee River, drains primarily agricultural land. Due to the high loss of sediment in the

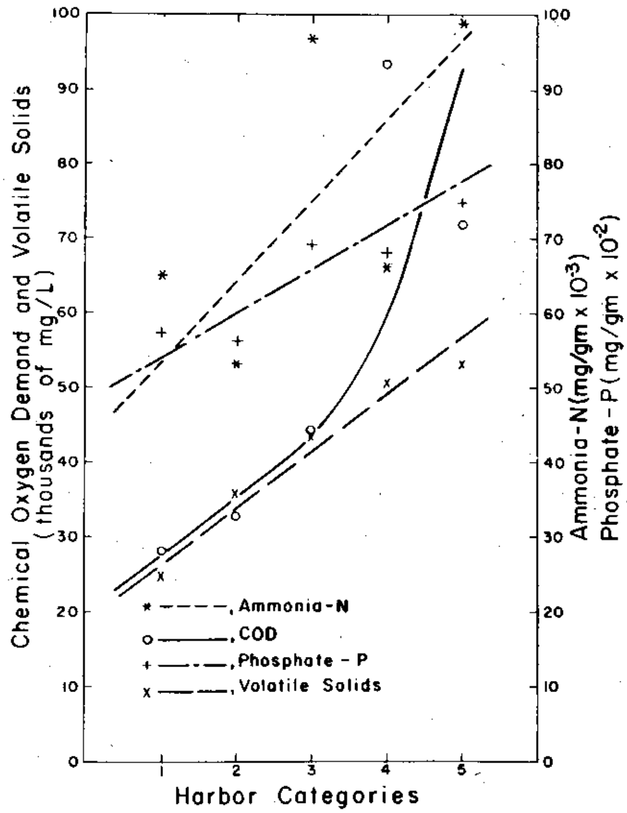


FIGURE 4–209 Classification of Harbor Sediment Quality on the Basis of Chemical Composition

After U.S. Army Corps of Engineers, Buffalo District, 1969

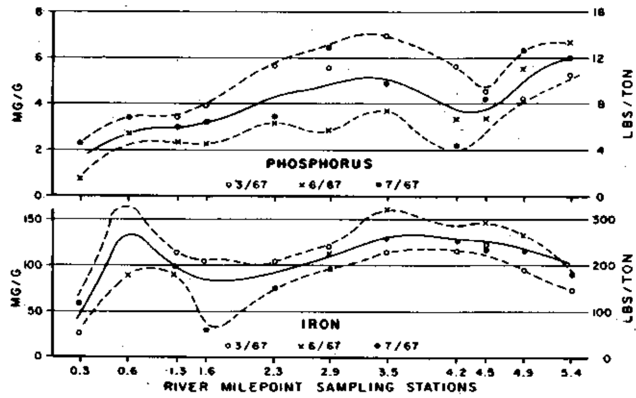


FIGURE 4–210 Distribution of Phosphorus and Iron Along the Cuyahoga River, near Cleveland, Ohio. River milepoint zero is the mouth of the river. Sampling dates are indicated by circles and crosses.

From U.S. Army Corps of Engineers, Buffalo District, 1969

rural portions of the Maumee basin, sediment composed of 80 percent silt and 20 percent sand accumulates rapidly in the harbor. The composition of dredged sediment from Maumee River and Bay is shown in Table 4–48. The importance of agricultural runoff is illustrated by the high proportion of nonvolatile solids, as compared with the highly volatile solid and oil and grease content of harbors in more industrialized areas.

Indiana Harbor, Indiana, is an artificial harbor with a small, heavily populated and industrialized drainage basin. The primary pollutants are solid wastes from steel mills and petroleum derivatives from refineries. Table 4–49 shows the relative importances of volatile materials and oil and grease in Indiana Harbor sediment. Other pollutants in the sediment include high concentrations of toxic metals, nitrogen, and phosphorus. Sediment from the canal at Indiana Harbor is toxic to "clean-water" taxa and will even restrict survival of pollution-tolerant taxa.

The data presented in this subsection show the potential hazards of polluted harbors and the nature of pollution that results from different cultural inputs. Flushing rate, constituent loading, harbor configuration, and sediment type play an important role in the effectiveness of a harbor as a pollution trap or source, and in the use of a harbor resource by multiple interests.

7.8 Loads and Trends

Previous subsections indicated that three interacting processes govern the chemical quality of lake water. These processes are rate of loading, rate of assimilation or release by the biota or sediment, and rate of outflow. The following subsections will present a basis for interpretation of past chemical composition of the lakes, present-day loads, areal variation in concentrations, and possible future consequences of control of loadings.

7.8.1 Historical Trends

Beeton[48] and Weiler and Chawla[877] reviewed the historical data on chemical composition in the Great Lakes (Figures 4–128, 4–138, 4–190, 4–194, and 4–202). The data were taken from the literature and represent samples of inconsistent quality because they were taken inshore, in the open lake, at water intakes, and elsewhere, and subjected to varying analytical techniques. Despite the inconsistencies, historical trends are apparent. In

TABLE 4-47 Comparison of Sediment Quality at Cleveland, Ohio

Parameter[1]	Cuyahoga River	Outer Harbor	Central Lake Erie (FWPCA,1968e)
Chlorine Demand	30	12	----
COD	240	95	41
BOD	15	5	1
Volatile Solids	125	65	63
Oil and Grease	35	8	----
Phosphorus	4	1.5	0.7
Nitrogen	5	1.6	1.8
Iron	110	45	35.5
Silica %	55	72	----

[1]All values mg/g (dry weight) unless otherwise noted
Source: U. S. Army Corps of Engineers, Buffalo District, 1969.

TABLE 4-48 Characteristics of Dredged Material in Maumee River and Bay

Parameter	Range	Mean
Volatile Solids (%)	5.8-10.5	8.3
Total Solids (%)	36.5-71.0	45.2
Oil and Grease (mg/g)	0.5-4.1	1.48
BOD (mg/g)	0.54-2.22	1.5
Settleability (% 1st hr.)	0.0-43.0	7.7
Settleability (hrs. for 90%)	20.0-59.0	41.5
pH	6.6-7.1	6.8
eH (volts)	-0.11-0.0	-0.09

Source: U. S. Army Corps of Engineers, Buffalo District, 1969.

general the data show little change in Lake Superior chemistry over the last hundred years. Constituent concentration of Lake Huron has increased due largely to inputs from Lake Michigan and Saginaw Bay. The other lakes indicate distinct upward trends of all measured constituents.

Observed Lake Superior chemical concentrations have remained essentially unchanged indicating that the lake receives loads that are essentially natural in origin and is at a steady-state condition. Under steady-state conditions inflow of a particular constituent equals outflow, and there is no change in composition of the lake. If one assumes that, on the average, the hydrologic cycle for a lake has not changed then a natural background concentration can be computed. For those constituents that are conservative or are known to be slowly or insignificantly assimilated by the sediment and/or biota, the natural background concentration is a valid concept. With biological and sedimentary assimilation, natural background calculations for nonconservative constituents represent minimum loads that would be exceeded by the amount that is assimilated.

The steady-state concentration in a lake serves as a model of the natural system for conservative and nonconservative constituents. The chemical balance model (Upchurch and Robb[810]) is similar to the water budget model presented in Section 4. The equation is

$$\sum L_{(R,P,G,D,S,B,)_{j,t+1}} + L_{O_{j-1,t+1}} - \sum L_{(O,E,D,G,S,B)_{j,t+1}} + L_{L_{j,t}} = L_{L_{j,t+1}} \qquad (41)$$

where L is the mass (load) of a constitute present in the lake (L), or introduced to or removed from the lake by runoff (R), precipitation (P), ground water (G), diversion (D), sediment (S), biota (B), outflow water (O), and evaporation (E). Ground water, diversion, sediment, and biota may act as sources or as sinks for the constituent, so they are included in the loads introduced and removed from the system. The subscript j refers to the lake in question, so LO_{j-1} is the load that is removed from the upper lake(s) (j-1) by outflow and introduced to the lower lake. The equation is solved by interaction over a period of years, where t is the previous year, and t+1 is the year in question. When combined with the mass balance equation for the Great Lakes water budget, concentrations of constituents in the lakes and connecting channels can be computed.

In reality, the above equations can only be solved for conservative constituents. If a load estimate for the contributions of diversions, runoff, and upper lakes is available, and if the loads contributed or removed by precipitation, evaporation, ground water, and sediment-water interaction are zero or negligible, then the equation can be solved simply. If a constituent is nonconservative, as they all are to some degree, the equation can be used to suggest minimum buildup and removal times only. The chemical budget approach will be an accurate predictive tool only when the following can be effectively quantified:

(1) contributions by eolian processes

(2) effects of precipitation and evaporation on chemical flux

(3) kinetics and rate coefficients for inorganic and organic sediment-water interactions

TABLE 4–49 Composition of Sediment Dredged from Indiana Harbor

Parameter[1]	Lake George Branch[2]	Grand Calumet River Branch[2]	Main Canal Comparable Stations 21[2]	1-5[3]	18[2]	Harbor Channel Comparable Stations 12-0[4]	1-1[3]
Total Solids %	42.5	40.9	73.6	47.5	60.5	37.9	45.0
Volatile Solids %	20.7	15.2	9.0	16.1	6.1	6.6	6.1
Oil and Grease %	14.2	5.92	---	---	0.32	2.79	---
BOD	6.24	4.17	5.25	---	1.13	---	---
COD	---	---	---	461	---	261/5	117
NH_3-N	---	---	---	0.07	---	0.26	0.09
Organic - N	---	---	---	2.09	---	0.76	1.68
Phosphorus - P	---	---	---	1.05	---	0.79	0.48

[1]All values mg/g dry basis except where noted

[2]All values are average (Lake Survey Center, NOAA, data)

[3]University of Wisconsin data

[4]FWPCA data

SOURCE: U.S. Army Corps of Engineers, Buffalo District, 1969.

(4) kinetics and rate coefficients for biotic assimilation and decay

(5) net ground-water flux.

In the steady-state situation the undertermined processes in a lake that affect the chemical balance reduce the measurable concentration of material by an unknown amount, so the natural background or steady-state concentration thus represents a minimum load. The natural background concentrations and minimum loads for the Great Lakes are shown in Table 4–50. The values were obtained by Upchurch[807] from diagrams modified from Beeton[48] and Weiler and Chawla,[877] in which the earliest steady-state concentrations, based on Beeton's regression lines, were used for the computations. The data in Table 4–50 show the loads in each lake, including contributions from the upper lakes. If the contributions of upper lakes are subtracted from the total load in each lake and adjustments are made for drainage basin area, the relative importance of the mineralogy of each drainage basin is apparent. Table 4–51 shows the annual rate of removal of dissolved solids, chloride, calcium, sulfate, and sodium, plus potassium in the early 1900s. These natural weathering rates, as indicated by dissolved solid removal, are commensurate with those calculated by Durum et al.,[231] who estimated an annual gross yield of dissolved solids of from 1×10^4 to 4×10^4 kg/km^2 for various drainage basins in the eastern United States. The low natural weathering rates in the Lake Superior drainage basin reflect the poorly developed drainage and slow weathering rates characteristic of the igneous and metamorphic rocks exposed in the Canadian Shield. The Lake Erie drainage basin in 1910 produced more quantities of constituents than the other lakes, probably because agricultural and urban land use and improved runoff were already major factors in lake chemistry. The other three lakes were essentially consistent in the production of quantities of chemical constituents, which supports the concept that the values used approximate steady-state concentrations.

7.8.2 Current Loads

It is not possible to estimate from lake chemical concentrations the present annual loads to the Great Lakes, because the assimilative capacity of a lake causes the instantaneous concentration of a constituent in a lake to lag behind the ultimate steady-state concentration for a given loading level. Since loads continuously change, a projected steady-state concentration based on a load estimate will not reproduce the natural system. Also, modern data, and to a lesser extent historical data, do not represent actual denudation rates because there are also contributions from the atmosphere and cultural wastes. For example,

TABLE 4–50 "Natural Background" Concentrations and Annual Loads to the Great Lakes

	Dissolved Solids		Cl^-		Ca^{+2}		SO_4^{-2}		Na^+ & K^+	
	Load	Conc.	Load	Conc.	Load	Conc.	Load	Conc.	Load	Conc.
Lake Superior (1890)[a]	3.9	63	0.19	3.0	0.79	13	0.23	3.7	0.21	3.4
Lake Michigan (1890)	6.1[b]	131[b]	0.22	4.6	1.5	32	0.38	8.0	0.14	3.0
Lake Huron (1910)	18	108	0.81	5.0	3.9	24	1.1	7.0	0.68	4.2
Lake Erie (1910)	26	144	1.6	9.0	5.6	31	2.4	13	1.2	6.8
Lake Ontario (1870)	30[b]	144[b]	1.5	7.3	6.4	31	3.0	14	1.4	6.6

NOTE: Load in 10^9kg/yr, includes contributions from upper lakes. Concentration in mg/l

SOURCE: Based on data of Beeton (1965), from Upchurch (1972)

[a]Date of determination used to compute steady-state concentration.

[b]Steady-state concentration estimated for the year 1910.

TABLE 4–51 Minimum Natural Weathering Rates of Each Great Lakes Basin

	Lake Basin				
	Superior	Michigan	Huron	Erie	Ontario
Dissolved Solids	3	5	6	10	6
Chloride	2	2	3	10	−2
Calcium	0.6	1.3	1.2	2.2	1.3
Sulfate	0.2	0.3	0.4	1.7	0.9
Sodium & Potassium	0.2	0.1	0.7	0.9	0.3

NOTE: Rates as 10^4kg/km^2-yr

Meade[530] studied the relative importances of natural, atmospheric, and cultural inputs to streams of the Atlantic States and concluded that about one-quarter of the dissolved solids in a stream were derived from atmospheric sources and about one-tenth from man-made wastes.

At the present time, even though the apparent loadings to the lakes are low because of slow mixing time and assimilation by the biota and sediment, they show significant increases over tributary loading at the turn of the century. Figure 4–211 shows the annual dissolved solid loads per square kilometer to each lake for 1910 (1890 for Lake Superior) and 1968. In all cases, except for Lake Superior, the loads have increased. The minimum increase due to man-caused input in Lake Erie is approximately 120 percent. This increase is extremely high when compared to the average of 35 percent estimated to be contributed by atmospheric and man-made sources in streams of the Atlantic States (Meade[530]). The minimum percent increases for the other lakes are Lake Michigan, 18 percent; Lake Ontario, 12 percent; Lake Huron, 8 percent; and Lake Superior, 7 percent. The apparent increase in water quality in Lake Superior may only represent differences in sampling methods and sample sites through the years. Representative tributaries to each lake are symbolized in Figure 4–211. Those streams that fall above the background and minimum present-day levels of dissolved solids are polluted.

Numerous attempts have been made to estimate loadings for various constituents in the Great Lakes. No one has made estimates for all of the lakes as an integrated system. Chloride budgets are most commonly studied because the data are accessible and chloride is essentially conservative. Among the studies of chloride loading in the Great Lakes are Ownbey and Willeke,[594] Ownbey and Kee,[593] and O'Connor and Mueller.[583] Regional, multicomponent load estimates have been made by the U.S. Army Corps of Engineers, Buffalo District[811] and the International Joint Commission[408] (Tables 4–52 through 4–54).

The previous load estimates are deficient in that they do not allow complete, simultaneous characterization of the entire lake system and all of the major inputs. To achieve complete characterization of the system, estimated inputs from unsampled streams must also be included. Table 4–55 shows estimated loads (Upchurch[807]) of dissolved solids, chloride, phosphate, nitrate, calcium, and silica to each lake in 1968. The data are based on discharge and chemical data where available. Municipal discharges into the lakes are included, where possible, in the values for the drainage basin in which the municipality falls. Where no data are available, estimates are made by compar-

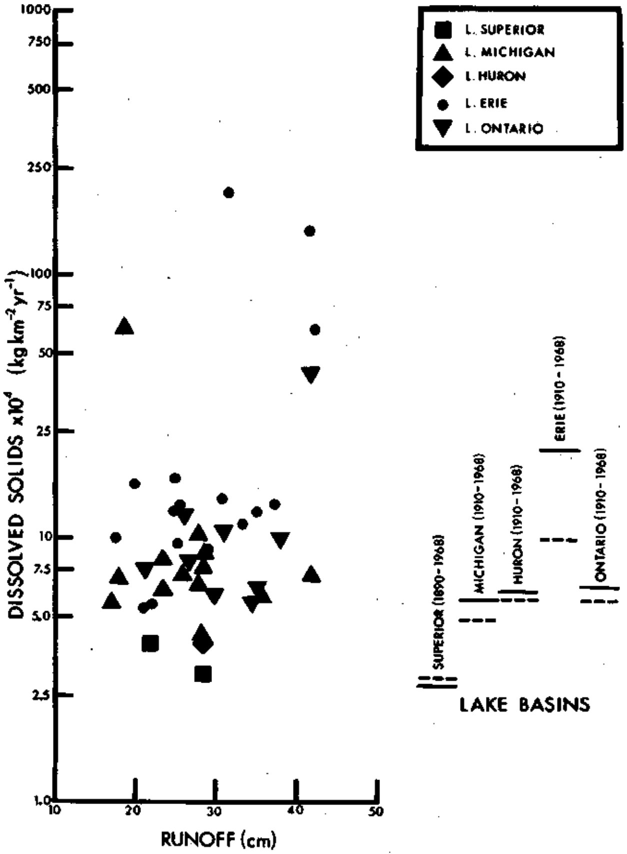


FIGURE 4–211 Dissolved Solids Loads from Great Lakes Tributaries (geometric figures) and Apparent Historical Range in Total Loads. Dashed lines represent earlier apparent loads.
From Beeton, 1965; Weiler and Chawla, 1969

ing soil and bedrock lithology with terranes that have similar geology and hydrology. The ungaged drainage basins are assumed to approximate the natural system, in which case lithologic control of composition can be demonstrated. Meade[530] has shown that on the Atlantic seaboard rainfall contributes a significant proportion of the dissolved solid load of streams, so one can assume that precipitation contributes an important amount to the total load in a lake. Few studies include chemical analyses of rainfall in the Basin. Junge and Werby,[442] Gorham,[292] and Winchester and Nifong[903a] present a few analyses of the Great Lakes Basin. The contribution of rainfall that has been included in the load estimate is based on these analyses (Table 4–55).

7.8.3 Loading and the Physical Environment

The hydrologic cycle has a profound effect on the concentration of a constituent in the lakes. The excess of precipitation over evaporation governs concentration or dilution of constituents. Also, the input from streams with chemical composition less than that of a lake will tend to dilute the lake. Kramer[472] considered the effects of evaporation on chemical equilibria in the carbonate system in the lakes. He attributed part of the approach to chemical equilibrium in Lake Erie (Figure 4–155) to the high rate of evaporation, as compared to total lake volume, in that lake. Comparison of the constituent distribution maps presented earlier shows the effects of inflow of dilute streams. Negative concentration gradients can be seen in Lake Huron near the outlet of the St. Marys River and in the lower lakes near the mouths of streams that drain relatively undeveloped basins.

Lake currents play an extremely important part in the distribution of chemical constituents. There are coastal currents in all of the lakes that tend to isolate the inshore areas from the main lake. These currents result from the interaction of prevailing wind systems, inflow and outflow of water, thermal regimes, and Coriolis effect on the lakes (Section 6, Water Motion). Cultural inputs discharge into these coastal zones. In Lake Superior, loads from Duluth-Superior generally move eastward along the southern shore. Loads from southern Lake Michigan are isolated to some extent by a semiclosed circulation gyre in the southern basin of the lake. Water that flows out of Lake Michigan moves along the western shore of Lake Huron, as does water from Saginaw Bay. Water from the Detroit River, Toledo, and Cleveland tends to follow the south shore of Lake Erie. In Lake Ontario, water from the Niagara River generally follows the south shore also. Although there is mixing in each lake by current eddying, diffusion, and dispersion, the coastal currents tend to limit the lateral distribution of chemical constituents. As a result, the concept of a homogeneous lake is not valid in mass balance studies.

Water quality is also controlled by the thermal regime in the lakes. During periods of thermal stratification (Sections 3, 4, and 6), certain chemical loads are isolated from complete mixing. Because of mixing and diffusion characteristics discharges may be restricted to the epilimnion. Since the greatest range in densities is at the thermocline, particulate organic material often floats on the thermocline. The solubility of gas in water is inversely proportional to the temperature of the water.

TABLE 4–52 Pollutants Contributed to Lake Michigan from Major Tributaries

Input	Total Soluble Phorphorus		Total Nitrogen		Toxic Metals[1]		Suspended Solids		Dissolved Solids	
	10^4kg/yr	Tons/yr	10^5kg/yr	Tons/yr	10^5kg/yr	Tons/yr	10^6kg/yr	Tons/yr	10^8kg/yr	Tons/yr
DIRECT TO LAKE MICHIGAN										
Manistique River	1.1	11	3.37	332	1.01	100	7.695	7,574	1.435	141,255
Manitowoc River	1.7	17	.65	64	.14	14	2.411	2,373	.215	21,170
Sheboygan River	1.7	17	1.75	172	.45	44	3.430	3,376	.410	40,332
Milwaukee River	3.8	37	4.12	406	.40	39	4.580	4,580	.697	68,620
Burns Ditch	8.8	87	3.43	338	.15	15	3.153	3,103	.668	65,700
St. Joseph River	16.2	159	21.77	2,143	2.89	284	43.203	42,523	6.378	627,800
Kalamazoo River	7.8	77	14.43	1,420	1.14	112	22.807	22,448	4.098	403,325
Grand River	32.3	318	27.55	2,712	4.19	412	45.613	44,895	6.638	653,350
Muskegon River	3.3	33	8.38	825	2.43	239	17.245	16,973	4.061	399,675
Pere Marquette River	.5	5	2.05	202	1.14	112	6.268	6,169	1.226	120,633
GREEN BAY TRIBUTARIES										
Fox River	40.3	397	90.10	8,870	.48	47.7	110.510	108,770	11.928	1,178,950
Oconto River	4.4	43	25.70	2,530	.56	55	11.125	10,950	2.077	204,400
Peshtigo River	2.3	23	5.24	516	1.96	193	13.350	13,140	2.503	246,375
Menominee River	11.7	115	20.46	2,014	---[2]	---[2]	42.276	41,610	5.006	492,750
Ford River	.4	4	1.92	189	41	40	2.392	2,354	.684	67,343
Escanaba River	2.0	20	4.29	422	1.52	150	16.261	16,005	1.687	166,075
Rapid River	4.2	41	1.21	119	---[2]	---[2]	1.439	1,416	.191	18,798
Whitefish River	1.3	13	.81	80	---[2]	---[2]	1.135	1,117	.445	43,800
TRAVERSE BAY TRIBUTARY										
Boardman River	1.6	16	---[2]	---[2]	---[2]	---[2]	---[2]	---[2]	.567	55,789

[1]Includes Copper, Cadmium, Nickel, Zinc, and Chromium.
[2]Not Sampled

SOURCE: U.S. Army Corps of Engineers, Buffalo District (1969).

TABLE 4–53 Loadings to Lake Huron

Parameter	Inflow from Lake Superior		Inflow from Lake Michigan		U.S. Tributaries		Outflow from Lake Huron	
	10^7kg/yr	Tons/yr	10^7kg/yr	Tons/yr	10^7kg/yr	Tons/yr	10^7kg/yr	Tons/yr
Chloride	7.9	78,000	28	280,000	96	950,000	100	1,000,000
Total Solids	290	2,900,000	650	6,400,000	530	5,200,000	2,200	22,000,000
Suspended Solids	7.9	78,000	9.7	95,000	29	290,000	160	1,600,000
Volatile Suspended Solids	7.9	78,000	9.7	95,000	9.1	90,000	53	520,000
Total Iron	3.7	36,000	1.3	13,000	0.61	6,000	3.6	35,000
Total Phosphate	0.29	2,900	0.58	5,700	0.51	5,000	1.5	15,000
Soluble Phosphate	0.14	1,400	0.28	2,800	0.34	3,300	1.2	12,000
Nitrate-Nitrogen	1.0	10,000	0.97	9,500	0.53	5,200	3.2	31,000
Ammonia-Nitrogen	0.58	5,700	0.91	9,000	0.50	4,900	1.9	19,000
Organic-Nitrogen	0.58	5,700	0.77	7,600	0.28	2,800	1.9	19,000
Calcium	94	930,000	140	1,400,000	82	810,000	480	4,700,000
Magnesium	21	210,000	53	520,000	23	230,000	160	1,600,000
Sodium	14	140,000	19	190,000	41	400,000	71	700,000
Potassium	7.3	72,000	9.5	94,000	7.5	74,000	17	170,000
Sulfate	21	210,000	91	900,000	48	470,000	300	3,000,000
Alkalinity ($CaCO_3$)	300	3,000,000	450	4,400,000	180	1,800,000	1,400	14,000,000
Hardness ($CaCO_3$)	330	3,200,000	530	5,200,000	270	2,700,000	1,600	16,000,000
Phenol	0.014	140	0.0097	95	0.0069	68	0.053	520
COD	44	430,000	24	240,000	26	260,000	120	1,200,000
BOD	7.3	72,000	9.6	94,000	4.0	39,000	17	170,000
DO	73	720,000	54	530,000	11	110,000	190	1,900,000
Flow (in cfs)		72,600		48,000		11,000		176,900

SOURCE: Data from U.S. Army Corps of Engineers, Buffalo District (1969).

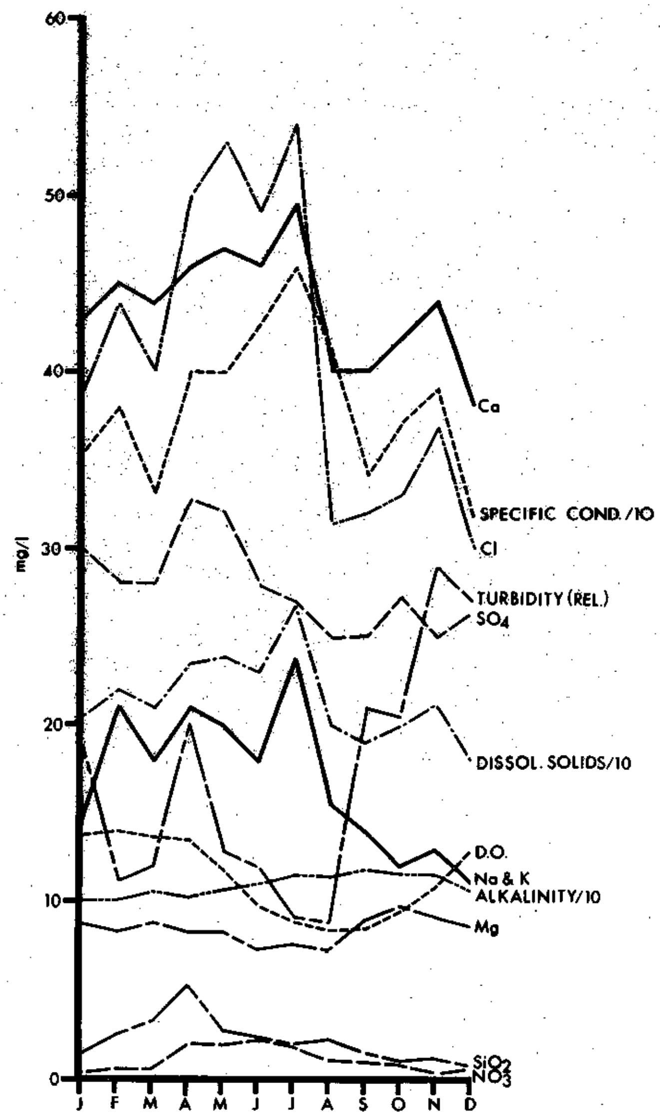


FIGURE 4–212 Monthly Variation in Composition of Lake Erie, Based on Averaged Data Collected over the Entire Lake

From Pinsak, 1970, unpublished

Therefore, high BOD water in the hypolimnion during summer stratification is isolated from the air-water interface by the warmer epilimnion. In the absence of exchange with the atmosphere, hypolimnion oxygen is consumed without replenishment and deoxygenation may occur if the hypolimnion volume is low. Until destratification in the fall, the only mechanism of chemical exchange across the thermocline is diffusion.

Owing to differences in the thermal regime, cultural loading, natural runoff, organic production and other causative factors, there is a cyclic variation in constituent concentration in the lakes. The smaller the volume of the lake, the more responsive it is to these variations. Figure 4–212 shows the seasonal variations of a number of constituents in Lake Erie. The curves are based on approximately ten years of data taken from all parts of Lake Erie (Pinsak[613]). The variations of some constituents, such as calcium, are similar to variations in tributaries (Figure 4–127), which suggests the importance of runoff as a contributor to the seasonal variation. Other constituents, such as dissolved oxygen, are related to stratification. Nitrate, silica, and sulfates appear to be negatively correlated with turbidity. Turbidity is most abundant during the period of spring runoff. It appears that runoff contributes the nutrients from the watershed, and algal production assimilates them. The increases in turbidity reflect algal production and sediment introduced by runoff.

7.8.4 Flushing and Future Trends

Many of the papers mentioned in this subsection have dealt with the time required for the lakes to be cleaned by flushing (also called natural displacement, retention, or residence time), presuming that chemical loads diminish in the future. Because of the lack of knowledge of the kinetics and rates of inorganic and organic reactions, no one can say how long it will actually take to clean up, or flush, the lakes. It has been demonstrated that complex interactions of sediment, biota, and water occur in the Great Lakes, the net result of which is the storage of vast quantities of chemical constituents in the sediment and food chain. A reduction in loading rates of these constituents will likely lead to release of the stored material and a significant delay in achieving a higher quality of water.

It is in the study of retention times in the lakes that use of conservative elements, such as chloride, become valuable. The calculated retention times of conservative constituents would correspond to minimum retention times for nonconservative constituents. Ownbey and Willeke[594] and Ownbey and Kee[593] studied chloride buildup in Lakes Michigan and Erie, and sulfate buildup in Lake Michigan. Their model accounted for increased loading from economic and demographic expansion and was simply a mass balance equation where

$$\frac{dQ}{dt} = R_g - R_l \qquad (42)$$

TABLE 4–54 Materials Balance for Lower Lakes, 1966–1967

	Chlorides[a]		Total dissolved solids		Total nitrogen[b]		Total phosphorus[b]	
	10^8kg/yr	10^3t/yr	10^{10}kg/yr	10^3t/yr	10^7kg/yr	10^3t/yr	10^6kg/yr	10^3t/yr
LAKE HURON								
Output	9.07	1,000	2.15	23,657	5.99	66	2.0	2.2
DETROIT RIVER								
Output	29.9	3,300	2.63	29,000	11.4	126	16.0	17.6
LAKE ERIE								
Total input	40.8	4,500	3.18	35,000	17.6	194	27.3	30.1
Total output	45.4	5,000	3.27	36,000	7.7	85	4.3	4.7
Difference	4.6	500	.09	1,000	9.9	109	23.0	25.4
% Difference or retained		11		3		56		84
NIAGARA RIVER								
Output	47.2	5,200	3.45	38,000	8.3	95	6.99	7.7
LAKE ONTARIO								
Total input	62.6	6,900	4.17	46,000	15.7	173	12.4	13.7
Total output	55.3	6,100	3.36	37,000	10.3	113	2.8	3.1
Difference	7.3	800	.81	9,000	5.4	60	9.6	10.6
% Difference or retained		12		20		35		77

[a]The difference between the inputs and outputs of chloride cannot be interpreted as an indication of the percent retained, but as a measure of the reliability of the determination of the materials balance. The difference of 11 and 12 percent between the total inputs and outputs for chloride for Lakes Erie and Ontario provides a good example of this reliability.

[b]It is assumed that the determination of the materials balance for total nitrogen and phosphorus is of comparable reliability to the chlorides.

SOURCE: International Joint Commission (1969).

Q is the amount of substance in the lake at time t. R_g is the material added each year from all sources and R_l is the rate of outflow multiplied by the concentration of the lake at the time of outflow. Ownbey and Willeke applied an increase in municipal loads of 1.79 percent per year, an increase in industrial loads of 1.9 percent per year, and a constant rural runoff, and they projected chloride buildup in Lake Michigan as follows: 1965, 7 mg/l; 1980, 7.9 mg/l; 2000, 9.6 mg/l; and 2020, 11.8 mg/l. Ownbey and Willeke also made the following estimates for sulfate buildup in Lake Michigan: 1965, 20 mg/l; 1980, 21.8 mg/l; 2000, 24.7 mg/l; and 2020, 29.2 mg/l. O'Connor and Mueller[583] estimated chloride loads in the Great Lakes system based on historical records and contributions of different water resource users.

Residence time calculations may be made from several assumptions. O'Connor and Mueller[583] used the time required to introduce a volume of water equal to the volume of a lake as a residence time. This calculation is analogous to the water budget calculations in Section 4 and depends on the volume, runoff, and outflow from upper lakes, outflow from the lake in question, precipitation, and evaporation. Using the data of Beeton and Chandler,[55] O'Connor and Mueller calculated the following residence time of water in the Great Lakes: Lake Superior, 191 years; Lake Michigan, 99.1 years; Lake Huron, 22.6 years; Lake Erie, 2.6 years; and Lake Ontario, 7.9 years. The residence times are predicated on complete mixing in each lake. Rainey[640] assumed complete mixing and equal precipitation and evaporation to calculate buildup and decay curves for the lakes. He used the following equation to characterize the buildup and decay of a constituent in the lakes:

$$C_2 = C_2^\circ \exp(-RT/V)\,[C_1+(Q/R)][1-\exp(-RT/V)] \qquad (43)$$

C_1 is the concentration of a constituent in the streams entering a lake and is constant, C_2 is the concentration of the constituent in the

TABLE 4–55 Estimated Modern Annual Loads to the Great Lakes, Exclusive of Loading from Upstream Great Lakes

	Dissolved Solids (10^8kg/yr)	Cl^- (10^7kg/yr)	PO_4^{-3} (10^5kg/yr)	NO_3^{-1} (10^6kg/yr)	Ca^{+2} (10^7kg/yr)	$SiO_{2\,aq}$ (10^7kg/yr)
LAKE SUPERIOR						
Nipigon Basin, incl. Long Lake & Ogoki Diversion	12[1]	4.1[1]	3.3[1]	13[1]	18[1]	13[1]
Michipicoten River	2.1[1]	.66[1]	2.7[1]	2.2[1]	3.3[1]	2.2[1]
St. Louis River	2.0[1]	1.9	2.4[1]	2.7	3.5	1.3
Kaministikwia River	2.0	.41	3.1	.037	2.7	1.8[1]
White River (Ontario)	1.7[1]	.38[1]	2.0[1]	1.7[1]	2.5[1]	1.7[1]
Montreal River (Ontario)	1.2[1]	.49[1]	1.5[1]	1.3[1]	1.9[1]	1.3[1]
Ontonagon River	1.2[1]	.22[1]	1.5[1]	1.2[1]	1.8[1]	1.2[1]
Magpie River	.79[1]	.18[1]	.98[1]	.82[1]	1.2[1]	.82[1]
Tahquamenon River	.77[1]	.24[1]	.95[1]	.78[1]	1.2[1]	.79[1]
Sturgeon River	.70[1]	.18	.87[1]	.72[1]	1.1[1]	.73[1]
Bad River	.52[1]	.18[1]	.64[1]	.54[1]	.79	.54[1]
Montreal River (Wisconsin)	.28[1]	.097[1]	.28[1]	.42[1]	.42[1]	.28[1]
Presque Isle River	.24[1]	.050	.30[1]	.25[1]	.37[1]	.25[1]
White River (Wisconsin)	.24[1]	.085[1]	.30[1]	.25[1]	.37[1]	.25[1]
Pigeon River	.21	.044	.40	.35	.39	.30
Black River (Wisconsin)	.18[1]	.064	.23[1]	.19[1]	.28[1]	.19[1]
Bois Brule River	.15[1]	.054[1]	.063	.048	.23[1]	.16[1]
Precipitation	3.0[1]	.88[1]	0[1]	Unknown	6.5[1]	0[1]
Other sources	16[1]	.43[1]	22[1]	18[1]	27[1]	1.8[1]
Total (Based on 26 sample sites, 823 analyses)	45	11	44	45	74	29
LAKE MICHIGAN						
Green Bay Complex Basin	13[1]	3.7[1]	19[1]	5.6[1]	19[1]	1.4[1]
Chicago-Milwaukee Complex Basin	11[1]	12[1]	16[1]	4.7[1]	16[1]	1.2[1]
Grand River	11	13	16	2.2	22	1.6
Fox River	10	7.8	10	.37	15	3.5
St. Joseph River	9.4	4.8	7.3	1.8	19	1.9
Seal Choix-Gros Cap Complex Basin	5.3[1]	.18[1]	8.0[1]	.23[1]	8.1[1]	.56[1]
Sable Complex Basin	5.2[1]	2.5	.48[1]	3.3[1]	11[1]	1.3[1]
Menominee River	4.3	.16	3.1	4.7	7.8	1.2
Kalamazoo River	4.2	4.0	2.5	.68	8.3	.69
Muskegon River	4.0	3.2	1.0	.41	5.1	.95
Manistee River	3.00	15	.58[1]	.31[1]	8.3[1]	1.2[1]
Traverse Bay Complex Basin	2.7[1]	.58[1]	.52[1]	.87[1]	7.4[1]	1.1[1]
Manistique River	2.6	.36	.60	.40	4.4	.88
Peshtigo River	2.1	.83	.61	.11	2.5	.74
Bay de Noc Complex Basin	1.9[1]	.32[1]	13[1]	.28[1]	5.1[1]	.66
Oconto River	1.4	.76	.40	.10	2.0	.47
Escanaba River	1.3	.22	.47	.079	2.2	.55
Menominee Complex Basin (excl. Menominee River)	1.3[1]	.16[1]	.25[1]	.25[1]	2.5[1]	.44[1]
South Haven Complex Basin	.82[1]	.82[1]	1.77	1.1[1]	1.8[1]	.20[1]
Black River (Michigan, Lower Peninsula)	.51[1]	8.7	.047	.22[1]	1.1[1]	.13
Precipitation	2.3[1]	.70[1]	0[1]	Unknown	5.1[1]	0[1]
Other sources	.66[1]	2.2[1]	6.4[1]	.86[1]	.85[1]	.84[1]
Total (Based on 77 sample sites, 1563 analyses)	98	82	110	29	170	22
LAKE HURON						
Saginaw River	15	130	42	16	---[2]	---[2]
Bruce Peninsula Complex Basin	6.8[1]	5.2[1]	3.0[1]	.60[1]	---[2]	---[2]
Thumb Complex Basin	6.3[1]	.16[1]	29[1]	6.6[1]	---[2]	---[2]
Maitland River	2.8	4.1	.49	.64	---[2]	---[2]
Maganatawan River	---[2]	1.8[1]	1.2[1]	.060[1]	---[2]	---[2]
French River	---[2]	1.6[1]	1.1[1]	.054[1]	---[2]	---[2]
Au Sable River (Michigan)	---[2]	.16	.81	.081	---[2]	---[2]
Mississagi River	---[2]	1.3[1]	.844	.042[1]	---[2]	---[2]
Rifle-AuGres Complex Basin	---[2]	.19[1]	.50[1]	.21[1]	---[2]	---[2]
Les Chenaux Complex Basin	---[2]	.16[1]	.700	.14[1]	---[2]	---[2]
Spanish River	---[2]	1.2[1]	.77[1]	.039[1]	---[2]	---[2]
Cheboygan River	1.4	.14	.69	.069	---[2]	---[2]
Severn River	1.2	1.1	.55	.097	---[2]	---[2]
Au Sable River (Ontario)	1.1	.53	.89	.44	---[2]	---[2]
Presque Isle Complex Basin	---[2]	.13[1]	.55	.11[1]	---[2]	---[2]
Parry Sound Complex Basin	---[2]	1.2[1]	12	.022[1]	---[2]	---[2]
Muskoka River	.99	.65	.43	.022	---[2]	---[2]
Thunder Bay River	---[2]	.12	.39	.12	---[2]	---[2]
Manitoulin Island Complex Basin	---[2]	.52[1]	.35[1]	.017[1]	---[2]	---[2]
Alcona Complex Basin	---[2]	.27[1]	.22[1]	.095[1]	---[2]	---[2]
Saugeen River	.57	.17	.052	.041	---[2]	---[2]
Kawkawlin Complex Basin	---[2]	1.6	2.5	.55[1]	---[2]	---[2]
Wanaptei River	---[2]	.32[1]	.222	.011[1]	---[2]	---[2]
Precipitation	2.5[1]	.74[1]	0[1]	Unknown	---[2]	---[2]
Other Sources	19	.68[1]	.63[1]	.18[1]	---[2]	---[2]
Total (Based on 46 sample sites, 332 analyses)	58	170	100	26		

[1] Indicates that the load was estimated by comparison with basins of known load, similar soil, and bedrock lithology, and similar hydrology. Adjustment was made for discharge.

[2] In the Lake Huron drainage basin there are insufficient data to allow estimation of loads for the constituents and/or drainage basins indicated.

TABLE 4–55 (continued) Estimated Modern Annual Loads to the Great Lakes, Exclusive of Loading from Upstream Great Lakes

	Dissolved Solids (10^8kg/yr)	Cl^- (10^7kg/yr)	PO_4^{-3} (10^5kg/yr)	NO_3^{-1} (10^6kg/yr)	Ca^{+2} (10^7kg/yr)	SiO_2 aq (10^7kg/yr)
LAKE ERIE (incl. Lake St. Clair)						
Rouge & St. Clair Complex Basins[3]	49	130	56	.92	130	.078
Grand River (Ohio)	31	130	200	2.8	2.5[1]	.35[1]
Maumee River	16	14	46	41	4.1	2.5[1]
Grand River (Ontario)	7.1	5.8	55	.37	7.7[1]	.66[1]
Thames River	4.7	5.3	9.2	.79	5.1[1]	.37[1]
Cuyahoga River	4.2	11	13	14	2.9[1]	.99[1]
Sandusky River	4.0	2.7	6.5	8.4	6.2[1]	.74[1]
Cattaraugus Creek	3.7[1]	1.5[1]	11[1]	7.2[1]	2.7[1]	.37[1]
Clinton River	1.9	3.6	27	1.9	1.7[1]	.12[1]
Portage River	1.8	2.9	5.4[1]	1.0[1]	1.0[1]	.16[1]
Black River	1.6	3.3	65	7.6	1.1[1]	.166
Raisin River	1.5	1.9	1.8	2.6	4.5	.54
Huron River (Ohio)	1.3	1.1	.81	1.2	.24[1]	.14[1]
Rocky River	1.2	2.1	19	2.4	.80[1]	.13[1]
Cazenovia Creek	1.1	.46[1]	3.5[1]	2.22	.84[1]	.11[1]
Big Creek	1.0	.38	.27	.050	.89[1]	.076[1]
Huron River (Michigan)	.98	1.7	5.0	.73	2.5	.46
Chagrin River	.86	1.1	5.1[1]	.41	1.2[1]	.17[1]
Vermilion River	.60	.61	.31	.81	.19[1]	.12[1]
Precipitation	.17[1]	.87[1]	0[1]	Unknown	.32[1]	0[1]
Other Sources	36[1]	77[1]	140[1]	25[1]	50[1]	2.8[1]
Total (Based on 90 sample sites, 1770 analyses)	170	400	670	120	230	11
LAKE ONTARIO						
Oswego River	59	250	5.6	19	96	.49
Genesee River	6.2	6.2	2.9	5.0	13	.86
Trent River	5.4	1.8	1.2	1.7	122	1.00
Black River	2.5	.44	1.6	2.0	5.1	1.8
Moira River	1.5	.74	1.0	.24	3.7[1]	.32[1]
Credit River	.67	.59	.81	.11	.88[1]	.075[1]
Humber River	.60	.96	.73	.032	.68[1]	.058[1]
Napanee River	.48	.33	.19	1.1[1]	1.1[1]	.093[1]
Salmon River	.44	.29	.097	.041	.97[1]	.082[1]
Twentymile Creek	.37	.23	.080	.041	.29[1]	.025[1]
Sandy Creek	.36	.23	.099	.20	1.0	.065
Don River	.34	.63	2.8	.035	.24[1]	.020[1]
Precipitation	.080[1]	.48[1]	0[1]	Unknown	.18[1]	0[1]
Other Sources	29[1]	31[1]	9.2[1]	16[1]	73[1]	2.77
Total (Based on 138 sample sites, 1435 analyses)	110	290	26	45	320	7.6

[1]Indicates that the load was estimated by comparison with basins of known load, similar soil, and bedrock lithology, and similar hydrology. Adjustment was made for discharge.

[2]In the Lake Huron drainage basin there are insufficient data to allow estimation of loads for the constituents and/or drainage basins indicated.

[3]Undifferentiated

lake at time $T=O$ (C_2°) and at time $T-1$ (C_2). R is the flow rate to and from the lake. Q is the rate of addition of the constituent, and V is the volume of the lake. Rainey estimated that 90 percent of the final concentration is achieved when the volume that has flowed through equals 2.3 times the volume of the lake. The flow-to-volume ratio of water in a lake controls the buildup or recovery rate of the lakes assuming uniform loading conditions. Lakes Erie and Ontario, which have high flow-to-volume ratios, would reach about 90 percent of the steady-state concentrations upon change in loading in approximately 6 and 20 years, respectively. Lakes Michigan and Superior, which have low flow-to-volume ratios, would reach 90 percent of their steady-state concentrations in about 100 years and more than 500 years, respectively. Rodin[678] pointed out that Rainey's model is a special case of a more complex system, and that the interaction of physical phenomena, such as stratification and source location play important roles in the rate of mixing in the lakes. Rodin expanded the work of Rainey to include the case where a critical concentration is reached. Upon reaching the critical concentration, above which water quality is impaired to the extent that it becomes useless, legislation or abandonment by water users prevents further increases and may cause water quality improvement. Sweers[778] considered Rainey's equation in light of flushing Lake Ontario. Stratification was considered in Sweers' model, and it was concluded that removal time was only slightly increased by the stratification.

Simultaneous solution of equation 43 for all the lakes and the mass-balance equation used for water budget calculations (Section 4), using yearly iterations, gives a buildup and decay model for chemical constituents (Upchurch and Robb[810]). The simultaneous solu-

TABLE 4–56 Chemical Loads[a] Used for Solution of the Chemical Budget Model

Load Condition	Lake Superior	Michigan	Huron	Erie	Ontario
Cl load in 1968	1.07×10^8	8.19×10^8	1.68×10^9	3.90×10^9	2.95×10^9
Dissolved solids load in 1968	4.48×10^9	9.73×10^9	2.72×10^{10}	1.69×10^{10}	1.07×10^{10}
Background Cl load	1.07×10^8	2.20×10^8	4.00×10^8	8.73×10^8	---[b]
Background Dissolved solid load	3.90×10^9	6.10×10^9	8.00×10^9	8.00×10^9	4.00×10^9
80% treatment cultural load (Cl)	1.07×10^8	2.80×10^8	6.56×10^8	1.48×10^9	5.90×10^8
80% treatment at Detroit (Cl)	1.07×10^8	8.19×10^8	1.68×10^9	2.88×10^9	2.95×10^9
80% treatment of Cl at Chicago, Milwaukee, Detroit, Toledo, and Cleveland	1.07×10^8	4.08×10^8	1.68×10^9	1.76×10^9	2.95×10^9

[a] All chemical loads are in kilograms per year.

[b] The chloride load in Lake Ontario is so low that it is masked by inflow from Lake Erie and cannot be calculated.

SOURCE: Upchurch and Robb, 1972.

tion approach has the following advantages:

(1) All of the lakes are interconnected, so water quality of downstream lakes depends on the quality of upstream lake water.

(2) Precipitation, evaporation, runoff, inflow from upper lakes, outflow, and ground water are included as identifiable variables; so the effects of natural or man-made variations in the water budget on water quality can be tested.

(3) The sources of chemical loads can be differentiated and variations in loading can be tested.

(4) The lakes are back-mixed to approximate natural mixing and assimilation.

For the purposes of this appendix, several assumptions have been made to simplify use of the simultaneous equation, chemical-budget model. A time increment of one year is used, so that known episodes of mixing, such as spring and fall overturn, are included. Since there are few data on the kinetics of the biotic- and sediment-interaction processes, conservative and near-conservative constituents are used, and the terms for sediment and biotic interaction are excluded. The net effect of ground water is assumed to be zero. The water budget values (Table 4–56) used are modified from Section 4 so that changes in storage in the lakes equals zero.

In the examples that follow, the reader is reminded that the buildup or flushing rates are provided to illustrate processes that control chemical composition only. Circulation, thermal stratification, location of point sources, and interaction with the biota and sediment inject unknowns into the model. Sedimentary and biotic interactions with the water are overriding factors for most chemical constituents and cause the times given in the following discussion to be minimal.

If no additional water quality controls are developed, and population and industrialization continue to increase, then loads and concentrations will increase proportionately and be subject to the criteria discussed by Ownbey and Willeke[594] and Rodin.[678] If there are no increases in loading and present loads are maintained, then the lakes will slowly reach a steady-state concentration. Figure 4–213 shows an example in which the initial concentration of chlorides corresponds to the 1968 concentrations reported by Weiler and Chawla,[877] and the loads are those given in Table 4–55. The large volumes of the upper three lakes cause lake water quality to respond slowly to loading, so these lakes would not reach steady-state concentrations for several hundred years. Lakes Erie and Ontario have high flow-to-volume ratios and adjust relatively quickly to load conditions. However, flow from the upper lakes is superimposed on the loads into Lakes Erie and Ontario, and complete adjustment cannot be reached until the upper lakes have stabilized. Remembering that the rates shown in Figure 4–213 are minimal because sediment- and biota-water interactions are not included, it is clear that foresight is needed to prevent further damage to the lakes. The lag in time between cause

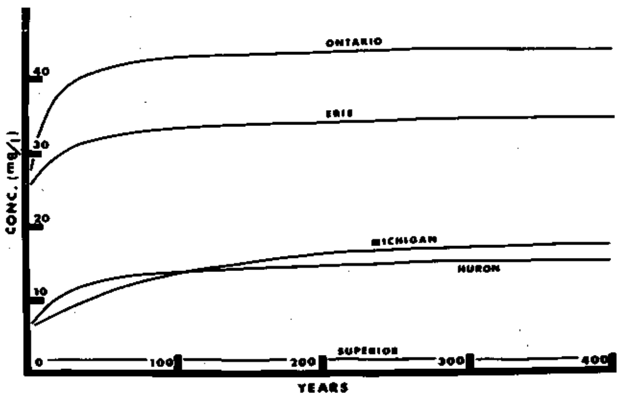


FIGURE 4–213 Buildup of Chlorides from Present Concentrations (Weiler and Chawla, 1969) Assuming a Steady Influx at Estimated 1968 Loading Rates

Figure from Upchurch and Robb, 1972

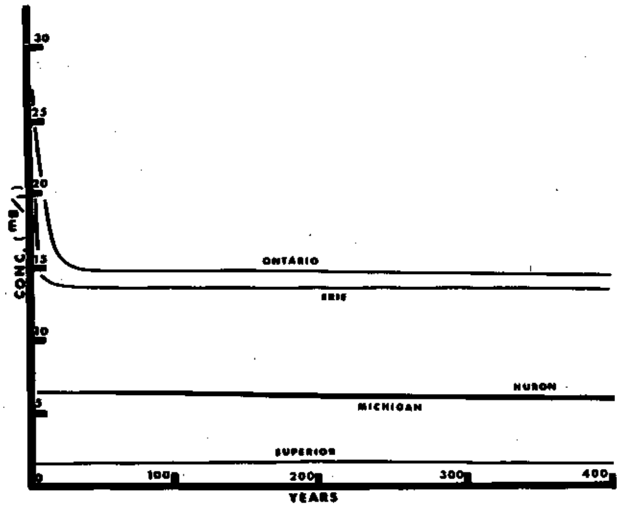


FIGURE 4–214 Projected Chloride Levels in the Great Lakes if All Cultural Loads are Reduced by 80% in All Lake Basins. Starting concentrations are from Weiler and Chawla, 1969. Loads are given in Table 4–56.

From Upchurch and Robb, 1972

(loading) and effect (lake water quality) means that present day man-caused loads need to be reduced considerably just to maintain the status quo. The example in Figure 4–213 is hypothetical and does not reflect a real situation because loading will not be held constant at the 1968 level.

The less the difference between actual chemical concentration and ultimate steady-state concentration, the more rapid is the adjustment to the steady-state concentration. For example, Figure 4–214 shows possible chloride concentrations, assuming that a chloride treatment policy is established. If cultural inputs are reduced by 80 percent, the responses of Lakes Erie and Ontario are rapid. Lake Erie has a higher background concentration than Lake Ontario, so after the initial flushing Lake Erie has a higher concentration. Lake Michigan is slow to adjust to the drop in loading because of the low rate of outflow and great volume of the lake. Lake Superior concentrations increase slightly due to the fact that background loads were slightly higher than present loads (Tables 4–50 and 4–55). If only certain problem areas were treated, such as 80 percent reduction of man-made waste from Chicago, Milwaukee, Detroit, Toledo, and Cleveland (Figure 4–215), then adjustment is noticeable, but increases in loading elsewhere in the system would cause continued increase in chloride concentrations. For example, Figure 4–215 illustrates that this treatment policy would result in rapid water quality improvement in the Lake Erie basin until loading in the upper lakes becomes dominant. Another approach to water quality control would be to arbitrarily reduce all man-made waste by 80 percent (Figure 4–172). If 80 percent treatment were achieved, excess conservative constituents could be flushed from the lower lakes in less than 40 years.

The above examples show the interdependence of the Great Lakes and give an idea of the changes in chemical composition that may result after abatement action with respect to a conservative constituent. Nonconservative constituents would require significantly longer times to adjust to steady-state concentrations because of biota- and sediment-water interactions. The amount of natural loading is also a factor in adjustment.

If there were no appreciable natural loading, which is the case for pesticides, toxic metals, and to some extent, nutrients, then a model that does not include background levels could be used. This type of model is analogous to that described by Rainey[640] and can be used to predict minimum flushing time of a lake or of a conserved constituent. Figure 4–216 shows the percent of a constituent remaining versus change in time, assuming complete cessation of loading at time zero and assuming a homogeneous lake. Based on the "no background" case, the residence time of water or a chemical constituent in a lake can be evaluated (Table 4–57).

It has not been the purpose of this subsec-

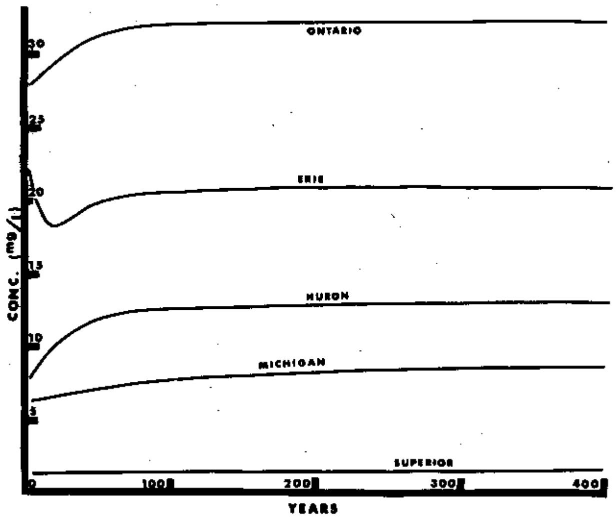


FIGURE 4–215 Projected Chloride Concentration Decay Given 80% Reduction in Loading in the Chicago-Milwaukee Complex Basin, Detroit, Toledo, and Cleveland. Starting concentrations are from Weiler and Chawla, 1969. Loads are given in Table 4–56.

From Upchurch and Robb, 1972

tion to predict how long it will take to clean up the lakes. However, the flushing rates and interactions that were calculated for conservative constituents do suggest two important facts. First, rapid adjustment of the lakes to changes in loading cannot be expected. Second, any action concerning a constituent that is widely used in the basin must include the entire basin. The consequences of lake restoration programs are discussed in Section 3.

7.9 Summary

The chemical processes that operate in the Great Lakes are complex interactions of introduced natural and man-caused loads with the biota and sediment of the lakes. In the absence of sufficient data to characterize the kinetics of the interactions, the actual extent of lake bottom and water degradation and the time required for the lakes to be naturally cleansed cannot be determined. Several types of chemical loads are known to degrade water quality in the Great Lakes. Nutrient loads stimulate plant production, which in turn combines with man's organic wastes to create demands on the oxygen system. Toxic metals and hard pesticides enter the food chain and are concentrated in organisms at successively higher trophic levels, where the toxicants may

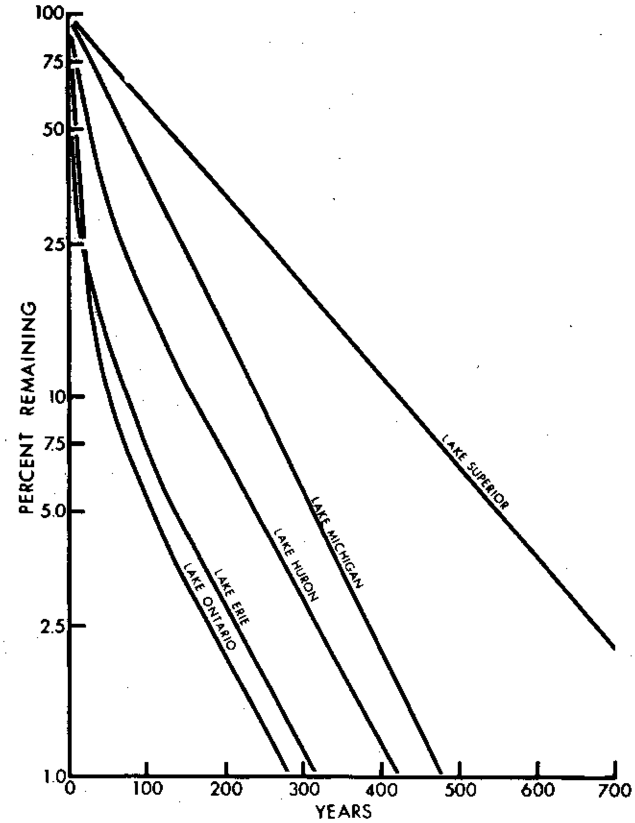


FIGURE 4–216 Time Required for Removal of Conservative Constituents in the Great Lakes, Assuming Cessation of All Input, No Sediment or Biotic Interaction, and Zero Background Level

make the organism unsafe for human consumption.

The five Great Lakes can be ranked according to the level of chemical quality. Lake Superior, located in a northern latitude with a small population in its drainage basin and with a large lake volume, is the purest of the lakes. Lake Huron, which receives water from Lake Superior and Lake Michigan, is second in order of decreasing water quality. The Lake Huron basin has a low population density, and Lake Huron has a large volume and receives inflow from Lake Superior, which tends to balance lower quality inflows from Lake Michigan and Saginaw Bay. Lake Michigan is third in order of decreasing quality. The southern portion of Lake Michigan shows signs of eutrophication, due to nutrient input from the agricultural and urban complexes adjacent to the lake. The northern half of Lake Michigan receives much higher quality tributary water than the southern basin, is somewhat isolated

TABLE 4–57 Approximate Residence Times of Water or Chemical Constituents

Lake	Time Required for[1] 90% Removal	99% Removal
Superior	420 years	840 years
Michigan	240 "	480 "
Huron	160 "	420 "
Erie	70 "	320 "
Ontario	50 "	280 "

[1]Assuming complete cessation of loading and conservation of the dissolved species

from the the southern basin by the general lake circulation pattern and acts as a buffer between lower Lake Michigan and the rest of the system. Lake Ontario receives poor quality water from Lake Erie in addition to inputs from within its own basin. Owing to the larger volume, Lake Ontario water is of higher quality than Lake Erie water. The dense population, high degree of industrialization, the high level of chemical loading, and its low volume, are the reasons that Lake Erie has the lowest quality water of the Great Lakes.

Much remains to be done to understand the chemical processes and interactions within the lakes. Sampling techniques need to be more refined: physical, chemical, and biological water quality monitors should be maintained throughout the year at statistically meaningful sites in the lakes. Laboratory and field studies need to be implemented to determine the nature and extent of sediment-water interaction, biotic assimilation, biological magnification, synergism of potentially harmful chemicals, and toxic limits of lake biota. The sediment-biota-water interactions need to be studied with respect to reaction kinetics and lake restoration techniques. The impact of structural and political action at the local, State, and Federal levels needs to be considered in the context of the Great Lakes as an interconnected system. For this purpose, systematic data on natural background loads, cultural loads, and the water budget must be obtained for use as a base in numerical simulation.

Known water contaminants, particularly nutrients, toxic metals, and pesticides, should not be released into the lakes, and political and structural measures should be taken to assure rapid abatement of such releases. In addition to abatement of waste loading, restoration methods should be investigated. The Great Lakes are dissimilar to upland lakes in several respects. These differences obviate the use of many restoration methodologies that could be applied to upland lakes. Therefore, abatement of waste loading, dredging, chemical treatment, introduction of exotic organisms, and any other restoration activity must be considered in light of its effect on the entire Basin. Since the lakes constitute a single system, their interactions emphasize the need for coordination of local, regional, State, and Federal programs.

Section 8

BIOLOGICAL CHARACTERISTICS

Robert G. Rolan and Edwin J. Skoch

8.1 The Bacteria and Fungi of the Great Lakes

8.1.1 Introduction

The bacteria and fungi of the Great Lakes have received little attention compared to such groups as the plankton, the macrobenthos, and the nekton. Most of the studies have consisted of routine determinations of densities of the coliform bacteria populations. The lack of information concerning the normal bacteria and fungi of the lakes is significant because understanding of the functional role of these organisms in nutrient recycling is fundamental to ultimate control of the eutrophication problem. Even the pathogenic bacteria and fungi, with their obvious public health significance, have not been adequately studied with regard to their occurrences and dispersal.

8.1.2 Bacteria and Fungi as Normal Lake Biota

8.1.2.1 Nutrient Cycling

Bacteria and fungi act as decomposers in the life cycle in a lake or ecosystem. In the functional classificaion of organisms, producers (e.g., phytoplankton) manufacture complex, organic molecules out of simple, inorganic precursors; consumers (e.g., animals) convert the organic molecules of their food into organic molecules of their own bodies, and decomposers convert molecules back to the simple, inorganic precursors. Without the decomposers, dead organic material would accumulate, never decay, and its nutrients would never be available for further growth of producer organisms. Some decomposers are chemoautotrophs, deriving energy needed for growth from the oxidation of certain inorganic molecules. These bacteria and fungi are also essential in making mineral nutrients available to producers. Others are involved, along with certain of the blue-green algae, in the indispensable job of nitrogen fixation. Another group of bacteria and fungi such as aquatic yeasts are basically consumers (Hedrick and Soyugenc[332]). They absorb soluble, organic nutrients from the water as their food source. They are important because they may be the only organisms capable of using this extremely dilute "soup" as food. Bacteria and fungi themselves account for little of the total biomass produced by a lake, but bacteria apparently are important as the main component of the diet of the oligochaete worms which are a component of the benthos of polluted lakes.

The paths followed by the chemical elements as they move through an ecosystem are referred to as biogeochemical cycles or ecocycles. The general features of such cycles are fairly well known, especially for the elements that are the most important macronutrients: carbon, nitrogen, phosphorus, and sulfur (Hutchinson[402]). The factors that control the rate and alternative routes of transfer of an element from one component of the ecosystem to another are not well known although availability and activity of bacteria and fungi are significant aspects. Accumulation of an element in one component of the ecosystem and its relative scarcity in another are often controlled by these microorganisms. The importance of bacteria in regulation is probably best known in the nitrogen cycle (Figure 4–217, see Subsection 7.5.6). Nitrogen fixation is ac-

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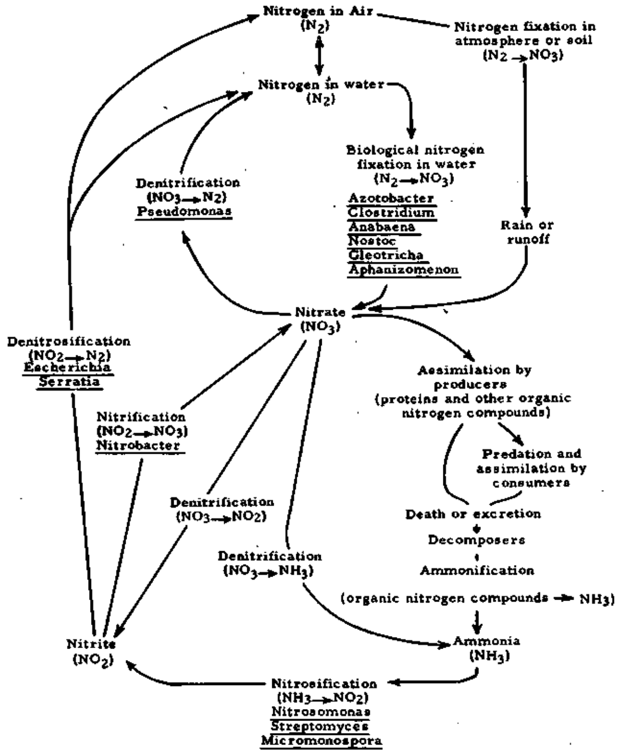

FIGURE 4–217 Nitrogen Cycle in Aquatic Environments

complished by at least six bacterial genera, including the aerobic heterotroph, *Azotobacter*, and the anaerobic heterotroph, *Clostridium*, and by certain blue-green algae (Hutchinson[402]). The algae are mostly photosynthetic autotrophs and do not require an organic food source as do the bacteria. Hutchinson[402] thinks that algal nitrogen fixation is relatively important, but that nitrogen fixation by aquatic, heterotrophic bacteria ordinarily is not, since these bacteria almost always require an organic food source that contains organic nitrogen. Regardless of how it is produced, most nitrate is used by the phytoplankton for the production of protein and other nitrogenous compounds in their tissues. After being routed through consumers, these nitrogenous compounds are eventually decomposed. The ultimate product is ammonia (NH_3). The production of ammonia is effected by nearly all decomposer bacteria and fungi, most of which act on only one or a few kinds of nitrogenous compounds. Ammonia may be lost to the atmosphere as a gas, used directly as an algal nutrient, or reconverted to nitrate through an intermediate step involving nitrite (NO_2). The bacteria engaged in nitrosification (the production of NO_2 from NH_3), and the nutrification of NO_3 from NO_2, are chemosynthetic autotrophs and do not require an organic food source since they derive their energy by oxidation of either ammonia or nitrite. Hirsh et al.[362] have evidence that the actinomycetes, *Streptomycetes* and *Micromonospora*, are also involved in the nitrosification step. Nitrosification and nitrification are inhibited by acid conditions, which may cause stagnation of the nitrogen cycle.

Availability of decomposer organisms during summer in the western basin of Lake Erie (Beaver[45]) indicated that a general pattern could be discerned although there were minor regional differences in distribution. Organisms capable of decomposing animal and plant protein were universally present. Microbes capable of carrying out the final stages of ammonification, such as the conversion of urea to ammonia, were generally distributed and abundant. Organisms that perform nitrosification were less abundant, and those capable of nitrification were scarce. Thus, it would appear that a real or potential bottleneck in the nitrogen cycle during the summer is at the nitrification step. The nitrogen fixing bacterium, *Azotobacter*, was found to be present in fair abundance, but Beaver did not demonstrate that it was actively fixing nitrogen under prevailing lake conditions.

Domogalla et al.[220] demonstrated that there are seasonal fluctuations in Lake Michigan and smaller lakes in the availability of free ammonia and nitrate, which correlate with the rate of denitrification or nitrification by the bacteria. Nitrate concentration reaches a maximum in March and then declines to low levels by midsummer, which corresponds with Beaver's observation on the low activity of nitrifying bacteria during summer. Spring and summer are the main growing seasons for phytoplankton so nitrate concentration should drop even if nitrification would continue unabated. Whatever nitrate is added during the summer by nitrogen fixation is also consumed so rapidly that it causes no apparent increase in free nitrate concentration. Denitrification to ammonia reaches a maximum in the summer; but, in contrast to nitrification, remains fairly high during the rest of the year, so the availability of free ammonia never appears to be limiting. At least some species of freshwater algae can use ammonia as a nitrogen source, and some can use both ammonia and nitrate, but the selective effect of the relative availabilities of these two nutrients has not been determined (Hutchinson[402]). An interesting point about the seasonal variations in nitrate abundance is that nitrate seems to become most abundant in early spring just as the growing season begins.

Domogalla et al.[220] also demonstrated the presence of bacteria that are not involved in the nitrogen cycle, but which decompose other complex, organic substances. They found that starch-hydrolyzing organisms are present nearly everywhere in various degrees. Cellulose decomposer organisms are scarce in some areas. Chitin decomposer bacteria, while widely distributed, have temperature optima well above that usually found in the Great Lakes. McCoy and Sarles[517] generalize that lake microfloras typically contain a well-balanced mixture of species capable of strong proteolysis (protein digestion) and decomposition of cellulose, chitin, pectins, and other complex biological molecules even though cellulose and chitin are among the most decay-resistant of natural substances. Cellulose is a major component of plant tissues and is largely responsible for their fibrous or woody texture. Chitin is a protein characteristic of the exoskeletons (shells) of insects and other arthropods. The role of detritus feeders and their symbiotic intestinal bacteria in the decomposition of cellulose, chitin, and pectins in fresh water has not been evaluated.

The actinomycetes are a poorly known group of microorganisms having characteristics suggesting relationships to both the true bacteria and true fungi, although they are more bacteria-like. The actinomycetes of freshwater lake sediments appear to be involved in the biodegradation of some of the more highly resistant substances such as cellulose, lignin, and chitin. Colmer and McCoy,[159] in studying this group in the muds of upland lakes in Wisconsin, found that population levels of *Micromonospora*, the most characteristic actinomycete genus in aquatic muds, showed a significant increase following the vernal overturn each year, but had relatively low populations at other times. They hypothesized that these slow-growing actinomycetes are at a disadvantage in competition with other decomposer organisms when readily degradable nutrient sources are available, as would be the case in the summer and fall. In the spring, when all the nutrients are either in an inorganic form or in resistant organic molecules, the actinomycetes, which can break down such organic molecules, flourish.

McCoy and Sarles[517] reiterate Birge's[68] conclusion that bacteria stand at the base of the fertility of lakes. In the case of eutrophication, due to the addition of allocthonous nutrients, the normal balance of producers-consumers-decomposers may be disrupted, resulting in the accumulation of organic material as a more or less permanent part of the lake sediments. These authors maintain that such imbalance results from the inability of bacterial population growth to keep up with the addition rate of organic nutrients because of some physical limiting factor and suggest that winter low temperatures do not allow the bacteria to decompose the sewage and other organic material which is added year-round. Since a certain portion of the organic matter is not decomposed, but is added to the sediments, there is a residual BOD which accumulates in the lake year after year. Dugan et al.[227] estimate that the annual organic input into Lake Erie is approximately 29×10^9 lbs., which is well above the capacity of the aerobic heterotrophic bacteria whose annual production is estimated at 1×10^8 lbs. The suspended bacterial mass in the lake at any given time in the summer is estimated at 5×10^7 lbs., and most of these cells may die and may be added to the sediments with the onset of winter. The cycling of BOD-bacteria organic matter can be represented as shown in Figure 4–218. Obviously, the solution to the BOD problem would be to reduce the BOD input into the lakes and/or increase the BOD output (e.g., by harvesting organic matter).

Bacteria and fungi are also important regulators of the phosphorus cycle. Gahler[280] summarized the evidence concerning the ability of some bacteria and fungi to use insoluble forms of phosphate directly. Some bacteria can use calcium phosphate or ferric phosphate as their sole phosphorus source. Colloidal phosphate in clay-loams can also be utilized. Various species of *Pseudomonas*, *Mycobacterium*, *Micrococcus*, *Flavobacterium*, and the fungi *Penicillium*, *Sclerotium*, and *Aspergillus* are capable of using tri-calcium phosphate, apatite, and other insoluble forms as their sole phosphorus source. The obvious implications of these findings are that the resolubilization of phosphates in sediments is not entirely dependent upon the oxidation-reduction potential. It has also been proposed that bacteria may resolubilize ferric phosphate by generating hydrogen sulfide, which then reacts with the ferric phosphate to produce ferrous sulfide and soluble phosphate.

Dugan et al.[227] mention a phenomenon which is not generally appreciated. Bacteria themselves compete with the phytoplankton for the available soluble phosphate and may

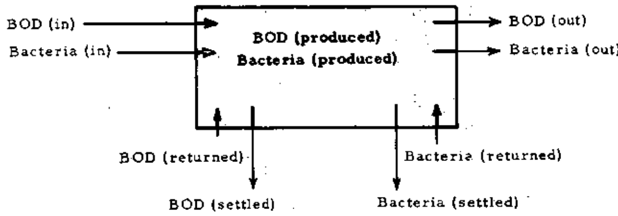

FIGURE 4–218 Compartments of BOD-Bacteria Exchange

From Dugan et al., 1969

have the advantage whenever the phosphate concentration is as low as 0.3 mg/l.

Bacteria and fungi cannot be ignored in the problem of nutrient enrichment of lakes. Kuentzel[478] indicates bacteria are intimately involved in controlling the amount of available carbon dioxide. Carbon dioxide cannot be obtained rapidly enough from carbonate salts or from the atmosphere to support bloom conditions. However, abundant amounts of carbon dioxide can be produced as the result of the heterotrophic nutrition of bacteria on organic carbon. Some algae require organic growth factors such as vitamins (Holm-Hansen[374]) and perhaps chelating agents (Lange[484]), or other poorly understood exometabolites produced by bacteria.

8.1.2.2 Other Aspects of the Ecology of Normal Lake Bacteria and Fungi

McCoy and Sarles[517] report that periphytic bacteria are generally more abundant than those suspended in water. Benthic bacteria appear to be more abundant in sediments at moderate depths than in either very shallow waters or at great depths. In shallow water, bacterial abundance is directly related to the relative abundance of vegetation. It may be argued, of course, that the relative scarcity of bacteria in vegetationless shallow areas is due more to the lack of productivity of the area than to any surface effect. Similarly, Graikoski[296] found greater suspended bacterial populations in shallow water of Lake Ontario than in deep water. The amount of vegetation in these shallow areas was not reported. Robohm and Graikoski[669] could find no consistent differences in the bacterial population levels from various depths in Lake Michigan. They also found that samples taken within relatively short distances of one another and at similar depths showed considerable differences in bacterial populations. The availability of surfaces is a very important factor in the ecology of aquatic bacteria and fungi. Stalked bacteria of the sulfur and iron chemoautotrophic groups and other sessile types are important components of the aquatic microflora. In fact, some sessile bacterial species have been discovered only through permitting them to grow on submerged microscope slides in their natural habitats. Fungi, apparently, do not grow when out of contact with an appropriate surface. Bacteria in suspension tend to aggregate with other seston, which provide considerable combined surface areas, including both plankton and non-living particles (Pfister et al.[606]). There is some evidence that nutrients and DDT strongly adsorb on such aggregations (Pfister et al.,[606] Dugan et al.[227]). These aggregates may then be consumed by detritus and filter feeders, providing a route of entrance for otherwise dilute nutrient and DDT concentrations into the biomass.

Weeks[875] determined that lake sediment bacteria, both aerobes and anaerobes, decrease in abundance with increasing depth of residence in the mud. The upper stratum, or mobile layer, had 2.5 times more bacteria than the more stable sediment. In the stable sediment, aerobes outnumbered anaerobes 10 to 1 to a depth of 6 cm. At 6 cm to 10 cm, anaerobes slightly outnumbered aerobes.

Chromogenic bacteria, those which produce colored colonies on laboratory media, are more common among aquatic bacteria than soil bacteria. McCoy and Sarles[517] note that chromogens may be common among aquatic bacteria because the pigments offer protection against damaging effects of solar radiation. Weeks[875] found that chromogenic bacteria, exclusive of the chromogenic actinomycetes, comprised 24.5 percent of those bacteria in the mobile layer and 20.7 percent in the 0 cm to 2 cm layer of formed sediment. Colmer and McCoy[159] determined similar patterns of distribution of the actinomycete, *Micromonospora*, which was essentially restricted to the sediments except during mixing periods when it is probably picked up from the bottom by convection currents. *Micromonospora* is not abundant in sandy littoral zones that have little or no vegetation and are subjected to vigorous wave action; rather it is associated with silty profundal areas rich in organic matter. As with bacteria, *Micromonospora* decreases markedly in numbers with increasing depth below the sediment-water interface.

In general, yeast populations increase with water depth. Hedrick et al.[334] found the greatest yeast cell densities at 100 m in the deep open waters of Lake Michigan, but in waters of intermediate depth, the greatest density was at 40 m to 50 m. In shallow areas, cell density was greatest at 15 m to 20 m, just above the bottom. The depth distribution of yeasts and molds in waters of Lake Ontario appears to be correlated with nitrite concentrations, which generally increase with depth (Hedrick and Soyugenc[332]). The most numerous species of yeast, *Candida guilliermondii* and *Rhodotorula mucilaginosa*, are also found regularly in low numbers near the surface. They cannot utilize nitrate as a nitrogen source but they can use both ammonia and organic nitrogen, which seem to be sufficiently available at all depths to promote their growth.

Some species of yeasts, such as *Hansenula* and a pink yeast, *Rhodotorula graminis*, are associated with muds. In contrast, the black yeasts, mainly *Aureobasidium*, are never found in muds, although they may be abundant in the overlying waters (Hedrick and Soyugenc[332,333]). The sediment yeasts are more closely related to terrestrial soil yeasts than to the water yeasts as a group (Hedrick and Soyugenc[333]). The diversity of yeasts in sediments also seems to exceed that in water (Hedrick et al.[334]). Hedrick et al.[335] found that the variety of yeasts in sediments of Lake Michigan is related to the depth at which the sediment is found. The greatest diversity occurs in the black, viscid muds characteristic of the principal basins. There are three species of yeast in this mud that occur in no other type. The red clays of plateau areas of the lake bottom containing iron oxides support the second greatest variety of yeast species. Grey-black clays and sandy-surfaced clays contain few kinds of yeast. Black and red-banded and the black mottled sediments, which have large amounts of iron sulfides, contain generally no yeasts.

Lake Erie seems to have greater yeast species diversity but lesser cell densities per unit volume than Lake Michigan (Hedrick et al.[334]). There also seems to be some differences in the species of yeasts present in Lakes Michigan and Ontario (Hedrick and Soyugenc[332]), but studies on this group are not extensive.

There is no doubt that the aquatic bacterial numbers and variety of species exceed those reported by nearly all investigators. This is due to the inadequacy of laboratory media for the growth of many types and to differences caused by varying periods and temperature of incubation. Robohm and Graikoski[669] observed the same high numbers of bacteria in nearshore samples after only two days of incubation as reported by Scarce,[714] but this distinction disappeared after 10 days of incubation because of the subsequent development of the more numerous slow-growing psychrophils of the deepwater samples. Direct microscopic counts of bacterial populations nearly always exceed estimates based on growth of laboratory media. Some of the most important bacteria, the sulfur- and iron-using species of chemosynthetic autotrophs, are seldom counted due to the lack of adequate techniques for laboratory culture (McCoy and Sarles[517]).

Virtually nothing is known concerning the psychrophilic and thermophilic bacteria of the Great Lakes, i.e., those bacteria adapted for growth at low or high temperatures, respectively. Robohm and Graikoski[669] indicate that psychrophils are relatively more numerous in deep lake water than in inshore areas. Farrell and Rose[258] confirm the importance of psychrophils in lake ecology, which comprise 41 percent to 76 percent of the bacteria suspended in lake water and 11 percent to 33 percent in the sediments. Virtually nothing is known concerning the differences in functional attributes of psychrophils relative to mesophils or thermophils. An understanding of the functional significance of thermophilic bacteria is fundamental to comprehension of the effects of discharge of thermal effluents from power generating plants. Stangenberg and Pawlaczyk[757] have found that temperature increases in rivers, due to such thermal discharges, have caused reduction of total bacterial populations, including a drastic reduction of psychrophils and some increase in thermophils. Seasonal changes in temperature in estuarine areas induce corresponding changes in the proportion of psychrophils and mesophils: populations shift toward predominantly psychrophilic bacteria in winter and predominantly mesophilic bacteria in summer (Sieburth[738]). It is reasonable to presume that similar changes occur among open lake bacteria, but the functional significance of such variations is unknown.

8.1.3 Bacteria and Fungi as Indicators of Pollution

8.1.3.1 Coliform Bacteria

The most common use of bacteria as indicators of pollution is the coliform index. The most common source of coliforms is domestic and feedlot sewage since the normal habitat of *Escherichia coli* is the intestinal tract of warm-blooded mammals. However, not all coliforms are fecal coliforms. *Aerobacter aerogenes*, for example, is usually a nonfecal form. It is also usually less common than *Escherichia coli* in surface waters, but occasionally may be locally abundant.

The presence of 5000 coliforms per 100 ml as a monthly pretreatment average is considered sufficient contamination to condemn water as not potable in Ohio. The danger of disease from colon bacilli in their natural habitat is slight, but they can cause infant diarrhea and local infections. However, coliforms do indicate a probability of the presence of dangerous pathogens that are also associated with sewage. Fecal coliform counts correlate more precisely with either the presence or absence of pathogens. The pathogens are normally not tested themselves because they are difficult to culture and are much less abundant than the coliforms. Pathogens associated with fecal contamination of water include the causative organisms of typhoid fever, cholera, leptospirosis, infectious hepatitis, and bacillary and amoebic dysentery. In regard to the correlation between coliforms and pathogens, the National Technical Advisory Committee on Water Quality Criteria to the Federal Water Pollution Control Administration[831] made the following statement:

> While the total coliform counts may be a satisfactory indicator in certain respects, the sub-committee believes that the variable correlation of total coliforms content with contamination by excreta suggest that total coliforms are not a satisfactory indicator of the possible presence of pathogens in recreational water.
>
> That portion of the total coliforms in water that are of fecal origin may range from 1% to more than 90%. At the 1% level, a standard of 1,000 coliform bacteria per 100 ml. would constitute an undue limitation on availability of water for contact recreation. At the 90% level, a limit of 1,000 counts per 100 ml. would constitute a threat to the health of a contact recreational user. Thus, total coliform criteria are not adequate for determining suitability of water for use for contact recreation.

A number of problems makes the interpretation of coliform counts rather difficult. Scarce et al.[716] found that the survival time in natural waters of coliforms and fecal streptococci, another group of bacteria indicative of sewage influx, was dependent on a variety of factors. Coliform counts nearly always showed an increase in the first few days following sewage mixing with Lake Michigan water. This aftergrowth indicates an ability of the coliforms to multiply for a short period of time outside the digestive tract. Fecal streptococci usually declined under the same conditions, although under certain circumstances these bacteria also demonstrated an ability to grow outside their mammalian hosts. The following factors affected survival time of these two types of sewage bacteria:

(1) temperature of the water into which the bacteria are discharged

(2) the abundance of organisms, such as protozoa, which feed on bacteria

(3) the amount of organic nutrients available for bacterial growth

(4) the initial population density of the bacteria

(5) the chlorination of the sewage effluent, and, presumably, the presence or absence of other toxic materials in the environment.

There were no consistent differences in coliform survival patterns at 5°C, 10°C, and 20°C, but at 35°C the aftergrowth and subsequent die-off occurred more rapidly. The authors think that this pattern can be attributed to the fact that 35°C is near the optimum temperature for coliforms and that predatory protozoans were inhibited by the warmth. Fecal streptococci, on the other hand, died away with increasing rapidity as temperature increased.

Another factor that influences the survival of coliforms is the clarity of the water (Federal Water Pollution Control Administration[832]). High light penetration is correlated with shorter survival times. Interpretation of coliform count data thus becomes extremely difficult. Heavy rainfall may lower the coliform count through dilution or may increase it if sanitary and storm sewers are combined and the flow rate during a storm exceeds sewage treatment plant capacity. Glatz[288] found significantly different coliform counts at the same site over five-minute intervals. Most of the older data are based only on total coliform counts which, as noted above, are ambiguous. Despite these difficulties, it is reasonable to accept long-term changes in average coliform counts at particular locations as indicative of environmental change, namely sewage discharge and degree of treatment.

Early reports of coliform counts in Lake Erie were low except in the immediate vicinity of large cities such as Erie, Pennsylvania, and Cleveland, Ohio (Zillig;[921] Gottschall and Jennings;[294] Ellms[240]). Beeton[49] reports that coliforms increased threefold in the western basin of Lake Erie from 1913 to 1946–48, but showed no significant increase elsewhere in the open lake. Total bacterial counts declined at the water intake at Erie, Pennsylvania during the period 1920–1957. During the years 1926 to 1942, the average coliform count per 100 ml was 70 for Lake Michigan in the vicinity of Chicago (Damann[181]). During the period 1943 to 1958, the coliform count declined to an average of 23/100 ml.

Data from various sources, mainly Jackson et al.[419] indicate a rank order of sewage discharge into the Great Lakes. In 1962, Lake Erie had the highest coliform counts, followed by Lake Michigan, Lake Huron, and Lake Superior. The last two receive little sewage. There were no data for Lake Ontario. Coliforms are normally evident in inshore areas rather than throughout a lake. Scarce[714] found essentially none in central Lake Michigan.

8.1.3.2 Total Bacteria

High levels of coliforms, fecal streptococci, and total bacteria in Lake Michigan are associated with urban centers discharging large amounts of sewage into the lake (Scarce[714]). In Green Bay, however, elevated total bacteria counts were found without corresponding increases in sewage discharge. Green Bay receives a considerable amount of allocthonous organic matter in the form of pulp, paper, and food-processing wastes, which could be expected to increase the total heterotrophic bacteria populations without increasing coliform and fecal streptococci. Total bacteria counts may reveal information that might be overlooked when full reliance is placed on fecal bacteria counts. Scarce also observed the familiar phenomenon of a lowered species diversity in polluted waters. A smaller variety of bacteria species occurs in polluted areas even though the total number of individuals may be very high.

8.1.3.3 Yeasts and Molds

The distribution of the two most common species of yeasts in Lake Ontario, *Candida guilliermondii* and *Rhodotorula mucilaginosa*, correlates with the densities of coliform bacteria (Hedrick and Soyugenc[332]). It is likely that those environmental conditions favoring the presence of coliform bacteria also promote the growth of these yeasts. In Lake Superior, the distribution of the greatest cell densities per unit volume of yeasts and molds in water seems to be related to the amount of organic nitrogen (Hedrick et al.[330]). The populations were lowest in open waters, high in harbors and near river mouths, and highest at the mouths of the rivers and streams that discharge considerable amounts of organic nitrogen into the lake. Yeasts and molds may, therefore, also be indicators of organic enrichment, whether or not this enrichment is associated with domestic sewage.

8.1.4 Bacteria and Fungi as Pathogens

8.1.4.1 Salmonella and Shigella

The occurrence of enteric bacteria pathogenic to humans in the water of the Great Lakes, at least in Lakes Erie and Michigan, is well established (Scarce and Peterson;[715] Peterson;[603] Clemente and Christensen;[150] and Dutka et al.[232]). All these reports describe many varieties of *Salmonella*, but *Shigella* organisms were not found. Certain kinds of *Salmonella* seem to be more common in spring and others in summer (Peterson[603]). Scarce and Peterson[715] note that salmonellae and the pathogenic enteroviruses such as poliovirus, ECHO, Coxsackie, and reovirus have prolonged survival times in receiving waters, and thus may present a health hazard. Two hundred and twenty-seven cases of salmonellosis were reported in Chicago in 1962 (Scarce and Peterson[715]). An explanation for the absence of *Shigella* in the above surveys may be found in the work of Hedrick[329] and Hedrick et al.[331] They found that waters of Lake Michigan were quite toxic to *Shigella* species, *Salmonella typhosa*, and *Salmonella paratyphi*, and less toxic or even nontoxic to *Escherichia coli* and *Salmonella schottmuelleri*. Hedrick[329] attributes this toxicity to dialyzable products of algae. Lake Michigan waters tend to be toxic more often in the late summer months when certain kinds of plankton algae are at a maximum. Antibiotic substances from actinomycetes should also be considered as a possible toxin.

A correlation between coliform counts and pathogenic bacteria is not obvious. Peterson[603] reported that *Salmonella* isolations increased sharply as coliform counts passed each of two plateaus, 100 and 1000 cells per milliliter. Dutka et al.[232] state that salmonellae could be isolated from water contiguous to the major population centers on the Great Lakes even when these waters conform to existing coliform standards. Clemente and Christensen[150] report a number of incidents in which no salmonellae were found in water samples with high coliform counts, and yet *Salmonella* was isolated from a Lake Erie sample having less than 100 coliforms per milliliter.

8.1.4.2 Botulism

The toxin of *Clostridium botulinum* has been cited as causing the death of large numbers of loons, gulls, grebes, and mergansers in Lake Michigan in 1963–64 (Fay et al.[259]). Mortality was related to the feeding habits of birds that eat fish and some larger aquatic invertebrates. The toxin is probably produced by *Clostridium* under anaerobic conditions in the sediments. The toxin enters fish and invertebrates during feeding or by absorption through the gills without apparent harm; they in turn are eaten by the birds who die. This is due either to the lower tolerance of these birds to the toxin of botulism, or to a biological amplification of the toxin (Jensen and Allen[430]). However, it has not been conclusively proven that these birds died from botulism (Herman[349]). Gulls can withstand very large doses of botulism toxin, as much as 200,000 mouse-lethal doses, with no visible effect. Local ornithologists who have been studying gull populations believe that the 1963 die-off was not excessive for a year in which many young birds were produced. Gull populations have increased about fourfold because of the abundance of alewife as food (Ludwig[508]). Therefore, more dead gulls are likely to be noticed even if the death rate remains the same; in fact, there may not actually have been a mass die-off of aquatic birds. Nonetheless, the diagnosis of botulism for the simultaneous die-off of four unrelated species is rather convincing for the following reasons: all the birds had similar feeding habits; they all showed symptoms of botulism paralysis while dying; and a necropsy isolated botulism toxin in each species.

Bott et al.[79] cite two incidents of human botulism from consumption of Great Lakes fish. Such cases may increase if conditions favorable for the development of *Clostridium botulinum* become more common. The resistant spore stage is extremely common, but the spores are of little significance if the proper type of anaerobic environment for the growth of the bacterium and production of its toxin does not exist. Bott et al.[79] relate the presence of the toxin in fish to its presence in the environment and not to the feeding habits of the fish. Thus, the fish of southern Green Bay, which has an environment conducive to the development of *Clostridium botulinum*, have a high incidence of the toxin. Bott et al. speculate that botulism should increase in any lake which is overenriched and develops anoxic conditions, but they point out that this has not happened in Lake Erie. Obviously, the environmental requirements of *Clostridium botulinum* are not so simple.

8.1.4.3 Parasitic Fungi

Beneke and Schmitt[61] and Schmitt and Beneke[720] report the presence of a number of parasitic fungi from sediments of the western basin of Lake Erie, some of which have been known to infect fish. There are no data on the incidence of such infections in the Great Lakes.

8.1.5 Actinomycetes as Causes of Tastes and Odors in Drinking Water

Unpleasant tastes and odors in drinking water are one of the common problems for filtration plants. Causes of these tastes and odors are generally conceded to be biogenic in origin although some odorous substances come from industrial wastes. Even so, Hoak[363] contends that phenolic tastes and odors derive from the microbial decomposition of tannins rather than runoff from steel production wastes, the source to which they are usually attributed. The more common tastes and odors are usually described as earthy, musty, or fishy. These odors have been customarily attributed to algal blooms, which show up in raw waters more or less simultaneously with the odorous substances (Palmer[595]), but there are reasons to think that actinomycetes may actually be responsible. Potos[623] reports the regular occurrence of a musty taste and odor problem at Cleveland's Crown Filtration Plant in summers since 1966 whenever the intake is inundated by hypolimnetic Lake Erie water. This occurs when winds blow out of the south for several days, causing displacement of the hypolimnion toward the southern shore. The plankton in this hypolimnetic water contains a number of algal genera which Palmer[595] associates with taste and odor problems.

Studies implicating actinomycetes in taste and odor production are scattered and go back to the start of this century. Thaysen[790] demonstrated that actinomycetes in organically enriched river sediments in England produced a substance with a musty odor. This substance was assimilated by fish and imparted an earthy taint that rendered the flesh inedible (Thaysen and Pentelow[791]). Egovora and Isachenko[239] showed that an earthy odor could be produced by actinomycetes growing on bottom muds. The most interesting aspect of this study was the apparent correlation with the texure of the bottom. The greatest amount of odor was produced in a sandy mud and the least in silty mud, the latter presumably being efficient in adsorbing the substance. The most convincing study of the role of actinomycetes in producing taste and odor substances was made by Silvey and Roach.[739] They correlate the production of odorous materials with the life cycle stage and the availability of organic nutrients. They describe the general life cycle based on laboratory cultures of seven genera of aquatic actinomycetes (Figure 4–219). In the presence of organic nutrients, the spores germinate and produce primary filaments that give off a strong fish odor for 2 days to 10 days depending on the temperature. In the absence of an adequate nutrient supply, the filament produces zygospores before death, otherwise it produces motile zygotes which develop directly into larger secondary filaments. Initially, the secondary filaments produce a strong grassy taste and odor for 2 days to 10 days. With a continuing nutrient supply, a pungent musty odor develops for the next 2 days to 10 days. Following this, there is a period of production of a slight musty "potato-bin" odor before sporulation. The genera which fit this pattern include *Aptisima*, *Calyptroida*, *Glancopprimenda*, *Brevisporulata*, *Pyrospora*, and *Aspyrospora*.

Silvey and Roach[739] maintain that the algae associated with taste and odor problems have been accused of causing these problems merely because of their coincidental presence. They suggest that certain blue-green algae, such as *Polycystis*, *Aphanizomenon*, and *Anabaena*, may have an indirect causal relation to the problem by being the nutrient source for actinomycete growth. These algae form floating mats, ranging in size from a millimeter to several inches, in which actinomycetes colonize. When the algae begin to die off the secondary filaments flourish on their remains and produce first a strong, nauseating, musty odor followed by a rotting-wood odor mixed with an earthy smell. If sufficient nu-

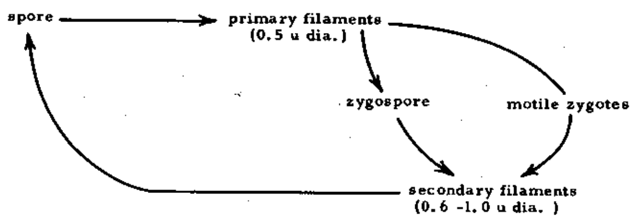

FIGURE 4–219 General Life Cycle of Aquatic Actinomycetes

trient material remains, another generation of primary filaments may be produced with the resulting fish odor. These authors maintain that destroying algae with algacides, a commonly used control measure, is self-defeating because the dead algae merely add to the nutrient sources of the actinomycetes. The actinomycetes themselves are unaffected by such algacides as copper sulfate and chlorine.

Since actinomycin and a number of other antibiotics are derived from soil actinomycetes, it is not surprising that aquatic actinomycetes produce such substances too (Safferman and Morris;[698,699] Kosmachev;[466] Ivanitskaya and Upiter[417]). There are hundreds of actinomycetes showing antibiotic properties, which are rather specific as to their target organisms. In view of the life cycle work of Silvey and Roach, it is interesting to speculate whether or not the actinomycetes produce their own organic nutrient source by poisoning algae. It has been suggested that antibiotics derived from actinomycetes could be used as specific algacides with low residual effects (Safferman and Morris[699]). Since one of the consequences of using this or any other type of algacide would be the liberation of organic nutrients for actinomycete growth and possible subsequent taste and odor production, such algacides would not obviate the necessity for controlling the algae through control of nutrient input to the lakes.

8.2 The Zooplankton, Zoobenthos, and Periphytic Invertebrates of the Great Lakes

8.2.1 Components of the Fauna

The invertebrate fauna of the Great Lakes is rich and diverse, comprising more than 500 species in ten phyla. A list of species arranged according to lake and major taxonomic groups

TABLE 4-58 Number of Species in Major Taxa Reported in the Great Lakes

	Superior	Michigan	Huron	St. Clair	Erie	Ontario
Protozoa (unicellular animals)	2	20	-	7	70	-
Coelenterata (hydras & jellyfish)	2	2	2	1	4	-
Rotatoria	8	64	6	109	147	6
Calanoid Copepods	8	8	8	6	9	10
Harpaticoid Copepods	1	1	-	-	1	-
Cyclopoid Copepods	5	6	2	9	10	1
Cladocera (water fleas)	19	20	27	8	48	8
Porifera (sponges)	-	1	1	1	1	-
Turbellaria (flatworms)	1	1	1	4	2	-
Bryozoa (moss animals)	1	2	1	1	1	-
Nematoda (roundworms)	1	1	2	1	1	1
Tubificidae (sludgeworms)	14	24	21	4	22	22
Enchytraeidae	1	1	-	-	1	-
Naididae	4	12	7	6	5	5
Lumbriculidae	2	-	-	-	1	-
Polychaeta	1	-	-	1	1	-
Hirudinea (leeches)	10	1	1	8	16	-
Sphaeriidae (fingernail clams)	14	19	24	3	19	24
Unionidae (mussels)	2	-	6	19	28	1
Gastropoda (snails)	24	3	31	29	24	28
Tardigrada (waterbears)	-	1	-	-	1	-
Hydracarina (water mites)	1	1	6	1	3	-
Ostracoda (seed shrimp)	1	1	1	1	1	-
Mysidacea (opposum shrimp)	1	1	1	-	1	-
Isopoda (aquatic sowbugs)	4	-	2	2	2	1
Amphipoda (scuds)	4	2	3	3	5	2
Decopoda (shrimp & crayfish)	3	-	-	2	4	1
Chironomidae (midges)	5	1	28	-	29	12
Other Diptera	-	-	2	1	3	-
Neuroptera	-	-	1	-	1	-
Hemiptera	-	-	1	-	4	-
Plecoptera (stoneflies)	-	-	-	-	1	-
Odonata (damsel flies)	-	-	-	1	2	-
Trichoptera (caddisflies)	-	-	3	-	14	-
Ephemeroptera (mayflies)	-	1	8	2	15	1
Coleoptera (beetles)	-	-	1	-	4	-
Total species	139	194	197	230	501	123
Blank categories	10	12	9	11	0	21
No. Research Reports	18	33	26	12	53	19

is presented in Table 4–58. This table reveals the following pertinent facts concerning knowledge of the invertebrates of the Great Lakes:

(1) Some groups of organisms have been studied much more extensively than others. These include the planktonic crustaceans, sludgeworms, fingernail clams, amphipods, midges, and mayflies. The rotifers and protozoans were extensively studied at the beginning of the century, but they have largely been ignored since then.

(2) Some groups of organisms have been studied more thoroughly in some lakes or portions thereof than in others. The plankton of Lake Ontario have received little attention in comparison to plankton of other lakes with lower human population densities in their watersheds.

(3) The entire invertebrate faunas of some lakes or their subdivisions have been studied much more thoroughly than others. Based on a number of research reports used to compile the list of species, the fauna of Lake Erie is the most thoroughly known, followed in order by those of Lakes Michigan, Huron, Ontario, Superior, and St. Clair. In Lake Erie, the majority of studies have been conducted in the western basin. Saginaw Bay, Georgian Bay, and the Straits of Mackinac are better known than the mid-lake regions of Lake Huron and the bays have been studied more thoroughly in Lake Ontario than the pelagic regions.

(4) Further research is necessary on the invertebrate faunas of the Great Lakes. The column in Table 4–58 entitled, "Blank Categories" is a rough index of the degree of ignorance about the fauna of each lake.

It is often difficult to assign a particular species to one of the categories: plankton, periphyton, or benthos. For example, the crustacean, *Mysis relicta*, spends the daylight hours on or near the bottom and can be called benthic; but at night, it migrates toward the water surface and is then obviously planktonic. Benthos is defined here as those organisms that live in or on a particulate substrate, such as mud or sand, most of the time. Periphyton are those organisms that characteristically live on submerged objects such as other organisms, rocks, logs, and pilings. Plankton are relatively weak swimming organisms that live suspended in the water. There is a problem in distinguishing true plankton (euplankton) from organisms that are accidental and temporary members of the plankton, especially among the Protozoa and Rotatoria. Many of these organisms are apparently tychopelagic, that is, they are normally members of the benthos that were swept up due to wave or current action and had not returned to the bottom at the time of sampling. Another problem develops in the marginal zone. The marginal zone encompasses those areas around the periphery of a lake and the shores of islands that are marshy, weedy, and/or can be described as baylets, coves, etc. This marginal zone will be included when there appears to be significant exchange of water between the zone and the lake proper. Methods used to collect organisms in these protected areas often make it impossible to distinguish between plankton, periphyton, and benthos.

8.2.2 Zooplankton and Zoobenthos as Environmental Indicators

8.2.2.1 Zooplankton

Plankton are transients carried from place to place in the water mass. Plankton reflect the integrated effects of all the environmental influences acting on them, but, since their source is generally unknown, interpretation is difficult. Plankton may not show the effects of pollution until far from the source (Davis[194]). Nonetheless, plankton are valuable indicators of environmental conditions in entire lakes or in large areas of lakes. For example, plankton in Lake Erie near the mouth of the Cuyahoga River are not particularly good indicators of pollution coming from the river (Davis[194]). Due to the dynamics of the mixing of the two different water masses, it is not possible to show the fertilizing effect of organic pollution from the river. However, toxic effects on lake plankton in the zone of mixing can be seen. The protozoan *Tintinnidium* and the microcrustacea *Daphnia* spp., *Diaptomus* spp., and *Epischura lacustris* were scarce in the zone of mixing where the iron concentration, a major, toxic, industrial waste of the local steel plants, exceeded 6 ppm. Davis concluded that the presence of many dead Copepoda and Cladocera indicate water highly polluted by industrial wastes, but other methods are more reliable and sensitive.

The following zooplankton are predominant in glacial lakes. Asterisks indicate the zooplankton characteristic of deeper lakes only (Eddy[235]). However, every one of the deep lake species has been collected from either or both Lake St. Clair and the western basin of Lake Erie.

Protozoa:	*Difflugia globulosa*
	Codonella cratera
Cladocera:	*Bosmina longispina**
	*Daphnia retrocurva**
	*Daphnia "longispina"**
	Chydorus sphaericus
Rotifera:	*Polyarthra vulgaris*
	Keratella cochlearis
	*Notholca longispina**
	Notholca striata
	Asplanchna priodonta
	Synchaeta stylata
Copepoda:	*Diaptomus ashlandi**
	*Diaptomus sicilis**
	Diaptomus oregonensis
	*Diaptomus minutus**
	*Epichura lacustris**
	Cyclops bicuspidatus
	*Mesocyclops edax**
	Limnocalanus macrurus

Certain species indicate either the trophic level or the warmth of the lower lakes. *Diaptomus siciloides* and *Diaptomus reighardi* are recorded only for Lake Erie and Lake Ontario. *Eurytemora affinis* has not been found in Lake Superior, but this may reflect only the limited time for range expansion in the Great Lakes which this recent invader from brackish environments has enjoyed. This species was not recorded in the Great Lakes until 1966. *Senecella calanoides* has not been taken in Lake Erie. Apparently, it is restricted to areas below the thermocline (Wells;[880] Robertson[664]), and much of Lake Erie lacks a hypolimnion. Nevertheless, Lake Erie has been sufficiently sampled, and no documentation of its presence exists. Therefore, the absence of *Senecella calanoides* may reflect some significant environmental control.

Among the cyclopoid copepods, the following appear to be lower lake species, as they are found only in Lakes Michigan, St. Clair, and/or Erie: *Cyclops americanus*, *C. ater*, *C. prasinus*, *C. phaleratus*, *C. vernalis*, *C. bicolor*, *C. fluviatilis*, *C. fimbriatus*, *C. serrulatus*, *C. albidus*, *C. quadricornus*, *C. robustus*, and *C. pulchellus*. Occurrence of *Cyclops americanus* is further restricted to the western basin of Lake Erie or nearshore areas such as Cleveland Harbor.

Among the Cladocera, the lower lake species seem to be *Bosmina obtusirostris*, *Ceriodaphnia lacustris*, *Ceriodaphnia rotunda*, *Daphanosoma brachyurum*, *Daphnia schodleri*, *Ceriodaphnia reticulata*, and *Daphnia longiremis*. *Daphnia pellucida*, on the other hand, may be indigenous to Lake Superior.

At least some *Daphnia* species are adaptable to low levels of dissolved oxygen, developing enough hemoglobin under semi-anaerobic conditions to give them a distinct red color (Hrbacek[386]). Their value as an organic pollution indicator is thus reduced. Hrbacek[386] showed that certain species of *Daphnia* are differentially favored over others when cultured in various natural waters. He concluded that pollution usually does not act directly on the zooplankton, but rather it changes their environment:

> A part of the changes in zooplankton, attributed to pollution, may be owing instead to the changed nutritional level that results from the development of bacteria or algae. Other changes are owing to changes in fish stock, since the oxygen deficiency, one of the most common consequences of pollution, affects predators more seriously than some species of coarse fish.

8.2.2.2 Zoobenthos

The benthos are better indicators of environmental conditions than the plankton because they are more or less fixed. The presence or absence and relative abundances of benthic taxa reflect the integrated effects of water that has passed through a particular location.

(1) Oligochaetes

Brinkhurst[97] chided those who, observing that tubificids are abundant in bodies of fresh water with excess organic matter, have proposed "various rather naive schemes of pollution detection and assessment." His studies have revealed that "there is no simple numerical relationship between the numbers of unidentified worm species, or the proportion of all worms in the fauna, and pollution of any but the must obvious, and demonstrably extreme, types." It is necessary to identify these worms to the species level to make full use of them as indicator organisms. Sampling variations are marked, but useful information on distribution of tubificid species can be extracted by mapping on the basis of order of magnitude differences (zone 1 = 1–9 worms/m^2, zone 2 = 10–99/m^2, zone 3 = 100–999/m^2 as the mean of three samples). Brinkhurst found that three categories of species could be distinguished:

(a) *Limnodrilus hoffmeisteri*, *L. claparedeanus*, and other *Limnodrilus*, *Tubifex tubifex*, and *Peloscolex mutisetosus* are most abundant in mouths of heavily polluted rivers.

(b) *Aulodrilus americanus* is most abundant in relatively clean waters of the open lake.

(c) *Limnodrilus udekemianus* occurs in shallow water regardless of pollution, and *Aulodrilus* spp. avoid some river mouths and not others.

Wright and Tidd[918] had earlier devised a simple index of pollution, which is still widely used, based on the total numbers of tubificids plus the mayfly nymph, *Hexagenia*:

no pollution	= 100 tubificids/m² and 100 *Hexagenia*/m²
light pollution	= 100-999 tubificids/m²
moderate pollution	= 1000-5000 tubificids/m²
heavy pollution	= 5000 tubificids/m²

This index is valid only for mud bottoms and *Hexagenia* is now absent from much of its former range in the Great Lakes.

Carr and Hiltunen[125] pointed out the inadequacy of using tubificid counts alone as the index of pollution. In the 1961 study the greatest worm density found anywhere in the western basin of Lake Erie was 15,000/m², and this was at the mouth of the Detroit River. However, according to Carr and Hiltunen "this high count does not in itself justify the designation of the mouth of the Detroit River as the most heavily polluted region because other less tolerant organisms were more abundant here than at certain stations with smaller worm counts." Hiltunen[360] pointed out that counts of aquatic oligochaetes are not very helpful. Not all aquatic oligochaetes are tubificids, but may in fact belong to other families (Naididae and Lumbriculidae) whose correlation with pollution has not been established. Occasionally, some oligochaete samples contain no tubificids.

The various species of oligochaetes fit Fjerdingstad's sparobic system in the following manner (Hiltunen[360]):

(a) saprobionts—*Limnodrilus cervix* and *L. maumeensis*.

(b) saprophiles and saproxenes— *Limnodrilus hoffmeisteri, Peloscolex multisetosus, Ilyodrilus templetoni*, and *Tubifex tubifex. tubifex*.

(c) saprophobes—*Stylodrilus heringianus, Peloscolex variegatus, Limnodrilus profundicola*, and possibly *Tubifex kessleri americanus. Tubifex tubifex* is present in many polluted areas and also in mesotrophic or eutrophic environments. Brinkhurst[93] found two oligochaetes that seem to indicate the influence of a polluting flow of the Saginaw River into Saginaw Bay. One of these is *Limnodrilus hoffmeisteri*. The other is a naidid, *Paranais litoralis*, which is restricted to salt or brackish water. Brinkhurst attributes its presence to the exceptionally high salinity of the Saginaw River, which at times has as much as 500 ppm chloride.

Limnodrilus hoffmeisteri is the characteristic tubificid of the highly polluted zone of Saginaw Bay (Schneider et al.[722]). Hiltunen[359] found that *Limnodrilus hoffmeisteri, L. cervix*, and *L. maumeensis* are highly restricted to inshore areas subject to organic pollution. Brinkhurst[93] proposed that the percentage of occurrence of *Limnodrilus hoffmeisteri* relative to all other oligochaetes might prove to be a useful indicator of organic pollution. Brinkhurst[91] lists the lumbriculid, *Stylodrilus heringianus*, as tolerant of a slight amount of pollution and Hiltunen[360] noted that the *Stylodrilus heringianus* is common throughout the Great Lakes except in areas that are excessively enriched or polluted. Both *Potamothrix moldaviensis* and *P. vejdovskyi* can tolerate some degree of organic enrichment. The naidid, *Nais elinguis*, is apparently associated with areas having much organic pollution, especially where *Cladophora* is present. Brinkhurst et al.[100] summarized the indicator values of various oligochaete species (asterisks indicate species restricted to upper Great Lakes):

(a) species restricted to grossly polluted areas: *Limnodrilus hoffmeisteri, L. cervix*, and *Peloscolex multisetosus*

(b) species often present in grossly polluted areas: *Branchiura sowerbyi, L. maumeensis*, and *L. claparedeianus*

(c) present in mesotrophic or eutrophic areas: *Aulodrilus* sp., *Potamothrix* sp., and *Peloscolex ferox*

(d) characteristic of oligotrophic areas: *Rhyacodrilus* sp.,* *Tubifex kessleri americanus*,* *Peloscolex variegatus*,* and *Stylodrilus heringianus* (Lumbriculid).

Brinkhurst[98] speculated on the significance of the pollution-tolerant species of tubificids in the overall problem of eutrophication: "They may prove to be beneficial where they are acting as sludge converters in situations where we have neglected to undertake the task ourselves. They may, however, promote eutrophication and be the object of control measures where a reversal of eutrophication is seriously undertaken." In other words, these worms may be involved in recycling into the water nutrients that otherwise would become fixed in the sediments.

(2) Chironomid Larvae

Brundin[109] emphasized the importance of midge larvae as sensitive indicators of trophic conditions in lakes. He proposed a "bottom faunistic lake-type" system based on the predominant chironomids present:

(a) ultraoligotrophic, deep—*Heterotrissocladius subpilosus* lakes
(b) ultraoligotrophic, shallow—*Tantytarsus-Heterotrissocladius* lakes
(c) moderately oligotrophic—*Tantytarsus lugens* lakes
(d) mesotrophic — *Stictochironomus-Sergentia* lakes
(e) eutrophic—*Chironomus* lakes
(i) moderately eutrophic—*Chironomus anthracinus* lakes
(ii) strongly eutrophic—*Chironomus plumosus* lakes.

Brinkhurst et al.[100] used chironomid larvae as indicators of trophic conditions in lakes by another system. They used the following trophic condition equation:

$$\text{Trophic Condition} = \frac{n_1 + n_2}{n_0 + n_1 + n_2}$$

In this equation, n_0, n_1, and n_2, are the number of species found in the lake which have a trophic index value of 0, 1, and 2, respectively, according to the following scheme:

(a) pollution intolerant (n_0) taxa (index value = 0): *Monodiamesa bathyphila, Protanypus forcipatus, Potthastia longimanus, Heterotrissocladius subpilosus, Paracladopelma obscura, Tantytarsus* sp., *Micropsectra* sp.

(b) moderately tolerant (n_1) taxa (index value = 1): *Demicryptochironomus vulneratus, Paralauterborniella nigrohalteralis, Stictochironomus* sp., *Xenochironomus* sp., *Ablabesmyia* sp., and *Thienamannimyia* group

(c) pollution tolerant (n_2) taxa (index value = 2): *Chironomus* sp., *Cryptochironomus* sp., *Microtendipes pedellus, Procladius denticulatus, Procladius bellus*, and *Coelotanypus concinnus*.

The theoretical minimum value is 0 (extreme oligotrophy) and the maximum is 2.00 (extreme eutrophy). On this basis, Brinkhurst et al.[100] calculated the following trophic conditions for some of the Great Lakes: Lake Huron, Georgian Bay, 0.13; Lake Ontario, 1.07; Lake Erie, Eastern Basin, 1.67; Lake Erie, Central Basin, 1.91; and Lake Erie, Western Basin, 2.00.

The value of chironomid larvae as local pollution indicators is questionable. Brown[106] could find no correlation between chironomid larvae and pollution influences from the Maumee River, using identifications only to levels higher than species. He concluded that the index value of these larvae rests with specific identifications. Carr and Hiltunen[125] found no consistent quantitative correlation of midge larvae and tubificids.

Chironomus larvae were abundant in heavily polluted areas, especially if the dissolved oxygen was low. *Procladius* (mostly *P. bellus)* was more widely distributed, and was most abundant where tubificids were numerous but only because it feeds on them. The highly polluted part of Saginaw Bay was characterized by *Chironomus plumosus, C. decorus* and *Procladius* sp., but *Chironomus* spp. were also found in the moderately polluted and unpolluted areas of the bay (Schneider et al.[722]).

Chironomus attenuatus is a highly adaptable species frequently found in polluted areas as well as unpolluted areas so it is a poor indicator (Curry[175]). This midge larva has a wide range of experimentally determined tolerances:

(a) wide range of temperature tolerance
(b) wide range of pH tolerance
(c) tolerance of anaerobic conditions
(d) tolerance of high levels of dissolved CO_2
(e) tolerance of high salinities
(f) tolerance of a wide range of sediment types.

Chironomus plumosus has narrower tolerance limits which tend to restrict it to polluted areas. Such evidence seems to indicate that this pollution indicator is excluded from cleaner areas by its own physiological tolerances rather than by competition with pollution intolerant species.

Adams and Kregear[4] found abundant *Chironomus* sp. at a location in Lake Superior having a high percentage of organic debris. *Calopsectra* and *Pentaneura* were also present. The correlation of *Chironomus* and *Pentaneura* with large accumulations of organic material has been noted in other studies.

(3) Mollusca

Sphaerium transversum occurs in both the polluted and marginally polluted sections of the Maumee River (Brown[106]) but is most abundant in the latter environment. Carr and Hiltunen[125] also note that *Sphaerium transversum* appears to be highly pollution tolerant since its distribution coincides with that of oligochaetes. *S. corneum,* also generally considered to be a pollution tolerant species, was found to be less tolerant than *S. transversum*.

With regard to mussels, Carr and Hiltunen[125] said "the presence of naiads is generally considered to indicate clean water." They are present in the open lake portion of Lake Erie.

Snails are generally not tolerant of highly polluted water. Operculate snails are particularly scarce in polluted areas except for *Valvata sincera* which seem to be positively correlated with high density occurrence of oligochaetes (Carr and Hiltunen[125]). The snail, *Bulimus tentaculata*, is also characteristic of the marginally polluted zone of the Maumee River (Brown[106]). Snails are abundant in the open lake portion of western Lake Erie.

(4) Amphipods and Isopods

Cook and Powers[163] stated: "It is well known that members of family Tubificidae (sludgeworms) prefer a habitat of organic sediment. Not as well defined, but generally conceded is the fact that Amphipoda (aquatic scuds) favor clean, clear water and a lake bottom of sand and gravel." However, Carr and Hiltunen[125] said: "The value of this amphipod (*Gammarus*) as an indicator of environmental conditions is little understood. It does not tolerate severe conditions but is able to withstand some types of pollution." Schneider et al.[722] found *Gammarus* to be concentrated in the zone of moderate pollution in Saginaw Bay whereas *Pontoporeia affinis* dominated in unpolluted areas.

The isopods *Asellus communis* and *Lirceus lineatus* are scavengers and are thus largely restricted to shallow enriched areas with much plant debris (Adams and Kregear[4]).

(5) Ephemeroptera

Mayfly nymphs of the genus *Hexagenia* are indicators of unpolluted waters where the bottom is mud (Wright[917]). *Hexagenia* is quite intolerant of low dissolved oxygen (Britt[101]). Pollution tolerance, however, is a matter of degree, and *Hexagenia* is tolerant of some pollution. It is extremely abundant in Lake St. Clair and occurs in moderately polluted areas in Saginaw Bay.

(6) Hirudinea

Leeches are tolerant of moderate degrees of pollution, tending to be mesosaprobic rather than polysaprobic (Carr and Hiltunen[125]).

(7) Trichoptera

Caddisfly larvae are considered by Carr and Hiltunen[125] to be "clean water" organisms.

(8) Chaoborus

Phantom midge larvae are highly tolerant of anoxic or nearly anoxic conditions in the hypolimnia of organically enriched ponds and lakes.

(9) Nematoda

Nematodes are generally found where organic debris is abundant (Adams and Kregear[4]).

8.2.3 Faunal Gradients

8.2.3.1 Lake Superior

There are three faunal environments in the eastern end of Lake Superior: boundary, shoal, and pelagic (Adams and Kregear[4]). The boundary environment consists of relatively shallow (less than 60 m to 90 m depth) areas of sand and rock along the south shore. The shoal environment is also shallow, but the shoals are isolated from land by intervening stretches of deep water. The shoal environment is an area of considerable sediment instability. The pelagic environment comprises all the deep-water areas, including a series of submarine canyons as deep as 370 m. The benthic communities of these environments are significantly different (Figure 4–220), although *Pontoporeia affinis* is found in all three. The boundary environment is the most diverse, much of which is associated with occurrence of organic detritus or attached vegetation. The shoal benthos are the least diverse, probably reflecting the relative uniformity and harshness of this environment in Lake Superior. Benthos from pelagic environment are typical of lake bottoms receiving minimal enrichment.

8.2.3.2 Lake Michigan

Oligochaete populations are concentrated at the southern end of Lake Michigan and the amphipod populations are concentrated in nearshore areas in northerly portions of the lake (Powers and Robertson[625]) (Figure 4–221 A&B), producing a south to north gradient in the ratio of amphipods to oligochaetes (Figure 221C). Distribution maps for the pollution-tolerant tubificids, *Peloscolex multisetosus* and *Limnodrilus cervix*, essentially correspond to the locations of the largest cities on the Great Lakes with the exception of Chicago (Brinkhurst[92]). Chicago is unique in that the sewage effluents are diverted away from

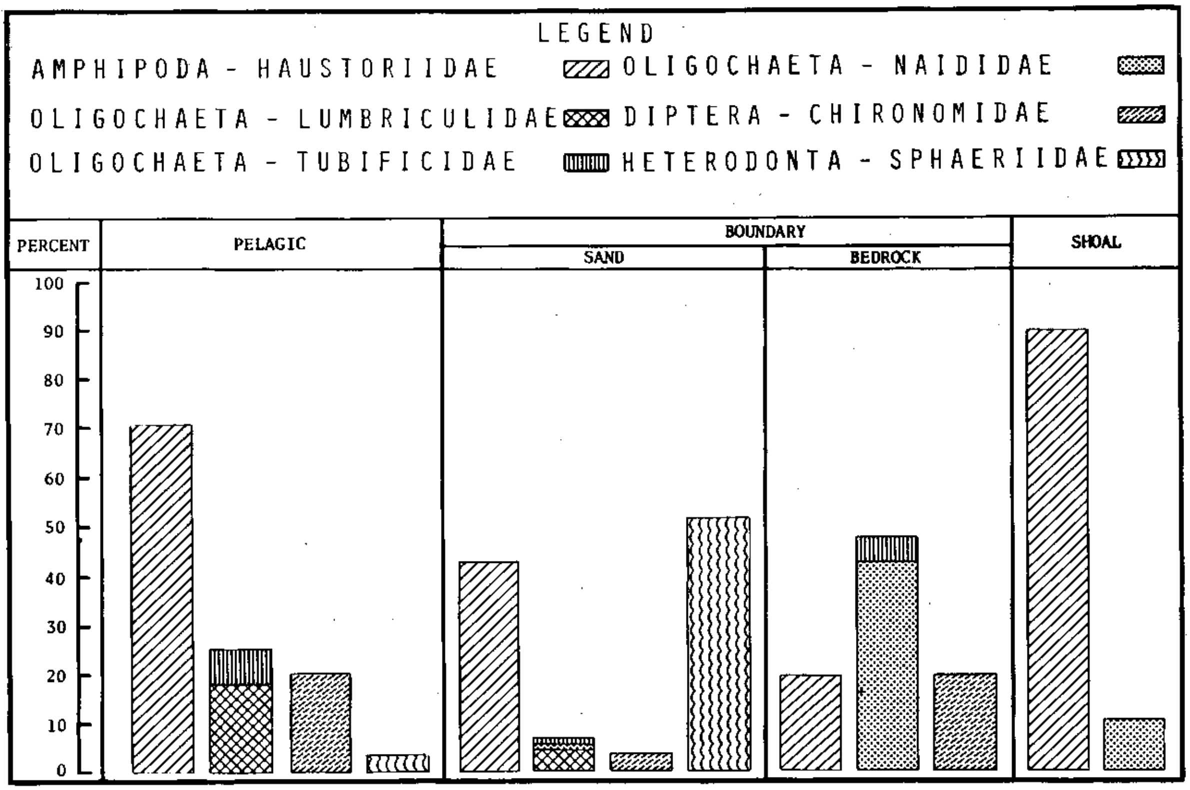

FIGURE 4–220 Faunal Composition of Eastern Lake Superior Biotypes

From Adams and Kregear, 1969

Lake Michigan into the Illinois River drainage system. The abundance of oligochaetes in southern Lake Michigan can be accounted for by the other cities in the Chicago area complex.

Total benthic production, as measured by biomass, is apparently constant within given depth ranges throughout the lake regardless of local dominance of different categories of organisms (Powers and Robertson[625]) (Figure 221D).

The only information on the zooplankton of Lake Michigan comes from Eddy,[234] who indicated that there are no qualitative differences in the plankton in various parts of the lake because of alleged homogeneity in that lake. The study did not include any quantitative analysis of relative abundances of various categories. It is unlikely that anyone today would agree that plankton gradients do not exist in Lake Michigan.

8.2.3.3 Lake Huron

The distributions of amphipods and oligochaetes in Lake Huron as presented here (Figures 4–222 and 4–223) are based on extensive sampling by Schuytema and Powers.[725] In general, more varied species are present in nearshore areas than either in the open lake or in Saginaw Bay. Relatively dense populations of amphipods and oligochaetes occur in the North Channel. This is contrary to the findings of Teter,[788] who found the amphipod *Pontoporeia affinis* to prefer deeper waters in the northern part of Lake Huron. Dramatic faunal gradients occur in Saginaw Bay where Schuytema and Powers found that *Pontoporeia affinis*, the predominant amphipod near the mouth of the bay, was gradually supplanted by *Gammarus* toward the interior. No *Gammarus* were found, however, near the mouth of the Saginaw River and few were to be found 15 miles out into the bay. Oligochaetes showed a contrasting distribution, being most abundant near the Saginaw River and other nearshore areas in the bay where amphipods were not common. On the basis of total numbers of benthic organisms, or biomass, Schuytema and Powers concluded that Saginaw Bay is the most productive part of Lake Huron, followed by the nearshore areas of the lake and, finally, the open lake. Brinkhurst[93] did a detailed analysis of oligochaete distribution in Saginaw Bay with results simi-

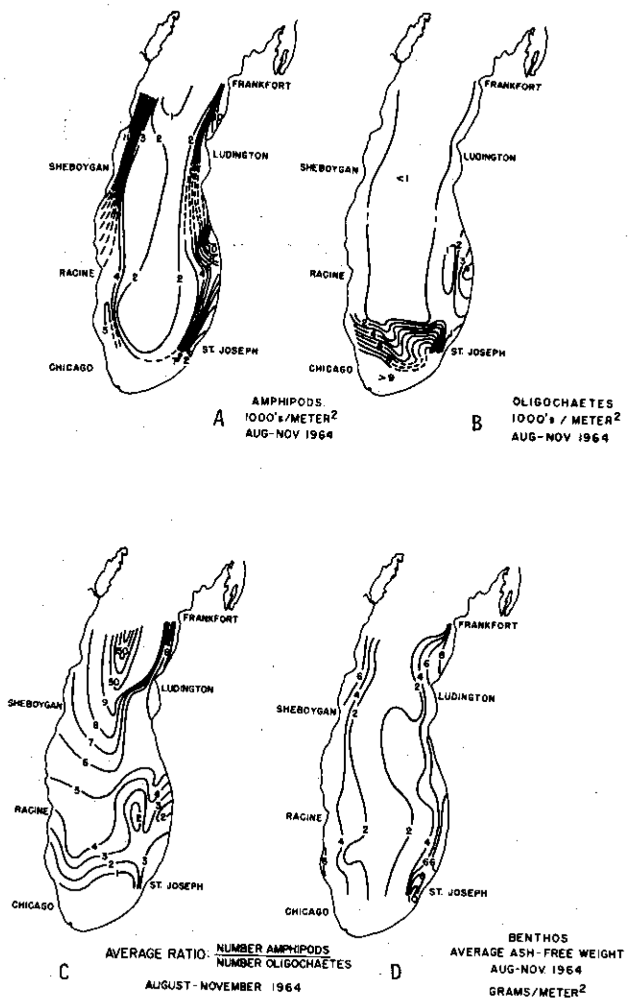

FIGURE 4–221 Average Number of Amphipods (A) and Oligochaetes (B); Ratio of Number Amphipods/Number Oligochaetes (C); and Benthos in Southern Lake Michigan (D); August to November, 1964

From Powers and Robertson, 1965

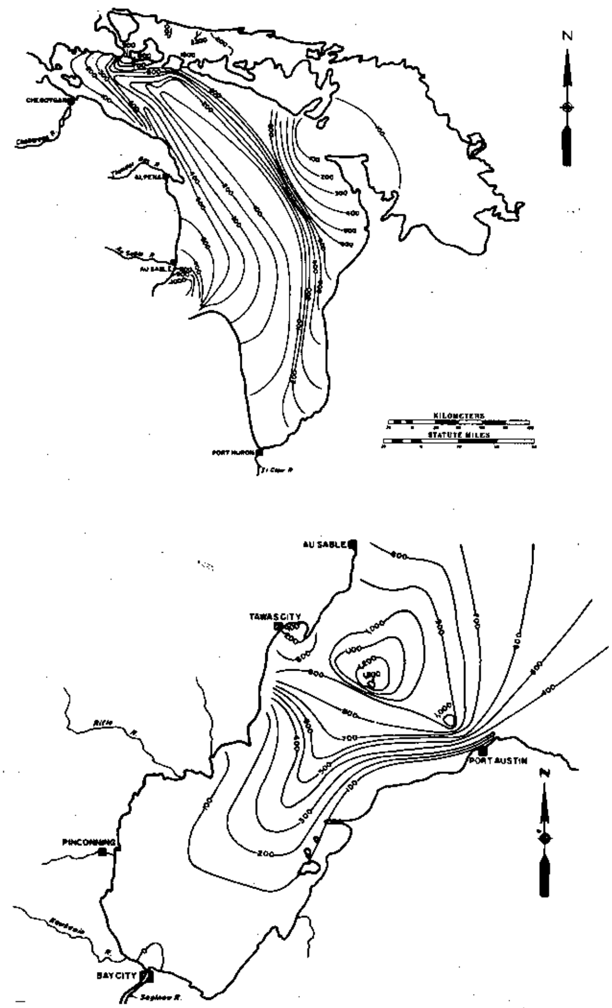

FIGURE 4–222 Mean Populations of Amphipods (numbers/m²) in Lake Huron, June to August, 1965; and in Saginaw Bay, April to September, 1965

lar to those of Schuytema and Powers. *Limnodrilus* spp., especially *L. hoffmeisteri*, are concentrated near the mouth of the Saginaw River. The distribution of this pollution-tolerant worm indicates organic pollution from the river; yet, correlation with the distribution of river sediments was poor. However, *Limnodrilus hoffmeisteri* does correlate fairly well with flow of the saline river water into the bay. Schneider et al.[722] divided Saginaw Bay into three zones from the Saginaw River to the lake. Productivity measured as total biomass of benthos is highest (4.51 g/m²), and lowest in the outer zone (3.46 g/m²). This is true regardless of the zone in which the reef is located. The low biomass is attributed to the relatively unstable substrate overlying the reef. *Gammarus* is most abundant in the middle zone, which agrees with observations by Schuytema and Powers. Chironomids and *Hexagenia* are generally most abundant in the inner zone along the northwest shore of the bay. However, chironomids of the sub-family Diamesinae are restricted to the outer zone.

8.2.3.4 Lake Erie

The three basins of Lake Erie are fairly distinct biotically. The oligochaetes are divisible into three associations which correspond

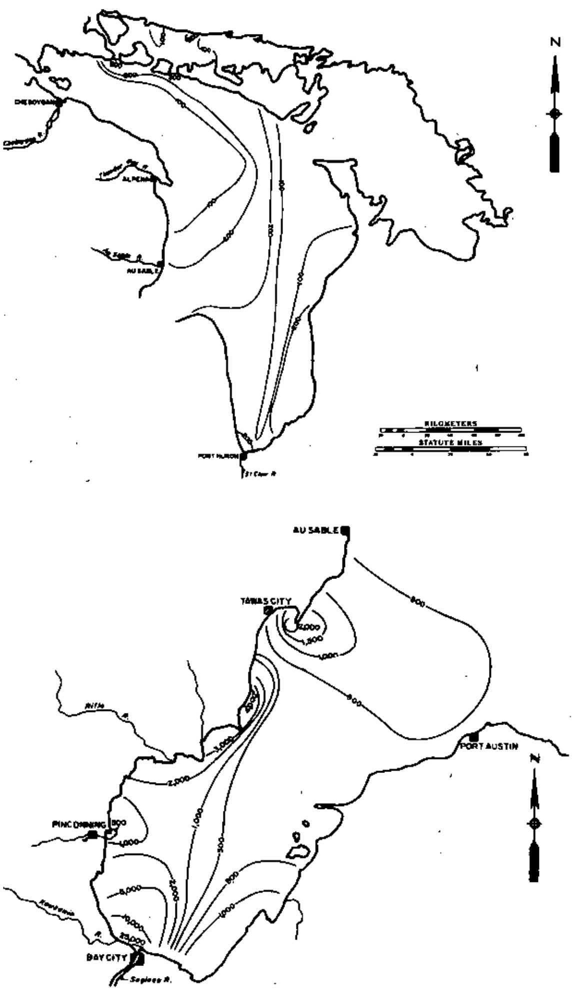

FIGURE 4–223 Mean Populations of Oligochaetes (numbers/m²) in Lake Huron, June to August, 1965; and in Saginaw Bay, April to September, 1965

fairly well with the three basins and decrease in abundance from west to east (Figure 4–224) (Brinkhurst et al.;[100] Brinkhurst[92]).

One of the most striking aspects of the chironomids of Lake Erie is a significant difference in the species composition in the various parts of the lake (Figure 4–225). As with the oligochaetes, the distribution of chironomid larvae indicate a west to east gradient although the slope is reversed (Table 4–59).

The distribution of sphaeriids in Lake Erie does not show distinct longitudinal gradients (Figure 4–226) as is the case with oligochaetes and chironomids (Table 4–59), but it apparently reflects depth preferences for some species. For example, *Sphaerium striatinum* is largely restricted to shallow areas including the western basin and the ridge that marks

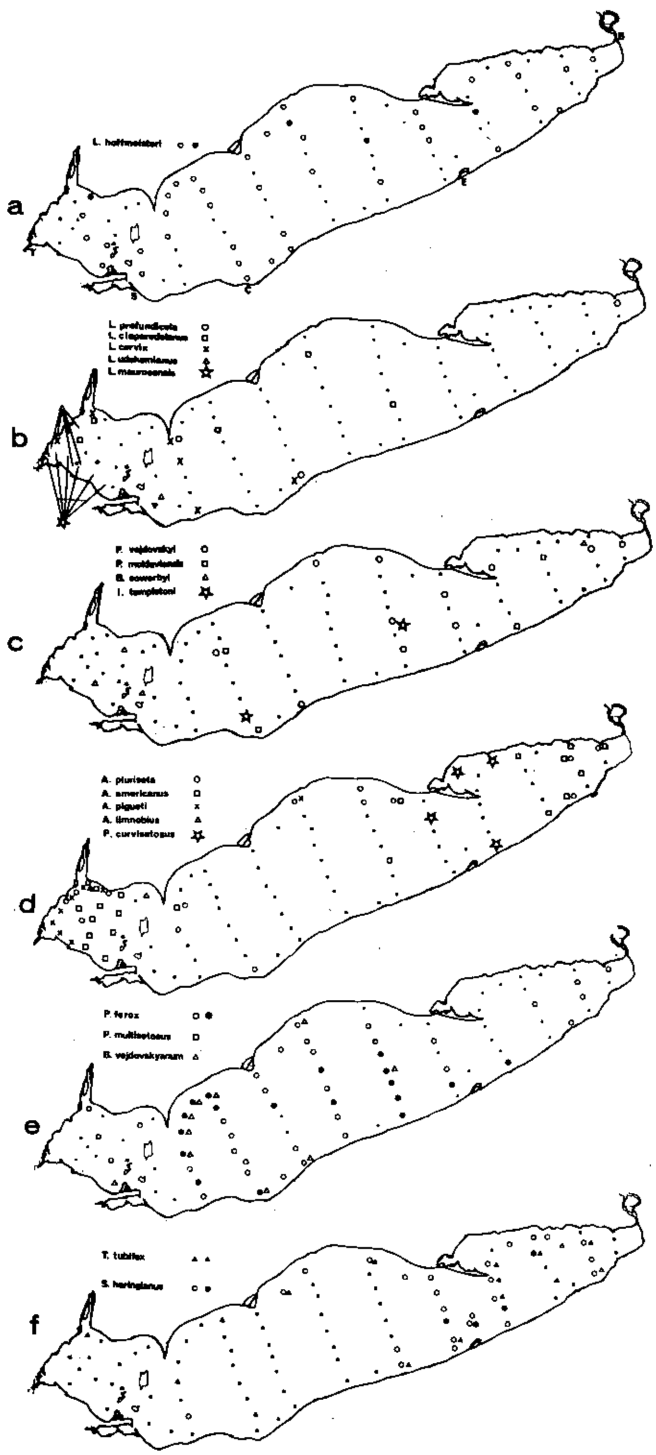

FIGURE 4–224 Distribution of Oligochaetes in Lake Erie. A single sample was taken from each station on each of 5 cruises. Dots indicate that the organism was absent from the sampling station. Open symbols indicate less than 10 organisms per sample. Closed symbols indicate 10 or more organisms in at least one sample.

From Brinkhurst et al., 1968; Brinkhurst, 1969

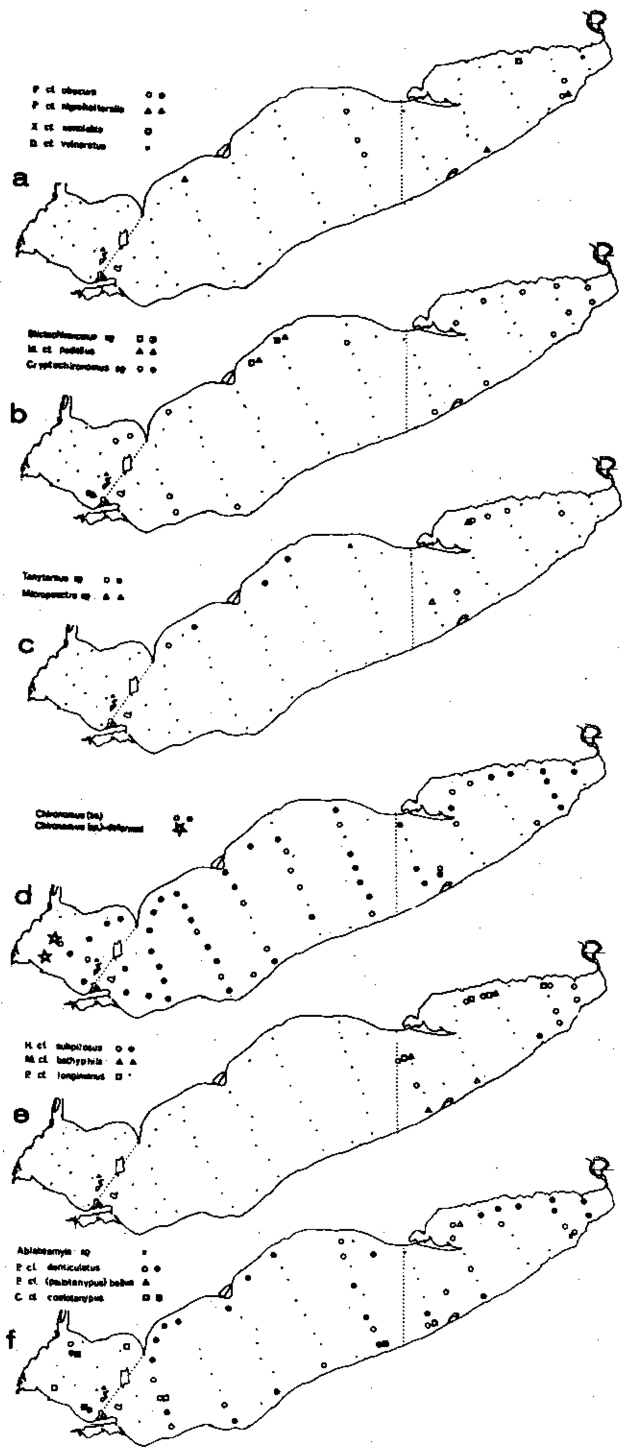

FIGURE 4–225 Distribution of Chironomids in Lake Erie. A single sample was taken from each station on each of 5 cruises. Dots indicate that the organism was absent from the sampling station. Open symbols indicate less than 3 organisms per sample. Closed symbols indicate 3 or more organisms in at least one sample.

From Brinkhurst et al., 1968; Brinkhurst, 1969

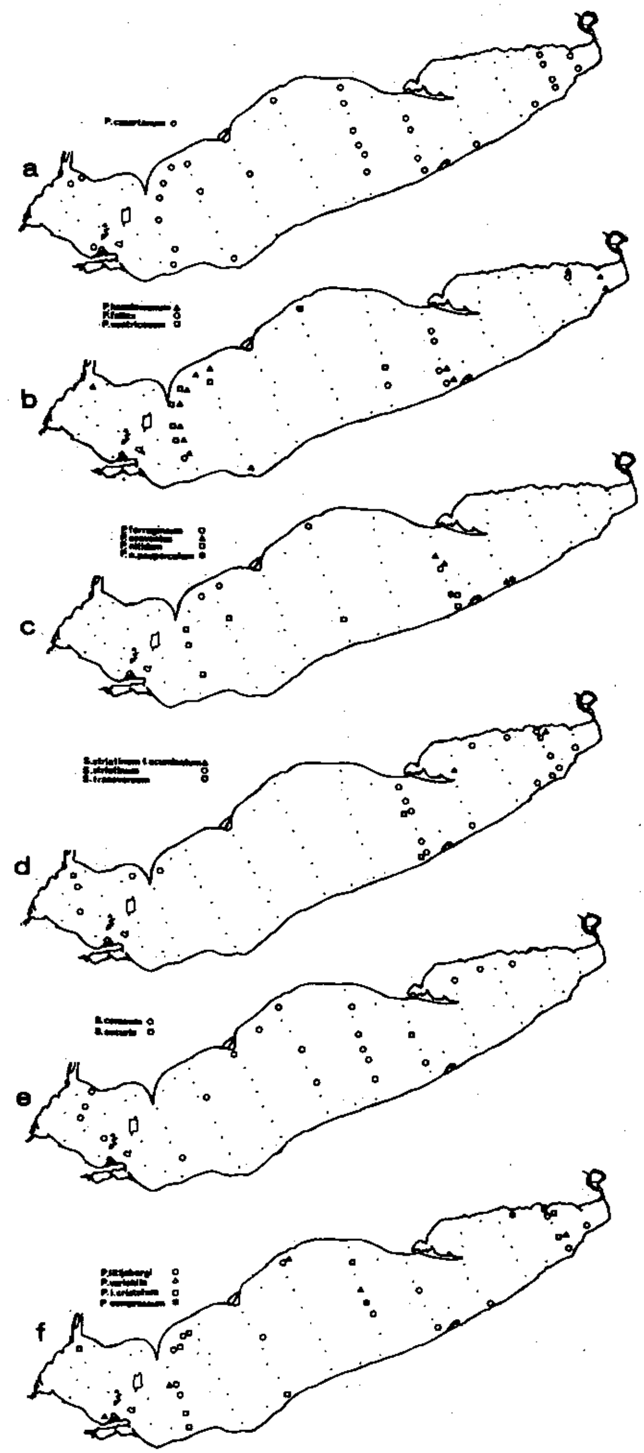

FIGURE 4–226 Distribution of Sphaeriids in Lake Erie. A single sample was taken from each station on each of 5 cruises. Dots indicate that the organism was absent from the sampling station. Open symbols indicate less than 10 organisms per sample. Closed symbols indicate 10 or more organisms in at least one sample.

From Brinkhurst et al., 1968; Brinkhurst, 1969

TABLE 4–59 Four Major Groups of Benthos in Lake Erie, April-August, 1967

Taxon	Percentage of Total Organisms Western Basin	Central Basin	Eastern Basin
Tubificidae	86	55	34
Chironomidae	6	23	24
Amphipoda	0	6	27
Pelecypoda	7	9	9

SOURCE: Veal and Osmond, 1968.

the division between the eastern and central basins.

Veal and Osmond,[846] using nearshore data, indicated diversity within benthic groups in Lake Erie from east to west. Diversity, in its most simple form, is the ratio of species to individuals present:

$$\text{Diversity} = \frac{\text{Number of Species}}{\text{Number of Individuals}}$$

Diversity generally tends to decrease in harsh environments. For example, subarctic environments have lower diversity than temperate environments, and polluted areas have lower diversity than unpolluted areas. Although Veal and Osmond used the ratio of the average number of genera instead of species to the average number of organisms per sample, the principle remains the same. Diversity decreases generally toward the western basin except for Long Point (Figure 4–227) which, because it is actively accreting, represents a harsh environment.

Zooplankton occurrence and abundance also differ between the three Lake Erie basins. Davis[197] points out that Wright and Tidd[918] found more than 2.5 times as many zooplankton of certain kinds in the western basin than he did two decades later in the Cleveland Harbor area. Davis' population estimates in Cleveland Harbor, however, were comparable to or exceeded those of Chandler[131] in the western basin. Although this apparent discrepancy could be explained by noting that all areas of the lake probably increased in productivity in the ten years between studies, it does not support the proposition that the western basin is highly productive compared to the remainder of the lake. Davis also pointed out that a high biomass of plankton in itself is not

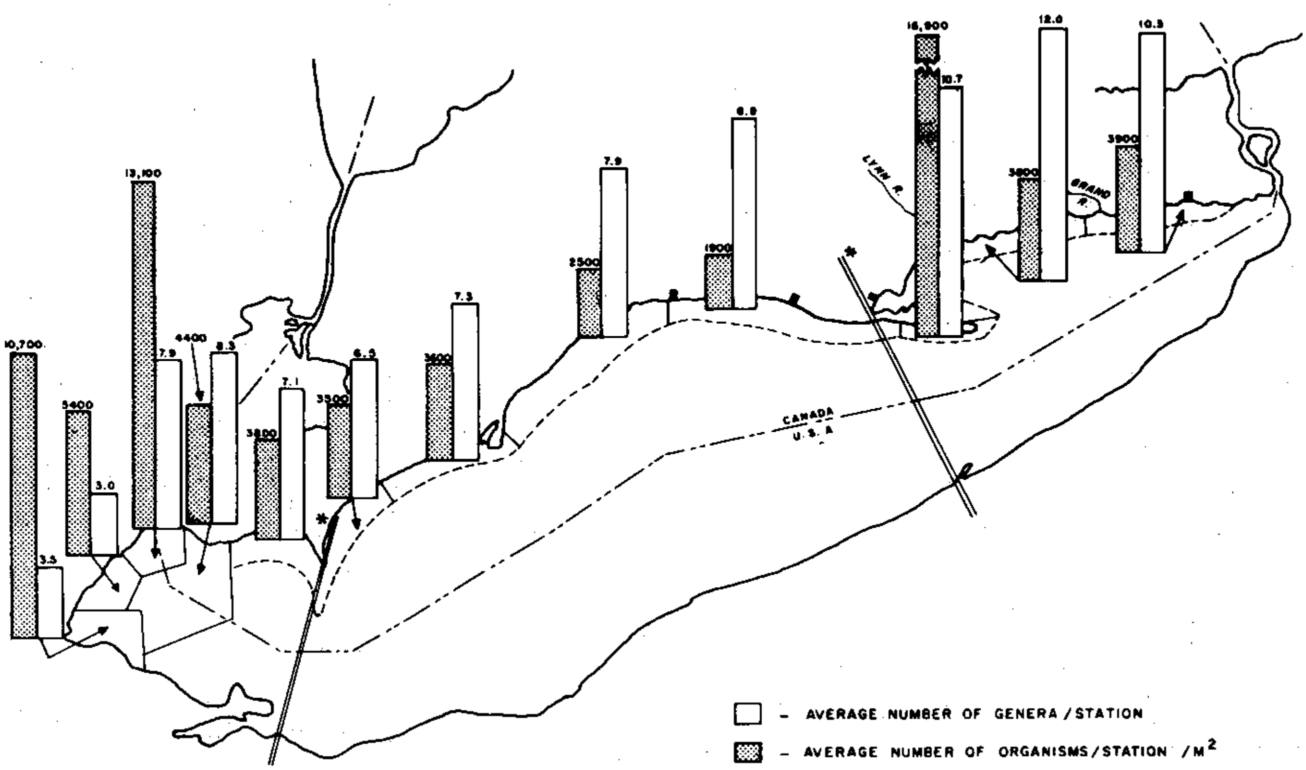

FIGURE 4–227 Average Number of Genera and Average Number of Organisms per Station in Lake Erie

After Veal and Osmond, 1968

conclusive evidence of high productivity. Such data, considered in isolation, give no information about the rates at which energy is being utilized and new living matter manufactured. Determination of phytoplankton production rates, rate of supply of allocthonous organic material (both of which are easier to measure than zooplankton production), and long-term patterns of zooplankton biomass levels are needed to resolve the question.

Differences in species distributions among the Lake Erie basins are more obvious than quantitative differences. Plankton data from a transect line extending the length of the lake during the month of July indicate the heterogeneity of the lake (Davis[192]). The western basin was richer in both number of species and abundance of rotifers than the rest of the lake. It also supported 2.5 times as many adult daphnids than the central basin and 3.8 times as many as the eastern basin. Large *Bosmina* populations were primarily found in the western basin. The western basin zooplankton also almost exclusively included such important species as *Daphnia retrocurva, Cyclops vernalis*, and the rotifer *Branchionus angularis*. Some species, such as the protozoan *Vorticella* and the various copepods were more abundant in other parts of the lake, and some species, such as *Diaptomus oregonensis*, *Cyclops bicuspidatus* and *Polyarthra vulgaris*, were virtually nonexistent in the western basin. Davis reported that *Daphnia pulex* was apparently more dominant in the eastern and central basins than in the western. Davis[192] was unable to determine whether the detailed differences among the basins are the result of a retarded development in some of the basins as compared to others, or whether there are real quantitative and qualitative differences, reflecting basically different ecosystems in the three basins.

Significant benthic faunal gradients exist within the western basin. Such gradients can be expected in the other basins as well, but they have not been clearly identified as is the case with the western basin where the majority of Lake Erie studies have been focused. Probably the earliest indication of gradients in the western basin was the work of Wright and Tidd[918] who found large populations of *Limnodrilus* and *Tubifex* near the mouths of the Maumee, Raisin, and Detroit Rivers and an absence of *Hexagenia* nymphs in the same areas. Along a transect from the mouth of the Maumee River into Lake Erie based on 1929–30 data (Figure 4–228), the number of tubificids per square meter declined and

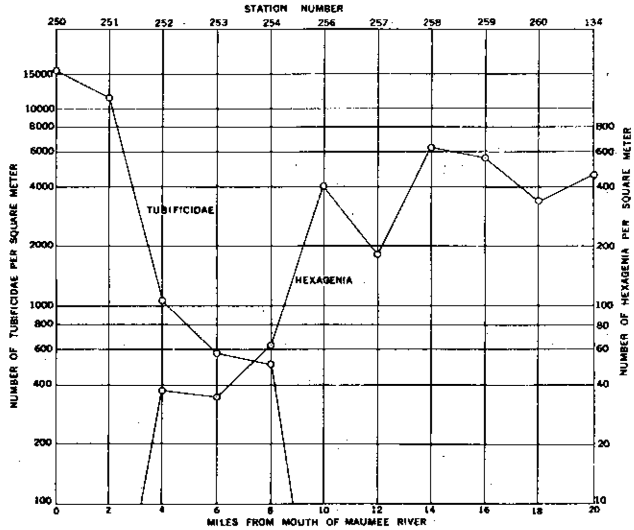

FIGURE 4–228 Abundance of Tubificidae and *Hexagenia* Along a Transect from the Mouth of the Maumee River Twenty Miles into Lake Erie
From Wright, 1955

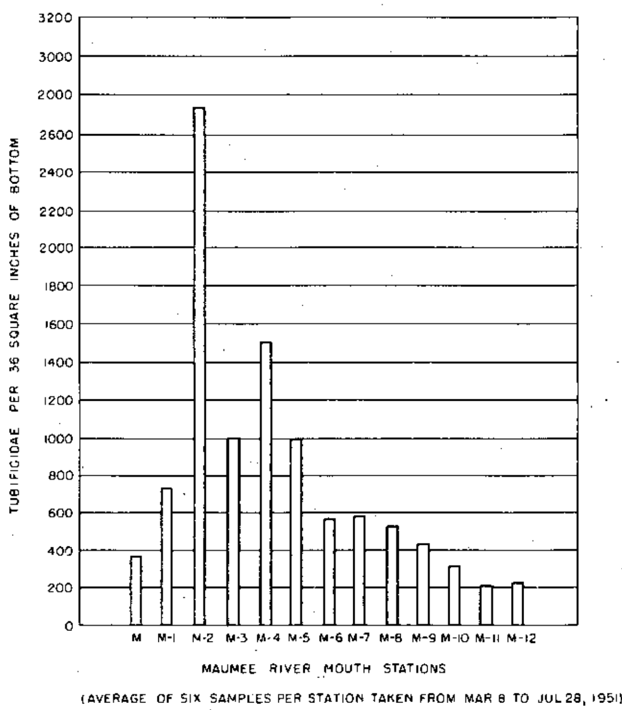

FIGURE 4–229 Tubificid Peaks at Maumee River Mouth Stations

Hexagenia increased lakeward (Wright[917]). Brown[106] presented similar data for the average population of tubificids collected in 1951 along a transect line beginning in the Maumee River and ending five miles out in the lake. These data (Figure 4–229) show a maximum population density of tubificids at

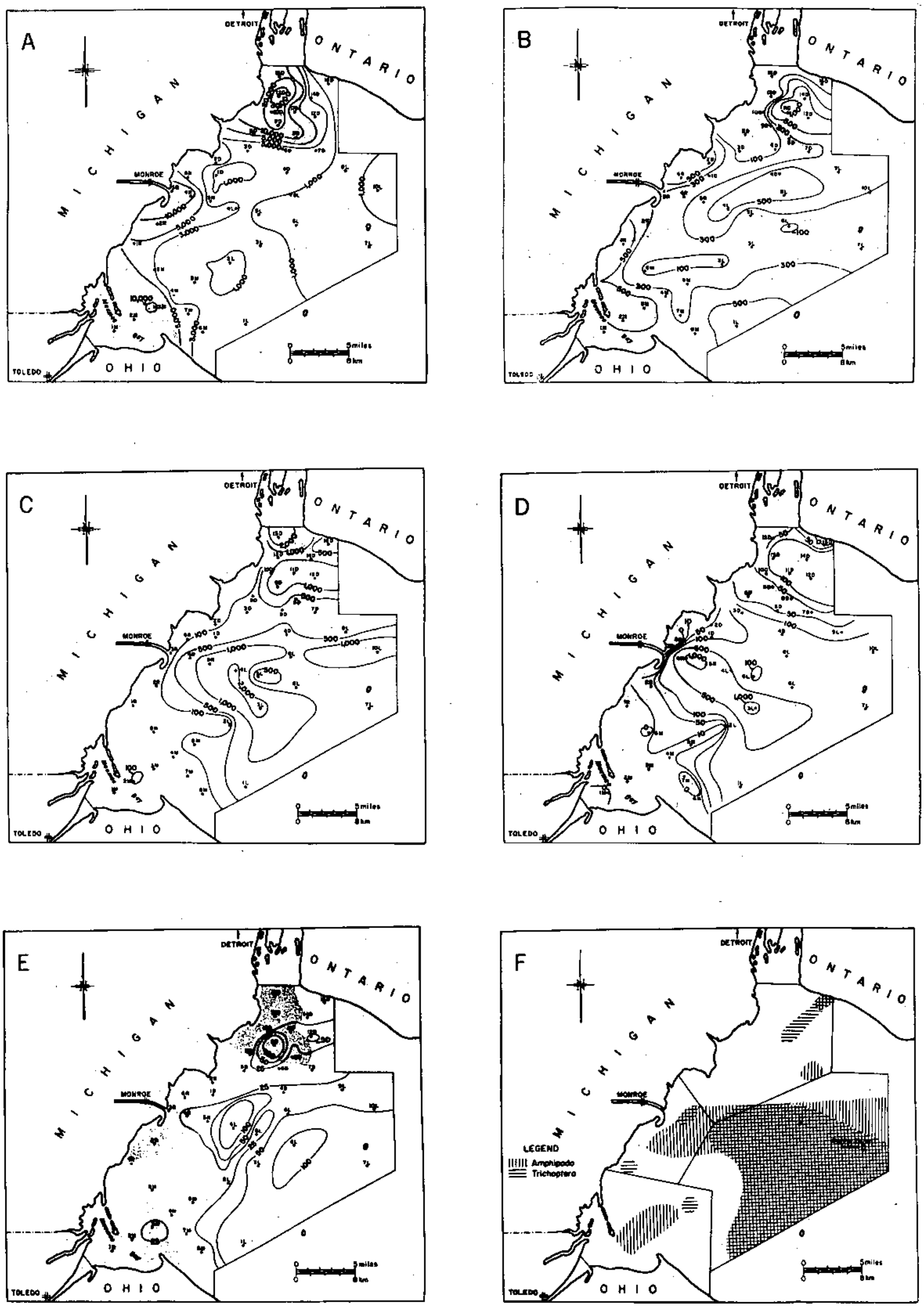

FIGURE 4-230 Distribution of Oligochaeta (A), Tendipedidae (B), Sphaeriidae (C), Gastropoda (D), Hirundinea (E), and Trichoptera and Amphipoda (F) in Western Lake Erie in 1961

From Carr and Hiltunen, 1965

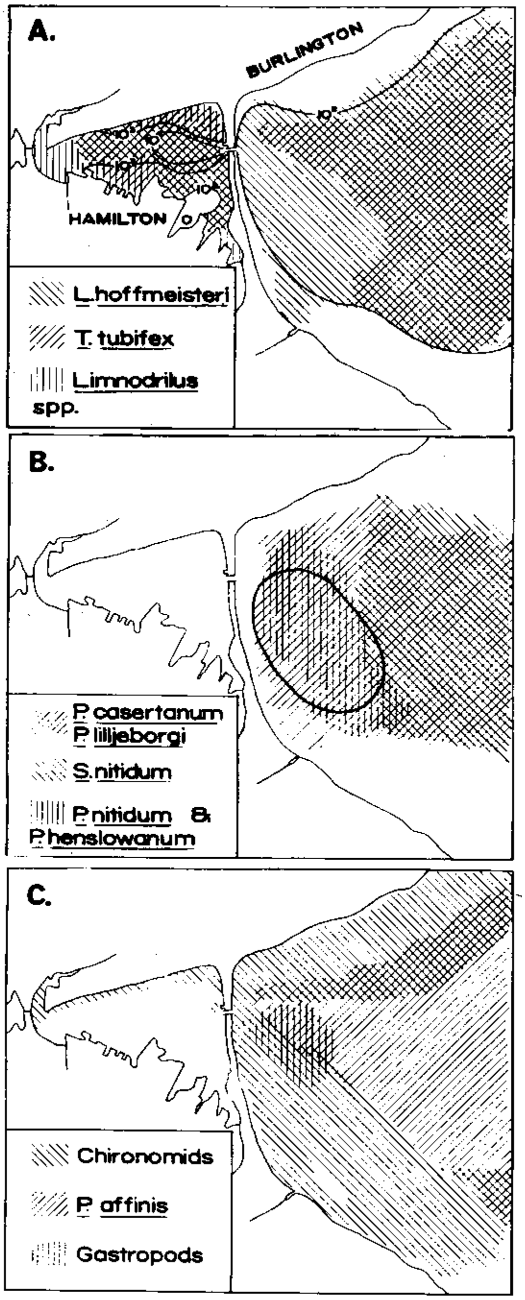

FIGURE 4–231 Distribution and Abundance (number/m²) of Some Macroinvertebrates in Hamilton Bay and Adjacent Lake Ontario. (A): Certain groups of Oligochaetes. The distribution of *Limnodrilus hoffmeisteri* is shown where it occurs as the only species of the genus present and also where it occurs with other members of the genus (shown as *Limnodrilus* spp.). (B): The most common sphaeriid clams, *Pisidium casertanum, P. lilljeborgi, P. henslowanum,* and *P. nitidum,* and *Sphaerium nitidum.* Total sphaeriids was greatest (250/m²) in the area circumscribed. (C): Chironomids, *Pontoporeia affinis,* and gastropods *(Valvata sincera* and *V. tricarinata).*

From Johnson and Matheson, 1968

the Toledo sewage disposal plant (Station M–2) and a decline in density lakeward. The two figures are not directly comparable since Brown expressed his populations as numbers per square foot (multiply by 9 to approximate Wright's data). Distribution of the major pollution-tolerant tubificids, *Limnodrilus hoffmeisteri, L. cervix, L. maumeensis* and *Peloscolex multisetosus* show their close relation to the three main rivers of the basin (Hiltunen[359]). Carr and Hiltunen[125] indicate a similar relationship with the distribution of all oligochaete species combined (Figure 4–230A), and also for chironomid larvae (Figure 4–230B), sphaeriids (Figure 4–230C), gastropods (Figure 4–230D), leeches (Figure 4–230E), trichoptera and amphipods (Figure 4–230F). None of these show the strong correlation to the river mouths seen in the oligochaete distribution, although chironomids and sphaeriids clearly favor lake areas influenced by rivers. Some species seem to correlate negatively with the rivers. Wood[913] identified *Hexagenia* nymphs in 1951–52 at all western basin stations except off the mouth of the Detroit River and in hard substrate areas near Point Pelee. In general, these nymphs occurred in greatest abundance in the eastern part of the western basin, away from the rivers. *Limnodrilus hoffmeisteri, L. cladaredeianus, L. cervix,* and L. *maumeensis* dominate the bottom fauna near the rivers with additional occurrence of *Tubifex tubifex* near the Detroit River (Brinkhurst et al.;[100] Brinkhurst[92]). *Aulodrilus* spp. *Potamothrix* spp., *Branchiura sowerbyi, Peloscolex ferox,* and *P. multisetosus* are the predominant tubificids in the open lake areas of the western basin.

Heterotrissocladius subpilosus is common in the eastern basin of Lake Erie, and absent in the central and western basins (Brinkhurst[92]). *Chironomus* spp. are most common in the western and central basins and least common in the eastern. *C. plumosus* is dominant in the western basin and *C. anthracinus* is dominant in the eastern basin.

Zooplankton also differs both quantitatively and qualitatively in the various parts of the western basin. Maumee Bay has the most abundant zooplankton populations followed in order by the Raisin River area, the Island area in the eastern part of the basin, and finally, by the Detroit River area (Wright and Tidd[918]). Low numbers of zooplankton in the Detroit River may be due to toxicity of Detroit River water or to other factors. The western basin is dominated by two water masses, the Maumee

River flow and the Detroit River flow (Jahoda[422]). These river water masses influence the distribution of zooplankton. *Diaptomus oregonensis*, and *D. minutus* are relatively unaffected, but *D. siciloides* definitely favors the Maumee water mass, and *D. sicilis* and *D. ashlandi* are abundant in the Detroit water mass. Jahoda also found that the lag in warming and cooling of the Detroit River imposes a lag on seasonal changes in plankton populations as compared to the Maumee River.

Studies in the central and eastern basins are less conclusive. Davis[193] described a gradient in phytoplankton and ciliate populations, from abundance nearshore to smaller populations lakeward into the central basin. This could be attributed to a pollution effect along the southern shore, or it could be due to a natural shore effect. Burkholder[115] reported higher populations of protozoans and rotifers in general in Long Point Bay and near Buffalo in the eastern basin. In addition to being relatively shallow, these areas are probably also enriched.

8.2.3.5 Lake Ontario

Hamilton Bay in the western end of Lake Ontario receives discharges from steel mills as well as domestic sewage effluent, and a definite toxic influence of the industrial wastes on the zoobenthos has been detected (Johnson and Matheson[434]). No macrobenthos are found in an area of about 2 km^2 where the Fe_2O_3 content of the sediments exceeds 25 percent. Elsewhere in the bay, *Limnodrilus hoffmeisteri* and *Tubifex tubifex* predominate on the organically enriched sediments and other *Limnodrilus* spp. occur on the less enriched sediments. The most favorable habitat for oligochaetes, in terms of biomass, is just inside the bay near the canal that connects to Lake Ontario. Worms here apparently benefit from both the sewage enrichment from the bay and the water from the lake. The distribution of various species in the lake shows an apparent influence of water from the bay (Figure 4–231), particularly *Limnodrilus hoffmeisteri*, *Tubifex tubifex*, *Pisidium casertanum*, *P. lilliborgi*, *P. nitidium*, and *P. henslowanum*, *Stylodrilus heringianus*, and various gastropods.

There are several more or less distinct zonal components of the Lake Ontario benthos (Brinkhurst[92]). *Tubifex tubifex*, *Limnodrilus hoffmeisteri* are especially abundant in grossly polluted areas, but not confined there, whereas *Illyodrilus templetoni*, *L. cervix*, *L. claparedeianus*, *L. udekemianus*, and *Peloscolex multisetosus* are confined to these areas. *Peloscolex ferox*, *Aulodrilus* spp., and *Potamothrix* spp. are characteristically distributed along the shoreline.

8.2.4 Evidence of Recent Changes in the Lakes

Changes in the distribution or abundance of organisms in a lake are generally regarded as the most sensitive measure of environmental change. Such changes are easier to interpret than physical and chemical changes alone and have more impact on public consciousness. Also, changes in occurrence or relative abundance of one species may have far-reaching effects on other species. The recent biotic changes, such as the appearance of the sea lamprey and the alewife in the Great Lakes, have generally been regarded as undesirable.

8.2.4.1 Lake Superior

Occurrence of *Diaptomus oregonensis* may be increasing in Lake Superior (Robertson[664]), although its existence had previously been reported there by Marsh.[513] Robertson[664] noted that *D. oregonensis* prefers the warmer waters of the southern Great Lakes, so its recent abundance in Lake Superior may relate to cultural development and consequent effects of thermal discharges into the lake.

8.2.4.2 Lake Michigan

Eddy,[234] comparing collections of zooplankton made in 1887–88 with his own made in 1926, concluded that there had been very little change in the plankton in the forty-year interval. As the earlier collections were not quantitative, this conclusion was based on species composition rather than abundance. Since then, a number of species have been found that may be recent faunal additions, including the copepods *Senecella calanoides* (first reported by Wells[880]), *Eureytemora affinis* (first reported by Robertson[664]), and *Cyclops vernalis* (first reported by Wells[880]). *C. vernalis* was reported as early as 1894 (Reighard[644]) from Lake St. Clair, the Detroit River, and Lake Erie. *Senecella calanoides* may have been found as early as 1898 in Lake Superior according to Juday,[440] so the appar-

TABLE 4–60 Density of Benthos in Saginaw Bay in Various Years (individuals/m²)

Benthos	1955	1956	1965
Amphipoda (Scuds)	123	200	330
Oligochaeta (Worms)	2,174	3,532	3,060
Sphaeriidae (Fingernail clams)	122	Trace	100
Chironomidae (Midge larvae)	424	294	360
Ephemeroptera (Mayfly nymphs)	63	9	1

SOURCE: Schneider, et al., 1969.

ently recent occurrence of these two species in Lake Michigan may only be increases in abundance. Wells[880] was also the first investigator to find the cladocerans *Eurycercus lamellatus* and *Daphanosoma branchyurum* in Lake Michigan. Bigelow[66] found *E. lamellatus* in Lake Erie and Smith[748] found it in Lake Superior; so this is another "addition" of questionable significance. The predacious cladoceran *Polyphemus pediculus* was first reported in Lake Michigan in 1960 by Wells.

Robertson[664] compared quantitative collections of calanoid copepods made in 1964 with similar collections made in 1954–55 by Wells[880] and 1964 populations were between those found in Lake Michigan in 1954–55 and those found in Lake Erie in 1956–57 by Davis.[193] Robertson suggests that this shift might reflect accelerated eutrophication of Lake Michigan.

Beeton[46] places some emphasis on the apparent replacement of *Bosmina coregoni* by *B. longirostris* as a parallel to the same change that occurred in Lake Zurich (Minder[546]) when that lake underwent rapid eutrophication. *Bosmina coregoni* has been recorded from Lake Michigan only by Eddy[234] who found it in abundance in both the 1887–88 and 1926–27 collections. Eddy also found *B. longirostris* and this has been the only *Bosmina* found in Lake Michigan since then by a number of investigators, although some only identified to genus (Wells;[880] McNaught;[525] Norden;[581] Gannon and Beeton[282]). The significance of this change is questionable because *B. longirostris* was identified in oligotrophic Lake Huron as early as 1915 (Sars[700]) and in Lake St. Clair in 1894 (Birge[68]), and *B. coregoni* was identified in Lake Erie in 1929 (Wilson[899]), 1933 (Ewers[250]) and in 1968 (Davis[192]). Beeton[46] also suggests the *Diaptomus oregonensis* may have increased in importance recently since it was not found by Eddy[234] but was abundant in Wells'[880] collections. It has been found more recently by Robertson.[664] However, it was also recorded from Lake Michigan in the nineteenth century (Marsh[514]).

A few signs of probable changes are also seen among the Lake Michigan benthos. Typical oligotrophic, profundal benthos were superseded at the south end of Grand Traverse Bay by species characteristic of small eutrophic lakes, such as *Chironomus anthracinus* and *Chaoborus punctipennis* (Henson.[343]

8.2.4.3 Lake Huron

The decline of *Hexagenia* (mayfly nymphs) that occurred in the western basin of Lake Erie may also have occurred in Saginaw Bay of Lake Huron. Schneider et al.[722] compared 1956 collections with those made in 1955 by Surber[768] and in 1965 by Schuytema and Powers[725] (Table 4–60). Fingernail clams also declined in 1956, but recovered by 1965. These data suggest that there was an environmental catastrophe in 1955 or 1956 from which the clams recovered, but the mayfly nymphs did not. Schneider et al.[722] suggested that the cause for *Hexagenia* decline in Saginaw Bay was depletion of dissolved oxygen at the bottom due to organic overenrichment and stagnation. *Hexagenia* distribution in the bay in 1956 (Schneider et al.[722]) clearly suggests the influence of the Saginaw River, which enters at the south end of the bay (Figure 4–232). Schneider et al.[722] also compared the wet-weight biomass of the total benthos for the three years mentioned. The biomass was 15.1 g/m² (13 g/yd²) in 1955 and 11.9 g/m² (10 g/yd²) in

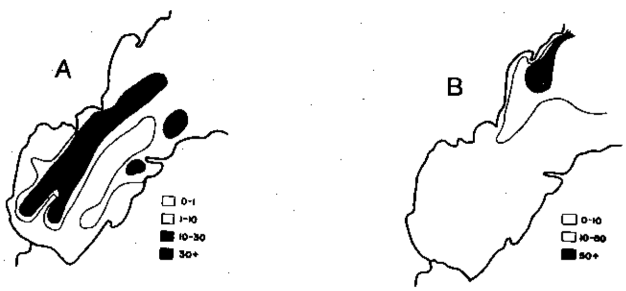

FIGURE 4–232 Average Number of *Diamesinae* per m² on June 7, 1956 (A); and *Hexagenia* per m² During 1956, in Saginaw Bay.
Schneider et al., 1969

1965, indicating no significant change. However, in 1956, the year of the disaster, the biomass was only 4.4 g/m^2 (3 g/yd^2).

Senecella calanoides (Robertson[664]) and *Eurytemora affinis* (Faber and Jermolajev[252]) may be recent zooplankton additions to the Lake Huron fauna.

8.2.4.4 Lake Erie

Britt[101] reported a disaster among the burrowing mayfly nymphs, *Hexagenia rigida* and *Hexagenia limbata,* in the western basin in early September, 1953. Dredge samples on September 5th contained 465 dead nymphs per m^2 and none living. Chironomid larvae also suffered 33 percent mortality, but sphaeriids and leeches seemed unaffected. Britt concluded that the nymphs had been dead only a few days, as they would decompose quickly at the high temperatures then prevailing. Subsequent sampling from September 14 to September 26 and on November 13 revealed *Hexagenia* in only 52 percent of the samples and none at the area where the dead nymphs were taken on September 5. The average density of *Hexagenia* in these collections was 55.3/m^2. Britt compared this with the 1929–30 sampling of Wright and Tidd[918] who found 283 and 510 nymphs/m^2 in 1929 and 1930, and 1951–52 data of Wood[913] who gives the mean density of *Hexagenia* in the western basin as 235/m^2. Brown[106] had found a mean *Hexagenia* density in the open lake waters of the western basin of 75.6/yd^2 in 1950. *Hexagenia* nymphs apparently were in a severe die-off period although the onset of this process may not have been sudden. Britt attributed the mortality to depletion of dissolved oxygen near the bottom. Dissolved oxygen was as low as 0.7 ppm at the station where all *Hexagenia* were dead during a period of stagnation in the western basin. It took a rare period of stagnation in the ordinarily well-mixed western basin to dramatically show what pollution can do to lake fauna.

In 1954 Britt[102] found that mayfly nymph populations were recovering in the western basin, there being an average 42.5 small *Hexagenia* per square meter in the area where all had died the previous September. *Hexagenia* eggs from one adult hatch over a period of many months, an adaptation which promotes species survival through times of environmental stress. However the recovery did not last long for this was no transient disaster to which the mayfly was adapted. Beeton[47] found that *Hexagenia* populations were again drastically reduced. Carr and Hiltunen[125] identified only one nymph per square meter in 1961. Veal and Osmond[846] found no mayfly nymphs whatsoever in 1967 at the stations Carr and Hiltunen had used. Hunt[392] reported a reduction in *Hexagenia* populations of the Detroit River from a maximum of 84/m^2 (22/yd^2) in his own 1955–56 study.

Chandler[130] found indication of a previous disaster. *Hexagenia* has a two-year life cycle in the western basin, with two separate age groups which hatch in alternate years. The group hatching in odd years during 1941–47 was consistently more abundant than the even-year group. Collections from 1928 showed that the even-year group was then the dominant one. This suggested to Chandler that sometime between 1928 and 1941 there was a catastrophe which decimated the even-year group.

Another indication of environmental change in the western basin is the trend in tubificid worm population densities. A high population density of these sludgeworms is generally an indicator of organic enrichment, typically by sewage. Dense populations of tubificids have been steadily expanding into the western basin from the major river mouths for most of this century. In 1930, Wright and Tidd[918] found significant numbers of worms only near the Maumee, Raisin, and Detroit Rivers. According to their classification, the heavily polluted area totaled 26 km^2 (1.1 mi^2), the moderately polluted was 46 km^2 (2 mi^2), and light pollution covered only 191 km^2 (8.2 mi^2). The entire polluted area covered less than eight percent of the western basin. By 1951 the boundaries of the polluted areas (Figure 4–233) had expanded lakeward into Maumee Bay; the heavily polluted area by 5.5 mi., the moderately polluted by 8 mi., and the lightly polluted by 6 mi. (Brown[106]). Carr and Hiltunen[125] found further expansion of tubificid populations (Figure 4–230). The zone of heavy pollution then covered 238 km^2 (10.2 mi^2) (a 900 percent increase over 1930); the zone of moderate pollution was 517 km^2 (22.2 mi^2) (an 1100 percent increase); and the lightly polluted area was 265 km^2 (11.3 mi^2) (an increase of 140 percent). Veal and Osmond[846] found similar populations in 1967 (Figure 4–234). Tubificids constituted 86 percent of all the benthos collected. The most common variety was *Limnodrilus hoffmeisteri,* and *L. cervix. Branchiura sowerbyi* was also found at a number of stations.

Hunt[394] found no significant change in the tubificid population of the Detroit River between Wright's 1929–1930 survey and his own

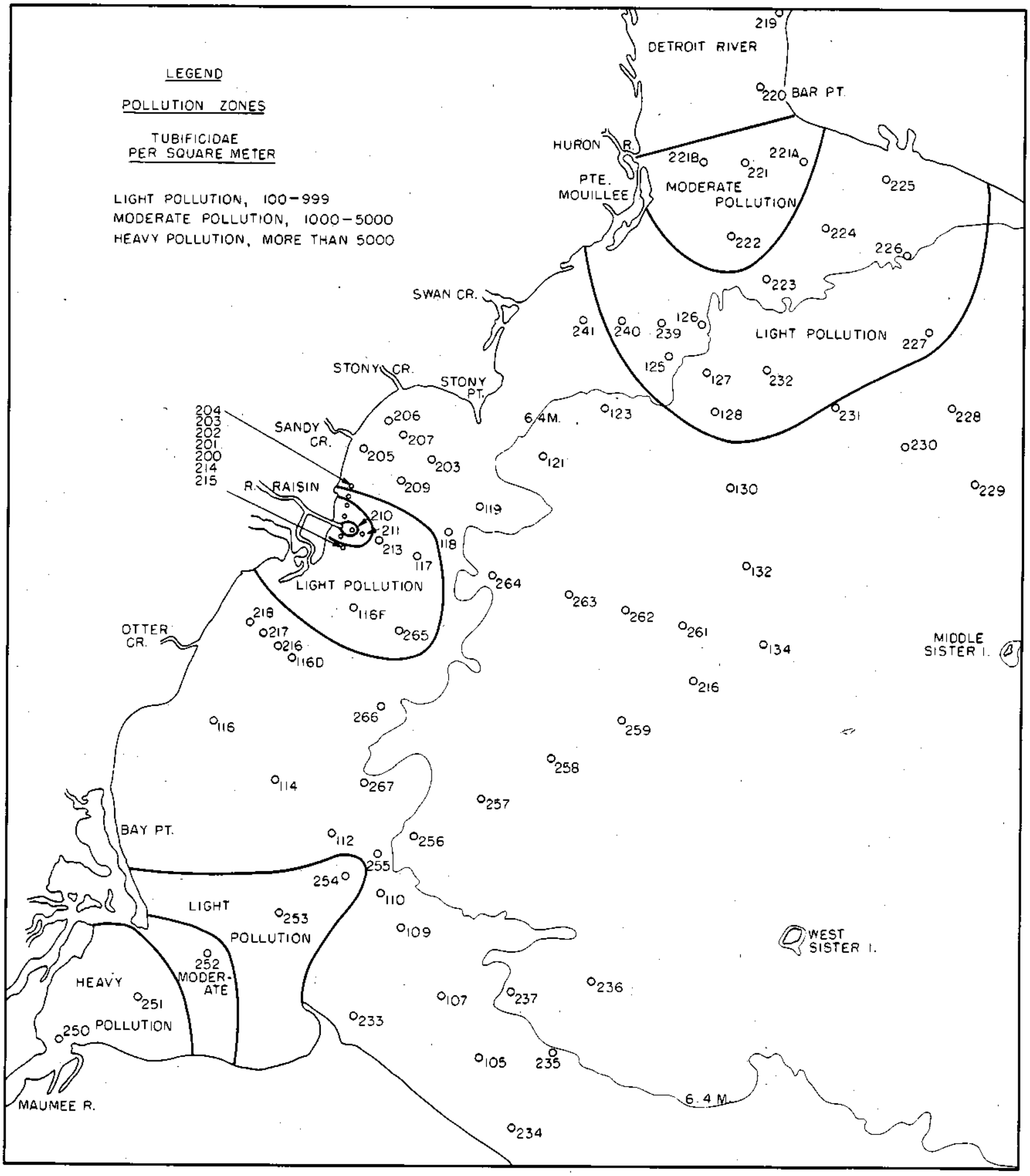

FIGURE 4–233 Tubificid Densities in Western Basin of Lake Erie, 1951

in 1955–56 (Table 4–61). Wright reported 122 to 1506/m² (102 to 1255/yd²) and Hunt found 13 to 2706/m² (11 to 225/yd²). Carr and Hiltunen[125] reported only three widely distributed genera of midge larvae in the western basin in 1961. *Procladius*, *Coelotanypus*, and *Chironomus* were restricted to polluted areas, especially ones with low dissolved oxygen. Veal and Osmond reported *Cryptochironomus* at only two percent of their sampling stations. Carr and Hiltunen noted that *Cryptochironomus* may be the victim of increasing pollution, because,

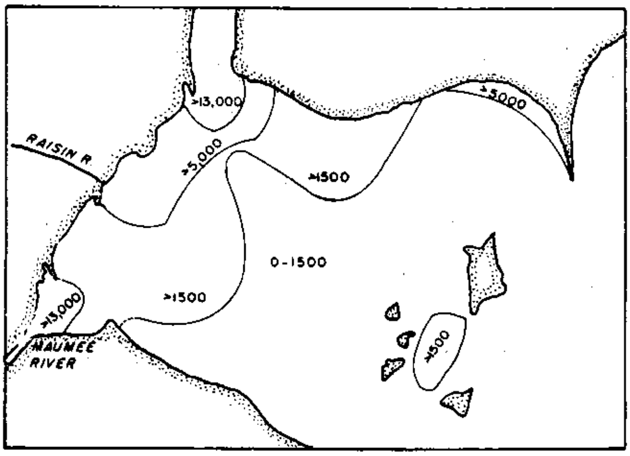

FIGURE 4-234 Number of Tubificids per m² in Western Lake Erie; April to August, 1967
From Veal and Osmond, 1968

TABLE 4-61 Abundance of Invertebrates in the Lower Detroit River

Animal Group	(#/m²)[a]	(#/m²)[b]
Tubificidae	122-1506	13-2706
Hexagenia	0- 204	0- 26
Sphaerium	0- 760	0- 348
Musculium	0- 397	0- 542
Pisidium	0- 145	0- 193
Gastropoda	0- 285	0-1486

[a]From Wright's 1929-1930 Stations 126, 220, 221B, and 222.

[b]From Hunt's 1954 Transects A and P.

SOURCES: Wright (1955) and Hunt (1957).

of the four genera, only *Procladius* and *Chironomus* are thought to be tolerant of polluted waters. Carr and Hiltunen reported that chironomid midge larvae were 4.4 times more abundant in 1961 than in 1929–30.

Carr and Hiltunen[125] also reported a nearly twofold increase in fingernail clams, an increase in snails by a factor of 5.5, and a reduction in pollution-intolerant benthos such as amphipods, caddis fly larvae, and mussels. Six species of fingernail clams were widely distributed in 1961, but *Sphaerium transversum* was most successful near the sources of pollution. *Valvata sincera* appeared to be the most pollution-tolerant snail. Its predominance is apparently a recent development since it was not found by Wright[917] in 1928–30 or by Brown[106] in 1951. The earliest record of this species in the western basin appears to be Wood's[913] collection of only four specimens in 1951–52. Hunt[394] found *V. sincera* in his 1955–56 study of the lower Detroit River although he did not indicate in what numbers. He did list a marked increase in snail density in the river from a maximum of 285/m² (237/yd²) in 1929–30 (Wright[917]) to 1484/m² (1236/yd²) in 1957.

Carr and Hiltunen also pointed out the apparent decrease in relative abundance of the amphipod *Gammarus* from 10 percent of the total zoobenthos in Wood's[913] study in 1951–52 to only 2 percent in 1961. They also found that caddis fly larvae were scarce in the western basin and were largely confined to open lake areas. Only 35 were found in the entire study. Brown[106] found about 13 caddis fly larvae/m² (14/yd²) in three out of fifteen grabs.

Carr and Hiltunen[125] reported a few phantom midge larvae (*Chaoborus*) in the western basin. Since this eutrophic-pond organism was not found in 1929–30 by Wright[917] but was found by Brown[106] and Wood,[913] it is likely that its presence is another indication of the organic pollution of the western basin.

Mussels (*Unionidae*) were also successful in the open lake away from the sources of pollution, and they were relatively numerous (4–14/m²) (3–12/yd²) in the Carr and Hiltunen survey. Wood[913] recorded the number of living and dead unionids of each species he collected in the western basin in 1951–52. He found 50 percent of the *Lampsilis ventricosa* and 79 percent of the *Elliptio dialatus* to be dead and speculated that this might represent a recent decline of these species.

A change in the bottom fauna in Sandusky Bay has also been recorded. This is not caused by pollution, but is due to a deliberately introduced exotic species, which has become a nuisance. The Japanese live-bearing snail, *Viviparus japonicus*, was stocked in Sandusky Bay in the 1940s to serve as a possible good source for channel catfish, Wolfert and Hiltunen.[911] The snail succeeded and has become a pest for local seine fishermen who may have their nets fouled by as much as two tons of snails in a single haul. Furthermore, as is often the case with species that have little effective predatory control of their population growth, these snails seem to be subject to periodic die-offs in large numbers.

Changes, perhaps less marked, have also been observed in the Lake Erie zooplankton. Concern about the effects of the organic pollution of Lake Erie on plankton was expressed as long ago as 1882 by Vorce,[866] the following quotation being perhaps the first of its kind for the Great Lakes:

TABLE 4–62 Comparison of Zooplankton Densities, Lake Erie Western Basin, 1938–1959

	Maximum Abundance (#/m³) Cladocera	Copepoda
1938–39 (Chandler, 1940)	17,000	70,000
1948–49 (Bradshaw, 1964)	48,150	97,044
1959 (Hubschman, 1960)	202,000	165,000

> For about the time named (two years) the municipal authorities of the City of Cleveland have pursued the practice of dumping into Lake Erie, at a point nine miles east of the city and eight miles from shore, all the garbage and night-soil from the city, amounting to a scow-load daily. This point was, after careful investigation, decided by the Board of Health to be so far from the water-works crib where the water-supply is taken, and in such a direction as to be free from all danger of affecting the water-supply. There have been rumors that the required distance has not always been reached before dumping the contents of the garbage-scows, and occasional instances of such dereliction have been proven, hence the increase in the number of forms of the *Infusoria* [*Infusoria*, in older terminology, are ciliated protozoans] and of their abundance suggests very forcibly the disagreeable query whether the dumping of such matter into the lake is not the direct cause of their appearance in the water-supply, not only by affording an admirably well-suited field for propagation but by diffusing them with their food supply through the influence of currents and storms over a vastly larger area than is generally believed.

It can be seen from this bit of history that many problems now facing us are not recent but only of different magnitude.

Knowledge of the plankton of Lake Erie is too fragmentary to reach valid conclusions about long-term changes (Davis[193]). This is even more true for zooplankton than for the phytoplankton. However, two trends can be noted with some confidence. First is an apparent increase in total zooplankton. Reighard[644] classified both Lake Erie and Lake St. Clair as plankton-poor lakes. Bradshaw[81] pointed to the increase in both *Cladocera* and *Copepoda* when comparing the data of Chandler,[131] Hubschman,[388] and his own, collected in 1949 (Table 4–62).

The second trend indicating long-term changes in Lake Erie is the recent occurrence or increasing abundance of two copepods. *Diaptomus siciloides*, generally considered a pond species, was considered rare before 1930 (Jahoda[422]), although Ewers[250] reported this species to be common in the stomach of fish taken in the western basin in 1929. It was more common by the time of Chandler's[131] study in 1938–39. Jahoda[422] found the copepod frequently in 1946–47. Davis[193] found it to be very abundant in Cleveland Harbor in 1956–57 and in the western basin of Lake Erie during the summer of 1956. The other copepod is *Eurytemora affinis*, a marine form unknown in the Great Lakes before it was reported in Lake Ontario by Anderson and Clayton[12] and in Lake Erie by Engel.[243] Another copepod may also be a significant addition to the Lake Erie fauna. Jahoda[422] reported *Diaptomus reighardi* for the first time in the lake. It was recognized again by Robertson.[664]

Brinkhurst et al.[100] point out the following:

> The hard parts of the chironomid larvae preserve well in lake sediments and, consequently, core analyses can, at least theoretically, provide information as to whether the present distributions represent recent developments. . . . If the remains of oligotrophic forms, now restricted to the eastern part of the lake, can be found in recent sediments from the western basin, this will provide direct evidence that the present distributions in Lake Erie are of recent origin.

This technique would verify changes in the chironomid component of the benthos.

8.2.4.5 Lake Ontario

The tubificid worms *Potamothrix* and *Aulodrilus* occur in the deeper, open waters of Lake Ontario rather than near shore (Brinkhurst et al.[100]). One would not expect to find these worms at such great depths, but rather in the shallower bays and harbors that are now occupied by pollution-tolerant species, such as *Limnodrilus*. The anomalous occurrence of these taxa may be evidence of eutrophication, *Potamothrix* and *Aulodrilus* being displaced by more pollution-tolerant species near shore, but finding a home in deeper areas due to the increased, but still moderate, amounts of organic nutrients that occur there.

Unfortunately, nothing can be said about changes in the zooplankton of Lake Ontario since the earliest comprehensive study was made in 1966 (Robertson[664]).

8.2.4.6 Great Lakes in General

Gannon and Beeton[282] ran a series of laboratory tests on the toxicity of sediments dredged from Buffalo Harbor, the Calumet River, Cleveland Harbor and the Cuyahoga River, Green Bay and the Fox River, Indiana Harbor, Rouge River, Maumee River, Great Sodus Bay, and Milwaukee Harbor. The test animals included *Pontoporeia affinis*, *Gammarus lacustris*, and *Chironomus tentans* among the

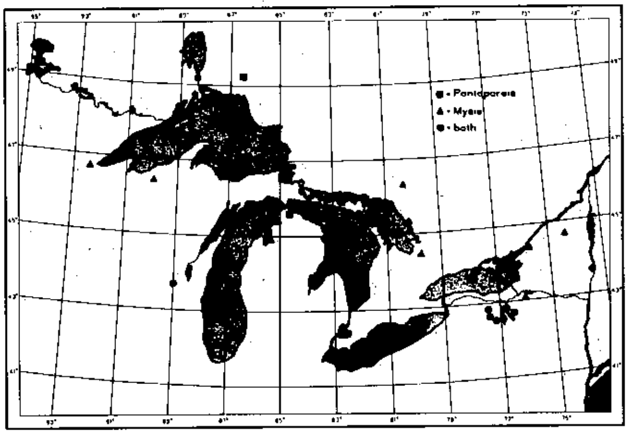

FIGURE 4–235 Distribution of *Pontoporeia* and *Mysis* in the Great Lakes

benthos and various species of *Daphnia, Bosmina, Ceriodaphnia, Cyclops,* and *Diaptomus* among the plankton. The levels of toxicity of many of these sediments range from acute to slight. There is no simple pattern of toxicity occurrence, but many of the rivers and harbors of the Great Lakes contain substances toxic to zooplankton and zoobenthos. These materials have not been identified, but Gannon and Beeton did find a rough correlation between toxicity and chemical oxygen demand (COD), volatile solids, phosphate, and ammonia. There is no indication that the toxicity of the sediments is part of a trend. However, toxic sediments should not be expected in the pre-industrial period, so these data could be a forecast of future conditions of the sediments in the open lakes.

Henson[343] maintains that major changes in the benthic fauna of the Great Lakes are inevitable since they are part of long-term geological changes:

> The present benthic fauna was derived from primary sources. The littoral communities are dominated by a pre-Pleistocene native fauna that was displaced by glaciation and migrated into the lake basins as the ice receded or was established in postglacial lakes. The profundal fauna is characterized by those species that inhabited the marginal proglacial lakes and during the Pleistocene, migrated into the Great Lakes by routes determined by ice fronts. A third element of the fauna is represented by those species that were introduced into the lakes in recent time.
>
> Ecologic requirements for the profundal species are not the same as those for the littoral species. The profundal components are oligothermal detritus feeders. The littoral components are favored by a warmer environment and are adaptable to a wide range of habitats around the profundal bottom. The two groups overlap in the sublittoral zone. . . . These two components are in active competition with one another, as evidenced by a large intermerging of range in depth of the species in the two zones.
>
> Eutrophication is a normal series of events that involves the diminution of the lake basin by sedimentation, the elimination of coastal irregularities and the concomitant enrichment from the drainage basin. Also to be considered is the trend toward a warmer climate in post-Pleistocene times. These factors lead to the conclusion that the processes of nature act against the profundal fauna in favor of the littoral species. Pleistocene glaciation brought to us a unique fauna of inestimable value in the trophic economy of the lakes, and the unwavering prognosis is that this ultraoligotrophic fauna will continully diminish.

Among the evidence that Henson gives for this replacement of profundal benthos by the littoral type is a map showing the present distribution of oligotrophic, profundal crustaceans, *Pontoporeia affinis* and *Mysis relicta* (Figure 4–235).

Mysis relicta was described in the western basin of Lake Erie in 1929–30 (Wright[917]). As *Mysis relicta* has not been collected since then in the western basin of Lake Erie, its apparent disappearance is more evidence of change supporting Henson's scenario in which profundal fauna are being replaced by littoral species.

8.2.5 Physical Factors Controlling Distribution of Zoobenthos and Zooplankton

8.2.5.1 Depth

Depth is frequently considered a factor controlling species distribution. Because many or most zooplankters exhibit diel vertical migrations, they are not greatly affected by depth. Therefore, this section is concerned primarily with the benthos. Some benthic species are restricted in their habitable depths. This is particularly true of the littoral benthos, many of which are either dependent on type of bottom, wave action, or light. Pulmonate snails in the western basin of Lake Erie tend to be most abundant in very shallow, littoral waters, whereas branchiates have a deeper range (Dennis[211]). This is to be expected since the pulmonates are air breathers and are obliged to return periodically to the surface, whereas branchiates respire by means of gills. Dennis found the greatest population densities of all types of snails within the first six inches of water. The first six inches is an important zone for many kinds of benthic fauna. Krecker and Lancaster[475] found that twice as many benthic species attained their maximum numbers in the first six inches than in any other comparable depth interval (Table 4–63).

TABLE 4–63 Depth Distributions of Shallow Littoral Benthos, Lake Erie Western Basin

Water Depth (inches)	Number of Species	Number of Indiv./m²	Number of Indiv./yd²
1-6	30	3000	(2500)
18	35	4800	(4000)
36	18	3600	(3000)
72	31	600	(500)

SOURCE: Krecker and Lancaster, 1933.

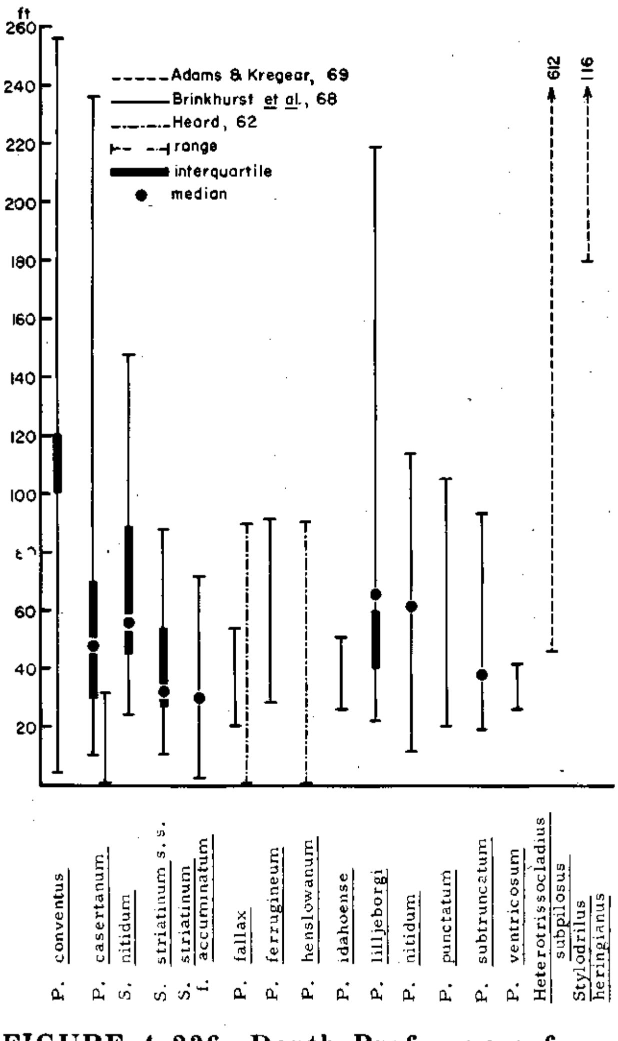

FIGURE 4–236 Depth Preferences for a Number of Benthic Species

Some benthic species can be described as eurybathic in that they are found at most depths except in the littoral zone or in profundal depths. Few species appear to be totibathic although Smith[748] reported collecting *Hydra carnea* from all depths in Lake Superior to 309 m (1014 ft). Figure 4–236 shows

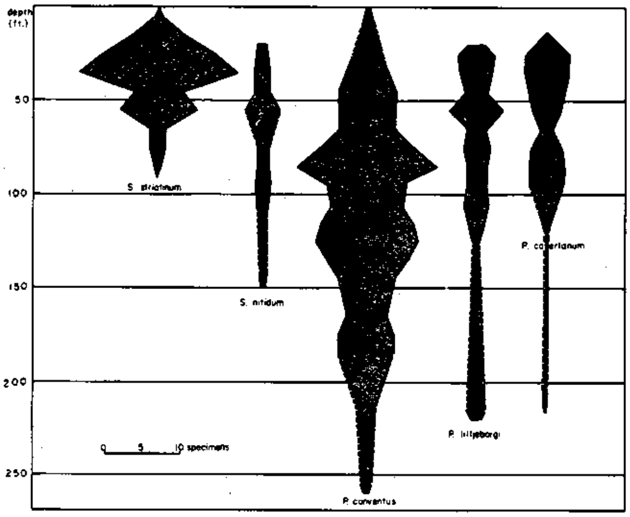

FIGURE 4–237 Relative Abundance of the Five Most Common Species of Sphaeriidae Found in the Straits of Mackinac with Respect to Depth. The widths of the polygons are proportionate to the total number of specimens collected within 10 ft depth intervals. The dashed lines indicate depths from which no specimens were collected.

After Henson and Harrington, 1965

the depth range for a number of the benthos based on data from Heard,[328] Henson and Herrington,[344] Brinkhurst et al.,[100] and Adams and Kregear.[4] Perhaps even more informative are the relative abundances of benthic species at various depths, (Henson and Herrington[344]) (Figure 4–237). In comparing the depth ranges of various Great Lakes benthos, the literature agrees generally as to whether a species is littoral, sublittoral or profundal, but precise depth ranges often vary widely. So many factors such as temperature, light intensity, dissolved oxygen, wave action, and the availability of food are related to depth that published depth ranges should be regarded as tentative.

Shallow water represents a dynamic environment with respect to wave action and the consequent instability of the bottom, but this zone seems to be most favorable for life. The shallow water of Lake Huron supports a greater diversity of benthos than deep water (Teter[788]). Perhaps most important is the fact that the shallow nearshore zones of the lakes are richest in food, due either to *in situ* production which is dependent on light penetration, or to the inflow of allocthonous material from the watershed. In Lake Michigan, Powers and Robertson[625] determined that there is a strong negative correlation between organic matter on the bottom, which includes the

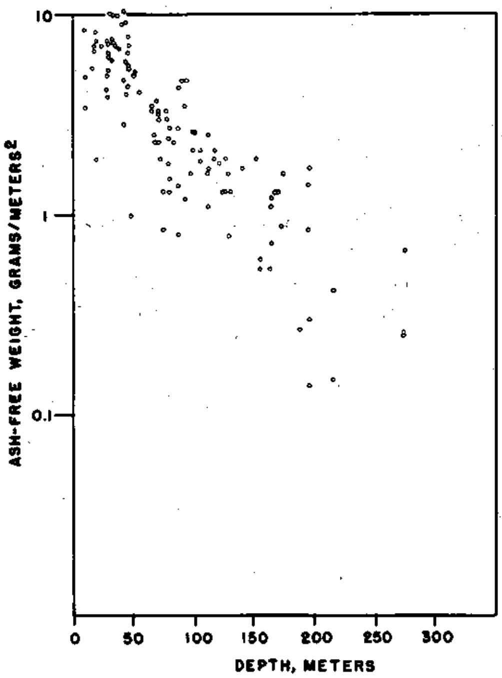

FIGURE 4–238 Distribution of Organic Matter Versus Depth in Lake Michigan
From Powers and Robertson, 1965

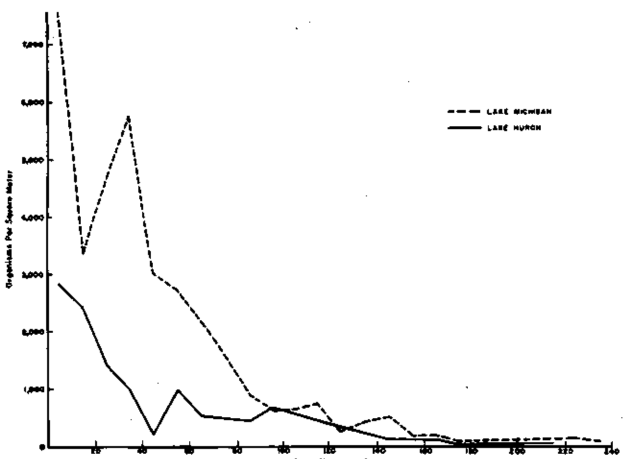

FIGURE 4–239 Comparison of Depth Distribution of Benthic Fauna, Lake Michigan, 1962–64, and Lake Huron, 1965
From Schuytema and Powers, 1966

benthos, and depth (Figure 4–238), indicating that food is most abundant in shallow areas. Schuytema and Powers[725] compared the depth distributions of the total benthic fauna in Lakes Michigan and Huron and found that the greatest part of the benthos is concentrated in shallow water in both lakes (Figure 4–239). In Lake Ontario, the greatest abundance of oligochaetes which, taken as a group, may be

TABLE 4–64 Mean Oligochaete Abundance at Various Depths in Lake Ontario

Zone	Abundance	
Littoral	90/m^2	(108/yd^2)
Sublittoral	270/m^2	(323/yd^2)
Profundal	490/m^2	(586/yd^2)

SOURCE: Johnson and Matheson, 1968.

regarded as pollution tolerant, increases with depth (Johnson and Matheson[434]) (Table 4–64).

Tubificids are found at all depths in the Great Lakes, but are least abundant above 3 m and below 66 m. They are most common between 33 m and 66 m (Henson[342]). Henson and Herrington[344] reported that the size of many fingernail clam species is diminished in the cold, deep water of the Great Lakes compared with the same species living in rivers and creeks.

Brinkhurst et al.[100] observed that the northern shore of Lake Ontario is not as steep as the American shore so if species were limited by depth, one would expect to find them first on the Canadian shore. The distribution of *Pisidium conventus* in Lake Ontario supports this observation as this species extends fur-

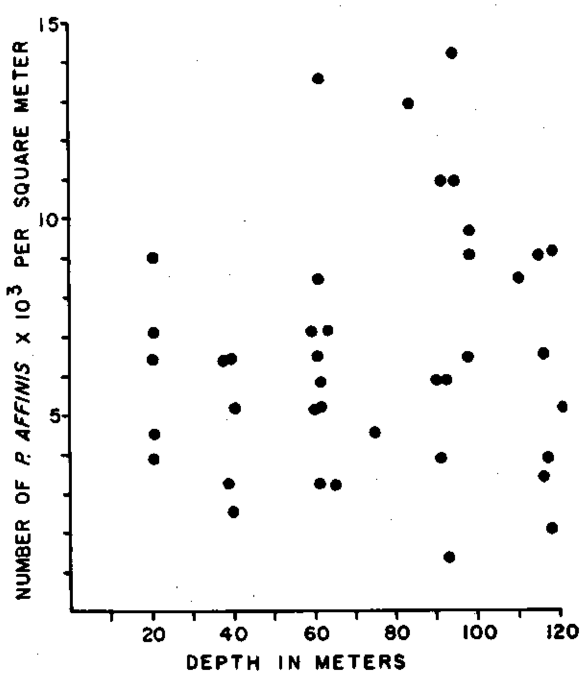

FIGURE 4–240 Relationship of the Number of *Pontoporeia affinis* to the Depth of Sampling
From Marzolf, 1965

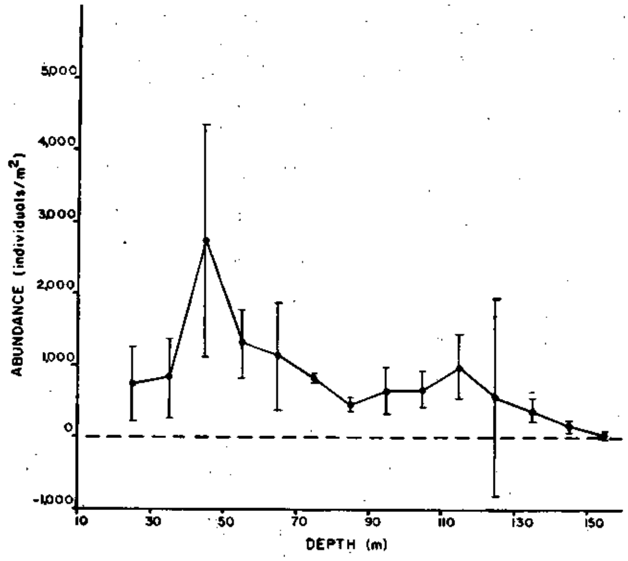

FIGURE 4–241 Mean Abundance of *Pontoporeia* in Lake Michigan in a Series of 10 m Depth Ranges in 1931–1932 with 95% Confidence Limits. The dashed line represents zero abundance.

Robertson and Alley, 1966

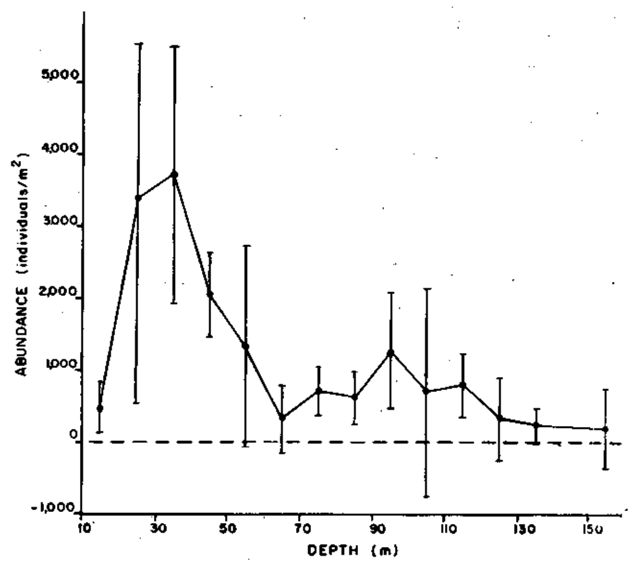

FIGURE 4–242 Mean Abundance of *Pontoporeia* in Lake Michigan in a Series of 10 m Depth Ranges in 1964 with 95% Confidence Limits. The dashed line represents zero abundance.

Robertson and Alley, 1966

ther from the shore on the northern side of the lake than on the south.

Pontoporeia affinis is an interesting species with regard to its depth distribution. Most investigators agree that it is one of the few truly eurybathic benthic forms outside the littoral zone. Marzolf[515] for example, found no correlation of the relative abundance of this amphipod with depth in Lake Michigan (Figure 4–240). In contrast, Robertson and Alley[665] reported that in collections made in both 1931–32 and 1964, *P. affinis* has a distinct zone of maximum abundance at 30 m to 40 m (Figures 4–241, 4–242). It appears that depth may not affect distribution, but it does have an effect on abundance of *Pontoporeia*. In South Bay of Lake Huron, Cooper[165] observed that *Pontoporeia* has a one-year life cycle in the shallow (mean 14 m) outer bay and a two-year life cycle in the deeper (mean 40 m) inner bay. This is most probably a temperature and/or food supply effect rather than depth related.

8.2.5.2 Substrate

The type of substrate is a factor which, at least to some extent, controls the distribution of benthic and periphytic animals. It is widely recognized that rocky and sandy substrata support a meager fauna compared to mud bottoms. Krecker and Lancaster[475] pointed out that bottom type cannot be regarded alone because bottom type also implies a specific type of lake environment. For example Schuytema and Powers[725] attributed the low numbers of *Pontoporeia* at the Bruce Peninsula entrance of Georgian Bay to the rocky bottom and shallow depths, while Adams and Kregear[4] found that *Pontoporeia* is able to flourish on a bedrock substrate if it is covered with epilithic algae. Sand bottoms are usually unstable, a situation that many species find intolerable. For example, Veal and Osmond[846] attribute the low densities of benthic invertebrates in portions of the Lake Erie central basin to shifting sediment as well as to the predominance of sand and gravel. Shelford and Boesel[732] distinguished two different benthic communities that occurred on different bottom types in the western basin of Lake Erie: the *Pluerocera-Lampsilis* community on sand and the *Hexagenia-Oecetis* community on mud. Krecker and Lancaster[475] related the benthos distribution to a rather complex series of bottom types in western Lake Erie (Table 4–65).

Some investigators make precise descriptions of the type of substrate in which they find various organisms. Attempts to correlate the abundance of oligochaete species with particle size of the sediments have usually failed to show any direct correlation. Henson,[342] however, found that the abundance of

TABLE 4–65 Number of Species and Individuals on Various Substrata

Substratum	Number of Species	Number of Individuals
Sand	6	200
Pebbles	8	300
Clay	14	800
Flat Rubble	18	1000
Block Rubble	17	1200
Shelving Rock	12	7700

SOURCE: Krecker and Lancaster, 1933.

oligochaetes in the Straits of Mackinac, when plotted against median particle size, was nearly a normal curve. Sediments having a high percentage of either sand or clay supported a smaller biomass. Henson and Herrington[344] reported the particle size preference of a number of fingernail clam species (Table 4–66) to show that this factor can serve as a partial basis for niche differentiation among closely related species.

Henson and Herrington also showed that sediment size preference may be influenced by depth. For example, *Sphaerium nitidum* apparently prefers coarse sediments in shallow water (Figure 4–243).

Organic content of sediments may have more influence than particle size. Occurrence of *Ilyodrilus templetoni* is positively correlated with organic content of sediments, while *Peloscolex ferox*, another species of tubificid, is negatively correlated with organic matter (Brinkhurst[93]). In Saginaw Bay, Schneider et al.[722] found that *Hexagenia* sp. and *Chironomus plumosus* are both positively correlated and *Cryptochironomus* and *Pseudochironomus* are negatively correlated with organic content of the sediments. In Hamilton Bay, Lake Ontario, *Limnodrilus hoffmeisteri* and *Tubifex tubifex* are numerous in profundal sediments that contain an excess of 0.25 percent organic nitrogen and 0.50 percent phosphorus and lose more than 10 percent weight upon ignition. Marzolf,[515] on the other hand, found no direct correlation between organic content of sediments and the density of *Pontoporeia affinis* populations in Lake Michigan, but in laboratory experiments this amphipod selected organic sediments or sediments having bacterial growth on the particle surfaces. Organic content seems to be a more important factor than sediment texture in determining the distribution and abundance of benthic species.

8.2.5.3 Water Movement

Water movement is important in the distribution of the benthos and periphyton. Some

TABLE 4–66 Sphaeriid (Fingernail Clam) Sediment Texture Preference

Species	Mean ϕ Size[1]	Description
S. nitidum	2.0–3.5	Sand
S. striatinum	1.5–3.5	Well-sorted, medium fine sand
S. striatinum form *acuminatum*	1.5–2.5	Tends to prefer coarser sand
P. casertanum	1.5–3.5	Well-sorted, medium fine sand
P. compressum	2.3–4.4	Modal around fine sand
P. conventus	3.0–4.0	Prefers silty sand
P. dubium	3.0–3.5	Fine sand
P. lilljeborgi	1.5–2.5	Prefers 90% coarse-medium sand with 10% silt
P. punctatum	2.4–3.5	Sand
P. subtruncatum	3.3	Sand
P. ventricosum	3.2–3.5	Sand
P. walkeri	3.2–3.3	Sand with vegetation

[1] ϕ units, are defined as the negative $\log_2$ of the particle size in millimeters.

SOURCE: Henson and Herrington, 1965.

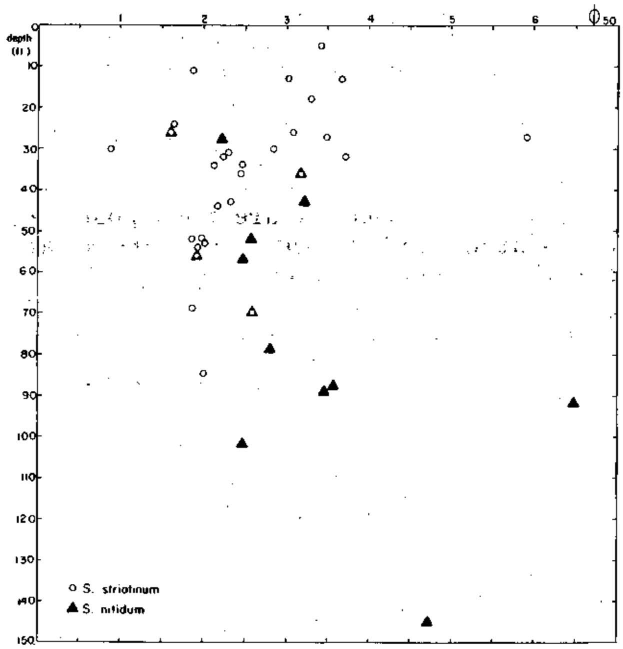

FIGURE 4–243 Samples Containing *Sphaerium striatinum* and *Sphaerium nitidum* Showing the Relationship Between Median Particle Size (ϕ_{50} average phi number) and Depth
Henson and Harrington, 1965

species may be adapted to high flow and wave action, but this environment is limiting to most species. Wave action controls animal distribution in two ways (Krecker[473]), first by striking the animal directly and, second, by causing an oscillation of the substratum. To these a third might be added, the scouring action of suspended particles. Where subject to wave action, the snail *Goniobasis livescens* tends to inhabit only large objects or avoids the waves by seeking the lower surfaces of rocky habitats (Krecker[473]). *Goniobasis livescens* also inhabits generally protected regions where its substrate preferences are not so narrow (Dennis[211]). Wave action is one of the major factors determining snail species distributions in the western basin of Lake Erie. Some species are inhibited by wave action if the substrate lacks large rocks; others can tolerate essentially no wave action and require vegetation substrata; while others need both vegetation and wave action. Mussels are completely lacking on certain wave-swept shoals in Lake Erie even though the bottom is suitable. Elsewhere in the lake these mussels are stunted compared to the same species in protected habitats (Brown et al.[105]). The stunting may be due to the continuous effort required of the mussel to stay in place or to some other factor, such as food availability.

Little information concerning the influence of waves on zooplankton is available. Windstorms may reverse the normal depth stratification of zooplankton species (Andrews[20]). Rotifer blooms occur during times of the year when there is little turbulence (Williams[897]). Wave action is also important in shallow areas some distance from shore, as in the shoal environment of Lake Superior (Adams and Kregear[4]). The Coreyon Reef also supports the lowest biomass in Saginaw Bay, presumably because of wave action (Schneider et al.[722]).

The effect of general lake currents has been little studied, perhaps because these currents are not yet well defined. Biological effects of seiches have not been extensively studied either. Seiches in the western basin of Lake Erie afford indispensible feeding and breeding grounds to fish (Krecker[474]). No one seems to have studied the probable limiting effects that seiches might have on periphytic organisms near the surface. This situation should be analogous to that of marine epifauna in the intertidal zone, except that seiches might be more limiting. Tides are predictable and marine organisms have become adapted to them on a clocklike basis, whereas seiches are irregular and marine organisms may have more difficulty adapting to them. Internal waves may also have a limiting effect on periphytic organisms. Distribution of certain benthos, such as *Chironomus plumosus*, may center at the bottom of the thermoclines (Bardach[40]). Shifting of the oxygen-deficient hypolimnion of the central basin of Lake Erie could have profound effects on the biota.

8.2.5.4 Temperature

Temperature in the Great Lakes varies depending on the latitude of the particular lake and its depth and this influences the distribution and abundance of invertebrate fauna.

The upper lakes are colder than the lower lakes and, therefore, have different zooplanktonic and zoobenthic fauna. The fauna is not entirely different, but many species have limited ranges or change greatly in relative abundance from one lake to another. Deep lakes are cold at depth and support fauna similar to northern lakes. This is obvious when one compares the western and eastern basins of Lake Erie, which are roughly at the same latitude but differ considerably in depth. Henson,[343] Henson and Herrington,[344] and Brinkhurst et al.,[100] pointed out that there is an oligothermic fauna, which is characteristic of the colder lakes, that persists as a profundal, glacial relict. Such organisms as *Sphaerium nitidum*, *Pisidium conventus*, *Heterotrissocladius subpilosus*, *Monodiamesa bathyphila*, *Rhyacodrilus* spp., *Pontoporeia affinis*, *Mysis relicta* and many other species are included.

Seasonal changes in zooplankton populations can be partially correlated with seasonal temperature variations, but other factors such as light intensity and photoperiod are also involved.

Finally, temperature changes due to thermal enrichment can affect fish, phytoplankton and, to a minor extent, bacteria. Thermal effects on zooplankton appear to be trivial and local, and thermal effects on the benthos may be nonexistent since the low-density warmwater layer cannot be expected to reach the lake bottom. However, power plants may damage zooplankton during passage through condenser pumps or poison them by using chlorine and other biocides used to keep condenser pipes free of fouling growths.

8.2.5.5 Light

As an environmental factor for lake invertebrates, light appears to be most significant indirectly. Light is an important factor in photosynthesis. This process is necessary for the nourishment and growth of phytoplankton, which act as food for the lake invertebrates. Light also influences water temperature. Light has considerable influence on the depth distribution of zooplankters, especially the Crustacea and their diel migrations. This is discussed in Subsection 8.2.6. Light intensity and depth of penetration influence the distribution of many benthic species. Photoperiod is involved in regulating the life cycles of many Great Lakes invertebrates, but definitive studies on this subject are lacking.

8.2.5.6 Chemical Factors

Although the chemical content of water, particularly dissolved nutrients for phytoplankton, has been studied rather extensively, this is not so relevant for marine animals because they generally feed on other organisms or solid detritus. Impact of toxic chemicals entering the Great Lakes is significant. However, little has been done to describe either the chemicals or their effects. Gannon and Beeton[282] demonstrated that many Great Lakes river mouth and harbor sediments contain substances toxic to benthic organisms. Johnson and Matheson[434] found a lack of tubificids in Hamilton Bay sediments, which have a high iron content. The toxicity, they noted, could be due to the iron directly or the high COD associated with its oxidation. With regard to zooplankton, Parker and Hazelwood[597] reported a positive correlation between *Daphnia schodleri* populations and high trace amounts of aluminum and magnesium and a negative correlation with high phosphate content in natural waters.

Most knowledge concerning the importance of specific chemicals dissolved in water to the well-being of zooplankton and benthos has to do with oxygen. Many profundal benthic species, notably species of chironomid midge larvae and various tubificids, have been observed to survive periods of very low dissolved oxygen in the hypolimnion. Chaoborid midge larvae can apparently adapt themselves to life in an anaerobic or nearly anaerobic environment. These species also seem generally tolerant of high CO_2 levels (Curry[175]). It seems probable that most aquatic invertebrates can adapt to some extent to changing levels of dissolved oxygen. Certain species of *Daphnia* develop a red color due to increased hemoglobin production during periods of low dissolved oxygen, and this permits increased survival time under anaerobic conditions (Hrbacek;[386] Fox[270]).

Leonard[493] has found that *Hexagenia limbata* and *Ephmera similans* can survive 0.20 ppm to 0.30 ppm of cyanide, which acts specifically to block oxidative metabolism, for 1 to 2 hours and that some other mayfly nymphs are even more tolerant. Cyanide tolerance may have some significance in the vicinity of steel mills since this is one of the components of wastewater from such plants.

8.2.6 Vertical Stratification and Diel Migrations

Diel migrations are regular cyclic changes in depth distribution over a 24-hour period. As a result of this migration pattern, many zooplankton species are restricted to a narrow stratum within the water column. Migration patterns are well known for the planktonic Crustacea, but the other major components of the plankton, the Protozoa and Rotatoria, are not generally noted for this phenomenon. Davis[193] observed that planktonic crustaceans in central Lake Erie tend to be more

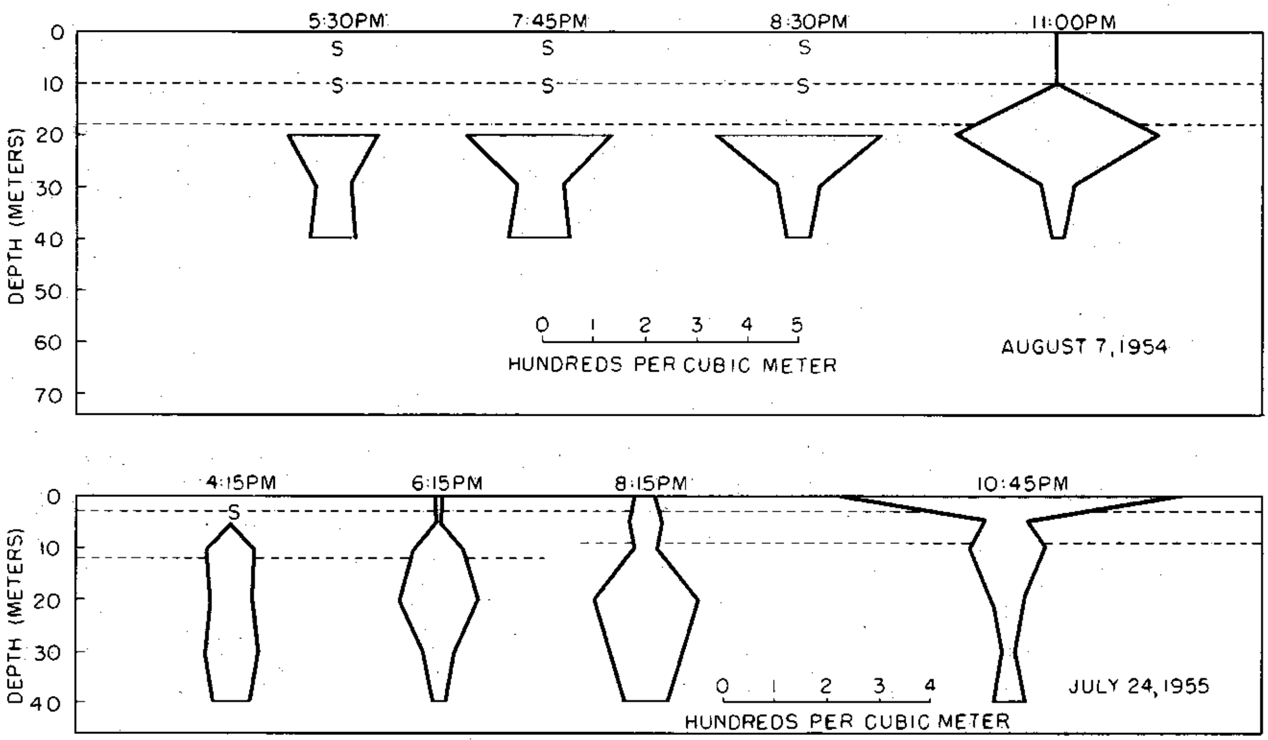

FIGURE 4–244 Vertical Distribution of *Limnocalanus macrurus* in Lake Michigan on August 7, 1954 (sunset 8:00 pm, EST), and July 24, 1955 (sunset 8:15 pm, EST). The broken lines represent the limits of the thermocline. The thermocline was pronounced on August 7. On July 24 it was distinct at 4:15, less so at 6:15, and weak at 8:15 and 10:45. The bottom line of each panel shows the depth of the lake at the sampling locality. No samples were taken below 40 m. (S) indicates samples in which *L. macrurus* did not occur.

After Wells, 1960

numerous at depths of 6 m to 12 m but rotifers and protozoans are not characterized by peak abundance at any specific depth. However, in an earlier paper Davis[196] reported that many species of rotifers show diel migration. The matter is further complicated by the observation of Jennings[426] that "during the daylight, the limnetic Rotifera are found in much greater numbers near the surface than near the bottom, reversing the condition commonly observed for the Crustacea." Exceptions are also found among protozoans. For example, Stehle[760] found that the ciliates *Codonella cratera* and *Coleps hirtus* are much more abundant in night net tows than in tows made during daylight hours.

Various crustacean species differ among one another in the extent to which they migrate daily and the depths at which they tend to concentrate (Jahoda;[422] Wells[880]). There are also differences between sexes and various developmental stages within the same species. Changes in light intensity and water temperature regulate diel migrations. Plankton, and semi-planktonic benthos such as *Mysis*, have visual pigment systems that seem best adapted to detect the light wavelengths that prevail at their habitual depths (Beeton;[52] McNaught and Hasler;[527] McNaught[525]). Absolute light intensity apparently bears only an imperfect relation to crustacean depth selection, but such things as changes in time of sunrise and sunset, moonlight, fog, and turbidity influence the onset and extent of migration (Jahoda;[422] Beeton;[54] Marzolf[515]). McNaught and Hasler[528] determined a linear relationship between the rate of vertical movement of crustacean zooplankters and the logarithm of the rate of change in light intensity. The slope of this line increased with increase in water temperature, apparently reflecting increase in metabolism. Reluctance of some zooplankters to migrate through the thermocline is well documented (Wells,[880] McNaught and Hasler[527]). *Limnocalamus macrurus* is a good example of a species which is known to stay largely within the hypolimnion during the summer (Wilson[901]) (Figure 4–244).

The reasons for vertical diel migrations have been explained by a number of theories (McLaren[522]); the following are the most commonly cited. The first is that Crustacea avoid predation by moving to the dark depths during the day (McNaught[425]). However, McLaren[522] pointed out that this theory is an oversimplification and there is little evidence that diel migration significantly reduces predation, day or night. The second theory proposes that such migrations are needed to provide a thorough mixing of the zooplankter species gene pools, thus avoiding the undesirable effects of localized inbreeding. McLarren[522] pointed out that once again the facts apparently do not support this theory. The third and most popular theory is that crustacean zooplankters rise to feed in the warmer, productive upper photic layers and then descend to the colder depths to slow down their metabolism, thus conserving energy for egg production (McLaren[522]). The behavior of *Limnocalamus* and the other species that apparently migrate upward only until they hit the warmer nutrient rich layers of the thermocline supports this explanation.

8.2.7 Feeding Relations

From an economic viewpoint, one of the most important things about zooplankton and zoobenthos is that they serve as food for fish of commercial or recreational importance or for smaller fish, which, in turn, are consumed by the larger species. Other forms of wildlife eat lake invertebrates, but there is little information specifically for the Great Lakes. Some ducks consume large quantities of snails and fingernail clams (Hunt[392]). Stomach-content analyses for 26 species of Great Lakes commercial, sporting, or forage fishes indicate that certain groups are more important than others as fish food (Table 4–67). In the interest of this discussion, only invertebrates are included in the table rather than a total dietary analysis. Some species usually considered piscivorous, such as perch and walleye, obviously feed on a variety of invertebrates as well. It should be recognized that the invertebrates listed for each fish species include those consumed at all developmental stages, for some of the species at least, and that feeding habits change considerably as fish mature. For example, Daiber[178] observed that sheepshead feed on planktonic organisms, mostly small crustaceans, until they reach a length of more than 20 mm, after which they concentrate on the benthos. Larger sheepshead eat crayfish and other fish, something clearly impossible for fry. A similar pattern was reported for yellow perch (Turner[805]). Dryer et al.[224] reported a predominance of planktonic crustaceans in the stomachs of lake trout up to about 8 inches in length, a predominance of *Mysis relicta* in trout from 8 inches to about 13 inches, and a predominance of fish remains in the larger trout.

An inspection of the table reveals the importance of the Copepoda, Cladocera, Hydracarina, Ostracoda, *Mysis*, Amphipoda, crayfish, chironomids and various larval insects, most notably Trichoptera and Ephemeroptera, as fish food. In general, the mollusks do not seem to be too important as fish food, because they have shells which would need to be crushed. Oligochaetes and leeches do not appear to be important either. Because tubificids make up a large portion of the benthos in polluted areas, this could represent a significant dimunition of the available fish food supply in such areas. Tubificids and leeches are soft-bodied creatures and may break down so rapidly that little would be left to identify in stomach contents other than the microscopic setae of the tubificids. There is not yet sufficient information with which to ascertain the importance of soft-bodied invertebrates as fish food.

The importance of planktonic organisms as fish food is indicated in other ways besides stomach content analyses. Game fish are attracted to a sewage plant outfall in Lake Erie near Cleveland either by the abundance of Crustacea in the area or, secondarily, by smaller fish (Metcalf[533]). The best fishing in Cleveland Harbor appears to be within the thermal plume of an electric generating plant. As previously stated, plankton are killed or maimed by passage through power plant condensers, so this easy prey may be the attractive feature.

How much of a species' feeding depends on preference and how much on availability of the prey organism is not indicated in Table 4–67. Fish do feed selectively when given a choice and, of course, prey preference is based partially on availability and partially on the previous experience of the predator. Faber and Jermolajev[252] found that young smelt selected mature female *Eurytemora affinis* in preference to all other planktonic crustaceans. Sibley[737] found that young fish seemed to eat copepods in preference to cladocerans. Essentially the opposite finding was made by Brooks,[103] who concluded that planktivorous

TABLE 4–67 Invertebrates Identified in Stomach Contents of Various Great Lakes Fishes

Invertebrate	Fish
COPEPODA	alewife, bloater, shiners, channel catfish, largemouth bass, yellow perch, walleye, smelt
Diaptomus	
D. ashlandi	shiners, yellow perch
D. minutus	bloater, white crappie, yellow perch
D. oregonensis	bloater, carpsuckers, white bass, largemouth bass, white crappie, black crappie, yellow perch, sheepshead
D. reighardi	
D. sicilis	bloater, shiners, white bass, smallmouth bass, black crappie, yellow perch
D. siciloides	white bass, yellow perch
Epichura lacustris	bloater, whitefish, shiners, white bass, smallmouth bass, white crappie, black crappie, yellow perch, walleye, sheepshead
Eurytemora affinis	smelt
Limnocalanus	alewife, shiners
L. macrurus	bloater, cisco or lake herring, lawyer, white bass, yellow perch
Canthocampus	largemouth bass
C. robertcokeri	carp
Cyclops	shiners, bullheads, channel catfish, white bass, largemouth bass, rock bass, yellow perch, smelt
C. albidus	mooneye, bullheads, smallmouth bass
C. americanus	whitefish, white bass, largemouth bass, white crappie, black crappie, yellow perch, walleye, sheepshead
C. bicuspidatus	bloater, carpsuckers, shiners, lawyer, white bass, largemouth bass, smallmouth bass, yellow perch, walleye
C. fimbriatus	yellow perch
C. phaleratus	carp
C. robustus	carpsuckers, carp
C. serrulatus	carp, shiners, bullheads, largemouth bass, smallmouth bass
C. vernalis	
Mesocyclops	
M. edax	bloater, whitefish, cisco or lake herring, white bass, largemouth bass, smallmouth bass, white crappie, black crappie, yellow perch, walleye, sheepshead
CLADOCERA	yellow perch
Acroperus	yellow perch
A. harpae	bullheads
Alona	shiners, bullheads, white bass, largemouth bass, yellow perch, smelt
A. affinis	carp, yellow perch
A. costata	largemouth bass, yellow perch
A. guttata	largemouth bass
A. quadrangularis	yellow perch
Alonella excisa	cisco or lake herring
A. nana	carp, bullheads
Bosmina	alewife, channel catfish, largemouth bass, yellow perch, walleye, smelt
B. longirostris	bloater, whitefish, shiners, white bass, largemouth bass, white crappie, black crappie, yellow perch, walleye
Ceriodaphnia	largemouth bass, yellow perch
C. laticaudata	bullheads, yellow perch
C. pulchella	bullheads, yellow perch
C. quadrangula	shiners
C. reticulata	bullheads, black crappie
Chydorus	shiners, lawyer, white bass, yellow perch, sheepshead
C. gibbus	bullheads
C. globosus	yellow perch
C. sphaericus	carpsuckers, bullheads, largemouth bass
Daphnia	alewife, carp, shiners, channel catfish, largemouth bass, yellow perch, sheepshead, smelt
D. galeata mendotae	bloater
D. "longispina"	cisco or lake herring, shiners, yellow perch
D. pulex	mooneye, whitefish, muskellunge, carp, shiners, white bass, largemouth bass, black crappie, rock bass, yellow perch, sheepshead
D. retrocurva	mooneye, bloater, whitefish, shiners, white bass, smallmouth bass, white crappie, black crappie, yellow perch, walleye, sheepshead
Daphanosoma	alewife, channel catfish
D. branchyurum	cisco or lake herring
D. leuchtenbergianum	whitefish, cisco or lake herring, shiners, white bass, largemouth bass, smallmouth bass, white crappie, black crappie, yellow perch, walleye, sheepshead
Eurycercus lamellatus	bloater, cisco or lake herring, yellow perch

TABLE 4–67(continued) Invertebrates Identified in Stomach Contents of Various Great Lakes Fishes

Invertebrate	Fish
Holopedium	yellow perch, smelt
H. gibberum	bloater, cisco or lake herring
Ilyocryptus sordidus	carp
I. spinifer	carpsuckers, carp
Latona	channel catfish
L. setifera	carpsuckers, sheepshead
Leptodora	alewife, bloater, cisco or lake herring, shiners, channel catfish, white bass, yellow perch, sheepshead
L. kindtii	shiners, white crappie, black crappie, walleye, sheepshead
Leydigia quadangularis	carp, bullheads
Macrothrix laticornis	carpsuckers
M. rosea	carpsuckers, carp
Monospilus dispar	yellow perch
Pleuroxus	largemouth bass
P. aduncus	carpsuckers, carp
P. procurvatus	largemouth bass
Polyphemus	alewife, bloater, largemouth bass
Scapholeberis aurita	carp
S. mucronata	largemouth bass
Sida	alewife, cisco or lake herring, shiners, channel catfish, white bass, largemouth bass, yellow perch, walleye, sheepshead
S. crystallina	largemouth bass, smallmouth bass, black crappie, yellow perch
Simocephalus serrulatus	carp, bullheads
S. vetulus	carp, bullheads
NEMATODA	carpsuckers, shiners, channel catfish, yellow perch
Hydra	alewife
ROTIFERA	alewife
Paludicella ehrenbergii	
OLIGOCHAETA	alewife, smelt
Tubificidae	bullheads
Limnodrilus	sheepshead
HIRUDINEA	sheepshead
SPHAERIIDAE	lake trout, bloater, whitefish, carp, lawyer
Pisidium	carp, smelt
P. conventus	bloater
P. lilljeborgi	bloater
P. nitidum	bloater
Sphaerium	lake trout, whitefish
S. nitidium	bloater
GASTROPODA	yellow perch
Gyraulus	alewife
Lymnaea	alewife
Physa	bullheads, yellow perch
Valvata	yellow perch
HYDRACARINA	alewife, bullheads, channel catfish, white bass, smallmouth bass, yellow perch, smelt
CONCHOSTRACA	lake trout
OSTRACODA	alewife, lake trout, bloater, carp, shiners, bullheads, smallmouth bass, yellow perch, sheepshead, smelt
Mysis	alewife, bloater, whitefish, lawyer, largemouth bass, black crappie, yellow perch, smelt
M. relicta	lake trout, bloater, lawyer, smelt
ISOPODA	alewife, yellow perch
Asellus	bullheads, yellow perch, sheepshead
AMPHIPODA	mooneye, lake trout, smallmouth bass, yellow perch, smelt
Gammarus	bullheads, channel catfish, white bass, largemouth bass, yellow perch, sheepshead, smelt
Hyalella	shiners, bullheads, largemouth bass, yellow perch
H. knickerbockeri	largemouth bass

TABLE 4–67(continued) Invertebrates Identified in Stomach Contents of Various Great Lakes Fishes

Invertebrates	Fish
Pontoporeia	alewife, smelt
P. affinis	lake trout, bloater, whitefish, lawyer
Crayfish	northern pike, carp, channel catfish, lawyer, largemouth bass, smallmouth bass, white crappie, rock bass, yellow perch, sheepshead
Cambarus	sheepshead
DIPTERA	lake trout
CHIRONOMIDAE	alewife, mooneye, lake trout, bloater, whitefish, carp, shiners, bullheads, channel catfish, lawyer, white bass, largemouth bass, white crappie, black crappie, rock bass, yellow perch, walleye, sheepshead, smelt
Chironomus	mooneye, channel catfish, largemouth bass, smallmouth bass, yellow perch, walleye, sheepshead
Orthocladius	smallmouth bass
Pentaneura	channel catfish
Tantytarsus	smallmouth bass
CULICIDAE	sheepshead
HELEIDAE	channel catfish, white bass, sheepshead
TIPULIDAE	mooneye, yellow perch, sheepshead
Sialis infumata	sheepshead
HOMOPTERA	mooneye
HEMIPTERA	mooneye, lake trout
CORIXIDAE	sheepshead
Corixa	northern pike, white bass, largemouth bass, yellow perch
Palmacorixa	sheepshead
ODONATA	lawyer
ZYGOPTERA	smallmouth bass, yellow perch
AGRIONIDAE	mooneye
TRICHOPTERA	mooneye, bloater, carp, shiners, bullheads, channel catfish, smallmouth bass, yellow perch, sheepshead, smelt
Hydropsyche	white bass
EPHEMEROPTERA	alewife, lake trout, northern pike, shiners, bullheads, white bass, white crappie, rock bass, yellow perch, sheepshead, smelt
Baetis	smallmouth bass
Caenis	bullheads, channel catfish, sheepshead
Ephemera	sheepshead, smelt
Ephemerella	smallmouth bass, sheepshead
Ephoron	bullheads, channel catfish, white bass, sheepshead
Heptagenia	mooneye, sheepshead
Hexagenia	channel catfish, smallmouth bass, sheepshead
Stenonema	sheepshead
LEPIDOPTERA	mooneye
COLEOPTERA	alewife, mooneye, lake trout, bloater, smallmouth bass, sheepshead
Psephenus	sheepshead
ELMIDAE	shiners

SOURCES: Baldwin, 1950; Boesel, 1938; Daiber, 1952; Drayar, et al., 1965; Ewers, 1933; Faber, 1966; Gordon, 1961; Hohn, 1966; Morsell and Norden, 1968; Norden, 1968; Schneiberger, 1937; Shelford and Boesel, 1942; Sibley, 1929; Tharratt, 1959; Tressler and Austin, 1940; Turner, 1920; Van Osten and Deason, 1938; Ward, 1895; Wiekliff, 1920; Wilson, 1960.

fish selected the largest available prey and thus chose cladocerans (*Daphnia*) before copepods. This prey size selection could shift the competitive balance between zooplanktonic herbivores so that the smaller Crustacea predominate when planktivory by fishes is more intense. Norden[581] used the electricity index of Ivlev to express mathematically the feeding preferences of larval alewife. The index equation is

$$E = \frac{r_i - P_i}{r_i + P_i}$$

where r_i is the percentage of any food item in the diet and P_i is the percentage of the same organism relative to the entire population of zooplankton in the environment. The maximum range of electivity is +1 to −1. A plus number indicates that the food species is preferentially selected, a negative number that it is rejected. Applying this equation Norden found that larval alewife change their preference to copepods from cladocerans as the season progresses (Figure 4–245). Rotifers are rejected at all times.

What, in turn, do the zoobenthos and zooplankton eat? Brown[106] suggested that tubificids eat organic detritus in sludge, but they apparently eat the bacteria contained within the sludge (Brinkhurst,[92] Coler et al.[158]). There seems to be some selectivity involved, since Brinkhurst recounted that some bacterial species pass through the tubificid digestive tract unharmed. Coler et al.[158] found that sludge worms (*Limnodrilus* sp., *Tubifex* sp. and *Peloscolex* sp.) consume *Escherichia coli*, *Sphaerotilus natans*, and *Aerobacter aerogenes*, but avoid ingestion of *Arthrobacter* sp., *Micrococcus flavus* and *Chromobacterium* sp. These data suggest that the susceptibility of *E. coli* to ingestion might account for its rapid disappearance from sewage-polluted water. Brinkhurst[92] noted that tubificids would eat *Chromobacterium* sp. and that these worms caused kill-offs when subsequently fed to turtles and fish.

Hiltunen[360] and Adams and Kregear[4] agree that most oligochaetes are herbivorous, but that *Chaetogaster* is predacious, perhaps even cannibalistic. Both observed harpaticoid copepods within the digestive tracts of these worms.

Leeches of the Great Lakes feed on a variety of organisms, including turtles, fish, snails, frogs, insect larvae, mammals and aquatic oligochaetes (Miller[545]). Brinkhurst[91] mentions erpobdellid leeches in particular as predators of tubificids, but Miller lists *Glossiphonia* spp. and *Placobdella* spp. as well as various erpobdellids as sludge-worm feeders.

Chironomid larvae as a group are herbivorous, but *Procladius* feeds extensively on tubificids (Carr and Hiltunen[125]). *Chaoborus* larvae feed voraciously on other zooplankton (Edmondson[237]).

Most of the benthic Crustacea (crayfish, *Asellus*) are detritus feeders and, although *Gammarus* is known to eat copepods, it too

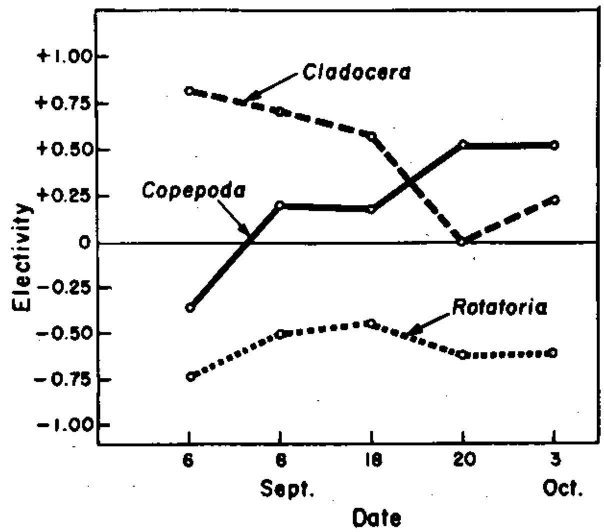

FIGURE 4–245 Electivity of Cladocera, Copepoda, and Rotatoria Sampled from Lake Michigan in 1967

From Norden, 1968

is probably mainly a detritus feeder (Reighard[644]). Field and laboratory evidence indicates that *Pontoporeia affinis* feeds on bacteria living on detritus and Marzolf[515] suggests that this is the mode of nutrition for most detritus feeders.

Most work on feeding relationships has been done on planktonic Crustacea because they are a direct link between the phytoplankton and the fish which are the consumers of most interest to man. A few generalizations can be made. Most cladocerans are planktivorous grazers (Edmondson[237]) except *Leptodora* and *Polyphemus*, which are predatory on other Crustacea. The calanoid copepods are filter feeders, feeding mainly on phytoplankton, whereas the cyclopoids are omnivores, feeding on all sorts of particulate material (Hubschman[388]). Hubschman's assignment of *Epischura lacustris* to the herbivorous category was contradicted by Rigler and Langford[655] who state that it can eat algae, but *Epischura* thrives on *Diaptomus*. Even among the filter-feeders, there is some selection of food. Burns[116] found that the size of plastic beads ingested by seven species of cladocerans increased with increasing body size. This ability to select food by size apparently helps reduce competition between closely related species of crustaceans (Hutchinson;[401] Fryer[278]).

An important question relating to this subject is how much of the food supply of the filter-feeding zooplankton comes from phytoplankton production and how much is alloc-

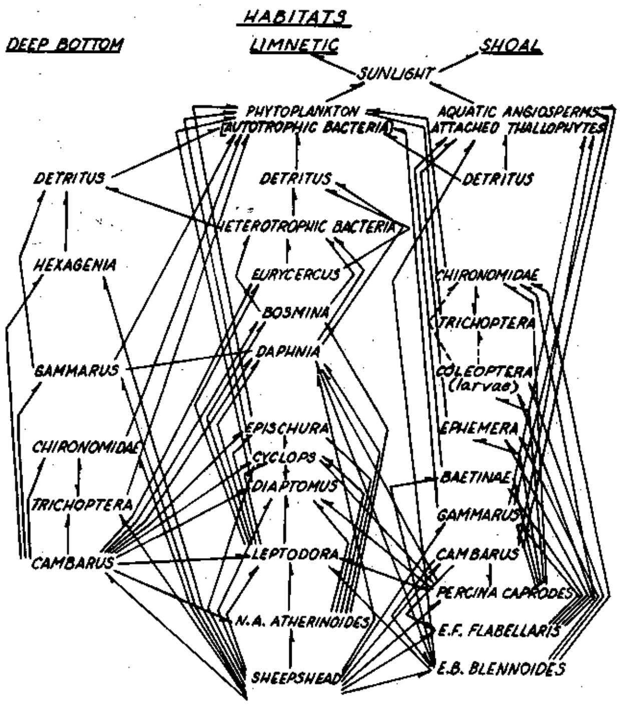

FIGURE 4–246 A Tentative Food Web in Western Lake Erie Using the Sheepshead as the Climax Organism

From Daiber, 1952

thonous particulate material. Allocthonous organic material is an important contribution of the watershed to lake enrichment. Suspended, non-living organic matter in a lake is termed trypton. Davis[188] cited four sources of trypton: the watershed, marginal marshy areas, dead and decaying plankters, and resuspension of bottom material.

Particulate matter in domestic sewage is probably an important food source for planktonic crustacea in Lake Erie (Wright[917]). Since zooplankters seldom have recognizable algae cells in their intestines (Edmondson[236]), some investigators have suggested that they mainly feed on detritus. Extensive analyses of the availability of phytoplankton and trypton relative to planktonic crustacean population in Lake Erie were carried out by Davis,[188] who concluded that the major source of food for these zooplankters was probably the algae, with trypton playing a secondary role. Edmondson[236] also dismissed dissolved organic material and suspended bacteria as significant food sources for planktonic crustaceans.

Finally, it appears that crustaceans can sometimes reverse the food chain by feeding on fish. Davis[190] observed *Cyclops bicuspidatus* and *Mesocyclops edax* nibbling on the fins of rock bass fry, causing visible damage. Fabian[253] added *Cyclops vernalis* to the list of fish-biters. A large number of Fabian's experimental fish died, presumably nibbled to death. Fabian suggested cyclopoid copepods may sometimes be a significant biotic limiting factor for some fish populations.

Daiber[178] diagrammed a tentative food web for the western basin of Lake Erie with sheepshead as the top consumer (Figure 4–246). The food web emphasizes the complexity of feeding relationships in the Great Lakes and the importance of all species for the well-being of those species in which man is primarily interested.

8.2.8 Reproduction

An understanding of population growth and regulation requires knowledge of the reproduction of the species in question. Little is known of the breeding seasons of Great Lakes invertebrates (Table 4–68). Where information is available for a number of closely related species, it can be seen that they often differ in their breeding seasons. Some zooplankters breed throughout the warm months, some prefer the colder months, and some do not breed during either the warmest or the coldest months.

The number and size of eggs in female zooplankters of the same species vary depending on external conditions. For example, the number of eggs produced by Lake Erie copepods decreases under unfavorable temperature and food supply conditions and also when young copepods are abundant (Ewers[249]). Hutchinson[401] attempted to synthesize the known facts about copepod reproduction into a general theory of feedback control on egg production. His hypothesis stated that "early in the season when the population is expanding into a lake rich in food, individuals producing many small eggs will leave most descendents, while later in the year when the population is larger and the food supply less, it is desirable to increase as far as possible the individual life expectancy of the nauplii produced" by producing larger eggs with more nutrient content. In his analysis of calanoid copepod reproduction in Lake Erie, Davis[189] could not find a consistent decrease in number of eggs produced from spring to autumn. Moreover, zooplankters from the eastern basin produced more eggs than those in the more highly enriched western basin. Davis concluded that seasonal and other variations in the number of eggs produced per female could not be corre-

TABLE 4–68 Reproductive Seasons of Some Great Lakes Zooplankton and Zoobenthos

Invertebrates	Reproductive Season
Diaptomus	
D. ashlandi	Breeding March--August and in October (Davis, 1961). Breeds April--September (Davis, 1962)
D. minutus	Breeding March--May; July--August (Davis, 1961). Breeds April--August (Davis, 1962)
D. sicilis	Breeding January--April and in October (Davis, 1961). Breeds April--June (Davis, 1962)
D. siciloides	Breeding May--November (Davis, 1961). Not parthenogenic (Ewers, 1936). Breeds June--October (Davis, 1962)
Epichura lacustris	Females apparently do not carry eggs. Breeding in May (Davis, 1961)
Limnocalanus	Females bearing spermatophores in January and March. Females apparently do not carry eggs (Davis, 1961)
Cyclops	
C. albidus	Not parthenogenic; breeds April--November (Ewers, 1936)
C. ater	Not parthenogenic; breeds in August (Ewers, 1936)
C. bicolor	Not parthenogenic; breed June--July (Ewers, 1936)
C. bicuspidatus	Not parthenogenic; breeds March--September (Ewers, 1936). Breeds April--October (Davis, 1962)
C. fimbriatus	Not parthenogenic (Ewers, 1936)
C. phaleratus	Not parthenogenic (Ewers, 1936)
C. serrulatus	Not parthenogenic; breeds March--November (Ewers, 1936)
C. vernalis	Not parthenogenic; breeds March--November (Ewers, 1936)
Mesocyclops edax	Not parthenogenic; breeds May--September (Ewers, 1936). Breeds June--September (Davis, 1962)
Tropocyclops prasinus	Not parthenogenic; breeds July--October (Ewers, 1936). Breeds July--October (Davis, 1962)
Bosmina longirostris	Breeds March--December (Davis, 1962)
Chydorus sphaericus	Breeds March--June; August--December (Davis, 1962)
Daphnia	
D. galeata mendotae	Breeds October--November (Wells, 1960)
D. "longispina"	Breeds June--December (Davis, 1962)
D. longiremis	Breeds June--August (Davis, 1962)
D. pulex	Breeds June--July; October--November (Davis, 1962)
D. retrocurva	Breeds June--November (Davis, 1962)
Daphanosoma	
D. leuchtenbergianum	Breeds August--October (Davis, 1962)
Leptodora kindtii	Parthenogenic reproducing females in western Lake Erie from late May to early November. Males occur late August to early November (Andrews, 1953)
Rotifera	Eggs deposited freely in water or attached to suspended particles, especially phytoplankters. Most abundant in May and October (Davis, 1962)
Branchionus angularis	Ovigerous females common in July (Davis, 1968)
Keratella	
K. cochlearis	Reproduction May--October (Davis, 1962). Reproduction May--June; late July--October (Davis, 1954)
K. quadrata	Reproduction May and June (Davis, 1962)
Branchiura sowerbyi	Breeds in summer (Aston, 1968)
Limnodrilus hoffmeisteri	Breeds at any time of the year (Brinkhurst, 1965)
Tubifex tubifex	Breeds at any time of the year (Brinkhurst, 1965)
Maididae	Peak of reproductive season may occur in late summer or early fall
Sphaeriidae	Breed year round (Hunt, 1962)
Viviparus japonicus	Reproducing in June (Wolfert and Hiltunen, 1968)
Pontoporeia affinis	Breeding season probably winter or early spring (Teter, 1960). Gravid females observed in September (Adams and Kregear, 1969)
Palaemonetes	Ovigerous--early July to late August (Burdick, 1940)

lated with the three basins of Lake Erie nor with the season of the year, except that egg production generally decreased in the late autumn.

8.2.9 Seasonal Patterns in Population Fluctuations

Chandler[131] and Davis[193,196] used comparable techniques to determine zooplankton populations from Lake Erie. Total zooplankton population fluctuations for parts of the years 1938, 1939, 1950, 1951, 1956, and 1957 (Figure 4–247) show winter minima and spring and autumn maxima, separated by summer depressions.

Figures 4–248, 4–249, 4–250, and 4–251 show the contributions to the total population fluctuations made by the three main components

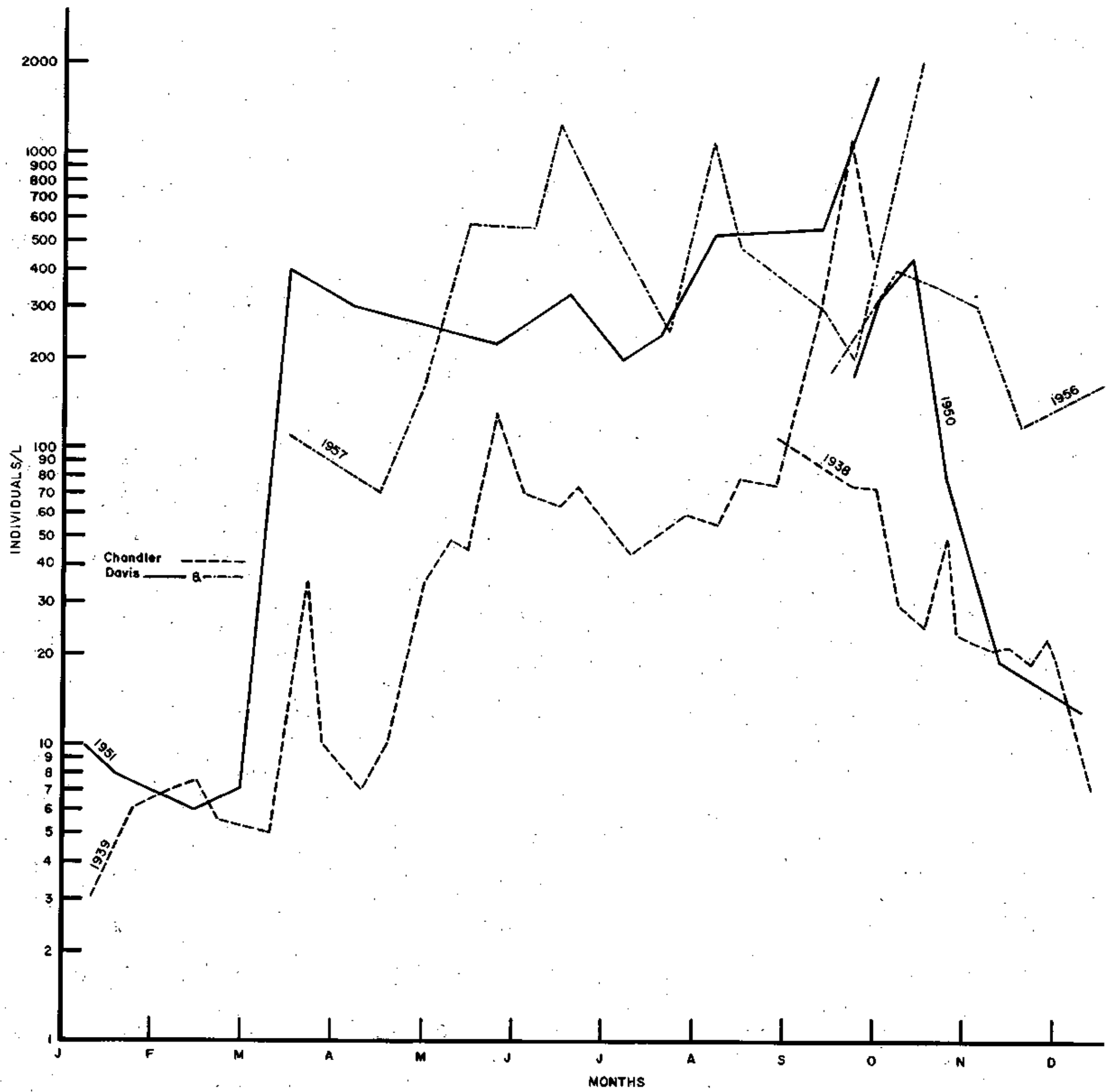

FIGURE 4–247 Total Zooplankton Population Fluctuations for Parts of the Years 1938, 1939, 1950, 1951, 1956, and 1957 for Lake Erie

After Chandler, 1940; Davis, 1954; Davis 1962

of the zooplankton, the Copepoda, Cladocera, and Rotatoria. These graphs were derived from the above papers and from Wright[917] whose data are for the years 1929 and 1930. Wright's data are not precisely comparable to those of Davis and Chandler because his Copepoda include only *Diaptomus* and *Cyclops* and his Cladocera includes only *Daphnia.* Major fluctuations in numerical densities of the total zooplankton are caused by the rotifers, particularly the summer depression and the fall maximum. Wright[917] did not observe an autumnal pulse of rotifers, but his rotifer data were not presented in a form that could be used here.

Chandler[131] and Davis[193,196] tend to agree as to the seasonal population density patterns of Copepoda, Cladocera, and Rotatoria, as does Wright[917] for Copepoda and Cladocera (Figures 4–249, 4–250, and 4–251). Data for 1938 to 1939 indicate larger populations, especially of copepods, in the western basin of Lake Erie than were observed in 1929 to 1930. The same is true for 1956 to 1957 data from Cleveland Harbor compared with 1950 to 1951 data. The population increases may indicate increased

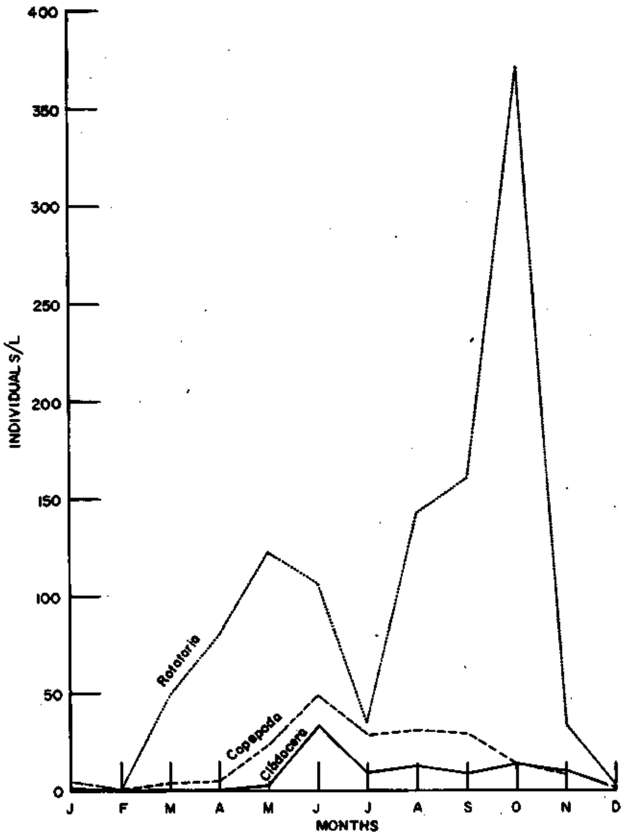

FIGURE 4–248 Seasonal Abundance of Three Major Components of the Zooplankton in Lake Erie

After Chandler, 1940; Davis, 1954; Davis, 1962; Wright, 1955

productivity over these intervals in Lake Erie. These data all indicate that both copepods and cladocerans have spring maxima in June and decline for the remainder of the year. They do not indicate the true significance of the Cladocera and Copepoda in total zooplankton, as they are based on numbers rather than on biomass.

Hubschman[388] made daily zooplankton collections by comparable methods during July and August (Figures 4–252 and 4–253). If these data are averaged with those used to construct Figure 4–247, one finds that the June maximum for copepods is maintained, but the cladoceran maximum is extended through June and July. Unfortunately, there is only one June observation in Hubschman's study. The data show the extreme variability in plankton population estimates based on samples taken on successive days. Even order of magnitude differences in estimates appear to be unreliable indicators of trends in population densities. As it seems unlikely that the populations oscillate daily to the extent indicated, it would appear that water masses moving past the sampling point are heterogeneous.

It is now obvious that more attention should be devoted to the statistics of sampling error. This has been a serious deficiency because much care should be normally exercised in making statistically valid counts of the organisms contained within the sample collections.

A detailed examination of the species population data in Eddy,[234] Wilson,[899] Chandler,[131] Wells,[880] and Davis[193,196] shows some partial seasonal consistency for some of the species. Some species seem to develop peak populations in the spring and fall, although any given species may not peak at both seasons in the same year. In this group are *Daphnia retrocurva, Bosmina longirostris, B. longispona, Cyclops bicuspidatus, Diaptomus ashlandi,* and *Epischura lacustris. Holopedium gibberum, Sida crystallina, Leptodora kindti, Chydorus sphaericus,* and *Daphnia galeata mendotae* apparently favor warm weather and thus peak in summer and fall. *Cyclops brevispinosus* probably also belongs to this group. Robertson,[664] in comparing the seasonal distribution of the four most common calanoid copepods in Lake Michigan with data reported by others for the same species, (Table 4–69) shows an interesting seasonal succession that apparently develops earlier in the more southerly Lake Erie. This pattern is not entirely consistent with data from Eddy,[234] Wilson,[899] and Chandler,[131] so generalization is not really possible at this time.

The copepods shift from predominance by cyclopoids in late June to predominance by calanoids in late August (Hubschman;[388] Davis[193]). There is a difference in feeding habits of the two categories: the *Cyclopoida* are largely carnivorous, whereas the *Calanoida* tend to be herbivorous. This may reflect a shift in available food species as the summer progresses.

Information concerning seasonal population fluctuations among the zoobenthos of the Great Lakes is even more scarce than for zooplankton. Teter[788] reported a lack of seasonal changes in the bottom fauna of Lake Huron even though he sampled twice a month from June through October. Brown[106] noted seasonal fluctuations in the tubificid populations in mouths of rivers draining into Lake Erie. These data, although not extensive, suggest peak populations in the spring with declines in the summer (Figures 4–254 and 4–255). The

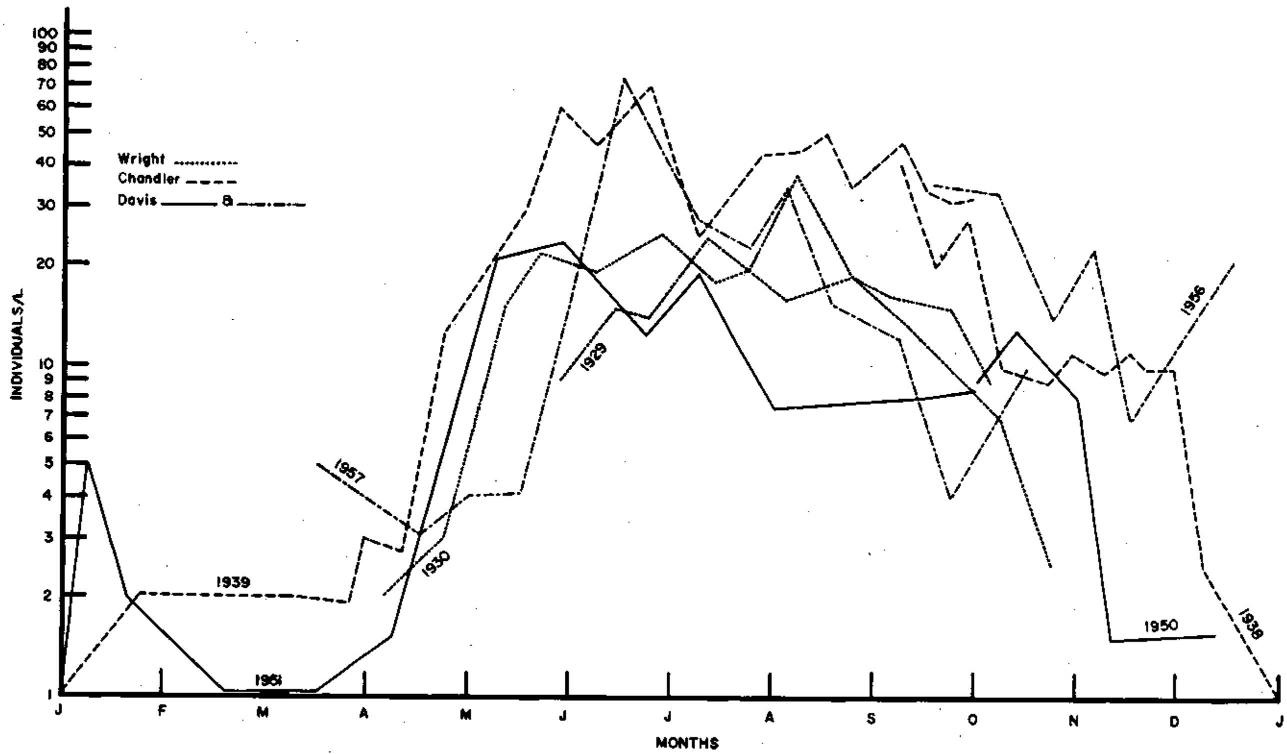

FIGURE 4–249 Seasonal Abundance of Total Copepoda in Lake Erie
After Chandler, 1940; Davis, 1954; Davis, 1962; Wright, 1955

relation of the population maxima to spring flooding is unknown. All worms in the Grand Haven area of Lake Michigan, except *Peloscolex variegatus*, peak in June (Hiltunen[360]) (Figure 4–256). *P. variegatus*, *Stylodrilus heringianus* and immature forms without capilliform setae showed maxima in October. Data from Benton Harbor, Michigan are not as extensive, but tend to confirm October peaks for *Stylodrilus* and immature worms without capilliform setae.

Other species peak in July or August. A seasonal fluctuation in the biomass of oligochaetes also occurs in the south end of Saginaw Bay (Schneider et al.[722]). The worm biomass is low in June, peaks in August, and diminishes again by the end of October. The most dramatic change was from 3.0 g/m^2 in June to 8.4 g/m^2 in August to 0.5 g/m^2 in October in the 1969 study.

8.2.10 Conclusions

The zooplankton and zoobenthos of the Great Lakes are of interest to planners and policy makers primarily as indicators of environmental quality and as links in the aquatic food chain upon which the fishery and many waterfowl depend. The ecosystem approach to environmental management requires a fundamental understanding of the components of the system. Literature on the invertebrates of the Great Lakes is extensive, but numerous and significant gaps of knowledge exist, and these gaps will inhibit sophisticated systems analysis.

The zooplankton and zoobenthos of the Great Lakes are incompletely cataloged, especially certain groups. Lake Ontario has been studied less extensively than the other lakes, and Lake Erie, especially the western basin, is the most thoroughly studied.

Conclusions concerning environmental changes in the lakes are tenuous, at best, in the absence of thorough biotic descriptions. There is, therefore, need to conduct limnological research in areas of the lakes which have been inadequately studied. These studies will provide baseline data against which future changes can be compared.

Changes in the zoobenthos and zooplankton of the Great Lakes have been adequately documented only for the western basin of Lake Erie and, to a lesser extent, Lake Michigan and Saginaw Bay. Changes may be the result

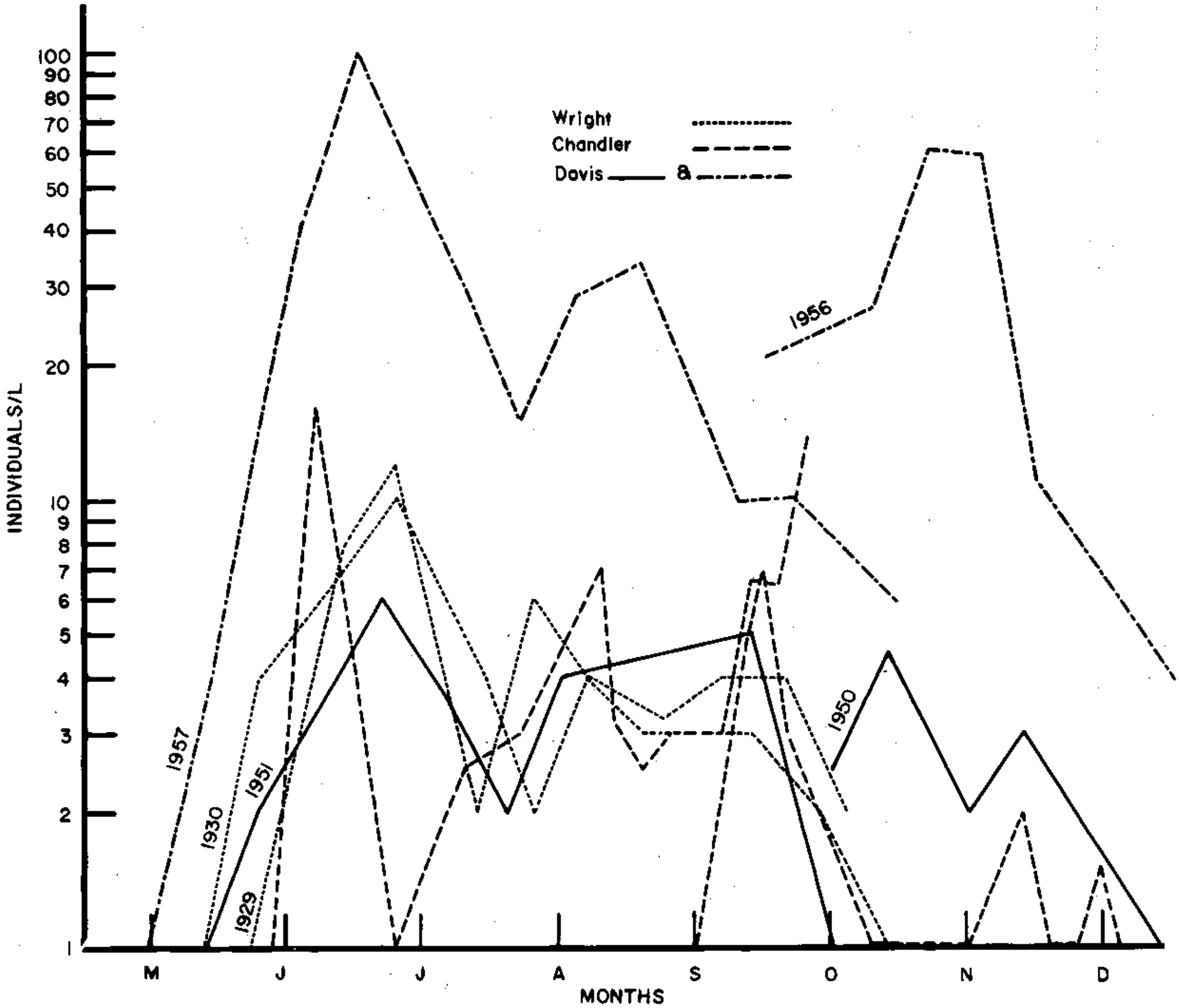

FIGURE 4–250 Seasonal Abundance of Total Cladocera in Lake Erie
After Chandler, 1940; Davis, 1954; Davis, 1962; Wright, 1955

of pollution, but other factors may have played a role of undetermined significance. Changes may have occurred in the other lakes but these would be difficult to ascertain. For example Lake Ontario fauna, especially the zooplankton, has incomplete historical documentation. The degree to which this lake may have undergone changes in the past cannot be demonstrated.

Methods for sampling and processing the zooplankton and zoobenthos vary, often making comparison of different studies difficult. Great Lakes researchers should establish some conventions or guidelines for these procedures, similar to the International Biological Program (IBP) handbooks. If nothing else, standard units for reporting data should be adopted.

The taxonomy of even the better known groups of zooplankton and zoobenthos is not completely established. The low level of support that systematics has received directly inhibits the understanding of Great Lakes ecology, so it is imperative that taxonomic research be given a higher priority.

Zooplankton are poor indicators of local pollution but are good indicators of over-all environmental conditions in the Great Lakes.

Zoobenthos can be used as indicators of local pollution if they are carefully classified and interrelationships properly interpreted. Use of organisms such as the tubificids and chironomids as indicators requires identification to the species level.

The distributions of zoobenthos and zooplankton species tend to have distinct gradients within each of the Great Lakes. These gradients are best documented for Lake Erie, Lake Michigan, Saginaw Bay and the North Channel of Lake Huron. Simple comprehen-

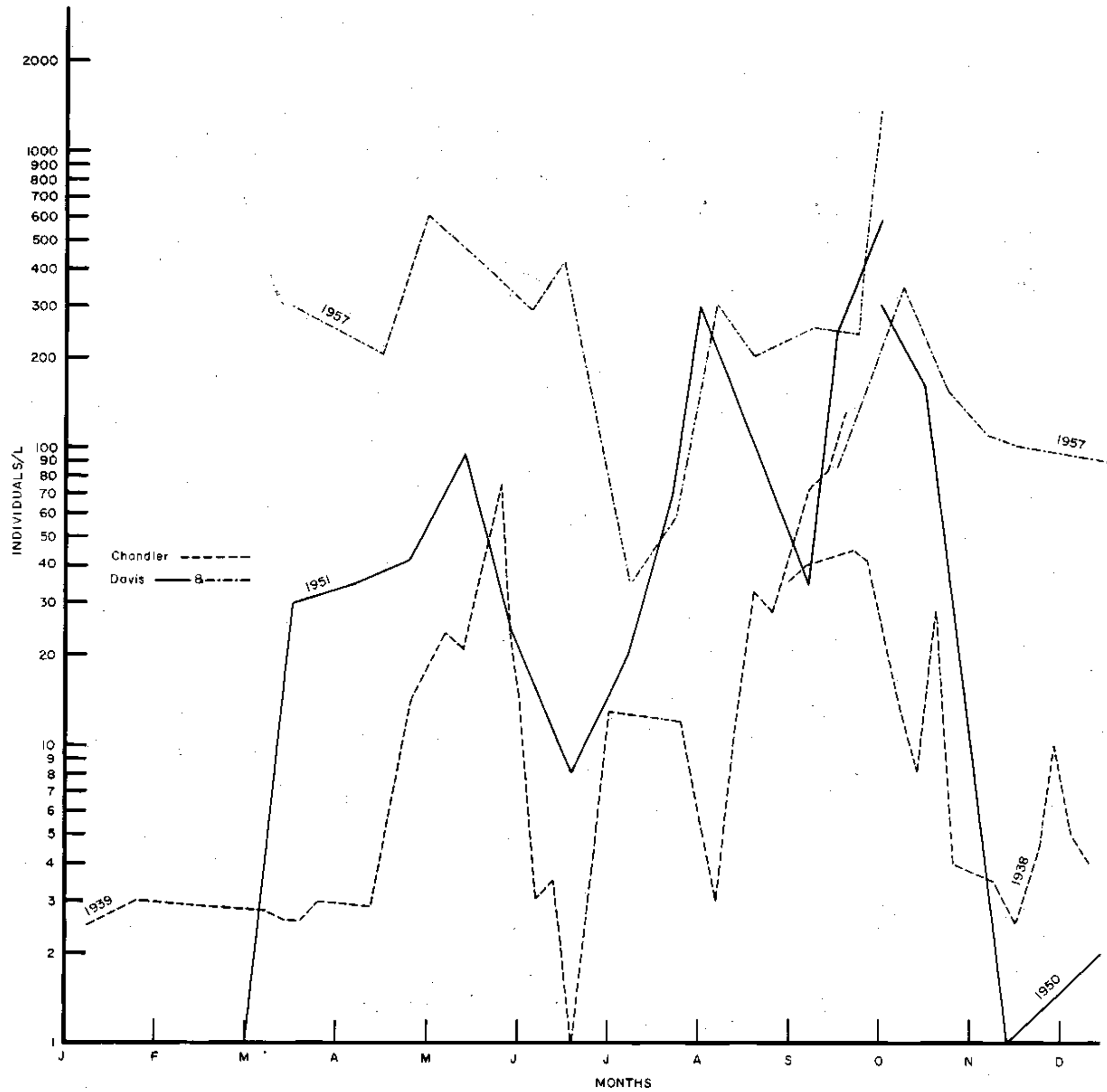

FIGURE 4–251 Seasonal Abundance of Total Rotatoria in Lake Erie
After Chandler, 1940; Davis, 1954; Davis, 1962; Wright, 1955

sive faunal description of a lake is clearly not possible.

Lake Erie probably contains more living material than at any time in the past. Species diversity is lower in the western basin than in the rest of Lake Erie, but the total biomass there is apparently greater. Similar faunal distribution patterns have been determined in southern Saginaw Bay and southern Lake Michigan and probably are a result of pollution.

Careful analyses of physical factors that govern the distribution of the Great Lakes zooplankton and zoobenthos are not numerous. A significant observation is that the distribution of benthic organisms is influenced by the availability of allocthonous organic material to a great degree.

Most species of Great Lakes fish feed heavily on the zooplankton and zoobenthos. Even the mainly piscivorous species rely on these organisms when they are fry. Most of the zoobenthos are detritus feeders and thus may consume significant amounts of allocthonous organic material or the bacteria that grow on such material. The zooplankton may also consume particulate allocthonous material, but apparently the grazing species derive most of their nutrition by feeding on the phytoplankton.

Life history data, such as reproductive pat-

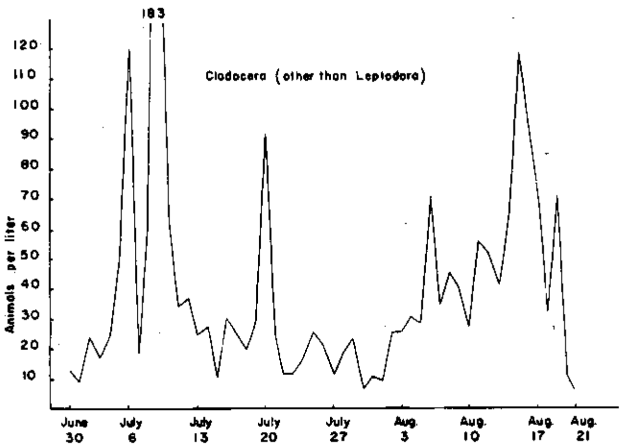

FIGURE 4–252 Daily Population Densities of Cladocera Other Than Leptodora
From Hubschman, 1960

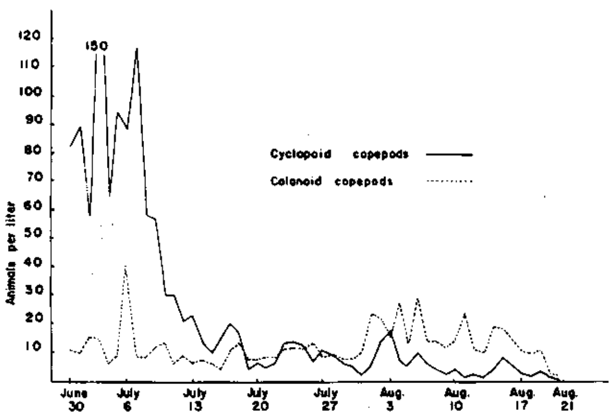

FIGURE 4–253 Daily Population Densities of Cyclopoid and Calanoid Copepods Collected in the Same Location Daily in the Bass Islands Region of Lake Erie in 1950
From Hubschman, 1960

terns and symbiotic relationships are too incompletely known to be of use in predicting zooplankton and zoobenthos population fluctuations. Zooplankton clearly undergo seasonal population fluctuations which are related, in part, to phytoplankton fluctuations. Zooplankton as a group have spring maxima and the rotifers regularly have a fall pulse as well. Seasonal population fluctuations probably occur among the zoobenthos, but have not been well documented.

8.3 Phytoplankton, Phytobenthos, and Phytoperiphyton of the Great Lakes

8.3.1 Components of the Flora

The Great Lakes flora discussed in this section include only the phytoplankton, phytobenthos, and periphyton. The terrestrial and semiterrestrial plants of the region are not included. It is often difficult to distinguish among the plankton, the benthos, and the periphyton. The euplankton are more diverse and more abundant in terms of biomass than the attached (benthic and periphytic) forms. The periphytic life habit appears to be more important among the algae than the benthic habit. Many types of diatoms and filamentous green and blue-green algae are periphytic on substrates such as rocks, pilings, and stems of higher plants. Some periphytic, filamentous algae break free of their attachments and become members of the plankton before dying.

The main categories of Great Lakes flora are: (1) Phylum Chlorophyta is a green algae and includes many filamentous species and

TABLE 4–69 Dominant Diaptomid Species in Lake Michigan in 1954–1955 and in 1964, and in Lake Erie in 1956–1957

Location and Date	Month J	F	M	A	M	J	J	A	S	O	N	D
Lake Michigan (1954-55) (Wells, 1960)					D.m.		D.a.		D.o.		D.s.	
Lake Michigan (1964)				D.m. & D.o.		D.a.				D.o.		
Lake Erie (1956-57) (Davis, 1962)			D.m.		D.a.				D.o.			

D.m. = *Diaptomus minutus*
D.a. = *Diaptomus ashlandi*
D.o. = *Diaptomus oregonensis*
D.s. = *Diaptomus sicilis*
SOURCE: Robertson, 1966.

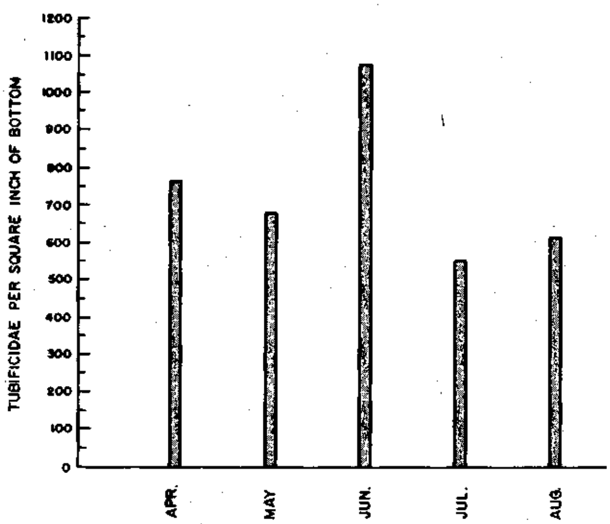

FIGURE 4–254 Tubificid Peaks at Black River Stations

Data from Brown, 1953

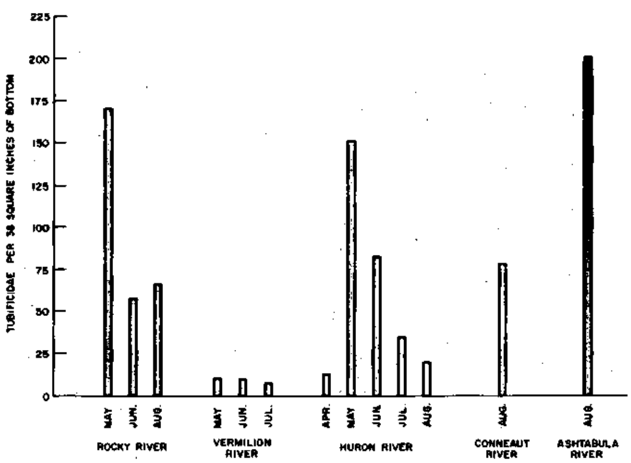

FIGURE 4–255 Tubificid Peaks in Five Lake Erie Tributaries

Data from Brown, 1953

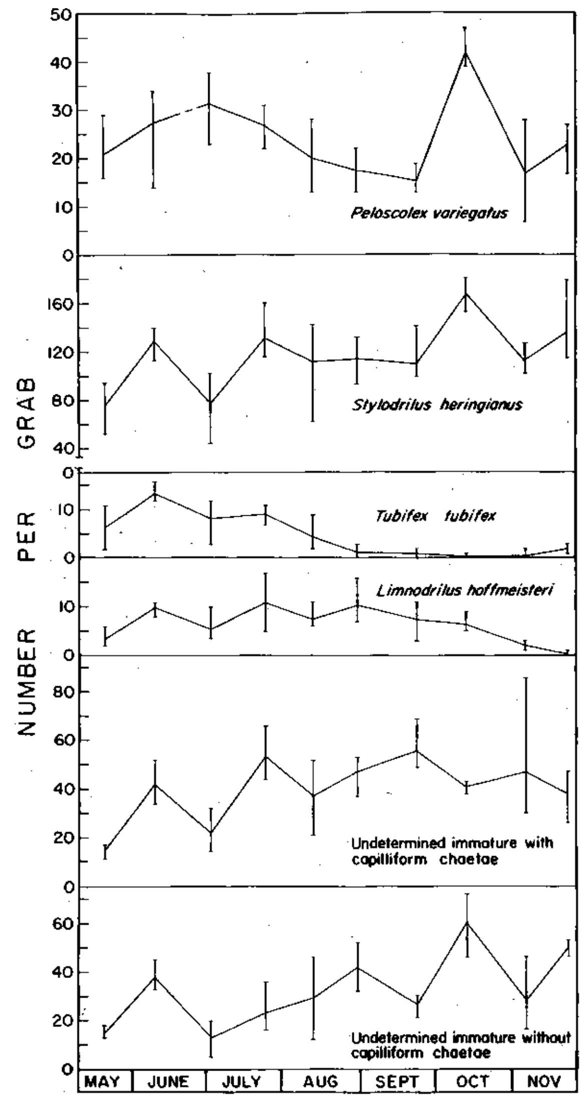

FIGURE 4–256 Average Number of Selected Oligochaetes in Samples near Grand Haven, Michigan; May to November, 1960. Vertical lines are ranges.

From Hiltunen, 1967

the desmids, as well as other types. Also included here but not classified with Chlorophyta are the stoneworts, *Chara* and their relatives, which comprise much of the benthic macroflora of parts of the Great Lakes.

(2) Phylum Chrysophyta is the yellow-green or yellow-brown algae. This group is associated with the diatoms, which are generally dominant among the phytoplankton of the Great Lakes.

(3) Phylum Cyanophyta is a blue-green algae and includes unicellular, colonial, and filamentous species, many of which are implicated in some of the undesirable consequences of eutrophication.

(4) Phylum Pyrrhophyta usually includes the dinoflagellates. These algae are widely distributed but not abundant.

(5) Phylum Rhodophyta is the red algae. These algae are very rare in the Great Lakes.

(6) Phylum Euglenophyta, the euglenoids, are quite small and do not preserve well. Some investigators believe this group may be more important to the productive economy of the Great Lakes than is generally realized.

(7) Phylum Spermatophyta includes most of the aquatic macrophytes. These are various pond weeds, which are more characteristic of

the marginal zone where there is protection from wave action than of the lakes proper.

The flora of the Great Lakes consists of a staggering number of species. Taft,[783] for example, lists 599 species of phytoplankton for the western basin of Lake Erie alone, although many of these are not actually lake species, but rather are found only in marshes and ponds of that area. In contrast, reports on the phytoplankton and benthic algae of Lake Huron are virtually absent. This absence of reports may give a false impression of a low diversity of algae in Lake Huron, but actually lack of investigations is the reason.

8.3.2 Sampling Problems

A major problem in interpreting literature on the benthos and plankton of the Great Lakes is the widespread inconsistency in sampling methods. Quantitative sampling has become common only in the last 25 years, and even during this period, checks have been conducted on the efficacy of sampling devices, the use of the same samples, or the statistical validity of sampling schemes. In the interest of comparison of results and cooperation between projects, methodologies must be agreed to and standardized.

Techniques for acquiring benthic samples have only recently been examined systematically. The type of organism sought dictates the method of sampling. For example, drag dredges must be used to recover certain forms such as mussels, but this technique then creates problems in converting results into quantitative units. Most benthic work has employed grab samplers. Because it is difficult to observe grab samplers at the actual moment of sampling, the effectiveness of these devices has largely been conjectural. Such samplers tend to produce a shock wave as they fall which could dislodge benthos as large as 8 cm (Wigley[890]). Sly[744] rated the popular Ekman dredge as adequate for work on soft sediments only, but considered the Petersen dredge, probably the most frequently used benthos sampler in the Great Lakes, to be a poor device for quantitative work on any bottom type. The ponar grab and the Shipek bucket sampler also received high ratings. Brinkhurst[92] reported that no grab sampler is adequate for sampling benthos such as the active oligochaetes, because the associated shock wave warns them; therefore, he developed the K-B core sampler.

In addition to inconsistencies in bottom sample recovery, there has been lack of uniformity in sample processing. Sediments are customarily screened through sieves or grit cloth to remove the benthos, but most meshes used are large enough to allow some of the smaller benthos such as ostracods and the polychaete, *Manayunkia*, to pass through. It is necessary to relate what is found in any given investigation to mesh size. Some workers have tried elutriation (Powers and Robertson;[625] Brinkhurst et al.[100]) and at least one attempted to float the benthos out in saturated sucrose solutions (Teter[788]).

Fixation of plankton and benthos in 5 to 10 percent formalin is a standard procedure and appears satisfactory except for forms with calcified structures. For these forms the formalin should be buffered by saturating with magnesium carbonate. Fixatives containing glycerine dissolve oligochaetes (Brinkhurst in comments following Davis[195]).

Some recently developed techniques for studying the plankton and benthos may deserve wider application. Robertson et al.[668] used a manned submersible to study *Mysis relicta*. Scuba diving has been used with success (Alley and Anderson[8]), but it requires some special techniques for realization of its full potential (Fager et al.[254]). McNaught[524,526] has been developing acoustical techniques for determining plankton distribution with simultaneous estimation of biomass.

The technical problems of plankton sampling have received considerable attention (Jossi;[439] Olson et al.[590]). Most quantitative plankton samples in the Great Lakes have been taken with the Clarke-Bumpus apparatus or the Juday plankton trap; little work has been done with pumps. Accurate estimates of the population of active zooplankters such as *Leptodora*, which are quite skillful in avoiding various sampling devices, are difficult to obtain (Davis[196]). The unreliability of single plankton samples was shown by Hubschman[388] (Figures 4–252 and 4–253). Daily variations in samples cannot be explained by real population changes and therefore reflect sampling deficiencies.

Another problem inherent in plankton sampling is the tendency of many species to swarm or clump, creating a high degree of heterogeneity in their dispersion through a relatively small area. Planktologists frequently report swarming or clumping of planktonic organisms. The benthos, which should be easier to sample because of their relative immobility, show the same phenomenon. Johnson and Matheson[434] found the standard deviation on counts of benthic organisms in replicate samples at the same station and time to range from 41 percent to 57 percent. Such variability questions the significance of anything less than order of magnitude differences when comparing numbers of organisms at two places or times. Investigators need to give careful thought to sampling programs. Results from systematic sampling patterns applied to the study of benthic organisms will be biased if the population or the environment contains a periodic variation in phase with the interval between samples (Alley and Anderson[8]). Replicate random sampling is recommended. Not only does this approach allow estimation of the mean and standard error, but certain environmental relationships may be revealed by the type of distribution of the data:

> If members of a population conform to a Poisson distribution, the density of individuals is low relative to the possible density that could exist in that area, and the members of the population are considered to be randomly spaced.
>
> If the effects of all environmental factors are small or the environmental factors are randomly distributed, the individuals will be dispersed as a normal distribution.
>
> Dispersion will follow the negative binomial $(q-p)^{-d}$ if one or a few environmental factors have a relatively great influence on the population. Individuals will occur in clumped groups under such circumstances.

Alley and Anderson found that small (2 mm) *Pontoporeia*, total *Pontoporeia*, and total benthos populations follow a normal distribution. Large *Pontoporeia* (7 mm), sphaeriids, and chironomids follow a Poisson distribution. Oligochaetes, on the other hand, follow the negative binomial, indicating their tendency to cluster. Distribution of oligochaetes is strongly and positively correlated with areas within which organic detritus is more abundant.

8.3.3 Taxonomic Problems

Advances in knowledge of the ecology of the plankton and benthos of the Great Lakes have been retarded by problems in identifying these organisms. The problems fall into two categories: those associated with inadequately resolved taxonomy, and those associated with difficulty in identifying species or the immature stages of a number of these invertebrates. As an example of the first category, Hiltunen[359] reported atypical forms of oligochaetes that did not belong to any presently known species classification. These forms may be either local variants or distinct species. As recently as the summer of 1970, Deevey[207] suggested that the Norther American plankton *Bosmina coregoni* should be subdivided into four species within a new genus, *Eubosmina*. The ecologist will be handicapped until the taxa are well defined.

Brinkhurst et al.[100] noted problems of the second category. Only adult tubificid worms can usually be identified at the specific level and only adult males among chironomid midges can be identified as to species. Copepods usually can only be speciated if they are adult males, although Czaika and Robertson[177] devised a tedious dissection method of identifying the copepodid stages of *Diaptomus* spp.

8.3.4 Floral Gradients in the Great Lakes

It is impossible to characterize any of the Great Lakes with a simple floristic description. Various regions within each lake have distinctive environmental properties that are reflected in differences in their phytoplankton communities. Therefore, investigation of the phytoplankton may reveal the prevailing ecological conditions in an area.

8.3.4.1 Lake Superior

There are six different offshore areas in the U.S. portion of Lake Superior on the basis of dissimilarities in diatom communities (Holland[371]). The most distinctive are the inner Apostle Islands area, which has the greatest standing crop (up to 2160 cells/ml), and the area west and southwest of the Keweenaw Peninsula, which has the least standing crop. Each area of the lake also exhibits its distinctive diatom species composition in terms of relative abundances, and some species are confined to single areas.

8.3.4.2 Lake Michigan

Damann[182] reported a consistent difference in the timing of phytoplankton pulses in southern Lake Michigan at Chicago and at Milwaukee. Phytoplankton near Chicago have vernal and autumnal pulses each year; near Milwaukee one annual pulse develops in the late spring and lasts most of the summer (see Subsection 8.3.6, on seasonal patterns in

TABLE 4–70 Abundance of Phytoplankton in the Western Basin of Lake Erie in 1930

Sector	Organisms/l
Maumee Bay	1260
Raisin River	751
Portage River	543
Islands	193
Detroit River	48

population fluctuations). Stoermer and Kopczynska[765] confirmed these observations and also described a similar late blooming of phytoplankton in the midlake portions of southern Lake Michigan. They also reported regional differences in the distribution of species, such as *Stephanodiscus hantzschii* which is largely confined to harbors and other inshore areas. Spring phytoplankton abundance from inshore to midlake is profoundly influenced by the thermal bar (Stoermer[764]) (see Sections 3 and 6). Spring phytoplankton standing crops were relatively higher on the warmer shoreward side of the thermal bar compared to the midlake side (1500–2000 cells/ml *vs.* 350–400 cells/ml). The greatest standing crop (3000 cells/ml) was found at the interface, within the thermal bar itself.

Consistent differences in areal distribution occur among species of *Melosira* from April through November (Holland[370]). *M. granulata* and *M binderana* were largely confined to Green Bay. *M. ambigua* was found in Green Bay and certain nearshore sites in Lake Michigan proper. *M. islandica* was usually found only in Lake Michigan proper. In a later study, Holland[372] found that *Fragilaria capucina* and *Stephanodiscus niagarae* were also more abundant in Green Bay than in the open lake. Additional lake species were *Tabellaria flocculosa*, *Cyclotella "glomerata-stelligera,"* *C. michiganiana*, *Asterionella formosa*, and *Stephanodiscus tenuis*. Average standing crops were higher in the bay than in the lake (944 *vs.* 517 cells/ml) as might be expected of a more enriched area.

8.3.4.3 Lake Huron

Two species of phytoplankton in Lake Huron show distinct, regional preferences (Fenwick[261]). *Tabellaria fenestrata* has a northern distribution, with some extension down the western shore to the mouth of Saginaw Bay, in surface waters. At five foot depth, the distribution extends further south and a general lakewide distribution becomes evident at 50 and 100 feet. The pattern suggests that water temperature influences the distribution of this diatom in Lake Huron. *Coelastrum reticulatum*, on the other hand, is restricted to the part of Lake Huron south of Saginaw Bay. It occurs at increasing depth further south in its range, which again suggests that temperature is involved, but that this species requires warmer waters than *Tabellaria fenestrata*.

8.3.4.4 Lake Erie

Wright et al.[918] found distinct differences between the phytoplankton communities of the Maumee Bay section and the island district of the western basin of Lake Erie in 1930. The phytoplankton in Maumee Bay usually maintained greater standing crops and abundance decreased with increasing distance from the mouth of the Maumee River. Mean abundance of phytoplankton in various sectors of the western basin in 1930 are shown in Table 4–70. The order of abundance of algal groups in Maumee Bay at that time was blue-green algae, green algae, and diatoms, whereas in the vicinity of the Bass Islands, diatoms were usually dominant.

Chandler and Weeks[136] reported that vernal and autumnal phytoplankton pulses in the western basin and at Cleveland were similar in overall duration, and in the spring, in species composition. The pulses began earlier in the season in the western basin, probably due to earlier warming of the shallow western basin.

Sullivan[767] found that the phytoplankton at the mouths of 10 Ohio tributaries to Lake Erie were essentially lake species and were similar at each entry. The more turbid tributaries, i.e., Maumee, Sandusky, and Portage Rivers, had lower standing crops at their mouths, but standing crops near the mouth of the Maumee River were still greater than in the open water of the western basin (Wright et al.[918]).

Michalski[535] reported a difference in the species composition of phytoplankton communities of the central and eastern basins as compared to the western basin. The central and eastern basins had significant populations of *Ceratium hirundinella*, *Peridinium* sp., *Pediastrum* sp. and *Staurastrum* sp. whereas the western basin did not. Michalski also found that phytoplankton standing crops, on the average, declined from west to east and noted that differences between vernal and autumnal phytoplankton pulses tended to be obscured, a symptom of eutrophication (Davis[191]). Snow and Thompson[750] also reported a west to east decrease in plankton standing crops and a distinction in the dominant plankton from each section. They correlated these differences with variations in concentration of hydroxyapatite in each of the basins. The pelagic portions of the central basin of Lake Erie include dominant diatom species that are distinctly different from those found in the western basin or nearshore in the central basin Hohn[368]). Within the western and central basins, the boundaries of water masses originating in the tributaries could be determined from qualitative and quantitative changes in the planktonic diatoms. All these observations tend to confirm a generally recognized west to east trophic gradient in Lake Erie.

8.3.4.5 Lake Ontario

Ogawa[586] found greater abundances of phytoplankton inshore near Toronto than farther out in the lake. Schenk and Thompson[718] were puzzled by the difference in long-term (1960 to 1963) standing crops determined at two nearby water filtration plants at Toronto. The Toronto Island plant, with intake located only 670 m (2200 ft) out into the lake, has an average standing crop slightly more than half that of the Harris plant, with intakes 2208 m (7500 ft) and 2430 m (7900 ft) out. The discrepancy might be due to the inhibition of photosynthesis by higher turbidity near shore. Nalewajko[568,571] reported that nearshore waters typically supported higher standing crops (514 cells/ml) compared with midlake areas of western and central Lake Ontario (201 cells/ml). *Stephanodiscus tenuis* was the most important species inshore but was displaced in midlake by *Melosira islandica* and *Asterionella formosa*. Phytoplankton were two to three times more abundant close to shore.

As might be expected, bays tend to be more enriched than exposed nearshore areas. Standing crops of phytoplankton in the inner portion of the Bay of Quinte were 10 times greater than those at the mouth of the bay (McCombie[516]).

8.3.5 Evidence of Changes in Great Lakes Flora

8.3.5.1 Lake Michigan

Damann[180] concluded that plankton standing crops had been increasing near Chicago since 1938, but he did not detect any trend of change in dominant species. Evidence of a long-term increase in phytoplankton standing crops is also evident in Chicago filtration plant records. Lackey,[479] on the other hand, reported both an increase in abundance of phytoplankton at the southern end of Lake Michigan and an increase in the number of genera and species of blue-green algae, diatoms and dinoflagellates. Chrysophyta, especially *Dinobryon*, are less important constituents of the Lake Michigan phytoplankton than earlier reports would suggest (Stoermer and Kopczynska[765]). They also reported that the diatom *Stephanodiscus hantzschii* is a relatively recent invader of Lake Michigan and occasionally creates nuisance blooms in the nearshore and in polluted harbors.

8.3.5.2 Lake Erie

Comparison of phytoplankton counts at the Cleveland, Ohio, Division Avenue Water Filtration Plant during the period 1927 to 1964 indicates two trends (Davis[198]).

First, there was a change in the species that predominated during various seasons. Dominance in the fall phytoplankton pulse shifted from *Synedra* to *Melosira* in the 1930s and 1940s and then to *Fragilaria* in the later years. *Melosira* replaced *Asterionella* as the dominant spring phytoplankton genus over the same period. Blue-green and green algae have recently become increasingly important at both seasons. *Melosira* and *Fragilaria* have also become predominant in the winter phytoplankton crop, displacing *Stephanodiscus* and *Cyclotella*. The trend away from diatoms and toward blue-green and green algae is also evident in the summer as *Anabaena* and *Pediastrum* have increased.

The second trend has been an overall increase in the phytoplankton standing crop, with the rate of increase accelerating after 1956 (Figures 4–257 and 4–258). Between 1929 and 1962 the mean annual increase in phytoplankton standing crop was 44.3 cells/ml/yr whereas the mean annual increase from 1956 through 1964 was 122.0 cells/ml/yr. This probably indicates an increasing rate of eutrophication (Figure 4–258). Background levels of

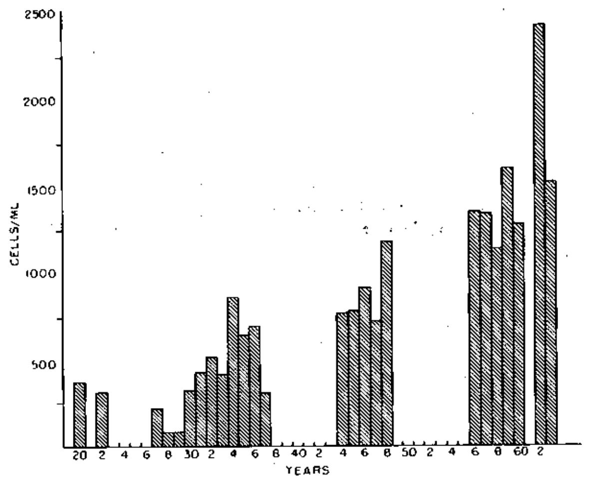

FIGURE 4-257 Average Phytoplankton Cells per ml for All Years with Complete Records, 1920 to 1963. Two weeks of records are lacking for 1960 near the height of the autumnal phytoplankton maximum.

After Davis, 1965

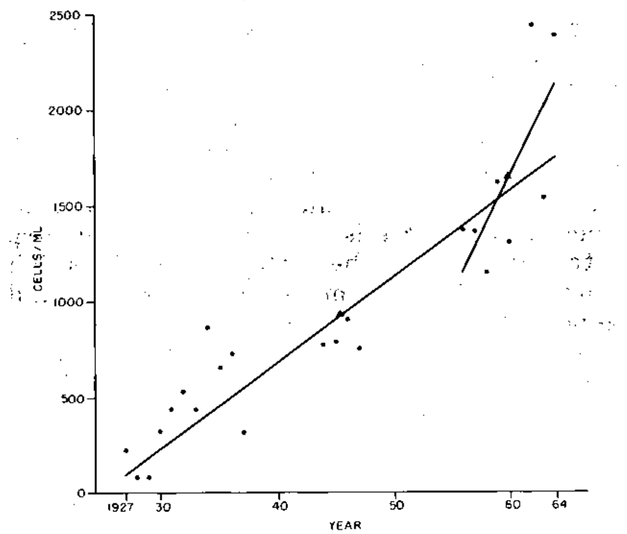

FIGURE 4-258 Regressions of Number of Phytoplankton Cells per ml Against Years. Each dot represents the average number of cells/ml for an entire year. For the years from 1927 through 1964 the regression is 41.3 cells/ml/yr. From 1956 through 1964 the regression is 122.0 cells/ml/yr.

After Davis, 1965

standing crops are increasing so that spring and fall pulses appear less pronounced.

Similar changes in dominant species have been noted in the western basin. *Asterionella formosa*, *Tabellaria fenestrata*, and *Melosira ambigua* were the dominant forms before 1950, but they have been supplanted by *Fragilaria capucina*, *Coscinodiscus radiatus*, and *Melosira binderana* (Verduin[853a]). *Cyclotella melosiroides*, a diatom unrecorded in western Lake Erie prior to 1950, has become a major component of the phytoplankton, comprising 75 percent to 95 percent of the phytoplankton volume in the winter and spring of 1954 (Hintz[361]). Hohn[368] reported changes in the diatoms of western Lake Erie from 1930 to 1935. The intensity of spring and fall pulses has quadrupled in contrast to the relative decrease in intensity at Cleveland during the same period. The planktonic diatoms of the open portions of the central basin of Lake Erie in 1960 were similar in species occurrence and abundances to those occurring in the Bass Island area of western Lake Erie prior to 1950. Four general categories of species change have occurred:

(1) Species that were present in large numbers and have disappeared or are rarely observed: *Cysotella stelligera*, *Rhizosolenia eriensis*.

(2) Species that were not present or rare and have now become dominant: *Melosira binderana*, *Diatoma tenue* var. *elongatum*, *Cyclotella meneghiniana*, *Stephanodiscus alpinus*, *S. tenuis*.

(3) Species that have remained stable quantitatively but have decreased drastically in percent occurrence: Tabellaria fenestrata, Asterionella formosa, Fragilaria crotonensis, Melosira granulata.

(4) Species that have increased in abundance but have maintained the same percent occurrence: *Melosira ambigua*, *Stephanodiscus* sp. 1.

The filamentous alga *Cladophora glomerata*, which always has been an important member of the periphyton and littoral benthos, has been increasing in abundance (Verduin[858]). This alga has become a nuisance in recent years because of the tendency for great masses of its filaments to break away from the substrate. These masses foul fish nets and beaches. The masses are often washed up on the beaches where they undergo decay. The resulting stench has forced closings occasionally with consequent economic loss to the resort industry.

Changes in abundance of aquatic macrophytes and benthic algae have been documented since the 1930s. In the case of the macrophytes, the change may be in the opposite direction than one would expect. As Davis[195] observed, "Lake Erie and Lake Ontario are deeply affected by enrichments from man's activities, so one would suspect that vegetation today would be much enriched compared to that many years ago. On the contrary, in the bays and ponds of Lakes Erie and Ontario, and in the Detroit and Niagara Rivers, . . . there has been a reported decrease." Two factors may override the expected fertilizer effect and reduce the abundance of macrophytes. One is the introduction of carp into Lake Erie in the 19th century. This fish uproots and eats some species of plants and generally stirs up the bottom. For example, vegetation density in a western Lake Erie marsh is inversely proportional to the carp population (King and Hunt[457]). The second influence is the increase in turbidity associated with increased silt entering the lakes.

8.3.5.3 Lake Ontario

Schenk and Thompson[718] detected trends in phytoplankton populations from a water intake near Toronto similar to those noted by Davis in central Lake Erie. Between 1923 and 1954 the standing crop approximately doubled, increasing by a mean of 5.6 areal standard units per year. The dominant genera in the spring pulse changed from *Asterionella to Cyclotella* and *Melosira* during this period.

McCombie[516] compared the results of his 1963–64 study of phytoplankton at the mouth of the Bay of Quinte with one conducted in 1945 (Tucker[804]). There was no clear indication of a trend toward larger standing crops, but the proportion of phytoplankton belonging to the genera *Tabellaria* and *Fragilaria* was smaller in 1963 and 1964 than in 1945. Also, the blue-green alga *Aphanizomenon* began to bloom a month earlier during the more recent study.

8.3.6 Patterns of Seasonal Change in Great Lakes Algae

8.3.6.1 Lake Superior

Putnam and Olson[635] observed only a single phytoplankton pulse during the period mid-June to late October, 1960; the peak occurred in July.

8.3.6.2 Lake Michigan

Daily[179] and Damann[183] observed a typical bimodal pattern for phytoplankton standing crops in 1937 to 1939 in southern Lake Michigan near Evanston, Illinois. Both the vernal and autumnal pulses were due to diatom maxima; other algal groups made only minor contributions to the overall standing crop. Later observations of phytoplankton seasonal patterns in Lake Michigan from the same site at Evanston indicate a significant change in phytoplankton composition over a relatively short period of time (Griffith[303]). A major spring pulse was observed in 1953 followed by five minor pulses at other times of the year. The blue-green algae *Cyanophyta* predominated over much of the year, falling below 50 percent of the standing crop only about 12 percent of the time.

Damann[182] compared Chicago waterworks data collected since 1926 with similar data collected at Milwaukee since 1940. A unimodal plankton peak occurs near Milwaukee, usually in July, whereas a typical bimodal peak occurs near Chicago.

Damann correlated these phenomena with temperature; the optimum temperature for the growth of diatoms, the principal component of Lake Michigan phytoplankton, lies between 10°C (50°F) and 14°C (57°F). The different peaks indicate the sensitivity of these organisms to temperature variations at the two intakes.

Stoermer and Kopczynska[765] described the vernal phytoplankton pulse as beginning in nearshore areas and coinciding with the progressive seasonal warming of water out into the open lake. This is not inconsistent with Damann's observations. They also suggested that the autumnal pulse may follow a reversed pattern as the lake cools, but the data are inconclusive. Stoermer and Kopczynska also found that phytoplankton at Milwaukee tends to pulse at about the same time as the midlake phytoplankton from the southern part of Lake Michigan. This is further confirmation of Damann's observations and suggests that a unimodal curve is characteristic of most of the lake. Control of phytoplankton population changes is probably not so simple because other temperature-related factors such as nutrient redistribution must certainly have an influence (Stoermer and Kopczynska[765]). Nearshore phytoplankton communities in Green Bay and near Ludington, Michigan, exhibit the typical bimodal annual abundance curve, whereas the communities of the open portions of upper Lake Michigan have a unimodal curve with the peak developing in the summer (Holland[372]). Since inshore water warms earlier and exceeds 14°C (57°F) during the summer, these areas can be expected to have bimodal phytoplankton abundance curves in accord with Damann's observations, whereas the slower-warming open lake will not. In this manner the number of pulses in a year may relate to location in the lake.

8.3.6.3 Lake Erie

Chandler[131,133,134] and Chandler and Weeks[136] determined that phytoplankton standing crops in the island district of the western basin follow the classical pattern for temperate zone lakes in having both a vernal and autumnal pulse. The main results of these studies are summarized in Table 4–71. The onset and duration, as well as the maximum development, of these pulses is quite variable. The spring pulses were almost completely dominated by diatoms, especially *Asterionella*. Blue-green and green algae become significant in the fall pulses. Chandler concluded that temperature and turbidity, rather than chemical factors control the magnitude of these spring phytoplankton pulses. In contrast, the fall pulses might be limited by a variety of chemical or physical factors.

Seasonal patterns were the same in 1929 and 1930 (Wright et al.[918]). Spring pulses occurred in May to June and were due almost entirely to diatoms. Autumnal pulses occurred in September to October with blue-green and green algae as well as diatoms present (Figure 4–259).

From records of Cleveland's Division Avenue Filtration Plant, Chandler observed that the overall duration of pulses is about the same as at the islands, but that both spring and fall pulses at Cleveland contained a smaller proportion of blue-green and green algae. Also annual variations in standing crop were more moderate than in the western basin.

From similar studies over a number of years in Cleveland Harbor and several miles outside the harbor, Davis[193,196] observed seasonal phytoplankton patterns similar to those observed in the western basin. The 1950 to 1951 seasonal succession of plankton categories was also essentially the same; phytoplankton were virtually 100 percent diatoms from winter through the spring pulse and remained dominant through summer and fall with green and blue-green algae becoming relatively more important. By 1956, blue-green algae were dominant in autumn and diatoms dominated in winter. In 1957, phytoplankton populations

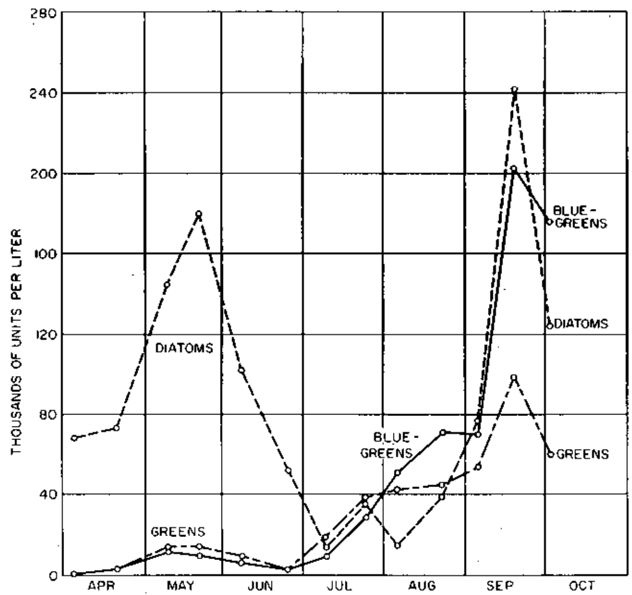

FIGURE 4–259 Seasonal Distribution of Diatoms, Green Algae, and Blue-Green Algae in the Island Section of Lake Erie, 1930
Data from Wright et al., 1955

in mid-June were phytoflagellates with some green algae. In July diatoms were predominant but were subordinate to an enormous algae bloom in the fall. Twenty-two investigations agree that diatoms are dominant in the spring, but the dominant genera vary between *Asterionella*, *Cyclotella*, and *Melosira* (Davis[194]).

Based on weekly samples from water intakes at 16 municipalities along the Canadian shore of Lakes Erie and Ontario from March 1966 to November 1967 and supplemented by samples, Michalski[535] reported that the phytoplankton in most locations conformed to the typical bimodal abundance pattern although some appeared to have three annual peaks. The most peculiar results were obtained from Kingsville, Ontario, where the plankton seemed to be in continuous bloom from October 1966 to November 1967. Michalski also reported the four dominant genera of phytoplankton for each season for the three Lake Erie basins. In neither 1966 nor 1967 were *Asterionella*, *Cyclotella*, or *Melosira* among the top four in any basin as Davis had reported 10 years earlier. Those dominant were usually *Stephanodiscus niagarae*, *Fragilaria capucina*, *Fragilaria crotonensis*, and *Tabellaria fenestrata*.

In the early summer of 1969, Kleveno et al.[459] found extensive beds of the benthic algae *Tribonema utriculosum* and *Oedogonium* sp.

TABLE 4-71 Seasonal Patterns in Phytoplankton Standing Crops, 1938–1942, in Lake Erie

	Autumnal Pulse		Vernal Pulse	
Pulse Duration	1938:	early Sept.--late Oct.	1939:	late Feb.--early April
	1939:	mid-Aug.--mid Nov.	1940:	mid-March--late May
	1940:	early Sept.--late Sept.	1941:	early Feb.--late May
	1941:	late July--late Nov.	1942:	early Feb.--mid-April
	1942:	mid-July--late Nov.		
Maximum Standing Crop (orgs./l)	1938:	330,000	1939:	247,000
	1939:	320,000	1940:	374,000
	1940:	95,000	1941:	971,000
	1941:	409,000	1942:	459,000
	1942:	470,000		
Composition (% diatoms)	1938:	70-90	1939:	50-100
	1939:	25-55	1940:	98
	1940:	77	1941:	98
	1941:	50	1942:	94
	1942:	76		

Source: Chandler, 1940, 1942b, 1944, 1945.

in the central basin hypolimnion. Light penetration was sufficient at that time to permit their growth. Kleveno et al.[459] postulated that the algae were killed in August by a reduction in light penetration because of an increase in the plankton in the epilimnion. The decomposing benthic algae caused a tremendous increase in biochemical oxygen demand, aiding in depletion of dissolved oxygen levels characteristic of the hypolimnion of Lake Erie's central basin in late summer. This observation has been essentially confirmed as a result of work carried out during 1970.

8.3.6.4 Lake Ontario

Schenk and Thompson[718] detected the bimodal annual phytoplankton curves at Toronto in most years from 1923 to 1954, but summer pulses were observed during five of these years. Autumnal peaks did not develop consistently in every year and were characteristically less pronounced than those in spring. The dominant genus of the spring pulse was *Asterionella* in the earlier years, but since 1941 *Cydotella* has often been codominant or dominant. On the basis of the Damann observation (Subsection 8.3.6.2) the phytoplankton at Toronto Island water intake may exhibit either one or two pulses, depending on temperature development and water mass movement. Nalewajko[571] observed the same phenomenon as in Lake Michigan in which the vernal phytoplankton bloom occurs first near shore and subsequently progresses into the open lake coincident with warming water. Both *Stephanodiscus tenuis* and *Melosira islandica* peaked and declined earliest at Gibralter Point, later 13 miles out, and still later 18 miles into the lake.

8.3.7 Trophic Relations

8.3.7.1 Primary Productivity

Primary productivity is the rate of community photosynthesis and is one of the best indications of the degree of eutrophication of a body of water. Productivity in aquatic habitats may be limited by factors such as temperature, light, the availability of carbon dioxide and the availability of other nutrients such as phosphorus and nitrogen. The process of photosynthesis can be simply represented:

$$\text{light energy} + 3CO_2 + 3H_2O \xrightarrow{\text{chlorophyll}} C_3H_6O_3 + 3O_2 + \text{organic energy}$$

Total community productivity is usually estimated by measuring the amount of carbon dioxide consumed or oxygen produced during a given time. Respiration, which is essentially the reverse process, occurs simultaneously with photosynthesis and also at night when photosynthesis cannot take place. Respiration can be represented as:

$$C_3H_6O_3 + 3O_2 + \text{organic energy} \longrightarrow 3CO_2 + 3H_2O + \text{heat energy}$$

Respiration is a function of all living things whereas photosynthesis is carried on only by green plants and certain bacteria. Gross primary productivity is the rate of production of new organic matter and is synonymous with the rate of photosynthesis. Net primary productivity is the rate of production of new organic matter that is not immediately consumed in respiration; thus the important relationship is as follows:

$$\text{net productivity} = \text{gross productivity} - \text{respiration rate}$$

Net productivity is of considerable interest in management of aquatic ecosystems. It indicates how much organic material is available either for additional growth within the system or for export out of the system. Export includes any harvest, such as fish, taken by humans. Growth of organisms within the system may not be desirable, as with the massive algal blooms of western Lake Erie or the population explosions of alewife.

It is customary to refer to the total respiratory activity of all organisms in a particular area as community respiration. If an ecosystem is in balance, then the gross primary productivity will equal community respiration. If the ecosystem is unbalanced, as when large amounts of organic material enter from the outside, then the gross primary productivity will equal community respiration plus net productivity.

Comparison of productivity and respiration data between the Great Lakes, or between different parts of the same lake, yields information on trophic conditions, including how much organic material is produced in the lake, how much is imported, and how organic material is utilized within the lake. Such data are more accurate in estimating the enrichment of a lake than biomass data or population data. High biomass and large population (standing crops), may not be indicative of high energy levels. Conversely, a small population may very actively metabolize energy. For example, summer phytoplankton populations are relatively low, but they support relatively high populations of zooplankton. The zooplankton are consuming the phytoplankton about as rapidly as they produce new cells. Thus, the phytoplankton may be highly productive, but they show no increase in numbers or biomass.

Since productivity data are so important, masses of such data should be available for the Great Lakes; however, this is not the case. Only a few productivity studies have been made. Even fewer studies of community respiration have been made. The range of productivity estimates for all the lakes is considerable (Table 4–72) and it is obvious that insufficient data have been accumulated to make many conclusions about the general levels of productivity in the Great Lakes. No productivity data are available for Lake Huron. The estimates reported for Lake Erie generally support the idea that this lake, and especially its western basin, is more productive than the other Great Lakes. Western Lake Erie is apparently much more productive than many smaller lakes that are considered eutrophic (Saunders[701]).

The wide range of productivity estimates in each lake is due partly to short-term environmental changes. For example, daily differences in temperature and sunlight cause fluctuations in production rates. The time of day at which the measurements are made also affects results (Verduin[855]). Another source of the variance in estimates of primary productivity is in the techniques of measurement (Gessner and Pannier,[296] Verduin,[859,861,862] Manny and Hall[511]). Great Lakes researchers should agree on some standard technique for estimating productivity.

Another problem in comparing productivity data is the reporting of results in noncomparable terms. Most results are reported in milligrams of carbon per square meter per day (mg C/m^2/da). Areal units such as these are preferable to volumetric units since light flux through the water surface determines the total amount of light energy available for photosynthesis. Much of the volume in the water column below the surface may be in the tropholytic zone, therefore productivity per unit volume cannot be related to productivity per unit area in any simple way. Unfortunately, some productivity studies report in volumetric terms with insufficient data for conversion to areal terms. Productivity data are occasionally reported in terms of carbon fixed per unit of standing crop of phytoplankton. This has revealed useful information about the nature of the photosynthetic process. For example, McQuate[529] and Verdiun[858 859] showed that productivity per cell is

TABLE 4–72 Comparison of Estimates of Gross Primary Productivity in the Great Lakes

Location	P_g (mgC/m^2/da)	Investigator
Lake Superior	185-1260	Putnam & Olson (1961)
	50- 260	
	76- 507	Putnam & Olson (1966)
Lake Michigan		
near Sturgeon Bay	114- 193	Saunders, unpublished
Grand Traverse Bay	359-1160	Saunders, et al., (1962)
Grand Traverse Bay	295- 536	Saunders, et al., (1962)
Grand Traverse Bay	260	Saunders, unpublished
near Grand Haven	8900	Manny & Hall (1969)
Lake Ontario		
Bay of Quinte	218-2560	Tucker (1949)
Lake Erie		
Western Basin	2640[a]	Verduin (1956)
Western Basin	1680[b]	Verduin (1956)
Western Basin	4558	Verduin (1959)
Western Basin	6150	Verduin (1962)
Western Basin	756-7340	Tucker (1949)
Western Basin	2160-4320	Verduin (1962)
Western Basin	97.6-371.5	Saunders, unpublished
Sandusky Bay	50-36000	McQuate (1956)
Central Basin	10650	Dobson (1967) after Manny & Hall (1969)

[a]In summer

[b]Mean July-January

SOURCE: Saunders, 1964

inversely related to standing crop of phytoplankton. In some way the phytoplankton are self-inhibiting, perhaps through competition for light, nutrients or carbon dioxide.

8.3.7.2 Extracellular Production

A portion of the well-known Odum[585] model of energy flow through an ecosystem showing only the producer level is depicted in Figure 4–260. Width of the energy line is proportional to the amount of energy flowing along each route. Limnologists are interested in net primary production because this category includes food energy available to nurture the primary consumers which may be fish or fish-food organisms. Only a part of the net primary production may be used by primary consumers with portions going into the non-used (NU) category. Part of the NU material is detritus, formed when producer organisms die without

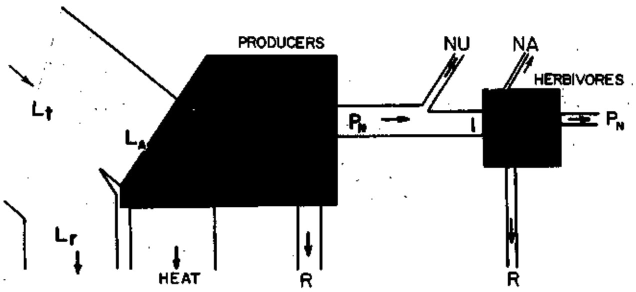

FIGURE 4–260 Energy Flow Through Producer Trophic Level

After Odum, 1971

B_1 = Biomass of producers
B_2 = Biomass of primary consumers (herbivores)
L_t = Total light energy striking producers
L_r = Light reflected from producers
L_a = Light absorbed by producers
P_G = Light energy captured as gross production
R = Energy lost in respiration (as heat)
P_N = Energy available for growth or transfer to next trophic level (net production)
I = Energy intake (food) for the next trophic level, the primary consumers
NU = Energy not used by the next trophic level
NA = Energy not assimilated (feces, etc.)
A = Energy assimilated

being eaten. The remainder represents soluble excretory products that are sometimes collectively termed the extracellular production. Both the detritus and the extracellular production can serve as food to heterotrophic bacteria. Extracellular production can amount to as much as 90 percent of the total photosynthetically-fixed carbon (Fogg[265]) although it is more commonly in the range of 1 percent to 3 percent (Nalewajko[568]). The amount of extracellular production seems to be correlated with phytoplankton growth rates (Nalewajko and Martin[572]). Therefore, in careful ecosystems analyses, extracellular production should not be ignored.

In addition to serving as a food source for bacteria, substances in the extracellular production appear to have other functions of significance to the ecosystem. Some algae excrete polypeptides that act as chelating agents for various metal ions such as copper, zinc, and ferric iron. For example, *Anabaena cylindrica* produces a polypeptide that isolates copper sufficiently well to protect the alga from the toxic effect of this ion (Fogg and Westlake[266]). The actual function of these products, however, may be to keep trace elements available. Another function suggested by Fogg[265] is extracellular digestion. At least one alga excretes a glutaminase that hydrolyzes glutamine to glutamic acid and ammonia. The alga uses ammonia as a nitrogen source. Many kinds of algae seem to release large amounts of their production as glycolic acid. This substance may be a growth regulator since laboratory work shows that algal cultures will not enter into the log growth phase until a certain minimal amount of glycolate has accumulated in the medium (Fogg[265]). This suggests that sudden onset of plankton blooms may be due to the accumulation of threshold levels of glycolic acid in lake water.

The antibiotic or toxic substances released by some kinds of algae are another important extracellular product. These are discussed in Subsection 8.3.10.4.

Even less is known about the primary productivity of other members of the first trophic level than is known about phytoplankton. There are apparently no published reports on the productivity of the aquatic macrophytes of the Great Lakes, and only two on the periphytic algae. Productivity of *Cladophora fracta* in Lake Ontario ranged from 1.27 ml O_2/hr/mg ash-free dry weight (AFD wt) in the fall to 2.63 ml O_2/hr/mg AFD wt in the early summer at Oswego. At Henderson Bay, some 50 km away, the range from fall to early summer was 0.50 ml O_2/hr/mg AFD wt to 2.35 ml O_2/hr/mg AFD wt (Jackson[418]). Early summer levels were about the same, but the fall productivity at Oswego may have been 2½ times greater than at Henderson Bay. The lack of information on the productivity of periphytic algae and aquatic macrophytes makes it impossible to compare their production relative to that of the phytoplankton for any of the Great Lakes. However, because of the extensive habitat of phytoplankton, they must be considered by far the most important.

8.3.7.3 Relation of Standing Crop to Productivity

Much of the apparent primary production measured under natural conditions cannot be accounted for on the basis of the standing crop of phytoplankton. Lake Erie, which is probably representative of temperate zone lakes, exhibits vernal and autumnal diatom maxima with winter and summer minima, but the annual photosynthesis curve is not bimodal; it peaks in summer when the diatom crops are at a minimum. Identification of the organisms responsible for this photosynthetic activity constitutes a major problem in assessment of primary production (Verduin[862]). McQuate[529] observed productivities averaging 2.3 μmol CO_2/l/hr in Lake Erie water from which the phytoplankton had been removed. Since algae were apparently not responsible for the observed production, McQuate speculated that the metabolism of bacterial communities (chemosynthetic, photosynthetic, and reducers) may contribute to the inverse correlations observed. Both Verduin and McQuate estimated primary production from carbon dioxide consumption. However, photosynthesis is only one of the metabolic processes which consumes CO_2, and neither author seems to have considered carboxylation by bacteria as an alternative explanation for the primary production they observed in the absence of phytoplankton. During the exponential growth phase of a community, synthesis of organic acids may utilize considerable CO_2 (carboxylation) above the quantities used in glucose production, and this process accounts for the low ratio of O_2:CO_2 change (Verduin[861]). Another explanation is that a productive phytoplankton community may be cropped off so rapidly by predators that their productivity is not expressed as a large standing crop. This is a significant problem because it represents a possible source of error in attempts to characterize the Great Lakes on the basis of their primary production and community respiration rates.

8.3.7.4 Relation of Algal Production to Dissolved Oxygen

The popular phrase "oxygen-consuming algae," conveys a misleading impression of the role of algae in eutrophication which could lead to incorrect decisions and improper action by planners, political leaders and the general public. The following statements would more correctly describe the relation of algal production to dissolved oxygen:

(1) Healthy, functioning algae produce much more oxygen than they consume.

(2) Oxygen is consumed in the Great Lakes by the respiration of plants and animals and in the microbial decomposition of dead organic matter.

(3) Decomposition of dead algae consumes oxygen just as the decomposition of sewage and other organic matter which enters the lakes via streams.

(4) Late summer depletion of hypolimnetic dissolved oxygen in the central basin of Lake Erie is due to the decomposition of masses of algae.

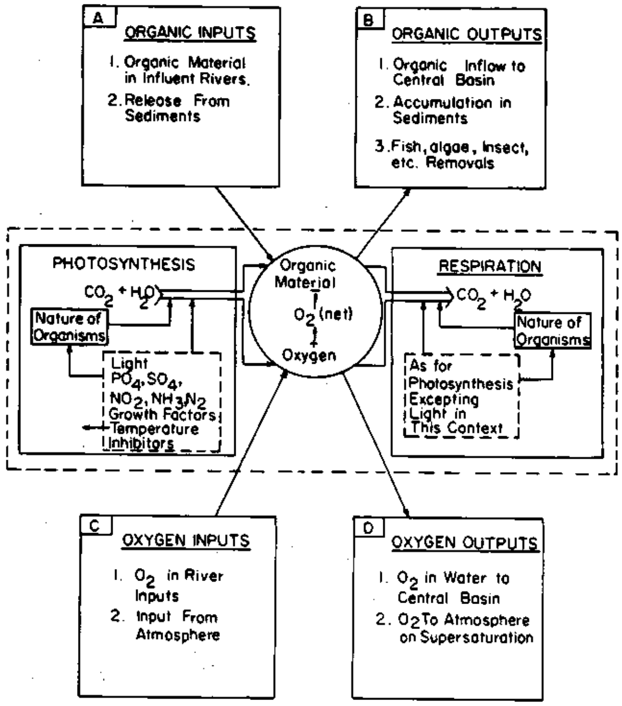

FIGURE 4–261 Elements of the Physical-Biological System of Western Lake Erie, with Oxygen as the Measure of Performance

From Randles et al., 1970

(5) Sudden die-offs of algal blooms in surface waters can lead to the depletion of dissolved oxygen.

(6) Organic material entering the lakes may be directly responsible for depletion of dissolved oxygen, as in western Lake Erie during periods of stagnation.

The interrelations of various factors which influence dissolved oxygen levels are summarized in Figure 4–261.

8.3.7.5 Secondary Production

Data on the algae and macrophytes found in the stomachs of 13 species of Great Lakes fish have been compiled from the five reports that contain such data, and are shown in Table 4–73. Many reports list invertebrates and fish in stomach contents, and some, not cited here, mention debris of unidentified plant origin in stomachs of fishes feeding mainly on invertebrates. However limited the information in Table 4–73 may be, it does indicate a distinct preference among fish for diatoms and green algae. Dinoflagellates and especially blue-green algae seem to be avoided relative to their natural abundance and diversity. The

TABLE 4–73 Algal and Macrophyte Food of Great Lakes Fishes as Determined by Stomach Analyses

Organism	Fish
Chrysophyta	
Diatoms	gizzard shad
Amphora ovalis	walleye (fry)
Cocconeis placentula	walleye (fry)
Coscinodiscus radiatus	walleye (fry)
Cyclotella meneghiniana	walleye (fry)
Cymatopleura sp.	bluntnose minnow
Cymatopleura solea	walleye (fry)
Cymbella sp.	pearl minnow
Diatoma elongatum	walleye (fry)
Encyonema sp.	bluntnose minnow, stoneroller
Fragilaria capucina	walleye (fry)
Fragilaria crotonensis	walleye (fry)
Fragilaria vaucheriae	walleye (fry)
Gomphonema sp.	bluntnose minnow, pearl minnow
Melosira ambigua	walleye (fry)
Melosira binderana	walleye (fry)
Melosira granulata	walleye (fry)
Meridion sp.	stoneroller
Navicula sp.	bluntnose minnow, pearl minnow, common shiner, golden shiner, stoneroller
Nitzschia gracilis	walleye (fry)
Nitzschia sigmoidea	walleye (fry)
Pleurosigma sp.	pearl minnow
Stephanodiscus astraea	walleye (fry)
Surirella augusta	walleye (fry)
Synedra sp.	bluntnose minnow, pearl minnow, common shiner, stoneroller
Synedra acus	walleye (fry)
Synedra ulna	walleye (fry)
Tabellaria fenestrata	walleye (fry)
Pyrrhophyta	
Dinoflagellates	gizzard shad
Ceratium hirundinella	walleye (fry)
Cyanophyta	
Blue-green algae	gizzard shad
Gomphosphaeria lacustris	walleye (fry)
Merismopedia sp.	golden shiner
Merismopedia tenuissimum	stoneroller
Oscillatoria sp.	bluntnose minnow, yellow perch, pearl minnow, common shiner, golden shiner
Chlorophyta	
Green algae	gizzard shad
Characium sp.	pearl minnow
Cladophora sp.	
Closterium sp.	bluntnose minnow, redpin shiner, bullhead, redhorse
Cosmarium sp.	bluntnose minnow, pearl minnow, redpin shiner
Cosmarium cyclicum	stoneroller
Oedogonium sp.	bluntnose minnow, pearl minnow, redpin shiner, stoneroller
Pediastrum sp.	bluntnose minnow, stoneroller
Pediastrum boryanum	walleye (fry)
Pediastrum duplex	walleye (fry)
Pediastrum simplex	walleye (fry)
Scenedesmus sp.	bluntnose minnow, pearl minnow
Scenedesmus abundans	stoneroller
Scenedesmus acuminatus	walleye (fry)
Scenedesmus arcuatus	stoneroller
Scenedesmus bijuga	stoneroller
Scenedesmus dimorphus	stoneroller
Spirogyra sp.	walleye (fry), bluntnose minnow, yellow perch, pearl minnow, redpin shiner, stoneroller
Staurastrum alterans	stoneroller
Staurastrum sebaldi	walleye (fry)
Ulothrix sp.	bluntnose minnow, yellow perch, largemouth bass, pearl minnow, redpin shiner, golden shiner, stoneroller, redhorse
Macrophytes	
Potamogeton sp.	mooneye
Scirpus sp.	mooneye

SOURCES: Bodola, 1949; Boesel, 1938; Hohn, 1966; Sibley, 1929; Tressler and Austin, 1940.

odorous or toxic substances associated with these algae may be fish repellants. Renn[645] noted that blue-green algae make poor fish food.

The principal consumers of phytoplankton apparently are zooplankton rather than fish, although Edmonson[238] has noted that zooplankters seldom contain recognizable algal cells in their digestive tracts. Feeding preferences of zooplankton may involve chemical selection, but particle-size selection is definitely involved (Burns[116]). There is no information concerning algal species that may be preferred by given species of zooplankton. Filamentous algae are probably not grazed by most zooplankton because of their shape. Consumption of phytoplankton by zooplankton may be very heavy at times. Davis[193] noted the simultaneous existence of minimum phytoplankton and the maximum of the larger zooplankters in both 1957 and 1951. This supports the hypothesis (Davis[197]) that the summer minimum is caused primarily by grazing activities of the zooplankton, although settling of algae could also be a factor.

8.3.8 Factors that Control the Growth and Abundance of Algae

8.3.8.1 Inorganic Nutrients

Any chemical element that is an essential component of one or more living plant molecules can theoretically limit the growth of algae if it is in short supply. Practically speaking, however, only a few of 23 biologically essential elements actually limit algal growth under natural conditions. The ones that most logically could be limiting are phosphorus, nitrogen and carbon. Levels of free silicon have been declining in Lake Michigan since 1926 and this nutrient may now be limiting for diatom growth in Lake Michigan (Stoermer[764]). Identifying the limiting nutrient, if only one is limiting, could help to focus efforts into reducing abundance of that element. Money might be saved by selecting the correct approach to reducing massive blooms of algae, one of the symptoms of eutrophication.

The concept of limiting factors incorporates the generally accepted idea that, at any given time, one environmental factor (in this case, a nutrient) will limit the growth of algae (Figure 4–262). The amounts used in Figure 4–262 are hypothetical and only serve to illustrate the principle. If the concentrations of all the ele-

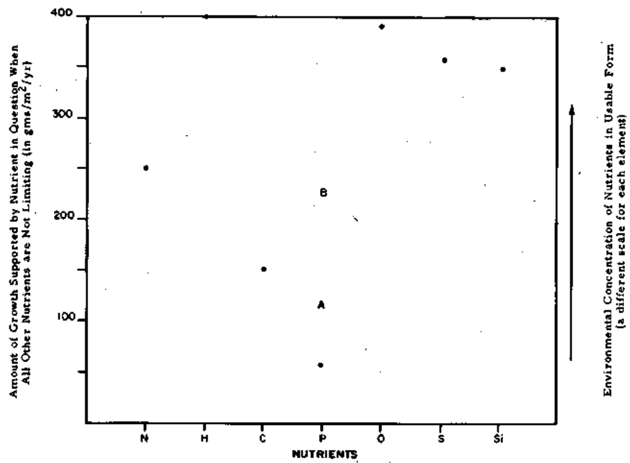

FIGURE 4–262 Hypothetical Concentrations of Some Nutrients Essential for Algal Growth, Illustrating the Concept of Limiting Nutrient

ments are represented by solid dots, P is limiting because its concentration permits growth only up to 50 gm/m²/yr. If the concentration of P is increased to position A, it is still the limiting element, but growth is increased to 125 gm/m²/yr. If the concentration of P is further increased to position B, P is no longer limiting because it no longer represents the least concentration. Instead C now becomes limiting. In this example, the concentrations of all the elements except one have remained constant, while in nature, nutrients are continually removed and added to the water by organic activities and by interactions with the sediments, the atmosphere, and surrounding land areas. Therefore, the nutrients present are also continually changing from forms available for plant nutrition to unavailable forms and back again. It is possible, therefore, for several different nutrients to be limiting at different times. One method for controlling algal growth and lowering the trophic state of a lake is to determine which nutrient appears to be limiting most of the time and to devise a feasible way of reducing its availability. The effect of the other elements would then be negligible as far as phytosynthesis and plant growth are concerned.

8.3.8.2 Phosphorus

Correlations between increasing concentration of phosphorus and increased algal growth are common in literature describing the Great Lakes. However, such correlations do not necessarily indicate phosphorus as the factor responsible for stimulating algal growth. Studies that have followed the concentrations of all the major nutrients simultaneously or that involve some experimental manipulation of the environment are not numerous in the Great Lakes. Furthermore, the few that have been done have produced some divergent opinions.

Neil and Owen[574] conducted an experiment on the influence of nutrients on *Cladophora* growth in Lake Huron, a lake in which this form does not normally grow. Several experimental sites were selected that appeared to have the physical characteristics necessary for growth of *Cladophora* except that nutrient levels were low. Several rocks covered with a growth of *Cladophora* were placed in each area. One area was fertilized with inorganic nitrate, another with inorganic phosphate, another with a mixture of inorganic nitrate, phosphate and potassium, and a fourth with sheep manure. Growth occurred in the latter three sites, but not in the first, although the *Cladophora* persisted there all summer. Neil and Owen surmised that phosphorus was limiting for *Cladophora* growth at these sites. On the other hand, Curl[174] concluded the opposite: that phosphorus is probably never limiting in the southern waters of Lake Erie. Jackson[418] demonstrated that phosphorus actually was limiting in Lake Ontario near Oswego. *Cladophora fracta* photosynthesis was stimulated to an extra 0.17 μg O^2/hr/mg AFD wt to 1.04 μg O^2/hr/mg AFD wt by the addition of phosphorus ($P^{32}O_4^{-3}$). Verduin[858] suggested that the metabolism of *Cladophora* is linearly proportional to the phosphorus supply in the 10 to 40 $\mu g/l$ concentration range. He reported the photosynthetic rates that appear in Table 4–74.

Davis[193] found from empirical analysis that the concentration of phosphorus and other nutrients in water showed no consistent correlation with phytoplankton standing crops. Because of time lag and utilization, algal properties presumably correlate most satisfactorily with conditions over the previous several weeks than with conditions existing at the time of the study. Consequently, *in situ* lake experiments appear to be the most promising approach to determining which factors are limiting under natural conditions.

8.3.8.3 Nitrogen

Nitrogen is often dismissed as a possible limiting factor for phytoplankton growth because molecular nitrogen, which is abundant in the atmosphere and dissolved in water, can be converted into biologically usable forms. Certain bacteria and some blue-green algae fix nitrogen. Therefore, if algae themselves can provide an unlimited supply of usable nitrogen, then the environmental source can never be limiting. However, Williams and Burris[893] found that only three blue-green algae species out of a group of ten could fix nitrogen. Even those species that are capable of fixing nitrogen do not do so at all times. The circumstances that induce nitrogen fixation are not well known. Taha[784] found that nitrogen fixation by *Anabaena*, *Calothrix*, and *Haplisiphon* increases with increasing light intensity and reaches a maximum at intensities far in excess of photosynthetic saturation levels.

In 1964, Casper[128] investigated a massive blue-green algal bloom consisting mainly of *Microcystis cyanea*, *Oscillatoria* sp., *Carteria* sp., *Aphanizomenon holsaticum* and *Anabaena circinalis* and concluded that nitrogen was limiting at the time of the bloom because nitrate nitrogen was extremely low (0.05 mg/l) while the total soluble phosphorus was at a level known to be non-limiting (0.13 mg/l). As mentioned above, however, correlation with existing conditions is nonconclusive.

TABLE 4–74 Photosynthetic Rates of *Cladophora* Relative to Phosphorus Concentration

Lake	Photosynthetic Rate (μmol CO_2/ml/hr)	Phosphorus (μg)
Northern Lake Michigan	37	5
Western Lake Erie (1949–50)	33	8
Eastern Lake Erie	35[1]	10
Western Lake Erie (1966–68)	153	30–40

[1]Approximate number

SOURCE: Verduin, 1969

8.3.8.4 Carbon

Carbon dioxide is a major raw material in photosynthesis, but it has generally been thought that so much bound CO_2 is in reserve in the water and in the atmosphere that CO_2 could never be in short supply. The flux routes that have an influence on dissolved CO_2 are shown in Figure 4–263. When CO_2 is removed from water for photosynthesis, its deficiency is not made up instantaneously from the atmosphere or the buffer system; otherwise, photosynthesis could not be measured by changes in

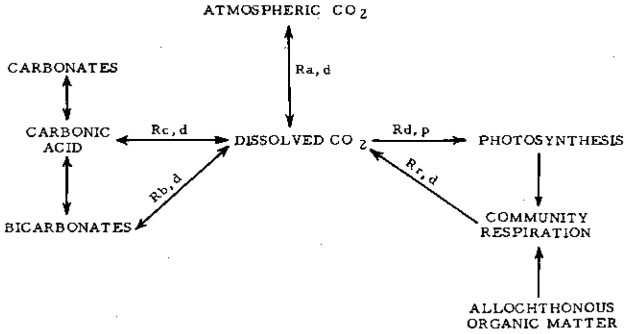

FIGURE 4–263 Sources and Sinks for Dissolved Carbon Dioxide. (Ra): respiration of atmospheric CO_2. (Rb): respiration of bicarbonates. (Rc): respiration of carbonic acid. (Rd): respiration of dissolved CO_2. (Rp): respiration of photosynthesis. (Rr): community respiration.

pH and alkalinity that are affected by changes in CO_2. A concern then is whether CO_2 concentration ever becomes low enough to limit photosynthesis of algae in the Great Lakes.

Kuentzel[478] stimulated renewed interest in CO_2 as a limiting factor. The basic points of his paper may be summarized as follows:

> Carbon dioxide is the major nutrient required for algal growth.
>
> The large amounts of CO_2 required for fast-growing massive algal blooms of blue-green algae cannot come from the atmosphere and/or dissolved carbonate salts via the normal physical-chemical processes. At most, about one mg/l of free CO_2 accumulated over a period of many hours or days can be expected.
>
> While phosphorus is a necessary element for algal growth, the amounts required to support massive blooms are quite low, about 0.01 mg/l (10 ppb) or less.
>
> The action of bacteria on ample amounts of organic matter can supply as much as 20 mg/l of CO_2 in a supersaturated state. Explosive logarithmic growth rates of bacteria under favorable conditions can deliver large amounts of CO_2 required for algal bloom development.
>
> In well-documented instances involving large lakes, the presence of decomposable organic matter and bacteria have produced massive algal blooms in waters containing not more than 0.01 mg/l soluble phosphorus. In other waters containing more than 0.01 mg/l soluble phosphorus, but relatively free from organic pollution, there was no nuisance algal problem. Thus, the availability of adequate amounts of CO_2 via the action of bacteria on decomposable organic matter determines massive blue-green algal growth even in the presence of excessive amounts of soluble phosphorus.

In laboratory experiments, carbon dioxide, supplied either by bacterial action or from gas cylinders, stimulated the growth of the blue-green algae, *Microcystis nidulans*, on a culture medium low in both phosphorus and nitrogen (Kerr et al.[451]).

Evidence concerning the possible limiting role of CO_2 in the Great Lakes is meager. Bound CO_2 is always present in quantities adequate to support photosynthesis in Lake Erie central basin waters (Davis[193]). However, is the sum of the rates $R_{c,d}$;$R_{b,d}$; and $R_{a,d}$ (Figure 4–235) sufficient to compensate for the rate of loss of CO_2 to photosynthesis ($R_{d,p}$) and still maintain the pool of dissolved CO_2 above the limiting concentration? As Kuentzel suggests, there must also be a high rate of CO_2 addition from the respiration of accumulated organic matter ($R_{r,d}$) to keep CO_2 from becoming limiting during bloom periods. Griffith[303] found some indication that CO_2 might limit photosynthesis in Lake Michigan. On the basis of incomplete data he suggests that the bicarbonate supply may have a decided effect upon phytoplankton productivity. Verduin[857] estimated the rate of absorption of CO_2 from the atmosphere at 13 millimole (mmol) CO_2/m^2/da (151 mg C/m^2/da) for the well-agitated waters of the western basin of Lake Erie. Referring to Table 4–72, it is evident that this rate of exchange, if it is valid, would be marginally adequate to support summer photosynthetic rates in Lake Superior and the more oligotrophic parts of Lake Michigan. This sort of comparison suggests that there must be a progressive drain on bound CO_2 during the seasons of highest productivity and/or that CO_2 is being supplied by the decomposition of allocthonous organic material. Verduin[857] pointed out that the mean summer productivity in the western basin of Lake Erie is 550 mmol CO_2/m^2/da and that only 13 mmol of this can be derived from solution from the atmosphere. He concluded that the remainder comes from respiration, but apparently did not consider the respiration of allocthonous material: "The CO_2 and O_2 economy of such a habitat is almost a *closed system economy* [emphasis added], with CO_2 produced by respiration of the aquatic community serving as the CO_2 supply for the autotrophic component, and the O_2 produced by the autotrophs serving as the supply for the total community." It should be noted that the O_2 produced in photosynthesis is not adequate for the heterotrophic organisms of the western basin in the absence of atmospheric replenishment. The mass mortality of mayfly nymphs (*Hexagenia*) due to anoxia caused by a period of stagnation in western lake Erie in 1953 attest to this (Britt[101]). The rapid development of anoxic conditions in this incident was attributed to a high biochemical oxygen demand in the form of accumulated allocthonous organic matter.

8.3.8.5 Practical Use of the Limiting Nutrient Concept

The International Joint Commission[407] recommended emphasis on the control and removal of phosphorus as the most feasible method for reduction or reversal of the undesirable effects of organic growth in the Great Lakes. The previous subsections have shown that all nutrients are more or less important. The question that then arises is whether growth of algae can be controlled by selectively reducing a single nutrient such as phosphorus. The documentation indicates that Lake Erie may already contain two to three times the limiting concentration of phosphorus, but that the availability of CO_2 or some other nutrient may be limiting much of the time. Nitrogen has been dismissed because all the nitrogen needed can allegedly be supplied by atmospheric nitrogen fixation, but it has been demonstrated that nitrogen-fixing blue-green algae need organically enriched water for nitrogen fixation.

Since any nutrient could be limiting, the practical problem is one of technology. Carbon in the form of organic carbon can be easily removed since conventional secondary sewage treatment involves oxidation to reduce BOD. Phosphorus can be removed in certain kinds of tertiary treatment processes. A desirable approach in highly eutrophic lakes would be to support programs which will reduce the input of phosphorus, nitrogen, and carbon to levels below the lake capacity for self-purification. Concentrating only on phosphorus removal will eventually produce the desired result, but a multi-nutrient removal program should be more quickly effective in the short term.

McMillan and Verduin[523] suggested that Baule's[44] concept of limiting factors may be operative: that all of the factors influencing a process are operative at all times, the degree of limitation being inversely, and exponentially, proportional to the relative abundance of each.

Control of phosphorus is technologically and economically feasible. A greater proportion of the phosphorus entering a lake can be made to pass through a wastewater treatment plant than any of the other nutrients. Also, existing phosphorus removal technology is better developed and less expensive than that for any other nutrient except carbon, which is removed in the process of reducing wastewater BOD. These are sound reasons upon which to base public policy, but they should not foreclose further consideration of the need to remove other nutrients.

Phosphates and other nutrient inputs to lakes can be reduced by changing habits of consumption as well as by sewage treatment, but the effects of these actions should be considered. Present day detergents are a major source of phosphates and environmentalists have mounted a campaign to replace phosphates in detergents. However, caution should be exercised as substitution of nitrite for phosphate could replace an algal bloom problem with a public health problem involving nitrite poisoning of public water supplies. Nitrilo acetate, the leading candidate as a substitute for phosphate in detergents, is a chemically stable chelating agent which is incompletely destroyed in sewage treatment plants. Preliminary tests on the pure compounds seem to assure its safety, but no one can guarantee that there will be no unexpected long-term tragic effect when the material is spread about in huge quantities and its effects are combined with those of many other substances (Abelson[2]).

8.3.8.6 Temperature

Laboratory measurements have established that the total process of photosynthesis is temperature dependent under optimum light conditions when single species are tested. In such cases the rate of photosynthesis approximately doubles with each increase of 10°C within the tolerable range of temperature. This is the typical Q_{10} effect so familiar to environmental physiologists. McMillan and Verduin[523] showed that the same phenomenon may occur when winter and summer photosynthetic rates are compared even though different species are involved at the two seasons. When they treated the productivities of *Cladophora glomerata* at 18°C and 16°C and of *Ulothrix zonata* at 7°C and 2°C as a single set of data, the Q_{10} was 2; that is, the rate doubled with each increase of 10°C. If this is a general phenomenon, one should expect the highest rates of productivity in aquatic communities to occur at the warmest season and vice versa, on the basis of temperature alone. Mean photosynthesis in western Lake Erie is more than seven times greater during midsummer than midwinter, but it would be difficult to separate light and temperature effects in these data (Verduin[862]).

8.3.8.7 Light and Turbidity

Light is one of the most important factors regulating growth of phytoplankton and periphytic algae, for it is the energy source for their photosynthetic activity. Three characteristics of light are important to algae: intensity, spectral quality, and duration.

Duration is a function of season. No work has been done to define the role of changing photoperiod on seasonal succession of phytoplankton in the Great Lakes, but it must have a considerable influence. Some work has been done with light intensities and spectral qualities since these influence primary productivity. These qualities of light are significant in the water where the plankton are located, rather than at the air-water interface.

Turbidity causes light penetration to vary by as much as a factor of 20 in the Lake Erie western basin (Chandler[132]). Turbidity has significant influence on both the abundance and composition of the phytoplankton in subsequent pulses (Chandler[133]). When turbidity is 20 ppm, the pulse is large, long, and composed of relatively more green and blue-green algae. Chandler[134] found further confirmation of the importance of turbidity when very low turbidities correlated with the largest phytoplankton crops of any of the years from 1938 to 1942. Verduin[860] found that the highest phytoplankton crops in the Bass Island region of western Lake Erie occurred in water having intermediate turbidity. Verduin suggested that the incidence of the maximum phytoplankton crops correlates with influx of clear water driven by northeast winds, which mixes with turbid, fertile water in the Bass Island region, creating large water masses having enhanced fertility plus sufficient transparency to promote utilization by phytoplankton.

Davis[196] could find no simple correlation between turbidity and phytoplankton abundance in the Cleveland Harbor area of central Lake Erie probably because of the overwhelming industrial impact. Griffith[303] observed a relation between turbidity and phytoplankton in Lake Michigan that agreed with Chandler's observations in one regard but not another. In agreement, she found that the relative abundances of green and blue-green algae increased with decreasing turbidity. In contrast, the higher phytoplankton pulses were preceded by high turbidities although during the pulse the turbidities were relatively low. Diatoms may be adapted to high turbidities although very high turbidities are inhibitory. Adaptation to high turbidities and low temperatures can account for diatom dominance in the annual pulses, especially in the vernal pulse.

The various factors that reduce light penetration have a retarding effect on primary production by preventing sufficient light to drive photosynthesis. Most lakes are thus divided into two zones, the trophogenic (euphotic) and the tropholytic (dyspotic). In the former, photosynthesis exceeds community respiration ($P>R$) so that an excess of organic matter is produced. The boundary between the two zones, where $P = R$, is called the compensation depth. The depth at which light penetration is 1 percent of the surface intensity is approximately the compensation depth.

Photosynthesis can be inhibited by high light intensities. Thus intermediate depth, rather than the water surface, is generally the most productive. The depth of greatest productivity is time dependent, since morning and afternoon light intensities may not be inhibiting at the surface. For example, Verduin[861] observed that surface phytoplankton productivities are maximal in midmorning, fall off by noon and continue to decline during the afternoon. Photosynthetic rates rose sharply between 0 percent and 30 percent of full sunlight, remained essentially constant between 30 percent and 80 percent, then reduced almost 20 percent. Putnam and Olson[634] suggested that photoinhibition in superficial layers is probably much reduced by continual circulation of waters within the epilimnion, thus minimizing the exposure of individual cells to high intensity light. Light penetration and compensation depth are important variables in controlling primary production.

Chandler's[134] diagram of the relation of factors influencing phytoplankton production in western Lake Erie is general enough to apply to all the Great Lakes and is a good way of summarizing the influence of climatic conditions on phytoplankton production (Figure 4–264).

8.3.9 Phytoplankton and Phytobenthos as Indicators of Environmental Quality

Three systems are generally used to evaluate environmental quality on the basis of biological criteria:

(1) presence or absence of particular indicator species

(2) population densities of certain general groups or organisms

(3) species diversity indices.

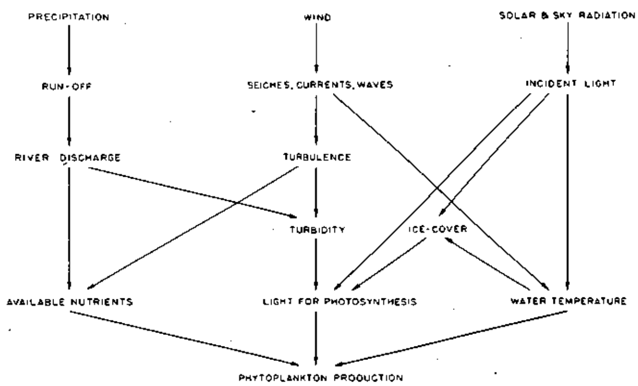

FIGURE 4–264 Relation of Certain Climatic Factors to Phytoplankton Production in Western Lake Erie

From Chandler, 1944

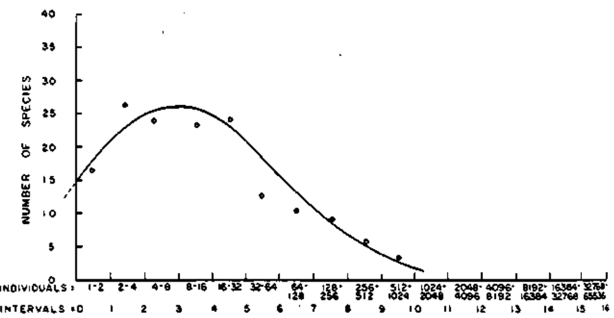

FIGURE 4–265 The Structure of a Natural Diatom Community, Ridley Creek, Pennsylvania

From Patrick, 1962

A fourth method, the use of physiological indices of sublethal stresses, is still in the developmental stage so it will not be discussed, nor will species diversity indices, because this method has not been widely employed in the Great Lakes. Reliance should not be placed on any one system (Cairns[118]), but rather all available evidence should be used in evaluating an environment. The properties of an ideal indicator species are very narrow tolerance limits for the environmental factor in question, and visibility, i.e., it must be easily observable. The concept that presence or absence of indicator species denotes certain environmental conditions has been somewhat discredited. The modern concept utilizes the entire community, or at least its more prominent members, as the indicator. For example, the most reliable method in considering algae as indicators of pollution is to study the algal community as a whole and consider the species, relative sizes of the populations of the various species, and the number of species (Patrick[598]). Patrick demonstrated that the diversity of diatom communities in ecologically similar stream segments is reduced as a consequence of pollution (Figures 4–265 and 4–266). This sort of relationship presumably can be extrapolated to lacustrine environments, but definitive work has not been performed in the Great Lakes. Rawson[642] summarized the properties of plankton that are generally accepted as defining oligotrophy or eutrophy (Table 4–75). These criteria were derived primarily from work in small lakes.

Although all degrees of intergradation are expected between the extremes, a typical eutrophic lake will have at least five times the standing crop of plankton of a typical oligotrophic lake (Rawson[642]). This is a helpful criterion, whereas number of species is not a reliable criterion. Water bodies with high phytoplankton standing crops also usually have low plankton species diversity (Williams[898]).

In eutrophic lakes it is difficult to distinguish between true limnetic species and those washed out into the open lake that are the so-called tychopelagic plankton characteristic of the marginal zone of marshes and baylets. As a consequence, the apparent diversity of the lake plankton is considerably increased, but does not characterize trophic conditions in the lake. The difference in frequency of water blooms is also real, but as Rawson noted, blooms may not occur at times convenient for investigation. So this leaves algal-indicator groups and species as the most useful keys to trophic conditions.

Two schemes used to classify lakes on the basis of their phytoplankton are measuring the numerical dominance by a particular group of species and measuring the variety of a particular group of species regardless of the numbers in which they occur. It is easier to determine the dominant species than to determine the diversity of a plankton community (Rawson[642]). The latter may be worth the effort, however, because the dominant species are often those with rather wide tolerance (eurybionts), and thus they may be a poorer indicator of trophic condition than the less frequent species. In this regard, Rawson determined a number of trophic-condition indices by comparing the abundance of various groups. These determinations require prior assumptions of the trophic state that each species indicates. Part of the difficulty with index equations is the inherent error in designating members of a particular algal group as oligotrophic or eutrophic indicators. This

TABLE 4–75 Phytoplankton of Oligotrophic and Eutrophic Lakes

Characteristics	Oligotrophic	Eutrophic
Quantity	Poor	Rich
Variety	Many species	Few species
Distribution	To great depths	Trophogenic layer thin
Diurnal Migration	Extensive	Limited
Water-blooms	Very rare	Frequent
Characteristic Algal Groups and Genera	Chlorophyta (green algae) Desmids (if Ca low) *Straurastrum* or Bacillariophyceae (diatoms) *Tabellaria* *Cyclotella* Chrysophyceae *Dinobryon*	Cyanophyta (blue-green algae) *Anabaena* *Aphanizomenon* *Microcystis* and Bacillariophyceae *Melosira* *Fragilaria* *Stephanodiscus* *Asterionella*

SOURCE: Rawson, 1956.

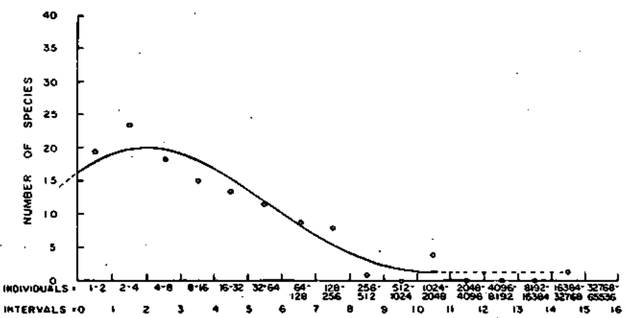

FIGURE 4–266 The Structure of a Diatom Community in a Moderately Polluted Environment, Nobs Creek, Maryland

From Patrick, 1962

should be done on a species by species basis, recognizing that most species will have indifferent values as indicators. Another problem is that relatively few species are oligotrophic indicators. Most species in oligotrophic lakes are simply tolerant to the conditions and are also found in more enriched lakes. *Dinobryon divergens* and *Uroglena americana* are truly oligotrophic species of algae. They thrive in low nutrient lakes and laboratory media, and also are inhibited by small additions of phosphate (Rodhe[677]).

The dominant algae in the upper Great Lakes are not those commonly cited as characteristic of oligotrophic lakes (Rawson[642]). In part, this exceptional distribution of phytoplankton in the Great Lakes may stem from the fact that these lakes tend to be morphometrically oligotrophic, i.e., oligotrophic due to their great volume rather than because of a low rate of nutrient addition (see Section 7). Rawson[642] used lakes of western Canada to prepare a tentative list of indicator species that he felt were appropriate for the large lakes of North America (Table 4–76). However, whether this list is applicable to the Great Lakes is debatable. Holland[371] noted that *Fragilaria capucina*, which appears in Rawson's list as an oligotrophic indicator, was associated by Davis[191] with the eutrophication of Lake Erie. She also noted that *Rhizosolenia eriensis*, which Jarnefelt (1961, cited in Round[684]) correlated with organic pollution in a small lake, was the fourth most abundant species in Lake Superior and "has declined to insignificance in Lake Erie since 1800." Nalewajko[568] designated *Melosira islandica* and *Asterionella formosa* as oligotrophic indicators in Lake Ontario and *Stephanodiscus tenuis* as a mesotrophic or eutrophic indicator. Stoermer and Kopczynska[765] concurred on the indicator value of *Melosira islandica* for oligotrophy in Lake Michigan. They listed *Diatoma tenue*, *Melosira granulata*, *Melosira binderana*, *Stephanodiscus hantzschii*, and *Spiruliana jenneri* as eutrophic indicators. Abundant occurrence of *Spirulina jenneri* is often considered

TABLE 4–76 Approximate Trophic Distribution of Dominant Limnetic Algae in Lakes of Western Canada

Oligotrophic	Mesotrophic	Eutrophic
Asterionella formosa	*Fragilaria crotonensis*	*Microcystis flos-aquae*
Fragilaria capucina	*Coelosphaerium naegelianum*	
Melosira islandica	*Ceratium hiundinella*	
Stephanodiscus niagarae	*Anabaena spp.*	
Tabellaria fenestrata	*Pediastrum boryanum*	
Straurastrum spp.	*Aphanizomenon flos-aquae*	
Tabellaria flocculosa	*Pediastrum duplex*	
Melosira granulata	*Microcystis aeruginosa*	
Dinobryon divergens		

SOURCE: Rawson, 1956.

to be presumptive evidence of organic enrichment and anaerobic conditions.

Holland[370] correlated the distribution of the species of *Melosira* in Green Bay and Lake Michigan with other indications of trophic state, specifically phosphate and nitrate concentrations and diatom standing crops. She found that Green Bay and a nearshore Lake Michigan site were more eutrophic than the other lake sampling stations. *Melosira binderana* and *Melosira granulata* were found only in Green Bay and at the somewhat less eutrophic inshore Lake Michigan site. These species were absent in oligotrophic portions in Lake Michigan. *Melosira islandica*, which was absent in the eutrophic areas, was characteristic of the open lake.

Williams[898] developed two indices of trophic condition based on phytoplankton samples. The first index involves making numerous collections over two years and recording the abundances and frequencies of occurrence of the four most common species of diatoms. The combined percentage of abundance of the most common species over the two years is multiplied by the density level to obtain the trophic index. The density level is a value from 1 through 9 and corresponds to the mean number of individuals per species per milliliter of sample; the larger the trophic index, the more eutrophic the water body. The index has a high degree of correlation with chemical and physical indicators of eutrophication (Table 4–77).

In his second index, Williams used the same plankton samples, but only the 10 samples having the highest standing crops at each site were employed. All phytoplankton genera were identified and counted. Those genera having 150 members or more per milliliter were considered dominant. Each dominant genus was assigned a weighting factor, 1 through 9, based on its abundance. All these weighting factors were added for all dominant genera in all 10 samples to arrive at the diversity density value; the higher this value, the higher the trophic state of the site (Table 4–78).

This method is valuable because the subjective judgment concerning the indicator value of a given species is eliminated. However, it is a slow method which gives information only on long-term trends and regional differences. It is not suitable for rapid surveys or for detection of transient polluting conditions.

The extensive limnological studies of small lakes in Europe and North America cannot serve as models which can be extrapolated uncritically to the Great Lakes. Algal communities that are reasonably indicative of the trophic conditions of each Great Lake or of local areas within each lake probably exist, but they have not yet been adequately defined. Such indicators of general conditions should be expected among the phytoplankton as well as among the benthic and periphytic plants. The phytoplankton are poor indicators of localized pollution conditions for the same reason as zooplankton (see Subsection 8.2, Zooplankton, Zoobenthos, and Periphytic Invertebrates of the Great Lakes). For example, phytoplankters were killed near the mouth of

TABLE 4–77 Diatom Trophic-Index Values, Upper Great Lakes

Lake Site	Dominant Species Percent Abundance	Density Level	Trophic Index
Lake Superior at Duluth	40.5	1	41
St. Marys River at Sault Ste. Marie	39.9	2	80
St. Clair River at Port Huron	46.7	3	140
Detroit River at Detroit	41.0	4	164
Lake Michigan at Milwaukee	57.2	4	229
Lake Michigan at Gary	65.4	5	327

SOURCE: Williams, 1964

the Cuyahoga River, but this response is an unreliable indication of pollution since moribund cells are often found in the absence of pollution (Davis[194]). The phytobenthos and periphytic algae, because of their immobility, should reflect local pollutional conditions more accurately. For example, certain species of *Oscillatoria* appear to be the only macroscopic life forms in the industrial section of the Cuyahoga River in Cleveland. The presence of these highly tolerant organisms in the absence of others may be a good indication of toxic conditions. Unfortunately, little work has been done in North America utilizing attached algae in lakes.

8.3.10 Nuisance Algal Problems

Blooms of various kinds of algae cause nuisance problems which result in economic loss to certain industries and to the public in general, particularly in the lower lakes. The main nuisance problems involve interference with recreation, fish net fouling, undesirable conditions in public water supplies, and toxic algal blooms.

8.3.10.1 Interference with Recreation

Cladophora, a filamentous green alga, grows abundantly in Lakes Erie and Ontario and to a lesser degree in Lakes Huron and Michigan (Neil and Owen;[574] Michigan Water Resources Commission[539]). Adams and Kregear[4] also identified *Cladophora* on rocky sites in the boundary environments of Lake Superior. *Cladophora* has become a nuisance in the lower lakes. Its filaments grow up to 15 inches long and then break off. The odor and discoloration caused by windrows of decomposing *Cladophora* that accumulate on beaches can force the closing of recreational areas (Neil and Owen;[574] Casper[128]).

TABLE 4–78 Phytoplankton Diversity-Densities, Upper Great Lakes

Site	Diversity-Density
St. Marys River at Sault Ste. Marie	3
Lake Superior at Duluth	11
Lake Michigan at Gary	97

SOURCE: Williams, 1964

In Lake Michigan, the main problem is *Spirogyra* rather than *Cladophora* (Michigan Water Resources Commission[539]). Broken *Cladophora* filaments settle to the bottom, and while their presence may bother some swimmers, the suspended *Spirogyra* stains bathing suits and consequently is the greater annoyance.

Blue-green algal blooms can also be unaesthetic. Casper[128] described a blue-green algal bloom that floated to the water surface and produced a green, frothy scum over approximately 800 square miles of the western basin of Lake Erie, completely enclosing the Bass Islands, a popular resort area.

8.3.10.2 Net Fouling

Floating masses of filamentous algae such as *Cladophora* foul the nets of commercial fishermen in the lower lakes, making them more difficult to haul. In Lake Superior, Putnam and Olson[635] reported the growth of slime on fish nets. Nets set for 10 days had heavy slime growths composed mainly of the Chrysophytes, *Tabellaria, Synedra, Cymbella, Dinobryon,* and *Fragilaria.*

8.3.10.3 Interference with Public Water Supply

Palmer[596] indicated that the presence of algae in public water supplies in Ohio clogged intake screens, formed unsightly mats on walls of sedimentation basins, caused difficulties in production of an alum floc, caused a reaction with chlorine used to destroy pathogens, and changed the pH and other physicochemical characteristics of water. One of the most troublesome problems created by algae is the clogging of sand filters in water filtration plants. The more frequently these filters are washed, the more expensive water purification becomes. The large filamentous algae may be the greatest offenders, but *Melosira* and *Anabaena* are most often implicated (Palmer[596]). At Cleveland, both the numbers and kinds of algae in Lake Erie water affect the length of filter runs. Diatoms were the most abundant organisms with *Melosira* predominating, and they seemed to be the chief offenders in filter clogging.

The most serious nuisance problem caused by algae is the production of undesirable tastes and odors in drinking water, although some varieties of actinomycetes fungi may share the blame. Decomposing masses of *Cladophora* in water can cause these problems (Neil and Owen[574]). The algal varieties most frequently associated with taste and odor problems in Lake Erie are blue-greens, especially *Anabaena*, but other types such as *Asterionella, Synedra,* and *Synura* are also suspect. Tastes from Lake Erie water at Cleveland, Lorain, Painesville, and Toledo have variously been described as chloro-phenolic, grassy, green corn, musty, and pig-pen (Palmer[596]). Reduction of tastes and odors involves chlorination and activated charcoal adsorption. These treatments increase the cost of water and often are not entirely successful in eliminating the offensive substances.

8.3.10.4 Toxic Algal Blooms

Some species of blue-green algae in the Great Lakes are capable of producing toxic substances that can kill animals. This capability represents a potential threat to public health. Conditions in lakes which favor the growth of blue-green algae are high nitrogen and phosphorus content, high carbon dioxide reserve in dissolved bicarbonates, and high temperatures (26°C to 30°C) (Prescott[629]).

Most of the evidence involving human poisoning by the products of toxic freshwater algae is circumstantial but fairly convincing (Ingram and Prescott[406]). Outbreaks of nausea and gastroenteritis coinciding with blooms of blue-green algae in public water supplies have occurred among humans in the United States. These epidemics of "intestinal influenza" were not caused by consumption of substandard or unsafe water as far as the usual bacteriological tests were concerned.

Ingram and Prescott[406] related many cases of mild to acute poisoning of domestic animals and wildlife to blue-green algal blooms. One report described death of sheep as occurring 1 to 6 hours after drinking the water in question; horses died in 8 to 24 hours; dogs in 4 to 5 hours; and pigs in 3 to 4 hours. Fencing off animals from the water containing the algal blooms prevented any further mortality in a similar incident. Symptoms of sub-lethal algae poisoning in domestic animals include severe constipation, general weakness, increased sensitivity to solar radiation, and often liver damage resulting in jaundice (Steyn[762]). Fish may also be killed by blue-green algae toxins. Decomposing *Aphanizomenon flos-aquae* killed black crappie, gizzard shad, golden shiners, orange-spotted sunfish, fathead minnows, bluegills, buffalo fish, sheepshead, perch, bullheads, pumpkinseed, and carp (Prescott[629]). The dissolved oxygen was adequate at all times. Shelbusky[731] found that massive decay of *Microcystis aeruginosa* in continuously aerated water caused death of fish in spite of the high oxygen supply.

There is no documentation that toxic blue-green algal blooms have occurred in the Great Lakes although blue-green algal blooms are well known. One of the mysteries of this problem is that toxicity is not associated with every bloom of blue-green algae even when the same species are involved. Those species that appear to produce toxins under some conditions are members of the genera *Microcystis, Anabaena, Aphanizomenon, Nodularia, Gloeotrichia,* and *Coelosphaerium.* Gorham[293] reported that toxicity occurred in some strains and not others. Toxin production is apparently controlled by both genetic and environmental factors.

The nature of the toxins of blue-green algae has not been well established, and there may be several different classes of chemical substances. It is not clear whether the chemical substances are always endotoxins or also include exotoxins. Wheeler et al.[884] reported that the toxin of *Microcystis aeruginosa* is an endotoxin that does not become a problem until released into the water during the decomposition of dead *Microcystis* cells. Prescott[629] suggested that products of protein decomposition, perhaps hydroxylamine or hydrogen sulfide, could be the toxic agents produced by *Aphanizomenon flos-aquae*. Lovw[506] reported that the toxin of *Microcystis toxica* is an alkaloid, but Gorham[293] was unable to find any alkaloid in *Microcystis aeruginosa* toxin. Gorham found that *Microcystis* produced an endotoxin called fast-death factor (FDF) because it kills mice in 30 to 60 minutes when administered orally or intraperitioneally. FDF is a low molecular weight polypeptide. Another toxin, slow-death factor (SDF), is produced by bacteria associated with the alga. SDF kills mice in 4 to 48 hours and is chemically and pharmacologically distinct from FDF. Gorham also found that *Aphanizomenon flos-aquae* toxin was indistinguishable from *Microcystis* FDF. *Anabaena flos-aquae*, on the other hand, produces a pharmacologically distinct toxin, very fast death factor (VFDF), which kills mice in 1 to 10 minutes. VFDF is toxic to waterfowl, whereas FDF apparently is not. According to Ingram and Prescott,[406] the toxin of an algal bloom was proven not to be botulinus toxin since it was not neutralized by polyvalent botulinas anti-toxin.

Toxins that are so mild as to go unnoticed may be produced by algae. The green alga, *Chlorella*, produces an antibiotic substance, chlorellin, which inhibits the ability of *Daphnia* to feed upon the alga (Ryther[696]). The blue-green algae are generally acknowledged to be undesirable fish food (Renn[645]). This suggests a possible functional significance of algal toxins. The algal toxins may inhibit algal consumption by predators, and may also be antibiotics that inhibit the growth of competitors. Gorham,[293] however, determined that *Microcystis* FDF does not inhibit the growth of various bacteria such as *Bacillus subtilis*, *Staphylococcus aureu*, *Escherichia coli*, or *Pseudomonas hydrophila*. The blue-green algae appear to be the only group of freshwater algae that might produce toxins of public health significance. One of the causes for public health concern is that blue-green algae toxins can survive the usual water purification processes. Wheeler et al.[884] found that alum coagulation and filtration actually enhanced the toxicity of *Microcystis aeruginosa* toxin for mice, and that the same treatment plus chlorination did not reduce the toxicity. However, coagulation, filtration, chlorination, and adsorption on activated charcoal does reduce the toxicity. Since blue-green algae toxins are obviously difficult to remove from water, prevention is the logical method for protecting public water supplies. The environmental requirements of blue-green algae are not well known, although in general they need organic enrichment and warm temperatures. The algae apparently need organic growth factors produced by other organisms (Provasoli[632]). Gorham[293] studied the growth requirements of one toxic strain of *Microcystis aeruginosa* (NRC–1) and one toxic strain of *Anabaena flos-aquae* (MRC–44) in the laboratory. These species have fairly critical requirements for certain minerals, but the requirements for light, temperature, pH, carbon dioxide, and chelators appear to be somewhat less exacting. There is very little or no correspondence between blooms generated under laboratory conditions and those found in nature. This suggests that the conditions that determine the later stages of bloom development may exert their effects at earlier stages, thereby complicating their detection and interpretation.

8.3.11 Conclusions

The flora of the Great Lakes are better known than are the invertebrate animals probably because of their direct effects on public water supplies. Most of the definitive phytoplankton studies have been made in Lake Erie, especially in the western basin, and the phytoplankton of Lake Huron are the least studied.

Algae in the Great Lakes are of interest to planners and the general public because they have a direct impact on daily lives. Algae are responsible for foul tastes and odors in drinking water supplies and for making some of the Great Lakes waters and beaches unappealing for recreational uses. They also represent a potential public health threat. The public widely recognizes that excessive algal growth and its associated problems are among the main symptoms of eutrophication, but it should also be aware that algae are at the base of the aquatic food chain, upon which recreational and commercial fisheries are dependent.

Taste and odors, and other algal problems associated with providing potable drinking water, have become increasingly serious in Lake Erie in recent years. Methods of treating such tainted waters are expensive.

Massive growths of *Cladophora* and other filamentous attached algae have become increasingly common in the lower lakes and southern Lake Michigan. The decomposition of these algae foul beaches and may deplete dissolved oxygen. Massive blooms of planktonic algae also contributed to the depletion of dissolved oxygen in Lake Erie when they die and decompose.

Some misunderstanding exists about the role of algae in the maintenance of dissolved oxygen. Living algae may be mistakenly held responsible for the depletion of dissolved oxygen when, in fact, healthy algae are oxygen producers. Accumulated masses of dead algae are responsible for the excessive oxygen depletion.

Certain species of blue-green algae which occur in the Great Lakes can produce toxic substances which have been implicated in the deaths of wildlife and livestock as large as cattle, and in the illness of humans in other areas. No such poisonings are documented in the Great Lakes, but the potential exists wherever eutrophication goes to an advanced state.

Phytoplankton can be used as indicators of general trophic conditions in the Great Lakes. The use of single species as an indicator is unreliable; rather the species composition and relative abundances of the entire phytoplankton community must be used. The value of some species as indicators in small lakes does not appear to be valid in the Great Lakes. Most trophic index equations are unreliable because they utilize only a portion of the community and do not include species level identifications.

On the basis of distribution of planktonic and periphytic algae, it is evident that the lakes are not homogeneous. There are differences between nearshore and offshore areas in each of the Great Lakes. Bays and harbors appear to be more eutrophic than open areas of the lakes. There are also distinct gradients of increasing eutrophication in Lakes Erie, Ontario, and Michigan related to metropolitan centers.

In Lake Erie, significant changes have occurred in the species composition, relative abundances of species, overall abundance, and seasonal abundance patterns of phytoplankton since a base documentation period in 1930. Evidence for similar changes in Lakes Ontario and Michigan exists, but is less conclusive. The relative abundance of *Cladophora* and other attached algae has also been increasing during this time.

The typical seasonal phytoplankton abundance pattern in the lower lakes and in nearshore southern Lake Michigan is two annual peaks, or pulses, one in the spring and one in the autumn. Characteristically both peaks are dominated by diatoms, but the autumnal peak has a larger proportion of green and blue-green algae. In the upper lakes, the typical pattern apparently is a single pulse in midsummer. These pulses appear to be controlled by changes in water temperatures as the seasons progress. Increasing eutrophication seems to obliterate the distinction between vernal and autumnal peaks in the lower lakes.

The most direct index of the trophic state of the lakes is the estimation of annual primary production through the measurement of algal photosynthesis. Most conclusions about the production of the lakes have been based on measurements of standing crop, but standing crop and production are not necessarily related.

Algae appear to be of little importance as a direct food for adults of most fish species. Most algal production is consumed by zooplankton, fish fry, zoobenthos and, as detritus, by bacteria and fungi. Under some circumstances, up to 90 percent of algal production may be released as soluble products in the water. These products are usable only by bacteria and a few other organisms.

The main inorganic nutrients controlling algal growth in the Great Lakes are phosphorus, nitrogen, and carbon. Each of these nutrients is abundant in sewage and other sources of input to the lakes. The sediments also provide a large reservoir, especially in Lake Erie. Inasmuch as phosphorus concentration may be several times more than the limiting level in some areas, reduction of other nutrients as well as phosphorus, when technologically and economically feasible, may ameliorate some of the undesirable effects of eutrophication more rapidly than phosphorus control alone.

Temperature has a profound influence on algal productivity. This effect helps account for seasonal differences in phytoplankton abundance and for differences observed at different latitudes in the Great Lakes.

Differences in photosynthesis due to latitudinal, seasonal, and daily changes of light penetration into the Great Lakes account for much of the observed differences in phytoplankton productivity. Photosynthesis is also inhibited by the high turbidity characteristic of portions of the Great Lakes.

8.4 The Nekton of the Great Lakes

8.4.1 Introduction

Major changes in the Great Lakes due to human activities such as construction of the Erie Canal, overfishing, and environmental degradation since the early 1800s have caused reduction in the commercial and sport fisheries. Changes have occurred in species composition of the fish population, certain species have been eradicated, and others have been introduced. The changes have been most pronounced in the Lake Ontario and Lake Erie basins, but they are also occurring in the other Great Lakes.

One of the greatest problems in describing nekton of the Great Lakes is the general lack of information about the distribution and population of the many fish species. Investigators have been hampered by a lack of knowledge about past conditions of the lakes, and thus are hard pressed to relate species and population changes to the changing environment. In addition, population changes may be due in part to activities of the commercial fisheries in the Great Lakes. Catch records from the commercial fisheries may also be misleading because they reflect only fishing habits or the fishing regulations; if a particular species becomes protected by law, then records of further catches no longer are available. Data on low value, undesirable food fish and forage fish are almost completely lacking, as are data on the sport fisheries. The burbot (*Lota lota lacustris*), a relatively unimportant fish in the commercial catch, has been reported to be decreasing or almost rare in Lake Erie, yet it is regularly found in the trap nets. Because it is of little value, catches are not kept, and no formal records of landings are made. Thus, by looking at recent records the burbot would appear to be extinct. Other fish had started to decline long before the records indicated. Due to their economic importance, they were more sought after, and thus catch records remained inordinately high.

Each of the lakes is interconnected, so interlake migration is easily accomplished. The nekton by definition are free swimming organisms. Thus they are able to migrate from one lake to another. However, each lake has a peculiar environmental setting that may be more or less attractive to the various species.

The fish fauna of the Great Lakes and their tributaries includes representatives of most of the families of North American fishes (Table 4–79). The list of scientific and common names are those used by the American Fisheries Society.[9] Table 4–80 is a listing of those species often referred to as chubs in fishery records.

The salmonids dominated the early fisheries of all the lakes; in Lake Superior no other group has produced as substantial catches (Beeton and Chandler[55]). Lake trout, whitefish, lake herring, and chubs were, until recently, the most important commercial species in Lakes Superior, Huron, and Michigan. Except for the chubs in all three lakes, the lake herring in Lake Superior, and the whitefish in Lake Michigan, this is no longer true. The shallow water areas of all the Great Lakes have yielded significant quantities of the perch (yellow perch, walleye, sauger), carp, smelt, catfish, and suckers as well as blue pike and freshwater drum. The latter two come principally from Lake Erie. A detailed review of the history and projected trends of the Great Lakes commercial fishery is included in Appendix 8, *Fish*.

The faunal composition of the lakes has been modified by the introduction and migration of exotic species since the late 1800s. Carp (*Cyprinus carpio*) and goldfish (*Carassius auratus*) were introduced during the late 1800s and were well established by 1900. These two species readily hybridize and are together listed as carp in catch records. The rainbow smelt (*Osmerus mordax*) were originally introduced in Lake Michigan tributaries in the 1920s and subsequently spread throughout the Great Lakes. Smelt are considered to be native to Lake Ontario (Beeton and Chandler[55]), and some may actually have migrated through the Welland Canal, as have the alewife (*Alosa pseudoharengus*) and the sea lamprey (*Petromyzon marinus*) which had also been confined to Lake Ontario by Niagara Falls. A similar migration by the white perch (*Morone americanus*) also seems to be taking place (VanMeter and Trautman[843]). Other fish such as coho salmon (*Oncorhynchus kisutch*) have also been introduced, but most have not become established as breeding populations in any of the lakes.

The U.S. Commission of Fish and Fisheries survey of the fishery resources was initiated in 1871 and marked the beginning of the Federal government's interest in the fauna of the lakes. The surrounding States also initiated fisheries commissions. These commissions were followed by the development of both Fed-

TABLE 4–79 Great Lakes Basin Fish

Common Name	Genus and Species	Lake Ontario	Lake Erie	Lake Huron	Lake Michigan	Lake Superior
PETROMYZONTIDAE						
American brook lamprey	*Lampetra lamottei*	stream	stream	stream	stream	stream
Silver lamprey	*Ichthyomyzon unicuspis*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Northern brook lamprey	*Ichthyomyzon fossor*	stream	stream	stream	stream	stream
Chestnut lamprey	*Ichthyomyzon castaneus*	---	---	lake & stream	lake & stream	---
Sea lamprey	*Petromyzon marinus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
ACIPENSERIDAE						
Lake sturgeon	*Acipenser fulvescens*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
POLYODONTIDAE						
Paddlefish	*Polyodon spathula*	---	lake & stream[1]	lake & stream[1]	lake & stream	---
AMIIDAE						
Bowfin	*Amia calva*	lake & stream	lake & stream	lake & stream	lake & stream	---
LEPISOSTEIDAE						
Spotted gar	*Lepisosteus productus*	---[1]	lake & stream	lake & stream	lake & stream	---
Longnose gar	*Lepisosteus osseus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
CLUPEIDAE						
Alewife	*Alosa pseudoharengus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
American shad	*Alosa sapidissima*	---	---[1 & 2]	---	---	---
Gizzard shad	*Dorosoma cepedianum*	---	lake & stream	lake & stream	lake & stream	---
ESOCIDAE						
Grass pickerel	*Esox americanus vermiculatus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Chain pickerel	*Esox niger*	stream	---[2]	---	---	---
Northern pike	*Esox lucius*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Muskellunge	*Esox masquinongy*	lake & stream	stream	lake & stream	lake & stream	lake & stream
COTTIDAE						
Fourhorned sculpin	*Myoxocephalus quadricornis*	lake & stream	lake & stream[1]	lake & stream	lake & stream	lake & stream
Spoonhead sculpin	*Cottus ricei*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Mottle sculpin	*Cottus bairdi bairdi*	lake & stream	lake & stream	---	---	---
Great Lakes sculpin	*Cottus b. lumlieni*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Slimy sculpin	*Cottus cognatus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
SCIAENIDAE						
Freshwater drum (sheepshead)	*Aplodinotus grunniens*	lake & stream	lake & stream	lake & stream	lake & stream	---
ATHERINIDAE						
Brook silverside	*Labidesthes s. sicculus*	lake & stream	lake & stream	stream	stream	stream
SERRANIDAE						
White bass	*Morone chrysops*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream[1]
White perch	*Morone americana*	lake & stream	lake & stream	---	---	---
CYPRINODONTIDAE						
Blackstripe topminnow	*Fundulus notatus*	---	stream	---	stream	---
Starhead topminnow	*Fundulus nottii*	---	---	---	stream	---
Banded killifish	*Fundulus diaphanus menona*	lake & stream	stream	stream	stream	stream
HIODONTIDAE						
Mooneye	*Hiodon tergisus*	lake & stream	lake & stream	---	---	---
OSMERIDAE						
Rainbow smelt	*Osmerus mordax*	lake & stream	lake & stream	lake & stream	lake & stream[2]	lake & stream
UMBRIDAE						
Central mudminnow	*Umbra limi*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
GASTEROSTEIDAE						
Brook stickleback	*Culaea inconstans*	lake & stream	stream	stream	stream	stream
Ninespine stickleback	*Pungitius pungitius*	lake & stream	---	lake & stream	lake & stream	lake & stream
Threespine stickleback	*Gasterosteus aculeatus*	lake & stream	---	---	---	---
PERCOPSIDAE						
Troutperch	*Percopsis omiscomaycus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
GADIDAE						
Burbot	*Lota lota lacustris*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
APHREDODERIDAE						
Pirate perches	*Aphredoderus sayanus*	stream	stream	---	stream	---
ANGUILLIDAE						
American eel	*Anguilla rostrata*	lake & stream	lake & stream[1]	---	---	---
POECILIIDAE						
Mosquitofish	*Gambusia a. affinis*	---	stream[2]	---	stream[2]	---
SALMONIDAE						
Lake Erie cisco	*Coregonus artedii albus*	---	lake & stream	---	---	---

[1]Possible or extinct species
[2]Introduced species

TABLE 4–79 (continued) Great Lakes Basin Fish

Common Name	Genus and Species	Lake Ontario	Lake Erie	Lake Huron	Lake Michigan	Lake Superior
SALMONIDAE (continued)						
Great Lakes cisco[3]	*Coregonus a. artedii*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Shortnose cisco[3]	*Coregonus reighardi*	---	---	lake & stream	lake & stream	lake & stream
Shortjaw cisco[3]	*Coregonus zenithicus*	---	---	lake & stream	lake & stream	lake & stream
Longjaw cisco[3]	*Coregonus alpenae*	---	---	lake & stream	lake & stream	lake & stream
Bloater[3]	*Coregonus hoyi*	---	---	lake & stream	lake & stream	lake & stream
Kiyi[3]	*Coregonus kiyi*	---	---	lake & stream	lake & stream	lake & stream
Blackfin cisco[3]	*Coregonus nigripinnis*	---	---	lake & stream	lake & stream	lake & stream
Deepwater cisco[3]	*Coregonus johannae*	---	---	lake & stream	lake & stream	---
Lake whitefish	*Coregonus clupeaformis*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Pigmy whitefish	*Prosopium coulteri*	---	---	---	---	lake & stream
Found whitefish	*Prospium cylindraceum*	lake & stream	---	lake & stream	lake & stream	lake & stream
Artic grayling	*Thymallus arcticus*	---	---	stream	stream	stream
Atlantic salmon	*Salmo salar*	---	---[1] & [2]	---	---	---
Brown trout	*Salmo trutta*	stream[2]	stream[2]	stream[2]	stream[2]	stream[2]
Rainbow trout	*Salmo gairdneri*	lake & stream[2]	lake & stream[2]	stream[2]	stream[2]	stream[2]
Brook trout	*Salvelinus fontinalis*	---	stream	stream	stream	stream
Lake trout	*Salvelinus namaycush*	---	lake & stream[1]	lake & stream	lake & stream	lake & stream
Coho salmon	*Oncorhynchus kisutch*	---[2]	---[2]	---[2]	---[2]	---[2]
Chinook salmon	*Oncorhynchus tshawytscha*	---[2]	---[2]	---[2]	---[2]	---[2]
Sockeye salmon	*Oncorhynchus nerka*	---[2]	---	lake & stream	---	---
PERCIDAE						
Walleye	*Stizostedion v. vitreum*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Blue pike	*Stizostedion v. glaucum*	---	lake & stream	lake & stream	---	---
Sauger	*Stizostedion canadense*	lake & stream	lake & stream	lake & stream	lake & stream	stream
Yellow perch	*Perca flavescens*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Blackside darter	*Percina maculata*	stream	stream	stream	stream	---
Logperch	*Percina caprodes*	lake & stream	lake & stream	stream	stream	stream
River darter	*Percina shumardi*	---	stream	stream	stream	---
Channel darter	*Percina copelandi*	lake & stream	lake & stream	lake & stream	---	---
Northern sand darter	*Ammocrypta pellucida*	lake & stream	lake & stream	---	lake & stream	---
Johnny darter	*Etheostoma nigrum*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Greenside darter	*Etheostoma blennioides*	stream	stream	stream	---	---
Iowa darter	*Etheostoma exile*	stream	stream	stream	stream	stream
Rainbow darter	*Etheostoma caeruleum*	stream	stream	stream	stream	---
Orangethroat darter	*Etheostoma spectabile*	---	stream	---	---	---
Fantail darter	*Etheostoma flabellare*	lake & stream	stream	---	stream	---
Least darter	*Etheostoma microptera*	stream	stream	stream	stream	stream
Scaly Johnny darter	*Etheostoma n. eulepis*	---	stream	stream	---	---
ICTALURIDAE						
Black bullhead	*Ictalurus melas*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Brown bullhead	*Ictalurus nebulosus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Yellow bullhead	*Ictalurus natalis*	stream	stream	stream	stream	stream
Channel catfish	*Ictalurus punctatus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Flathead catfish	*Pylodictis olivaris*	stream	lake & stream	---	stream	---
Stonecat	*Noturus flavus*	lake & stream	lake & stream	stream	stream	---
Tadpole madtom	*Noturus gyrinus*	lake & stream	lake & stream	lake & stream	lake & stream	---
Brindled madtom	*Noturus miurus*	stream	stream	---	---	---
Eastern madtom	*Noturus insignis*	stream	---	---	---	---
CENTRARCHIDAE						
Smallmouth bass	*Micropterus dolomieui*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Largemouth bass	*Micropterus s. salmoides*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
White crappie	*Pomoxis annularis*	lake & stream	stream	stream	stream	---
Black crappie	*Pomoxis nigromaculatus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Rock bass	*Ambloplites r. rupestris*	lake & stream	lake & stream	stream	stream	stream
Warmouth	*Chaenobryttus gulosus*	---	stream	---	stream	---
Green sunfish	*Lepomis cyanellus*	stream[1]	stream	stream	stream	---

[1]Possible or extinct species
[2]Introduced species
[3]Called chubs in fishery records

TABLE 4–79 (continued) Great Lakes Basin Fish

Common Name	Genus and Species	Lake Ontario	Lake Erie	Lake Huron	Lake Michigan	Lake Superior
CENTRARCHIDAE (continued)						
Pumpkinseed	*Lepomis gibbosus*	lake & stream	lake & stream[1]	stream	stream	stream
Bluegill	*Lepomis m. macrochirus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Orangespotted sunfish	*Lepomis humilis*	---	stream	---	---	---
Redear sunfish	*Lepomis microlophus*	---	---	---	stream	---
Longear sunfish	*Lepomis megalotis peltastes*	stream	stream[2]	stream	stream	---
CATASTOMIDAE						
Bigmouth buffalo	*Ictiobus cyprinellus*	---	lake & stream	---	---	---
Black buffalo	*Ictiobus niger*	---	---	---	stream	---
Quillback	*Carpiodes cyprinus*	lake & stream	lake & stream	lake & stream	lake & stream	---
River carpsucker	*Carpiodes c. carpio*	---	stream[1]	---	---	---
Black redhorse	*Moxostoma duquesnei*	lake & stream	stream	stream	stream	stream
Golden redhorse	*Moxostoma erythrurum*	stream	stream	stream	stream	---
Northern redhorse	*Moxostoma m. macrolepidotum*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Greater redhorse	*Moxostoma valenciennesi*	stream	stream	stream	stream	stream
Silver redhorse	*Moxostoma anisurum*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
River redhorse	*Moxostoma carinatum*	---	---	---	stream[1]	---
Harelip sucker	*Lagochila lacera*	---	---[1]	---	---	---
Northern hog sucker	*Hypentelium nigricans*	---	stream	stream[1]	stream	---
White sucker	*Catostomus c. commersoni*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Longnose sucker	*Catostomus c. catostomus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Spotted sucker	*Minytrema melanops*	---	stream	---	stream	---
Lake chubsucker	*Erimyzon sucetta kennerlyi*	lake & stream	lake & stream	lake & stream	lake & stream	---
Creek chubsucker	*Erimyzon oblongus claviformis*	---	stream	---	stream	---
CYPRINIDAE						
Carp	*Cyprinus carpio*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Goldfish	*Carassius auratus*	lake & stream	lake & stream	lake & stream	---	---
Golden shiner	*Notemigonus crysoleucas*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Lake chub	*Couesius plumbea*	lake & stream	---	---	---	---
Hornyhead chub	*Hybopsis biguttata*	stream	stream	stream	stream	stream
River chub	*Hybopsis micropogon*	stream	stream	---	stream	---
Silver chub	*Hybopsis storeriana*	---	stream	---	---	---
Bigeye chub	*Hybopsis a. amblops*	stream	stream	---	---	---
Creek chub	*Semotilus atromaculatus*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Pearl dace	*Semotius m. margarita*	stream	stream	stream	stream	stream
Blacknose dace	*Rhinichthys atratulus*	lake & stream	stream	stream	stream	stream
Longnose dace	*Rhinichthys cataractae*	lake & stream	stream	stream	stream	stream
N. Redbelly dace	*Chrosomus eos*	stream	stream	stream	stream	stream
S. Redbelly dace	*Chrosomus erythrogaster*	---	stream	stream	stream	---
Finescale dace	*Chrosomus neogaeus*	stream	---	---	stream	---
Redside dace	*Clinostomus elongatus*	stream	stream	---	stream	---
Pugnose minnow	*Opsopoeodus emiliae*	---	stream[1]	---	stream	stream
Suckermouth minnow	*Phenacobius mirabilis*	---	stream	---	---	---
Emerald shiner	*Notropis atherinoides*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Silver shiner	*Notropis photogenis*	---	stream	---	---	---
Rosyface shiner	*Notropis rubellus*	---	stream	stream	stream	---
Redfin shiner	*Notropis umbratilis cyanocephalus*	---	stream	stream	stream	---
Common shiner	*Notropis chrysocephalus*	stream	stream	---	---	---
Common shiner	*Notropis cornutus*	lake & stream	stream	stream	---	---
Spottail shiner	*Notropis hudsonius*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Blackchin shiner	*Notropis heterodon*	lake & stream	lake & stream	lake & stream	lake & stream	lake & stream
Bigeye shiner	*Notropis boops*	---	stream	---	---	---
Spotfin shiner	*Notropis spilopterus*	lake & stream	lake & stream	lake & stream	lake & stream	---
Bigmouth shiner	*Notropis dorsalis*	stream	stream	---	stream	strean
Sand shiner	*Notropis deliciosus stramineus*	stream	stream	stream	stream	stream
Mimic shiner	*Notropis volucellus*	stream	stream	stream	stream	stream
Blacknose shiner	*Notropis heterolepis*	stream	stream	strean	stream	stream

[1]Possible or extinct species
[2]Introduced species

TABLE 4–79 (continued) Great Lakes Basin Fish

Common Name	Genus and Species	Lake Ontario	Lake Erie	Lake Huron	Lake Michigan	Lake Superior
CYPRINIDAE (continued)						
Ghost shiner	*Notropis buchanani*	---	stream[1]	---	---	---
Popeye shiner	*Notropis ariommus*	---	stream[1]	---	---	---
Weed shiner	*Notropis texanus*	---	---	---	stream	---
Ironcolor shiner	*Notropis chalybaeus*	---	---	---	stream	---
Silverjaw minnow	*Ericymba buccata*	stream	stream	stream	stream	---[1]
Brassy minnow	*Hybognathus hankinsoni*	stream	stream	stream	stream	stream
Bullhead minnow	*Pimephales vigilax perspicuus*	lake & stream	lake & stream[1]	lake & stream	lake & stream	lake & stream
Fathead minnow	*Pimephales p. promelas*	lake & stream	stream	stream	stream	stream
Bluntnose minnow	*Pimephales notatus*	lake & stream	stream	stream	stream	stream
Stoneroller	*Campostoma anomalum*	stream	stream	stream	stream	---

[1]Possible or extinct species
[2]Introduced species
[3]Called chubs in fishery records

TABLE 4–80 List of Species Called "Chubs" in Fishery Records

Common Name	Species
Cisco or Lake herring	*Coregonus artedii*
Shortnose cisco	*Coregonus reighardi*
Shortjaw cisco	*Coregonus zenithicus*
Longjaw cisco	*Coregonus alpenae*
Kiyi	*Coregonus kiyi*
Deepwater cisco	*Coregonus johannae*
Bloater	*Coregonus hoyi*
Blackfin cisco	*Coregonus nigripinnis*

eral and State fish hatcheries designed to continue the propagation on a large scale of commercially valuable species. An estimated 32.2 million pounds of Great Lakes fish were handled each year by commercial outlets (Beeton and Chandler[55]). Despite control over fishery activities and surveillance of populations, changes occurred in the overall species composition as human population steadily increased on the shores of the Great Lakes.

8.4.2 Lake Superior

The major changes in the fish population of Lake Superior seems to have been the effect of predation by the sea lamprey on both lake trout and whitefish stocks. Before 1900 the fish catch, in order of importance, consisted of lake trout (*Salvelinus namaycush*), whitefish (*Coregonus clupeaformis*), lake herring (*C. artedii*), cisco or chubs (*Coregonus* spp.) and walleye (*Stizostedion v. vitreum*). The lake herring became the major commercial species by 1900. By 1940, whitefish and lake trout were drastically declining. Increases in smelt populations after their introduction in 1912 combined with the whitefish and lake trout decline have resulted in the following catch order: lake herring, smelt, chubs, whitefish, and lake trout. Control of the lamprey has led to an increase in the lake trout population (Smith[747]) so the commercial importance of this fish may be reestablished. The introduction of the coho salmon, another strong predator, is an additional factor that may affect further species and population changes (Beeton[46]).

8.4.3 Lake Michigan

The first of many historical changes in fish populations in Lake Michigan was the decrease in lake sturgeon (*Acipenser fulvescens*), which is attributed to commercial fishermen (Smith[747]). Prior to 1900 the fisheries catch in order of abundance consisted of lake herring, lake trout, yellow perch (*Perca flavescens*), whitefish, chubs, and suckers (*Catostomus* spp.). By 1930, this order had changed to lake trout, chubs, lake herring, smelt, suckers, carp, and whitefish. Carp had been introduced in the 1880s and smelt in 1912 (Van Oosten[844]). Coincident with the increase in lamprey populations the changes have become even more pronounced with the severe decrease in the lake trout and whitefish and the appearance of large numbers of alewife. Lake trout declined from 5.4 million pounds in 1945 to less than 500 pounds in 1953 (Beeton[46]). The 1965 fishery consisted of alewife, chubs, carp, yellow perch, whitefish, and smelt.

Lake herring started to decline as alewife and smelt populations increased, and it is probable that the rapid reproduction of alewife along with predation by the lamprey was responsible. The major herring fishery was in Green Bay, and the degradation of that area probably accounts for a portion of the decline (Beeton[46]).

By 1925 the Lake Erie cisco (chub) fishery had declined to the point that the Lake Michigan chub catch became important. However, even this fishery catch has changed since then. By 1932 the larger chubs (*C. johannse*, and *C. nigripinnis*) were becoming scarce in Lake Michigan and the net size was reduced to allow the capture of the smaller fish (*C. alpense*, *C. kiyi reighardi*, and *C. senithicus*). These smaller species, 66 percent of the population in the 1930s, declined only 6 percent by 1960. The smallest species *C. hoyi*, which had been an important food for the lake trout and had comprised about 30 percent of the population in 1930, were 94 percent of the chub population by 1960 (Beeton[46]).

8.4.4 Lake Huron

Available information on the fish populations of this lake comes primarily from commercial fishing records. The chubs (deepwater ciscoes) have remained a dominant group in the lake, although changes have occurred in the general fish populations since 1900. Before this time the catch consisted of lake trout, lake herring, yellow perch, walleye, whitefish, and suckers. By 1940 the yellow perch population had declined and carp had assumed commercial importance. In 1968 the catch consisted of carp, yellow perch, chubs, whitefish, walleye (*Stizostedion v. vitreum*), and suckers as the predominant species. The total production of fish dropped from 21.6 million pounds in 1900 to 5.1 million pounds in 1968.

The sea lamprey, which had become established earlier here than in Lakes Michigan and Superior, seems to have been responsible for the decline of the lake trout population after 1940. Decline of the whitefish on the other hand seems to have been due primarily to the use of deepwater trapnets and heavy fishing, although the effect of sea lamprey predation and adverse environmental factors cannot be ignored. In general, the changes in populations occurred earliest in Saginaw Bay and may be attributed there to increasing pollution loads. The sauger (*Stizostedion canadense*) started to decline in 1935 to a catch of only a few hundred fish a year during the last few years. There has also been a dramatic increase in the alewife population.

In general then, the changes in Lake Huron can be attributed to several factors: sea lamprey predation, overfishing, and changes in the environment.

8.4.5 Lake Erie

Lake Erie is the most productive of the Great Lakes and currently produces about 50 million pounds of fish per year, about 40 percent of the total Great Lakes fish production. Over the years this level of production has changed little in poundage but dramatically in species composition. In 1899 the major species in the catch were lake herring (cisco), blue pike (*Stizostedion vitreum glaucum*), carp, yellow perch, sauger, whitefish, walleye, suckers, and white bass. Lake herring (cisco) production decreased after 1924 although it continued into the 1950s, and the sauger started to decline after 1920, while walleye became more abundant. By 1940 the fisheries were dominated by blue pike, whitefish, yellow perch, walleye, sheepshead (*Aplodinotus grunniens*), carp, and suckers. During the past 25 years the blue pike, lake herring (cisco), sauger, and whitefish have almost disappeared from the lake. Smelt have become an important part of the fisheries since 1952. By 1968 the fisheries catch consisted of yellow perch, smelt, sheepshead, carp, white bass (*Roccus chrysops*), catfish, and walleye.

No single factor seems to have been the cause of the historical changes in the fish populations. The immigration of the sea lamprey has never been important in Lake Erie as few streams can be used for breeding. Fishing pressure by both commercial and sport fishermen has been intense on some species, yet the effect is hard to determine. Although lake trout fishing was never important, the decline and disappearance of the species probably indicates the development of an unfavorable environment. The progressive change in the fisheries began in the Detroit River area and spread slowly into the western basin. Decline of lake herring and whitefish production began in the Michigan portion of the western basin of the lake. The collapse of the blue pike and sauger fishery occurred during the period when changes in the benthos (Hiltunen[359]) first occurred.

8.4.6 Lake Ontario

Commercial fisheries have not been as important in this lake as in the other Great Lakes, although they were well developed long before records were kept. Thus any early changes are not well documented. However, some of the pronounced changes in the fish populations prior to 1900 have been noted. An example is the Atlantic salmon (*Salmo salar salar*) which, although abundant in the early years, had almost disappeared by 1880. The cause seems to be development of settlements on the tributary streams.

Lake herring, chubs, channel catfish and bullheads (*Ictalurus* spp.), yellow perch, whitefish, northern pike, suckers, and lake sturgeon dominated the catches in 1899. The 1968 catches indicate the decline of lake herring, lake trout, whitefish, and blue pike that has occurred since that time, just as in Lake Erie. The catch now consists mainly of carp, white perch, yellow perch, eels, bullheads, rock bass, and sunfish. The total production of 2.7 million pounds, about 12 percent of which is U.S. catch, is quite a reduction from the 7.5 million pounds in 1890. The American eel (*Anguilla rostrata*) has comprised a relatively larger proportion of the catch because of the increased demand for and value of this species. Carp production was not significant until after 1914. The marked population increase of the white perch (*Roccus americanus*) has only occurred in recent years. It is now one of the most important commercial species in the lake. The major important changes are the decline of the blue pike, lake herring, and disappearance of lake trout. This may be evidence of a change in the habitat. The collapse of the lake herring followed a pattern similar to that which occurred in Lake Erie, but it started here about 15 years later. The blue pike fishery collapsed at about the same time as in Lake Erie, and the decline is similar in the two lakes. The sea lamprey has been in the lake for many years because no barrier such as Niagara Falls ever existed between Lake Ontario and the Atlantic Ocean.

8.4.7 Great Lakes in General

Historical changes have occurred in the commercial fisheries of the Great Lakes. Some are related to environmental changes and some to the fishery itself. Further changes will occur which may be systematic as in the past or they can be catastrophic. The discovery of mercury contamination in the Great Lakes in 1970 has resulted in an almost total cessation of commercial fisheries activity in Lake Erie by United States fishermen. This is especially true of the walleye catch, which was still of importance. However, even the sale of perch has declined. Several fishing companies have closed down, leaving only a very small number of American boats in operation. In addition, new species such as coho and king salmon have been introduced. These species may cause changes in the populations. These types of effects along with changes in the environment may cause most commercial activity to cease and could even cause many of the species listed in Table 4–79 to become extinct.

Even though the commercial species have great value and are the best documented, these fish species make up only a small fraction of the total species of the Basin (Table 4–79). Changes in the stream fauna have been just as dramatic, if not as well documented.

In the basins of Lakes Ontario and Erie, and lower Lake Michigan, stream pollution has resulted in broken distribution patterns of many of the smaller species. The majority of the stream species, in particular, members of the Percidae (darters) and Cyprinidae (minnows), exist only in scattered stream locations and in the relatively unpolluted headwaters.

The fish component of the nekton is the most significant, but other faunal species for which little documentation exists in the Great Lakes can also be considered as nekton. These organisms, reptiles and amphibians, are commonly neglected in nekton studies, but are important members of the ecological system.

The snapping turtle (*Chelydra serpentina*) and painted turtle (*Chrysemys picta*) commonly occur throughout the Great Lakes Basin and are often important fish predators. The common northern water snake (*Natrix sipedon sipedon*) also occurs commonly and is probably another predator. Although both of these groups of animals are common, no data are available as to their influence on other nektonic organisms of the Great Lakes Basin.

The three most widespread and common amphibians are the bullfrog (*Rana catesbeiana*), the green frog (*Rana clamitans melanota*), and the leopard frog (*Rana pipiens pipiens*). As adults these organisms are often predators on fish and arthropods as well as prey for larger nektonic species. During the tadpole or immature stage they are prey for carnivorous fishes. Although amphibians are a common part of the ecosystem, they too have been neglected in the literature.

8.4.8 Summary

Fish are sensitive to changes in their environment. Numerous changes have occurred in the Great Lakes fisheries and from the standpoint of commercially important species, these have been documented, but any environmental changes that may have been responsible for population shifts have not generally been established. The sport fisheries have kept records on introductions of new species or restocking of natural species, but little definitive information exists about numbers of the sport catch or relative abundance of particular species. Consequently, relative changes in overall fish populations are not well known; so attempts to correlate poorly documented changes with environmental modification could lead to erroneous conclusions. It can be assumed, however, that changes in certain species will result in adjustments in other species so that a natural balance can be maintained in the system.

Section 9

SEDIMENTOLOGY

Thomas L. Lewis and Charles E. Herdendorf

9.1 Sedimentology of Lake Superior

9.1.1 Lake Basin Morphology

Lake Superior is divisible into two basins on the basis of structural trends. A northeast-southwest trending western basin conforms to the axis of a synclinal trough (Figure 4–8), with more easily eroded sedimentary rocks in the basin center. Prominent land features, including the Bayfield Peninsula, the Keweenaw Peninsula, Isle Royale, and the pronounced faults at Keweenaw Peninsula and between Isle Royale and the northern shore are aligned with the same northeast-southwest trend. In general, the western basin has a shelf that slopes gently from the southern shore out to depths of 180 m (600 ft.), and a very steep shelf that borders the northern shore (Figure 4–23). Magnetic and gravity surveys have defined the tectonics of the western basin (White;[886] Wold[910]).

The eastern lake basin contains pronounced north-south topographic trends (Figure 4–23), for which explanations are not obvious. Although there is a general east-west structural trend of the Precambrian rocks east of Lake Superior, diabase dikes and belts, Keweenawan lava flows, and conglomerate zones trend north-south and represent a younger structural development (Hough[380]). This trend may persist under the eastern part of the lake resulting in strongly ridged topography rising as much as 90 m to 150 m (290 ft. to 500 ft.) above the lake bottom.

Detailed bottom topography can be visualized in an isometric projection as used by McKee[520] who recognized six distinct physiographic provinces within the lake basin. These topographic patterns resemble those on shore and can be related to the local geology.

Berkson and Clay[63] investigated nearshore areas near Frieda, Michigan, with side-scan sonar, underwater television, and diver observations, and were able to recognize bedrock ledges in depths from 6 to 12 m (20 to 40 ft.).

9.1.2 Areal Distribution of Bottom Sediments

Distribution of surface sediments and sediments at 10 cm below the surface (Figures 4–267 and 4–268) indicate a narrow band of red, brown, and black sands bordering the southern shore of Lake Superior and extending along the northeastern shore past Thunder Bay (Lake Survey Center[826]). The sands grade lakeward to red-brown silts and muds, which completely surround the eastern, southern, and northwestern edges of the lake and extend to roughly 90 m to 120 m (300 ft. to 400 ft.) depth; a narrow zone of black mud occurs in deep water east of Duluth. Gray-green mud covers most of the central portion of the lake extending close to the northern shore.

The persistence of specific environments is striking. The nearshore sand zone is only a thin veneer at some places, but continuous bands are generally persistent along the south shore between the eastern edge of the basin and the Keweenaw Peninsula, and west of the Keweenaw Peninsula extending to Duluth. A wider belt of argillaceous sand farther offshore extends nearly around the Keweenaw Peninsula. These coarser sediments grade into red clays and brown-tan clays that are subparallel to the nearshore sediments. A wide zone of the brown-tan clay

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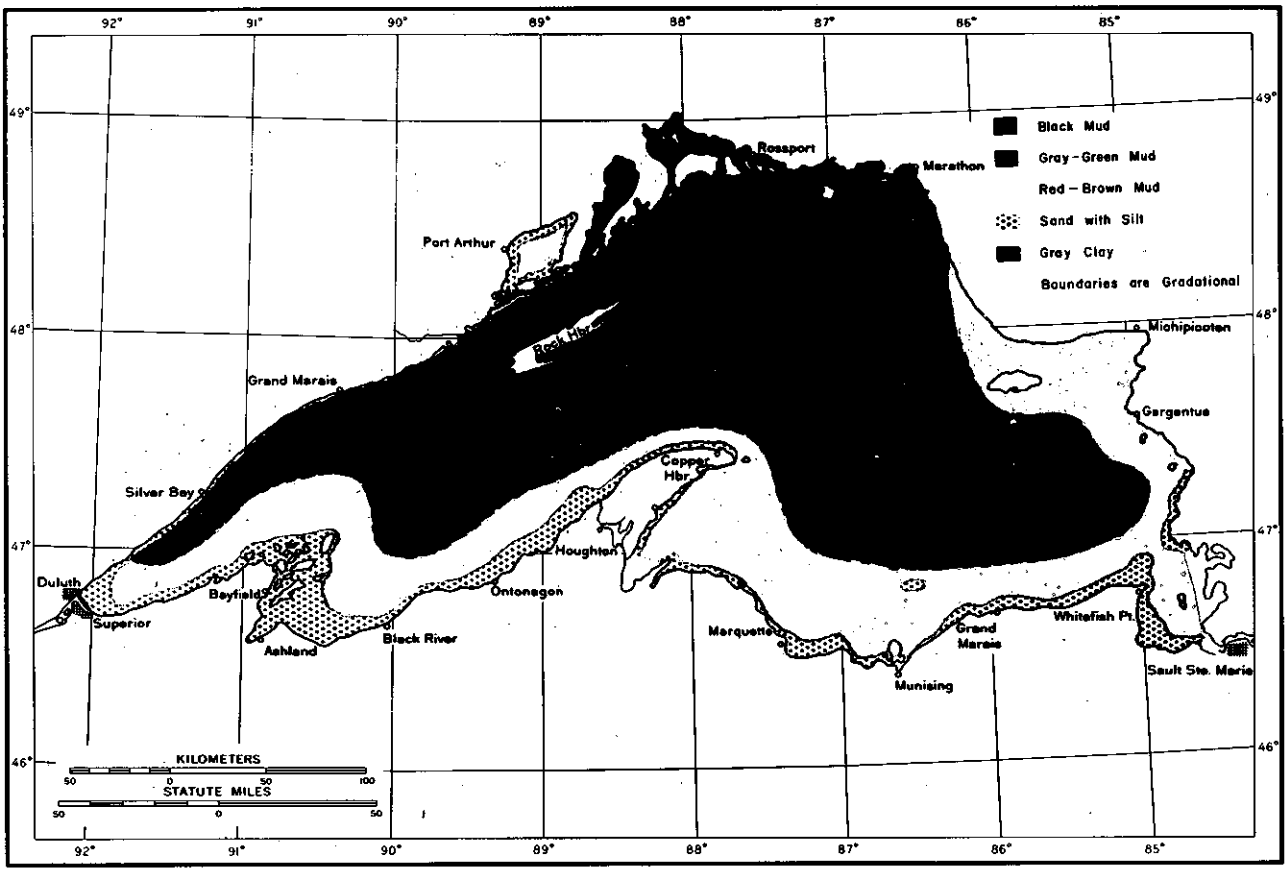

FIGURE 4–267 Sediment Distribution at the Surface, Lake Superior
From Lake Survey Center (NOS–NOAA), unpublished

crosses the southwestern part of the lake and extends out to the 400-foot depth. The remainder of the lake bottom which covers a relatively large area is essentially gray clays except for a small zone of gray to green mud between Isle Royale and the north shore.

The eastern basin of Lake Superior can be subdivided into boundary, shoal, and pelagic environments (Adams and Kreager[4]). These environmental boundaries (Figure 4–269) are based upon both sediment and the benthic fauna. The boundary environment is 2 kilometers to 10 kilometers wide along the southern periphery of the eastern basin, including the southeastern and northeastern shorelines of the Keweenaw Peninsula. Bedrock is frequently exposed, but sand (median diameter average of 2 phi) is the dominant sediment of this environment. This sand is well sorted; sources are sandstone bluffs, dunes, and unconsolidated glacio-lacustrine sediments bordering the area. The absence of boundary deposits along the north and east shores and the restricted distribution around the Keweenaw Peninsula reflect a lack of source materials in those areas.

The shoal environment is restrictive, being confined to positive topographic features that project to within 30 meters (100 ft.) of the water surface. Sediments consist of cobbles to moderately sorted fine sand, with small amounts of silt and clay. The coarse particles of varying composition indicate that the shoals are covered by lag deposits derived from glacial material.

The deepwater, pelagic environment includes most of the eastern basin lakeward of the boundary environment, and extends to the northern and eastern shore of the lake. The surface layers include lacustrine muds that vary from greenish-gray in color in the central and northern parts of the basin to reddish-brown in the south. These muds overlie compact gray clays in parts of the basin and red clays with coarser textures in the southern part of the basin. The sediments range in size from sand to clay, with scattered angular pebbles. The sediments average 50 percent sand

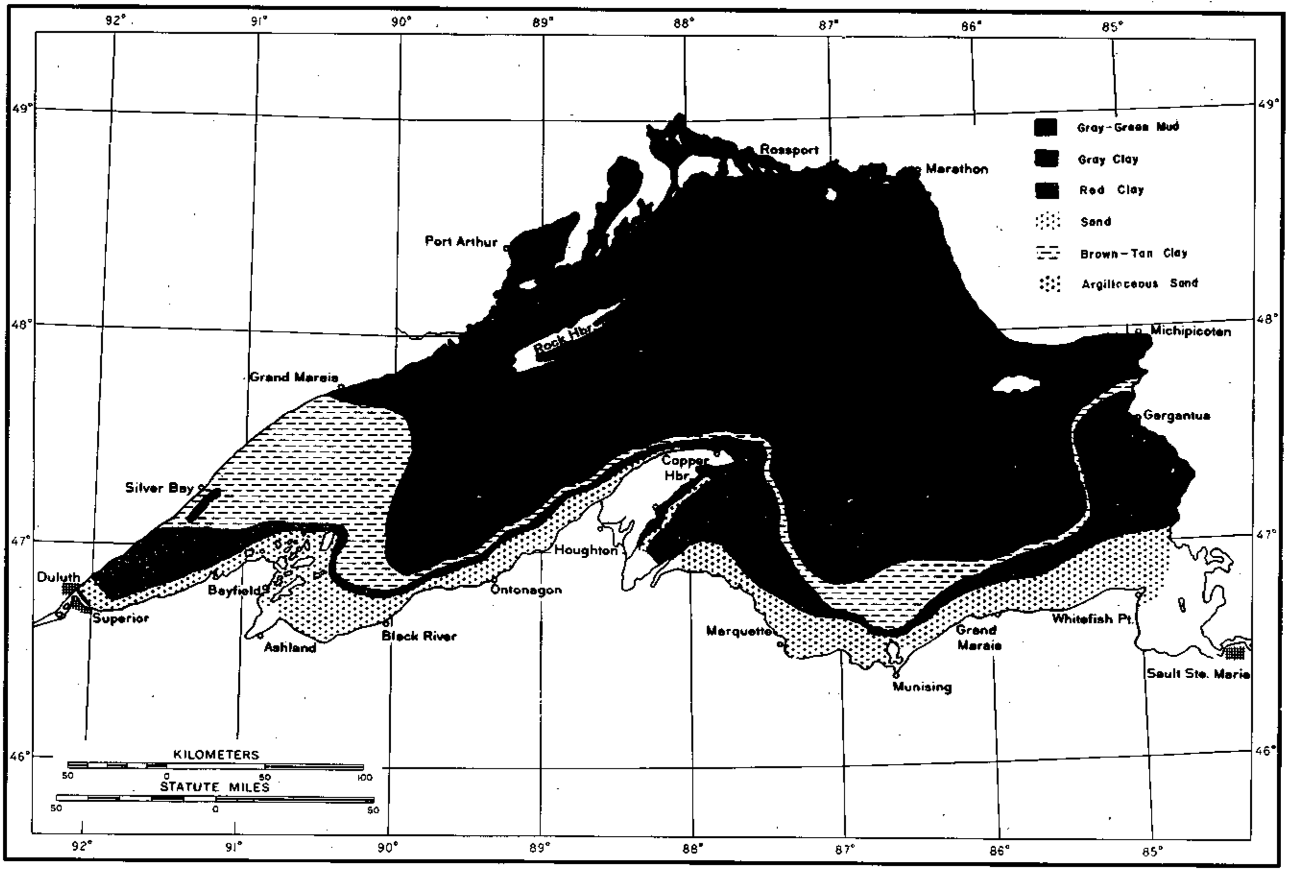

FIGURE 4–268 Sediment Distribution at a Depth of 10 cm, Lake Superior
Lake Survey Center (NOS–NOAA), unpublished

in the southern and eastern parts of the basin and only 6 percent in the central and northern parts. The fine sediments of the central and northern portions of the basin are supplied by inflowing rivers, winds blowing over the lake, and materials suspended by wave and current action in the littoral zone. The coarse sediments along the southern edge are derived from the boundary environment and the shoals. Sand-size sediments, in deep troughs, may have been transported by turbidity currents or they may be glacial in origin.

Most of the sand of the bayhead bars in western Lake Superior contains 85 percent to 89 percent quartz and is derived from till bluffs along the south shore, and concentrated by westward longshore drift (Loy[507]). These bars are also modified by lake level changes and artificial nourishment from dredge spoil in the area.

Sediment of the shallow area of the eastern basin near the St. Marys River and Michipicoten Harbour, Ontario, consists of sand on the nearshore shelf and topographic highs and silt and clay in the deep areas (Mothersill[562]). Sands of varying grain size and mineral composition are recognized on the shelf, but no variation is recognized in the 2 to 150 cm thick silt-clay covering in deeper areas.

Several restricted areas of the Superior nearshore have been studied to develop techniques distinguishing depositional environments, sediment sources, and direction of sediment transport. Plots of standard deviation versus particle diameter based on sediment samples in Douglas County showed good separation (85 percent) of fluvial and nonfluvial sediments and excellent (97 percent) separation between littoral and neritic samples (Dickas[215]). Studies of nearshore sediments at Little Lake Harbor by Bajorunas and Duane[36a] and Saylor and Upchurch[712a] document bar and trough movement and effect of waves on littoral drift and the formation of bars. Upchurch[806a] developed a potentially useful technique for determining littoral drift direction, source, and erosional and depositional sites in the nearshore area based on

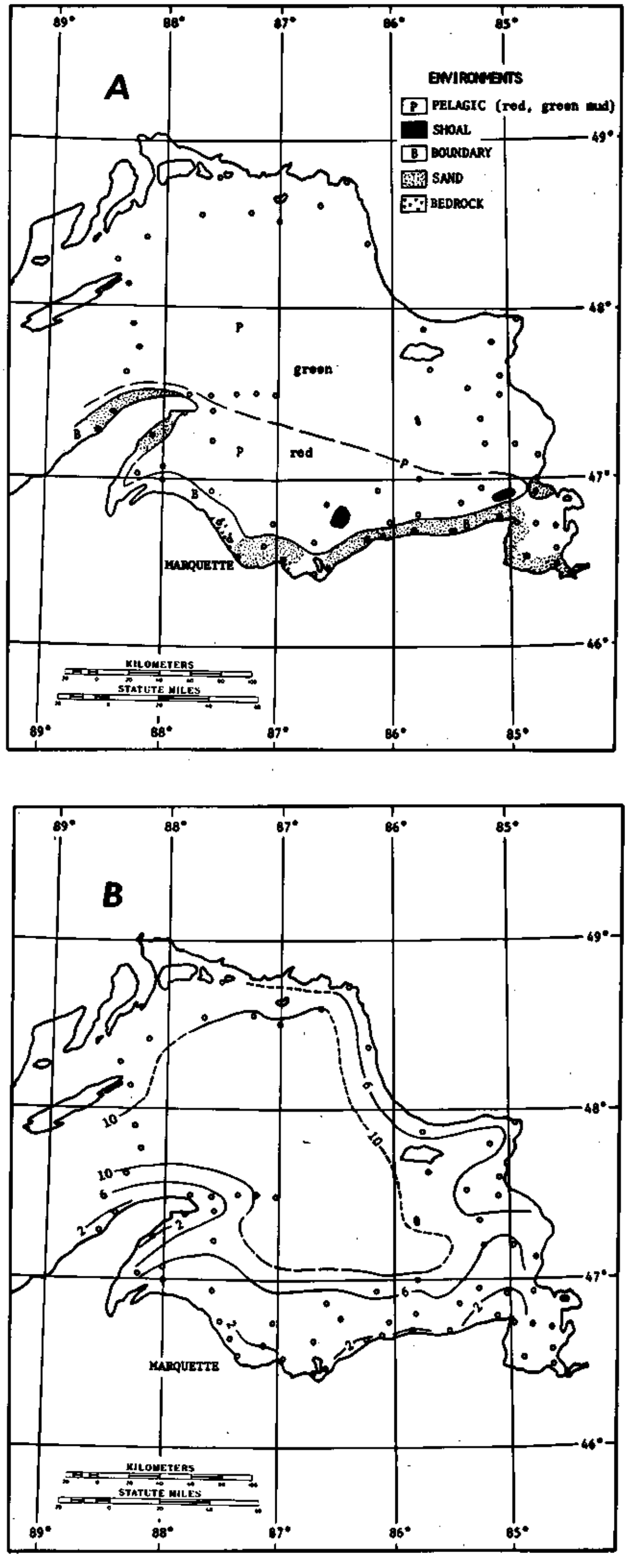

FIGURE 4–269 Environmental Boundaries (A) and Median Phi Diameter Bottom Sediment (B) in Eastern Lake Superior

From Adams and Kregear, 1969

mixed population analyses of sediment and the fact that changes in proportions of the log-normal components of sediments can be related to erosion, deposition, selective sorting, and direction of drifts.

9.1.3 Vertical Distribution of Bottom Sediments

Numerous studies based on core data and seismic profiling, most notably by Zumberge and Gast,[923] Reid,[643] Wold,[910] and Farrand,[256] preceded most surficial sediment studies. Seismic profiling has aided in defining thickness of the unconsolidated sediments (Wold[910]). Deep bedrock valleys contain as much as 300 m (1,000 ft.) of sediment. A trough between Isle Royale and the north shore contains 230 m (750 ft.) of sediment. Most of the deep north-south topographic features in the eastern basin are filled with at least 120 m (400 ft.) of material. Several east-west bedrock valleys have been completely obscured by Recent and Pleistocene sediments.

Reid[643] studied grain-size distribution; varves; and composition, including carbonate content, organic composition, and a magnetic fraction of supposed micrometereorites in several cores off Munising, in Keweenaw Bay, and in one core in Siskiwit Bay near Isle Royale. Except for two cores close to the south shore near Munising that are entirely sand, few cores were taken in depths less than 150 m (500 ft.). All cores show an expected decrease in particle size towards deeper water. Varves, alternating light and dark layers, were recognized in the northern half of the lake. Darker layers contain volatile material, and lighter layers contain mostly carbonates. In general, the percentage of volatile material (varying from 0 percent to 12 percent) is highest in deeper water sediments (compare with Figure 4–187). Analyses of clay-sized fractions indicate the presence of quartz, carbonaceous material, carbonates, illite, and/or montmorillinite.

The stratigraphy of deepwater deposits above the bedrock base examined by Farrand[256] consists essentially of silty glacial till with zones of well sorted, brown sand, which represent glacial outwash, overlain by red, lacustrine clay that is stratified in the lower part and typically varved in the upper part of the section. The clay unit varies in thickness from about 200 cm to 1200 cm (6.5 ft. to 39.4 ft.). The red varves grade upward into gray varves, which contain some of the finest-grained lake sediments, averaging 92 percent finer than one micron. Thin zones of brown clay containing either isolated grains or thin layers of sand overlie the gray varves in some cores. Clay minerals predominate in the gray sediments, and quartz, calcite, and other nonclay minerals predominate in the red sediment (Farrand[256]). Amphiboles and garnets are common in the red clays, but are rare in the gray clays. The transition from red to gray clay marks a changing sediment provenance. Farrand points out that the variations in recent sediments can be related to different sources. For example reddish-brown sediments in the southwest may be from iron ranges and red sediments of Keweenaw Age, and gray clays in the northeastern basin from light granitic rocks of the Canadian Shield.

9.1.4 Geochemistry of Sediments

Relatively high concentrations of manganese, copper, lead, and zinc occur at the sediment surface (Nussmann[582]). Absorption is responsible for the concentrations of copper and zinc (see Section 7). Surface enrichment of manganese is due to upward migration of manganese and precipitation at the sediment water interface (Figure 4–201). The surface enrichment of all these elements occurs wherever the rate of sedimentation is low.

A comparison of the mineralogy of sediments from Lake Michigan and from the eastern portion of Lake Superior (Callender[120]) indicates that the Lake Superior sediments have less quartz, calcite, and dolomite, and greater amounts of potassium feldspars, sodium feldspars, and clay minerals than the Lake Michigan sediments (Tables 4–81, 82, 83) (Callender[120]). In a comparison of average chemical composition of the sediments from Lakes Superior and Michigan, calcium, magnesium, and carbonate are less common in Lake Superior sediments, organic carbon and iron are more common and manganese is the same. Sediment pore water in Lake Superior contains less calcium, magnesium, sodium, potassium, and chloride, more iron, and equal silica and manganese compared to Lake Michigan sediment pore water. Concentration of calcium and magnesium in Lake Superior sediment pore water is higher than in lake water.

Most of the calcium is derived from amorphous phosphates or collophane, and most of the magnesium comes from chlorite in the Lake Superior sediments (Callender[120]). Chlorite and mixed-layer clays are the major clay minerals in the Lake Superior sediments. The chlorite minerals account for most of the excess magnesium and 60 percent of the sedimentary iron, the remainder of which is an authigenic hydrated oxide.

TABLE 4–81 Summary of Mineralogical Data

	Sediment Horizon[1]			
	Lake Michigan		Lake Superior	
Mineral	Surface	<1 meter	Surface	<1 meter
Quartz	61	46	51	39
Potassic feldspars	6	4	10	6
Sodic feldspars	6	5	18	17
Calcite	3	13	2	15
Dolomite	17	25	2	4
Clay minerals	7	7	17	19

[1]Percent of total mineral composition

SOURCE: Callender, 1969.

9.2 Sedimentology of Lake Michigan

9.2.1 Lake Basin Morphology

The relationship between basin shape and bedrock geology in Lake Michigan is fairly well established (Thwaites;[798] Emery;[241] Hough;[380] and Webb and Smith[873]). The lake is topographically divisible into three basins (Figure 4–25): a northern basin between the Mackinac Straits and Manistee, Michigan, with a prominent northeast-trending central depression bordered on the east and north by irregular topography; a midlake high trending from Manistee to Milwaukee, Wisconsin, bordered on the north by a ridge, and on the south by a flat shelf; and a southern basin underlying the remainder of the lake. Green Bay on the west side is separated from the main lake basin by the prominent Niagara Escarpment (Figure 4–7).

The western side of the northern basin slopes gently towards the center, following the dip of the bedrock off the Niagara Escarpment (Figure 4–8). The eastern portion of the northern basin is composed of north-south oriented ridges and troughs; Grand Traverse Bay is part of this province. The ridge and trough province is underlain by rocks of the Devonian Age Detroit River Group, Dundee Limestone, and Rogers City Formation. The irregular topography is thought to result either from collapse due to solution of limestone or anhydrite in the Detroit River Formation (Webb and Smith[873]), or from complex periglacial drainage systems (Hough[380]). Similarly, the deep south-trending depression in

TABLE 4–82 Average Chemical Composition of Upper Great Lakes Sediments

Component[1]	Lake Michigan Basin Southern		Middle		Northern		Green Bay		Lake Superior
Calcium	5.95	(3.41)[2]	4.07	(3.62)	5.72	(4.51)	2.99	(2.05)	1.38
Magnesium	2.32	(0.85)	1.76	(0.61)	1.15	(0.18)	0.82	(0.50)	1.08
Iron	1.80	(0.68)	1.88	(0.44)	1.77	(0.85)	1.60	(0.80)	2.36
Manganese	0.072	(0.09)	0.10	(0.11)	0.14	(0.12)	0.136	(0.24)	0.067
Carbonate	8.50	(4.19)	6.44	(4.56)	8.77	(4.35)	4.75	(3.32)	1.14
Organic carbon	1.56	(0.69)	1.01	(0.89)	1.69	(0.83)	2.59	(1.39)	2.44
Total nitrogen	0.204	(0.09)	0.183	(0.11)	0.237	(0.11)	0.31	(0.20)	0.23

[1]Weight percent
[2]( ) Standard deviation

SOURCE: Callender, 1969

TABLE 4–83 Average Chemical Composition of Upper Great Lakes Sediment Interstitial Waters (mg/l)

Component (ion)	Lake Michigan Basin Southern	Middle & Northern	Green Bay	Lake Superior	Lake Water Lake Michigan	Lake Superior
Calcium	44.7	42.6	39.9	28.4	33	12
Magnesium	15.0	16.5	17.8	4.3	11	2.8
Sodium	17.3	5.7	6.6	3.3	3.7	1.1
Potassium	2.5	1.8	1.9	1.4	1.0	0.6
Chloride	35.6	16.9	22.4	3.7	7.4	1.9
Silica	29.0	37.7	37.6	34.1	0.8[1]	2.1
Iron	0.316	0.84	2.56	3.48	~0.005	0.011
Manganese	0.398	1.41	1.95	1.37	0.003	~0.002
pH	7.49	7.29	7.07	6.99	8.25	7.4
Eh	+389[2]	+224[2]	+172[2]	+255[2]	--	--

[1]From Great Lakes Environmental Research Laboratory, NOAA.
[2]Millivolts

SOURCE: Callender, 1969

the northern basin may be a result of collapse from solution of the Silurian Age Salina Salt and/or later glacial modification.

An escarpment formed by the Middle Devonian Traverse Group can be traced across land southwestward from the Straits to Frankfort, Michigan, and across the lake from Frankfort to Port Washington, Wisconsin. South of this escarpment, the more easily eroded Upper Devonian Antrim Shale forms subparallel depressions that underlie the broad southern basin. The eastern side of the southern basin is shaped from outcrops of the more resistant Mississippian Age Marshall Sandstone.

A description of the present straits connecting Lakes Michigan and Huron is contained in the Lake Huron section.

9.2.2 Areal Distribution of Bottom Sediments

9.2.2.1 Nearshore Distribution

Powers[628] described source materials to Lake Michigan. Casey[127] and Fisher[262] described shoreline erosion and nearshore sedimentation between the Wisconsin-Illinois line and South Chicago. Other studies include beach erosion (Brater[84]); House Document descriptions of Milwaukee County, Wisconsin, the Illinois shore, and Berrien County, Michigan; and sediment characteristics between Lakeside, Michigan, and Gary, Indiana (Hawley and Judge[326]). Work by Davis[201] and Davis and McGeary[204] relate topography and shoreline stability along the southeastern shore. Hulsey[391] described the beaches and nearshore sedimentation along the eastern shore.

The impressive beaches, dunes, and nearshore bar complexes along the eastern and southeastern Lake Michigan coastline have long been attractive study sites. A treatise by Cressey[169] carefully delineates beach variations, erosion problems and direction of sediment transport along some Michigan beaches, and describes the nature of wind activity, dune forms, and causes of dune accumulation in the Indiana sand dunes. Contrasts of texture and mineralogy between beach and dune sands from Indiana Dunes State Park were documented by Rimsnider.[657] Descriptions by Evans[245,246,247,248] of nearshore and beach characteristics along the eastern shoreline have been important sedimentological contributions. These include the origin and classification of beach cusps, formation of submerged troughs and ridges in areas of abundant sediment supply and gently sloping bottom, relation of submerged sand ridges to beach cusp formation, and the formation and maintenance of spits and bars by swash and backwash of oblique waves. A petrographic study (Pettijohn[604]) of samples from selected eastern, western, and southern Lake Michigan beaches relates progressive north-south changes (direction of littoral drift) in texture, carbonate content, and heavy mineral frequencies.

Beach and nearshore studies of selected areas over extended time periods have resulted in better delineation of progressive onshore-offshore textural and mineralogic variations; changes in the direction of littoral drift; the relationship of changing sand-body geometries with time; and the effects of hydrologic and meterologic variables on some of these changes.

The nearshore environment along the southeastern shore of Lake Michigan from Lakeside, Michigan to Gary, Indiana, consists of a gently sloping bottom with offshore sand bars and troughs that can be traced for long distances in aerial photographs (Hawley and Judge[326]). The offshore bars, which can be detected along this entire 34 miles of coast, shift slightly from one year to the next. The bottom is composed dominantly of medium- and fine-grained sand, and it appears to shift over coarse lag materials or silt- and clay-sized sediments. Net littoral drift is southerly.

Continuous offshore bars also conform to the strand line in Berrien County and Allegan County, Michigan, along the southeast and eastern shore northeast of Lakeside (McGeary;[519] Davis;[201] Davis and McGeary[204]). Grain size in the surf zone is highly variable, and a decrease of median size was not detectable over shore distances (305 m or 1000 ft.) from shore. Grain size generally increases in troughs and decreases on bar crests. Sorting decreases in troughs and increases on top of the bars. In general, the short-term nearshore distribution of sediments is stable even after minor storms. Fluorescent-dye tracers indicate that transport in the nearshore is rapid, that wind direction determines the direction of sediment transport, and that nearshore transport is both toward the strand and along the shore.

Most beach sediment along the eastern shore of Lake Michigan is fine- to medium-grained well sorted sand (Hulsey[391]). Coarse poorly sorted sand occurs locally, particularly where glacial till borders the lake. This coarse sand grades into medium sand in the direction of sediment transport. Abundant heavy minerals, including iron species, garnet, hornblende, pyroxenes, and epidote, are present. Garnet and iron species occur in coarse sediment, near sites of active shore erosion, and hornblende and pyroxenes concentrate in the medium grain sizes. Both north and south sediment transport by longshore drift occur. South of South Haven net sediment transport is to the south, and north of Holland to Big Sable Point the direction is to the north. In the embayment between Big Sable and Little Sable Points, net littoral drift is to the south and again is to the north above Ludington.

Movement of offshore bars is sensitive to changes in lake level (Saylor and Hands[712]). A one-half meter rise in lake level over a two-year span displaced bar crests and troughs shoreward an average of 30 m (100 ft.) in the vicinity of Little Sable Point. Upward growth of bars lagged behind lake level rise allowing for greater shoreward penetration of waves and concomitant shore erosion. The linear growth of bars and exponential increase of distance between bar crests with distance offshore both maintained equilibrium during the shoreward shift.

Continuous monitoring of beach and nearshore processes reveals correlation of these variables during a season with changes in barometric pressure (Davis and Fox[203]). Low energy conditions relate to high pressure and allow formation of shallow, discontinuous sand bars and sinuous, cusped shorelines with small embayments adjacent to occasional rip

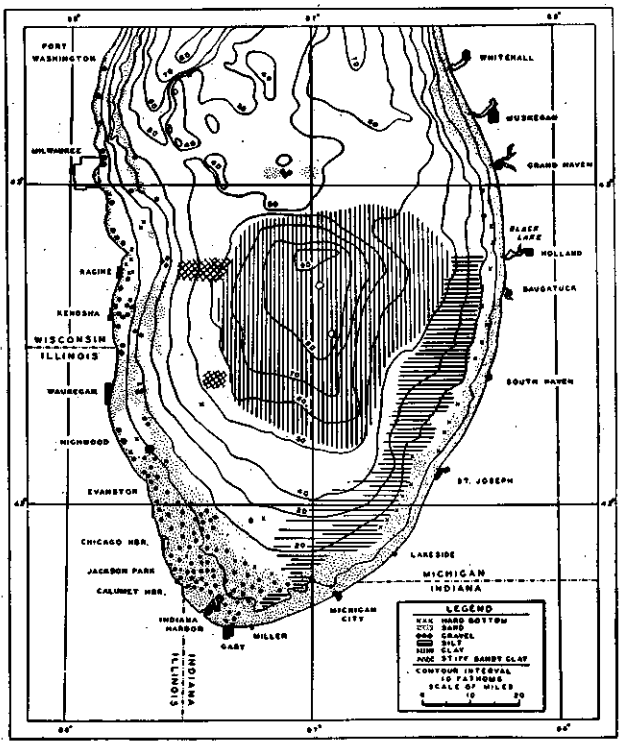

FIGURE 4–270 Sediment Distribution in Southern Lake Michigan, 1935
From Hough, 1935

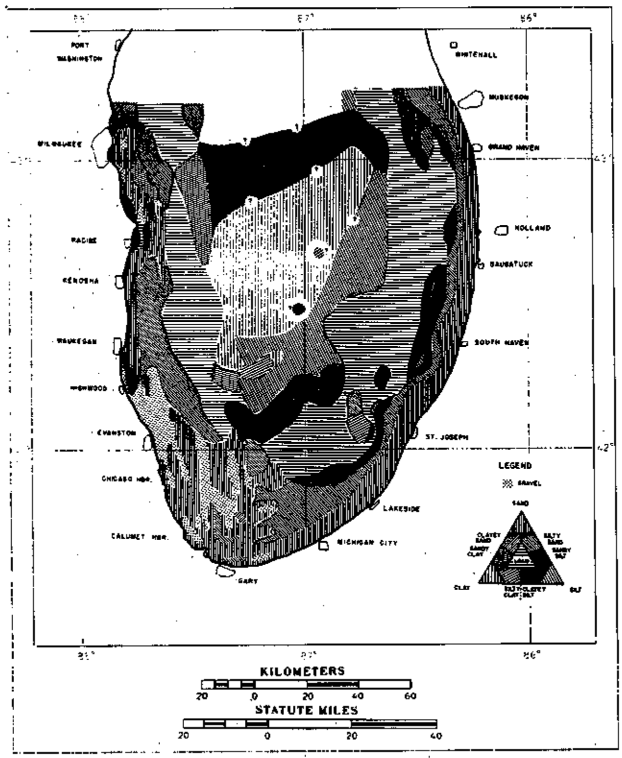

FIGURE 4–271 Surficial Sediments of Southern Lake Michigan, 1962 to 1963
From Ayers and Hough, 1963–64

channels that cut the bars. During times of falling barometric pressure, which relates to high energy, rapid longshore currents are produced by higher waves. Deflection of those higher velocity currents by the sinuous shoreline produces rip currents which erode channels through the bars and accumulates sand at sites between these rip channels. With a return to low energy conditions, the original discontinuous bar system is reconstructed, but at a site displaced along shore from its original position.

9.2.2.2 Open Lake Distribution

Hough[377] provided details of beach, nearshore, and deepwater deposits south of a latitude through Port Washington (Figure 4–270). Samples of beach sand along the western shore are essentially finer than those of the eastern shore. Bottom deposits of the eastern half of the area are sand. Recent sediments generally grade to silt and clays in deep parts of the lake. The western and southwestern sides of the basin are generally covered by glacial till or veneers of lag gravel deposits derived from the till. Stiff (cohesive) reddish-brown, sandy clay occurs west of the deepwater clay, notably east of Racine and Waukegan. A shelf off Kenosha is covered by glacial till inshore and by sand on the outer edge. Off Chicago, sand is found in broad ridges with gravel and till in troughs between these ridges. Average sand size associated with the gravel in the Chicago region bears no relationship to depth of water or distance from shore.

Ayers and Hough[31] show distributions based on field description only (Figure 4–271); however, the coverage is comprehensive. Surficial sediment distribution was essentially the same as that described 27 years earlier. This correlation may be gross because of the difficulty in relating field descriptions with detailed laboratory analyses. Sediment distribution patterns based on both size analysis and field description (Figure 4–272) extend knowledge of sediment distribution northward of the midlake shelf (Powers and Robertson[626]). Silt as used here includes both silt and clay material. Clay-silt overlying stiff plastic clay is referred to as layered deposits. Anything hard, such as bedrock, gravel, cobbles, or till are labeled hard. Layered deposits and silt obviously predominate. The silt covers

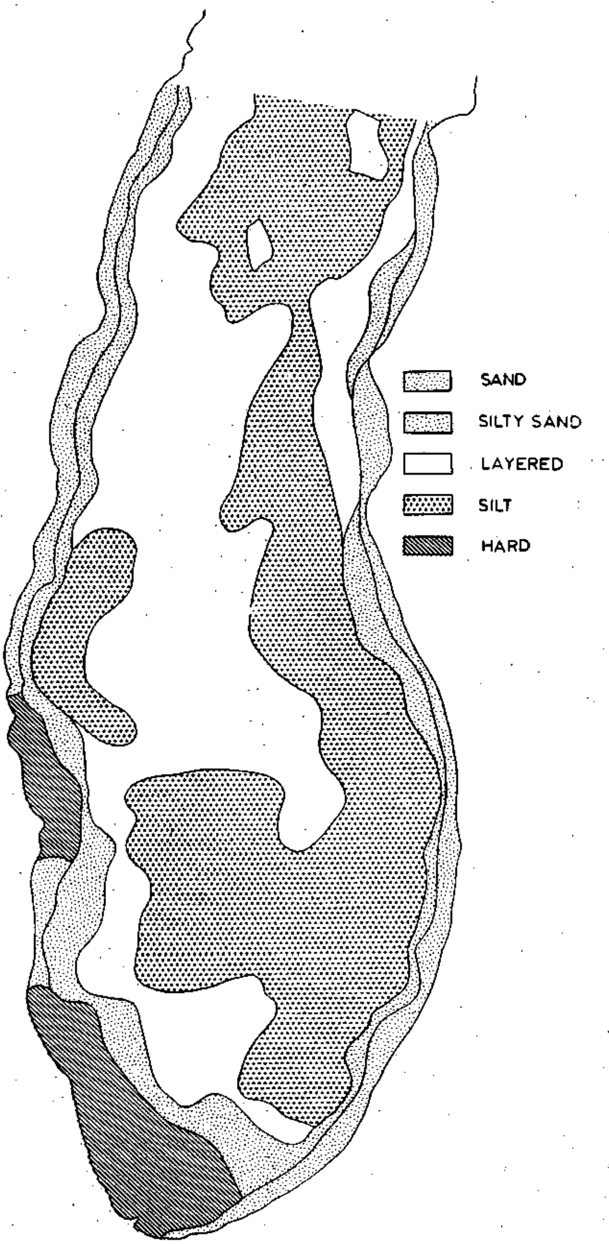

FIGURE 4–272 Distribution of Sediment Types in Southern Lake Michigan
From Powers and Robertson, 1968

much of the northern basin, a channel on the eastern side of the lake that interrupts the shelf, and much of the southern basin. Layered deposits cover most of the peripheral part of the northern basin, separating deepwater silt deposits from nearshore bands of sand and silty sand and deepwater silt from offshore silty sand along the western side of the Southern basin. Hard bottom coincides with areas previously described as till and lag gravels in the southwestern nearshore area.

Particle size distribution of samples taken by Ayers and Hough[31] from the southwestern and western nearshore areas of Lake Michigan substantiates previous conclusions (Somers and Josephson[753]). Tills eroded by waves and currents along the western, nearshore areas, provide a source for sand, silt, and clay deposits. In addition, some sand in offshore areas north of Chicago has a restricted median diameter range for some distance, suggesting that it may have been deposited during the rise of lake level from the low Chippewa Stage (Hough[380]).

Some deepwater sediments are bimodal resulting from periodic influxes of medium-fine sand during violent storms (Cote[167]). Cote describes an offshore increase of grain size at 17 m to 32 m (55 ft. to 105 ft.) depths in southeastern Lake Michigan before decreasing toward deeper water.

Sediment distribution patterns in the northern basin are not well known. Lake Survey Center, National Ocean Survey (Figure 4–273) indicates that fine- to medium-grained and fairly well sorted sand covers most of the northern part of the lake bottom near the Straits and occur as narrow bands parallel to both shorelines. Two isolated patches of argillaceous sand extend offshore on either side of Traverse Bay. Extensive areas of brown and reddish-brown clay with thin zones of quartz sand border the east and west sides of the deep basin. Brown and reddish-brown clay with occasional gray-brown mud, and a well defined area of gray-green mud cover the deep portion of the northern basin.

In general, the lake bottom topography exerts strong control on sediment distribution in the ridge and trough province of northeastern Lake Michigan (Moore[550]). Coarse sediments occur on the ridges and ridge flanks, and fine sediments are restricted to troughs (Figure 4–274). Most bottom sediments are well sorted, except at the base and the flanks of troughs where accumulations by slumpage occur. Sediments in Little Traverse Bay and the associated shelf area show a regular grain-size variation with change in depth of water and topography. Generally, carbonate content increases with a decrease in the median diameter of the particles and it decreases in deep troughs and bays. Pyrite in the lake sediments is higher than in the glacial till on adjacent shores. The high pyrite content is associated with shells and shell fragments. Clay minerals are predominantly illite, followed by mixed-layered clays, and then chlorite. Clay-mineral composition shows no variations with changes in depth of water, distance from shore, or depth of burial. No variation occurs between clay-mineral composition of lake sediments and glacial tills from the adjacent shores.

Nearshore, deep areas contain muddy sand deposited from currents or wind transport. A deep basin in the center of Manitou Passage around Sleeping Bear Point contains clay, while most of the adjacent shallow, shelf areas (less than 20 m or 70 ft.) are floored with clean sand or with a gravel-cobble-boulder pavement overlying clay till (French[273]). An onshore moraine (Sleeping Bear Hill) is actively eroding, and the adjacent offshore shoal, floored by medium-coarse sand and protective gravel-cobble pavements, is the remnant of the western part of this moraine. Sand has been moved inland by wind to produce dunes on the hill.

9.2.3 Vertical Distribution of Bottom Sediments

Core studies in Lake Michigan combined with high resolution sub-bottom seismic profiling studies, provide a fair representation of lake sub-bottom sediments.

The area of the lake between Green Bay and a line from Kenosha, Wisconsin to South Haven, Michigan, consists of a deepwater sequence, including gray lacustrine clay at the top grading downward through red clay, blue-gray clay, and a lower red clay which rests on top of red, glacial till (Hough;[381] also see Snodgrass;[749] and Shea[730]). The sequence is typical of depths greater than 107 m (350 ft.) below the present lake level. At shallower depths, the cores contain thin layers of sand, frequently with shells of a shallow-water species interspersed in this standard sequence. The truncation of clay zones and subsequent deposition of sand occurred during a low lake stage named Lake Chippewa by Hough.[381]

In deep parts of the northern lake basin glacial till is covered with a complete sequence of lake clay deposits, the lower part of which is red clay with small amounts of organic matter (Hough, in Ayers and Chandler[30]). The red clay grades upward to gray, becoming continuously darker up to the sediment-water interface. Black color bands in the gray clay contain iron sulfide and small amounts of organic matter. The sequence records low organic productivity extending from the last glacial event until nearly modern times.

Shallow and deepwater cores in and near

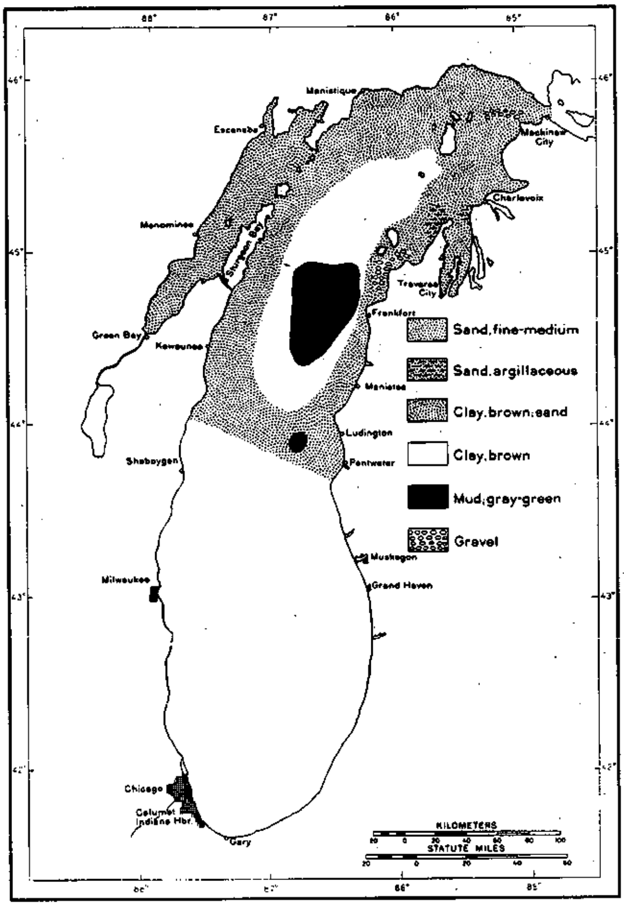

FIGURE 4–273 Distribution of Sediment Types in Northern Lake Michigan
From Lake Survey Center (NOS-NOAA), unpublished

Little Traverse Bay contain an uninterrupted sequence of dark gray clays in the bay and in deepwater troughs (Moore[550]). In depths less than 72 m (235 ft.) coarse sediment is intermixed at various levels with the clay. This sequence varies greatly reflecting changing environments of shallow-water deposits during progressive deepening of lake water from the Lake Chippewa low-water stage.

High resolution, sub-bottom seismic profiling revealed several lithologic variations at depth in Green Bay and southern Lake Michigan (Meyer et al.[534]). The lithologic units include, from top to bottom, modern sediments, varved sediments, and a rough reflective zone. A similar sequence occurs in the eastern and central portion of southern Lake Michigan.

Lacustrine sediments, cored at 65 km (4 mi) intervals along a line extending from 19 km to 52 km (12 mi to 32 mi) due east from Waukegan, Illinois, by the Illinois Geological Survey, includes the following sequence (from top to bot-

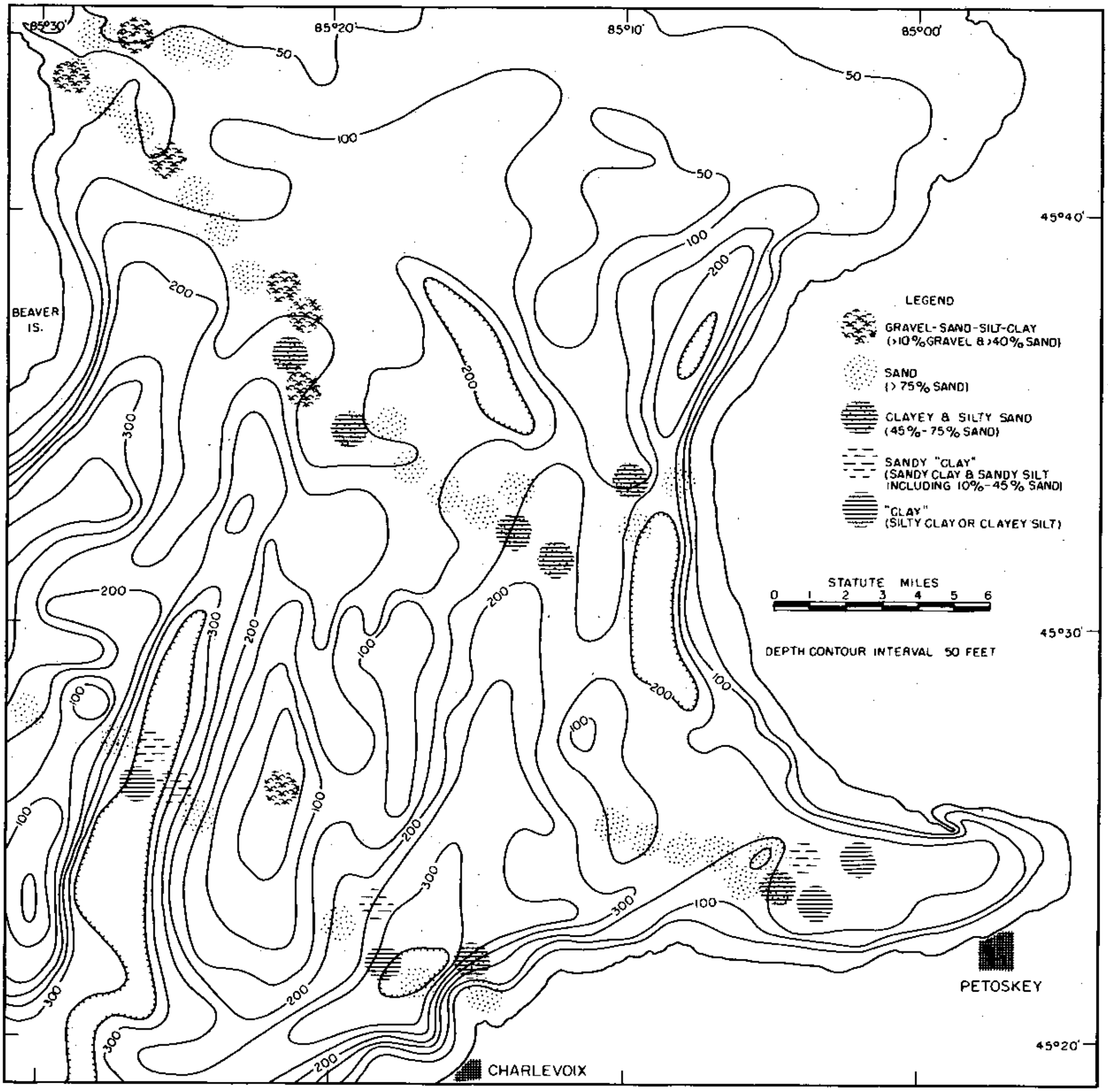

FIGURE 4–274 Areal Distribution of Sediments in Northeastern Lake Michigan, Based on Gravel, Sand, Silt, and Clay Content

After Moore, 1960

tom): a few centimeters of sandy silt clay; 0.5 m to 1 m (1.5 ft to 3 ft) of dark gray, silty clay with thin, black clay layers; 0.5 m (1.5 ft) of brownish-gray, silty clay with thin, dark layers; 0.75 m (2.5 ft) of orange-brown clay; homogeneous, pink clay 1 m (3 ft) thick; glacial outwash, and till. In all cores, grain size decreases with depth in the sediments. Illite, chlorite, and expandable clays decrease downward and kaolinite decreases upward.

Strata in southern Lake Michigan cores have been assigned formation names (Lineback et al.[498]). The uppermost formation (Lake Michigan Formation) is divided into six members and one bed on the basis of color, water content, cohesiveness, grain size, and mineralogy. Using high resolution sub-bottom profiling techniques, Lineback et al.[499] have recognized three unconformities and various overlapping relations of the units of the Lake Michigan Formation.

9.2.4 Geochemistry of Sediments

The relationship of organic carbon to depth and sediment types has been discussed in Section 7. Organic carbon increases with depth, but not at a uniform rate (Figure 4–187). Also, organic carbon is frequently associated with specific sediment types (Powers and Robertson[626]). The smallest quantities of organic carbon occur in sand (0.04 percent to 0.22 percent), followed by silty sand (0.16 percent to 0.71 percent), then in upper silt layers of the layered sediment (0.66 percent to 1.69 percent), and finally, in silt from the deepest parts of the lake (ranging above 1.70 percent). Organic carbon content within the same depth range increased with decreasing grain size. Powers and Robertson could see no relationship between the organic carbon found in sediments and the amount of particulate and dissolved organic matter found in the water, so they concluded that no relationship between quantity of organic matter in the sediments and productivity of the water can be made.

Surficial sediments of Lake Michigan appear to be significantly coarser and contain more sand-sized material than sediments at depth below the interface (Callender[120]). The same is true of Green Bay, where the surficial sediment is mainly sand and silt. In addition, surficial sediments contain approximately 35 percent more quartz than deeper sediments, while feldspars and iron remain essentially equal. Calcite and dolomite increase significantly with depth but not uniformly. The dolomite-calcite ratio of surface samples averages 6:1, whereas the ratio of deeper samples decreases to 2:1. Manganese content increases two to five times in surface samples with the most pronounced increase in Green Bay. In general, the most organic material occurs in southern Green Bay surficial sediments, which receive the discharge from the Fox River. Organic-carbon fixation by the phytoplankton is also higher in Green Bay than in Lake Michigan.

A regional comparison of the geochemistry of sediments in Lake Michigan indicates that the calcium, magnesium, and carbonate content of Green Bay sediments is lower than that of other Lake Michigan sediments; iron stays relatively the same; manganese increases two-fold and organic carbon is significantly higher in Green Bay than in other Lake Michigan sediments.

Interstitial pore water calcium and magnesium concentrations are at least 30 percent higher than in lake water. In the southern basin interstitial sodium is 400 percent greater than in lake water and, in other parts of the lake, is as much as 60 percent greater than in lake water. Interstitial potassium content is 200 percent higher than lake water. Chloride is 500 percent higher in the southern basin and 200 percent to 300 percent higher elsewhere. Silica in pore water may range 1,000 percent to 1,700 percent greater than in lake water. Iron increases from 0.3 mg/l in the southern basin to 2.5 mg/l in Green Bay, and manganese increases from 0.4 mg/l to 2.0 mg/l.

In general, interstitial water is in equilibrium with calcite and dolomite in Lake Michigan (Section 7). Most of the authigenic manganese compounds and some of the iron compounds originate within the sediments, where these metals are brought into solution under low Eh-pH conditions, and migrate to the sediment surface where they are precipitated (Figure 4–201). At least 60 percent of the sedimentary iron and most excess magnesium not combined in dolomite is bound up in clay minerals. The remaining iron occurs as authigenic hydrated oxide (ferric hydroxide, see Section 7) with which all of the sedimentary manganese is associated.

Green Bay is considered to be polluted where the Fox River discharges fine-grained organic-enriched sediment, and less polluted in the north part which is characterized by medium sand. Most of the metallic elements added to Green Bay water are derived from rivers, particularly those entering northern Green Bay which contribute dissolved iron and manganese (Callender and Rossman[121]). Ferromanganese nodules have been formed on the floor, but are presently dissolving in the southern basin as a result of oxygen depletion of the sediment-water interface (see Section 7). Sediments in Green Bay show an inverse depth relationship between sedimentary and interstitial manganese with the sedimentary manganese increasing to a maximum near the sediment-water interface. Sedimentary iron remains constant with interstitial iron slightly decreasing towards the sediment-water interface. Manganese nodules have also been found at scattered localities in Lake Michigan (Rossman and Callender[682]). Possibly as much as one-half of the manganese found in the lake water has been derived by leaching of manganese and iron from the iron deposits of the Canadian Shield.

The trace elements As, Br, Cr, Cu, Ni, Pb, and Zn have been detected within the upper portions of much of the sediment in southern Lake Michigan in concentrations 5 to 10 times greater than in the underlying sediment (Shimp and Leland[734]). Concentration of these trace elements in Recent sediments are posi-

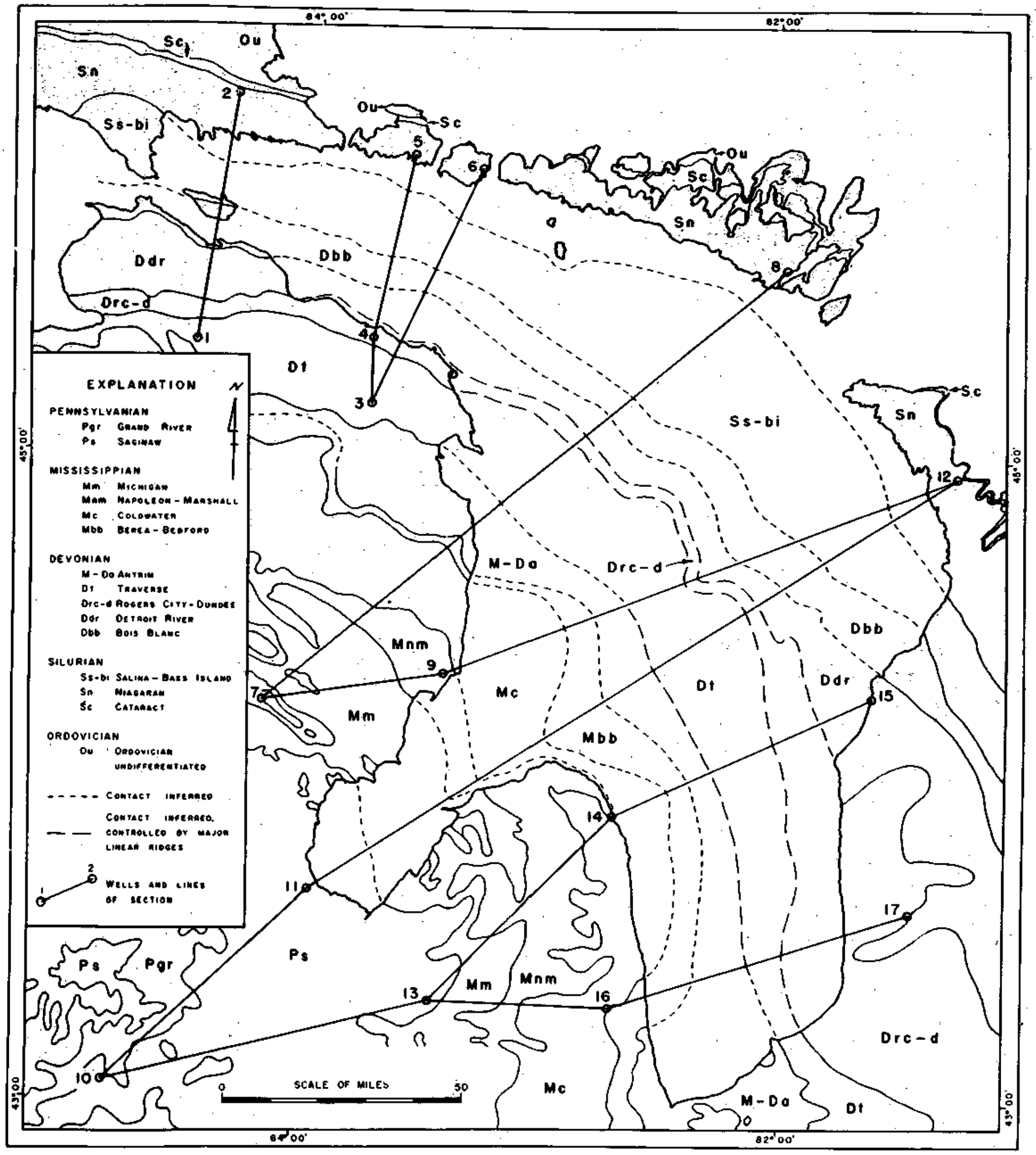

FIGURE 4–275 Bedrock Geology of Lake Huron

After Cvancara and Melik, 1961

tively correlated with the quantity of organic carbon present. These concentrations may reflect the extent of pollution in southern Lake Michigan. See Section 7 for a discussion of significance of trace elements.

Concentration of phosphorus correlates directly with arsenic, iron, and organic carbon in the sediments (Schleicher and Kuhn[719]). High arsenic content (5 mg/l to 30 mg/l) was identified at the sediment-water interface west of Benton Harbor, Michigan, east of Waukegan, Illinois, and southwest of Grand Haven, Michigan (Ruch et al.[686]). The arsenic varies directly with the organic carbon content; so it may be a result of man's activities in the drainage basin.

Kennedy et al.[450] found mercury accumulations from 0.1 mg/l to 0.4 mg/l in the uppermost fine-grained sediment in southern Lake Michigan and noted that mercury concentrations vary directly with organic carbon and total sulfur. Background mercury levels found at depth in cores were 0.032 ppm to 0.060 ppm. Little or no mercury was found in the sandy areas of the southern and southwestern shores.

9.3 Sedimentology of Lake Huron

9.3.1 Lake Basin Morphology

The basin morphology of Lake Huron is well known (Hough;[380] and Cvancara and Melik[176]). The lake basin axis follows the strike of the rock units which are dipping southward and westward toward the center of the Michigan Structural Basin (Figure 4–275). The Niagara Escarpment separates Georgian Bay from the main lake (Figure 4–7). Two major linear ridges capped by the Rogers City and Dundee Formations and the Upper Devonian Traverse Group (Figure 4–275) separate the lake bottom into two structural provinces. A flat, southwestern structural province is underlain by Mississippian and Upper Devonian shale and sandstone. In the northeastern province, between the Niagara Escarpment and the subparallel linear ridges, the bathymetry is irregular because of the presence of Silurian reefs and possibly because of collapse structures resulting from the solution of Upper Silurian Salina Salt.

9.3.2 Areal Distribution of Bottom Sediments

Distribution of sediment at the bottom of Lake Huron has not been well defined except for detailed work in Saginaw Bay and the Straits of Mackinac. In general, the periphery of the lake from the shoreline out to 20 km (12.4 mi) is bordered by coarse- to fine-grained and sand deposits (Figure 4–276). Presence of coarse gravel and boulders of igneous, sedimentary, and metamorphic rocks could represent lag deposits from tills. Some sand reflects the availability of chert and dolomite from bedrock bottoms. Thin veneers of dark gray to brown silty clay grade to dark, gray-brown clays in the central parts of the basin. Dark gray and reddish limonitic clay and very dark gray to black clay along with shale occur locally. Nothing is known of detailed size or compositional variations or geochemical relationships of these sediments so little can be suggested about sediments sources or dispersal.

Saginaw Bay is divided into two parts by a shallow, northwest-southeast extending shoal (Wood[914]) (see Section 8 for discussion of the ecology of the shoal). Sediments range in size from large pebbles to clay, but medium- to fine-grained sand is common in all parts of the bay (Figure 4–277). Apparently, the main sedimentary features of the bay relate to the overall circulation pattern within the lake (see Section 6). Currents move southward along the western edge of Lake Huron, circulate through Saginaw Bay, and exit into Lake Huron along the southeastern shore.

In the Straits of Mackinac and northwestern Lake Huron (Figure 4–278) sand and silty sand cover much of the bottom from shorelines out to depths of 31 m (100 ft) (Lauff et al.[486]). As expected, silts are concentrated in the deeper parts of the Straits. However, lesser amounts of silt occur in upper Lake Michigan and the Straits than in open Lake Huron. This overall pattern, along with deficiencies of silt and better sorting of sediments in channels, suggests that bottom currents are sufficient to maintain a net transport of fine-grained material from west to east into Lake Huron. The Straits and the South Channel are essentially floored with hard, red and gray glacial clay.

In the lower part of Lake Huron (Duane[225]), beaches on the American shore are dominantly sand with some granules, pebbles, and cobbles. Offshore, a zone of boulders and cobbles with little sand separates the beach from a well-defined, submerged, sand shoal. Canadian beaches are more coarse and sand occurs offshore only as a thin veneer overlying glacial clay. Similar composition and grain size of sediments in the suspended load and bed load of the St. Clair River indicate that probable sources of these sediments are the nearshore areas of lower Lake Huron.

In Georgian Bay northeast of Tovermory (Sly[745]), bedrock outcrops and boulder debris are common around islands and submerged reefs in depths from 5 m to 30 m (16 ft to 100 ft); mud covers the deeper bottom. Surficial deposits thicken eastward toward the center of Georgian Bay.

9.3.3 Vertical Distribution of Bottom Sediments

Sediments from deep water in northwestern Lake Huron (80 m to 107 m or 257 ft to 345 ft) contain an average of 20 cm (18 in) of yellow-buff clay overlying 110 cm (43 in) of gray clay, which in turn overlies masses (up to 150 cm or 58 in thick) of red clay containing thin zones of sand and silt (Figure 4–279). Shallow-water cores (less than 71 m or 230 ft) contain a sharp boundary between the gray clay and underlying red clay, which is marked by sand, pebbles, and shallow-water gastropod and pelecypod shells. This zone is interpreted as representative of a low-water stage.

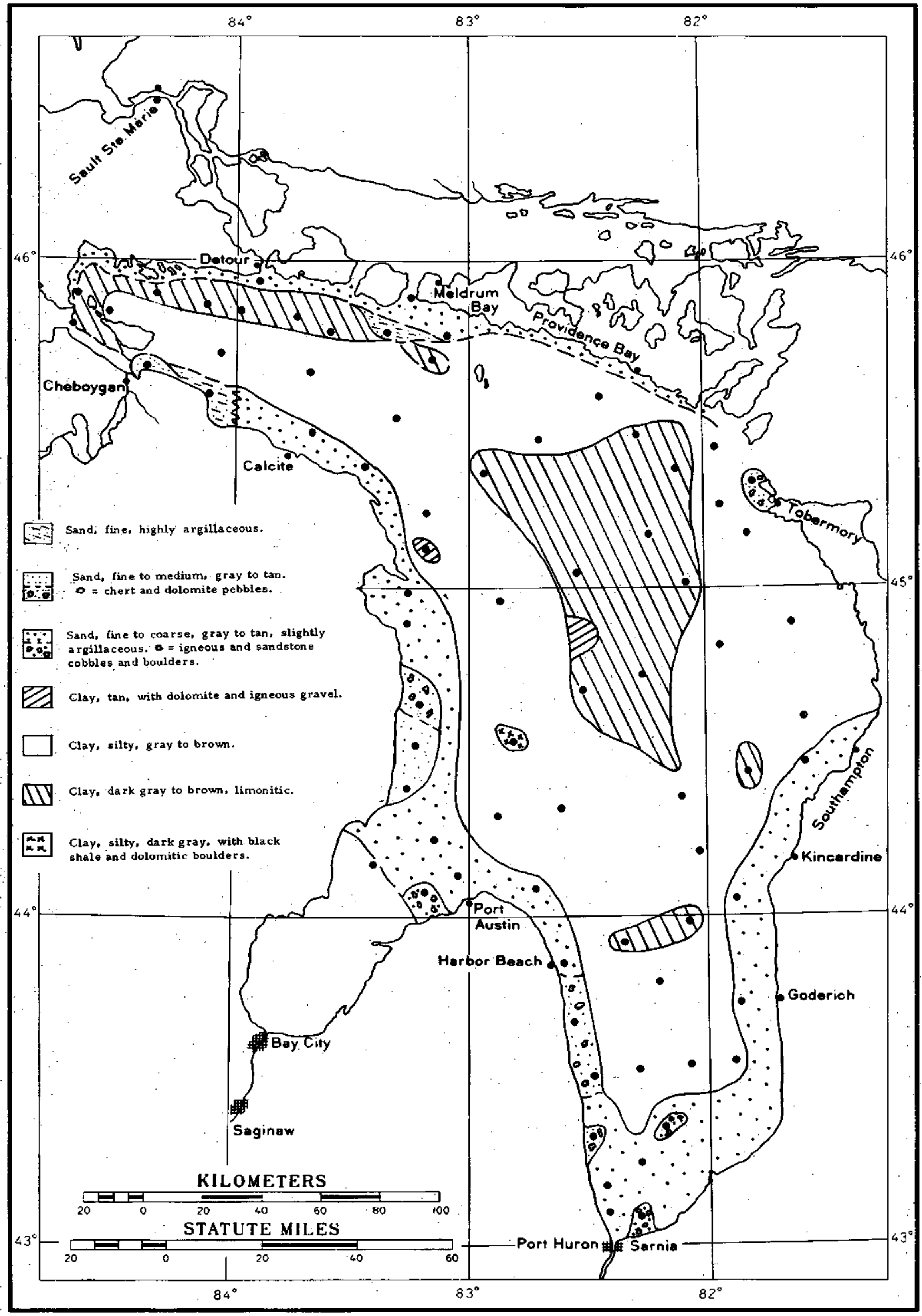

FIGURE 4–276 Field Description of Lake Huron Bottom Sediments
Lake Survey Center (NOS–NOAA), unpublished

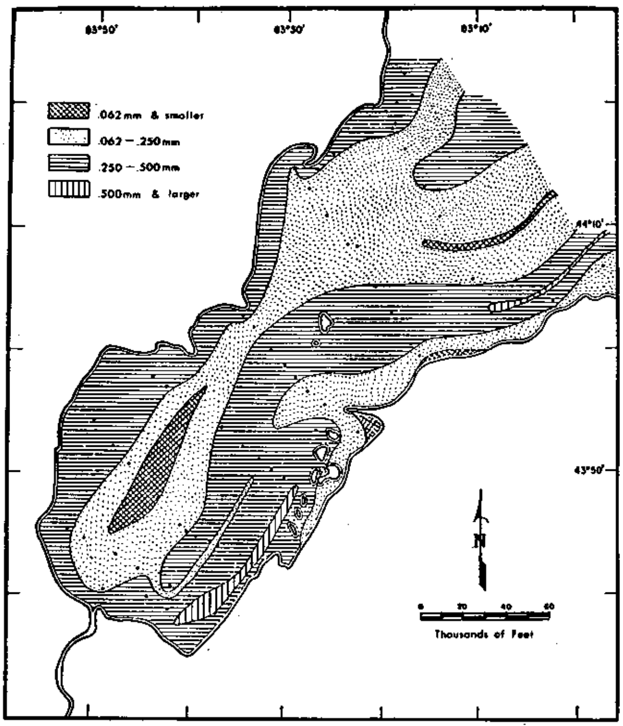

FIGURE 4–277 Areal Distribution of Major Median-Diameter Size Grades in Saginaw Bay
After Wood, 1958

9.4 Sedimentology of Lake Erie

9.4.1 Lake Basin Morphology

Lake Erie is a relatively narrow and shallow lake with its long axis oriented east-northeast (Figure 4–280). The lake is naturally divided into three basins: western, central, and eastern (Table 4–84).

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 m and 11 m (25 ft and 35 ft) (Figure 4–280). 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 is flat except for the steep-sided islands and shoals in the eastern part. The deepest soundings are 19 m (62 ft) in a small depression north of Starve Island Reef and 16 m (54 ft) in another depression south of Gull Island Shoal.

The central basin is separated from the western basin by the island chain and Point Pelee, and 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 (61 ft) and a maximum depth of 26 m (84 ft). 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.

TABLE 4–84 Morphometry of Lake Erie Basins

Characteristic	Lake Erie Basin Western	Central	Eastern
Maximum length (miles)	50.0	132.5	85.0
Maximum breadth (miles)	40.0	57.2	47.5
Maximum depth (feet)	62.0	84.0	210.0
Mean depth (feet)	24.2	60.7	79.9
Maximum depth/mean depth	2.8	1.4	2.7
Area (square miles)	1,265.0	6,246.0	2,408.0
Volume (cubic miles)	5.8	71.8	36.4
Shoreline (miles)	268.3	373.3	263.3
Percent of total area	12.8	62.9	24.3
Percent of total volume	5.1	63.0	31.9
Percent of total shoreline	31.7	37.1	31.2
Longitudinal axis bearing	N67°W	N67°E	N67°E

SOURCE: Verber (1960) modified.

The eastern basin is relatively deep and bowl-shaped. A considerable area lies below 37 m (120 ft), and the deepest sounding of 64 m (210 ft) is about 8 miles east-southeast of Long Point, Ontario.

9.4.2 Basin Geology

Carman[123] attributes the varying depths of the Lake Erie basins to differential erosion by preglacial streams, glaciers, and postglacial, lacustrine processes. The strata of the central and eastern portions of Lake Erie dip slightly to the southeast and have a general east-west strike direction roughly paralleling the lake. Lake Ontario is separated from Lake Erie by the resistant Silurian limestones and dolomites of the Niagara Escarpment. The central and eastern basins of Lake Erie are underlain by nonresistant shale, shaly limestone, and shaly sandstone of Upper Devonian Age (Figure 4–281).

The southward advance of Pleistocene glacial ice was obstructed by the Mississippian Escarpment 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 and the shallow

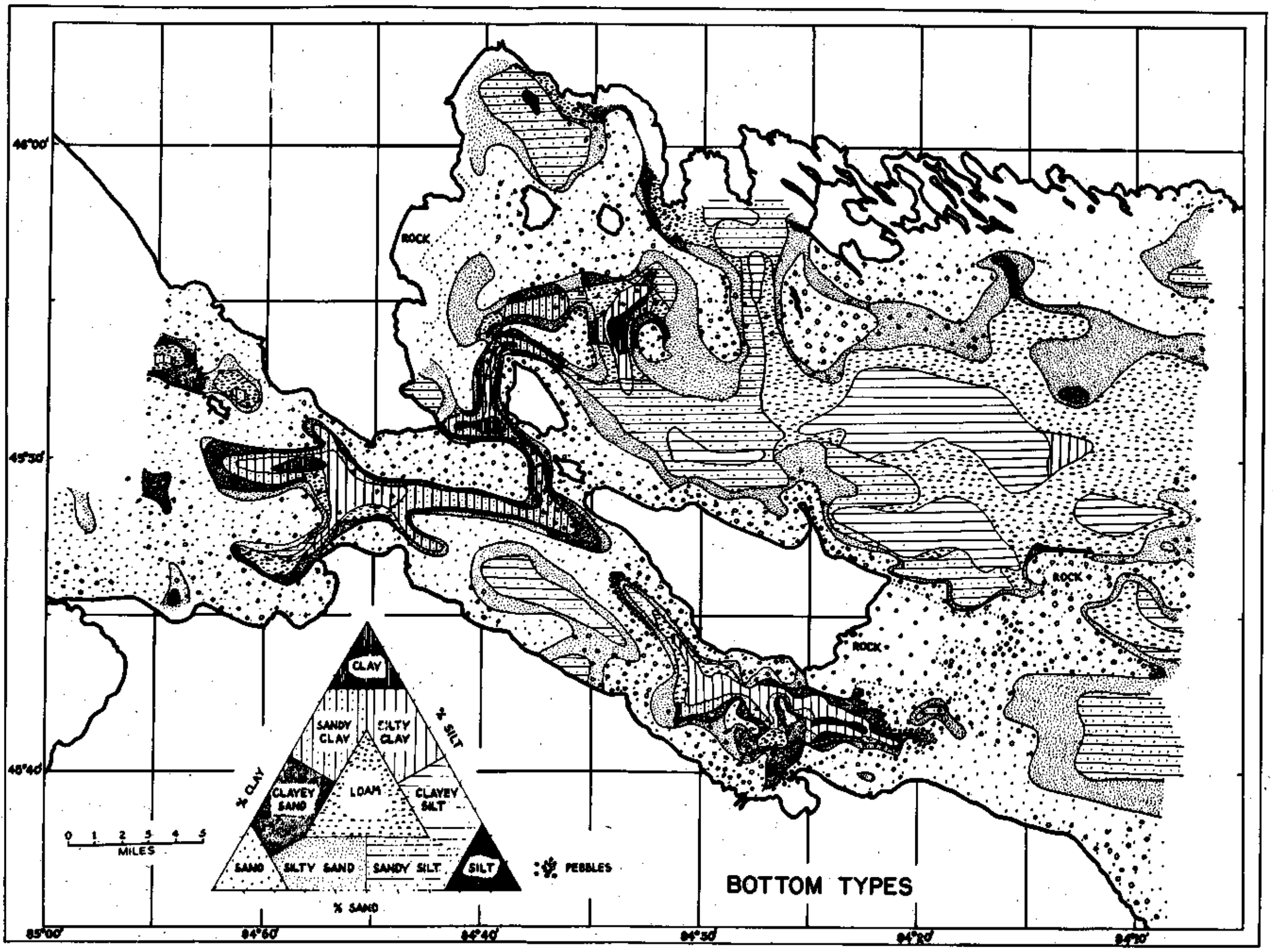

FIGURE 4–278 Bottom Types of the Straits of Mackinac and Upper Lake Huron
From Lauff et al., 1961

western basin is underlain by Silurian and Devonian limestone and dolomite on the northward plunging end of the Findlay Arch (Figure 4–3). Glacial erosion had relatively slight effects on these resistant rocks. The islands in western Lake Erie are arranged in two north-south belts that correspond with the outcrop patterns of the two most resistant rock formations. The Kelleys Island-Pelee Island belt is underlain by the Columbus limestone and the Bass Islands are underlain by the Put-in-Bay dolomite (Figure 4–281).

9.4.3 Areal Distribution of Bottom Sediments

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 bedrock and rubble, shale bedrock shelves, and erratic cobbles and boulders composed chiefly of igneous and metamorphic rocks. The distribution of bottom sediments is related to the bottom topography (Figure 4–282). The broad, flat areas of the western and central basin, and the deep areas of the eastern basin have mud bottoms. Midlake bars and nearshore slopes comprise mostly sand and gravel or glacial till. Rock is exposed in the shoals of western Lake Erie and along the south shore of the central basin and both shores of the eastern basin. In general, sand is limited along the shoreline, but extensive dune and beach deposits are found at several places. Notable dunes have been formed at the base and southwest side of Long Point, Point Albino, and Sturgeon Point, all in eastern Lake Erie. These dunes were formed presumably under the influence of the prevailing southwest winds. Littoral currents have concentrated sand in spits and baymouth bars at such places as Point Pelee, Pointe Aux Pins, and Long Point, Ontario; North Cape, Michigan; East Harbor and Cedar Point, Ohio; and Presque Isle, Pennsylvania.

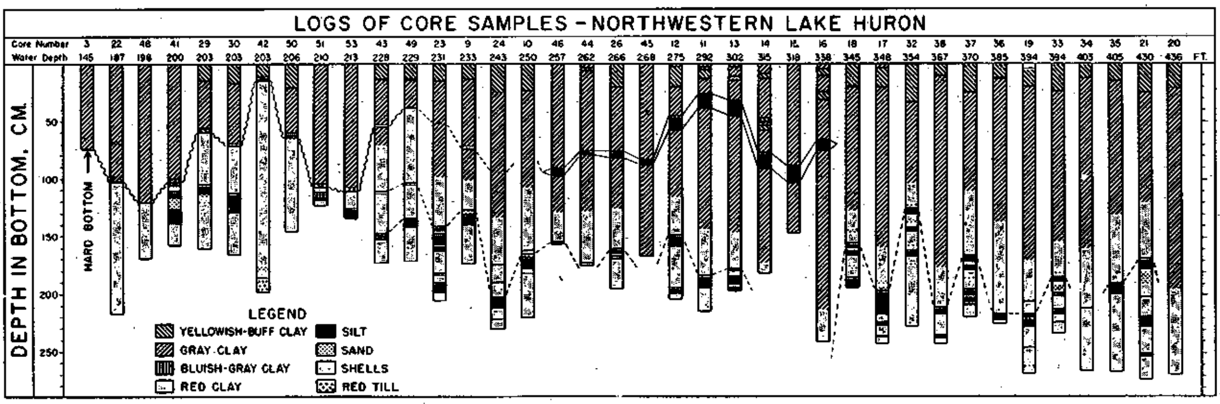

FIGURE 4–279 Logs of Core Samples from Northwestern Lake Huron

From Hough, 1962

Pegrum[600] observed that most of the bottom of eastern Lake Erie is mud and clay bounded by relatively steep slopes of sand and gravel or rock. The massive spits at Presque Isle and Long Point are the largest accumulations of beach sand in Lake Erie. Rock is exposed in a narrow strip along most of the eastern basin's shoreline, shale along the south shore, and limestone along the north shore.

The bottom surface material of the Ohio portion of central Lake Erie consists of silt and clay (77 percent), sand and gravel (22 percent), and shale bedrock (1 percent). The unconsolidated material apparently has been derived mainly from glacial deposits, with bedrock supplying a lesser amount of material. Sand and gravel lag deposits and till occur close to the south shore, particularly from Cleveland

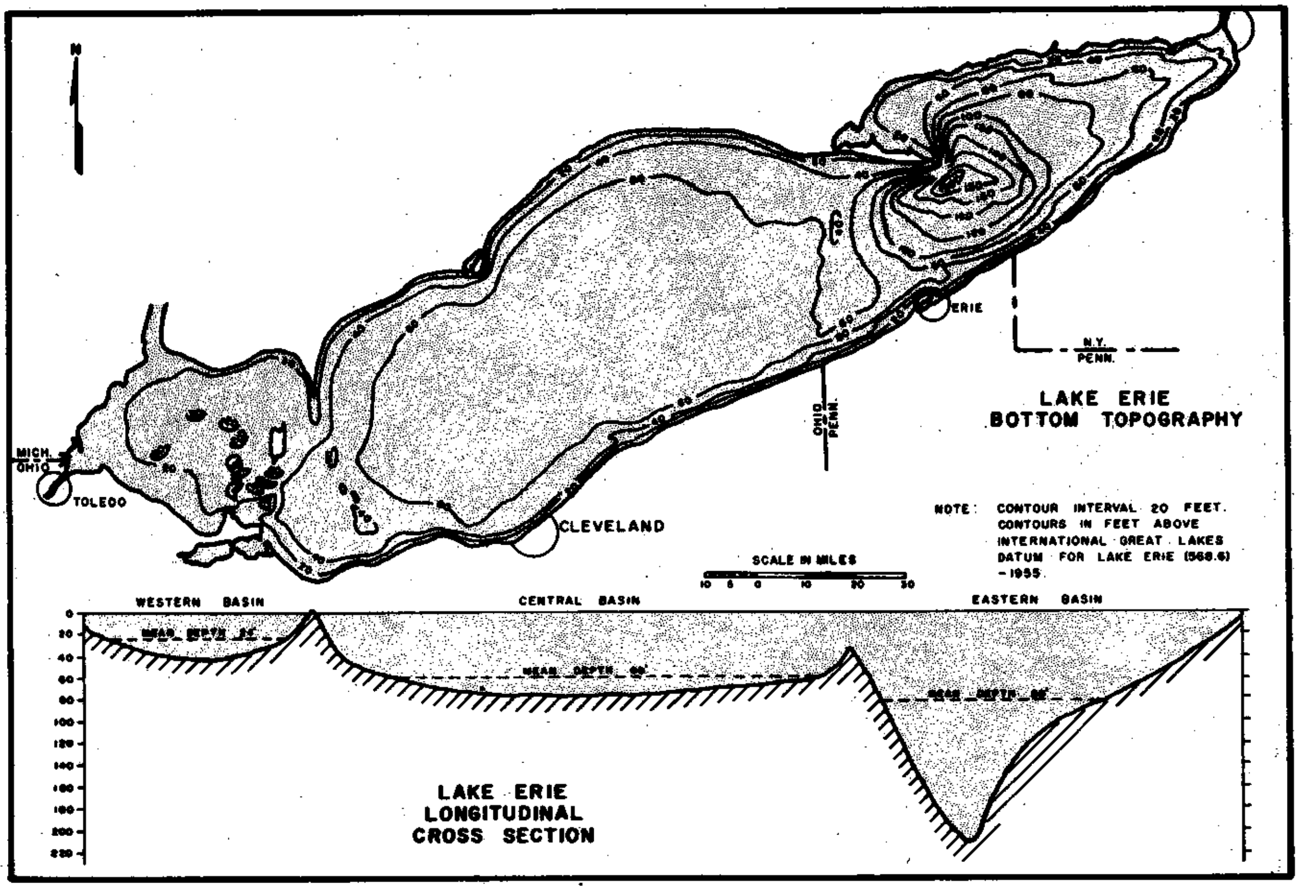

FIGURE 4–280 Bottom Topography of Lake Erie

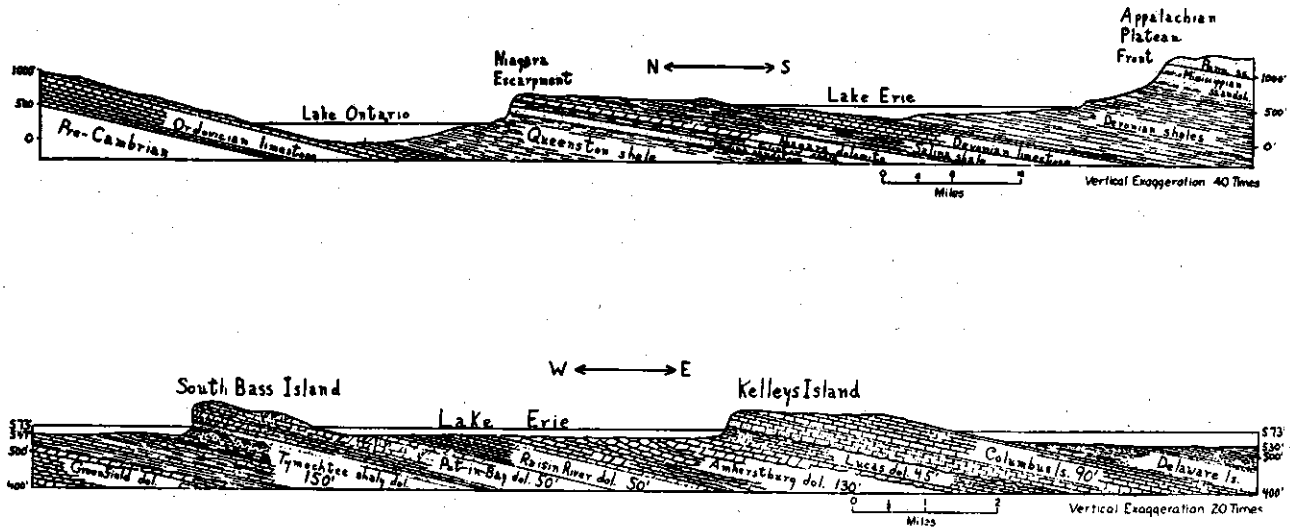

FIGURE 4–281 Geologic Cross Sections Through the Lake Erie Region

After Carmen, 1946

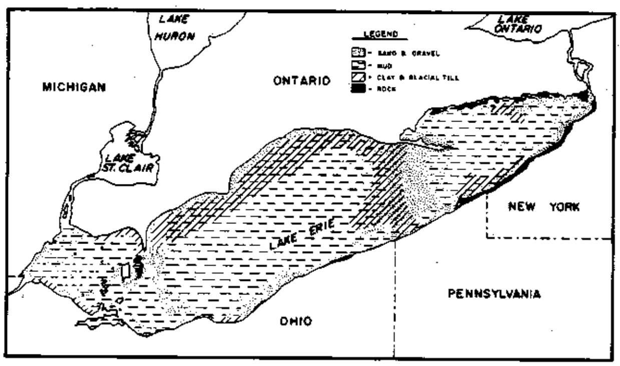

FIGURE 4–282 Sediment Distribution in Lake Erie

eastward. Extensive glacial clay deposits are also exposed along the north shore of the central basin. Large quantities of sand and gravel occur in the lake north of Vermilion, nearshore from Cleveland to Fairport, and midlake off Ashtabula and Conneaut. Other sand and gravel deposits, which have been designated commercial sand dredging areas on both sides of the international boundary, are the low morainal ridge between Vermilion and Point Pelee, a deposit five miles north of Fairport, and the bar between Erie and Long Point (Hartley[321]).

The bottom deposits of the Ohio portion of western Lake Erie consist of nearly two-thirds (58 percent) mud, semifluid silt, and clay-sized material (Verber;[847] Hartley[319,320]). Sand (17 percent), mixtures of mud and sand (12 percent), mixtures of sand, gravel, and coarser material (7 percent), glacio-lacustrine clay (3 percent), and limestone and dolomite bedrock (3 percent) account for the remaining bottom material. Peat and plant detritus occur in isolated areas along the low marshy shores. Sand concentrations in Maumee Bay and near the entrance to Sandusky Bay are sites of commercial sand-dredging.

9.4.4 Vertical Distribution of Bottom Sediments

Ross,[681] Hartley,[320] and Herdendorf[346,347] made borings into subsurface bottom deposits in the Lake Erie islands area by the "jetting method." These borings show a predominance of lake-deposited material with only thin glacial till overlying bedrock. Preglacial buried valleys are indicated by bedrock topography, which in some places has 200 feet of relief. Some borings indicate the possibility of interglacial or postglacial buried valleys and lower lake states. Beach deposits and peat have been found 11 m to 24 m (35 ft to 80 ft) below the present lake level, buried under sediments, which have been subsequently buried in deeper water. A radiocarbon date of 6550 ± 134 years B.P. (Before Present) was obtained for a sample of oak wood taken north of Port Clinton 7 m (23 ft) below the lake bottom. This date allows calculation of a sedimentation rate of 0.1 m/century (0.35 ft/century).

The deepest boring by the Ohio Department of Natural Resources was completed in 1961 about 48 km (30 mi) north of Cleveland (Figure 4–283). At a water depth of 26 m (84 ft), the bottom surface sediments consist of gray-

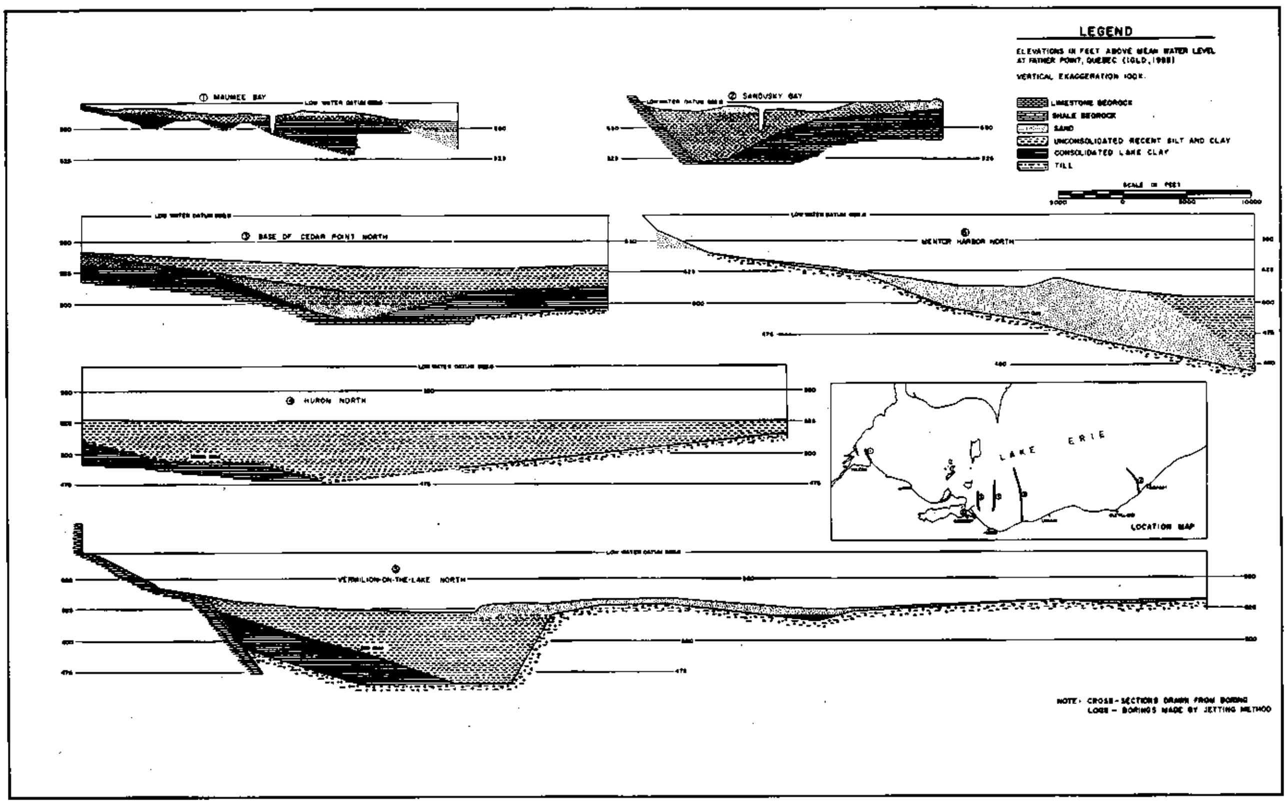

FIGURE 4–283 Cross Sections of Lake Erie Bottom Sediments

brown mud. Successively lower samplings at 1.5 m (5 ft) intervals yielded soft gray-brown clay that became stiffer downward. At 34 m (111 ft) of bottom penetration, rock or hard till that could not be penetrated was reached. The depth was 59 m (195 ft) below the water surface. Volatile material ranged from 5 percent to 35 percent for the clay sediments.

Buried marsh deposits in the western basin and relict beach deposits, wave-cut terraces, and intrabasin discharge channels in the central basin have been interpreted as evidence of former low water levels (Lewis et al.[496]). Radiocarbon dates of 10,200 and 11,300 years B.P. on organic deposits from the western basin suggest that early Lake Erie came into existence about 12,400 years ago, with a water level 30.5 m (100 ft) lower than at present. Lewis postulated that from this stage the lake level rose rapidly as the Niagara outlet area was isostatically uplifted following deglaciation, and that the lake reached its present level 9,000 to 10,000 years ago. A more recent radiocarbon date by the Ohio Division of Geological Survey (Herdendorf[346]) of 4335 ± 135 years B.P. for plant detritus covered by 3.4 m (11 ft) of sediment indicates that the present area of western Lake Erie may have been the site of ephemeral ponds. Apparently, uplift of the Niagara outlet did not result in the flood of western Lake Erie until sometime after this date.

A seismic reflection survey in the central basin of Lake Erie in 1960 (Wall[867]) made possible the mapping of four distinct sub-bottom units: shallow-water deposits, compact glacio-lacustrine clay, glacial till of Lake Border Age, and Paleozoic bedrock. Presence of a channel somewhat south of the present lake axis seems to have been caused by fluvial erosion. A maximum unconsolidated sediment thickness of 83 m (275 ft) was found in central Lake Erie. In western Lake Erie an eastward flowing preglacial drainage system has been inferred from the bedrock topography (Hobson et al.[364]). The maximum bedrock relief is 67 m (220 ft) and the thickness of the unconsolidated sediments ranges from 0 m to 40 m (130 ft) (Figure 4–284).

Recent sedimentation in Lake Erie can be attributed to two primary sources: suspended solids from inflowing streams and material contributed by shore erosion. Over 6,000,000 tons of clay, silt, and sand are transported annually to Lake Erie from its tributaries (Table 4–85).

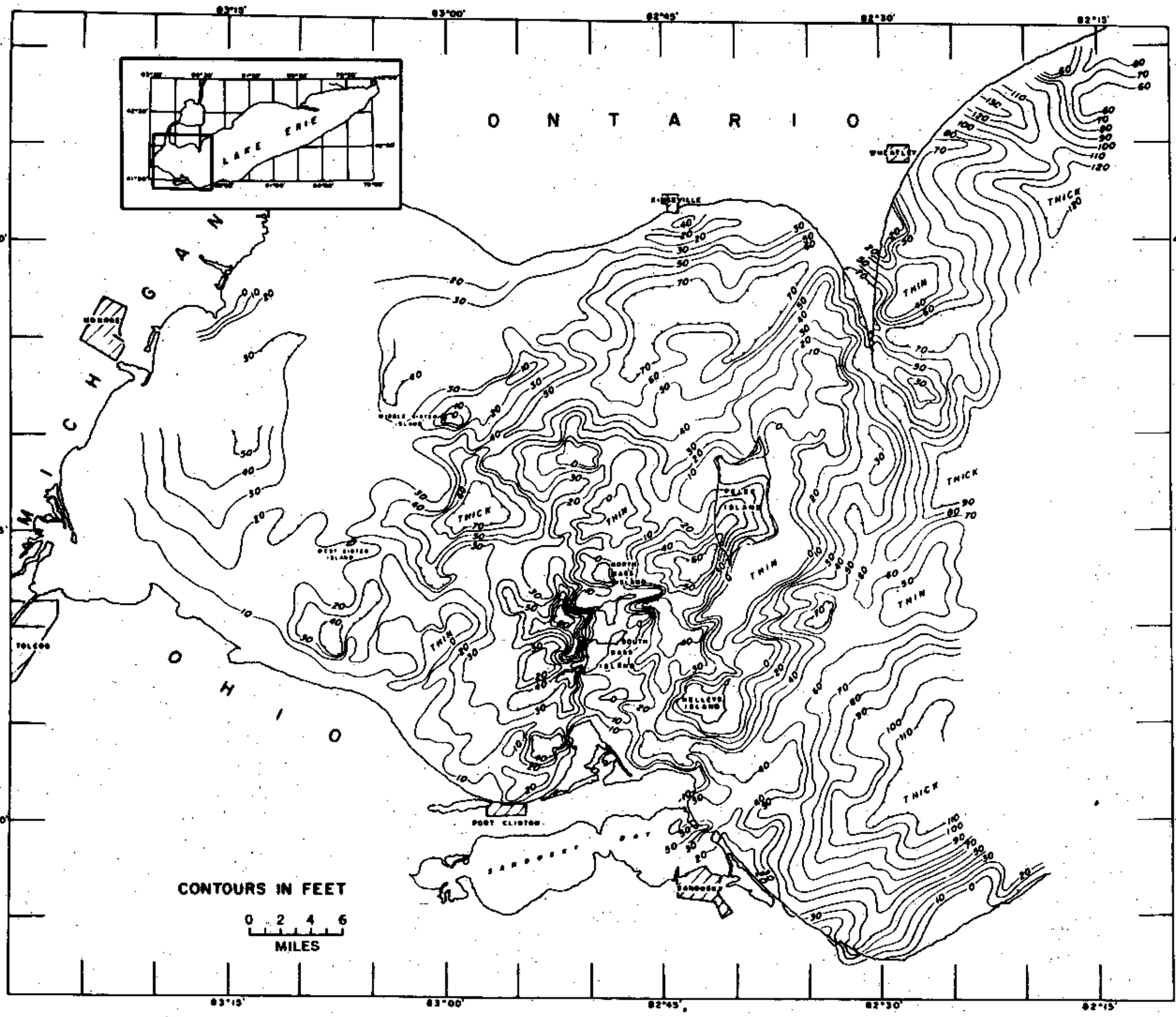

FIGURE 4–284 Sediment Thickness in Western Lake Erie

After Hobson, Herdendorf, and Lewis, 1969

Shore erosion of the glacial till and lacustrine clay is a locally acute problem. Maximum shore erosion based on volume of material removed occurs along the north shore of the central basin between Port Stanley and the base of Long Point, although the low-lying south shore of Maumee Bay has experienced the maximum shore recession, which has been as high as 6 m (20 ft) per year. Estimates of erosion rates for the Ohio shoreline indicate that about 7,600 m^3 (10,000 yd^3) of shore material per mile of shore are eroded each year. If this average is extended for the entire Lake Erie shoreline, 6,500,000 m^3 (8,500,000 yd^3) of shore materials are contributed to the lake each year, which would equate to an average thickness of 0.25 mm (0.01 in) if spread uniformly over the bottom.

9.4.5 Chemistry of Sediments

Kramer[468] analyzed random bottom sediment samples from Lake Erie by X-ray methods. Quartz was present in all samples but generally only in minor amounts in samples finer-grained than sand. The predominant clay mineral is montmorillonite, with kaolinite second in importance. All of the samples high in clay materials were also high in carbonaceous content and were positive to tests for sulfide ions.

Organic carbon in Lake Erie sediments (see Section 7) ranges from 0.23 percent to 3.60 percent (Kemp and Lewis[449]); low values are attributed to dilution of sediments with coarser, nonclay particles. Total chlorophyll pigments (*a* and *b*) range from 0 mg/kg to 30 mg/kg dry

TABLE 4-85 Runoff Data for Tributary Streams to Lake Erie

Streams	Drainage Area (sq.mi.)	Average Discharge (cu.ft./sec)	Suspended Solids[1] (tons/year)	Dissolved Solids[1] (tons/year)
MICHIGAN				
Detroit River	---	176,000	1,570,000	33,580,000
Huron River	900	570	1,800	73,000
Raisin River	1,000	670	4,700	91,200
Others	1,200	720	4,000	25,000
OHIO				
Ottawa River	200	120	1,000	5,000
Maumee River	6,600	4,740	2,270,000	1,370,000
Toussaint River	100	80	700	4,000
Portage River	600	390	120,000	91,200
Sandusky River	1,400	1,060	270,000	446,400
Huron River	400	310	12,000	50,000
Vermilion River	300	220	9,000	40,000
Black River	500	390	15,300	66,400
Rocky River	300	280	29,500	131,400
Cuyahoga River	800	800	260,000	419,800
Chagrin River	300	320	35,000	90,000
Grand River	700	770	212,000	1,340,000
Ashtabula River	100	170	5,500	32,000
Conneaut Creek	200	240	4,000	20,000
Others	1,100	880	200,000	300,000
PENNSYLVANIA				
Otter Creek	200	200	4,000	20,000
Others	200	220	4,500	25,000
NEW YORK				
Cattaraugus Creek	500	800	137,600	226,700
Buffalo River	400	540	74,500	357,300
Others	300	490	60,000	150,000
ONTARIO				
Grand River	3,000	2,490	375,000	500,000
Others	3,200	2,530	350,000	450,000
LAKE ERIE TRIBUTARIES TOTALS	24,500	196,000	6,030,100	39,904,400
Municipal and Industrial[2]	---	---	87,200	179,000
LAKE ERIE GRAND TOTALS	24,500	196,000	6,117,300	40,083,400

[1]Estimated

[2]Outflow direct to Lake Erie

SOURCES: U.S. Geological Survey; Ontario Water Resources Commission; Ohio Department of Natural Resources, and Federal Water Pollution Control Administration

TABLE 4–86 Lake Erie Bottom Sediment Chemistry

Constituent	Western Basin	Central Basin	Eastern Basin	Entire Lake Basin
Total Iron (%Fe)	3.30	3.50	1.44	2.98
Total Phosphate (% PO_4)	0.290	0.195	0.151	0.197
Sulfide (%S)	0.023	0.097	0.004	0.065
Total Nitrogen (%N)	0.042	0.193	0.092	0.149
Ammonia Nitrogen (%NH_3-N)	0.019	0.009	0.007	0.013
Nitrate-Nitrite Nitrogen (%NO_2, -NO_3, -N)	0.0001	0.0002	0.0004	0.0002
Organic Nitrogen (%Org. N)	0.023	0.184	0.085	0.139
Volatile Solids (ppm)	23.4	21.4	7.4	18.3
COD (ppm)	6.35	5.57	2.78	4.51

SOURCE: Federal Water Pollution Control Administration, 1963

weight and pheophytin (*a* and *b*) concentration ranges from 0 mg/l to 192 mg/l dry weight of sediments.

The Federal Water Pollution Control Administration, now the Environmental Protection Agency, began a program in 1963 to test the chemistry of recent Lake Erie sediments. A summary of their findings for the first two years of sampling is presented in Table 4–86.

The mineralogical and chemical composition of Lake Erie sediments are covered in more detail in an International Joint Commission report on the sedimentology of Lake Erie (Lewis[495]).

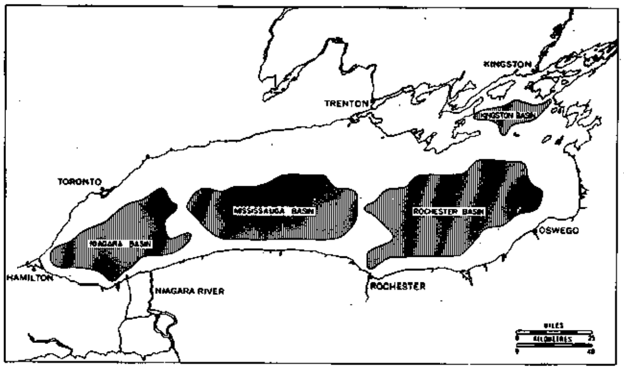

FIGURE 4–285 Distribution of the Four Depositional Basins in Lake Ontario

From Thomas, 1969b

9.5 Sedimentology of Lake Ontario

9.5.1 Lake Basin Morphology

Lake Ontario is elongated approximately east-west, and the deep lake basins parallel this axis. Both the southern and northern shorelines trend essentially parallel to the strike of the southward dipping strata that underlie the lake. Thomas[795] described four depositional basins, three of which are separated by moraines. The northeast (Kingston) basin is isolated by a bedrock sill (Figure 4–285).

Sutton et al.[773] found considerable variation in bottom topography along the southern shore between the Niagara River and Stony Point, New York. Bottom gradients range between 1.9 m/km to 11.7 m/km (10 ft/mi to 62 ft/mi). Between Braddock Bay west of Rochester, New York, and the Niagara River, the offshore gradient increases markedly along a line approximately 1.6 km to 2.4 km (1 mi to 1.5 mi) from shore. A similar change in gradient occurs off the Niagara River approximately 4.8 km (3 mi) from shore. Between Rochester, New York, and Mexico Bay at the southeastern corner of the lake, the bottom topography is much more irregular; gradients are generally higher than those encountered in the western part of the lake, and changes in slope much less pronounced. The eastern end of the lakes is marked by a smooth floor with a consistent gradient of 5.7 m/km (30 ft/mi).

The southern shore and probably most of the western and northwestern shores show evidence of submergence. Extensive drowning is seen on the southern shore where bays are separated from the lake by extended bars and spits. Well defined sand and gravel bars exist at Burlington, Ontario, impounding Hamilton Harbor; at Braddock Heights west of Rochester; at Irondequoit Bay near Rochester, and at Sodus and Little Sodus east of Rochester, New York. The latter embayment appears to follow lowland segments between drumlin masses. The eastern shoreline includes bars and spits with high dune masses enclosing bays and ponds to the east.

9.5.2 Areal Distribution of Bottom Sediments

9.5.2.1 Nearshore Distribution

Nearshore sediments extend out to depths from 40 m to 80 m (132 ft to 264 ft) along the north and south shore (Lewis and McNeeley;[497] Thomas et al.[796]). These sediments include silty, fine sand; gravel; limestone bedrock; gray shale bedrock; and reworked till consisting of unsorted sand and pebbles. There is a general reduction of particle size lakeward toward the basin centers. Various bottom types in the Canadian nearshore areas (Rukavina[689]) include 23 percent bedrock, 39 percent glacial drift, 9 percent gravel and pebbly sand, 12 percent sand, 10 percent silt-sand, and 7 percent silt-clay (Figure 4–286). Percentage distributions along the southern and eastern shores (Sutton et al.[773]) include 75 percent boulder beds and till, 10 percent bedrock, and 15 percent sand and gravel (Figure 4–287).

The nearshore bottom in the reach between the Niagara River and Hamilton, Ontario, is either represented by glacial drift grading lakeward to sand, silt, and clay or by extensive bedrock and drift with no sediment cover (Rukavina[689]). Extensive sand-silt and silt-clay deposits extend off the Hamilton bar. A broad bedrock shelf with occasional patches of sand extends north of Hamilton nearly to Toronto, Ontario. A large sand deposit off Toronto has resulted from severe erosion of high bluffs of glacial sands and silts. The reach from Toronto to Whitby, Ontario, includes a thick veneer of glacial sediment, gravel, and pebbly sands with some isolated bedrock shelves offshore. Small sand patches occur near the shoreline where there are small reentrants in the coastline. Nearshore areas from Whitby to Wellington, Ontario, are lined by either glacial

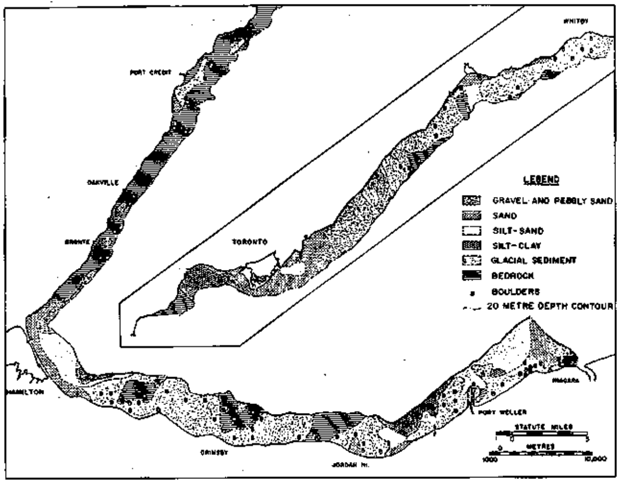

FIGURE 4–286 Nearshore Sediment Facies of Lake Ontario; Niagara to Whitby, Ontario
From Rukavina, 1969

materials of bedrock (Rukavina[688]). Glacial deposits or lag gravels derived from them predominate in the area west of Colborne, Ontario, while bedrock occurs east of Colborne. Restricted sand deposits occur near creek mouths or as thin, discontinuous wedges adjacent to the shorelines. Extensive sand deposits only occur immediately to the west and east of Presque Isle Peninsula. Sediment accumulation patterns suggest a west to east sediment drift.

Nearly continuous boulder beds and till extend out to depths of 15 m (50 ft) along much of the southern and eastern shorelines of Lake Ontario (Figure 4–287) (Sutton et al.[773]). Beach sands are generally restricted to areas adjacent to stream mouths or to spits and bars that extend eastward across the fronts of bays and ponds. Large sand concentrations occur north of the Niagara River, at Rochester, New York, and at the eastern end of the lake. Two smaller deposits occur east of Nine Mile Point near Oswego, New York, and off Hamlin Beach between Niagara and Rochester, New York. Elsewhere, sand occurs in small isolated patches. Generally, the sand grades lakeward into silt and mud deposits below the 15 m (50 ft) level.

Most of the gravel and boulder patches are presumed to be lag deposits originating from erosion of submerged tills. Most of the sand presumably originated from currents and wave erosion of submerged nearshore tills, perhaps during lower stages of lake levels. Sutton et al.[772] and Woodrow et al.[915] relate sediment variations of nearshore sands west of Rochester to possible drowned beaches developed during a lower lake level.

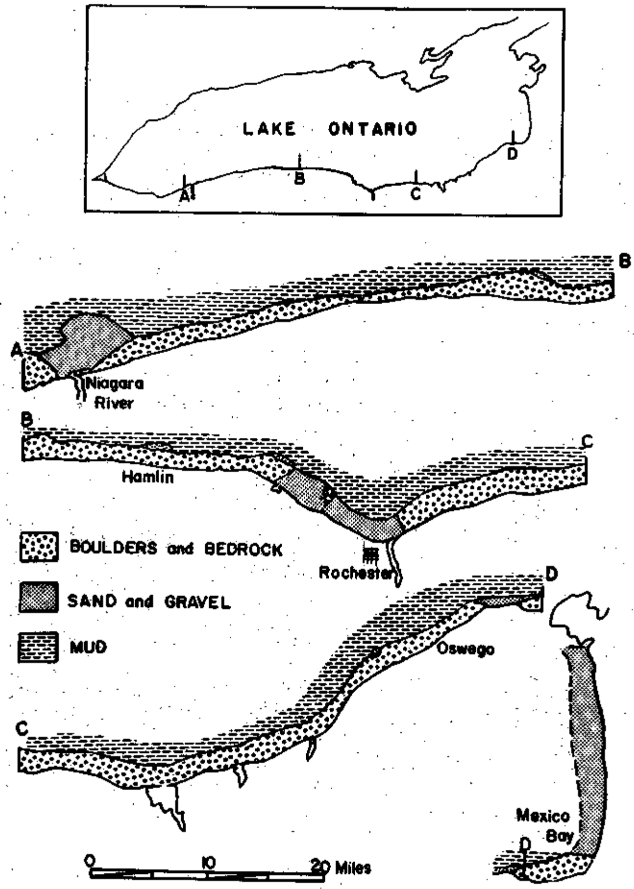

FIGURE 4–287 Bottom Materials Along the Southern and Eastern Shores of Lake Ontario
From Sutton, Lewis, and Woodrow, 1970

Shore or beach sands are mostly medium- to coarse-grained, in contrast to fine- to medium-grained lake sand, and there is a general gradation to finer sizes lakeward (Sutton et al.[773]). Average sand size decreases from the Niagara River to the eastern shore, although all sands are well-sorted. There is little significant difference in sorting between nearshore and lake sand in the western part of the lake. However, the eastern nearshore sand is significantly better sorted than lake sand.

Coakley[154] traced sediment transport through changes in sand texture and mineralogy as well as by fluorescent-coated sands at selected sites between Toronto and Burlington, Ontario. Directional variations of heavy mineral suites showed no trends, primarily because of the homogeneous mineral composition of glacial source material on the shoreline. Textural variations indicate that local sources contribute to the sand deposits studied, but trends related to direction of transport are obscure and inconclusive in this restricted investigation. Fluorescent dye tracers indicate that transport is related to wind direction and the morphology and orientation of the shoreline.

9.5.2.2 Open Lake Distribution

Most of the deeper parts of the lake basin consist of muds (Figure 4–288). These muds are plastic clays or silty clays that are usually medium-gray in color with crude laminations composed of horizontal aligned specks or pods of black greasy clay. A belt of glacial lacustrine clay occurs off the central part of the north shore in depths ranging from 80 m to 120 m (262 ft to 394 ft) in the west and 49 m to 100 m (161 ft to 328 ft) in the east. This clay is calcareous, devoid of organic detritus, exhibits varve-like laminations and occasional limestone pebbles, and is generally firmer than most Recent muds. A second belt of such sediment, covered by a thin veneer of Recent mud, extends north-south between Toronto and the southern shore.

A single layer of stiff, orange-colored clay, which ranges from 0.5 cm to 10 cm (0.2 in to 4.0 in) thick, is widespread and frequently overlain by a thin layer of gray mud (Lewis and McNeeley[497]). In addition, an extensive zone of surficial black sand occurs in nearshore sediments and in the sands overlying the glaciolacustrine clays adjacent to the northern shore (Figure 4–288). The sand grains are coated by a black substance of undetermined composition.

9.5.3 Chemistry of Sediments

Composition of the large boulders and cobbles can be directly related to either local bedrock or to glacial origin. Principal components of the sands consist of quartz, with lesser amounts of feldspar, heavy minerals, and fragments of siltstone and carbonate shells. The total heavy mineral content of the sands varies considerably, averaging 5.6 percent in the nearshore sands, 6.9 percent in the western lake sands, and 10.4 percent in the eastern lake sands. Concentration of heavy minerals increases as the sediment size decreases lakeward and in the general west-to-east direction. Coch[155] indicated that the well-sorted beach sands between Webster and Oswego, New York, have a higher percentage of heavy minerals than those that are poorly sorted.

The mud in offshore areas is composed of 65

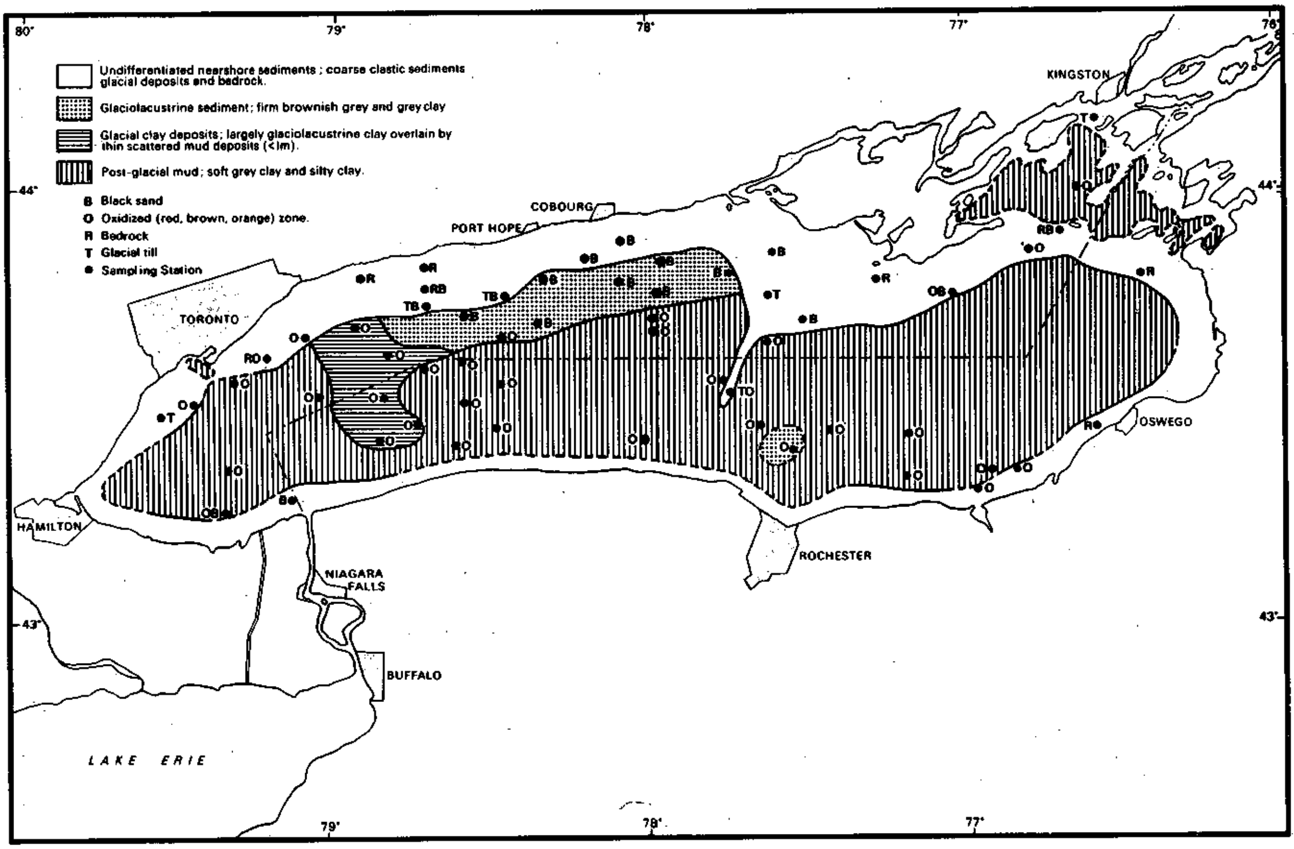

FIGURE 4–288 Distribution of Lake Ontario Bottom Sediments

From International Joint Commission, 1969a

percent clay materials (Kemp and Lewis [449]) composed predominantly of illite with subsidiary kaolinite and chlorite (Thomas et al.[796]).

Lewis and McNeeley [497] noted (Figure 4–289) that high amounts of organic matter relate directly to occurrence of mud in the centers of the basins, and a high concentration of organic matter also occurs off the mouth of the Niagara River. The surficial muds are zones of rapid decomposition of the organic fraction (Kemp and Lewis [449]). However, chlorophyll is mostly decomposed in the water column. Concentration of both the organic material and remaining chlorophyll products in the sediment decreases rapidly below the interface. Organic carbon content increases with increase in clay content and also with decreasing grain size. Apparently, carbon is predominantly absorbed by the clay particles; the amount of absorption is related to the clay surface area.

Variations in feldspar types occur from nearshore to offshore areas (Thomas [795]). There appears to be a progressive loss of calcic plagioclase (laboradorite) followed by sodic feldspar (albite) leading to offshore enrichment of potassic feldspar (microcline and orthoclase). A constant ratio of quartz to feldspar cations (K, Na, Ca) in Lake Ontario sediments suggests that the regional feldspar distribution is not a result of mechanical abrasion or distance of transport but results from chemical weathering related to the length of time of transport.

Cronan [170] found that Fe and Mn contents of Lake Ontario nodules were similar to those of deep-sea nodules; however, Ni, Cu, Zn, and Co contents were lower, and Pb content was higher. The regional distribution of Mn, Ni, Co, and Zn varies inversely with Fe and may be related to a change in Eh. Comparative analyses of interstitial and bottom water indicate that concentrations of Mn, Fe, Ni, Cu, Pb, and Zn are higher in the interstitial water suggesting that concretions may result from upward diffusion of these elements from buried sediments. Cr and Co are present in low concentrations in Lake Ontario and Cd and V were not detectable (Chau [138]); Cu, Fe, Pb, Mn,

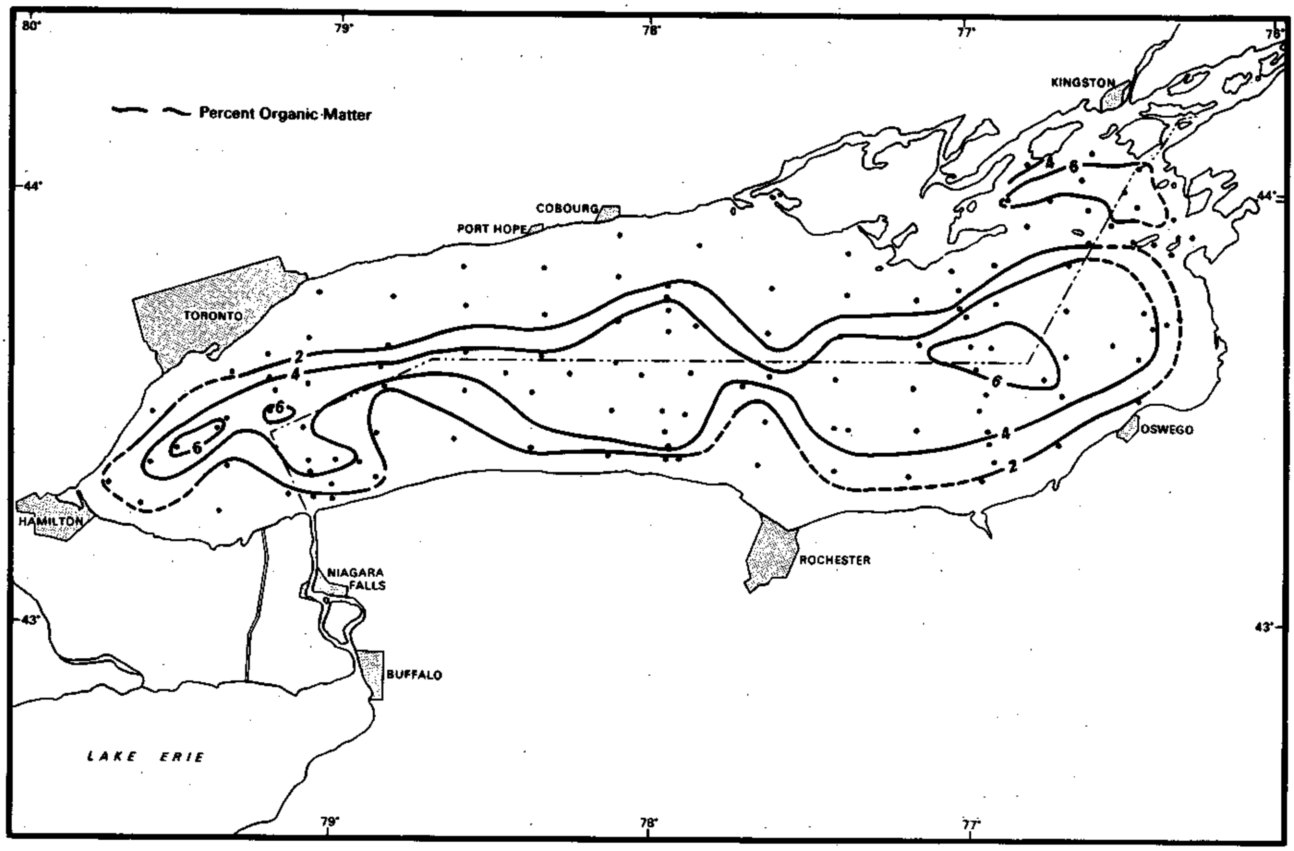

FIGURE 4–289 Distribution of Organic Matter in Lake Ontario Surficial Sediments
From International Joint Commission, 1969b

Mo, Ni, Sr, and Zn vary both spatially and seasonally. Generally, higher concentrations of the latter group have been found in the eastern and western parts of the lake and lower concentrations in the central basin. High concentrations of trace elements also correlate directly with high values of chlorophyll *a* in the western basin tending to relate the abundance and distribution to cultural impacts.

Section 10

UPLAND LAKES

David C. Norton

10.1 Introduction

Upland lakes are generally defined as any body of standing water with a surface area greater than one acre. In this appendix, an upland lake is defined as any body of standing water considered important to the State in which it is located. Thus, the Michigan Department of Natural Resources does not inventory lakes under 2 hectares (5 acres) surface area, as they are primarily concerned with the thousands of larger lakes in the State. Illinois, on the other hand, has few lakes and so inventories lakes as small as 0.1 ha (0.3 acres) surface area. When speaking of upland lakes it is, therefore, convenient if common terminology with a known size connotation is used. The following is a suggested classification relating to lake size, depth, and nearshore slope:

(1) Size (surface area)
- (a) small: 6 hectares (15 acres) or less
- (b) medium: 6–40 hectares (15–100 acres)
- (c) large: 40 hectares (100 acres) or more

(2) Depth
- (a) shallow: 5 meters (15 feet) or less
- (b) intermediate: 5–15 meters (15–45 feet)
- (c) deep: 15 meters (45 feet) or more

(3) Slope
- (a) gentle: 3° or less
- (b) moderate: 4° to 6°
- (c) steep: 7° or more

Lake size categories are arbitrary because size differences as such do not relate to specific conditions of lake state, although the interrelationship of area and depth does affect the rate at which lakes are altered naturally and by land-use patterns. A shallow lake bottom can be entirely covered by aquatic plants if the environment is hospitable. This is because 5 m (15 ft) is the approximate lower limit for benthic aquatic plants in this region. Deeper than 15 m (45 feet), the bottom is essentially devoid of photosynthetic plant life. Classification of nearshore slopes is based on their suitability for wading and swimming. A gentle slope is most acceptable for public beaches; a 1.5–2 m (5–6 ft) depth at 67 m (200 ft) offshore is most desirable. Moderate slopes are suitable for restricted swimming and wading nearshore, but steep slopes are too severe for public beaches.

The Great Lakes Basin contains a greater abundance of upland lakes than other areas of comparable size. The large number of lakes is a consequence of Pleistocene glaciation. The last ice sheet retreated from the Basin 8,000 to 10,000 years ago. As this is a relatively short period of time geologically, these Wisconsin-age deposits and the hummocky topography have not yet been eroded away. Hence, there is an exceptionally large number of depressions capable of holding water. The youth of the topographic surface is evident in the degree of development of the drainage pattern, which is still controlled to a large degree by such minor relief features as recessional moraines and abandoned beach ridges. There is a total absence of major tributaries. As drainage improves within the Basin, the number of lakes can be expected to decrease as a result of the lowering of lake outlets and the lowering of the water table.

Both glacial and nonglacial aspects of lake distribution are illustrated in the State of Wisconsin. The southwestern portion of the State, the "classical driftless area," unlike the remainder of the State, has no glacial cover. The difference in lake density in the two areas is apparent (Figure 4–290). The driftless area has a low lake density when compared to those portions of the State with glacial cover. The greater number of lakes in the glacial residue is due to the irregular and hummocky topography combined with poor drainage. The smaller number of lakes in the driftless area is

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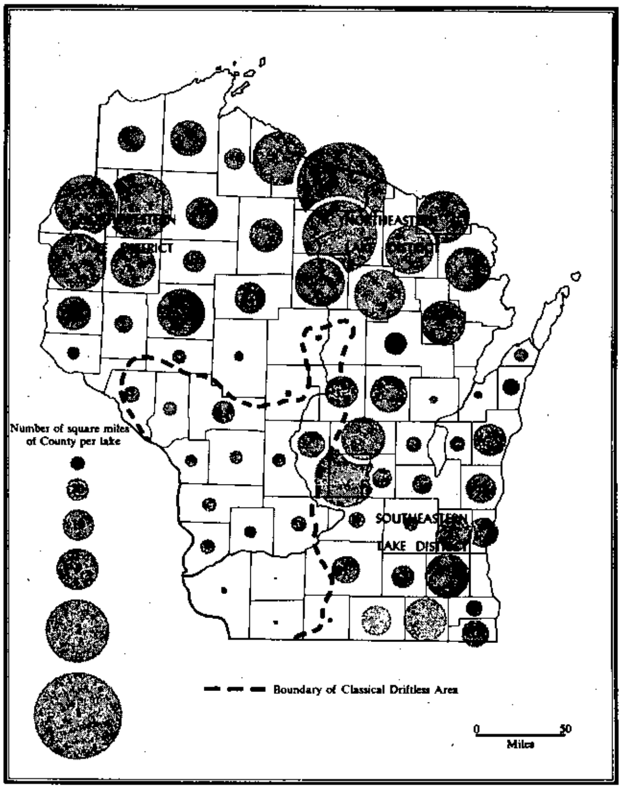

FIGURE 4–290 Density of Lakes in Wisconsin by County. The areas of the circles are proportional to the mean number of lakes per square mile. The scale at the left is the reciprocal of this, namely, the number of square miles of county for each lake. The dashed line represents the boundary of the driftless area.

From Frey, 1966

due to well-developed dendritic drainage characterized by topography dissected by steep valleys.

10.2 Lake Formation in the Great Lakes Basin

The glacial deposits associated with the upland lakes of the Great Lakes Basin fall into three catagories: recessional moraines (sandy-limey soils); ground moraines (sandy-limey soils); and glacioaqueous strata in the form of glaciofluvial or outwash deposits (sandy soils) and glaciolacustrine or lake deposits (clayey-limey soils). Appendix 3, *Geology and Ground Water*, more fully discusses the distribution of glacial deposits. Recessional moraines occur as hills or ridges, while ground moraines (often called till plains) have an undulating topography. Glacioaqueous strata underlie essentially featureless plains.

Five types of lakes were formed during the glacial epoch, and two more types were subsequently formed in the post glacial era. The glacially formed lakes are till plain lakes, morainal-dam lakes, kettle lakes, erosion lakes, and periglacial lakes. The non-glacial lakes are post-glacial lakes and man-made lakes.

Till lakes occur in natural depressions resulting from the irregular deposition of till. They are usually shallow to intermediate in depth, have gentle to moderate nearshore slopes, and are of irregular outline. Houghton Lake in Roscommon County, Michigan, is located on ground moraine, and is the largest till lake in the Great Lakes Basin. Several adjoining depressions on a till plain surface may be connected to create a lake of lobate outline. Lakes Corey and Pleasant in St. Joseph County, Michigan, are examples of lobate outline lakes (Scott[726]).

Morainal-dam lakes were formed behind recessional moraines that ponded water in areas where the land surface sloped toward the recessional moraine. These lakes are elongated, either parallel to or normal to the morainal dam. Parallel-oriented lakes are often part of the regional drainage system, as they lie in valleys adjacent to this topographic barrier. Normal-oriented lakes are not usually contained in the regional drainage system as their lowest point, the recessional moraine, does not usually permit outflow. In lakes of both orientations the nearshore slope is usually steeper along the dam than along the remaining shore, and the lakes have a wedge-shaped profile normal to the dam. Devil's Lake, Sauk County, Wisconsin, and Fortune Lakes in the Iron River district in the Upper Peninsula of Michigan are examples of morainal-dam lakes (Scott[726]).

Kettle lakes were formed by the melting of large ice blocks that were stranded upon glacial retreat in ground or end moraine, or in outwash deposits. Lakes of the latter origin are often referred to as "pit lakes," and, when present in large numbers, the area is said to be one of "pitted outwash." Kettle lakes usually have a regular outline, have steep nearshore slopes, are deep with respect to their surface area, and are usually small. Medium-sized kettle lakes are not as regular in outline as small kettle lakes, since more than one block may have been involved in their origin. Portage Lake, Crawford County, and Pontiac and Cass Lakes, Oakland County, are a few of Michigan's many kettle lakes. Higgins Lake, in Roscommon County, Michigan, is the largest kettle lake in the Basin.

TABLE 4–87 A Generalized Summary of Genetic Lake Types With Some of Their Physical Characteristics

LAKE TYPE	SURFACE SIZE[1]	DEPTH[2]	SOIL TYPE	NEARSHORE SLOPE[3]	GEOMORPHOLOGY	ASSIMILATION CAPACITY
Till Plain Lakes	Usually small to medium, seldom large	Shallow to intermediate	Sandy-limey	Gentle to moderate	Ground moraine	Low to moderate
Morainal Dam Lakes	Generally medium, sometimes large	Intermediate to deep, deepest portion near dam	Usually sandy-limey	Steep near dam, gentle elsewhere	Usually on ground moraine	Moderate to high
Kettle Lakes	Small to medium	Intermediate to deep	Sandy-limey or sandy	Moderate to steep	Morainal, more rarely on outwash	Low
Erosion Lakes	Small to large	Intermediate to deep	Sand & gravel, variable amounts of clay	Moderate to steep	Bedrock & thin morainal deposits	Moderate to high
Periglacial Lakes	Usually small to medium. A few large.	Usually shallow to intermediate	Variable	Variable	Variable	Variable
Post Glacial Lakes	Generally small	Usually shallow	Variable, related to mode of origin	Variable	Variable	Variable
Man-Made Lakes	All sizes depending on purpose of builder	Variable	Variable	Variable	Variable	Variable

[1]Surface Size-Small: 6 ha (15 a) or less; Medium: 6-40 ha (15-100 a); Large: 40 ha (100 a) or greater.

Erosion lakes occupy basins formed by glacial scouring and are the result of differential erosion of bedrock surfaces. The more resistant bedrock remained as ridges; but the softer bedrock was gouged out. These lakes generally have long parallel shores, and are deep. The Finger Lakes of New York are the largest examples of upland lakes of this origin in the Basin. The greatest number of these lakes occur in northern Minnesota which has hundreds of small erosion lakes with a general east-west orientation, parallel to the ice movement.

Periglacial lakes formed along margins of the glaciers where the topography sloped toward the glacier, which served as a dam and water supply. As the glaciers retreated the boundaries of these lakes changed, often uncovering outlets that drained the lakes. Where the topography was suitable, the lakes remained. The prehistoric Great Lakes are examples of periglacial lakes.

Post-glacial lakes were formed by the action of surface water, wind, and ground water after glacial retreat. These forces led to creation of four types of lakes: oxbow, bar, recession, and sink-hole lakes. Oxbow or crescent lakes are river meanders that were cut off from the main stream by the formation of a new channel. Such lakes occur on river flood plains, as along the Huron River in Washtenaw County, Michigan. Bar lakes occur in drowned valleys (rias) and embayments that have been isolated from a larger lake or stream by sand spits. Numerous bar lakes occur along the eastern shore of Lake Michigan, including Pentwater Lake, Oceana County, and Crystal and Torch Lakes, Antrim County, Michigan. Recession lakes are created in small basins on a lacustrine plain which has been exposed by the lowering of the water level of a large lake. The largest upland lakes in the Great Lakes Basin, such as Lakes St. Clair, Nipissing, Simcoe, and Winnebago, fall in this category. Wind erosion creates depressions that may act as lake basins. These blow-out lakes are not common and are generally small and shallow. Silver Lake, Oceana County, Michigan, may be an example. It is often difficult to distinguish between blow-out, bar, and recessional lakes when they are closely associated with sand dunes. Sink-hole lakes occur in regions underlain by limestone. Groundwater solution creates cavities in the limestone into which the surface layer collapses to form a depression. Long Lake, Alpena County, (Fritz and Nelson[276]) and Ottowa Lake, Monroe County (Lane[483]) are two of Michigan's sink-hole lakes.

Man-made lakes are those created or significantly altered in size by man. Artificial structures that regulate pre-existing lakes do not qualify a lake for this category unless the surface area has been increased by over 50 percent.

A summary of the seven lake types is presented in Table 4–87. The characteristics compared are surface area, depth, soil type, nearshore slope, geomorphology, and assimiliation capacity. The assimilation capacity is a measure of the capability of a lake to cleanse itself of undesirable chemicals through mixing, out-flow, seepage, and sedimentation. Assimilation capacity is, therefore, an index of pollution susceptibility. The greater the assimilation capacity of a lake, the less likely it is that the lake will become unsuitable for desired use.

10.3 Lake Processes in the Great Lakes Basin

Lakes begin to interact with their environment immediately after formation. As every upland lake is a small ecosystem, dynamics of the environment cause a tendency toward a series of metastable phases. It is therefore necessary to understand and interrelate the variables that affect the system. The variables involved are hydrological, geological, biological, chemical, and cultural.

Hydrologic variables relate to water supply and loss, and form two basic lake types. The first is an influent lake (seepage lake) which derives its water primarily from ground water and/or springs, and the second is an effluent lake (drainage lake) which derives its water from inflow and loses water through seepage. The former is dependent on water table levels and is only a topographic depression through the water table. The latter is dependent on inflow rates. As water table levels fluctuate more slowly than surface inflow, stage changes in influent lakes are less pronounced than in effluent lakes where drought or rain modify the inflow and cause a corresponding change in the stage. Precipitation and runoff data are presented in Sections 1 and 4 of this appendix. Ground water is not as evenly available as precipitation in the Great Lakes Basin due to variations in the thickness and permeability of the unconsolidated overburden (Appendix 3, *Geology and Ground Water*). When ground water is tapped, the water table will be locally depressed. Should this depression encroach on the boundary of an influent lake or the feeder stream(s) of an effluent lake, the lake level will drop accordingly. The time required for this stage change can be as rapid as a few hours in sandy lake basins to a few days in clayey lake basins. Evaporation from upland lakes is insignificant in their total water budget. Their small volume allows rapid temperature changes in response to air temperature changes. In late fall, the period of highest evaporation in the Great Lakes, upland lakes cool rapidly and freeze over earlier thus reducing the potential for evaporation.

The geologic variables are those which relate to lake basin composition and modification through erosion and deposition. The original basin is important in that its size and composition will, in part, determine the nature of shoreline modification possible and the type of both peripheral and aquatic plants first established.

It is possible to surmise lake origin in a given area, if average lake size, lake abundance, and geomorphology of the area are known. If numerous regular small lakes occur in an area characterized by glaciofluvial strata, they are kettle lakes. A large lake in the same strata indicates that some other factor was involved in the formation of the lake, such as a morainal dam. A single large lake in a till plain area along a well-defined recessional moraine is also a morainal-dam lake. Irregular shallow lakes in ground moraine are till plain lakes.

Most lakes on a till plain have sandy bottoms near shore. They often have well-developed beaches and are usually suitable for water contact sports. Sedimentation is often greater within morainal-dam lakes than in other lakes on the till plain because they are a part of the drainage system. Because upland lakes are low energy environments, they act as sediment traps. Streams are high energy environments; this difference in energy levels causes particulate matter to drop out of suspension as streams enter lakes. Upland lakes also receive sediment through sheet wash, which relates directly to slope of the backshore. If a steep backshore area is used for recreation, the problem is compounded because the whole area is kept non-compact through agitation.

Lakes on a glaciolacustrine plain differ from lakes on a till plain in that they tend to be shallow with gentle nearshore slopes. These lakes are associated with dense concentrations of aquatic plants that contribute considerable amounts of organic material to the bottom deposits. Lakes on a glaciolacustrine plain are of low value for water contact sports because of the aquatic growth. However, the plant growth makes these lakes excellent wildlife sanctuaries.

10.4 Aging—The Trophic Sequence

A lake normally goes through a sequence of physical and biological stages from youth through old age. A four lake-age stage classification can be applied in the Great Lakes Basin although boundaries are somewhat arbitrary:

(1) Oligotrophic lakes are characterized by a deficiency in nutrients, by low sediment supply, and by low productivity.

(2) Mesotrophic lakes are characterized by a balanced supply of nutrients, moderate productivity with a diversified population, and moderate basin filling due to sedimentation.

(3) Eutrophic lakes are characterized by excessive nutrient levels, high productivity, and accelerated basin filling due to sedimentation resulting from high productivity.

(4) Hypereutrophic lakes have high nutrient levels and high productivity, but they have markedly less diverse fauna and flora populations and have rapid basin filling leading to lake extinction.

Upland lakes of various ages and trophic stages are unequally distributed over the Basin. Trophic status of lakes in the Basin has not generally been determined, but approximations are meaningful in the context of this appendix. The highest density of oligotrophic lakes in the Basin lie in Minnesota because these are cold erosion lakes which characteristically have low nutrient sources. Mesotrophic lakes are more common than oligotrophic lakes. These two lake types combined account for only one-third of all upland lakes in the Basin. The majority of lakes in the Great Lakes Basin are eutrophic or hypereutrophic.

The greatest number of lakes today (about 50 percent) are eutrophic. The lakes have become increasingly similar throughout the Basin due to migration of lake fauna and flora via waterways, over land, by wind, and by accidental transplants from one body of water to another by carriers such as animals, birds, and man. Initially, glacial melt water was quite pure, but as the lake waters received drainage and interacted with their environment, they became chemically enriched. The enrichment made increased productivity possible. A balance between enrichment and lake size comes about in the mesotrophic stage and is indicated by maximum species diversity. Total productivity of a mesotrophic lake is one-half what the lake will have in its eutrophic stage. Although mesotrophic lakes are more useful to man than eutrophic lakes for recreation and water supply, eutrophic lakes are suitable for most recreational activities or water supplies even though fish species are not diverse and some swimmers might consider submerged vegetation offensive. Excess nutrients can produce symptoms of a later trophic stage within a short period even though the later trophic stage would normally require many years to evolve.

The hypereutrophic stage arbitrarily begins as total productivity begins to decline, overall species representation is rapidly reduced, and sedimentation accelerates. A lake late in the hypereutrophic stage is a marsh or an algal-green pond. Following the hypereutrophic stage there is dry land.

A lake may also become dystrophic. This is a significant departure from the oligotrophic-mesotrophic-eutrophic-hypereutrophic sequence and is characterized by low dissolved oxygen, abundant material in suspension, poor development or absence of macrofauna, a sparse plankton population of low diversification, an absence of fish, acid water, and a bog flora. A dystrophic lake does not follow the typical trophic sequence; it merely becomes smaller as aquatic vegetation fills it in. Because variations occur characteristics such as size, depth, slope, and productivity should be used when describing a dystrophic lake.

The four lake-age stages have common interdependent parameters that vary in each lake stage (Figure 4–291). The aging sequence indicated is a natural one, but man can influence the rate of change in the sequence by modifying inputs of parameters. For example, rough fish are introduced into a small, shallow, early eutrophic body of water having good water clarity and a considerable growth of submerged, rooted aquatics. The rough fish stir up the bottom, placing suspended solids into the water. These suspended solids reduce light penetration to the extent that a large die-off in submerged aquatics occurs. The aquatics begin decomposing and use up dissolved oxygen (DO) to such an extent that sport fish requiring high DO die. A considerable portion of the aquatics cannot be assimilated in the low DO environment so they re-

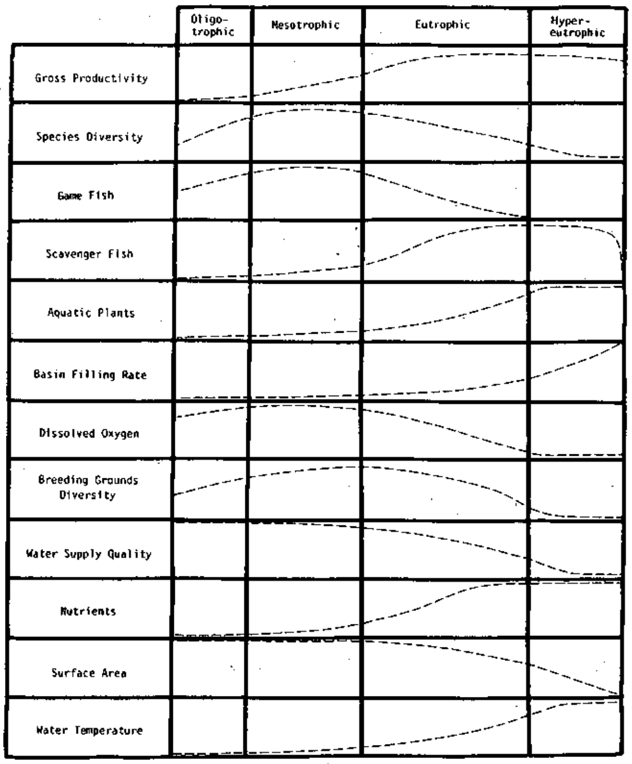

FIGURE 4–291 Graphic Summary of Interrelated Parameters Through Four Trophic Stages for an Ideal Lake

main on the lake bottom and release nutrients which are then available to the algal population. It should be apparent that changes in any factor affecting a lake can have dire consequences.

10.5 Succession in Bog and Marsh Lakes

There are many marsh (hypereutrophic) and bog (dystrophic) lakes in the Great Lakes Basin. These two types of lakes constitute the final stages of a lake before dry land appears. Therefore, recognition of their characteristics is helpful in determining the trophic level of all lakes in the Basin. These lakes originated in glacial material. Infilling by organic and inorganic material have modified the lakes to their present condition. Marsh and bog lakes occur in all glaciated areas due to the hummocky topography and associated poor drainage. Other factors favorable for marsh and bog formation in the Great Lakes Basin are abundant rainfall, high humidity, low soil temperatures, minimal runoff, high ground-water table, and luxuriant plant growth.

Although conditions are suitable for marsh or bog development, these lakes are not equally represented in all size classes or in all areas of the Basin. Marsh and bog lakes in the Great Lakes Basin are usually small to medium in size.

The filling in of a marsh or bog lake coincides with an increase in organic content of its sediment. Thick organic sediments tend to seal the bottoms of bog lakes; therefore, little mineral or other matter is added by ground water (Welch[879]). The primary source of water for a bog is runoff, which permeates through the peripheral vegetative mats and peat. Water content of the peat is very high and particulate organic matter is 5 to 8 percent (Brame and King[82]). Although marshes are also insulated from ground water, this factor is not as important as in bog lakes because marshes usually are contained in a drainage system. Sealing is due to organic clays in marshes as compared to the more granular peat deposits of bogs.

Lakes representing all stages of maturation are found in the Basin indicating different aging rates. Many former lakes have already passed through all the stages into extinction. Extinction comes about by two processes: marginal encroachment and bottom encroachment. The first process is more important in the extinction of bogs and the latter of marshes, although exceptions do exist. The components of marginal encroachment are plant ecesis, decay, and decomposition in nearshore areas. Bottom encroachment comes about by growth and decay of emergent plants and by sedimentation. The sediment is usually inorganic at the outset and becomes more organic with increasing abundance of plants. The plants cover a much greater percentage of the bottom in the latter method of extinction.

Some young bog lakes have small, segmented fringes of sedge mats composed primarily of the sedge *Carex* and the moss *Sphagnum* while older bogs have mats covering large sections of the shore. The mats are anchored along the shore and advance lakeward with their outer portions floating on the water surface. The mats, therefore, reduce the open water of the lake, and provide a footing for terrestrial plants. Bogs may have a false bottom, composed of finely divided plant material in suspension just above the true bottom. A definite concentric zonation characterizes the flora about bog lakes where topography is suitable. Each zone has different plant members and requirements for existence (Figure 4–292). As the mat encroaches on a lake surface, it acts as a barrier to light pen-

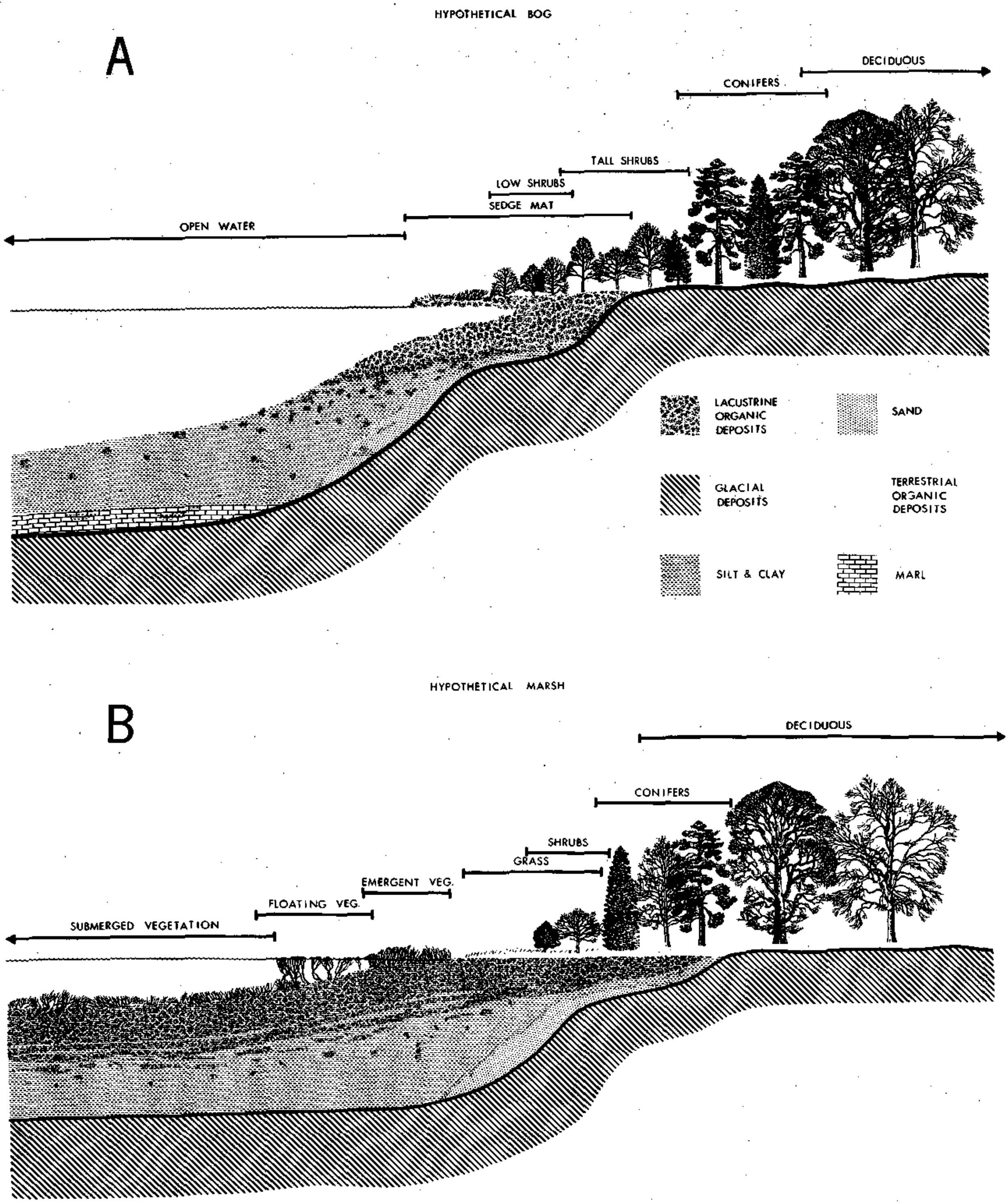

FIGURE 4–292 Comparison of the Flora and Sediment Between a Hypothetical Bog (A) and a Hypothetical Marsh (B)

etration, making it impossible for aquatic plants to grow under the mat. As plants in the mat die, most of the residue settles to the lake bottom under and in front of the mat. Some of the finer debris is carried into open water. Low dissolved oxygen in the lake water and rapid deposition rates combine to yield incomplete lation of peat deposits. Aquatic plants seldom grow in a bog lake as the water is usually unsuitable for their growth.

Marshes differ from bogs in the plant succession near the water's edge (Figure 4–292). Zonation is not as evident in marshes as in bogs. Marshes develop in lakes that were initially shallow or were greatly reduced in depth by sedimentation. As part of a drainage system, flushing of the lake water impairs accumulation of organic acids. Bulrushes and similar plants establish themselves along the lake margins. Lakeward, emergent plants give way to submerged plants. As the lakes fill in, these plant associations move toward the deeper portions of the lake until the entire lake basin is covered with aquatic plants. The bottom deposits become increasingly organic in composition, and sediment particle size becomes increasingly finer along the shore, due to the reduction of wave and current energy. With final filling, terrestrial plants quickly cover the newly formed land. Odum[585] estimates that as little as 25 to 100 years is required to change from an extinct lake to a conifer forest.

Soil composition of the original basin is important in the initial stages of lake development because soil composition governs the sequence of plant establishment and the suitability of the substrata for aquatic ecesis. Water in marshes tends to be basic while water in bogs is more acidic. Marshes occur along drainage systems that supply them with neutral or slightly basic water which is maintained by the natural buffering of ground waters that originate in carbonate-rich soil (Hutchinson[402]). The fact that bog waters do not react with ground water is supported by the fact that many bogs do lie in calcareous tills where the ground water is buffered by carbonate equilibria. Bogs are usually isolated from local drainage and thus cannot dissipate by flushing or diluting the excess organic acids that are formed or that drain into them. If the organic debris supplied to the lake is incompletely oxidized leaving high BOD and low dissolved oxygen, then humic acids accumulate and the lake becomes dystrophic. Acidity of bog water comes from a variety of organic acids combined with variable amounts of sulfuric acid. The organic acids are derived from decay and incomplete oxidation of organic detritus. The sulfuric acid is derived in two ways: by rainwater containing small amounts of sulfate percolating through the peat, losing cations, and gaining hydrogen ions by exchange with the humus portions of the peat; and by oxidation of ferrous sulfide from the peat (Frey[274]). Other acids, such as carbonic acid, are known to exist in natural waters, but they are usually present in negligible amounts.

10.6 Upland Lake Water Chemistry

The water in upland lakes is, in varying degrees, separated from the ground water by a seal which represents the initial deposits of silts and clays formed during the lakes' early history, as Broughton[104] found in his study of upland lakes in northeastern Wisconsin. This seal not only allows a more stable lake level than immediate ground-water level, but it also allows for considerable differences in water chemistry between lake water and ground water. Varying uptake by aquatic plants also accounts for some of this difference. The source water for the lakes also varies throughout the Basin. This combination of the effect of sealing and the variation of source water enables chemically dissimilar lakes to coexist within close proximity. A primary difference in water chemistry between the Great Lakes and upland lakes is the lower assimilative and dilution capacities of upland lakes. Because upland lakes have smaller volumes, they cannot dissipate chemical loads and are therefore subject to a more rapid rate of aging. Also, the small volumes and small drainage areas cause the chemistry in upland lakes to reflect soil mineralogy and soil chemistry of the adjacent area.

Much of the extensive literature on upland lake chemistry is summarized in Hutchinson.[402] Wisconsin lakes have been thoroughly studied, and a fair quantity of data exists for lakes throughout the Basin.

The small areas, low volumes, and small watersheds of upland lakes make them subject to rapid changes in water quality and trophic state. The water quality of upland lakes unaffected by man is closely related to bedrock and glacial-deposit lithology and mineralogy. Thwaites[799] compared the chemical compositions of ground water, streams, and upland lakes in different glacial regions of Wisconsin and showed a strong correspondence between the three (Figure 4–293). Ryder[695] related upland lake water chemistry to glacial history in Ontario. He showed that upland lakes in the Precambrian Shield have lower dissolved solid concentrations than lakes in Pleistocene glaciolacustrine deposits. The lower dissolved solids result from slower dissolution of silicate minerals. The chemical control of upland lakes

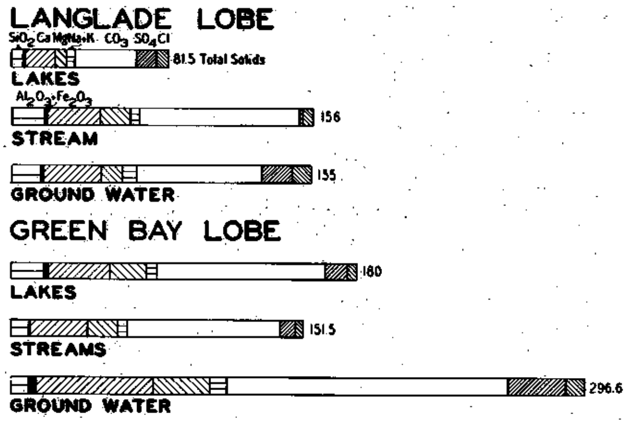

FIGURE 4–293 Relation of Ground Water, Stream, and Upland Lake Composition (mg/l) in Two Glacial Terrains in Wisconsin

From Thwaites, 1943

is, therefore, a function of the chemistry of the surrounding terrain. Areas rich in limestones and dolomites will contain lakes with high dissolved solids, calcium, magnesium, and bicarbonate loads. Lakes in areas of silicate mineral-rich till or igneous or metamorphic bedrock contain lower dissolved solid loads dominated by such cations as sodium, potassium, iron, and calcium.

The type of development around an upland lake governs the nature of loading. Upland lakes that have industry developed along the shores often receive wastes from the industry and rapidly deteriorate in quality. Lakes in suburban areas receive overflow from septic tanks, runoff from fertilized lawns, pesticides from spraying around homes, and other incidental contaminants. In rural areas upland lakes receive crop fertilizers, animal wastes, sediment, pesticides, and incidental wastes. The net effect of the loads of toxicants and nutrients from the various sources is to accelerate eutrophication and restrict use of the water as a resource.

Although the small volume of these lakes emphasizes the effects of loading and aids in rapid deterioration of water quality, the same feature makes restoration of water quality feasible. Lake restoration is discussed in Section 11 of this appendix.

10.7 Problems Associated with Upland Lakes

The type and degree of degradation relate to all the factors described above so lake problems must be considered individually rather than categorically. A given lake may have problems during any trophic stage, but the problems are not usually considered critical until the lake is in the eutrophic stage. A lake may exhibit multiple problems, but one problem is usually dominant. As most problems encountered are of a recurring nature, the most prevalent ones are described below along with suggested solutions (Minnesota Department of Conservation[547a]). Solutions vary from control of a problem to complete elimination.

Algae are a manifestation of water that is too fertile and of low clarity. Excessive algal growth results in unpleasant appearance, odor, deoxygenation of the water (during periods of die-off), and an accumulation of an organic ooze on the bottom. The condition may be natural or induced by man. The following are possible solutions:

(1) Nutrient removal can be accomplished by advanced waste treatment of sewage inflow, control or removal of septic tanks, provision for an additional water source of uncontaminated water for dilution, recycling of the lake water by pumping it upland and allowing it to seep through the soil back into the lake, and possible dredging of high nutrient sediment.

(2) Control of rough fish that keep shallow bottom areas stirred up, thus providing nutrients to the algae. When these species are controlled, water clarity may improve to the extent that additional sunlight will reach the bottom and enable rooted aquatics to establish themselves and become a seondary problem.

(3) Chemical treatment using sulfate is effective in the elimination of algal growth. The chemical must be applied repeatedly for full algae control. It is possible that it may be harmful to game fish by damaging their gills, thus enabling rough fish populations to increase.

(4) Nutrient inactivation requires the addition of an agent that will bond with, adsorb, or otherwise prevent nutrients from recycling. Lake bottom nutrients can be inactivated by covering them with an impermeable material (U.S. Environmental Protection Agency[839]).

Rooted aquatic plants (weeds) appear in clear lakes which are fertile. Any clear, shallow lake is susceptible if nutrients are added, as the lake bottom would receive sufficient solar radiation for photosynthesis. Swimming and boating activities are reduced or halted on lakes with severe weed problems. The following are various solutions:

(1) Nutrient removal procedures are the same as those discussed under algae.

(2) Chemical treatment by the use of herbicides is effective in reducing a current crop of weeds, but the problem will recur if the treatment is not continued. Once the weeds are under control, algae often becomes a problem.

(3) Mechanical removal by harvesting weeds provides short term benefits. Dredging eliminates the weeds and a portion of the nutrients and so is the best immediate treatment, but only a portion of the cure. For the cure to be complete, nutrients entering the system must be significantly reduced. If dredging deepens the water to more than 5 m (15 ft), light penetration will usually be too slight for weed growth.

Eurasian milfoil (*Myriophyllum spicatum L.*) has recently become a problem in the aquatic plant community (Michigan Out-of-Doors[537]). Milfoil is a rapid growing, fast spreading, bottom rooted, emergent plant. Native plants are shaded out and die because of the dense milfoil stands. The weed greatly restricts lake use and causes unsightly surface conditions. Milfoil can be controlled by harvesting or herbicides, but total elimination has not been achieved.

Swimmers itch results when ducks infested with blood flukes pass the eggs of the flukes into a lake. The eggs hatch into miracidia which develop into larvae within a snail host. The larvae then search for a bird host and may penetrate a swimmer's body in error. The unfortunate swimmer will than have an itch which persists until the larvae die. The only attempt at control of this problem has centered around the extermination of the infected snails. The following are various solutions:

(1) Chemical treatment using copper sulfate has been used in killing infected snails. It is suspected that this chemical also kills natural competitors of these snails, and, therefore, may inadvertently create a greater problem. Bayluscide is a much more deadly compound than copper sulfate. It is only mildy toxic to man and other mammals, but it is lethal to fish and amphibia as well as snails. It should be used with great caution.

(2) The introduction of competing animals or predators is an extremely desirable alternative to that of chemical treatment. Research is required to isolate members in these two categories.

Water level fluctuation is an expensive and difficult problem to control. Because runoff and ground water fluctuations are essentially beyond man's control, only control structures offer a solution. Those lakes maintained primarily as reservoirs are periodically lowered when water is needed downstream. If a reservoir lake is to serve more than a single purpose, a balance must be achieved between multiple objectives. If control structures are not maintained, they should be removed.

Sedimentation problems arise from two sources: through the natural process of lake aging, and through excessive erosion from projects such as construction or channel modification. Sedimentation can be controlled by the following methods:

(1) Land can be managed through contour plowing of farmlands, planting vegetation on eroding slopes, and construction regulations. Much of the sedimentation problem can be solved permanently using these methods.

(2) Dredging is an effective control, but it is not a cure because dredging results in increased sedimentation rates in the immediate area.

Pollution of upland lakes originates from three major sources. First, agricultural runoff contributes sediment, fertilizer, herbicides, pesticides, fungicides, and animal wastes. Second, industry contributes thermal and a variety of chemical inputs. Third, municipal wastes contribute nutrients derived from insufficiently treated sewage, lawn fertilizers, weed killers, road salt, minor sediment, and septic tank nutrients. The following are actions for prevention or restoration:

(1) Point sources of pollution must be identified and estimates must be made of contribution from non-point sources such as agricultural and urban runoff.

(2) The method of solving the problem must be decided upon.

(3) The project of halting the pollution must be initiated. Varying and opposing interest within a community often make implementation very difficult.

10.8 Upland Lake Distribution

The size and number of upland lakes per square mile in the Basin is directly related to occurrence of different types of glacial deposits (Figures 4–294 and 4–295). It is apparent that outwash and ground moraines contain about twice as many lakes per square mile as glacial lake plains. The greatest number of lakes occur when the outwash or ground moraine is associated with strong recessional moraine topography. When bedrock is at or near the surface in strong relief, there are few lakes. When bedrock is at or near the surface

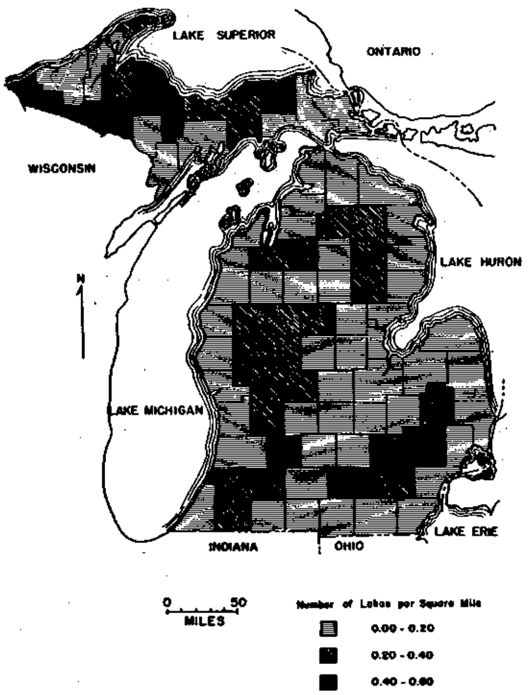

FIGURE 4–294 Relative Density of Lakes in Michigan by County

From Chandler, 1966

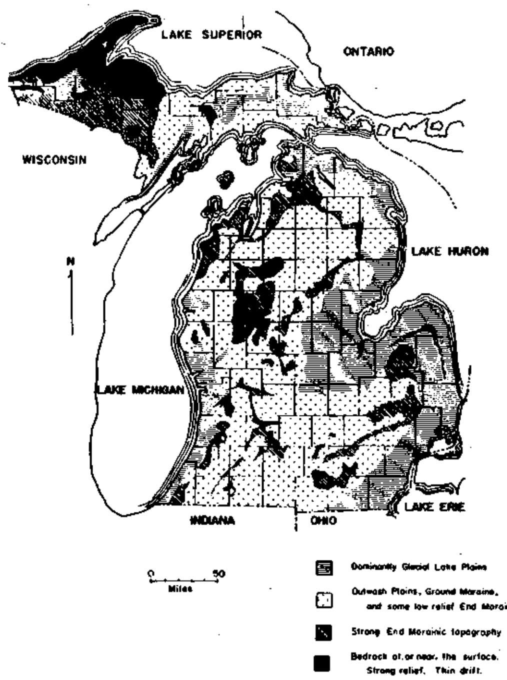

FIGURE 4–295 Generalized Slope and Relief in Michigan

From Chandler, 1966

in slight relief, there are many lakes because drainage is poor. Detailed surface strata maps are available in Appendix 3, *Geology and Ground Water*. The surface strata maps may be used with Figures 4–296, 297, 298, 299, and 300 which indicate the upland lake distribution in each planning area of the Basin. The distribution is presented as the percent of each county's surface area covered by lakes and the number of lakes/km^2 $\times$ 10^3. These figures allow the reader to ascertain both inter- and intracounty and planning subarea variation. Table 4–88 addresses specific needs and summarizes upland lake statistics by planning subareas. Blanks in the table indicate insufficient information.

10.9 Comparability of the Data

Upland lake data vary from State to State because of differences in priorities set by each State and a lack of interstate coordination of criteria. However, information is available in each State's Department of Natural Resources. This information is usually in unpublished file reports dealing with individual lakes, or, more rarely, river basins or counties. Wisconsin publishes "Lake Use Reports" and reports on "Surface Water Resources" in various counties. The Wisconsin reports are useful for local planning.

The minimum size lake surveyed by the individual States varies significantly (Table 4–89). Because a standard minimum size for all States could not be established with the records currently available, the minimum lake size recorded by each State was used. Thus, the data presented in Figures 4–296, 297, 298, 299, and 300 are not to the same base. The basic discrepancy is that some States have more lakes than indicated, but these lakes are extremely small. The States that do not survey small lakes are those with an abundance of lakes.

All the terminology used by various Great Lakes States to describe upland lakes is listed below. The obvious inconsistency is that different descriptions are indiscriminantly used to describe the same types of lakes on an interstate basis:

(1) Michigan

(a) Bog lakes have brown acid water, few electrolytes, highly organic sediment, low calcium, nitrogen, and phosphorus, low dissolved oxygen, and biota dominated by the microflora and microfauna lakeward and by

TABLE 4–88 A Summary of Upland Lake Statistics by County for Each Planning Subarea

Location	Number of Lakes	Lake Area hectares	Lake Area acres	%	Percent Cold Water	Percent Inter-mediate	Percent Warm Water	Percent Dry	Percent Game	Percent Marginal	Percent Fish & Game	Percent Not class-fied	Percent Centrar-chid	Percent Walleye	Percent Trout
PSA 1.1															
MINNESOTA															
Carlton	74	3,620	8,941	1.6	--	--	--	12.1	14.9	25.7	0.0	16.2	10.8	17.5	02.7
Cook	809	41,351	102,137	11.5	--	--	--	47.6	0.7	4.8	0.1	25.9	0.6	7.5	13.1
Lake	818	53,559	127,350	9.6	--	--	--	58.2	6.1	9.3	0.1	8.3	1.7	10.8	5.5
St. Louis	880	125,366	309,655	7.9	--	--	--	46.4	5.5	13.6	0.1	15.3	5.8	10.5	2.8
WISCONSIN															
Ashland	71	1,958	4,837	0.7	09	54	37	--	--	--	--	--	--	--	--
Bayfield	318	8,417	20,792	2.2	04	56	40	--	--	--	--	--	--	--	--
Douglas	110	4,791	11,833	0.2	01	45	54	--	--	--	--	--	--	--	--
Iron	213	13,349	32,971	6.8	00	53	47	--	--	--	--	--	--	--	--
Total	3,293	252,411	618,516	(5.1)[1]											

Location	Number of Lakes	Lake Area hectares	Lake Area acres	%	Percent Bog	Percent Marsh	Percent Warmwater	Percent 2-Story	Percent Coldwater	Shoreline km	Shoreline mi
PSA 1.2											
MICHIGAN											
Alger	279	5,043	12,456	2.2	03	02	63	23	09	496.5	307.8
Baraga	163	5,515	13,623	2.4	31	04	56	08	01	292.9	181.6
Chippewa	153	4,527	11,181	1.1	17	38	36	08	01	329.0	204.0
Gogebic	278	15,280	37,742	5.3	21	05	51	19	04	674.2	418.0
Houghton	138	9,259	22,869	3.5	27	12	41	17	04	386.0	239.3
Keweenaw	46	2,198	5,429	1.6	11	07	61	15	07	111.9	69.4
Luce	231	6,776	16,737	2.9	46	05	26	18	05	381.9	236.8
Marquette	420	11,019	27,218	2.3	11	03	63	14	09	884.2	548.2
Ontonagon	76	4,436	10,957	1.3	53	12	20	08	08	136.3	84.5
Total	1,784	64,053	158,212	(2.5)[1]							

Location	Number of Lakes	Lake Area hectares	Lake Area acres	%	Percent Cold Water	Percent Inter-mediate	Percent Warm Water	Percent Bog	Percent Marsh	Percent Warm Water	Percent 2-Story	Percent Cold Water	Shoreline km	Shoreline mi
PSA 2.1														
MICHIGAN														
Dickinson	119	2,555	6,310	1.3	--	--	--	48	09	21	20	2	200.8	124.5
Iron	314	10,140	25,046	3.3	--	--	--	29	25	31	13	2	357.4	221.6
Menominee	53	1,826	4,510	0.7	--	--	--	49	17	34	0	0	122.1	75.1
WISCONSIN														
Brown	1	17	42	0.0	0	0	100	--	--	--	--	--	--	--
Calumet	8	50	124	0.1	0	50	50	--	--	--	--	--	--	--
Door	10	1,219	3,011	1.0	0	78	22	--	--	--	--	--	--	--
Florence	80	2,166	5,350	1.7	1	54	45	--	--	--	--	--	--	--
Fond du Lac	33	655	1,619	0.3	0	76	24	--	--	--	--	--	--	--
Forest	155	8,280	20,451	3.2	2	41	57	--	--	--	--	--	--	--
Green Lake	10	5,804	14,336	6.3	0	80	20	--	--	--	--	--	--	--
Keweenaw	9	89	221	0.1	0	78	22	--	--	--	--	--	--	--
Langlade	167	3,190	7,879	1.4	5	31	64	--	--	--	--	--	--	--
Manitowoc	55	553	1,367	0.4	0	61	39	--	--	--	--	--	--	--
Marinette	159	5,317	13,134	1.5	1	47	52	--	--	--	--	--	--	--
Marquette	53	1,980	4,892	1.7	0	57	43	--	--	--	--	--	--	--
Menominee	49	979	2,419	1.5	2	58	40	--	--	--	--	--	--	--
Oconto	142	4,676	11,550	1.6	1	50	49	--	--	--	--	--	--	--
Outagamie	2	27	66	0.0	0	50	50	--	--	--	--	--	--	--
Shawano	54	3,678	9,084	1.5	6	65	29	--	--	--	--	--	--	--
Sheboygan	35	830	2,050	0.6	0	86	14	--	--	--	--	--	--	--
Waupaca	117	2,696	6,660	0.3	0	61	39	--	--	--	--	--	--	--
Waushara	64	1,740	4,297	1.1	0	78	22	--	--	--	--	--	--	--
Winnebago	6	68,644	169,550	59.1	0	100	0	--	--	--	--	--	--	--
Total	1,695	127,111	313,968	(3.9)[1]										

[1]Average

TABLE 4–88(continued) A Summary of Upland Lake Statistics by County for Each Planning Subarea

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Percent Coldwater	Percent Intermediate	Percent Warmwater	Average Depth meters	Average Depth feet
PSA 2.2									
ILLINOIS									
Cook	197	2,013	4,972	0.8	--	--	--	--	--
Du Page	52	185	458	0.2	--	--	--	--	--
Kane	16	93	230	0.1	--	--	--	--	--
Lake	92	4,666	11,525	3.9	--	--	--	--	--
McHenry	30	754	1,863	0.5	--	--	--	--	--
Will	40	638	1,576	0.3	--	--	--	--	--
INDIANA									
Lake	5	415	1,024	0.3	--	--	--	5	18
LaPorte	--	--	--	--	--	--	--	--	--
Porter	10	152	375	0.1	--	--	--	12	40
Starke	6	738	1,822	0.9	--	--	--	8	26
WISCONSIN									
Kenosha	24	1,386	3,423	2.0	0	87	13	--	--
Milwaukee	13	39	96	0.1	0	8	92	--	--
Ozaukee	14	109	270	0.2	0	64	36	--	--
Racine	16	1,461	3,608	1.7	0	88	12	--	--
Walworth	34	5,071	12,526	3.5	0	71	29	--	--
Washington	47	1,283	3,168	1.2	0	63	37	--	--
Waukesha	70	6,120	15,116	4.2	2	66	32	--	--
Total	666	25,123	62,052	(1.2)[1]					

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Percent Bog	Percent Marsh	Percent Warmwater	Percent 2-Story	Percent Coldwater	Ave. Max. Depth m	Ave. Max. Depth ft	Shoreline km	Shoreline mi
PSA 2.3													
INDIANA													
Elkhart	8	276	682	0.2	--	--	--	--	--	8	26	--	--
Lagrange	57	1,997	4,932	2.0	--	--	--	--	--	12	38	--	--
Marshall	16	1,352	3,340	1.2	--	--	--	--	--	14	47	--	--
Noble	69	1,608	3,971	1.5	--	--	--	--	--	12	38	--	--
St. Joseph	9	134	330	0.1	--	--	--	--	--	13	41	--	--
Steuben	73	3,476	8,585	4.3	--	--	--	--	--	12	39	--	--
MICHIGAN													
Allegan	98	4,243	10,481	2.0	1	6	90	3	0	--	--	228.4	141.6
Barry	167	5,092	12,577	3.5	4	19	69	7	0	--	--	322.4	199.9
Berrien	32	1,118	2,761	0.7	6	0	94	0	0	--	--	73.1	45.3
Branch	71	3,292	8,130	2.5	3	7	41	49	0	--	--	188.6	116.9
Calhoun	90	1,915	4,731	1.0	1	13	51	34	0	--	--	165.5	102.6
Cass	103	3,848	9,505	2.1	17	20	24	38	0	--	--	245.8	152.4
Clinton	27	328	809	0.2	19	15	52	15	0	--	--	29.8	18.4
Eaton	28	325	802	0.2	7	11	75	7	0	--	--	42.3	26.2
Hillsdale	89	579	3,899	1.0	0	0	98	2	0	--	--	163.1	101.1
Ingham	27	354	875	0.0	44	4	52	0	0	--	--	35.3	21.9
Ionia	28	901	2,226	0.6	4	4	89	4	0	--	--	64.4	39.9
Jackson	96	3,973	9,814	2.2	4	9	74	13	0	--	--	232.7	144.3
Kalamazoo	74	3,955	9,768	2.7	0	5	81	14	0	--	--	185.5	115.0
Kent	186	3,785	9,350	1.7	8	6	84	2	1	--	--	331.9	205.8
Montcalm	160	3,456	8,536	1.9	8	3	86	4	0	--	--	244.4	151.5
Ottawa	24	2,009	4,962	1.4	0	4	96	0	0	--	--	135.0	83.7
St. Joseph	80	3,661	9,042	2.3	14	9	63	15	0	--	--	281.0	174.2
Shiawassee	23	1,632	4,030	1.2	0	4	78	17	0	--	--	37.6	23.3
Van Buren	107	2,553	6,305	1.6	1	1	94	4	0	--	--	168.2	104.3
Total	1,742	55,862	140,443	(1.5)[1]									

[1]Average

TABLE 4–88(continued) A Summary of Upland Lake Statistics by County for Each Planning Subarea

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Percent Bog	Percent Marsh	Percent Warmwater	Percent 2-Story	Percent Coldwater	Shoreline km	Shoreline mi
PSA 2.4											
MICHIGAN											
Antrim	49	8,953	22,114	7.3	2	8	76	6	8	241.3	149.6
Benzie	57	7,183	17,741	8.8	5	2	74	19	0	173.4	107.5
Charlevoix	42	10,174	25,131	9.5	5	38	36	19	2	195.3	129.1
Delta	117	1,816	4,486	0.6	21	21	43	9	6	163.9	101.6
Emmet	28	4,307	10,634	3.6	16	32	26	26	0	117.3	72.7
Grand Traverse	82	7,772	19,198	6.5	2	10	66	21	1	273.7	169.7
Kalkaska	95	5,790	14,301	3.9	1	5	67	18	8	169.2	104.9
Lake	118	1,872	4,623	1.3	5	17	48	28	2	168.6	104.5
Leelanau	31	7,175	17,722	8.0	10	3	65	23	0	161.5	100.1
Mackinac[2]	171	11,329	27,983	4.3	44	34	22	0	0	389.8	241.7
Manistee	42	3,496	8,635	2.4	10	5	71	7	7	126.3	78.3
Mason	72	3,638	8,986	2.9	17	3	72	8	0	147.9	91.7
Mecosta	91	3,882	9,588	2.7	10	13	56	21	0	293.6	182.0
Missaukee	32	5,161	12,747	3.5	13	22	63	3	0	95.5	59.2
Muskegon	73	4,391	10,846	3.4	4	18	73	4	1	168.1	104.2
Newaygo	143	3,657	9,034	1.7	10	6	66	17	1	282.3	175.0
Oceana	66	1,502	3,711	1.1	5	5	73	18	0	129.7	80.4
Osceola	80	1,210	2,991	0.8	16	10	65	8	1	154.0	95.5
Roscommon	61	15,414	38,073	11.4	31	29	38	5	2	239.2	148.3
Schoolcraft	430	11,553	28,535	3.8	7	34	52	5	2	736.3	456.5
Wexford	26	2,612	6,452	1.8	38	8	38	15	0	93.1	57.7
Total	1,906	119,597	303,531	(4.3)[1]							

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Percent Bog	Percent Marsh	Percent Warmwater	Percent 2-Story	Percent Coldwater	Shoreline km	Shoreline mi
PSA 3.1											
MICHIGAN											
Alcona	47	5,264	13,001	3.0	6	38	30	19	6	126.3	78.3
Alpena	24	6,921	17,094	4.7	8	21	67	4	0	152.4	94.5
Arenac	8	77	190	0.1	75	13	13	0	0	11.9	7.4
Cheboygan	45	21,074	52,052	11.3	22	18	33	20	7	294.0	182.3
Crawford	37	5,154	12,731	3.5	8	16	46	30	0	72.6	45.0
Iosco	53	4,644	11,470	3.3	28	30	28	13	0	233.1	144.5
Mackinac[2]	171	11,329	27,983	4.3	44	34	22	0	0	389.8	241.7
Montmorency	89	4,926	12,166	3.4	11	29	36	18	6	202.1	125.3
Ogemaw	130	2,360	5,829	1.6	5	8	78	8	2	201.5	124.9
Oscoda	73	7,972	19,690	5.5	0	11	66	21	3	146.9	91.1
Otsego	116	3,149	7,779	2.3	11	35	24	29	0	219.4	136.0
Presque Isle	77	5,912	14,602	3.5	10	12	68	10	0	233.7	144.9
Total	870	78,782	194,587	(3.9)[1]							

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Percent Bog	Percent Marsh	Percent Warmwater	Percent 2-Story	Percent Coldwater	Shoreline km	Shoreline mi
PSA 3.2											
MICHIGAN											
Bay	4	62	154	0.0	0	25	75	0	0	9.7	6.0
Clare	124	2,154	5,321	1.5	4	20	67	9	0	231.6	143.6
Genesee	78	2,560	6,324	1.5	0	3	74	23	0	181.6	112.6
Gladwin	49	2,785	6,878	2.1	12	4	65	12	6	305.0	189.1
Gratiot	20	557	1,375	0.4	0	55	35	10	0	55.7	34.5
Huron	5	63	155	0.0	0	100	0	0	0	10.8	6.7
Isabella	32	438	1,082	0.3	0	3	78	19	0	56.5	35.0
Lapeer	129	4,067	10,045	2.4	0	10	74	16	0	211.0	130.8
Midland	10	926	2,287	0.7	10	0	90	0	0	53.4	33.1
Saginaw	6	584	1,442	0.3	0	67	33	0	0	28.5	17.7
Tuscola	35	564	1,392	0.3	0	51	26	23	0	70.0	43.4
Total	492	14,760	36,455	(0.9)[1]							

[1] Average
[2] Included in PSAs 2.4 and 3.1

TABLE 4–88(continued) A Summary of Upland Lake Statistics by County for Each Planning Subarea

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Percent Marsh & Bog	Percent Marsh	Percent Warmwater	Percent 2-Story	Percent Coldwater	Shoreline km	Shoreline mi
PSA 4.1											
MICHIGAN											
Lenawee	74	9,431	23,294	4.8	0	0	100	0	0	148.2	91.9
Livingston	171	3,849	9,506	2.6	6	2	84	8	0	366.1	227.0
Macomb	29	530	1,308	0.4	0	0	83	17	0	61.9	38.4
Monroe	7	590	1,457	0.4	0	0	86	0	14	18.1	11.2
Oakland	394	15,283	37,749	6.8	0	2	62	37	0	852.1	528.4
Sanilac	9	33	82	0.0	0	100	0	0	0	5.8	3.6
St. Clair	19	696	1,720	0.4	11	58	21	11	0	54.0	33.5
Washtenaw	119	3,289	8,125	1.8	3	1	89	8	0	249.8	154.9
Wayne	52	939	2,319	0.6	0	10	90	0	0	97.4	60.4
Total	874	34,670	85,560	(2.0)[1]							

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Ave. Max. Depth m	Ave. Max. Depth ft
PSA 4.2						
INDIANA						
Adams	2	28	69	0.0	4	13
Allen	4	130	320	0.1	9	29
De Kalb	6	124	307	0.1	13	42
OHIO						
Allen	47	383	946	0.4	--	--
Auglaize	13	1,049	2,592	1.0	--	--
Crawford	18	94	231	0.1	--	--
Defiance	12	428	1,057	0.4	--	--
Erie	41	317	782	0.5	--	--
Fulton	16	108	267	0.1	--	--
Hancock	23	146	361	0.1	--	--
Henry	16	844	2,085	0.8	--	--
Huron	39	303	749	0.2	--	--
Lucas	26	133	329	0.1	--	--
Mercer	3	4,498	11,109	3.8	--	--
Ottawa	44	1,011	2,498	1.5	--	--
Paulding	13	456	1,127	0.4	--	--
Putnam	11	38	94	0.0	--	--
Sandusky	11	52	129	0.0	--	--
Seneca	16	42	103	0.0	--	--
Van Wert	19	45	110	0.0	--	--
Williams	34	114	330	0.1	--	--
Wood	8	28	69	0.0	--	--
Wyandot	22	448	1,106	0.4	--	--
Total	444	10,819	26,770	(0.4)[1]		

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %
PSA 4.3				
OHIO				
Ashtabula	64	1,598	3,946	0.9
Cuyahoga	8	55	137	0.0
Geauga	29	378	933	0.4
Lake	15	29	71	0.0
Lorain	92	287	708	0.2
Medina	70	213	527	0.2
Portage	32	2,697	6,661	2.1
Summit	35	1,981	4,892	1.9
Total	345	7,238	17,875	(0.7)[1]

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Ave. Depth m	Ave. Depth ft	Shoreline km	Shoreline mi
PSA 4.4								
PENNSYLVANIA								
Erie	15	738	1,822	0.1	5	16	--	--
NEW YORK								
Cattaraugus	40	4,879	12,051	1.4	-	--	198.39	123.00
Chautauqua	35	5,960	14,720	2.1	-	--	136.69	84.75
Erie	31	238	589	0.1	-	--	41.42	25.68
Niagara	10	834	2,061	0.6	-	--	25.76	15.97
Total	131	12,649	31,243	(0.9)[1]				

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Shoreline km	Shoreline mi
PSA 5.1						
NEW YORK						
Allegany	28	1,177	2,906	0.4	61.29	38.00
Genesee	13	145	358	0.1	24.77	15.36
Livingston	13	4,364	10,778	2.6	89.21	55.31
Monroe	21	544	1,344	0.3	59.37	36.81
Orleans	7	181	448	0.2	37.60	23.31
Wyoming	27	588	1,453	0.4	51.42	31.88
Total	109	6,999	17,287	(0.7)[1]		

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Shoreline km	Shoreline mi
PSA 5.2						
NEW YORK						
Cayuga	28	20,612	50,912	11.4	237.61	147.32
Herkimer	330	12,974	32,045	3.5	1,022.56	633.99
Madison	21	1,259	3,110	0.7	102.42	63.50
Oneida	57	1,788	4,417	0.6	167.79	104.03
Onondaga	36	7,118	17,581	3.5	195.55	121.24
Ontario	9	4,656	11,501	2.8	85.58	53.68
Oswego	74	24,942	61,606	10.0	327.05	227.57
Schuyler	5	811	2,003	0.9	37.74	23.40
Seneca	10	18,278	45,146	21.4	159.24	98.73
Tompkins	9	109	269	0.1	15.81	9.80
Wayne	13	88	218	0.1	25.37	15.73
Yates	1	4,742	11,712	5.3	94.19	58.40
Total	593	97,377	240,520	(5.0)[1]		

Location	Number of Lakes	Lake Area hectares	Lake Area acres	Lake Area %	Shoreline km	Shoreline mi
PSA 5.3						
NEW YORK						
Jefferson	38	2,563	6,330	0.8	161.52	100.14
Lewis	118	2,336	5,770	0.6	244.45	151.56
St. Lawrence	232	14,782	36,512	2.1	744.87	461.82
Total	338	19,681	48,612	(1.2)[1]		

[1]Average

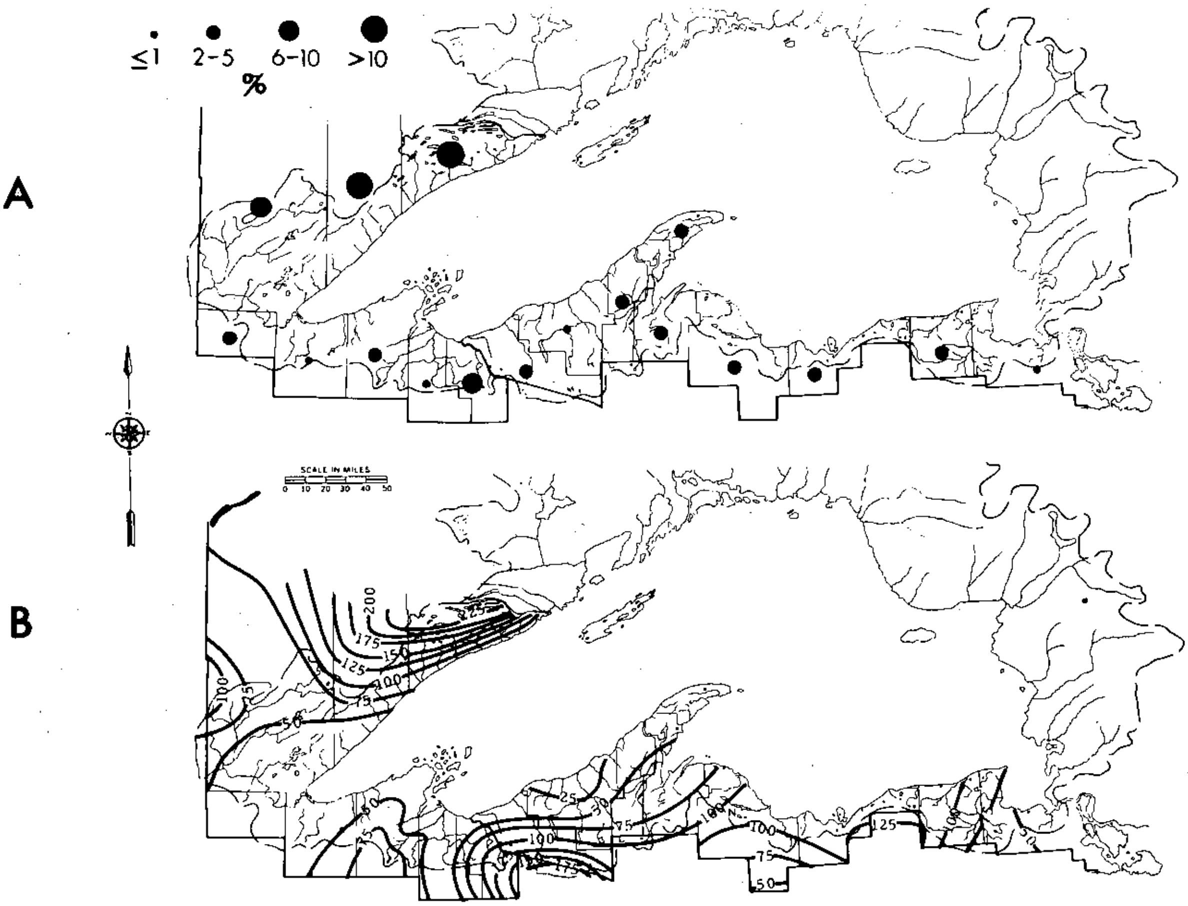

FIGURE 4–296 Distribution of Upland Lakes in Plan Area 1 in Terms of Percent of Each County's Surface Covered by Lakes (A) and Number of Lakes/km² × 10³ (B)

sedges shoreward. These are usually dystrophic lakes.

(b) Marsh lakes have clear alkaline water, many electrolytes, highly organic sediment, high calcium, nitrogen, and phosphorous concentration, low dissolved oxygen, dense rooted emergent aquatic plant growths, warmwater fish subject to winterkill, and blue-green algal blooms. These are usually hypereutrophic lakes.

(c) Warmwater lakes are usually thermally stratified in summer, have many electrolytes, moderate dissolved oxygen, organic and inorganic sediment, and large numbers of warmwater fish. These are usually eutrophic lakes.

(d) Two-story lakes have an epilimnion and hypolimnion, abundant dissolved oxygen, warm- and coldwater fish, a diversified flora, and primarily inorganic sediments. These are usually mesotrophic lakes.

(e) Coldwater lakes are usually deep, non-fertile, have small diversified fauna and flora, coldwater fish, inorganic sediments, and high levels of dissolved oxygen. These are usually oligotrophic lakes.

(2) Minnesota

(a) Dry lakes are dry lake basins which were lakes until they were drained about 1900 for use as farmland as well as lakes for which there is no information. (Minnesota lists "dry" and "no information" separately.)

(b) Game lakes are too shallow for fish because of winterkill, but they have an abundance of emergent aquatic plants suitable as waterfowl habitat. These lakes usually are marshes and are hypereutrophic.

(c) Marginal lakes are shallow with barren shores and are not good for fish or fowl.

(d) Fish and game lakes are good for fish and waterfowl.

(e) Not classified lakes are fish lakes which are not classified as to type of predominant fish.

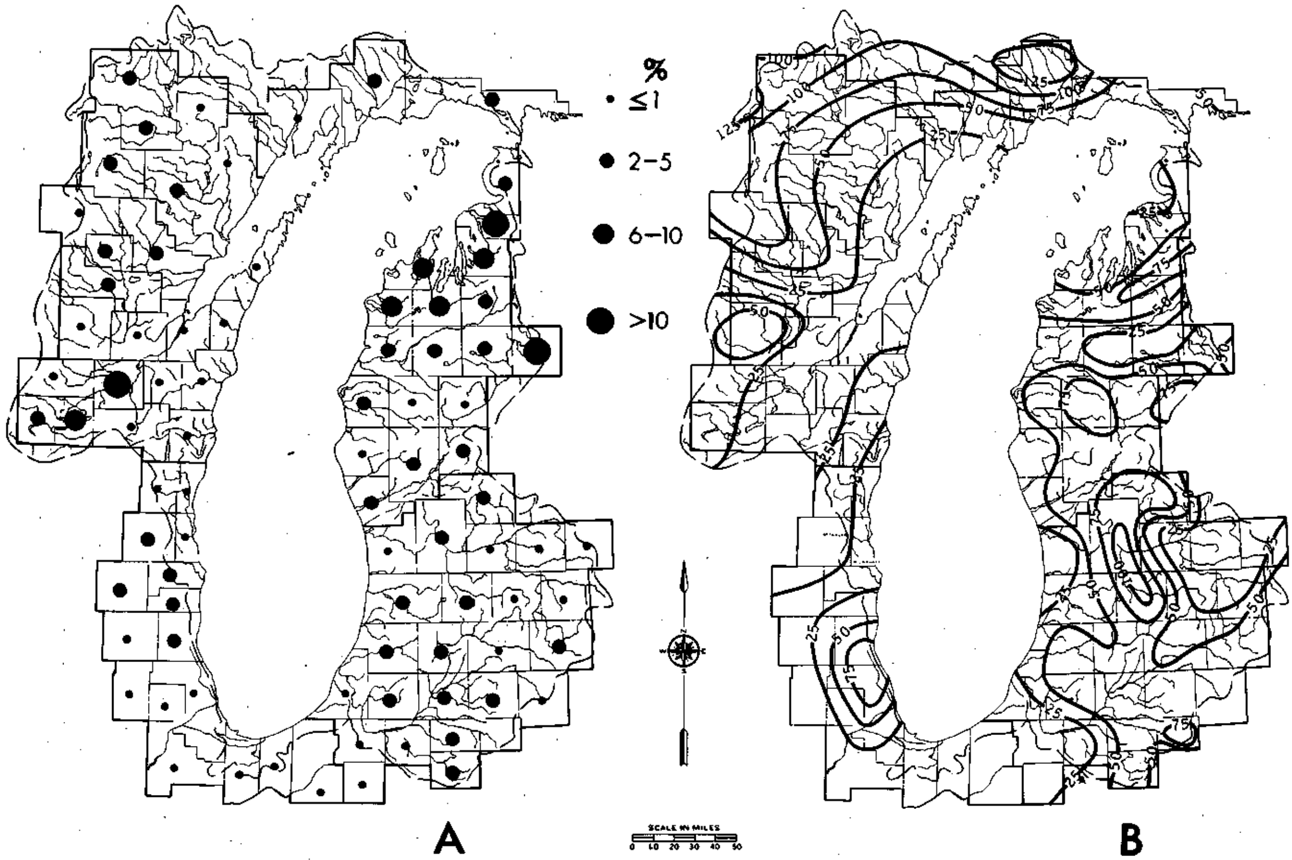

FIGURE 4–297 Distribution of Upland Lakes in Plan Area 2 in Terms of Percent of Each County's Surface Covered by Lakes (A) and Number of Lakes/km² × 10³ (B)

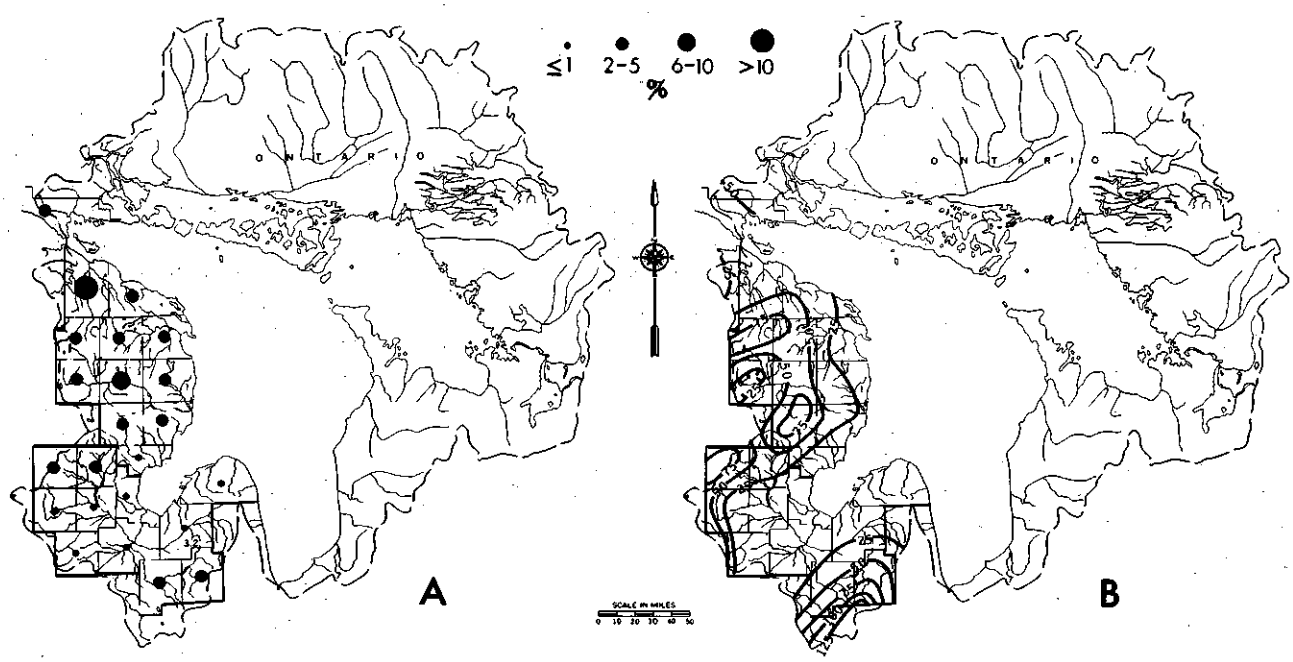

FIGURE 4–298 Distribution of Upland Lakes in Plan Area 3 in Terms of Percent of Each County's Surface Covered by Lakes (A) and Number of Lakes/km² × 10³ (B)

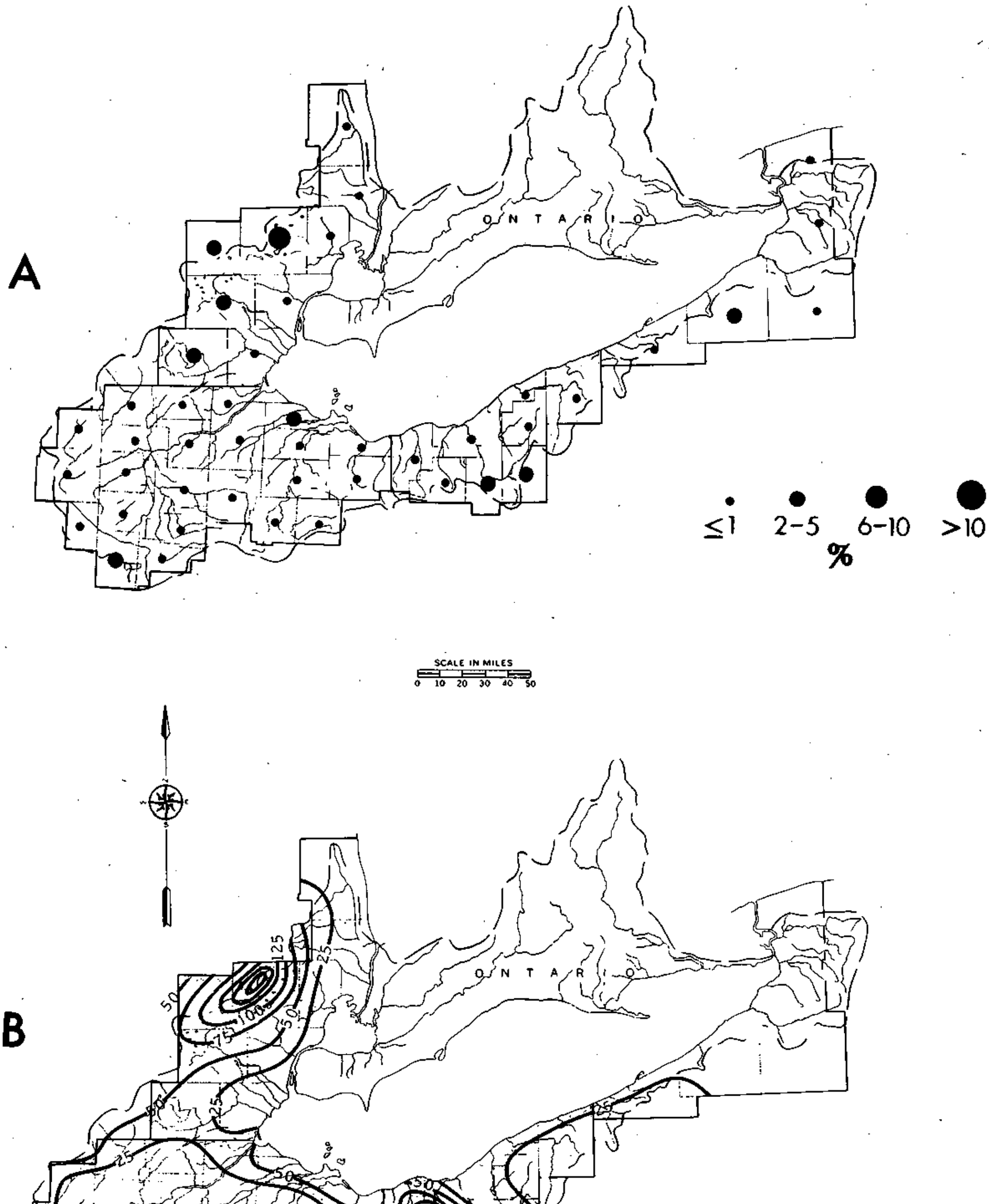

FIGURE 4–299 Distribution of Upland Lakes in Plan Area 4 in Terms of Percent of Each County's Surface Covered by Lakes (A) and Number of Lakes/km² × 10³ (B)

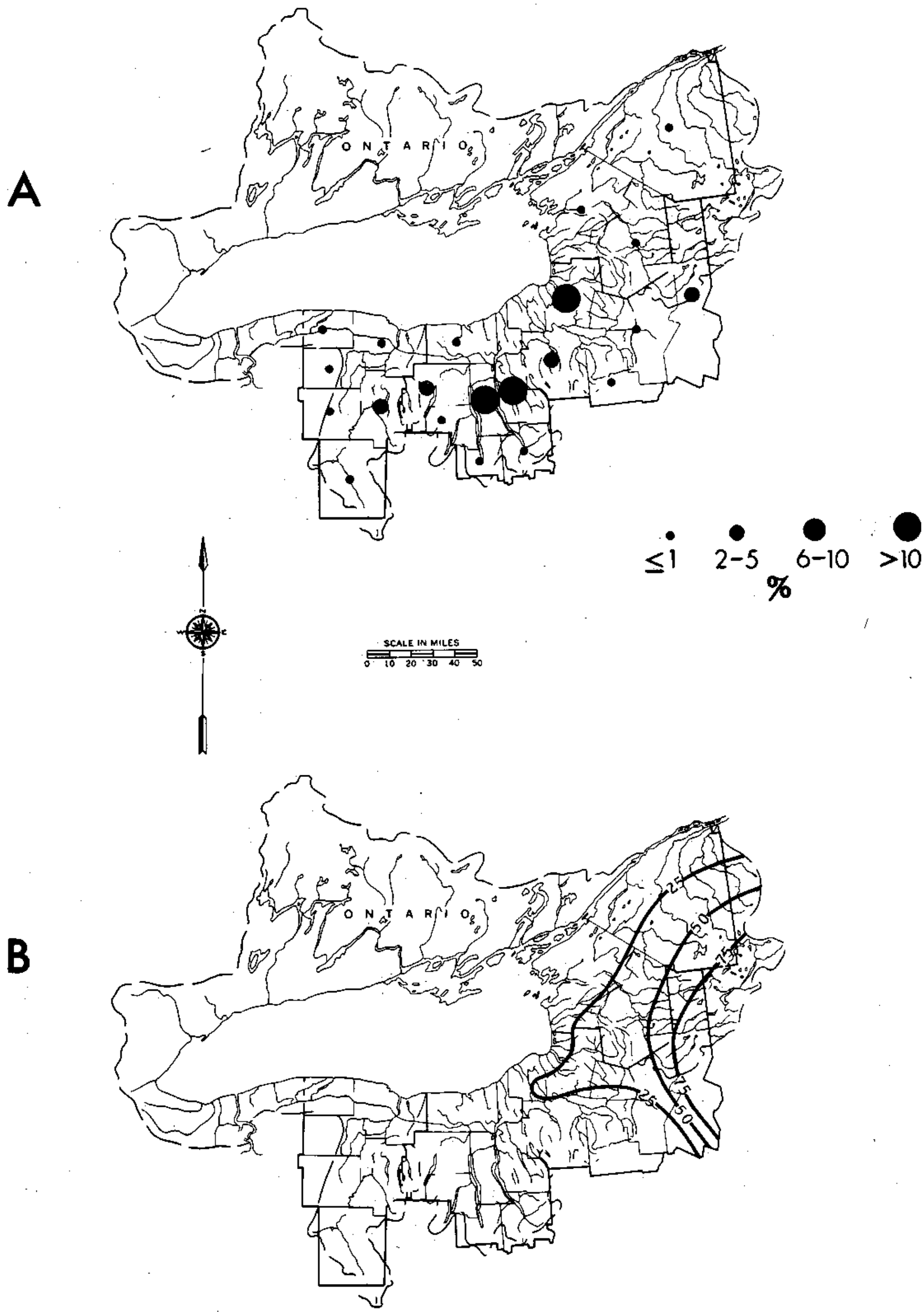

FIGURE 4–300 Distribution of Upland Lakes in Plan Area 5 in Terms of Percent of Each County's Surface Covered by Lakes (A) and Number of Lakes/km$_2$ × 10^3 (B)

TABLE 4–89 Minimum Lake Size Surveyed

State	Hectares	Acres
Illinois	0.1	0.3
Indiana	4.0	10.0
Michigan	2.0	5.0
Minnesota	4.0	10.0
New York	2.6	6.4
Ohio	0.3	1.0
Pennsylvania	1.2	3.0
Wisconsin	0.3	1.0

TABLE 4–90 A Comparison of State Lake Types

Wisconsin	Michigan	Minnesota
Warm Water	Bog & Marsh	Game
Intermediate	Warm Water	Fish & Game Centrarchid
	Two-Story	Walleye
Cold Water	Cold Water	Trout Dry Marginal

(f) Centrachid lakes have only warmwater fish such as panfish.

(g) Walleye lakes have warm- and coldwater fish.

(h) Trout lakes have only coldwater fish such as trout.

(3) Wisconsin

(a) Coldwater lakes have trout as their only type of fish

(b) Intermediate lakes have walleye and all other combinations of fish

(c) Warm lakes have bass and/or panfish only.

The above terminology is related to lake type in Table 4–90 using temperature as a basic criterion. The Wisconsin classification is based on the species of fish present in the lakes (State of Wisconsin[906]). Bass and panfish in a lake indicate warm water. Trout alone indicates cold water. Any combination of warm- and coldwater indicator fish species indicates intermediate water temperature.

10.10 Lakes in Michigan

The State of Michigan has the most complete historical and current data on upland lakes. The Michigan Department of Natural Resources estimates that there are more than 7,700 lakes greater than 2 hectares (5 acres) in surface area in the State. Lakes under 2 hectares have not been inventoried. The small lake category, 2–6 ha (5–15 acres), includes more than 3,600 or 47 percent of the total number of lakes in the State. As stated earlier, the smaller the lake the greater the tendency to become a marsh or bog lake. Michigan has approximately 2,000 marsh or bog lakes of which almost 1,300 or 67 percent fall in the small-size category. The number of lakes per county is usually positively correlated with the percent marsh and bog lakes per county. The distribution of marsh and bog lakes (Figure 4–301) in Michigan parallels the principal recessional moraines (Figure 4–9). Streams are not as well developed in the eastern heavy marsh and bog region of Michigan as in the southwestern portion of the State, and therefore, are not as effective in removing the excess surface water of the area as those in the southwest.

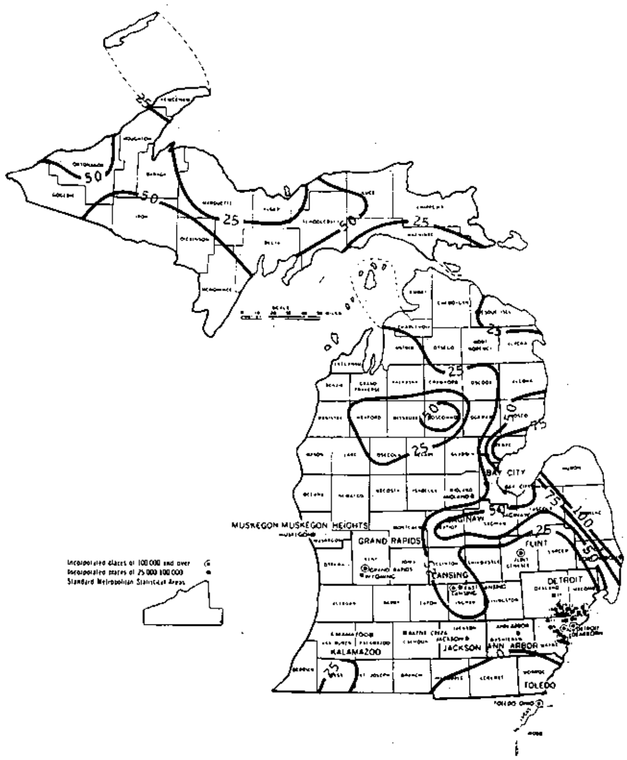

FIGURE 4–301 Distribution of Marsh and Bog Lakes in Michigan, in Terms of Percentage of Lakes of All Types

Data from Michigan Water Resources Commission, 1965

Marsh distribution has not changed significantly in approximately 100 years, although individual marshes have changed markedly. Davis[187] compiled a map of the original swamp areas in the lower peninsula of Michigan from data obtained prior to 1873. The map matches Figure 4–301 which is based on data collected in 1965. The similarity in distribution of marshes and bogs in 1873 and 1965 indicates that areas and conditions for marsh and bog development have not changed significantly during the last century.

10.11 Upland Lake Data Requirements

There is a lack of consistency in the manner in which each State has surveyed its upland lakes. This inconsistency is quite evident in Table 4–88, which incorporates data from more than 15,000 upland lakes. If one acre were used as the minimum lake size, 30,000 lakes could be listed as Basin lakes. Because of the States' criteria for lake classification are so vague and inconsistent, a comprehensive survey is needed. The Water Resources Division, U.S. Geological Survey, at Albany is conducting a survey that will include approximately 4,000 New York lakes. Greeson[300] has listed the parameters to be surveyed on 21 representative lakes (Table 4–91). Computerization of the data would make retrieval and manipulation rapid and exact. If representative upland lakes in the Basin were surveyed in a similar manner, identification of key indices, classification, problem identification, and limnological planning would be greatly facilitated. Legislation to support such activity exists in the Federal Water Pollution Control Act Amendments of 1972, PL 92–500. Included within this legislation (Subsection 304 [i]) is the requirement that the U.S. Environmental Protection Agency issue such information on methods, processes, and procedures as may be appropriate to enhance the quality of the nation's publicly owned lakes. State-of-the-art information has now been presented (see U.S. Environmental Protection Agency[839]). Also included in this legislation is the "Clean Lakes Section, 314," which states that each State shall prepare or establish, and submit to the Administrator for his approval the following items:

(1) an identification and classification according to trophic condition of all publicly owned freshwater lakes in such State

(2) procedures, processes, and methods (including land use requirements), to control sources of pollution of such lakes

(3) methods and procedures, in conjunction with appropriate Federal agencies, to restore the quality of such lakes.

10.12 Summary

Glaciation of the Great Lakes Basin resulted in the creation of thousands of upland lakes. The origin of a given lake has influence on its general characteristics. After creation, lakes begin a natural aging process, eutrophication, which encompasses physical, chemical, and biological successions.

The distribution of upland lakes in the Great Lakes Basin is not uniform in terms of size, density, or trophic state. The larger and greatest number of lakes are in areas of till deposits, and the least number of lakes are in glacial lake plains. The upland lakes north of the 43rd parallel are usually in an earlier trophic stage than those south of this parallel. This physiological division is the result of climatological variations, degree of man-made pollution, and the fact that the glaciers retreated from the north a few thousand years later than from the south.

As the Great Lakes Basin becomes more populated, increasing use of the upland lakes will accelerate lake aging and/or pollution. To adequately measure future changes in the upland lakes, their current state must be known. Since an optimistic figure for completion of a one-visit lake survey as outlined above would be in terms of 200 man-years, the survey should be initiated in the near future. With such a survey, individual lake changes could be documented and diagnosed and a basis established for planning and development.

Changes in trophic state of the upland lakes will be negligible by the year 1980 although individual lakes may change dramatically. By 2020 half of the upland lakes could exhibit signs of the eutrophic stage due to accelerated aging. Since pollution of lakes has not been abated, trophic change of upland lakes will continue at an accelerated rate. However, this must be controlled if the upland lakes are to serve man in the foreseeable future.

TABLE 4–91 Survey Parameters

CHEMICAL

specific conductance	turbidity	copper
pH	MBAS (detergents)	gallium
color	dissolved oxygen	germanium
residue on evaporation	concentration	iron
calcium	percent saturation	lead
magnesium	spectrographic analyses	lithium
hardness (Ca + Mg)	herbicides in water	manganese
sodium	2, 4-D	molybdenum
potassium	2, 4, 5-T	nickel
mercury	silvex	rubidium
bicarbonate (HCO_3)	insecticides in sediment (same	silver
carbonate (CO_3)	as above) selected lakes only	strontium
alkalinity	herbicides in sediment (same	tin
sulfate	as above) selected lakes only	vanadium
chloride	total carbon	zinc
fluoride	organic	zirconium
dissolved solids (calc.)	inorganic	titanium
silica (SiO_2)	aluminum	insecticides in water
phosphorus (as ppb in P)	barium	aldrin
inorganic soluble	beryllium	DDD
total soluble	bismuth	DDE
total particulate	boron	DDT
N-cycle	cadmium	dieldrin
ammonia-N (NH_4)	chromium	endrin
nitrite-N (NO_2)	cobalt	heptachlor
organic nitrogen		lindane
total nitrogen (calc.)		

BIOLOGICAL

phytoplankton	chlorophyll	streptococci, fecal
qualitative identifications	a	nutrients (a total of 21, all of
total concentrations	b	which are included in the list
(quantitative)	benthos	of chemical parameters)
total seston	coliform, total	level of productivity
	coliform, fecal	

PHYSICAL

water temperature	vertical stratification (cont.)	volume
air temperature	depth	total
vertical stratification	maximum	usable storage
water temperature	mean	dead storage
dissolved oxygen	width	stage-volume relationship
pH	maximum	development of volume
chemical analyses of epilimnion	mean	flow through time (when possible)
and hypolimnion during periods	length	stage variation (if necessary)
of stratification	maximum	fetch
length of shoreline	axis	maximum
development of shore	Secchi disc	axis
	light transparency	precipitation
	drainage area	hydrographic contours of bottom
	surface area	(major lakes only)

OTHER

counties	ownership	type usage of lake
number	type	regulation
names	name	type
quadrangle	address	extent
drainage basin	land usage of shoreline	controller and address
major	types	formation of lake
minor	percent of each	natural
coordinates of location point	land usage of drainage basin	enhanced
effluent tributary	types	artificial
	percent of each	numerical coding of lakes

Section 11

LIMNOLOGICAL ASPECTS OF WATER RESOURCE UTILIZATION

11.1 Introduction

Structural or nonstructural modifications of a lake environment or of inputs or outflow will cause changes in the lake ecosystem. Discrete changes may be more or less imperceptible in the broad system depending on degree of alteration, but the cumulative change is recognizable. In this same manner the resource cannot be exploited for single interests because of the impact on the extremely complex societal demands. Conflict of interest is inherent in any multipurpose approach to planning and management, and this occurs at several different levels. In addition to urban versus rural, commercial versus environmental, upstream versus downstream, local versus regional, there is also competition on the larger scale between regions with different interests. Thus, the development and management of our natural resources must be through assessment and coordination of all actual and potential users. For this reason, interrelationships and impacts of current and potential limnological problems on optimum utilization and management of the Great Lakes and upland lakes are presented.

As a first step each of the limnological aspects that have been discussed is related to the principal Great Lakes water uses with an indication of its impact on the desired use (Table 4–92). This table can be used as a guide in selecting topics of special interest in evaluating consequences of the water resource utilization to satisfy a particular need. Traditional planning techniques overlook many of the interrelationships discussed in this appendix because the significance of these factors has not long been recognized in the complex attempts to satisfy all interests while maintaining the integrity of the aquatic system. Because environmental impact is an integral part of planning, the detailed discussions referenced in Table 4–92 should be included in management considerations.

An alternative to oversimplifications would be the utilization of computers to analyze large volumes of multivariate data so that a variety of alternatives may be evaluated in light of their impact on the ecosystem, as well as their impact on other demands. However, this method would be, at best, subjective. There are at present insufficient data and computer hardware to develop completely objective, comprehensive models for most Great Lakes problems, but the Great Lakes Basin Commission study of feasibility of Limnological Systems Analysis has identified those geographical and subject areas that can be described mathematically with current technology.

11.2 Current and Projected Water Resource Utilization Problems

11.2.1 Municipal and Industrial Water Supplies

Many limnological factors influence the use of lake water for municipal and industrial water supplies (Table 4–92). Direction and intensity of currents and waves, water stratification, and internal waves affect short-term changes in water quality by directing flow and influencing mixing and dispersion of inputs. Little can be done about stratification, currents, and circulation-induced problems other than to consider them in planning. Contamination of water with toxic elements, pesticides, and pathogenic micro-organisms poses much greater hazards. Care should be taken to locate intakes away from possible sources and out of the zone of influence of such contamination until introduction of the contaminants is stopped. In addition to preventive measures, lake restoration techniques are required to eliminate those hazardous constituents or pollutants already in the lakes.

11.2.2 Water Storage

Major concern with water storage comes from power, navigation, shore properties, and

TABLE 4–92 Relative Importance of Limnological Factors in Great Lakes Resource Utilization

Section	Water Supply Municipal	Water Supply Industrial	Water Storage	Shore Property	Navigation	Fish & Wildlife	Recreation	Power Generation	Waste Disposal
1 General Basin Character									
Basin Morphology	minor[1]	minor	minor	major[2]	major	minor	major	major	major
Basin Climate	minimal[3]	minimal	major	major	minimal	minimal	major	major	minimal
Basin Geology	minor	minor	minimal	major	minimal	minor	minor	minimal	minimal
Lake Levels & Discharges	minor	minor	major	major	major	minor	minor	major	minor
3 Physical Characteristics									
Turbidity	major	major	minimal	major	minimal	major	major	minimal	major
Density	minor	minor	major	minimal	minimal	major	major	major	major
Water Temperature	minor	minor	major	major	minimal	major	major	major	major
4 Hydrometeorology									
Radiation	minimal	minimal	major	minimal	minimal	major	minor	minimal	minimal
Wind	minimal	minimal	minor	major	major	minor	major	minimal	minimal
Air Temperature	minimal	minimal	major	major	minimal	minimal	major	minimal	minimal
Humidity	minimal	minimal	major	minor	minimal	minimal	minimal	minimal	minimal
Precipitation	minimal	minimal	major	major	minimal	minor	major	minor	minimal
5 Ice Cover	minimal	minimal	minor	major	major	minor	major	major	minimal
6 Water Motion									
Surface Wind Waves	major	minor	minimal	major	major	major	major	minimal	major
Long-Period Waves	minor	minimal	minimal	major	major	minimal	minor	major	minor
Surface Currents	major	major	minimal	minor	major	major	major	minimal	major
Internal Circulation	major	major	minimal	minimal	minimal	major	minimal	minimal	major
Internal Waves	major	major	minimal	minimal	minimal	minimal	minimal	minimal	major
Turbulence & Diffusion	major	major	minimal	major	minimal	major	major	minimal	major
Harbor Currents	major	major	minimal	minor	major	minor	major	minimal	major
Harbor Flushing	major	major	minimal	minor	minor	major	major	minimal	major
7 Chemical Characteristics									
Dissolved Solids	major	major	minimal	minimal	minimal	major	minimal	minimal	major
Carbonate System	major	major	minimal	minor	minimal	major	minor	minor	major
Oxygen & Redox Potential	major	major	minimal	minor	minimal	major	minor	minimal	major
Chloride	minimal	minimal	minimal	minimal	minimal	minimal	minimal	minimal	minor
Phosphorus System	major	minor	minimal	major	minimal	major	major	minimal	major
Nitrogen System	major	minor	minimal	minor	minimal	major	major	minimal	major
Hydrocarbons & Other Carbon Compounds	major	minor	minimal	major	minimal	major	major	minimal	major
Calcium & Magnesium	minor	major	minimal	minimal	minimal	minor	minimal	minimal	minor
Sulfur Cycle	minor	minor	minimal	minimal	minimal	minor	minimal	minimal	major
Silica & Silicate Compounds	minimal	minimal	minimal	minimal	minimal	minor	minimal	minimal	minor
Iron & Manganese	minor	major	minimal	minimal	minimal	minor	minimal	minimal	major
Trace Elements	major	major	minimal	minimal	minimal	major	minimal	minimal	major
Radionuclides	minor	minor	minimal	minimal	minimal	minor	minimal	minor	major
Chemical Loads & Trends	major	major	minimal	minor	minimal	major	major	minor	major
8 Biological Characteristics									
Nekton	minor	minor	minimal	major	minimal	major	major	minimal	major
Bacteria & Fungi	major	minimal	minimal	major	minimal	major	major	minimal	major
Zoobenthos	minimal	minimal	minimal	minor	minimal	major	major	minimal	major
Zooplankton	minor	minimal	minimal	minor	minimal	major	major	minimal	major
Phytoplankton	major	major	minimal	major	minimal	major	major	minimal	major
Phytobenthos	major	major	minimal	major	minimal	major	major	minimal	major
9 Sedimentology									
Sediment Distribution	minor	minor	minimal	major	minor	major	major	minimal	major
Sediment Flux	minor	minor	minor	major	major	major	major	major	major
Sediment Composition	minor	minimal	minimal	minimal	minimal	minor	minor	minimal	major
10 Upland Lakes									
Eutrophication	major	minor	minimal	major	minimal	major	major	minimal	major

[1] Minor means presently or soon to be of minor importance on resource utilization
[2] Major means presently or soon to be of critical importance to resource utilization
[3] Minimal means little forseeable impact on resource utilization

consumptive water-use interests. The volume of water available to satisfy user demands will be more than adequate in the foreseeable future. Diversions, control structures, and changes in the thermal budget of the lakes can cause long-term changes in the volume of stored water, but greater variation in lake storage results from variations in the hydrologic cycle. It would be difficult to compensate for natural variations because of inability to make adequate long-term forecasts. However, as indicated in Section 4 and Appendix 11, *Levels and Flows*, if the effects are not compensated for, there could be a potential shore properties problem in changing lake levels with diversions, control structures, and changes in the thermal budget.

Water withdrawals could cause changes in lake levels and storage. For example, the diversions in the vicinity of Chicago have produced a net drop in the levels of Lakes Huron and Michigan of 0.07 m (2.8 in). Future demands will call for more interbasin and out-of-basin diversions. A diversion from Lake

Huron to the Detroit metropolitan area is near completion, and proposals have been made for exportation of water from Lake Superior to fill needs in the southern half of the Great Lakes Basin, for importation of water from Canada into the Great Lakes (Kierans[454]), and from the Great Lakes to the southwestern States (Laycock[490]). These and other diversions could affect lake levels significantly and should be critically evaluated since they affect other resource use categories (Table 4–92).

11.2.3 Shore Property

The shores of the Great Lakes and the upland lakes are highly sensitive to changes in the ecosystem. Waves and currents affect the shoreline through periodic damage by storm waves and long-period waves, and sediment erosion, transport, and deposition. These natural forces are uncontrollable but their effects can be controlled through use of coastal protective structures and implementation of coastal zoning. Changes in thermal characteristics of the lakes may modify the fauna, flora, and climate along the coasts. Plans for discharge of thermal wastes should account for these changes over short- and long-time periods. Thermal wastes might reduce localized damage problems by eliminating or shortening the period of ice cover. In the Great Lakes, regional steps must be taken to prevent undersirable faunal die-offs, algal blooms, and spread of pathogenic bacteria. In the future, unless steps are taken immediately to reduce waste inflow to the lakes, the consequence will be increased loss of shore-use areas by contamination.

11.2.4 Navigation

Factors that affect navigation on the lakes include basin morphology, lake levels, ice cover, sediment flux, surface waves, and wind. Natural forces can be accounted for in ship design. Maintenance of navigation channels as related to sediment flux and basin morphology can affect the lake ecosystem as can land use practices. Extension of the navigation season by ice breaking and ice retardation is presently being attempted. Before drastic changes are made in navigation practices and structures, however, effects of increased winter flows on lake levels, the lake thermal budget, and shore properties need to be assessed.

11.2.5 Fish and Wildlife

Fish and wildlife, including all elements of the organic community from plankton to neustonic waterfowl, are affected in many ways. Nearshore effects are most apparent. Sediment flux and turbidity affect solar radiation, a basic energy source; surface and internal circulation affects the accessibility of nutrients and, in the case of overenriched waters, the distribution of undesirable algae and heterotrophic organisms. Many minor taxa in lakes are stenothermal and may not be able to withstand excessive thermal loading. Undoubtedly the major stimulus in modification of the existing Great Lakes organic community comes directly or indirectly from influx of chemicals. Lake enrichment by phosphates, high BOD wastes, and nitrates can be reduced with advanced waste treatment. However, guidelines and standards must account for population increase and reflux of nutrients already assimilated into lake sediment. A critical threat to actual survival exists from toxic elements such as mercury, cadmium, arsenic, hexavalent chromium, selenium, and copper, and from toxic hydrocarbons, such as phenols, detergents, and pesticides. Toxic levels have not yet been reached in the Great Lakes for most of the known chemicals. However, some fish have been withdrawn from the market because they contain levels that exceed standards for human consumption, and bird populations suffer from pesticides ingested through predation on Great Lakes taxa. Other mortalities may result in all taxa through the synergistic effects of combinations of toxicants or through effects of toxicants combined with other stresses such as thermal enrichment or competition with exotic species. The introduction of exotic species may have positive or negative effects on the quality of Great Lakes fish populations. Caution should be exercised in allowing introduction of species as a management alternative.

11.2.6 Recreation

Recreational uses of the lakes include boating, fishing, water contact activities, and tourism. The hydrodynamic and hydrometeorological factors affecting use of the lakes include storms, waves, undesirable air and water temperatures, and turbidity. Little can be done in the open lakes to obviate these problems, but structural measures can be employed on a restricted basis inshore. Chemical wastes present problems such as increased turbidity; propagation of unsightly organisms such as algae; dead fish; undesirable fish; unpleasant odors; and oil slicks. Sediment flux and distribution may enhance or degrade bathing areas and probably will increase.

11.2.7 Power Generation

The lakes are used in hydroelectric, steam, and nuclear power generation. Levels and flows of the lakes and connecting channels govern the availability of water for hydroelectric power and are discussed in Appendix 10, *Power*, and Appendix 11, *Levels and Flows*. Thermally enriched discharge from steam and nuclear power plants is discussed in Section 6 of this appendix. The ultimate effects of local or regional increases in water temperature on changes in lake climate, water levels, chemistry, and biota is largely conjectural. Few problems with the availability of cooling water or boiler water are anticipated; the problem is with disposal. Use of thermally enriched water to locally enhance sport fishing and water contact activities needs to be considered as an alternative.

11.2.8 Waste Disposal

The capacity of the lakes to assimilate wastes has a limit based on volume and retention time. Upland lakes are particularly susceptible to chemical and biological loading from shore properties. It appears that with projected population trends, even currently accepted treatment levels may not improve lake water quality appreciably in the long term. In order to maintain existing conditions the level of treatment of wastes must increase as the population increases. Furthermore, management techniques must be developed to prorate waste discharges so that States adjacent to lower lakes will have water quality and waste disposal advantages similar to those above them in the lakes system. This will require a sliding standard for water quality. For example, although Lake Superior can assimilate much more loading before deterioration is noticeable, increased loading should not be allowed because the influx of high quality water from Lake Superior helps to maintain the quality of water in the lower lakes. From the opposite view, however, it can be argued that an increase in nutrient loading will increase lake productivity and aid fish production.

11.3 The Present Data Base as a Limnological Planning Tool

Although a casual overview may suggest that the data base in the Great Lakes is adequate for assessing planning alternatives, close scrutiny indicates that relatively few investigations contribute to an understanding of the large scale response of the lakes. A reason for the lack of systematic data necessary for fulfilling planning needs lies in the great cost inherent in obtaining a statistically sound, regional data set. For example, the costs of operating large research vessels are high and a number of such vessels or other instrument platforms is required over relatively long time periods to define the temporal and spatial characteristics of a lake. Consequently, the state of knowledge is limited to data collected primarily from local short-term or special-purpose surveys. A survey of papers and reports on the Great Lakes by area and subject through 1970 (Table 4–93) to identify data arrays that might be suitable for inclusion in systems analyses revealed both subject and geographical gaps in the data base. Lake Erie has been the subject of about half of the reports examined and most of these are restricted to the western basin. In decreasing order, studies on Lakes Michigan, Ontario, Huron, and Superior account for the other half. Of these studies, physical limnology, biology, and ecology have received about equal attention. Every lake, however, has significant gaps in the data base available from the literature.

One problem of using data from the literature is that it may consist primarily of summaries of the actual data that are not amenable to reinterpretation. Also, much of the massive data arrays collected by the Federal agencies have never been published or publication lags behind collection. It is apparent that a major data storage or data cataloging center must be developed for the Great Lakes area through which data can be obtained or sources identified. Success of that center will depend on the cooperation of the investigators, institutions, and agencies.

11.4 International Field Year for the Great Lakes

The International Field Year for the Great Lakes (IFYGL), a joint National Research Council of Canada and U.S. National Academy of Sciences contribution to the International

TABLE 4–93 Distribution of Great Lakes Studies by Area and Subject Exclusive of Taxonomic Studies

	Lake					
	Superior	Michigan	Huron	St. Clair	Erie	Ontario
% of Total	8	21	8	1	47	15
% Devoted to:						
Geochemistry	<1	1	1	0	6	3
Physical limnology & hydrology	2	13	4	0	15	6
Biology & Ecology	6	6	3	<1	17	5
Pollution	<1	1	<1	<1	9	1
% that are of possible regional significance	52	64	74	100	64	43

NOTE: See Table 4-58

Hydrologic Decade is an intensive effort to systematically study the hydrologic cycle, energy balance, and physical, chemical, and biological limnology of Lake Ontario and its drainage basin. The IFYGL has the potential to revolutionize data collection, reduction, and dissemination in the Great Lakes because, for the first time, regional synchronous data were taken over and within an entire lake with real-time retrieval. The data collection network consisted of buoys, coastal towers, oceanographic vessels, aircraft, satellite imagery, and inland hydrological and meteorological stations operating from April 1, 1972 through March 31, 1973. The data base, probably the most comprehensive ever on a lake, is available at Canadian and U.S. repositories. It will continue to be the subject of intensive analyses. In addition to exercising international and national cooperation at all levels the program provides a sound basis for development of regional resource plans. Bolsenga and MacDowall[78] give a detailed description of the IFYGL.

11.5 Limnological Systems Analysis

Underlying all of the water resource problems, planning decisions, and management programs, is a need for objective, rapid appraisal of projected trends, planning alternatives, and priority assignments, and a logical assessment of consequences. In 1969 the Great Lakes Basin Commission recognized this need and began a program to test the feasibility of developing mathematical models that simulate responses of the Great Lakes. These tools would be used in developing planning alternatives. A contract was let in January 1971 to determine the feasibility of developing the models, to evaluate the current data base, and to demonstrate the applicability of pertinent models to Great Lakes planning problems through development of a simple pilot model.

A description of the limnological systems analysis as a basic input to the proposed Great Lakes Environmental Planning Study is summarized as follows (Great Lakes Basin Commission[299]):

> The major objective of a Great Lakes Limnological Systems Analysis Program is to develop a model or models of the physical, chemical and biological processes in the Great Lakes in sufficient detail to enable planners, engineers and economists to assess the consequences of alternative planning and resource development strategies. The models developed in the first cycle will serve as planning aids for formulating and modifying optimum and suboptimum coordinated plans for the water and related land resources of the Great Lakes. . . .
>
> Input data to the Limnological Systems Analysis models should include runoff variables critical to the environment. The operation of the models with these inputs, using appropriate physical, chemical, and biological functional relationships, will yield output appropriate to the evaluation of the economic and aesthetic goals of the Commission. The variables selected for output from the model(s) will be environmental rather than economic in dimension.
>
> The physical boundary . . . will, for the time being, be limited to the lakes system proper. The design of the Limnological Systems Analysis models will be such that at some future date the systems analysis can be expanded into the tributary drainage basins. There may also be expansion into the areas of cultural and political input for optimization of overall use of the water and related land resources. . . .
>
> The systems may comprise a series of models, concerning separate problems of the basin, i.e., hydrodynamic, water quality and ecology, and others. These models must be modular and must be compatible for an integrated usage if multiple models are considered feasible. . . .

The program, by estimating the magnitude of effect and extent of imbalances on the natural system caused by variation in input, or modification of chemical, physical or biological parameters, will enable some specific resource planning problems of the Great Lakes to be examined, such as:

(1) Long and short-term variations in water quality and improvement of the total natural system by control of a segment of the environment.

(2) Projected effect of cultural and industrial development on the water resources system under present practices.

(3) Relationship of waste discharges to sport and commercial fisheries on the Great Lakes in current and projected time frame.

(4) Effect of water level fluctuations and related phenomena on shore properties throughout the Great Lakes.

In the planning process the models will aid in examining problems of effective water resource utilization through the assessment of alternatives leading to solutions and problems such as:

(1) Coordinated use of the Great Lakes by multiple competing interests.

(2) Accurate assessment of water quality and quantity in current and projected time frame.

(3) Optimum depth of navigation channels for most economical relationship between maintenance and development of shipping capability.

(4) Assessment of recreational use of the Great Lakes in current and projected time frame.

(5) Proposed management of the Great Lakes Basin leading to a desired balance of the ecosystem.

(6) Improving the quality of the Great Lakes or portions thereof through waste treatment and lake restoration programs.

The level of detail necessary for utilizing . . . [model] output . . . for planning purposes will be less stringent than that required for operation[s] and . . . management. . . . For purposes of . . . [Level B] detail, assumed relationships may be usable, but . . . the adequacy of such relationships [must be evaluated] for operation and management purposes. . . .

One of the primary objectives of the Systems Analysis Study is to bring together in a systematic manner all of the pertinent data and results of studies developed through research and investigation by many universities, States, Federal agencies and others. The development of a model for the Great Lakes will also tend to bring together in an orderly fashion various systems analysis studies underway, or proposed for study, in various areas of the Great Lakes.

Design of the models will be such that interactions between the operation and design models of Federal and State agencies, industrial and municipal resource users, and research institutions can be tested, and regional, long-term results obtained. For the first time State and Federal agencies will have a common link in an objective system that can allow testing of individual actions against multifple diverse interests. In addition, scope and intensity of data collection can be designed to be responsive to regional problems, based on data sensitivity determinations from the pertinent models. The result will be greater understanding, cooperation, and mutual benefit for the Great Lakes Basin Commission and other water-resource users.

11.6 Lake Restoration

One element of a comprehensive list of national priorities recommended by the Commission on Marine Science, Engineering and Resources[160] is a water quality restoration project in the Great Lakes. The restoration program was to consist of three phases: stop influx of pollutants; test the feasibility of reducing damage already done; and if feasible, institute an action program to restore the lakes. The projected cost of the program was $15 million annually for the period 1971–75, and a projected $20 million annually for 1976–80, for a total of $175 million. The program was adopted in concept by the Administration and listed as a priority national project. Since that time the lake restoration project has been altered to a program of restoration studies for all lakes in the nation. The concept that smaller lakes, particularly lakes in the southeast, can be studied and extrapolations made to the Great Lakes has altered the original intent of the program. Few of these extrapolations are applicable. Lakes prototypical to the Great Lakes should be similar in distribution of photic and profundal zones, and have two seasons of stratification and mixing, ice cover, equivalently constructed aquatic ecosystems, and similar sedimentological and chemical systems. There are no such equivalent lakes in the United States. Although restoration studies of upland lakes are vital, if the ultimate goal is deceleration of eutrophication processes in the Great Lakes, then the original intent of the Commission on Marine Science, Engineering and Resources needs to be reemphasized.

The restorative phase should be an International-Federal-State cooperative endeavor with several concurrent steps. A three- to five-year planning and feasibility study period is needed, during which smaller Great Lakes Basin lakes, such as Lake St. Clair, the Finger Lakes, or Lake Winnebago, are used to test alternatives. At the same time, mathematical modeling and intensive data collection should be implemented on the Great Lakes, while phase 1 preventive programs are continued, and socio-political arrangements are fashioned to accommodate the chosen restoration techniques and trade-offs that must result. An extended period of action follows the feasibility period. The action must be dynamic to account for increased stress on the lakes from population growth, industrialization, utility development, and recreation/leisure-time demands.

11.6.1 Lake Restoration Techniques

Knowledge of lake restoration techniques is based largely on test cases conducted on small lakes in North America and Europe. The applications have met with varying degrees of success (Table 4–94). Treatment techniques may be classified as external or as internal (Table 4–95).

External treatment consists of measures applied in the drainage basin of a lake that will reduce the rate of pollution input. These generally align with the initial or preventive phase of lake restoration. The following are basic external treatment techniques:

(1) Runoff diversion is diversion of tributaries or runoff from watershed areas of poor quality so that the pollutant load bypasses the lake.

(2) Soil conservation reduces sediment loss and increases water and waste retention on the drainage basin so that natural waste assimilation and recycling can be accomplished.

(3) Runoff treatment involves conventional waste treatment of natural and agricultural runoff.

(4) Control of chemical additives can cause reduction of phosphate, organic fertilizer, and pesticide influx by conservative use on the watershed and by selection of biodegradable chemicals.

(5) Sewage diversion uses the same principle as runoff diversion by bypassing a lake with municipal and industrial wastes.

(6) Waste treatment reduces pollutants by advanced sewage treatment before their discharge into the lakes. This is the first or preventive phase of lake restoration.

(7) Flow augmentation increases tributary discharge by releasing water from reservoirs during low flow or heavy pollutant loading periods. This technique is applicable to rivers and small lakes, but the residence time of water in the Great Lakes makes this an unworkable alternative.

The internal treatment technique has been successful in small lakes. However, applicability of these techniques to the Great Lakes is probably limited to restricted bays and estuaries. Internal treatment techniques are basically the following:

(1) Plant harvesting is the physical removal of aquatic weeds and algae to reduce sedimentation, BOD, and nutrient recycling.

(2) Chemical treatment with herbicides or toxicants controls unwanted flora and fauna. Treatment with flocculants precipitates solids and nutrients, but flocculants have the disadvantage of being nonspecific; so desirable faunal elements may be affected.

(3) Dredging is the physical removal of sediment and BOD-creating organic debris.

(4) Mechanical destratification destroys the thermocline to allow reoxygenation of hypolimnetic water and increased assimilation and dilution capacity. Destratification is accomplished by stirring or bubbling.

(5) Morphological modification by dredging or structural modification alters circulation patterns or flushing characteristics.

(6) A few small lakes have been partially drained by pumping. Pump discharge is allowed to recycle to the lake by percolation through the ground where soil minerals and taxa can remove the undesirable constituents.

(7) Biomanipulation is the introduction or encouragement of certain taxa to reduce an undesirable constituent and/or create a resource.

(8) Bottom sealing is done by using sand, clays, plastics, and other materials to form a barrier at the sediment-water interface to isolate high BOD organics and nutrients in bottom sediment from potential interaction with the water column.

(9) Thermal manipulation by selective introduction of heated or cooled water may alter circulation or reduce stratification. Anticipated effects are the same as those in item 4.

Some of the treatment techniques have already been used in the Great Lakes. Diversion of the Chicago River system into the Illinois River watershed is an example of runoff and sewage diversion. This technique has drawbacks in that the lake levels may be affected and the wastes are not eliminated, but only passed on to other areas. Lampricides, which have been used with some success in the Great Lakes Basin, are an example of chemical treatment.

Potentially feasible restoration techniques in the Great Lakes were reviewed by Battelle Northwest.[43] They concluded that restoration of the Great Lakes is possible and recommended the following steps:

(1) Identify the economic criteria that can be quantified in order to evaluate the costs and benefits associated with various treatment alternatives.

TABLE 4–94 Examples of Lake Restoration

Restoration Technique and Lake	Location	Effectiveness	Reference
WASTE TREATMENT			
Annecy	France	Eutrophication slowed	Laurent, et al., 1970
Leman	France	Eutrophication continues	Laurent, et al., 1970
Vattern	Sweden	Turbidity reduced	Scandinavian Times, 1970
Shagawa	Ely, Minnesota	EPA Test Project	Brice & Powers, 1969
Stone	Cass County, Michigan	No change to date	Tenney, et al., 1970
INTRODUCTION OF FORAGE FISH			
Clear	California	70%-80% decrease in algae	Civil Engineering, 1970
DIVERSION OF WASTE EFFLUENT			
Annecy	France	Eutrophication slowed	Laurent, et al., 1970
Monona	Madison, Wisconsin	N & P decreased, little decrease in algae	Lee & Fruh, 1966
Nantua	France	Some success	Laurent, et al., 1970
Washington	Seattle, Washington	P decreased, N shows little decrease, algal declines	Edmondson, 1970
Waubesa	Madison, Wisconsin	(see Lake Monona)	Lee & Fruh, 1966 Mackethun, 1965
AERATION			
Cox Hollow	Wisconsin	DO increased, constituents oxidized	Brezonik, et al., 1970
DESTRATIFICATION			
Boltz	Northern Kentucky	Water quality improved; algal productivity increased	Symons, et al., 1970
Falmouth	Northern Kentucky		Symons, 1969
Vesuvius	Southern Ohio		
DILUTION WITH NUTRIENT-POOR WATER			
Green	Seattle, Washington	Definite improvement	Oglesby, 1968
Bled	Yugoslavia	Definite improvement	Sketeli & Rejic, 1963
DREDGING			
Green	Seattle, Washington	Definite improvement	Oglesby, 1968
Carlinville	Illinois	Sediment removal	Roberts, 1969
HERBICIDE APPLICATION			
Multiple examples	Various	Effect varies	Holm, et al., 1969
ALUM TREATMENT			
Bangsjon	Stockholm, Sweden	P reduced	Jernelov, 1970
Horseshoe	Wisconsin	Temporary improvement	Univ. of Wisconsin & Wisconsin Department Natural Resources, 1970
PUMPING WITH GROUND-WATER RECHARGE			
Snake	Wisconsin	Apparent success	Univ. of Wisconsin & Wisconsin Department Natural Resources, 1970
SOCIAL-POLITICAL ACTION			
Wolverine	Michigan	Indeterminate	Huron River Watershed Council, 1970
Zurich	Switzerland	Apparent success	Thomas, 1962
TREATMENT WITH FLY ASH			
Stone	Michigan	Temporary improvement	Tenney & Echelberger, 1970

(2) Implement measures to prevent further water quality deterioration.

(3) Implement techniques to restore the quality of those portions of the Great Lakes that are presently impaired.

(4) Designate a lead agency to coordinate the agencies and organizations that are concerned with Great Lakes water quality and to implement and manage restoration plans.

Water quality deterioration in the Great Lakes was attributed by Battelle Northwest[43] to the following causes, in order of decreasing impact:

(1) High Impact

TABLE 4–95 Application of Lake Restoration Techniques to Specific Water Quality Problems

	Nuisance Algal Growth	Nuisance Aquatic Vegetation	Fishkills & Bacteria Decline	Bacterial Contamination	Toxicant Contamination	Oil & Brine Contamination	Unstable Water Levels	Siltation & Excessive Sediment	Excessive Dissolved Solids	Undesirable Biotic Elements	Undesirable Solid Wastes
Diversion of Urban Storm Runoff	B	B	B	B	B	B	S	B	B	-	S/E
Diversion of Rural Storm Runoff	B	B	B	B	B	B	B	B	B	B	-
Sewage Diversion	B	B	B	B	B	-	-	S/E	B	B	B
Algal Harvest	S/E/A	S/E/A	S/E/A	-	S	-	-	S	-	B	-
Use of Growth Inhibitors	B	B	A	B	A	-	-	A	A	A	-
Flow Augmentation	S	S	S	S	-	S	S	A	A	A	-
Dredging	S/E	S/E	A	-	S/E	S/E	-	S/E	S/E	S/E/A	S/E
Advanced Waste Treatment	B	B	B	B	B[1]	B	-	-	B	B	B
Herbicide Treatment	S/E	S/E	A	S/E	A	-	-	A	A	B/A	-
Treatment with Other Pesticides	A	A	A	S/E	A	-	-	A	A	B	-
Destratification	S/E	-	S/E	S/E	-	-	-	-	-	S/E	-
Harvest of Aquatic Weeds	S/E/A	S/E	S/E/A	-	S	-	-	S/E	S/E/A	S/E/A	-
Intensive Soil Conservation on Drainage Basin	B	B	B	B	B	-	-	B	B	B	-
Chlorination of Storm Runoff	-	-	B	B	-	-	-	-	A	-	B
Pesticide Control in Basin	B[1]	B[1]	B	B[1]	B	-	-	-	B[1]	B[1]	-
Morphology Changes To Increase Flushing	S/E	S/E	S/E	S/E	-	-	A	A	A	S/E	-
Public Action Group Activity	-	-	-	-	-	S/E	-	-	-	-	B
Control of Feedlots	S/E	S/E	S/E	S/E	-	-	-	S/E	S/E	-	-
Exchanges of Septic Systems for Sewage Treatment	B	B	B	B	B	-	-	-	B	-	-
Mechanical Aeration	B[1]	-	B[1]	-	-	-	-	-	-	B[1]	-
Impede Light Penetration	B[1]	B[1]	B[1]	-	-	-	-	-	-	B[1]	B[1]
Lime Treatment in Lake	-	-	S[1]/E[1]/A	-	S[1]/E[1]/A	-	-	-	A	-	-
Alum Treatment in Lake	S/E/A	S/E/A	S/E/A	-	-	-	-	-	A	-	-
Pumping with Ground Water Recharge	S	S	S	S	S	-	-	S[1]	S	-	-
Specific Treatment for Limiting Nutrient	B	B	B	B	-	-	-	-	B[1]	B	-
Introduction of Consuming Organisms	B	B	B[1]	B[1]	-	B[1]	-	-	-	B	-

[1]Although potentially effective, technique not designed for treatment of problem.

S = May be suitable for small upland lakes.
B = May be suitable for both upland lakes and Great Lakes.
E = May be suitable for Great Lakes embayments.
A = May have adverse effects on a water-quality problem.

(a) municipal wastewater
(b) agricultural runoff
(c) sediment interchange
(2) Medium Impact
(a) industrial wastewater
(b) combined storm sewage
(c) urban land drainage
(d) dredging
(e) tributary inflow
(f) fisheries considerations
(3) Low Impact
(a) watercraft wastes
(b) oil discharges
(c) thermal discharges
(d) waterfowl
(e) subsurface disposal
(f) atmospheric quality deterioration.

In addition to adherence to Federal water quality recommendations, Battelle Northwest[43] suggested that the following be implemented to restore lakes:

(1) Maximize nutrient removal from municipal wastewater.
(2) Improve land management practices to eliminate agricultural runoff.
(3) Subject maximum amounts of combined storm sewage to secondary treatment and design all future sewer systems with separate storm and sanitary sewers.
(4) Cease all disposal of dredgings, garbage, trash, and refuse into the lakes.
(5) Remove rough fish and harvest desirable fish to the maximum feasible extent.
(6) Harvest aquatic weeds and isolate the nutrients contained therein from the lakes.
(7) Treat watercraft wastes to the equivalent of secondary treatment.

It is obvious that five of the seven measures are preventive and only two are restorative actions.

It is apparent that for overall treatment of the Great Lakes only the preventive or external techniques which have been tested are economically feasible; additional alternatives must be developed. Application of the other alternatives to specific problems may be economically and physically expedient. Consequently, the primary thrust of the lake restoration program in the early or preventive stage of development must be a combination of soil conservation, control of chemical additives, and waste treatment. The first two techniques are well understood and, although specific implementation methodologies should be developed, the major obstacles to implementation are legislative and economic. Techniques for advanced waste treatment are also available, but are costly. Low cost treatment plans are needed to augment conventional waste treatment designs.

One problem that is evident from the loading studies in Section 7 is the effect of treatment on present chemical loads. If the load estimates by Upchurch[807] are accurate, then present external treatment criteria may be too low to achieve an improvement in water quality. For example, lake enforcement conferences have suggested 80 percent phosphorus removal as an achievable goal. In order to reduce primary production to the point that algae cease to be a problem, phosphorus, or some other nutrient, must become a limiting nutrient. Studies with chlorides indicate that 80 percent removal of man-made wastes, which is practically impossible because agricultural runoff is included in this category, will allow reasonably good reduction of wastes in Lakes Erie and Ontario, but will only sustain existing conditions in Lakes Huron and Michigan. Therefore, although 80 percent removal of phosphorus is a necessary first step in lake restoration, improvements in waste treatment are needed for more effective nutrient removal. A few simple projections can also be made regarding phosphorus. Oglesby[587] studied the effects of flushing Green Lake, Seattle, Washington, with nutrient-poor water. After a period of time equivalent to replacing the lake water five times, an improvement in those water quality criteria linked to phosphorus was noted. This implies that phosphorus bound in the sediment was either isolated or released upon cessation of waste inflow. It also took five times the water replacement time to remove a sufficient amount of the active, bottom-sediment phosphorus to establish a new equilibrium with the water and thus effect the noted improvement. If results from this small lake were projected to the Great Lakes, phosphorus reduction to the concentration required to improve phosphorus-linked water quality criteria would be in the range of 15 to 950 years, based on retention times given for the Great Lakes in Subsection 7.8.4. Uncertainties in projecting from small to large lakes have already been cited and there is evidence (Gumerman[307]) that, at one extreme, Lake Superior may require no water replacement while, at the other extreme, Lake Erie may require many more than five cycles. Times could be open to question with nonconservative constituents, but the principle is valid and must be considered. Since Lake Superior has no problem with overproductivity, only Lake Michigan, with a water residence time of 100 years, would not benefit from phosphorus control over a short period of time.

Greeson[301] summarized the literature on requirements for algal growth. His conclusion was that from 0.002 to 0.090 mg/l of phosphorus is sufficient for algal production. If this is the case, then the maximum loading of phosphorus into a lake for limitation of primary production can be estimated. For example, Figure 4–178 indicates a maximum of 0.005 mg/l phosphate (equivalent to about 0.002 mg/l) in northern Lake Michigan. If this is assumed to be the maximum allowable phosphate content in a phosphorus-limited system, then the ideal phosphate concentration throughout Lake Michigan should be 0.005 mg/l. Assuming that inflow equals outflow and assimilation is at a steady state, the maximum annual loading can be no more than the product of annual outflow and the concentration of phosphate or

$$(3.7 \times 10^{13}\text{l})\,(5 \times 10^{-9}\text{kg/l}) \sim 2.34 \times 10^{5}\text{kg of P}$$

Any excess over an annual load of 2×10^5kg of phosphate is, therefore, assimilated by plants and becomes excess productivity or is stored in sediment. Upchurch[807] (Section 7) estimated an annual phosphate load in Lake Michigan of 110×10^5kg. To reduce that load to 2×10^5kg would require approximately 98 percent removal, which is the same order of reduction suggested by Vollenweider.[864] Ninety-eight percent removal would require treatment far in excess of that anticipated by present planning. The loading estimates published by the U.S. Army Corps of Engineers, Buffalo District[811] (Tables 4–52, 53, and 54) are even higher and indicate even more treatment.

Another important consideration in external treatment for Great Lakes restoration is the role of limiting nutrients. Kuentzel[478] suggested that phosphorus reduction may not be feasible because it is already present in excess in most lakes; therefore, it no longer serves as a limiting nutrient. He suggests that BOD and organic waste control be a goal in lake restoration. Nitrogen is thought to be a limiting nutrient in certain coastal marine environments and should be considered in the control of plant production in the Great Lakes. Abbott[1] has suggested that other constituents besides phosphorus, nitrogen, or carbon could be limiting. Abbott postulated that vitamins or metals may limit productivity in some systems. If controls combining the best existing technology with clean water objectives are instituted, these controls should consider phosphorus, nitrogen, organic wastes and other carbon sources, trace metals, and other macro- and micronutrients as limiting factors within the limnological system and limit their concentration if technologically feasible.

Chemical control on the watershed must be strictly enforced and supported by an active research program. Many commonly used chemicals, particularly organic chemicals such as most pesticides have been shown to damage terrestrial as well as aquatic ecosystems. In combination with loss of heavy metals to the aquatic environment, these chemicals may pose the ultimate threat to the lake system. Restoration can begin immediately with control over or prohibition of chemicals known or suspected to be harmful.

In broad terms lake restoration should be directed toward the restoration of water quality to some desired level and improvement of the total environment for the maximum benefit to the population. Feasibility of any technique must be tested at the lake scale, and the relationship of effects on the total system must be determined. The entire approach to lake restoration must be based on the concept that restoration is not merely a process that arrests factors which cause degradation of a lake; rather, restoration consists of varied approaches aimed at rejuvenation or reversal of existing trends.

Section 12

SUMMARY AND RECOMMENDATIONS

12.1 Current Status of the Great Lakes

The Great Lakes are in danger of irreparable damage from the introduction of wastes of one kind or another. At the present time the quality of the lakes is such that simply maintaining them at present quality levels will be a major task in view of increasing population, industrialization, urbanization, and leisure time available for lake use. Restoration of the lakes to some desired earlier level of quality is technically feasible, but requires a willingness on the part of the people to support long-range, large-scale, costly programs.

12.1.1 Lake Superior

Lake Superior is essentially oligotrophic and shows no overall change in quality in the last century. Its large total volume and the large volume of hypolimnion make the lake insensitive to wastes that are currently being introduced. Local problem areas of varying scales do exist in Duluth and other urban areas, in mining regions north of Duluth, in the Keweenaw Peninsula region, at paper mills, and at other industrial waste outfalls throughout the basin. One problem that may arise in the near future is the loss of toxic elements from some of those industries. Introduction of taconite into the lake north of Duluth is considered to be a hazard and litigation is under way to remedy the problem. The fishery has changed as a result of man's activities, but there appears to be little change in other aspects of the biota. Fishery changes include the introduction of smelt and the decline of lake trout and whitefish coincident with modified fishing practices and the introduction of the sea lamprey. Lamprey control, restocking with lake trout, and the introduction of salmon will cause further changes in the fish population and presumably an improvement in use of the resource.

12.1.2 Lake Michigan

Major environmental deterioration is not yet evident in the major part of Lake Michigan. However, Green Bay and portions of the lake south of a line from Milwaukee to Muskegon are deteriorating. The flow-through time for Lake Michigan is slow, so wastes introduced into the lake have a tendency to remain there. The large volume gives it a great capacity to assimilate inputs, but unless rapid and comprehensive action is taken to reduce waste introduction, this capacity will soon be exceeded. Population growth in the Lake Michigan basin is projected to continue. Due to the increased population and waste loads, maintenance of lake water quality and restoration will become disproportionately more difficult without adequate treatment. Present problems include increasing concentrations of nutrients and other dissolved constituents, oxygen depletion in Green Bay, near oxygen depletion in many harbors under ice cover in the southern basin, heavy chloride concentrations near Manistee and Ludington, oil spills, overproduction of algae, and fish-kills. Relative abundances of planktonic and benthic species have changed, and several new species have appeared in the lake. In Green Bay and other restricted areas most of the normal, oligotrophic biota have been replaced by pollution-tolerant species. Fish populations have changed radically. Lake trout have ceased to be important and the introduced smelt, carp and alewife have become major members of the total catch. With the predation of the sea lamprey on the trout, smelt, carp, and alewife have had few natural predators to control their numbers. Introduction of salmon into Lake Michigan seems to have alleviated this problem, and with an active lamprey-control program trout are also again becoming major predators on the "trash fish." Management of the Lake Michigan fish population can be instrumental in achieving a desired ecological balance, but only if the water quality of the lake is not allowed to deteriorate.

12.1.3 Lake Huron

Most of the inflow to Lake Huron is from Lake Superior and the upper, relatively unaffected part of Lake Michigan. Therefore, Lake Huron displays many of the same characteristics as Lake Superior. Water quality has not changed greatly in the last century. However, Saginaw Bay and the heavily used harbors do show strong evidence of excess waste loading. Because of the large volume of the lake, these loads have little effect on the open lake north of Saginaw Bay. As population pressures increase in the Lake Huron, Superior, and Michigan basins, the quality of Lake Huron water can be expected to deteriorate. Pollution-generated stresses on the biota in Saginaw Bay have caused major changes. Fisheries throughout the lake have changed as well. Carp have been introduced, and lake trout and walleye have been reduced in importance, presumably in response to sea lamprey predation and poor fishing practices. Introduction of salmon and lamprey control measures have had the same effects as in Lake Michigan.

12.1.4 Lake St. Clair

Little is known about Lake St. Clair even though the lake is relatively small and is adjacent to a major urban area. Influx of water from Lake Huron coupled with rapid flushing controls the overall quality of the lake. The greatest problem in Lake St. Clair is the influx of municipal and industrial wastes from the surrounding area. This influx also constitutes a portion of the contamination introduced to Lake Erie via the Detroit River. The wastes include excess nutrients and high BOD organic wastes. Toxic metals, including but not restricted to mercury, are known to be introduced both upstream and downstream from the lake. Removal of these toxic materials from the lake will continue to be a problem even after cessation of waste introduction, but it must be addressed if Lake Erie water quality is to be improved.

12.1.5 Lake Erie

Lake Erie has the greatest need for restoration. Restoration is possible within a few decades if decisive action is taken. Problems stem from the interaction of four factors: the bedrock of the lake and the drainage basin contain natural pollutants; the lake basin is extremely shallow and contains only two percent of the water in the Great Lakes system; a major megalopolis has developed along the American shore; and the lake receives polluted water from upstream areas. Restoration of Lake Erie must include adequate action in Lake Michigan and Lake Huron to achieve acceptable water quality. Problems in Lake Erie include overenrichment with nutrients and concommitant algal growth, turbidity, deoxygenation in the central basin during summer, toxic element contamination, inadequate shore-use control, and loss of habitats necessary for removal of nutrients and development of a stable biota. Increases in the concentrations of most constituents due to population and industrial growth have been dramatic in the past and will continue if unchecked. The biota has undergone drastic changes and consists primarily of pollution-tolerant taxa. Although the fish catch is still the largest in the Great Lakes, many desirable species have been reduced or disappeared. Critical areas in Lake Erie include most of the western and central basins, and segments adjacent to the large metropolitan areas. Many harbors are incapable of supporting desirable life of any sort.

12.1.6 Lake Ontario

Although most of the water in Lake Ontario comes from Lake Erie and the Toronto-Hamilton area introduces pollutants, the lake is in somewhat better shape than Lake Erie due largely to the volume to surface ratio of the lake coupled with a relatively short water replacement time. Even so, the poor overall water quality must be improved. This can only be accomplished through action in both the upstream lakes and in the Lake Ontario basin itself. Primary problems in Lake Ontario reflect the influence of Lake Erie, and include the buildup of chemical constituents and nutrient supply. Major problem areas are the urban-industrial complex from Hamilton to Toronto, Canada, and Rochester, New York. Projected problems include further overenrichment and toxic element contamination near the two urban areas. Biotic changes, including fisheries, have been as drastic as those in Lake Erie.

12.2 Future Needs

This appendix has shown basic needs in two areas. First, there is a need for a basic data, multidisciplinary integration of the data, and definition of fundamental responses and relationships that describe the limnological processes in the lakes. Secondly, there is a need to develop and implement institutional arrangements, restoration techniques, optimum resource-utilization plans, and monitoring systems in order to improve and/or maintain the viability of Great Lakes Basin lakes as resources.

To better understand the chemical, physical, and biological processes that operate in the Great Lakes in order to accomplish goals and objectives as described in this appendix, the following areas of research should be emphasized.

12.2.1 Water Motion

(1) Study the directional characteristics of wind waves to define temporal and spatial aspects of the generation, growth, and decay of wind-wave spectra.

(2) Study air-water interactions to understand the nonlinear energy transfer from winds to waves, and from waves to waves.

(3) Develop instruments to measure wind stress, turbulence, and atmospheric pressure fluctuations at the lake surface. Incorporate these measurements with wind-wave and long-period wave studies.

(4) Conduct theoretical, experimental studies of long-period waves, using the hydrodynamic equations with nonlinear terms included. Study the effects of earth rotation, bottom friction, and density stratification.

(5) Develop instruments to measure pressure fluctuations at the lake bottom for lake-scale synoptic monitoring of variations of surface motions.

(6) Study the genesis, transmission, and extent of water-level oscillations having periods of five minutes to several hours.

(7) Describe open-lake circulation and its interaction with nearshore currents to determine the response and decay of both current types.

(8) Improve techniques to measure currents for harbor flushing determinations, lake circulation, and mass transport.

(9) Determine water temperatures of tributaries and of lakes since lake stratification can alter the current regime.

(10) Use techniques for multispectral sensing in the visible and thermal infrared spectrum for identifying, measuring the extent of, and tracing movements of water masses.

12.2.2 Hydrometeorology

(1) A comprehensive study of the heat energy budget of the entire Great Lakes is necessary if improvements are to be obtained for predictions related to hydrometeorology. The use of existing facilities and instrument networks and the IFYGL program can become the basis for a study of this kind.

(2) The use of buoy stations for monitoring water temperature profiles and meteorological parameters and the use of remote infrared sensors to detect and trace areal temperature distributions should be investigated. Data collection must extend over a period of time long enough that valid statistical analyses can be made and data collection techniques evaluated. Knowledge of winter temperature structure of the lakes is necessary for energy budget determinations and for gaining a complete understanding of ice cover growth and decay.

(3) Heat budget studies of the lake as a part of ice forecasting require data on the areal extent, distribution, thickness, and structure of lake ice. Because of the technological advances in instrumentation for remote sensing, both in the active and passive phases, data on the quantity and quality of ice accretion and distribution can now be gathered, and in-depth synoptic pictures of ice cover can be made.

(4) The effect of thermal discharges on the lakes needs to be assessed. The added heat affects evaporation, extent and period of ice cover, and other hydrometeorological factors in the immediate discharge area, but the long-term, lake-scale effect of these inputs in unknown.

(5) The effects of ice cover on the biological characteristics of the lakes should be investigated, because changes in the extent or time of an ice cover will affect the biological system.

(6) Greater or lesser amounts of ice mean a greater or lesser degree of retardation to the flow in the connecting channels. The long-term effect of a modified period of ice cover on lake levels must be determined.

(7) The relationship between over-land and over-water meteorological variables needs to be determined. Clarification of these relationships would allow the utilization of on-land

data, which are easier and more economical to obtain.

(8) A set of terms and definitions must be compiled for lake ice. Some terms have diverse meanings and almost all are a carry-over from sea ice. These terms should be redefined, and if necessary, new ones should be introduced to create an effective classification of Great Lakes ice.

12.2.3 Chemistry

(1) Detailed, synoptic assessments of water quality, including major constituents, trace elements, toxicants, and organic chemicals must be made at meaningful frequencies.

(2) Winter collection of water and sediment chemical data must be implemented.

(3) A survey of potentially hazardous chemicals must be implemented. Special emphasis should be given to organic pesticides, and heavy metals such as selenium, arsenic, hexavalent chromium, cadmium, zinc, iron, copper, tin, cobalt, nickel, lead, boron, and manganese.

(4) Sediment-water interactions that remove contaminants from the lake water and the kinetics of the reactions need to be determined. Techniques to insure chemical isolation of the sediment without injuring the system need to be developed as does a lake restoration technique.

(5) Water quality standards for the Great Lakes need to be continually reevaluated to insure equitable use of the system to all parties and to insure future water quality.

(6) Contributions of constituents to and from ground water must be identified.

(7) Accurate assessments of chemical loads to the lakes must be made. Data presented in Section 7 suggest that waste treatment objectives are too low. Accurate load evaluation is the key to proper waste load allocation.

(8) For lake restoration, a study of limiting factors for algal production and treatment levels is needed. Treatment systems must be multipurpose in order to remove phosphates, BOD, toxicants, and other, yet to be identified, pollutants.

(9) An enforcement program should be implemented to identify sources of waste discharge. The feasibility of chemical tracers, unique to a specific company and required by law, should be investigated. Michigan presently identifies point discharges to its surface water.

(10) Coordination should be established between basin planners, agricultural interests, urban interests, and Great Lakes research groups to assure soil conservation, control of chemical additives, and waste treatment levels that are adequate for lake management objectives.

(11) Contingency plans for oil spills and wellhead losses should be developed and the treatment activities should be practiced.

12.2.4 Biology

(1) The role of bacteria and fungi in nutrient cycling should be emphasized, particularly with regard to the influence of specific environmental factors such as pH, oxidation-reduction potential, temperature, specific chemical pollutants, and symbiotic relationships.

(2) Effect of mechanical disruption of lake thermal stratification on bacteria and fungi should be a part of the evaluation of this technique as a treatment for summer anoxia in the hypolimnion.

(3) In view of the apparently high BOD in Lake Erie and other lakes, and the apparent changes induced in bacterial and fungal populations by temperature changes, the potential increase in the available nutrient supply through thermal enrichment should be estimated.

(4) The development of improved culturing techniques for some of the more obscure groups of bacteria and fungi is essential. Culturing techniques should be standardized to facilitate comparison of results.

(5) Fecal coliform counts should replace the total coliform analysis as an index of domestic pollution. Counts of total bacteria should be employed as a measure of total available organic matter.

(6) Levels of pathogenic bacteria and viruses should occasionally be determined as a check on the validity of the coliform index. If techniques for these analyses become less tedious and expensive, they should become routine.

(7) In addition to infectious diseases, a threat to human and wildlife health and life exists from the toxic products of certain bacteria and fungi, notably botulism toxin and alfatoxin. Occurrence of these toxicants in the Great Lakes should be routinely investigated.

(8) The organisms involved in producing undesirable tastes and odors in drinking water supplies may be bacteria and fungi rather than plankton. Control of this problem

requires study of the occurrence and metabolism of the organisms involved.

(9) Precipitation of phosphates into the sediments is not recommended as a means of reducing plankton growth in view of the ability of bacteria and fungi to resolubilize phosphates.

(10) The zooplankton and zoobenthos of the Great Lakes are of interest to planners and policy-makers primarily as indicators of environmental quality and as intermediate members of the aquatic food chain. The environmental quality approach to management requires a fundamental understanding of the components of the system. Before Great Lakes ecosystems can be properly managed there must be increased understanding of the components, including the zooplankton and zoobenthos. The literature on invertebrates of the Great Lakes is extensive, but this review reveals gaps that will inhibit systems analysis.

(11) The zooplankton and zoobenthos of the Great Lakes are incompletely catalogued. Further distribution studies are needed.

(12) Great Lakes researchers should establish guidelines for sampling and processing the zooplankton and zoobenthos similar to the International Biological Programme handbooks so reasonable comparisons can be made. If nothing else, standard units for reporting data should be adopted.

(13) The taxonomy of zooplankton, phytoplankton, zoobenthos, and phytobenthos is not completely established. The low level of support that systematics has received directly inhibits the progress of Great Lakes ecology; so support needs to be increased.

(14) Changes in the zoobenthos, phytobenthos, zooplankton, and phytoplankton of the Great Lakes are probably the result of compositional changes, but climatic changes may also have had an effect of undetermined significance. Baseline information on planktonic and benthic taxa must be obtained so that there will be a basis for comparison with future studies.

(15) Algae in the Great Lakes are of considerable interest to planners and the general public because they directly affect daily lives. The varieties and abundance of algae needed to maintain the desired fisheries while minimizing the problems associated with the overabundance of algae must be determined.

(16) Phytoplankton can be used as indicators of general trophic conditions in the Great Lakes. More studies are needed to validate and possibly simplify trophic indices and expand their usefulness in managing the Great Lakes.

(17) Because of their immobility benthic and periphytic algae should be reliable indicators of local pollution. Their usefulness as local indicators needs to be applied to lakes, as opposed to streams, where most of the existing studies have been made.

(18) The most direct index of the trophic state of the lakes is the estimation of annual primary production through the measurement of algal photosynthesis. Conventions on methods and units for studying and reporting phytoplankton crops and productivities must be established.

(19) The main inorganic nutrients contributing to algal growth in the Great Lakes are phosphorus, nitrogen and carbon, although silicon may be limiting to diatoms in the more eutrophic lakes. To achieve desired goals control measures should seek to reduce the input of nitrogenous and carbonaceous compounds as well as phosphorous organic matter and its decomposition products in general.

(20) Fish species composition, trends in species abundance in selected areas, locations of spawning areas, location and distribution of eggs and larvae of various species, feeding habits in different areas for the various species, improved appraisals of sport and commercial fish landings, and distribution and effects of introduced fish species need to be investigated and catalogued.

(21) Bioassay work on Great Lakes taxa in Great Lakes environments is needed to determine toxicity (acute and chronic) for assemblages of organisms in multivariate systems.

(22) Behavioral and physiological studies are needed to determine the metabolic, reproductive, and synecologic success of Great Lakes taxa in a competitive ecosystem subjected to chemical stresses.

12.2.5 Sedimentology

(1) The sediments of Lake Erie have been studied in greater detail than those of the other Great Lakes. Physical characteristics of the sediments are fairly well known, but their role in mineralogical and chemical cycling is poorly understood. Research is needed to determine the role of sediments in lake ecology.

(2) Investigations of grain size of sediments should be standardized and measurements carried out at the .25 ϕ interval.

Such data lend themselves to adequate statistical measure, including computer analysis of moments, and trend and factor analysis.

(3) Analyses of variance should be conducted to determine optimum sampling patterns for different sedimentary environments now that general sediment distributions are known. These analyses would optimize sediment collection and analyses.

(4) More frequent applications of statistical parameters of size data would be useful in mapping of dispersal trends, particularly with coarser sediments in the nearshore areas. Combination of various parameters in groups are useful in delineating some environments of deposition.

(5) Few thorough petrographic descriptions have been made of lake sediments. Quantitative variations should be determined to delineate dispersal trends and relate sediment accumulations to possible sources.

(6) Few data relating movement of particles carried by suspension have been collected. More extensive studies should be made, particularly in harbor areas, where sediment accumulation from suspension infills dredged channels. Such studies should be coordinated with current and conductivity measurements. Both directions and rates of dispersal should be determined.

(7) Sediment tracer studies in the nearshore environment are rare. Little is known of the volumes or rates of sediment removal and dispersal. Such studies will be useful in identifying important areas of extensive shoreline erosion and sedimentation.

(8) Elemental exchange at the sediment-water interface, migration, and changes with depth below the interface need to be effectively determined. Little is known of the role of organic sediment in ion exchange and ion adsorption surface area and sediment composition.

(9) More sedimentological studies that use tracer elements are needed to identify sources of pollution.

12.2.6 Limnological Resource Utilization

(1) Technical and socio-political techniques must be improved to insure reduction of chemical, sedimentary, and thermal waste input to the lakes from the Great Lakes Basin.

(2) The present data base should be improved so that objective determinations of the chemical, biological, geological, physical, and socioeconomic stresses on the aquatic system can be evaluated. Particular emphasis should be given to filling those data gaps identified in this appendix.

(3) A data storage and retrieval system is needed that can make data assembly and prepublication data dissemination effective. Periodic announcements of work planned and in progress would aid in coordination of programs.

(4) Comprehensive study programs, such as the IFYGL program on Lake Ontario, should be funded for each lake. The moored instrument platforms utilized in each lake should be maintained for regional synoptic monitoring of lake climate, thermal budget, chemical indices, and circulation. The real-time data output would be a valuable operations tool to aid in use of the lake resource for shipping, waste assimilation, shore property protection, recreation, power generation, and fisheries.

(5) Cooperative studies by teams from various disciplines are needed to reduce duplication, and make better use of facilities and equipment. Such efforts would be invaluable in interpreting interrelated data and providing systematic solutions to problems.

(6) Mathematical process-response models should be encouraged from all Great Lakes interest groups. Our knowledge of the Great Lakes has reached the point that pure description should be deemphasized, and fundamental relationships and multidisciplinary interactions should be emphasized. Operation, maintenance, and planning can be made more responsive by use of mathematical models.

(7) Emphasis should be placed on compatibility of mathematical models so that State variables can be standardized. The GLEPS program should be publicized and promoted as a communication link between the respective models developed by particular agencies and interest groups.

(8) Economic, sociological, and demographic studies should be initiated to determine both tangible and intangible costs and benefits of improvement or loss of Great Lakes resources. Mathematical models should then be used as tools to optimize resource utilization and minimize real and intangible losses in quality of the Great Lakes environment.

(9) Lake restoration techniques must be tested in lakes protypical of the Great Lakes. Presently accepted techniques, which are applicable to small lakes should be adopted for use in upland lakes and tested for use in the Great Lakes. Concurrently, new and innova-

tive techniques for both large and small lakes must be encouraged.

(10) A water quality monitoring system with adequate sampling frequency throughout the year must be implemented. Annual and short-term loads for each lake could then be computed and used in management decisions.

(11) A reevaluation of treatment level goals is needed to account for present loading and to develop plans for increased treatment required to account for population growth and increased water use.

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GREAT LAKES BASIN FRAME-
WORK STUDY - APPENDIX 4

TITLE GREAT LAKES BASIN FRAMEWORK STUDY - APPENDIX 4

DATE DUE	BORROWER'S NAME

GREAT LAKES BASIN COMMISSION

Frederick O. Rouse, Chairman

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