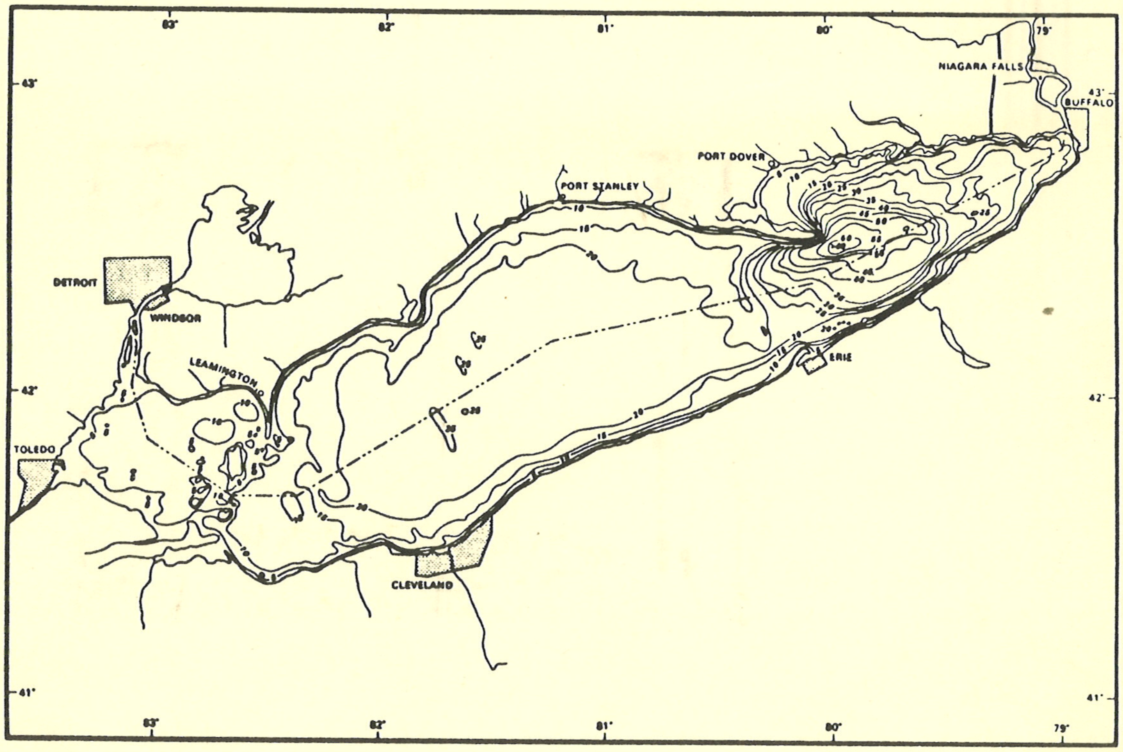
NOAA Estuary-of-the-Month

Seminar Series No. 14

DEPARTMENT OF COMMERCE • UNITED STATES OF AMERICA

Lake Erie Estuarine Systems: Issues, Resources, Status, and Management

April 1989



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NOAA Estuarine Programs Office

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Lake Erie Estuarine Systems: Issues, Resources, Status, and Management

Proceedings of a Seminar
Held May 4, 1988
Washington, D.C.

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary

National Oceanic and Atmospheric Administration
William E. Evans, Under Secretary

NOAA Estuarine Programs Office
Virginia K. Tippie, Director

LAKE ERIE AND ITS ESTUARINE SYSTEMS

(Issues, Resources, Status, and Management)

an
ESTUARY-OF-THE-MONTH
SEMINAR

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edited
by
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15 January 1989

PREFACE

This volume contains the proceedings of a one-day seminar on Lake Erie with emphasis on its nearshore and coastal wetland areas. The presentations were made on 4 May 1988 at the Herbert C. Hoover Building of the U.S. Department of Commerce in Washington, D.C., as part of a series of "Estuary-of-the-Month" seminars sponsored by the NOAA Estuarine Programs Office (EPO). The objectives of this series are to bring to public attention the important research and management issues regarding our nation's estuaries.

The Laurentian Great Lakes of North America represent our nation's "sweetwater seas" and its "fourth coast." The National Sea Grant College Program administered by NOAA includes active research, education and extension programs in most of the Great Lakes States. Furthermore, the southern shore of Lake Erie in Ohio is the site of the only freshwater National Estuarine Research Reserve. Therefore, it was appropriate that the Estuary-of-the-Month seminar series would include Lake Erie.

The present seminar was originally arranged and organized by Dr. C. E. "Eddie" Herdendorf, recent director of the Ohio Sea Grant Program as well as director of The Ohio State University's Center for Lake Erie Area Research (CLEAR) and its Franz Theodore Stone Laboratory on South Bass Island in Lake Erie. In view of his ensuing retirement, Dr. Herdendorf asked me to assume the roles of coordinator and moderator of the seminar and editor of the proceedings.

The title of this volume undoubtedly raises some eyebrows. Indeed, researchers actively debate the use of the terms "estuary" and "estuarine" to describe certain estuarine-like physical processes characteristic of many of Lake Erie's wetlands and its flooded tributary mouths. Contrasting views on the appropriate terminology are found in several of the presentations. Thus, it is important, in order to understand the estuarine-like characteristics of these areas, that these proceedings present first the geological and physical nature of Lake Erie and its coastal regions. The succeeding papers summarize the chemistry and biology of the nearshore and coastal areas, both within the historical context and the context of present conditions of pollution and physical modification. Of great importance to the future condition of the Lake Erie ecosystem are the views and policies of government, throughout the local, state or provincial, and national hierarchy as well as at the binational level. These issues are succinctly covered by representatives of the Ohio Department of Natural Resources, the U.S. Environmental Protection Agency's Great Lakes National Program Office, and Environment Canada's Inland Waters Directorate.

The seminar originated through discussions in 1987 between Dr. Herdendorf and Dr. James Thomas, then of the Estuarine Programs Office, followed by later coordination with Dr. Carl Berman and Dr. Joe Bishop of the EPO, as well as with Dr. Virginia Tippie, EPO Director. Special appreciation is extended to Ms. Terri Weininger for retyping several of the manuscripts, and to Ms. Nancy Creamer for editorial assistance, both at Heidelberg College. The Ohio Sea Grant College Program supported travel costs for two of the participants under federal grant number NA84AA-D-00079, the National Sea Grant College Program, NOAA, U.S. Department of Commerce. Dr. David B. Baker, Director of the Water Quality Laboratory at Heidelberg College, generously provided the use of computers, supplies, secretarial assistance, and some of my time for coordination and editorial efforts.

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OVERVIEW OF LAKE ERIE AND ITS ESTUARIES WITHIN THE GREAT LAKES ECOSYSTEM

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INTRODUCTION

The St. Lawrence Great Lakes of North American comprise about 20% of the world's supply of surface freshwater. This concentration is rivaled only by Lake Baikal in Siberia and the rift valley great lakes of east Africa. Taken together these three loci account for over 60% of the water in the earth's freshwater lakes (Herdendorf 1982). Like the oceans, large lakes can possess estuarine-like environments in the lower reaches of tributary streams. These types of environments are particularly prevalent in our Great Lakes where crustal rebound, following deglaciation, has caused the northern portion of the basin to rise over 100 m. As a result, the lower courses of the southern tributaries have been flooded, creating the drowned river mouths typical of estuarine systems. The following overview will discuss the natural setting of the Great Lakes with particular focus on Lake Erie, the most southerly of the Great Lakes and thus the one exhibiting the best developed estuaries. This discussion will be followed by a review of the cultural setting of the Great Lakes region, the impact human settlement has had on the ecosystem, and attempts to manage of our delicate freshwater estuaries.

The North American Great Lakes system within the United States extends from Duluth, Minnesota, at the western end of Lake Superior, to Massena, New York on the St. Lawrence River (Fig 1). It possesses a shoreline length of over 6,000 km and a water surface area of 158,000 km^2. The Great Lakes are located within the highly industrialized northcentral United States. The Great Lakes drainage basin covers only 4% of the United States land area, but it has 15% of the nations' population and produces 50% of the nation's steel. The basin consists of land and water areas of 183 counties in eight states. The coastal resources of the Great Lakes, including their estuaries and wetlands, are invaluable assets to the region and to the nation as a whole. The need to wisely develop these resources within the context of sound environmental practices is a continuing challenge for resources managers.

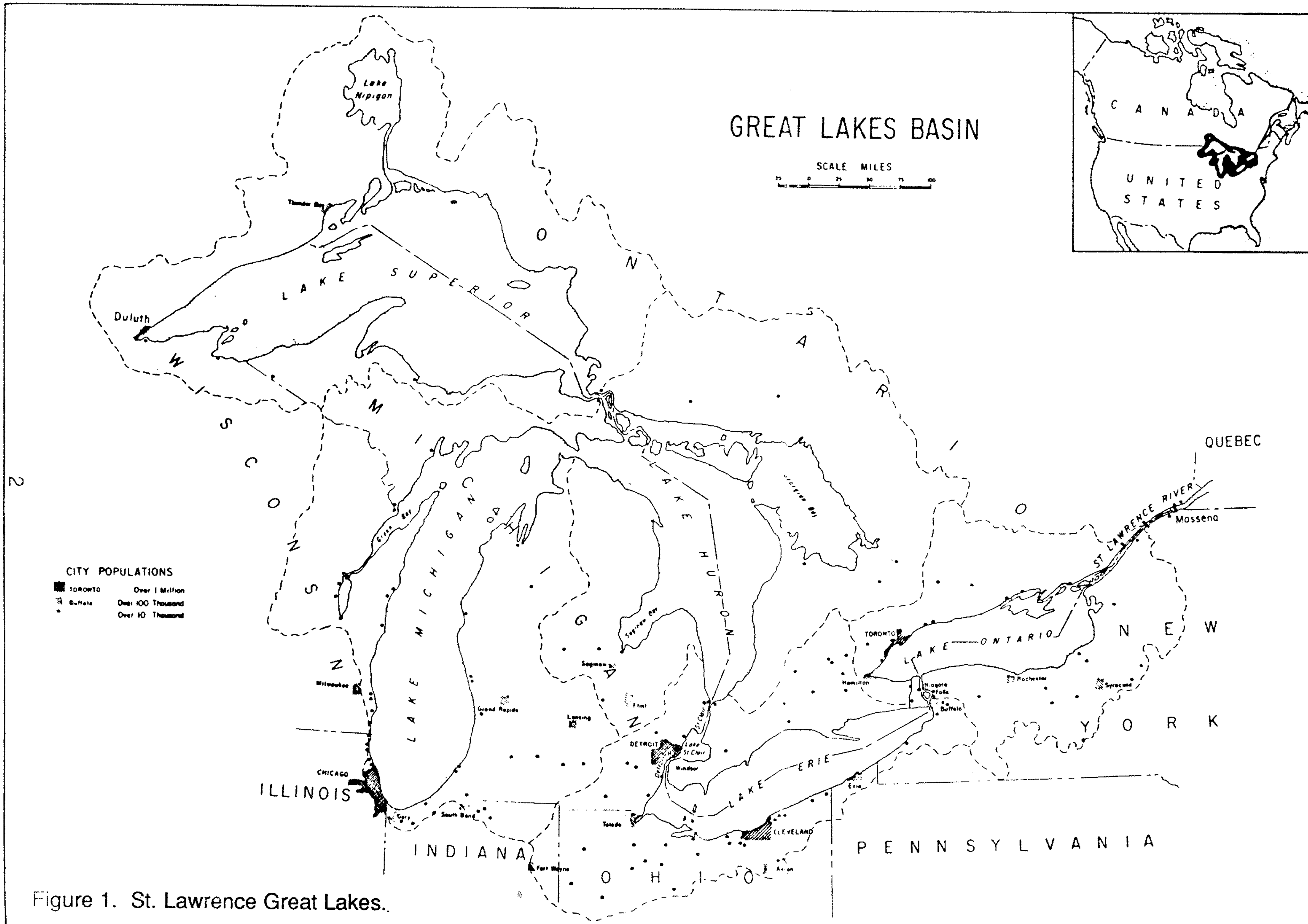

Figure 1. St. Lawrence Great Lakes.

NATURAL SETTING OF THE GREAT LAKES BASIN

Morphometry of the Great Lakes

The five Great Lakes range in surface area from 82,100 km^2 (Lake Superior) to 18,960 km^2 (Lake Ontario) and in volume from 12,100 km^3 (Lake Superior) to 484 km^3 (Lake Erie). Morphometric dimensions of the Great Lakes and their connecting waterways are listed in Tables 1 through 4. The relative depths, surface elevations, and water storage capacities of the five Great Lakes are graphically shown on Fig. 2.

Rawson (1939) was among the first limnologists to articulate the interractions of the major physical and chemical factors which control the productivity of a lake. Fig. 3 shows his attempt to organize the physical and chemical factors in the metabolism of a lake. This organization has stood the test of time and provides us with a useful conceptual model for developing a classification and inventory of aquatic habitats. Rawson (1955) further demonstrated that in large lakes, morphometry is a dominant factor in productivity. There is a tendency for standing crop per unit area to decrease with an increase in maximum depth. Wetzel (1983) points out that the morphology of a lake basin is best described by a detailed bathymetric map (Fig. 4) and that such a map is essential for the evaluation of the effects that morphology has on nearly all of the physcial, chemical, and biological procresses of a lake. Useful morphometric information contained on a bathymetric map includes: (1) area, (2) mean and maximum depth, (3) volume, (4) fetch length, (5) shoreline length, (6) basin slope, and (7) orientation (Hutchinson 1957). Rawson also showed the factors influencing lake productivity could be grouped into three categories: (1) edaphic, e.g., total dissolved solids, nutrients, (2) morphometric, e.g., mean depth, lake surface area, and (3) climatic, e.g., air temperature, latitude. He demonstrated that given adequate information, on these factors, a multiple correlation analysis would show a direct relationship to fish production.

Thus, lake morphometry has a profound influence on the quality and quantity of important fish and wildlife habitat. Those habitats that are most critical are often near the coast and subject to human perturbation. Each Great Lake can be divided into two zones: (1) an offshore pelagic zone, characterized by fine-grained sediment types, great depths, and a generally less diverse habitat than nearshore and (2) a nearshore zone which contains important spawning and nursery habitat for fish. This zone is the receptacle for nutrients, contaminants, and sediments from the surrounding watershed, and is prone to development, with its accompanying water intakes, rip-rapped harbors and shorelines, power plants, sewage treatment plants, industrial outfalls, and wetlands destruction. Basin morphometry is a confining factor for fish since it sets the limits within which species can reproduce, feed, and compete. In the Great Lakes, some species of fish spawn every month of the year and each species has specific spawning requirements. The open water pelagic zone is used by such species as bloaters and deepwater sculpin. The nearshore

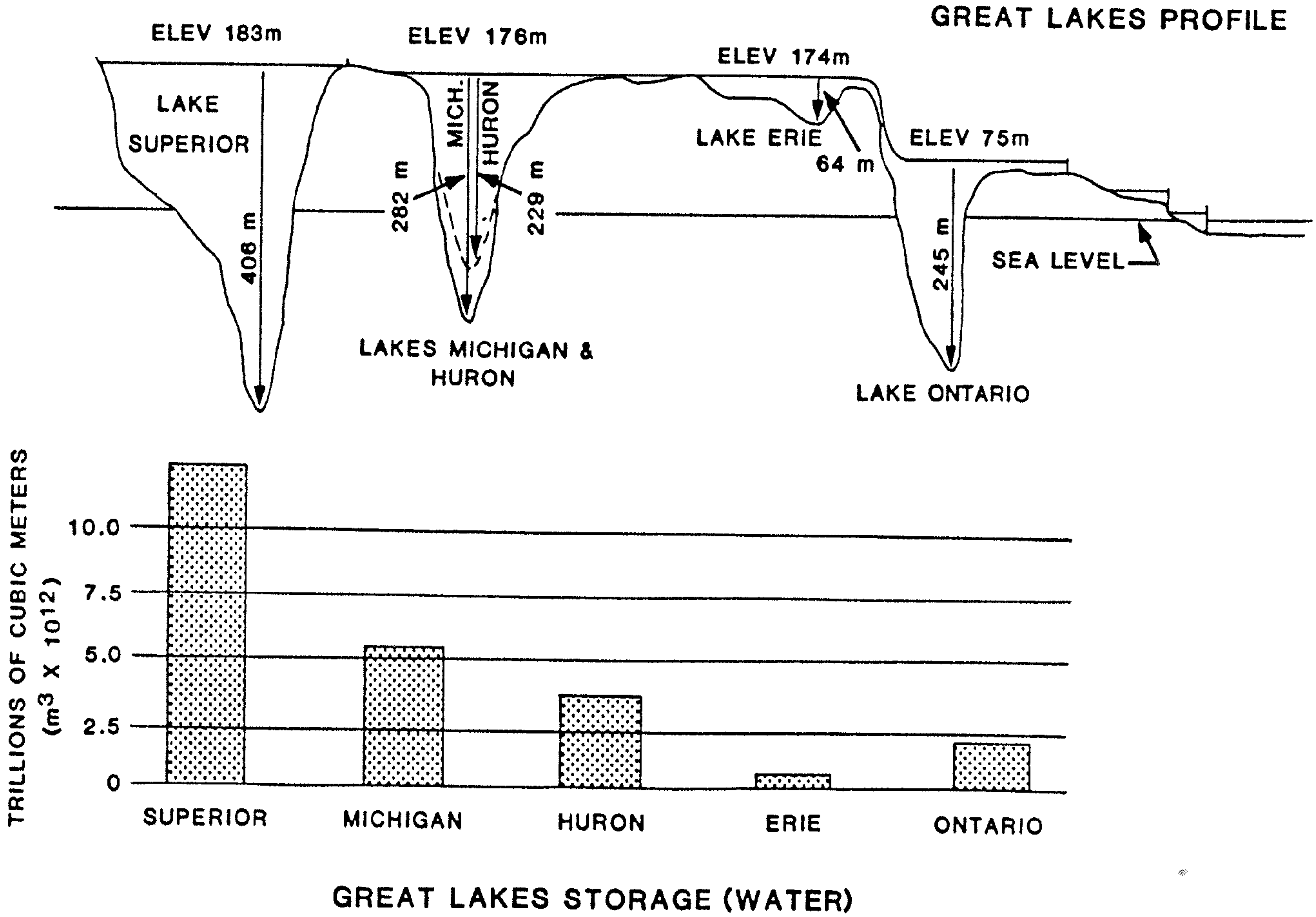

Figure 2. Morphometric relationship of the Great Lakes.

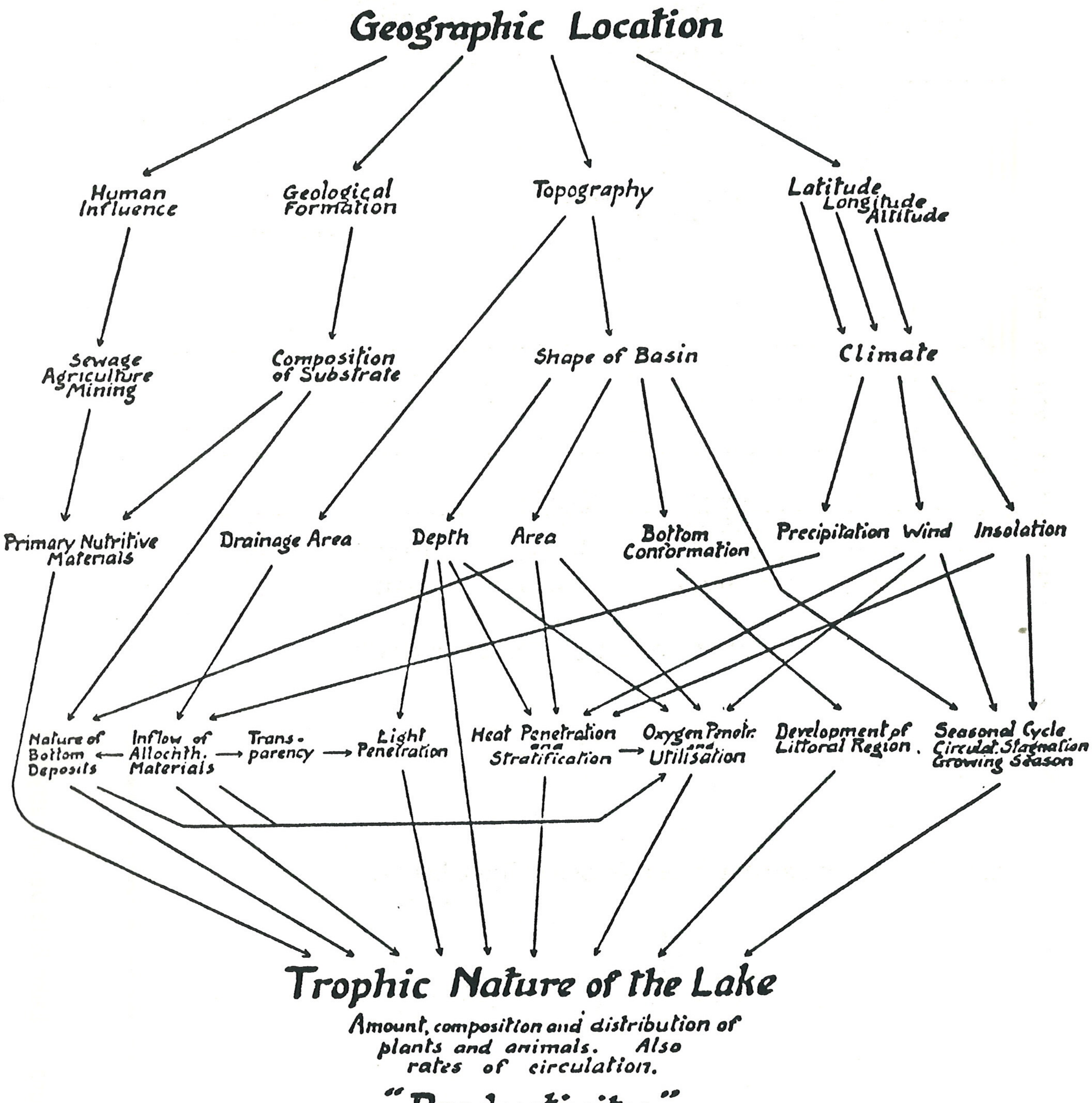

Figure 3. Factors influencing the biological productivity of a lake (after Rawson 1939).

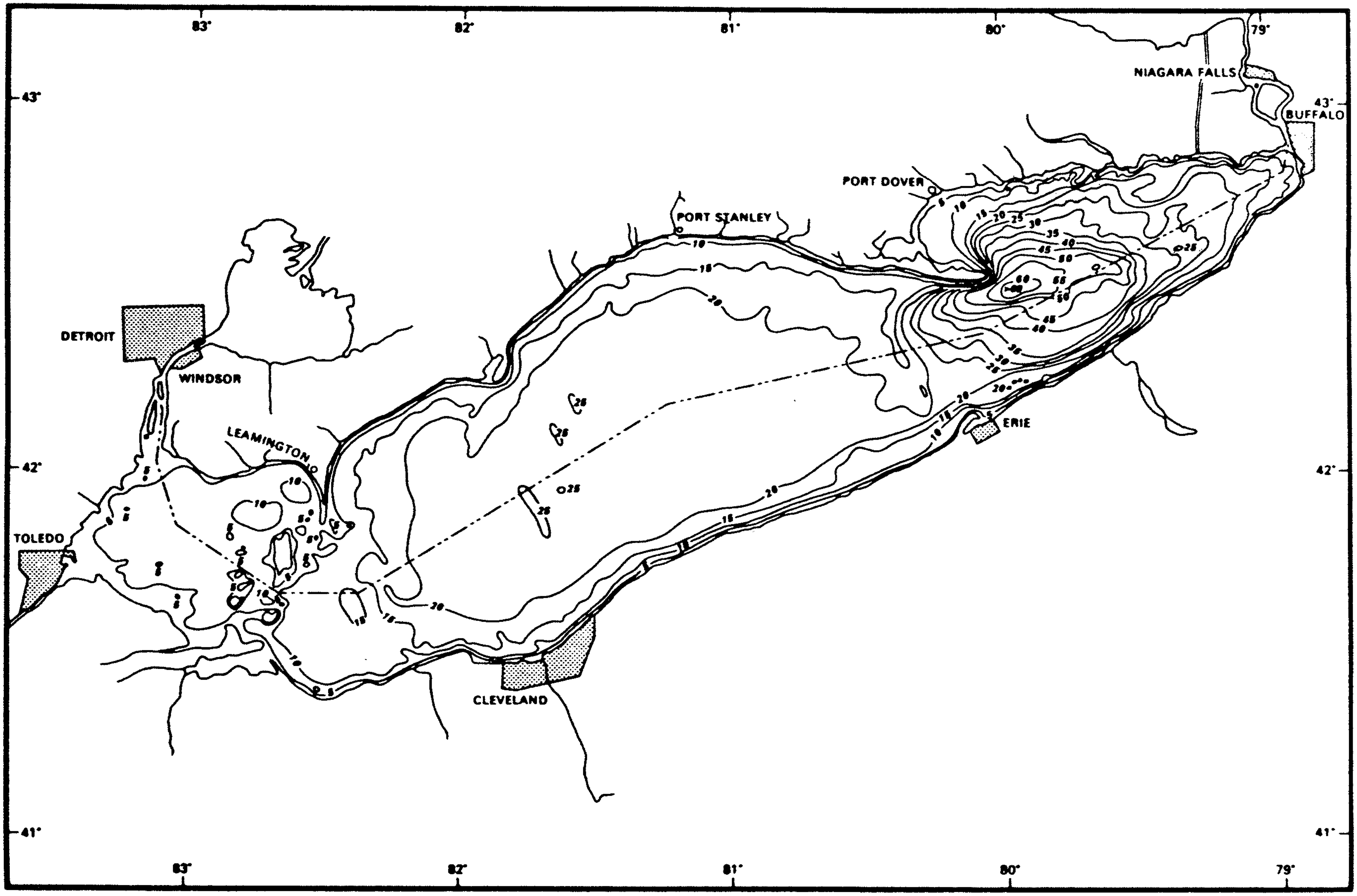

Figure 4. Lake Erie bathymetry (m).

pelagic zone is used by alewife, rainbow smelt, yellow perch, white bass, and gizzard shad, while the nearshore benthic environment is used by slimy sculpin, trout-perch, and johnny darters to cite a few examples (Jude et al. 1979). Connecting rivers, lakes, and estuarine marshes such as Saginaw Bay, Sandusky Bay, and Green Bay, are also important spawning and nursery areas for such species as white suckers, carp, emerald shiners, yellow perch, walleye, and northern pike. Thus, the quantity and quality of these habitat types are critical elements affecting the final species composition in each of the Great Lakes.

A total of 1,370 coastal wetlands fringe the Great Lakes and their connecting channels, for a combined wetlnad area of 1,209 km^2 (Table 5). The greatest number and area of coastal wetlands ring Lake Michigan, the only Great Lake entirely within the United States. Lake Superior has the second highest number of wetlands, but they are relatively small in size. On the average, the largest wetlands are found along Lake Huron and its discharge channel to the south, particularly the delta wetland of the St. Clair River which covers 35 km^2. The highly industrialized Lake Erie shore has the smallest number and area of wetlands while Lake Ontario has the smallest average size of wetlands, largely due to isolated marshes in the Thousand Islands are of the St. Lawrence River. The presence or absence of estuaries and coastal wetlands is largely dictated by the geomorphology of a given shoreline and the recent history of water level fluctuations. Each lake has a particular set of geomorphic features which exert control on wetland development (see Paleogeography and Geomorpholgy chapter).

Hydrology of the Great Lakes

By oceanic standards the Great Lakes are small, having a total area of 244,000 km^2 or about 0.25% of the world ocean. But as we have seen, by lake standards they are large. However, the relative dimensions of the Great Lakes and the oceans are remarkably similar. For example, comparison of the largest and deepest ocean, the Pacific, with the largest and deepest Great Lake, Superior, reveals that both are about 4,000 times as wide as their mean depths, and 1,500 times as wide as their maximum depths (Ragotzskie 1983). As in the oceans, the circulation of the Great Lakes is primarily wind-driven. Currents in the Great Lakes tend to be parallel to the coasts. Ekman transport and the resulting coastal upwelling or downwelling leads to strong horizontal temperature gradients normal to the coast. The overall circulation pattern takes the form of gyres, either encompassing an entire lake as frequently occurs in Lake Ontario or as several gyres as in Lake Michigan and Lake Superior (Ragotzskie 1983).

The tides of the ocean also have their analogy in the wind-driven seiches of the Great Lakes. These surface oscillations which are always present may attain vertical ranges of 2 m or more during persistent wind episodes and must often be taken into account by ship captains when entering harbors with entrance channels of limited depth. Mortimer (1971) demonstrated that these seiches rotate much like tidal waves; however, they are more complex in that several modes of oscillation can occur simultaneously. Lunar tides also occur in the Great Lakes, attaining up to 18 cm on Great Bay of Lake Michigan but only 3 cm on Lake Erie. Wind waves of the Great Lakes do not, of course, attain the huge dimensions of those in a North Pacific cyclone, but fall storms frequently generate waves in excess of 5 m in Lake Superior and 12-m waves have been reported. Great Lakes storms are particularly fearsome, however, both becuase of the suddenness with which they can develop and the steepness of the waves themselves. Coupled with subfreezing temperataures which cause instant freezing of freshwater spray on hulls and superstructure, the short steep waves and hurricane-like winds of an early winter cyclonic storm have sunk literally thousands of Great Lakes vessels, from early schooners and steamboats to modern 700-ft ore carriers like the Edmund Fitzgerald which was lost in Lake Superior during a November storm in 1977 (Ragotzkie 1983).

The thermal cycle in all these lakes is similar (Fig. 5), but with variations resulting from differences in latitude and depth. From November to late May the water in all lakes is nearly homothermous, although there may be a slight inverse stratification in mid-winter. In shallow, western Lake Erie winter homothermy often exists at less than 1.1°C and in Lake Superior homothermous winter temperatures of 1.7°C extend to at least 200 m but the deep-bottom water remains near 3.9°C. Thermal stratification occurs in all lakes, forming in early June in Lake Erie and in mid-July in Lake Superior. The depth of the epilimnion varies with each lake, although it is approximately 15 m in mid-summer in all except Lake Erie, where it may extend to 20 m. Stability of thermal stratification is generally low, in that both the temperature gradient and the actual temperatures are low (Chandler 1964).

Waters of these lakes are clear except in western Lake Erie. Secchi disc readings of 12 to 15 m are common in the open lakes, with decreasing values near shore. Transparency values in western Lake Erie are often less than 3 m, and less than 1 m in the estuaries.

As part of a global hydrological system, the Great Lakes continually receive moisture from air masses carried into the region by prevailing westerly winds. Correspondingly, the basin loses moisture in departing air masses and the outflow from the St. Lawrence River. On balance, the quantity of water lost approximately equals what is gained, but lake levels can vary substantially over short-term, seasonal and long-term periods.

Great Lakes water levels are regulated, but only in part. The outflow from Lake Superior has been controlled completely since the construction of a 16-gate dam across the outlet (St. Mary's River) in 1921. The only other regulated lake, Lake Ontario, has been controlled since the St. Lawrence Seaway was completed in 1958. The regulation of Lake Superior, including the Long Lac and Ogoki diversions, caused a slight increase (7.6) cm in Lake Erie water levels; the regulation has no effect on Lake Ontario. The Chicago diversion passes water out of Lake Michigan through the Illinois waterway and on to the Mississippi River. Flow through the Chicago diversion is limited by a U.S.

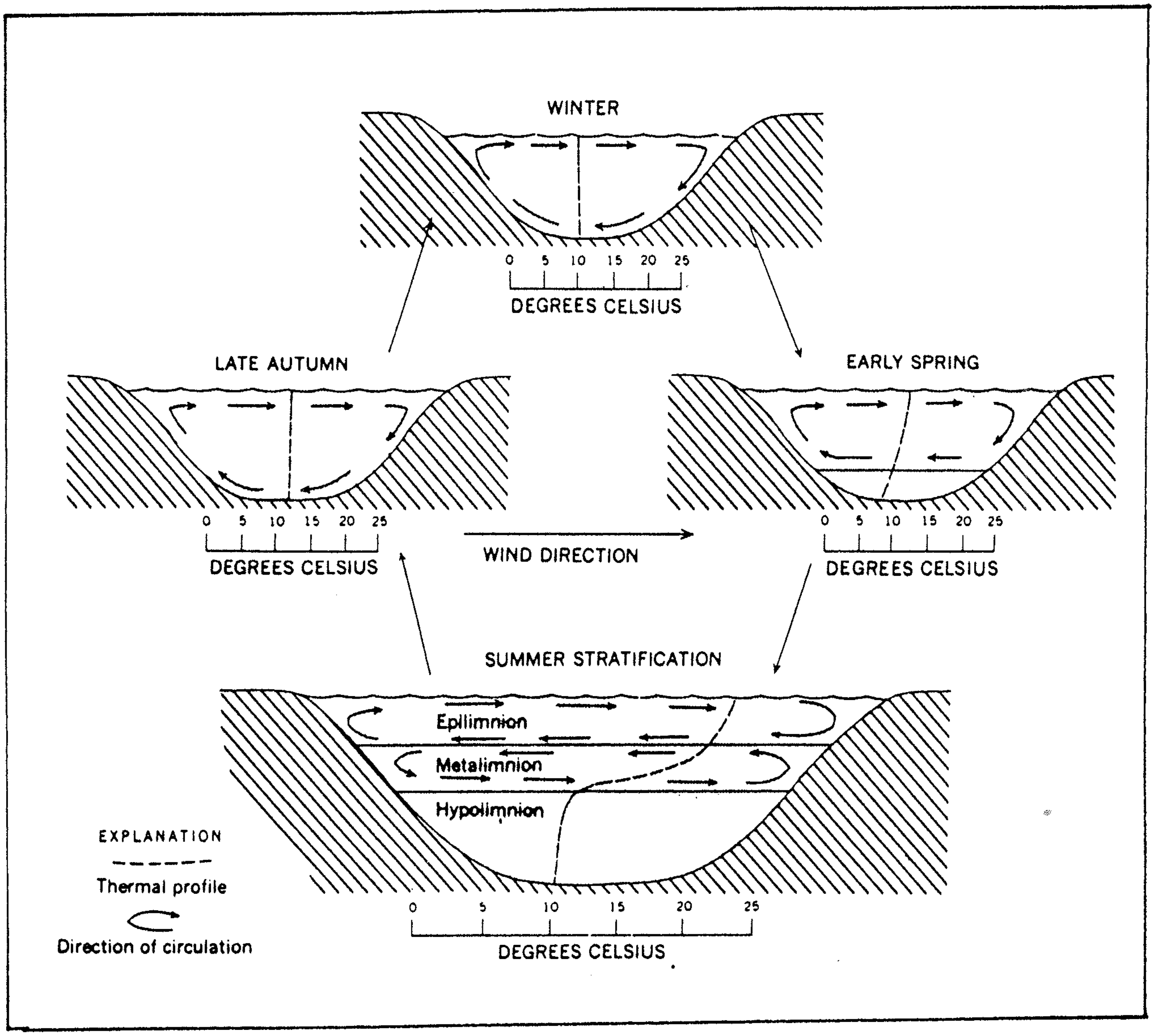

Figure 5. Circulation and stratification in the Great Lakes.

Supreme Court decree to 90 m^3/s. The long-term effect of this diversion has been to lower the water level in Lake Erie by 4.3 cm. The diversion of water from Lake Erie to Lake Ontario through the Welland Canal has resulted in a lowering of 13.5 cm in Lake Erie levels and a consequently slight lowering of lakes Michigan-Huron levels. Since 1950, this diversion has averaged about 198 m^3/s, currently 266 m^3/s and is used for navigation and power generation. Also, a diversion of about 31 m^3/s is made during the navigation season from the Niagara River at Tonawanda for use in the New York State Barge Canal. Other than these minor diversions, no regulation of Lake Erie water levels is presently possible. The net effect of all Great Lakes regulations and diversion has been to lower the level of Lake Erie by 10.2 cm.

NATURAL SETTING OF THE LAKE ERIE BASIN

Lake Erie Morphometry

Lake Erie is one of the largest freshwater lakes in the world, ranking 9th by area and 15th by volume. It is the southernmost of the North American Great Lakes, lying between 41°21'N and 42°50'N latitude and 78°50'W and 83°30'W longitude. The lake is narrow and relatively shallow for a lake of its size with its longitudinal axis oriented east-northeast (Fig. 4). Lake Erie is approximately 388 km long and 92 km wide, with a mean depth of 19 m and a maximum sounding of 64 m. The lake has a surface area of 25,657 km^2, a volume of 484 km^3, a shoreline length of 1,402 km, and a surface elevation of 173.9 m above mean sea level. Based on bathymetry, Lake Erie can be naturally divided into three basins: western, central and eastern (Fig. 6).

Western Basin. The western basin, lying west of a line from the tip of Pelee Point, Ontario, to Cedar Point, Ohio, is the smallest and the shallowest with most of the bottom at depths between 7 and 10 m. In contrast with the other two 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. Topographicaly, the bottom is monotonously flat, except for the sharply rising islands and shoals in the central and eastern parts. The maximum depths in the basin are found in the interisland channels. The deepest sounding, 19 m, was made in a small depression north of Starve Island Reef; south of Gull Island Shoal, in another depression, a depth of 16 m has been recorded.

Central Basin. The central basin is divided from the western basin by the island chain and from the eastern basin by a relatively shallow sand and gravel bar (Fig. 7) between Erie, Pennsylvania and Long Point, Ontario. The central basin has an average depth of 18.5 m and a maximum depth of 26 m. Except for the rising slopes of a bar extending south-southeastward from Pelee Point, Ontario, the bottom of the central basin is extremely flat. This bar forms a depression in the bottom between it and the islands, known as the Sandusky sub-basin.

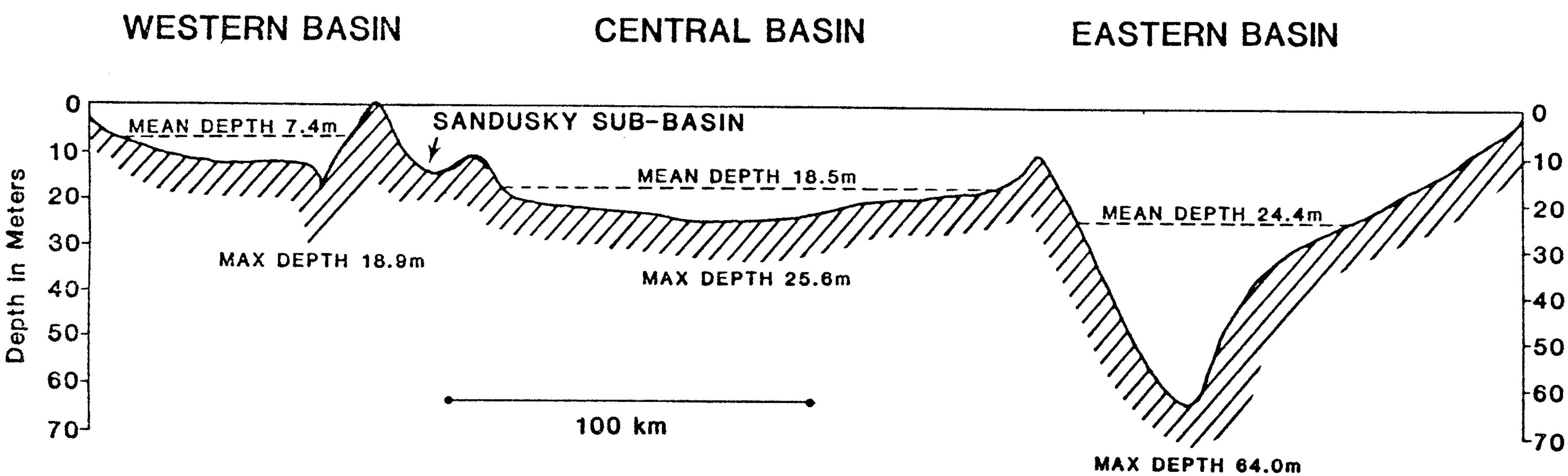

Figure 6. Bathymetric cross-section of the Lake Erie Basin.

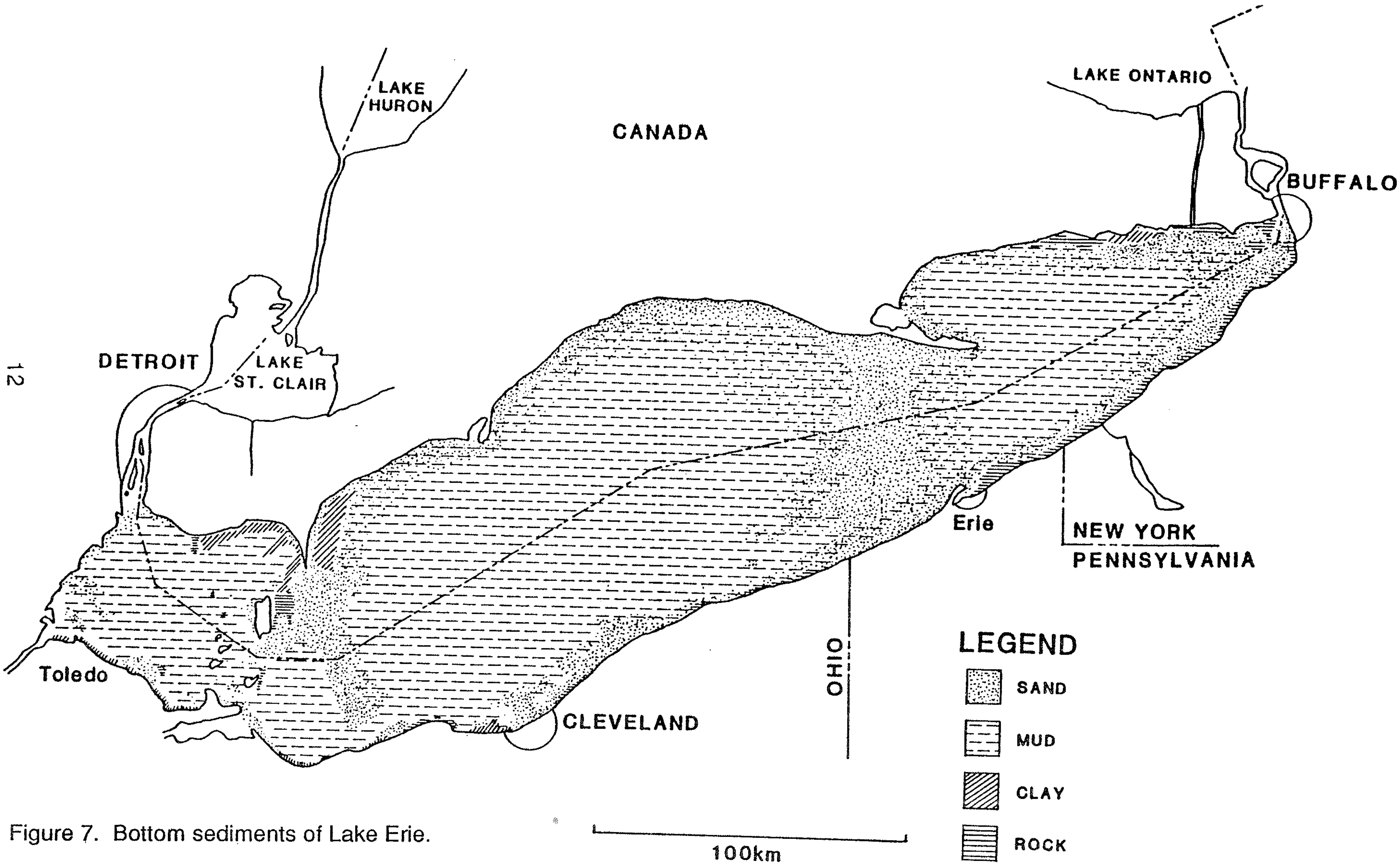

Figure 7. Bottom sediments of Lake Erie.

Topographically, then, central Lake Erie can be divided into two parts; the Sandusky sub-basin and the much larger basin to the east. The roughly triangular Sandusky sub-basin covers an area of approximately 1350 km^2 or about 8.5% of central Lake Erie. On the west, the sub-basin is bounded by the islands on the east side by the Lorain-Vermilion sand and gravel deposit (Fig. 7), a ridge or bar crossing the lake between Lorain and the tip of Point Pelee. Over half the area of the sub-basin has depths greater than 12 m. Here the bottom is very flat; slopes of more than 0.5m/km are virtually non-existent. Silt and clay make up more than 95% of the bottom materials in the flat area. Water depths less than 12 m are found only on the shoreward rising slopes and on the Lorain-Vermilion sand and gravel deposit.

Eastern Basin. The eastern basin is relatively deep and bowl-shaped. Most of the basin's bottom lies below 25 m and the deepest sounding, 64 m, is found east-southeast of Long Point, Ontario. This basin is separated from the central basin by a glacially deposited bar which extends from the base of Long Point on the Ontario shore to Presque Isle at Erie, Pennsylvania. The bar contains a notch, known as the Pennsylvania channel, which reaches a depth of over 24 m and provides a subsurface connection for water circulation in both directions between the two basins.

Lake Erie Hydrology

Five natural hydrologic factors account for the net supply of water to estuaries and coastal wetlands: (1) precipitation, (2) runoff, (3) ground water, (4) evaporation and (5) intrustion of lake water. While the major source of water to Lake Erie is the upper Great Lakes via the Detroit River, several watersheds drained by 10 major streams and numerous small ones discharge into the western basin of Lake Erie. Each of these tributaries has a drowned mouth, creating estuarine conditions which have fostered the formation of coastal marshes.

More than 90% of the total inflow to Lake Erie comes from the Detroit River, the drainage outlet for the Upper Great Lakes. The average annual inflow at the head of the Detroit River is 5,140 m^3/s, equivalent to 6.4 m of water covering Lake Erie. Surface runoff from the drainage area enters the lake via many smaller tributary rivers or by direct runoff from the shore area. Average annual runoff is estimated at 580 m^3/s, outflow from Lake Erie is through the Niagara River at Buffalo and the Welland Canal diversion at Port Colborn. Combined outflow averages about 5,730 m^3/s annually, equivalent to 7.1 m of water over Lake Erie.

Water depth in the lower Detroit River is influenced to a large extent by the water level of Lake Erie. Strong easterly winds can produce water levels in western Lake Erie which are 5 m above those in eastern Lake Erie. As a result, a partial reversal of flow in the Detroit River can be caused by water levels at its mouth being up to 1 m higher than at its head; under normal conditions there is typically a 1 m fall from Lake St. Clair to Lake Erie. Current velocities average 2.4 km/hr in the channels on both sides of Grosse Ile. Speeds are less in shallows adjacent to the islands and channels, but at no place can the water be termed stagnant. The lowest flows of the Detroit River ordinarily occur in February (4,500 m^3/s) and the highest in July or August (5,600 m^3/s).

Two large rivers enter western Lake Erie and dominate water quality conditions in that basin. The Detroit River with a mean flow of 5,140 m^3/s is the connecting channel for drainage from the upper Great Lakes and delivers 1.6 million tons of suspended solids and 33.6 million tons of dissolved solids to the lake each year. The Maumee River, at 137 m^3/s is only 3% of the Detroit River flow but yields 2.3 million tons of suspended sediment and 1.4 million tons of dissolved material. This river drains 17,000 km^2 of primarily low lying farmland which acounts for its high sediment load. The high turbidity of the Maumee River significantly diminishes water clarity around the southern islands.

The waters of the western basin are more turbid than the other basins because of: (1) large sediment loads from the Detroit, Maumee, Portage and Sandusky rivers, (2) wave resuspension of silts and clay from the bottom, and (3) high algal productivity. Becuase the Detroit River accounts for most of the flow of water into Lake Erie it controls the circulation patterns in the western part of the basin. Its inflow penetrates far southward into the basin, retarding the dispersion of the sediment-laden Maumee River and the Michigan shore streams which results in high concentrations of contaminants along the western shore.

The Sandusky River is the largest stream flowing directly into the central basin. This river drains an area of 3,700 km^2, has an average flow rate of 30 m^3/s, and discharges 270,000 tons of suspended sediment and 450,000 tons of dissolved solids to Sandusky Bay annually. Other major steams in the central basin include the Cuyahoga River, Grand River, Black River, and the Huron River with discharges of 23, 22, 11, and 9 m^3/s respectively.

Although the central basin receives over 95% of its inflow from the western basin, the water is considerably less turbid and less biologically productive. Drainage from the western basin and inflow from the Sandusky River and other Ohio tributaries are concentrated in the Sandusky sub-basin and along the south shore where biolgoical productivity and contaminants are the highest.

Water temperatures in the central and eastern basins are isothermal from fall to late spring; thermal stratification normally occurs below 15 m from June until September. In the central basin during the latter part of the stratified period the thin hypolimnion (cold, bottom water layer) may lose all of its dissolved oxygen (Fig. 5). The western basin typically freezes over each winter and the central and eastern basins occasionally freeze from shore to shore, except in the vicinity of isolated thermal discharges.

The storage capacity of Lake Erie is approximately 2.75 times the average annual inflow into it from tributary streams and the upper Great Lakes. Therefore, the theoretical retention of water entering the lake at the western end flowing out the Niagara River is approxiametly 1,008 days. The shallow western basin of Lake Erie has a volume of 25 km^3 and a water retention rate of about 53 days. The central basin's volume is 155 km^3 and its retention rate is 322 days and the deeper eastern basin has a volume of 304 km^3 and a retention rate of 635 days. The formation of a summer thermocline (Fig. 5) in the central and eastern basins causes these rates to be reduced in the epilimnion (warm, surface water layer).

The average annual rainfall in the Lake Erie basin is about 89 cm and ranges between 81 and 97 cm. The total land area which drains into Lake Erie, excluding that above the head of the Detroit River, is only about three times the area of the water surface of the lake. The large expanse of water affords a great opportunity for evaporation which has been estimated to be between 84 and 91 cm. This amount of evaporation is approximately equivalent to the average annual rainfall over the lake. During dry periods more water may be evaporated from the lake than flows into it from all of its tributaries. Under these conditions Lake Erie delivers into the Niagara River a smaller quantity of water than it receives from the Detroit River.

Lake Erie is noted for its severe storms, intense wave attack, and rapid water level changes. The high energy produced by these storms limits the existence of coastal wetlands to places where some type of natural or artificial protection is available. Correspondingly, the coastal marshes of western Lake Erie fall into three categories depending on the type of protection for the aquatic vegetation: (1) coastal lagoons behind barrier beahes, (2) estuarine tributary mouths, and (3) managed marshes protected by earthern and rip-rap dikes.

The record high water levels in Lake Erie during 1972-73 and again in 1985-86 contributed greatly to increased erosion and flooding of the shores. Because the narrow beaches fronting the coast were submerged, the shore bluffs were exposed to direct wave attack by storm waves and erosion by alongshore currents. Severe storms during these periods resulted in profound changes in shoreline configuration, disruption of coastal facilities, extensive property damage and loss of valuable coastal wetlands.

Water level changes on Lake Erie are of two principal types: (1) long-period fluctuations and (2) shore-period fluctuations. Long-period fluctuations are related to volumetric changes of the lake, caused principally by variations in precipitation, evaporation, and runoff. These changes include both seasonal fluctuations and those occurring over a period of several years. Short-period fluctuations are due to a tilting of the lake surface by wind or by atmospheric pressure differentials. Wind tides, seiches, and harbor surges, which have periods from a few seconds to several days, are examples of short term fluctuations. Solar and lunar tides are negligible, resulting in maximum fluctuations of 3.3 cm.

Long-period water level fluctuations. The highest and lowest average monthly levels on Lake Erie generally occur in June and February, respectively. This seasonal variation typically ranges from 0.3 to 0.6 m. The plane of reference for charts and navigational works on Lake Erie is known as Low Water Datum (LWD), and stands at an elevation of 173.3 m above the mean water level at Father Point, Quebec. The water level at Father Point, known as the International Great Lakes Datum or IGLD, 1955, approximates sea level at the place where the flow from the Great Lakes enters the ocean in the Gulf of St. Lawrence. The mean level of Lake Erie for the period of record (1900-86) is 173.8 m as measured by the U.S. Army Corps of Engineers and the National Oceanic and Atmospheric Administration. The highest average monthly level recorded was 174.9 reached in June 1986 and the lowest average monthly level recorded was 173.0 m in February 1936. This represents a range in lake elevation of nearly 2 m and a change in the lake's volume of approximately 10%.

Long-term variations in lake levels are the result of persistent low or high precipitation. In the mid-1960s the Great Lakes basin experienced low precipitation and correspondingly near-record low water levels in the lakes. In 1972-73, and again in 1985-86, precipitation was high and lake levels were extreme high. Records at Cleveland going back more than 100 years indicate no regular, predictable cycle of levels. The interval between periods of high and low water can vary widely.

Short-period water level fluctuations. Water levels at the ends of Lake Erie (Toledo and Buffalo) have a much greater flucttuation than near the center. Tilting of the lake surface is analogous to the up and down movement of the ends of a teeter-totter while the center is stable. High water levels coupled with northeast storms have produced a maximum rise in level of 3.1 m above Low Water Datum at Toledo. Conversely, low water and southwest winds have lowered the level to 2.4 m below Datum, a range of 5.5 m. Under the influence of wind, currents tend to bank up water on the windward shore. This forced movement of the lake surface is known as wind tide and the amount of rise produced is the wind setup. The resulting free oscillation of the lake surface caused by the inequality of water level is called a seiche. Such free oscillations are nearly cotinuous in the islands region and most often have a period of 12 hours and an amplitude of less than 0.7 m with a maximum amplitude of 2 m.

The major seiches on Lake Erie are essentially parallel to the longitudinal axis of the lake. Seiches along this axis have a period of approximately 12 to 14 hours. Seiche periods as recorded for 3 years at a water level gauge at Put-in-Bay on South Bass Island indicated that longitudinal seiches were occurring about 44% of the year. Surface winds from the southwest or northeast are likely to produce such seiches along the long axis of the lake. Wind records from Sandusky, Ohio are in agreement with the frequency of seiche periods; surface winds from these directions ocur approximately 150 days or 41% of the year (Herdendorf and Braidech 1972).

LAKE ERIE ESTUARINE SYSTEMS

Delineation of Freshwater Estuaries

The Great Lakes are characterized by a wide variety of coastal features, including: bedrock cliffs, clay bluffs, sand beaches, marsh wetlands, and stream mouths. Tributaries enter the Great Lakes in three ways: (1) as free-flowing, single-channel streams at their mouhts, (2) through deltaic distributary sytems, or (3) at estuaries formed in the drowned mouths of the streams. To some degree estuaries are present on all of the Great Lakes but they are best developed in Lake Erie where crustal movements have extended them as far as 15 km upstream from the lake at the lower reaches of major rivers.

Great Lakes estuaries is a relatively new concept (Brant and Herdendorf 1972) and deserves some explanation. The arms of lakes that extend landward have evaded description and recognized distinction. For the most part such linear bodies of water have been refered to as river to within some indistinct proximity to the lake; whereas in reality these consist of a mixture of characteristics of these two water regimes. More recently, the *Glossary of Geology* (Bates and Jackson 1980) defined "freshwater estuaries" for the Great Lakes as "the lower reach of a tributary to the lake that has a drowned river mouth, shows a zone of transition from stream water to lake water, and is influenced by changes in lake level as a result of seiches or wind tides."

An estuary is usually defined as that part of the lower river course that is affected by the mixng of water from the stream with that from the receiving sea. Fairbridge (1968) considers an esttuary to exist where the riverbed is "overdeepened" i.e., it lies below mean sea level and at least from time to time there is encroachment of seawater upstream. He goes on to explain that the single most important reason for the overdeepening is the postglacial rise of sea level.

The Great Lakes owe their origin to physiographic changes induced by Pleistocene glaciation. As the ice sheet paused in advances or retreats, ridges or moraines of glacial till were built up at their margins damming the natural drainage and forming glacial lakes. Lake Erie is the remnant of such a lake, which at its highest stage extended as far south as Fort Wayne, Indiana with its outlet to the southwest via the Wabash River. As the ice retreated, other outlets were uncovered and new lake stages were formed at successively lower levels. When the last glacier retreated from the bedrock sill at the head of the Niagara River, a new and final drainage outlet was made available. However, at that time the bedrock sill was as much as 30 m lower than at present because of the depression that had taken place under the weight of the glacial ice (Lewis et al. 1966).

Lake Erie tributaries, which developed as the high lake stages drained from the basin, were accelerated by base level lowering when the Niagara outlet was uncovered. Valleys were deeply cut into the glacial till at this time. With the eventual rebound of the outlet and the subsequent rise in water level, the lake encroached up the valleys forming the present drowned river mouths or estuaries (Herdendorf 1987).

Schubel and Pritchard (1971) analyzed Pritchard's (1967) definition of an estuary in detail and after comparing it with ten other definitions, concluded that it most clearly described the phenomena:

> "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water from land drainage."

According to this definition there are three characteristics which distinguish estuaries from other bodies of water: (1) an estuary is a coastal feature with some constriction at its opening to the sea; (2) an estuary has a free connection to the sea sufficient to allow continuous exchange of water between the ocean and the estuary and (3) an estuary is a place where there is a mxing of two kinds of water, river and sea.

These three basic concepts: (1) constriction, (2) continuous water exchange and (3) mixing of two kinds of water, can logically be applied to the Great Lakes. The foregoing discussion describes the existence of the first two situations in the Lake Erie system. Considerable evidence is also available to describe the mixing of two distinct water masses in zones, referred to as lake estuaries. Measurements of water quality and currents (Schroeder and Collier 1966, Brant and Herdendorf 1972) also demonstrate the encroachment of Great Llakes water into tributary mouths and the subsequent mixing of lake and river water in that area. This process is a necessary criteria for an estuary. For example, within the estuary of the Cuyahoga River, a nearly fourfold decrease in river mineralization was observed as it mixed with and was diluted by Lake Erie water. The extent of lake intrusion is affected by stream gradient, bathymetry, wind-tide, seiches and fluctuations in streamflow and lake level.

Comparison of Estuaries with Inland Wetlands

Estuaries and coastal wetlands differ in several ways from inland wetlands. The coast is subject to temporary, short-term water level changes. Seiches and storm surges affect the wetlands adjacent to shorelines of western Lake Erie and the lower Detroit River by raising or lowering the lake level as much as 2 m in a single day. Long-term cyclic water level changes, related to water budgets of the lake basins, also affect the coasstal wetlands. Such fluctuations, occurring over a period of approximately 7 to 10 years, may cause vegetation dieback, erosion of the wetlands, or lateral displacement of the vegetative zones of wetlands. Many coastal wetlands, such as those along western Lake Erie, are exposed to relatively high wave energy. Such is not the case in the more quiescent inland wetlands.

Coastal wetlands along the Great Lakes do not appear to exhibit senescnece, i.e., the aging process associated with inland freshwater wetlands. This process leads from open ponds to densely vegetated marshes, and eventually to dry fields. Because of the fluctuating water levels of the Great Lakes, constant rejuvenation of wetland communities occurs. As a consequence, diagrams in textbooks illustrating the gradual senescence of freshwater wetlands are more applicable to inland wetlands of the glaciated Midwest than to the Great Lakes coastal wetlands. Many inland freshwater wetlands undergo senescence and terrestrialization as a result of the formation of secondary and tertiary peat deposits. Peat is not common in coastal waters, but occurs in some lagoons. Coastal wetlands often display a diversity of landforms not normally encountered in other wetland environments. Owing to changes in the water levels of the Great Lakes since the retreat of the Pleistocene ice sheets, landforms such as barrier bars, deltas, beachs, spits, lagoons, and natural levees have been deposited or formed along the shoreline. Many of these geomorphic features promote the formation of wetlands, each with distinctive features, which results in the great variety and diversity of coastal wetlands found in the Great Lakes region.

Function and Value of Estuaries and Coastal Wetlands

Great Lakes estuaries and coastal wetlands are highly productive, diverse communities which i nterface between terrestrial and aquatic environments. The most obvious and unique feature of these wetlands is their characteristic vegetation, which provides a diverse community structure offering cover and food for the animal components of the system. Because of the ability of this vegetation to slow the flow rate of water passing through, wetlands are valuable for erosion control, trapping sediments before they reach the open lake, and attenuating the force of moderate waves to lessen their destructive power. However, intense lake storms can uproot macrophytes and eventually destroy wetlands. The same vegetation provides a natural pollution abatement mechanism by serving as a filter for coastal tributaries by reducing the quantity of nutrients and toxic pollutants being washed into the Great Lakes. Coastal wetlands are highly valued as recreational sites for activities such as hunting, trapping, fishing, boating access to larger bodies of water, birdwatching, and general aesthetic enjoyment. The combination of recreational desirability, agricultural and residential potential, and the proximity of estuaries and coastal wetlands to larger bodies of water have contributed to their status as endangered environments (Fig. 8). Their unique properties are susceptible to numerous natural and human-caused environmental disruptions that are now causing coastal wetlands to disappear at an alarming rate.

Estuaries of the Great lakes are multi-functional in nature because these environments are part of both the upland and the open-water ecosystems. It is the interface with the lakes that multiplies the wetland functions and contributes to their dynamics. In general, a multi-functioning wetland tends to have a higher value than those with narrower functions. However, coastal wetlands which are isolated by barriers or degraded by factors such as land drainage or high water may exhibit fewer functions and therefore have lower value. Coastal streams

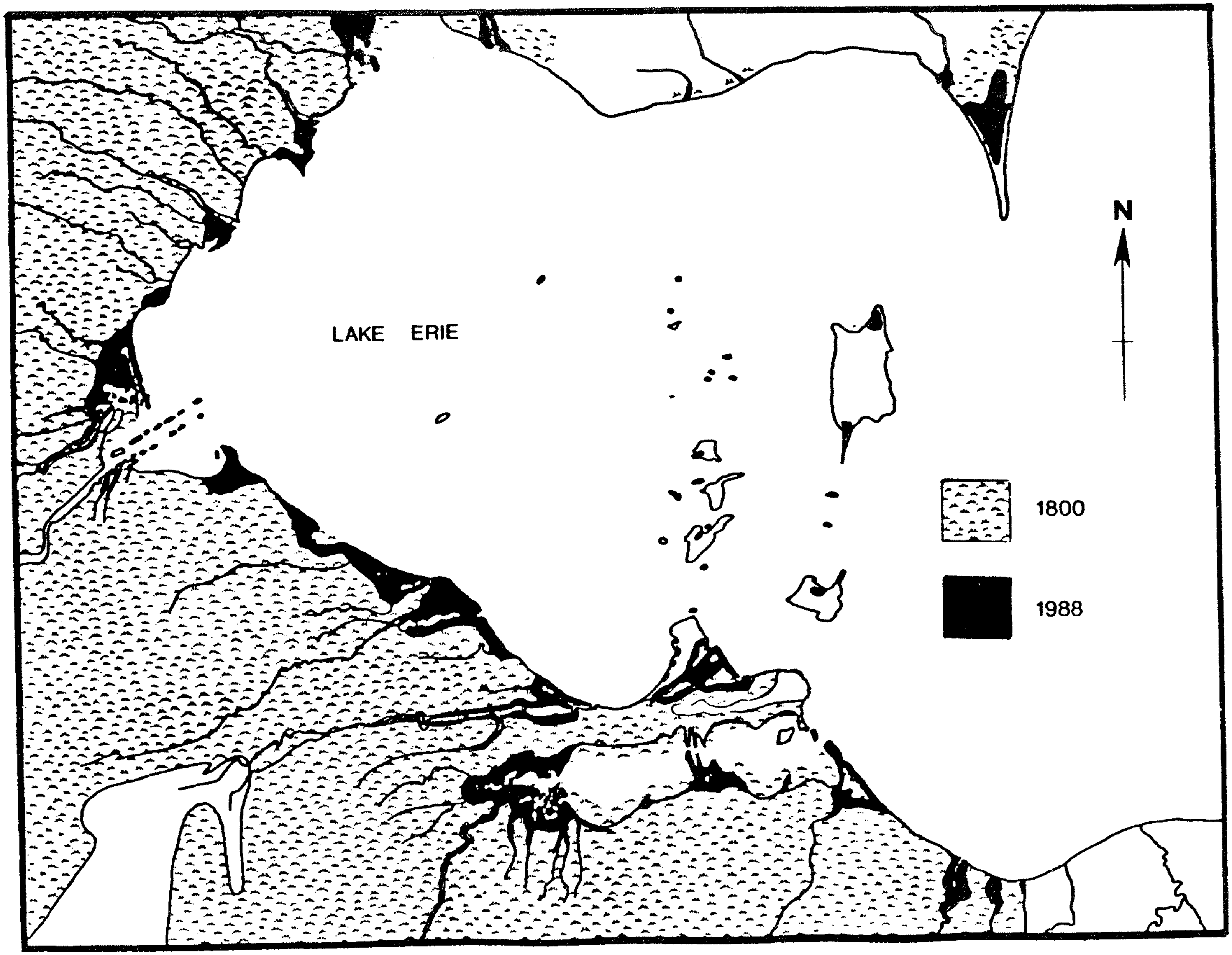

Figure 8. Loss of coastal wetlands surrounding western Lake Erie 1800-1988.

and waterways enhance the interactions, whereas obstacles such as dikes result in coastal wetland fragmentation and loss of function. The effect of long-term lake level changes on the function of the coastal wetlands can also be significant. Function loss, then, can result from both upland-derived and lake-derived forces.

CULTURAL IMPACTS

The Great Lakes and the Lake Erie of today have been greatly modified from their natural condition, in terms of appearance of the coastline and of water quality. The Great Lakes were recognized by the first European settlers to the region as a natural concourse for colonization and trade (see Burns 1985). The region was also rich in natural resources, including timber, ores, furs, and fertile soils.

The growth of Ohio's population since the early 1800s (Fig. 9) exemplifies the population growth throughout the entire Great Lakes region and reflects the tremendous exploitation of the region's resources which has occurred over the past 200 years (see Burns 1985, and Rousmaniere 1979). The diversity of major cargoes handled at the eight Ohio ports on Lake Erie in 1986 and 1987 (Table 6) demonstrates the continued vital importance of the lake as a transportation route for ensuring the industrial and economic health of the basin.

The early development of commerce, particularly the availability of cheap raw materials for making steel, resulted in large concentrations of heavy industry and large metropolises, including Buffalo, Cleveland, and Toledo, on Lake Erie's shores. The lake was assumed by most to have an infinite capacity to receive wastes without adverse effect, and municipalities and industries discharged large amounts of a great variety of byproducts into its tributaries or directly into the lake itself. By the late 1950s and 1960s this practice had resulted in many noticeable changes in the appearance of the lake, such as discoloration by chemical effluents and the growth of algal mats which washed up on public beaches, as well as in the make-up of its biota, including the fish and invertebrates (Cap and Frederick 1981). Disposal of untreated human wastes into the lake caused health hazards due to bacteria and viruses, and most public beaches were closed. In industrialized areas persistent toxic and harzardous chemical wastes accumulated in the sediments of the lower reaches of rivers, in harbors, and in other areas near shore. Some flammable chemical wastes floated on the surface and made possible the infamous fires on the lower Cuyahoga River in Cleveland in the 1960s. Some localities were so severely polluted and so devoid of fish during that period that the popular press declared Lake Erie to be "dead." The magnitude of the pollution of Lake Erie has been described in detail in several books, including *Erie, the Lake that Survived* by Burns (1985), and *The Enduring Great Lakes*, edited by Rousmaniere (1979).

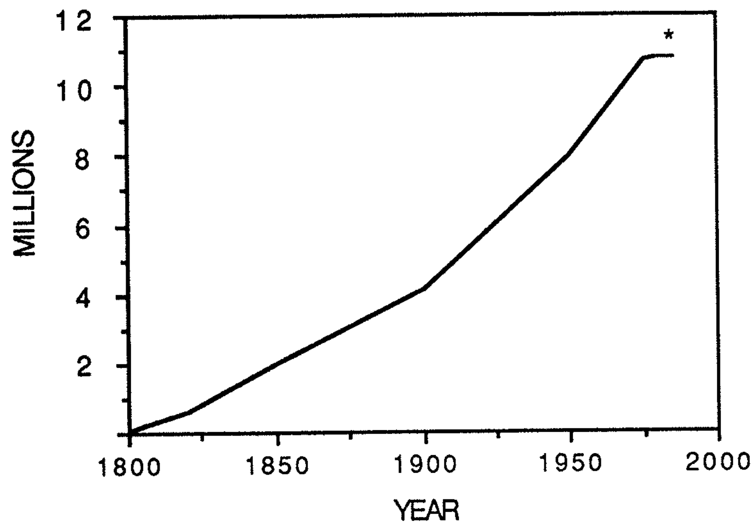

Figure 9. Population growth in Ohio since 1800.

Table 6. Major cargoes handled at Ohio's eight Lake Erie ports, 1986-1987 (Ohio Dept. Transportation 1987).

Toledo	General cargo, coal, iron ore, bulk liquids, grains, petroleum, dry bulk, fertilizers, project cargoes
Sandusky	Coal, sand, limestone, gypsum ore, road salt, potash
Huron	Grain
Lorain	Taconite, sand, aggregates, millscale, limestone, potash, coal, coke
Cleveland	Steel, general cargo, dry bulk
Fairport Harbor	Limestone, ore, salt, sand, gravel
Ashtabula	Ores, stones, newsprints, coal, bulk cement, bulk & general cargo
Conneaut	Coal, coke, iron ore, limestone, coke breeze

Table 7. Some of the substances included on the International Joint Commission's 1986 "working list" of chemicals in the Great Lakes Basin.

PESTICIDES

Insecticides

Halogenated[a] -- aldrin, chlordane, DDT (DDD, DDE), dieldrin, endosulfan, endrin, heptachlor, heptachlor epoxide, lindane and congeners, toxaphene

Organophosphorus/carbamate[b] -- carbofuran, chlorpyrifos, diazinon, fonofos, malathion, terbufos

Herbicides

Triazines[b] -- atrazine, cyanazine, metribuzin, simazine

Others[b] -- 2,4-D, 2,4,5-T, alachlor, linuron, metolachlor, trifluralin

OTHER ORGANICS[c]

alkylated tins[b], benzene, chlorinated benzenes, chlorinated phenols, chlorinated PAHs, chlorinated toluenes[b], 1,2 dichloropropane, ethylbenzene, halogenated ethanes, halogenated ethylenes, halogenated methanes, isophorone, N-nitrosodiphenylamine, polychlorinated biphenyls, phenol, polynuclear aromatic hydrocarbons (PAHs), phthalate esters, 2,3,7,8-tetrachlorodibenzo-p-dioxin, toluene, xylenes[b]

METALS[a]

antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium

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[a] Only those compounds on U.S. EPA list of 129 Priority Pollutants are shown.
[b] None are U.S. EPA Priority Pollutants.
[c] On U.S. EPA list of 129 Priority Pollutants unless footnoted

Federal (U.S and Canadian) as well as state and provincial legislation in the 1960s and 1970s, along with the Great Lakes Water Quality Agreements of 1972 and 1978, began the process of reducing or eliminating many pollutants to Lake Erie. Today the International Joint Commission (IJC) maintains a "Working List" of more than 350 pesticides, other organic compounds, and metals in the Great Lakes Basin, which include the 129 "priority pollutants" designated by the U.S. EPA (Great Lakes Water Quality Board 1987). Some of these are listed in Table 7. Eleven persistent, toxic chemicals or chemical groups which are widespread throughout the Great Lakes (Table 8) have been designated by the IJC as "critical pollutants" which need the most immediate remedial action.

Concurrent with the growth and impact of industry and commerce along the shores of Lake Erie, the watersheds draining into the lake were also tremendously modified. Trautman (1981) described the pristine forests and streams characteristic of the Lake Erie basin at the time of the first European explorations and early settlements:

> Overwhelming evidence indicates that between 1750-1800 forests covered most of the Ohio Country, leaving the remainder in marshes, swamps, brush, 'bowling greens,' sandy beaches, and in wet,dry, tall grass, and wild plum prairies. . . Prior to 1800 the living and dead vegetation covering the Ohio Country was sufficient to prevent erosion of soil except in restricted areas along stream banks, beaches and steep hillsides. . . The streams were narrow and deep, they contained much brush and down timber but where shaded there was little aquatic vegetation. The waters were normally clear, containing little soil in suspension except during some freshets and floods. The bottoms of the waters were free of clayey silts, and were largely composed of sand, gravel, boulders, bedrock, and organic debris.

Most of this terrestrial forested ecosystem was radically transformed over the next 150 years, particularly in the southwestern drainage to the lake, to a man-managed agroecosystem which contains only relict farm woodlots and "green

Table 8. Substances in the Great Lakes designated as "critical pollutants" by the International Joint Commission (Great Lakes Water Quality Board 1987).

Total polychlorinated biphenyls (PCBs)
DDT and metabolites
Dieldrin
Toxaphene
2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD)
2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-TCDF)
Mirex
Mercury
Alkylated lead
Benzo(*a*)pyrene (B(*a*)P)
Hexachlorobenzene (BHC)

corridors" along streams. Of the period between 1851 and 1900 Trautman (1981) states: "Each year the amount of land increased which had been drained, ditched and/or tiled. . . Inorganic and organic pollutants increased greatly in number and amount. Clayey silt-bearing waters became conspicuous and widespread, and the silting over of stream and lake bottoms developed rapidly." Similar practices were prevalent as well in the western Canadian drainage of the lake.

The once-extensive system of marshes, swamps and wetlands which prior to 1850 covered an area of approximately 4,000 km^2 (1,540 sq. miles) between Vermilion, Ohio and the Detroit River and extended into Indiana along the Maumee River, was largely converted to highly-productive agricultural land during the next 100 years by draining, filling and diking. Today only about 150 km^2 of coastal marshes and wetlands remain (Herdendorf 1987).

Of the five Great Lakes basins, the Lake Erie basin presently has the smallest proportion of forested watershed (17%) and the highest proportions of agricultural (59%) and urban/industrial (9%) land-use (Table 9). The other four Great Lakes have at least 50% of their watersheds forested, no more than 32% in agriculture, and 4% or less in urban/industrial land-use. The most extensive agricultural land-use in the Great Lakes is in the southwestern drainage of Lake Erie (northwestern Ohio, northeastern Indiana and southeastern Michigan). In the northwestern Ohio watersheds in 1976, agriculture accounted for 77% of the land area, forests for only 8% (Baker 1988).

The intensive agriculture in the southwestern Lake Erie drainage has resulted in the export via tributaries of thousands of tons of sediment and its associated pollutants annually to Lake Erie's harbors, estuaries, and nearshore areas. Rural nonpoint source pollution (largely agricultural) is responsible for 51% of the total phosphorus delivered to the lake (Yaksich 1983). Rivers in the region also experience the highest residual concentrations of the herbicides used with corn and soybeans found anywhere in North America (Baker 1988). Phosphorus, as the limiting nutrient in Lake Erie, plays a major role in determining the amount of algae produced annually in the lake and ultimately the extent of anoxia (lack of oxygen) which develops each summer in the deeper waters of the central part of the lake. The U.S. and Canada have developed ongoing programs to reduce the export of phosphorus to the lake (Great Lakes Phosphorus Task Force 1985). Billions of dollars have been spent in both countries to reduce phosphorus inputs from point sources, such as municipal treatment plants, using such measures as phosphate detergent bans imposed by Michigan, Indiana, New York, Ontario, and in 1988, Ohio, and setting a maximum limit on phosphorus in waste treatment effluents of 1.0 mg/L. From all sources combined, the total amount of phosphorus entering Lake Erie on an annual basis is over twice the amount entering Lake Michigan and about three times the amount entering Lake Huron (Table 10), despite Lake Erie's much smaller water volume and shallower basin and thus its much more limited capacity to utilize the excessive phosphorus without deleterious effects.

Table 9. Land use in the Great Lakes Basin (Internat. Joint Commission 1980).

Lake	Forest	Agricultural	Urban/ Industrial	Other[a]
Erie	17	59	9	15
Superior	95	1	0.2	4
Huron	66	22	2	10
Michigan	50	23	4	23
Ontario	56	32	4	8

[a] Scrub, brush, wetland

Table 10. Estimated total phosphorus load (metric tons) to lakes Michigan, Huron, and Erie, 1975-1982 (Lesht and Rockwell 1987).

Year	Michigan[a]	Huron[a]	Erie[a]	Erie[b]
1975	7,049	3,641	12,722	18,246
1976	6,656	4,145	14,336	18,668
1977	4,666	3,106	13,496	19,312
1978	6,245	4,598	18,351	13,312
1979	7,659	4,224	10,861	12,530
1980	6,574	4,650	13,775	9,863
1981	4,091	2,824	9,372	--
1982	4,084	4,032	11,269	--

[a] Data from International Joint Commission
[b] Data from Yaksich et al. (1982)

Measures aimed at point sources of phosphorus have been successful in reducing the total loading of phosphorus to the lake; however, nonpoint source (mostly agricultural) controls have been much harder to legislate and to implement. Most of the effort in the nonpoint source arena has involved the sponsoring of conservation tillage demonstration projects within the Lake Erie basin, both in the U.S. and Ontario, with the purpose of documenting the effectiveness of reduced tillage methods in slowing soil erosion and phosphorus loss while maintaining profitability for the farmer (Honey Creek Joint Bd. Supervisors 1982, National Assoc. Conserv. Districts 1985). Most aspects of the demonstration programs have been successful, yet farmers and landowners on the whole have been slower to adopt conservation tillage and other "best management practices" (e.g., stream bank erosion control, and livestock waste management) than desirable to measurably reduce phosphorus loading to the lake.

Unquestionably, the extensive urban and industrial development of the Lake Erie shore and the land-use changes in its drainage basin over the past 200 years have resulted in major environmental problems for the biota of the lake (see the papers in this volume by Johnson, Klarer, Monaco and Lorenz, and Stuckey) as well as for the millions of people who rely on the lake for drinking water, fish, recreation and industrial uses. Of 50 pollution issues presented for prioritization to representatives of the coastal zone management offices and National Sea Grant College Program institutions in the Great Lakes states (Harvey and Zacherle 1984), the following issues were ranked as the ten most important (in order of decreasing importance): (1) Effects of synthetic organic chemicals on the marine environment, (2) effects of ocean dumping of sewage sludge (probably in reference to open lake dumping of dredge spoils), (3) deterioration of the Great Lakes as a drinking water source, (4) cumulative effects of man-induced changes on selected coastal areas and estuaries, (5) adequacy of baseline information, (6) effects of agricultural nonpoint source contamination in estuaries and coastal areas, (7) long-term effects of PAHs and their metabolites in the marine environment, (8) effects of nutrient loading on estuaries, coastal zones and the Great Lakes, (9) effects of pipeline discharge of industrial waste, (10) effects of urban and suburban nonpoint source contamination in estuaries and coastal areas.

The International Joint Commission has identified several emerging issues for the Great Lakes:

• New persistent toxic substances, which will be introduced to the Great Lakes ecosystem in increasing quantities, "with production capacity and consumptive demand greatly exceeding government capacity for regulation and enforcement."

• Biotechnology, which holds the potential for solving pollution problems, such as creation of wetlands for waste treatment, and new technologies for toxic waste disposal and recovery. Genetically engineered bacteria could be developed for improving the performance of water and sewage treatment plants, as well as for modifiying, enhancing and manipulating species "to sustain continued high levels of resource productivity," and for reducing the dependence of agriculture on chemical pesticides.

• Waste management, including the handling and disposal of wastes from agriculture, mining, industry and municipalities; as well as the threat to groundwater and surface water by leachate from both inactive and currently operating dumpsites.

• Deficiency of present institutional arrangements to respond adequately to either the increasing complexity of emerging Great Lakes issues or their consequences.

• Enforcement and surveillance to prevent unregulated discharges and to provide compliance monitoring. "While public concerns and expectations for the environment will result in increasaed legislative and regulatory responses, the ability to implement the approaches and achieve the desired goals will continue to be severely constrained by a lack of human and financial resource commitments."

• Allocation and beneficial uses of Great Lakes resources in the presence of competing and conflicting demands.

• A growing policy role for corporations in achieving the Great Lakes Water Quality Agreement objectives. "A major challenge for industry over the near term will be the extent to which innovation and clean technology is applied to production activities. . . Governments cannot implement the Agreement alone and, therefore, it will be essential that this emerging trend of corporate assistance be encouraged and supported to bring additional expertise and resources to bear on water quality problems in the Great Lakes."

• Heightened public concerns over the state of the Great Lakes ecosystem, and heightened public expectations of both industry and governments to remedy the pollution problems in the Great Lakes (Great Lakes Water Quality Board 1987).

In order to launch a concerted and effective effort toward improving the water and sediment quality in the most severely impacted areas of the Great Lakes, the International Joint Commission has established 42 "Areas of Concern" (AOCs) in the Great Lakes and their connecting channels. Those along Lake Erie (Fig. 10) include the Detroit River and the lower 2.6 miles of the River Raisin in Michigan; the lower parts of the Maumee, Black, Cuyahoga and Ashtabula rivers and their harbors in Ohio, the Buffalo River in New York, and Wheatley Harbour in Ontario. The pollutants in these AOCs have come from rural and urban nonpoint sources, industrial and municipal point sources, combined sewer overflows and waste disposal sites. Present-day major sources of contamination include "in-place pollutants" which are trapped in or slowly released from sediments in the AOCs. Table 11 lists the major types of problems in the Lake Erie AOCs (Great Lakes Water Quality Board 1985). All of the problems probably exist to some extent in each AOC.

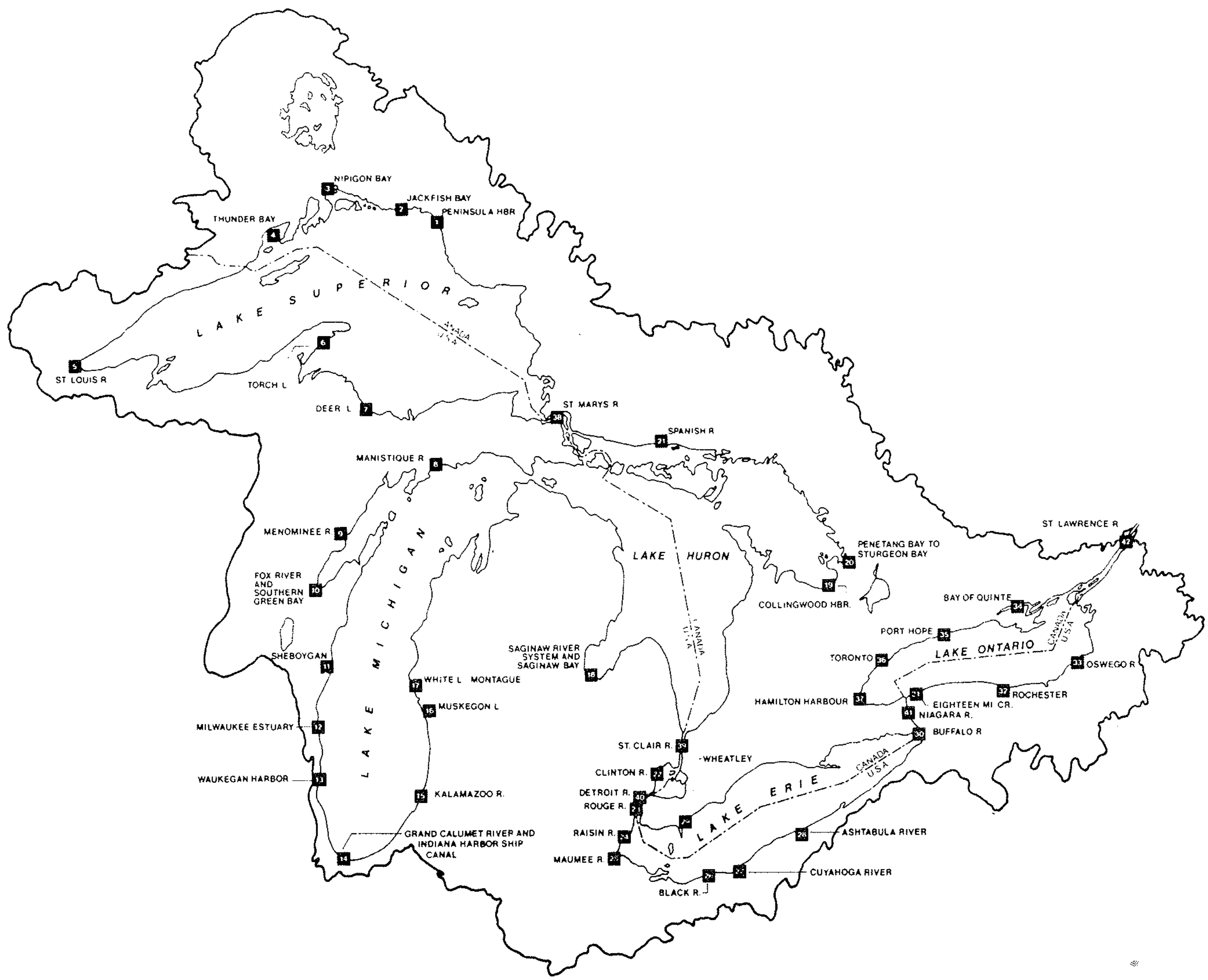

Figure 10. Areas of Concern in the Great Lakes Basin (Great Lakes Water Quality Board 1987).

A coordinated and formalized effort to improve each of the 42 AOCs is being developed by means of a Remedial Action Plan (RAP). These plans are drawn up by RAP committees comprised of members from local, regional and state or provincial governments, from industries, environmental organizations, and the public at large. Of the Lake Erie AOCs as of early 1988, the only RAP that had been submitted to the IJC's Water Quality Board for review and potential future implementation was that for the River Raisin. That river, which enters the lake at Monroe in the southeastern corner of Michigan, contains high concentrations of PCBs in sediments, water and fish. Consequently, a state fish consumption advisory is in effect for that AOC. The state department of natural resources has included several landfills, waste lagoons and industrial sites within the AOC on a priority cleanup list. The proposed RAP will compile existing data for use in developing a plan to restore fishing in the AOC; it will determine data deficiencies and recommend new investigations to help define the problems and sources; and further, it will recommend appropriate remedial actions (Great Lakes Reporter 1988).

Some parts of the Lake Erie ecosystem have shown improvement since the early 1970s, when many of the programs to reduce or eliminate pollution from point sources were first initiated. The apparent quality of the lake's water has greatly improved, as judged by the reduced presence of the summer algal mats and the reopening of beaches all along the lakeshore. The high productivity of recreational fish species such as yellow perch and walleye in the western basin, and less so in the central basin, have led to the claim that Lake Erie is the "walleye capitol of the world." In 1982 recreational boating and fishing together comprised an approximately $19 million annual industry in the central basin, and the value of private-boat and charter sportfishing in the western basin alone in 1981 was $155 million (Hushack et al. 1985). While localized severe pollution remains, particularly in the Areas of Concern, the open lake and many nearshore regions are showing sign of improvement, as measured by reduced fecal bacterial counts and a trend toward lower mean annual phosphorus and chlorophyll *a* concentrations in the open lake. The complexity of the recovery

Table 11. Major types of pollutants in the Lake Erie Areas of Concern (Great Lakes Water Quality Board 1985).

Type	Area of Concern
Conventional Pollutants	All
Heavy Metals	All
Toxic Organics	All
Contaminated Sediments	All
Impacted Biota	All except Wheatley Harbour
Fish Consumption Advisories	All except Maumee R. and Cuyahoga R.
Aesthetics	All except Ashtabula R., Buffalo R., and Wheatley Harbour
Eutrophication	Maumee R., Wheatley Harbour, Detroit R.
Beach Closings	Detroit R.

process is pointed out, however, by the less encouraging response of other important indicators, including an apparently increasing or stabilized oxygen depletion rate in the central basin hypolimnion and a steadily increasing open-lake nitrate+nitrite concentration (Great Lakes Water Quality Board 1987). In the presence of modern civilization, Lake Erie cannot be returned to its pristine condition; to return it to an acceptable quality will require a long-continuing major investment of funds and human resources committed to scientific investigation, technological advancement and concerted management.

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PALEOGEOGRAPHY AND GEOMORPHOLOGY

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PALEOGEOGRAPHY

Paleozoic Era

The bedrock of the Lake Erie Basin was formed during the middle portion of the Paleozoic Era, that span of time from 300 to 500 million years ago. The varying depths of Lake Erie's three basins are attributed to differential erosion of the bedrock by preglacial streams, glaciers, and post-glacial lake processes. This erosion is largely in response to the hardness and structure of the underlying formations. Lake Ontario is separated from Lake Erie by resistant Silurian limestones and dolomites of the Niagara Escarpment. However, the central and eastern basins of Lake Erie are underlain by nonresistant shale, shaly limestone, and shaly sandstone of Upper Devonian Age, which dip gently to the southeast. Inland along the south shore, eastward from Cleveland, the Portage Escarpment, composed largely of Mississippian sandstone, rises 100 m above the level of the lake and forms the northwest front of the Appalachian Plateau (Fig. 1).

An outcrop belt of Devonian shales swings inland between Cleveland and Sandusky and continues southward through central Ohio in response to the structural pattern of the bedrock. The shallow western basin is underlain by Silurian and Devonian limestones and dolomites on the northward plunging end of the Findlay Arch of the Cincinnati Anticline. Glacial erosion had relatively slight effects on these resistant rocks other than to form impressive grooves such as those found on Kelleys Island and the Bass Islands. The glacial scour was probably controlled by the preglacial stream valleys, resulting in the shallow basin and the island chains. The bedrock in the islands area of western Lake Erie is sedimentary in origin and was deposited as lime muds in shallow, warm Silurian and Devonian seas which covered the region from 410 to 375 million years ago. The existence of evaporite beds such as halite (rock salt) and gypsum indicate that several isolated basins occurred at this time. Enclosed by barrier reefs, the waters were repeatedly evaporated to form the massive salt deposits. The salt beds which are currently being mined 700 m below the lake bottom at Cleveland were deposited during the Silurian Period. Following the erratic fluctuations in the Silurian climate conditions became more stable in the Devonian Period. The warm, clear waters of the Devonian sea can be inferred from the abundant fossil corals and other invertebrates found in the rocks on Kelleys and Johnson islands.

While the shallow Devonian sea occupied the islands area, the Appalachian Mountains were being built to the east. Recent studies of plate tectonics indicate that the collision of the northwest coast of Africa and that of eastern

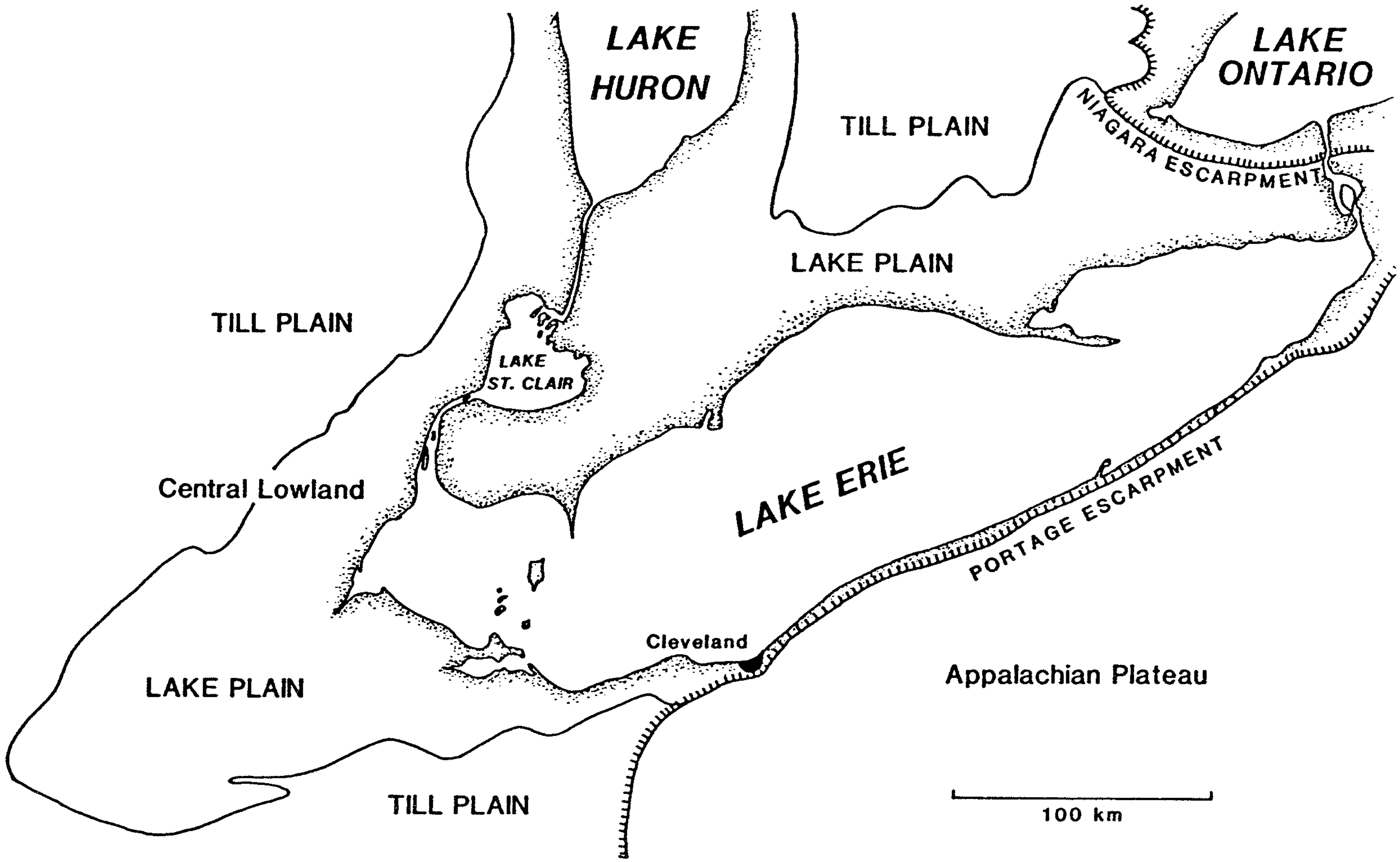

Figure 1. Physiographic regions of the Erie Basin.

North America caused the sediments in the Appalachian geosyncline to be folded into a formidable mountain chain. Erosion of these newly formed mountains resulted in the deposition of shales and sandstones which cover the limestones in central and eastern Lake Erie. Much of the south shore of central Lake Erie is a wave-cut bluff composed of hard, black shale (Ohio Formation) of Upper Devonian Age.

Following the deposition of the black Devonian shales, during the Mississippian and Pennsylvanian periods, new deltas were built from the north into the shallow mid-continent sea where Lake Erie is now located. Sandstones and shales were deposited inland from what is now the lake's south shore to form the red beds of the Bedford Shale, the ridge-forming strata of the Berea Sandstone and the "pudding stone" quartz pebbles of the Sharon Conglomerate. A long period of erosion ensued following the deposition of the Upper Paleozoic rock and little is known of the geologic processes for over 250 million years. Here, the geologic record stops until the glacial deposits of the Pleistocene Epoch.

Pleistocene Epoch

Geologically speaking, the last glacier retreated from the Lake Erie basin in very recent times -- less than 12,000 years ago. The glacial history of the basin starts much earlier, though; about a million years ago the first ice sheets invaded the Lake Erie Region from the northeast. As the ice overrode the resistant limestone which now forms the brink of Niagara Falls, it dug deeply into the softer Devonian shales of western New York. The ice front was obstructed by the steeply rising Portage Escarpment (Fig. 1) which lies a few kilometers inland of the present south shore of the lake between Buffalo and Cleveland. Thus the glacier was deflected to the west along the outcrop of the soft shale. These shales were scoured to form the deep bottom of the narrow eastern basin (see Overview Chapter). Farther west, where the width of the shale belt is greater, glacial erosion resulted in the broader -- but shallower -- central basin. The western basin owes its islands, reefs, and shallowness to the tough Devonian and Silurian limestones and dolomites which resisted glacial scour.

During the long period between the deposition of Paleozoic sediments and the first glacier advance -- approximately 250 million years -- an extensive river drainage system cut into the rocks. Several theories have been put forth on how this river system developed and what the drainage pattern looked like just prior to glaciation. The most plausible shows a divide running roughly east-west through the mid-portions of Ohio and Indiana (Fig. 2); south of this divide a major river system (Teays River) drained westward and into the preglacial Mississippi River, while to the north of the divide, drainage was through the basin which now holds Lake Erie and northeast along the ancestral St. Lawrence River valley (Spenser 1891). The preglacial topography of the Lake Erie basin has been inferred from test borings and seismic measurements of the sediments overlying the bedrock surface. Hobson et al. (1969) discovered a trellis-shaped stream pattern formed in the western basin (Fig. 3), with the islands and reefs standing as former hills between the trellis streams. The match between the preglacial drainage pattern inland from the shore and the pattern found offshore is exceptionally good which adds confirmation to the early work of Spencer. The main-trunk stream apparently entered the present lake basin from the northwest and exited in the vicinity of the Niagara River.

The Pleistocene glaciers followed these preglacial valleys, scouring them deeper and smoothing their meanders as they moved southwest. The end result was much broader and deeper stream valleys. Since the retreat of the last glacier, over 30 m of sediment have been deposited in many of the glaciated valleys to give the current Lake Erie a much smoother and flatter bottom than it had when water first filled the basin. As the ice sheets paused in their advance or retreat, moraines were built up of rock debris (till) at the ice margins. In places, end moraines were deposited in such a way as to dam the natural drainage and thereby form large lakes in the scoured depressions (Flint 1971). Lake Erie is the remnant of such a lake, which at its highest stage was 70 m above the present level of the lake. As the ice retreated, new outlets (Fig. 4) were uncovered and several lake stages were formed at successively lower levels.

The chronology of lake stages in the Erie basin relates a fascinating story of glacial action, movements of the earth's crust and erosion by the lake waters to form the lake we see today. Noted researchers including Leverett and Taylor (1915), Hough (1958, 1963) and Forsyth (1971) have contributed materially to our knowledge of the sequence of events which have taken place during the evolution of Lake Erie. The story begins nearly 15,000 years ago when the last Pleistocene glacier, known as the Wisconsin ice sheet, was forming the Fort Wayne Moraine in northwestern Ohio, northeastern Indiana and southwestern Michigan (Fig. 5). As the ice retreated from this moraine the first lake in the Great Lakes basin was formed between the glacier and its ridge.

Low, continuous sandy ridges within a few kilometers of the lake shore, in southeastern Michigan, northern Ohio and northeastern Pennsylvania, are the most conspicuous reminders of the former glacial lakes. These abandoned beaches have long been used by the people living near Lake Erie. Numerous east-west roads follow these ridges and many early homes were built on them. Each ridge represents an ancient beach formed along the shore of a former lake which once occupied the Lake Erie basin at an elevation higher than the present lake. Because these former lakes (Maumee, Arkona, Whittlesey, Warren, Wayne, Grassmere and Lundy) each had a different outlet and stood at a different elevation, each stage is marked by a separate set of beaches at a characteristic elevation. Beaches formed by a slowly falling water level are much more pronounced than those which have been totally submerged by a higher level. Because submergence permits the erosion of former beaches by waves and alongshore (littoral) currents, only three former beaches are easily recognizable, Maumee, Whittlesey and Warren (Fig. 6). At several places in northcentral Ohio where the former lake shore was rocky (such as Amherst,

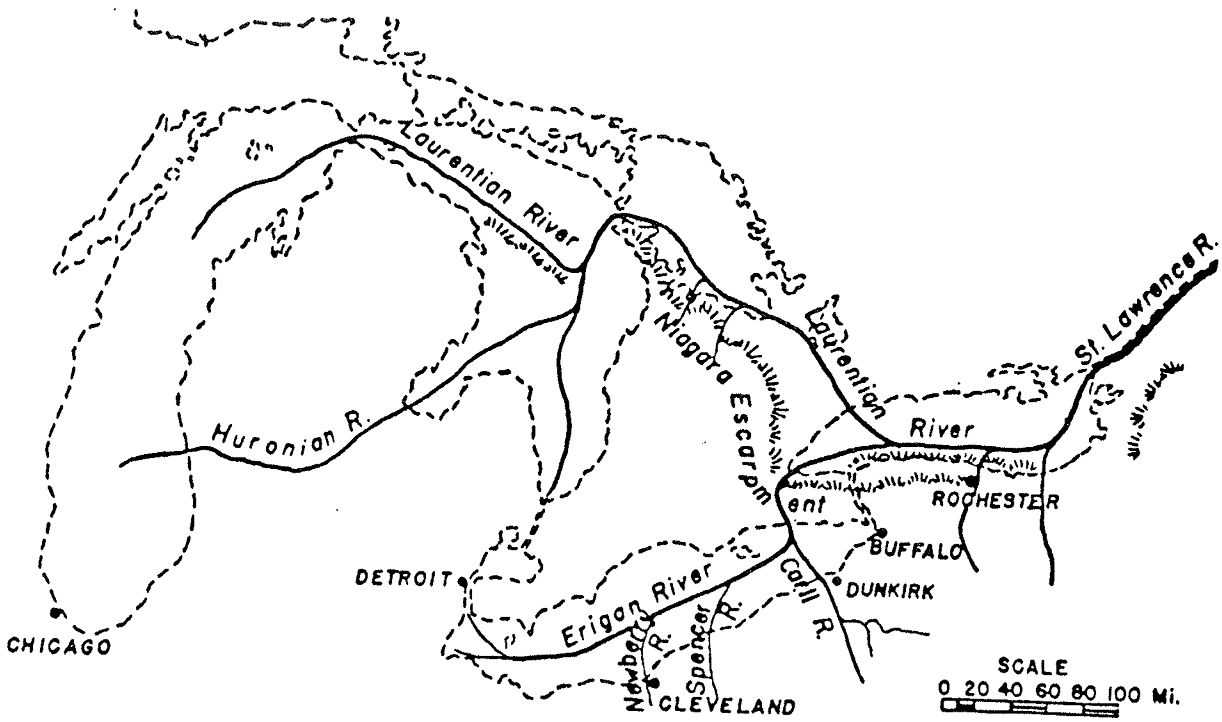

Figure 2. Preglacial drainage system of the Great Lakes region (after Spencer 1891).

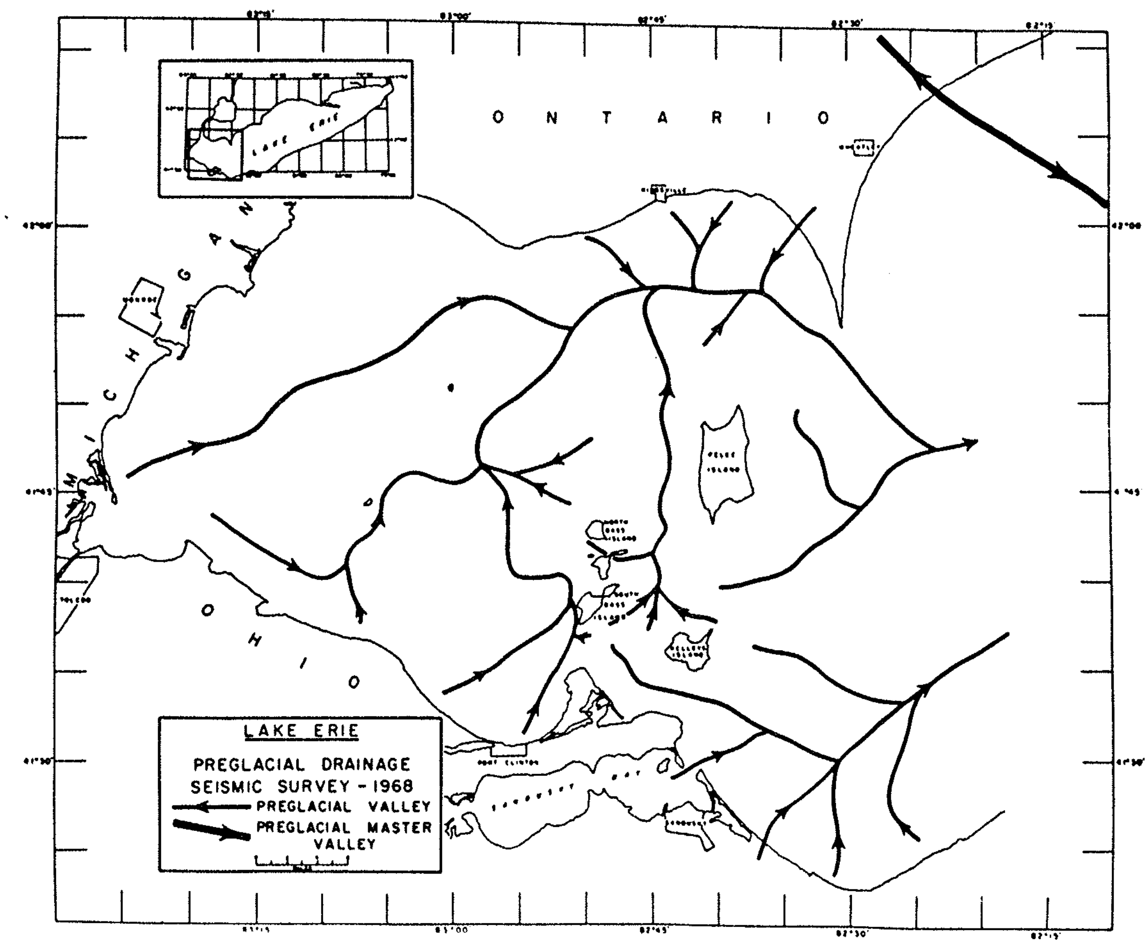

Figure 3. Preglacial drainage pattern of western Lake Erie Basin (after Hobson et al. 1969).

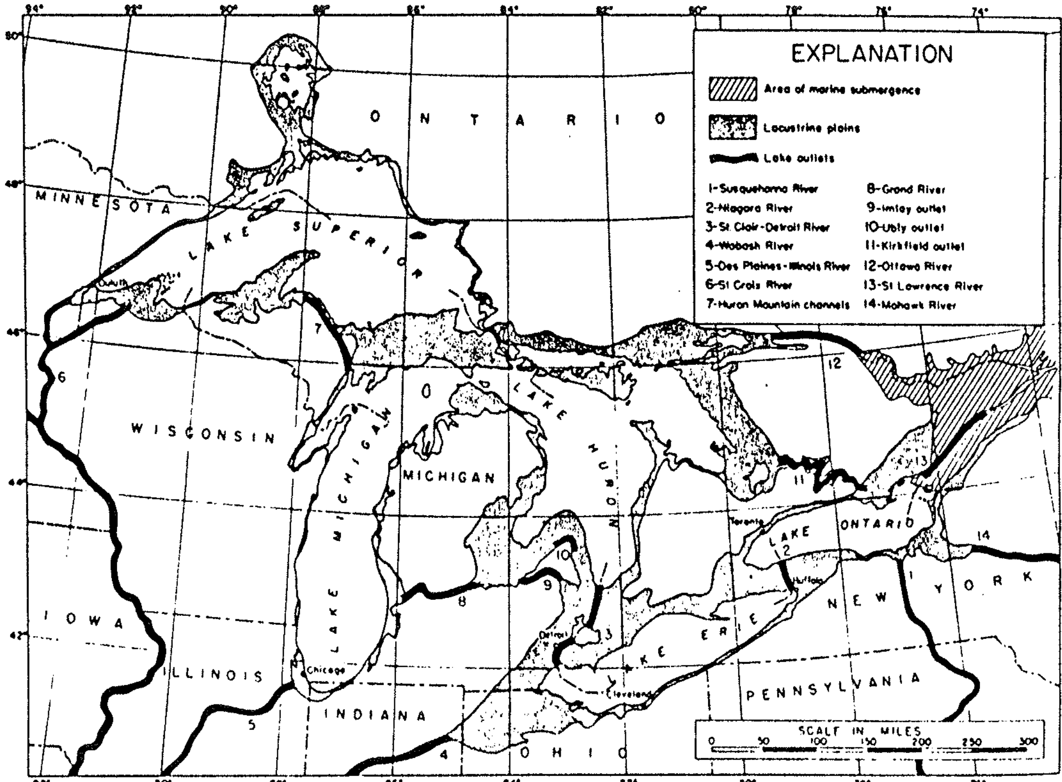

Figure 4. Outlets of the glacial lake stage in the Great Lakes Basin (after Leverett and Taylor 1915).

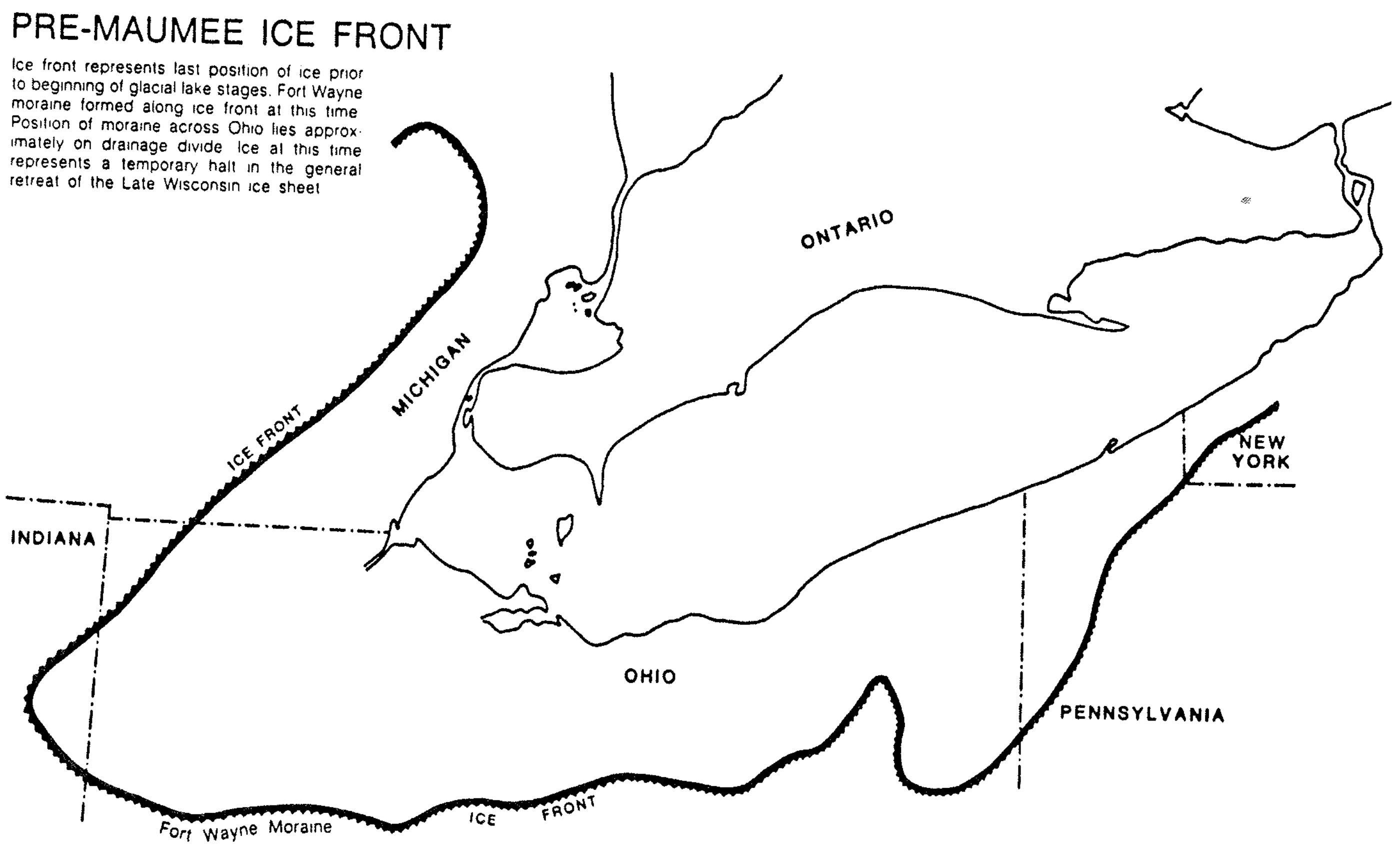

Figure 5. Pre-Maumee ice front.

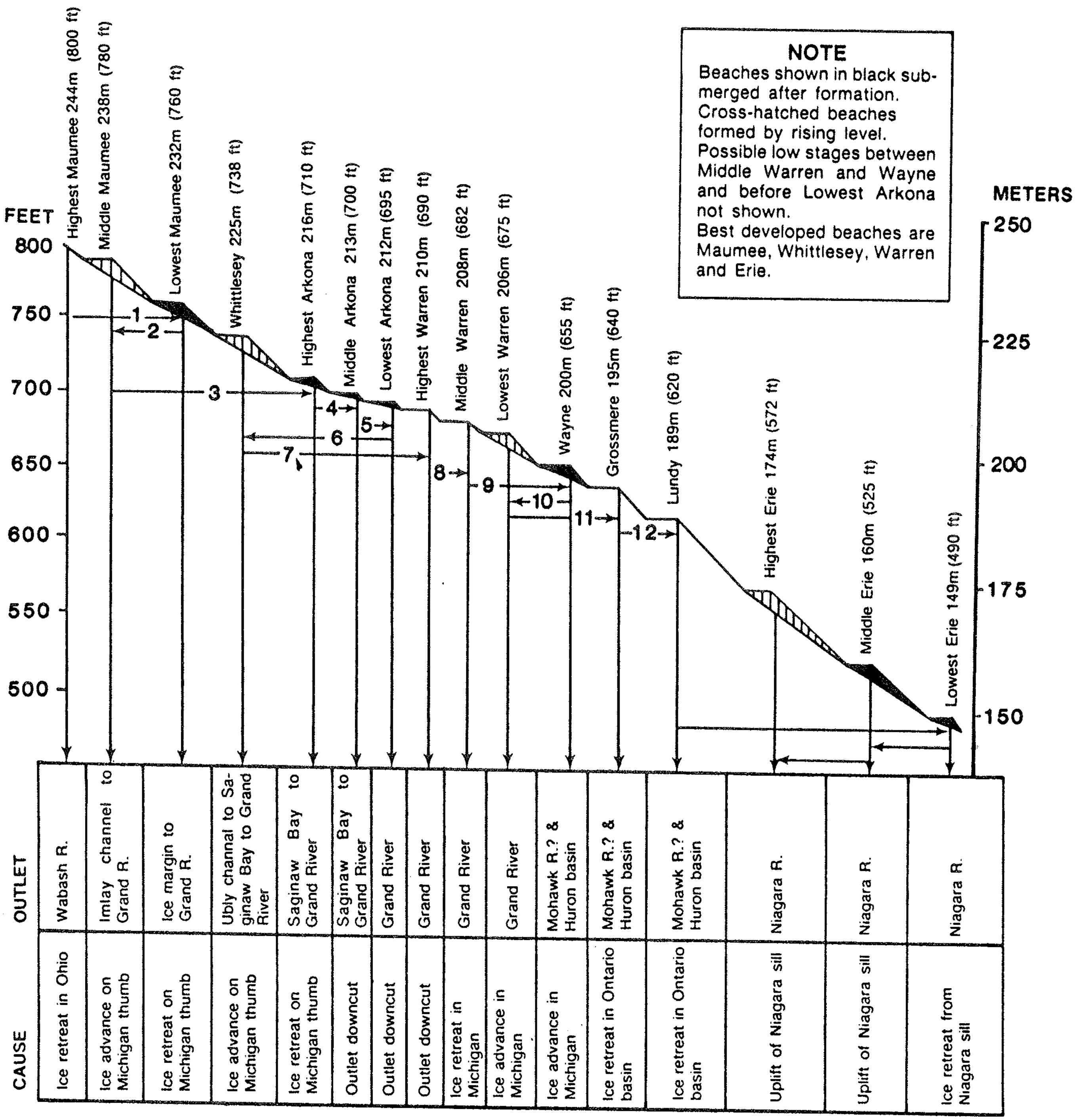

Figure 6. Chronology of glacial lake beach ridges in the Erie Basin.

Berlin Heights, and Castalia), spectacular cliff features resembling sea caves, arches and stacks can be seen.

Highest Lake Maumee (Maumee I). The highest stage of Lake Maumee, surface elevation 244-247 m above sea level, was formed when the ice front retreated from the Fort Wayne Moraine and occupied the position of the Defiance Moraine. Drainage was westward through the Fort Wayne outlet into the Wabash River. Fig. 7 shows the extent of Lake Maumee I and the inferred location of the glacial ice front at that time. Thus, this lake extended as far southwest as the present city of Fort Wayne, Indiana and drained via the Wabash and Mississippi rivers to the Gulf of Mexico.

Lowest Lake Maumee (Maumee II). The second and lowest stage of Lake Maumee, 232 m, resulted from ice retreat in Michigan opening the Grand River outlet (Fig. 8). Bottom deposits in Lake Erie indicate that during this stage the ice front stood between Avon Point, Ohio, and Point Pelee, Ontario. At Cleveland, it apparently reached across the present shore to the Portage Escarpment. The Euclid Moraine at this location most likely marks the position of the ice at that time. Another lobe of ice apparently stood in the western basin of Lake Erie at the same time, the front extending from Point Pelee south-southwest of Kelleys Island, then west to Catawba Point. It then curved southwestward toward Port Clinton and northwestward to Niagara Reef, and then occupied a curved position, convex southward and touching the present Michigan shore in the vicinity of Stony Point, Michigan.

Middle Lake Maumee (Maumee III). Advance of the ice in Michigan closed off the outlet of Lake Maumee II and raised the level to 238-241 m (Fig. 9). Waters then discharged through both the Imlay Channel in Michigan and through the Fort Wayne outlet again (Fig. 10). The ice in the Erie basin had retreated to the vicinity of Erie, Pennsylvania. A very wide sand and gravel bar extends across Lake Erie from Erie, Pennsylvania, to Long Point, Ontario. The ice front apparently occupied the position of this bar at this time during most of the ensuing lake stages. Coverage of such a large area by sand and gravel indicates the occurrence of a major frontal moraine system in this region.

Lake Arkona. Following the last stage of Lake Maumee, the ice again retreated in Michigan allowing water to flow into Saginaw Bay and lowering the level in three substages to 216 m, then to 213 m and finally to 212 m by minor ice movements and Grand River outlet downcutting in the Saginaw Bay area. During this stage the ice apparently retreated beyond the eastern basin of Lake Erie, since the Arkona beach extends to the eastern end of the present lake. General ice retreat throughout the Great Lakes Region brought an end to the Arkona stage. Some researchers, including Hough (1963), believe that the ice may have retreated far enough at this time to uncover outlets to the east lowering the level in the Erie basin an unknown amount, possibly below the present level of Lake Erie. This low stage has been named Lake Ypsilanti.

Lake Whittlesey. The next lake stage, following the Lake Ypsilanti stage, stood at 224 to 226 m above sea level (Fig. 11). This stage was created by ice damming the drainage and transferring outflow to the Ubly channel in Michigan. This is known as the Lake Whittlesey stage and is marked by the most pronounced abandoned beach ridges in the Lake Erie basin. During Whittlesey time the ice front apparently occupied the position of the Port Huron Moraine, which was built at this time. The ice front in the Erie basin probably again laid along the ridge from Erie to Long Point, Ontario. Because Lake Whittlesey existed for a comparatively long period, the ice front probably retained approximately the same position for an equal length of time. If so, it appears that the Port Huron Moraine could have been built at the same time merely by a pause in the general retreat of the ice. It also appears that the major portion of the ridge from Erie, Pensylvania across Lake Erie to Long Point, Ontario, formed at this time. Before the end of Lake Whittlesey the ice retreated somewhat in the eastern basin of Lake Erie but did not leave the basin entirely. This accounts for weak beach development east of Dunkirk, New York. Hough (1963) describes a possible low water stage following Lake Whittlesey which drained to the east, but this may fall between substages of Lake Warren.

Lake Warren and Lake Wayne. Ice retreat in Michigan closed the Lake Whittlesey stage and lowered the level to the highest Lake Warren stage at 210 m (Fig. 12). However, ice still occupied the eastern basin of Lake Erie at this time with the ice front again along the moraine from Erie to Long Point. Ice retreat in the Saginaw Bay area lowered the level to 208 m. Discharge during both levels was down the Grand River. A short time later a lowest Warren at 206 m may have occurred due to minor ice retreat and outlet down-cutting. Lake Warren was the latest stage in the Erie basin to produce conspicuous beach features. Water apparently stood at this level for a considerable length of time.

General ice retreat from the Great Lakes area occurred after the lowest Warren stage and another low water stage followed in the Lake Erie basin, the evidence of which is the buried St. David Gorge of the Niagara River. Following the retreat of ice from the Port Huron Moraine, there was a general readvance, but ice apparently did not progress as far southward as the moraine. Although the ice never invaded the Lake Erie basin again, it did readvance to the Niagara Falls area and the land south of Lake Ontario. At this time, the water in the Lake Erie basin was again raised to the lowest Warren level at 206 m, after a pause at the Lake Wayne level of 200 m. Lake Wayne probably drained through the Mohawk River to the east. Ice damming of that outlet caused the Warren waters to again discharge through the Grand River outlet.

Lake Grassmere and Lake Lundy. The end of the Lake Warren-Lake Wayne sequence was brought about by ice retreat, probably from the New York and Michigan areas, lowering the level to the Grassmere stage at 195 m and then to the Lundy stage at 189 m (Fig. 13). Some investigators believe the drainage continued eastward during these stages, while others contend that drainage was westward into the Lake Huron basin. Both the Lake Grassmere and Lake Lundy stages were brief as evidenced by weak and discontinuous beach features.

HIGHEST LAKE MAUMEE

Ice front at time of Highest Lake Maumee occupied position of Defiance Moraine and lake occupied area between Defiance and Ft. Wayne moraines draining into Wabash River. It is possible that ice had retreated previously and then re-advanced to the Defiance moraine so that original Highest Maumee may have been somewhat larger than shown. Ice at this time represents a temporary halt in general retreat of Late Wisconsin ice sheet. Maximum water depth of Highest Lake Maumee about 30m (100 ft.)

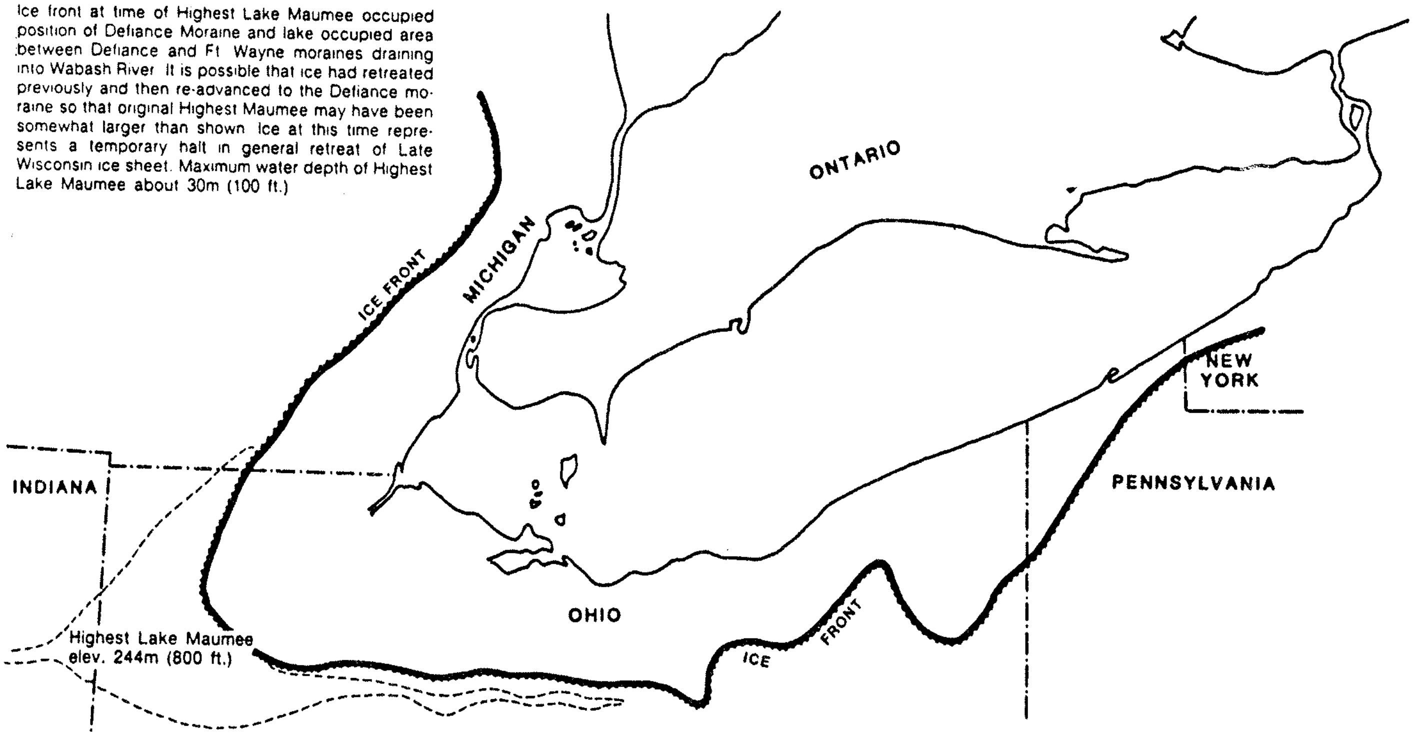

Figure 7. Highest Lake Maumee.

LOWEST LAKE MAUMEE

The second or lowest stage of Lake Maumee occurred when ice retreated from the Defiance moraine and opened a lower outlet near Imlay, Michigan draining westward into Grand River. Position of ice front marked by sand and gravel covered till ridges in Lake Erie. Lowest Maumee beaches formed approximately along Ft. Wayne and Defiance moraines. Beach along south shore ends at Cleveland. Maximum water depth of Lowest Lake Maumee near 76m (250 ft.).

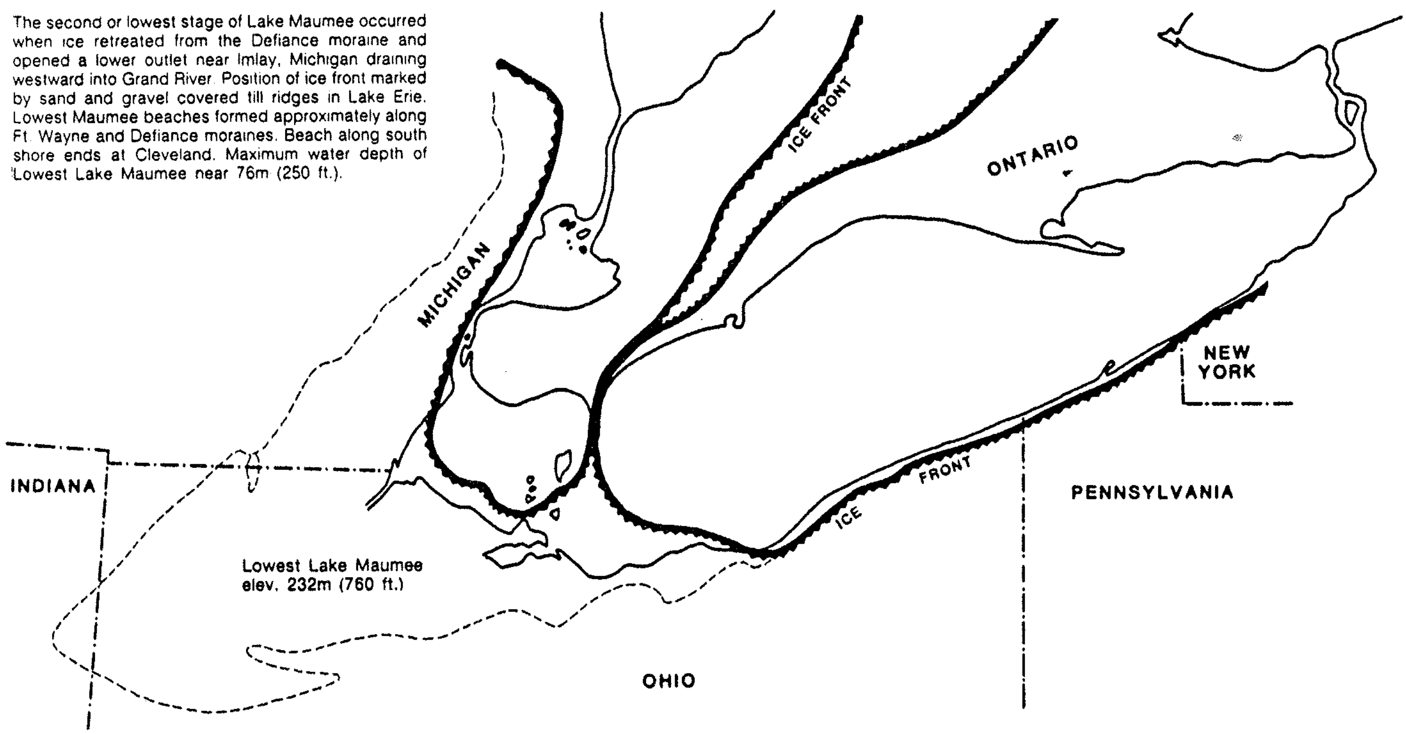

Figure 8. Lowest Lake Maumee.

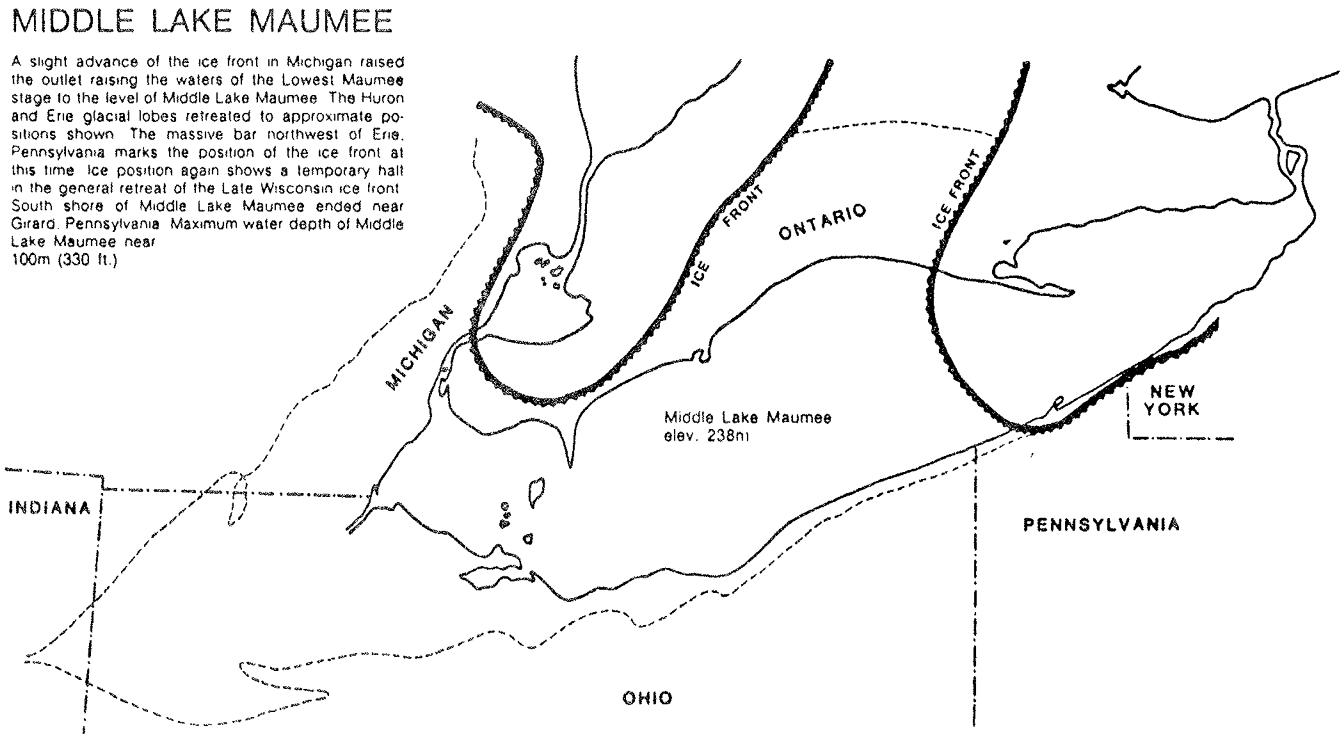

Figure 9. Middle Lake Maumee.

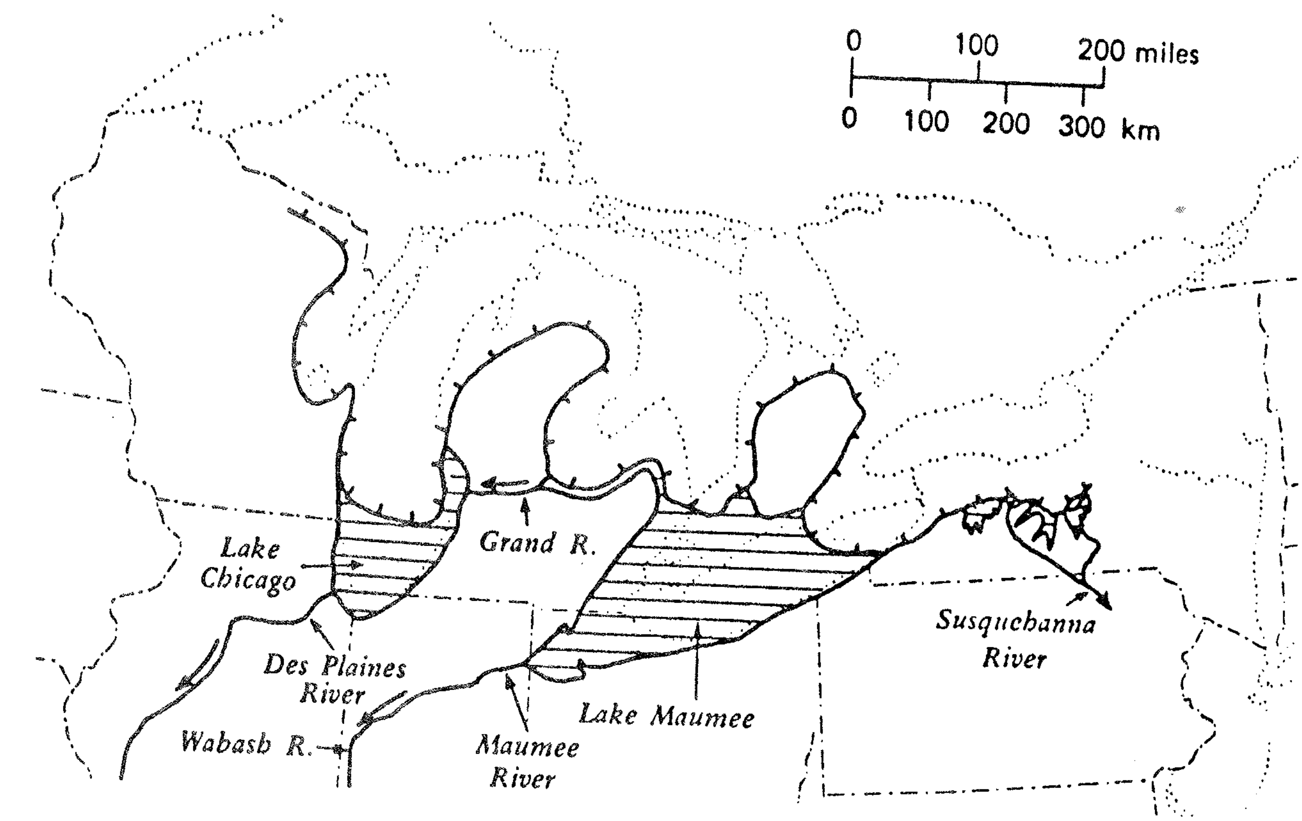

Figure 10. Lake Chicago and Lake Maumee stages (after Hough 1958).

LAKE WHITTLESEY

Lake Whittlesey was formed by ice advance after retreat had ended Arkona stage Ice advance was major and has been called the Port Huron substage Ice front as shown represents position of the Port Huron moraine Bar north of Erie, Pennsylvania marks ice border in Lake Erie Former drainage was dammed and drainage was transferred to the Ubly channel in Michigan Lake Whittlesey is marked by strongest beach system in Erie Basin Lake Whittlesey south shore ends near east end of Lake Erie Maximum Lake Whittlesey water depth near 88m (290 ft)

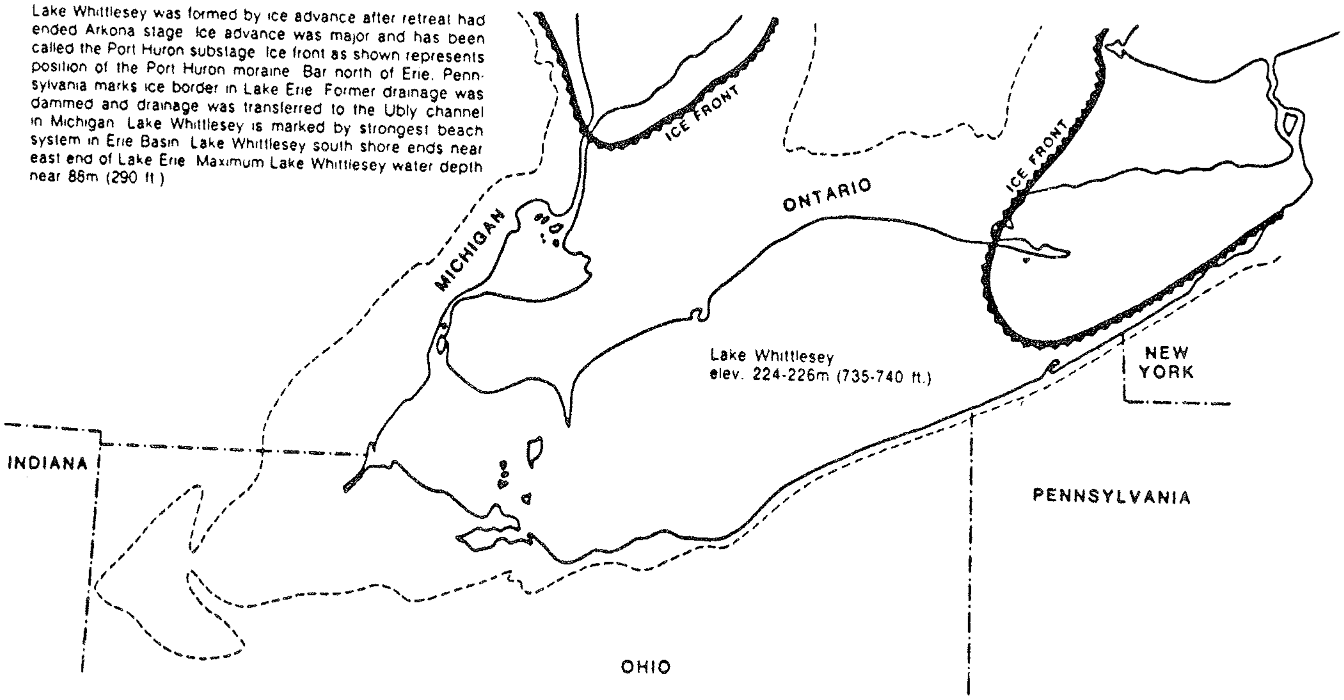

Figure 11. Lake Whittlesey.

LAKE WARREN

The ice front at this stage has retreated so far to the northward that Lake Chicago occupies the southern half of the Lake Michigan basin and some adjoining territory. The waters in front of the Huron and Ontario lobes are united and form Lake Warren. These waters have united near the front of the ice with the Finger Lakes to the east and Lake Saginaw to the west. Their drainage is westward across the southern peninsula of Michigan by way of the present valley of the Grant River Maximum Lake Warren water depth about 70m (230 ft)

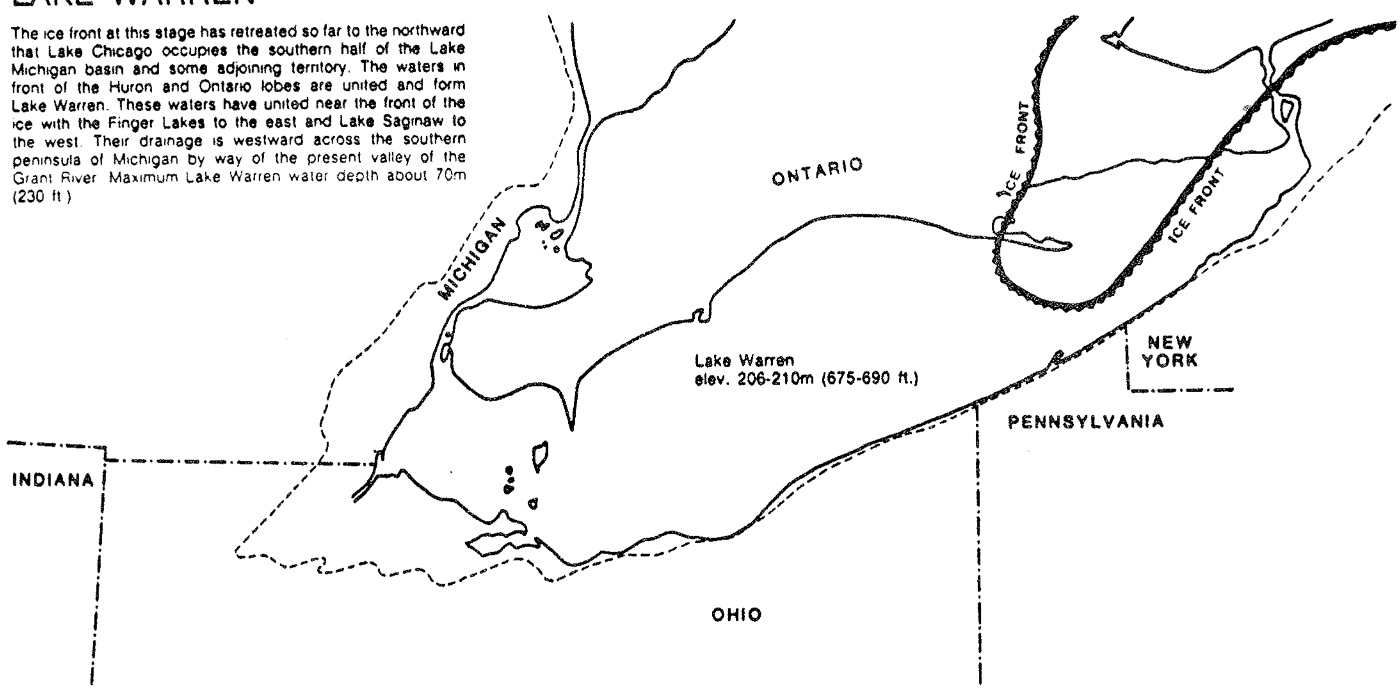

Figure 12. Lake Warren.

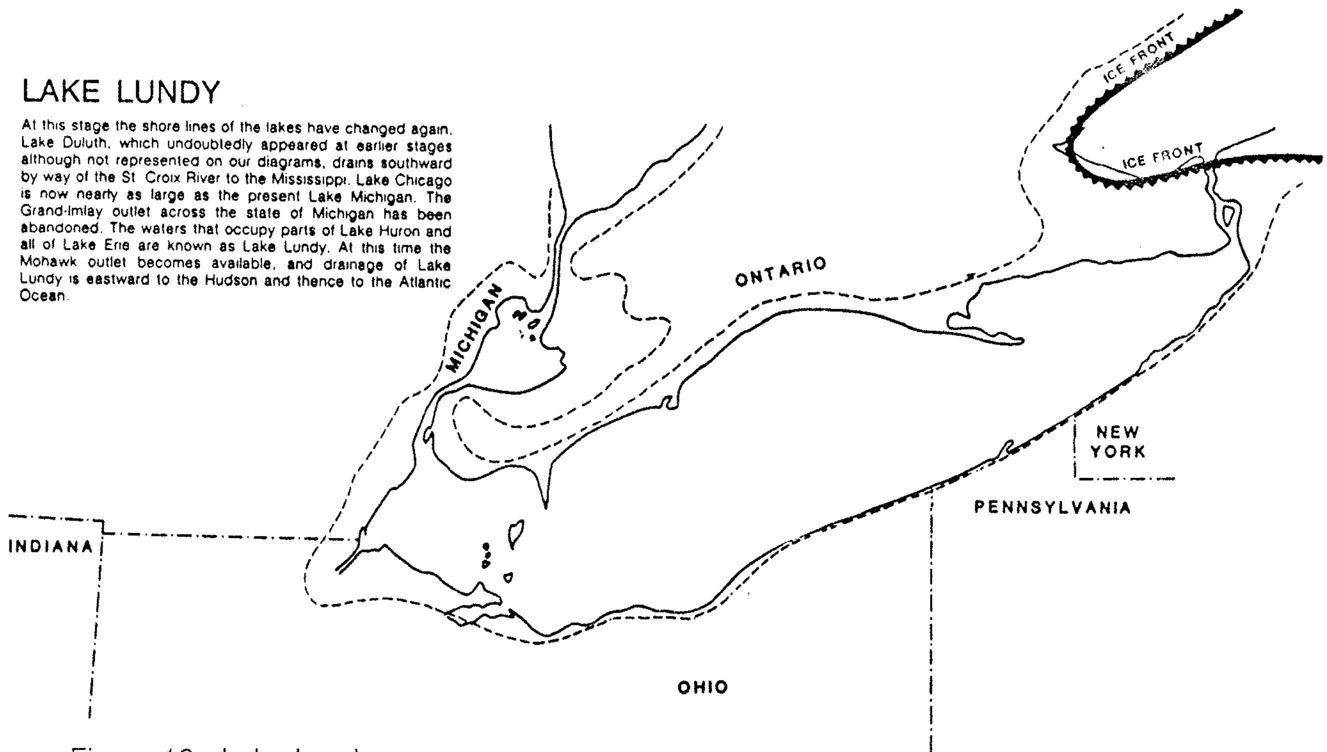

Figure 13. Lake Lundy.

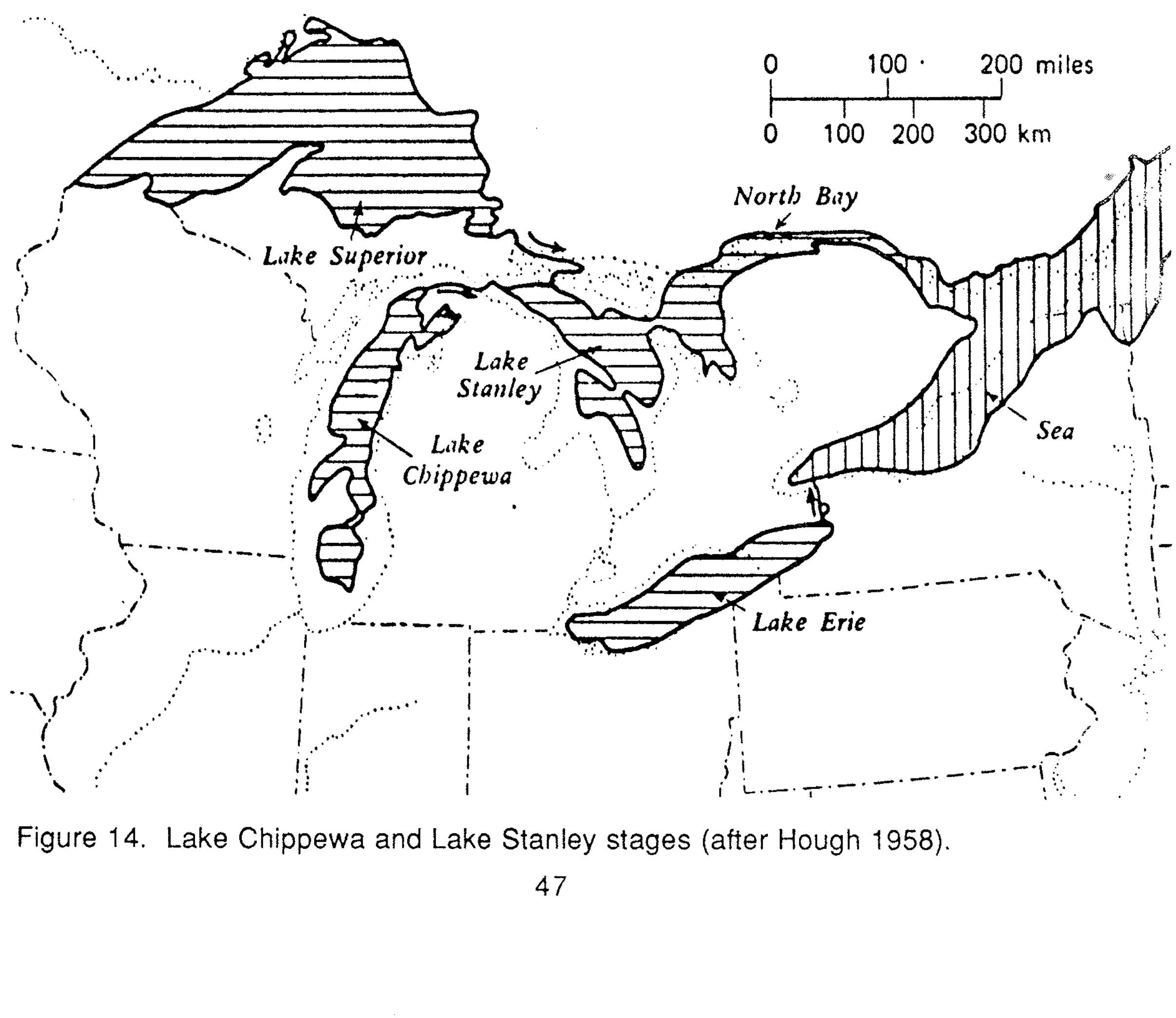

Figure 14. Lake Chippewa and Lake Stanley stages (after Hough 1958).

Post-Glacial Lake Erie

Early Lake Erie. The ice front was located near the eastern end of the basin during the Lake Lundy stage. When the ice retreated, it brought the Lake Lundy stage to a close and lowered the level to a low Early Lake Erie stage which drained of the first time through the present Niagara River gorge. This initiated the Early Lake Algonquin stage (184 m) in the Lake Huron and Lake Michigan basins and drainage into Lake Erie. The ice continued its retreat until the Kirkfield outlet to Lake Ontario was opened, lowering the level in the Huron and Michigan basins and stopping their drainage into Lake Erie. Later, a slight readvance of the ice dammed the Kirkfield outlet raising the Huron and Michigan waters to the Lake Algonquin stage (184 m), again discharging into Lake Erie.

Another ice retreat finally ended the Lake Algonquin stage by uncovering a lower outlet, probably the old Kirkfield outlet. The drainage from the upper lakes was lost to the Erie basin. The upper lakes then went through a series of successively lower stages until the North Bay-Ottawa River outlet was opened to the St. Lawrence embayment of the Atlantic Ocean. This created the lowest Lake Chippewa and Lake Stanley stages in the Lake Michigan and Lake Huron basins respectively (Fig. 14). From this time on, the level in the Michigan and Huron basins was controlled by uplift of the North Bay-Ottawa River outlet. This period of gradually rising levels lasted until the Lake Nipissing stage in the Huron basin. Water was again transferred to the Erie basin (via Lake St. Clair and the Detroit River) and this flow has remained until the present.

During the period between the Early Lake Algonquin and Lake Stanley stages in the Huron basin, Lake Erie probably remained at a fairly constant level of 143 to 149 m (Fig. 15). Since Early Lake Algonquin time the level in the Erie basin has been controlled by uplift of the Niagara sill (elevation of the bedrock at the head of the Niagara River). The Early Lake Erie stage was confined mainly to the eastern basin east of Erie, Pennsylvania, but a very shallow lake may have existed as far west as Avon Point, Ohio. Drainage into the eastern basin was by way of a channel about 10 km off the present shore northwest of Erie, Pennsylvania. This channel still exists but is filled to some degree with sediment. Field evidence for this low stage of Lake Erie is presented in Fig. 16.

Middle Lake Erie. Uplift of the Niagara sill ended the Early Lake Erie stage and the water rose gradually to an elevation of about 160 m. It remained long enough to create beach features now found on the lake bottom. This stage, called Middle Lake Erie (Fig. 17) actually was a static phase in a rising level created either by a pause in uplift or a balance between uplift and downcutting of the outlet. Middle Lake Erie probably extended as far west as Kelleys Island, being very shallow west of the Lorain-Vermilion morainic sand and gravel bar. This bar and the bar from Erie, Pennsylvania, to Long Point were beaches at that time.

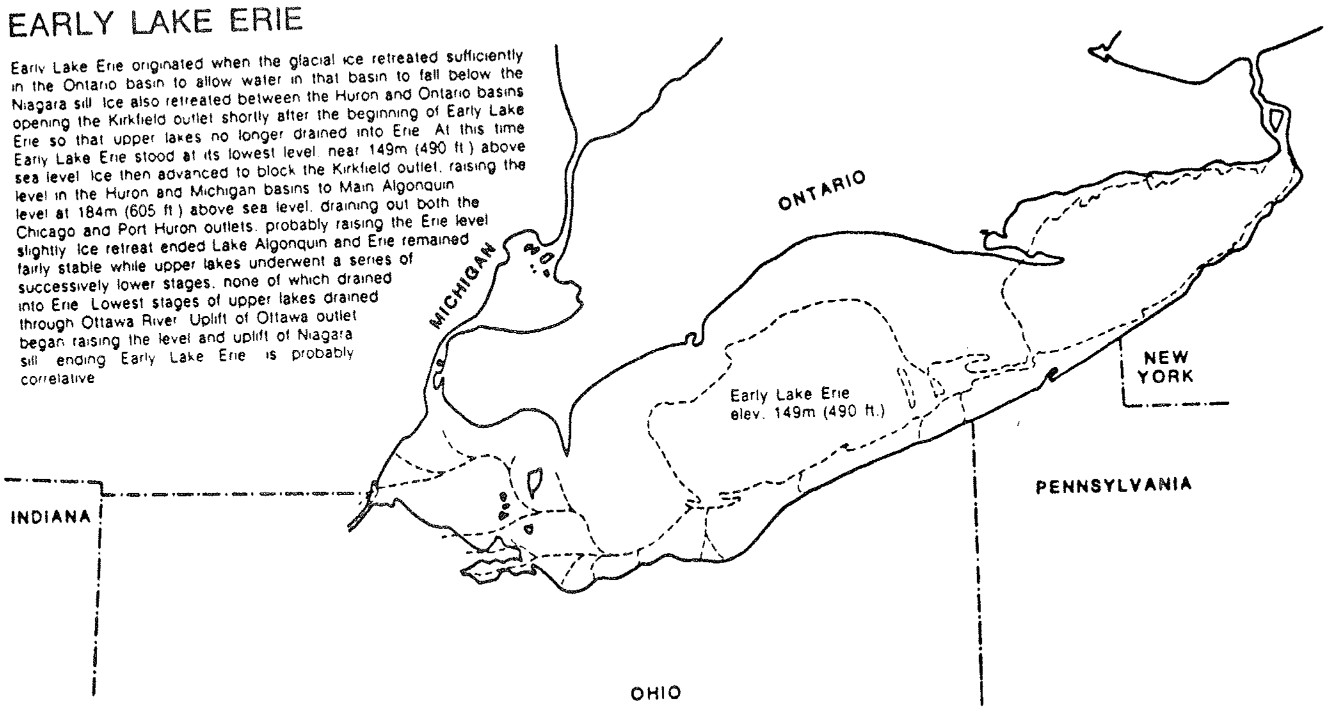

Figure 15. Early Lake Erie.

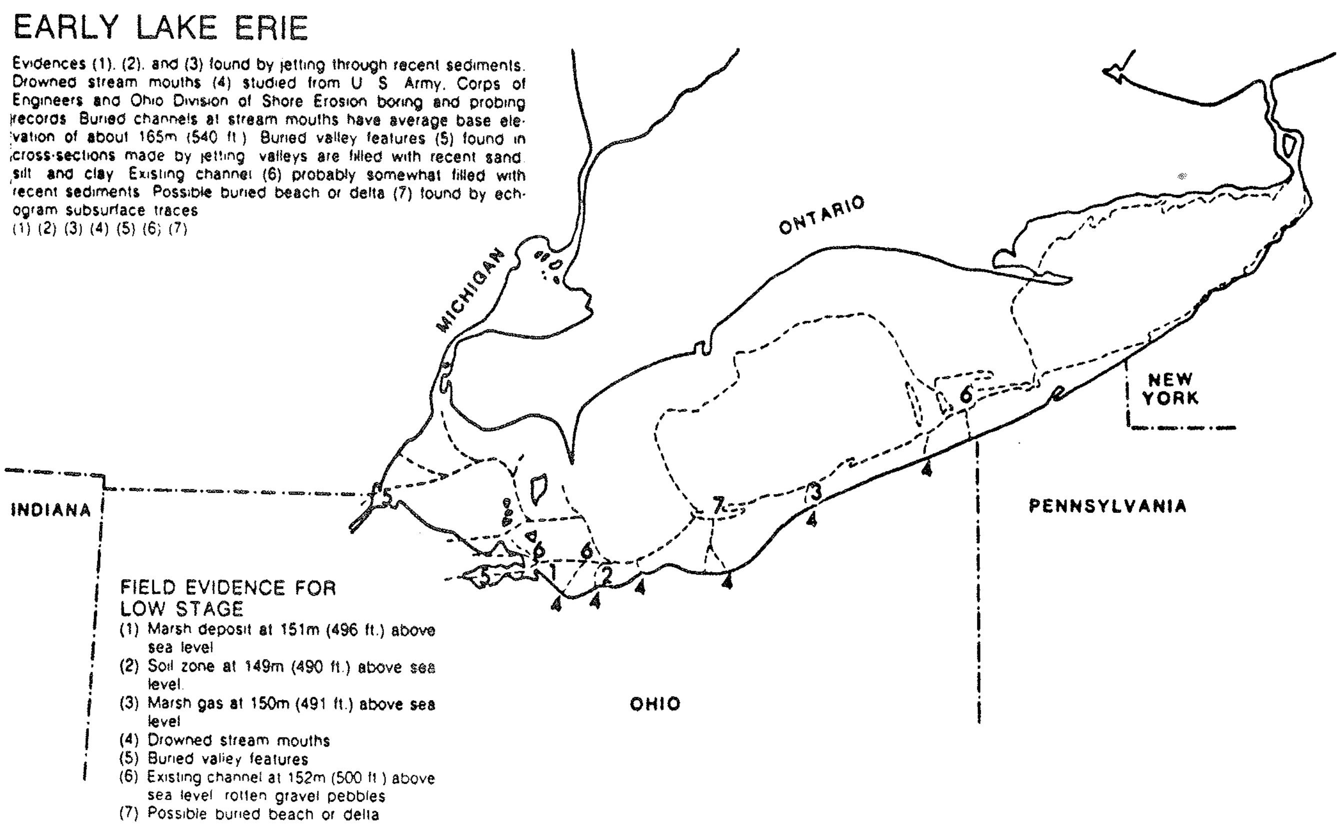

Figure 16. Early Lake Erie.

MIDDLE LAKE ERIE

Middle Lake Erie was probably created by a rising water level, caused by uptilting of the outlet at Niagara Falls. It appears to have halted at this elevation long enough to have created extensive and well-developed beach features. Beach ridges, now expressed as massive bars, were built over wide areas, expecially south from Point Pelee, south of Pointe aux Pins, Long Point, along central section of south shore, and on the morainic ridge south of Long Point. Bay at southwest end of lake probably averaged less than 6m (20 ft.) in depth, central portion probably 15 to 18m (50 to 60ft.), east end up to 60m (200ft.). Uplift of Niagara Falls ended Middle Lake Erie; levels in Huron and Michigan basins were rising but still draining through Ottawa River.

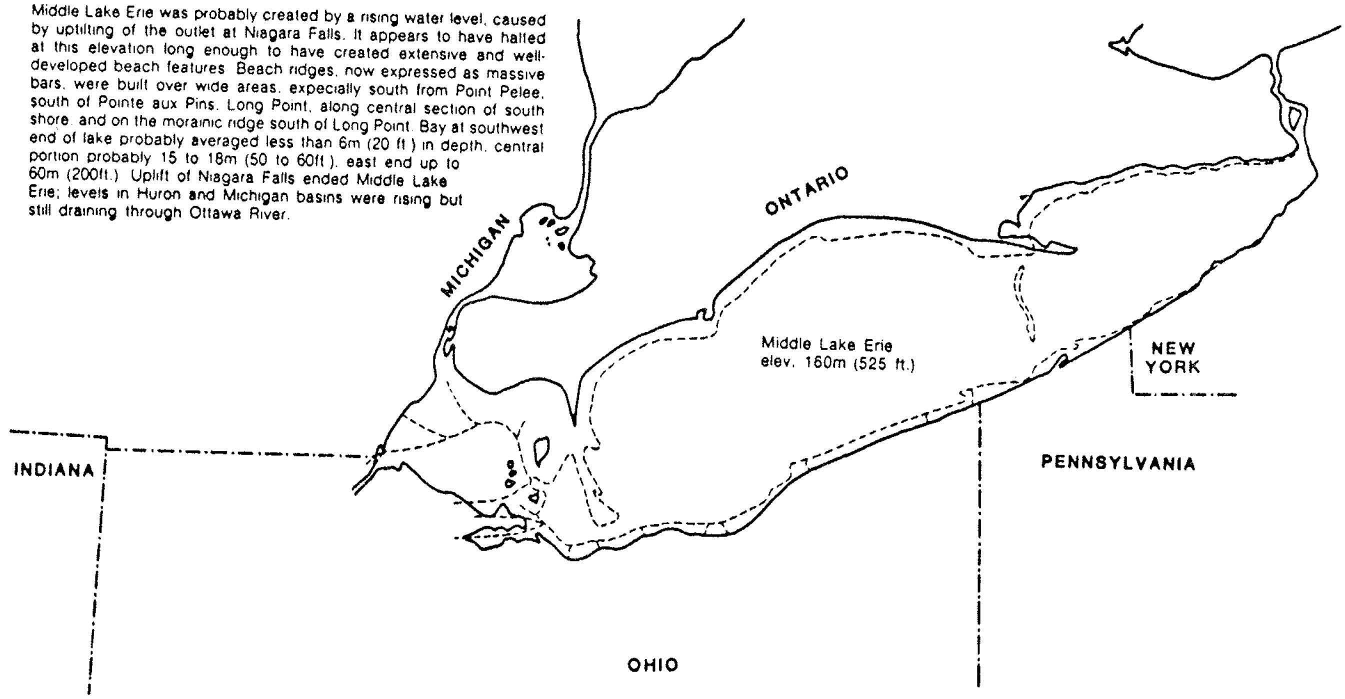

Figure 17. Middle Lake Erie.

MODERN LAKE ERIE
ORIGINAL SHORELINE

Comparison of solid line and dashed line indicated relative amounts of shore erosion or accretion since the beginning of the present lake stage.

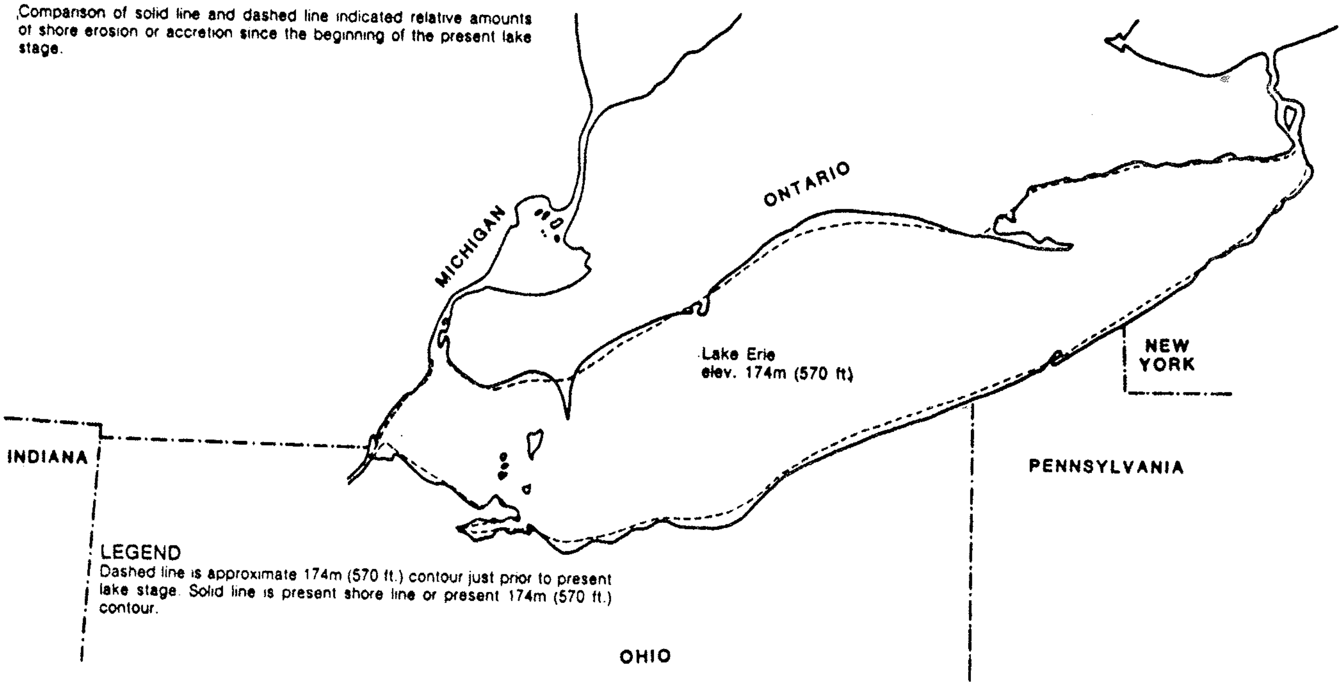

Figure 18. Modern Lake Erie.

Highest Lake Erie (Modern Lake Erie). Uplift of the Niagara sill ended the Middle Lake Erie stage and the level rose gradually to its present elevation of 174 m. Fig. 18 illustrates the original shoreline of Lake Erie when it reached its present level approximately 4000 years ago. Shore processes of erosion and accretion have modified the shore significantly since that time. Crustal uplift continues today, but only at a very slow rate (less than 3 cm per century). It is doubtful that drainage into Lake Erie from the upper lakes has affected its level to a great degree; the variation in level caused by the drainage transfers during the Lake Algonquin and Lake Nipissing stages was probably less than 3 m. The Niagara River has the capacity to dampen the effect of greatly varying lake input.

In summary, the sequence of events from Lake Maumee to Lake Lundy occurred in a brief 2000 year span from 14,000 to 12,000 years ago (Table 1). When the last glacier retreated from the vicinity of Buffalo, a new drainage outlet became available through the Niagara River. However, the new outlet was as much as 30 m lower than at present because the land surface had been depressed by the weight of glacial ice which was approximately 2 km thick. This new and very low outlet caused a massive flood of water to exit the lake basin toward the east, resulting in the drainage of the western end of the lake and the formation of separate, shallow lakes in the central and eastern portions of the lake basin. During this low lake stage (12,000 to 4,000 years ago), much of the western basin was dry and exposed to erosion, which greatly altered and reshaped the bottom surface. The Niagara outlet gradually rebounded to its present elevation, and Lake Erie correspondingly rose from this low elevation of 143 cm to its present level. Fig. 19 illustrates the amount of crustal (isostatic) rebound that has taken place in the Great Lakes basin since the deglaciation. As the lake rose, waves and currents cut into the lake bottom, locally excavating the glacial deposits and exposing some of the shallowly buried bedrock. The exposed bedrock now forms the islands, reefs and rocky shorelines of the lake. Also during the low lake stage, tributary valleys were deeply entrenched. When the lake eventually rose, these river mouths were drowned forming the excellent estuarine harbors along the south shore (Brant and Herdendorf 1972).

GEOMORPHOLOGY

Coastal Geomorphology

Four states and one province border Lake Erie, each exhibiting distinct physiographic features along the coast. The highest concentration of coastal marshes occurs in western Lake Erie where they fringe the shorelines and estuaries of Michigan, Ohio, and Ontario. These wetlands occupy about 23% of the 189 km shore and encompass an area of 268 km^2.

Michigan. The Michigan shoreline of western Lake Erie consists of low-lying marshes and sand beaches. Submergent and emergent wetlands surround the islands at the mouth of the Detroit River. At Stony Point, on the shoreline of Brest Bay, a brecciated dolomite forms a rocky shoreland with

Table 1. Glacial lake stages in the Erie Basin.

	Age (years ago)	Elevation (m above sea level)	Outlet
Lake Erie (modern)	4300	174	Niagara River
Lake Erie (middle)	9000	160	Niagara River
Lake Erie (early)	12,200	150-143	Niagara River
Lake Lundy	12,400	195-190	Mohawk River or Lake Huron Basin
Lake Grassmere	12,500	195	Mohawk River or Lake Huron basin
Lake Wayne	12,600	200	Mohawk River, NY.
Low water stage	12,700	<150?	Niagara River (?)
Lake Warren	12,800	210-206	Grand River, Mich.
Lake Whittlesey	13,000	224	Ubly Channel Grand River, Mich.
Lake Ypsilanti	13,200	<150?	Niagara River (?)
Lake Arkona	13,300	217-212	Grand River, Mich.
Lake Maumee (III)	13,500	238	Imlay Channel, Mich. Wabash River, Ind.
Lake Maumee (II)	13,800	232	Imlay channel, Grand River, Mich.
Lake Maumee (I)	14,000	244	Wabash River, Ind.

Sources: Leverett and Taylor (1915), Hough (1963), Herdendorf and Braidech (1972)

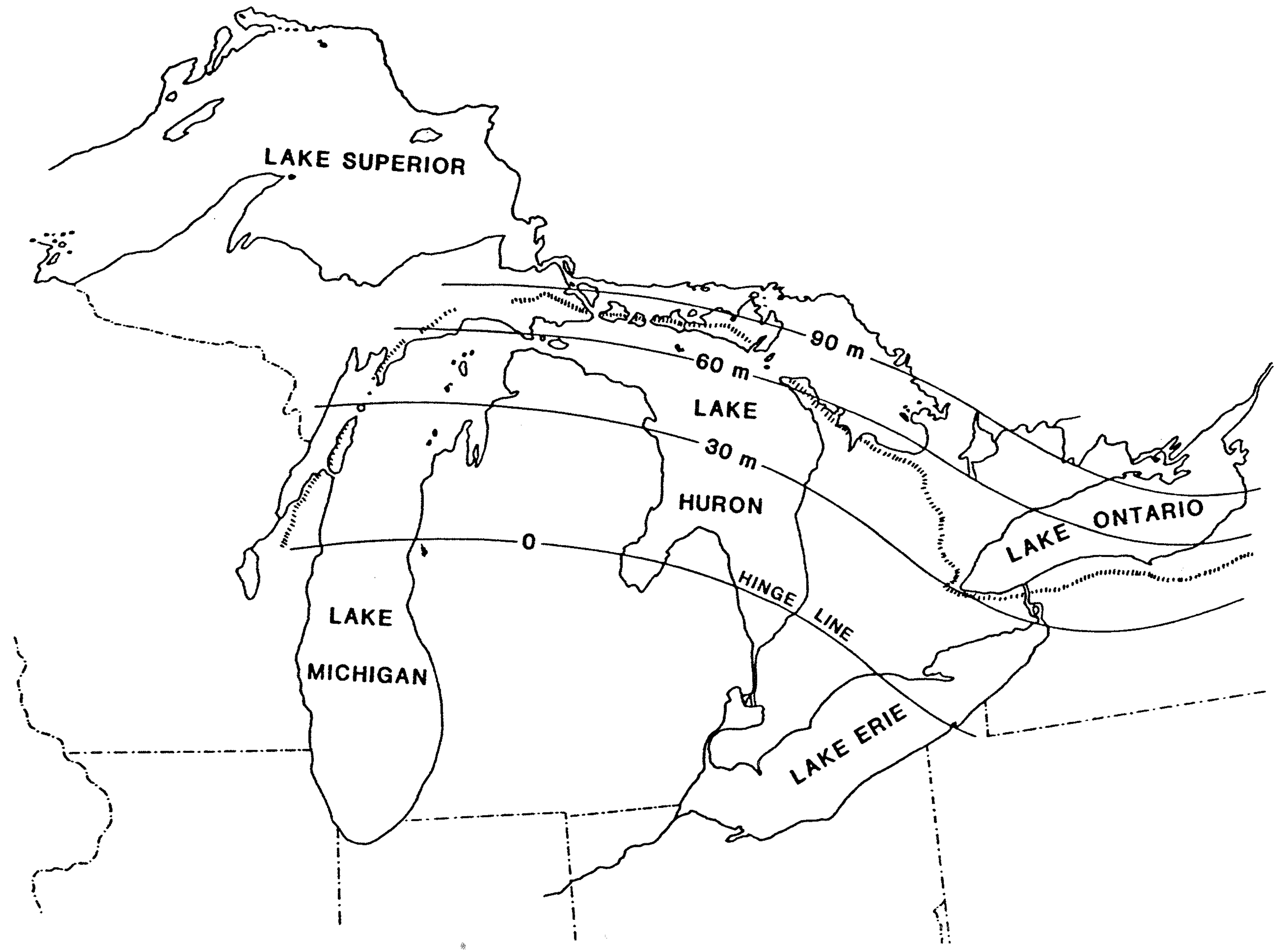

Figure 19. Crustal (isostatic) rebound following deglaciation of the Great Lakes region.

boulders and sand. A 6-km-long sand spit, known as Woodtick Peninsula, forms the northern edge of Maumee Bay and provides protection for the wetlands which have developed in that portion of the bay.

Ohio. The Ohio shore of western Lake Erie in its natural state is generally a marsh area fronted by low barrier beaches and numerous estuarine river mouths (Fig. 20). Earthen and rock dikes now protect most of the shore except for the rock-bound Erie Islands. East of Port Clinton the ground elevation rises and at the headlands known as Catawba Island, the shore material is ledge rock which stands over 10 m high. To the east, a strip of high ground connects to another headland known as Marblehead. Northeast of this crescent-shaped strip are three open water marshes called West, Middle, and East Harbors which are fronted by a sandy barrier beach. The Bass Island-Kelleys Island group of 12 bedrock islands have shores similar in nature to the headlands. Small embayments on the larger islands contain wetlands. Sandusky Bay is separated from Lake Erie by two sand spits: Sand Point projects south from Marblehead and Cedar Point extends northwest from near Huron. These spits protect extensive wetlands throughout the bay. One of the largest concentrations of wetlands on Lake Erie is found at the head of Sandusky Bay.

East of Cedar Point, the shore characteristics change abruptly; the low marshy backshore typical of most of the coast from Toledo to this point disappears and is replaced by low bluffs of glacial till, lacustrine sediments, and black shale. The bluffs rise from 3 m near Vermilion to 16 m near Cleveland and 20 m at Ashtabula. The only wetland development along this reach of shoreline is found at the estuary mouths of the tributaries such as the Huron River and Old Woman Creek. The best wetland occurs at Mentor marsh, the abandoned valley and delta of the Grand River which now enters Lake Erie several kilometers east of the marsh. Beaches along this reach are narrow except where affected by large navigation structures at the major harbors. Table 2 contains length and area information on the major estuarine river mouths along the Ohio shore of Lake Erie.

Ontario. The Ontario shoreline of western Lake Erie consists of a variety of types, including the marshy shores of the Detroit River mouth, glacial till and lake sediment bluffs along most of the lake shore, and a magnificent sand spit at Point Pelee. Because of the generally higher nature of the shoreline, fewer marshes occur here than along the Michigan and Ohio shores. Three streams -- Big Creek, Cedar Creek, and Hillman Creek -- have estuarine mouths where wetlands have developed. Point Pelee marshes, the largest Canadian wetlands in western Lake Erie, are excellent examples of lagoons protected by barrier beaches. Small wetlands are also located on Pelee Island and East Sister Island.

Pennsylvania. The Pennsylvania coast of Lake Erie contains bluffs ranging from 15 to 30 m high and is composed of silt, clay, and shale bedrock with moderate-width sandy beaches. However, the most prominent feature of the coast is Presque Isle Peninsula, a 2.5-km-long sand spit which encloses

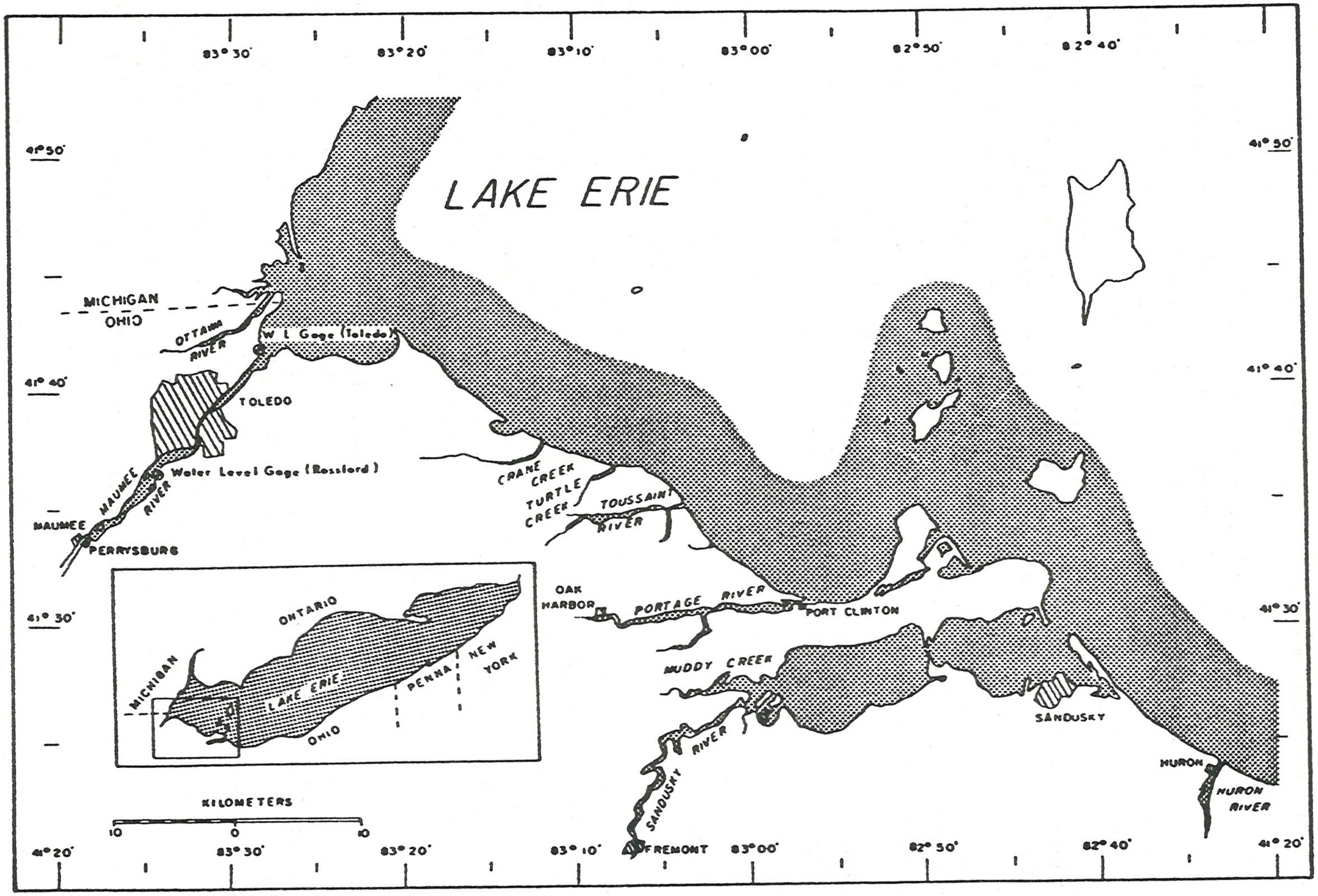

Figure 20. Estuaries along the south shore of western Lake Erie (after Brant and Herdendorf 1972).

Table 2. Lake Erie estuaries in Ohio.

Estuary	Drainage area (km^2)	Estuary length (km)	Estuary area (km^2)	Estuary l/a ratio
Ottawa River	446	10.9	2.2	5.0
Maumee River	17,115	23.8	11.6	2.1
Crane Creek	144	9.1	0.7	13.0
Turtle Creek	89	9.0	0.8	11.3
Toussaint River	370	16.1	3.9	4.1
Portage River	1505	25.2	10.4	2.4
Muddy Creek	288	8.3	1.8	4.6
Sandusky River	3678	24.8	5.3	4.7
Huron River	1052	7.4	1.6	4.6
Old Woman Creek	69	2.1	0.3	7.0
Vermilion River	694	2.4	0.3	8.0
Black River	1217	6.6	0.9	7.3
Rocky River	759	0.8	0.1	8.0
Cuyahoga River	2095	7.2	1.0	7.2
Chagrin River	684	1.4	0.2	7.0
Grand River	1826	5.3	0.8	6.6
Ashtabula River	355	2.8	0.3	9.3
Conneaut Creek	490	2.0	0.2	10.0
Totals	32,876	165.2	42.6	mean 6.8

Source: Brant and Herdendorf (1972)

Erie Harbor. As discussed earlier, the natural construction of this spit has created numerous lagoons where wetlands have developed.

New York. The New York shoreline of Lake Erie, characterized by bluffs, generally well above the limit of wave uprush, is shale which has resulted in narrow shingle beaches. A few sand beaches occur, mainly between Silver Creek and Cattaraugus Creek. Because of the nature of the coast, wetlands are sparse along this reach. Several small wetlands have formed along the Niagara River, particularly on Grand Island.

Formation of Estuaries and Coastal Wetlands

As we have seen, the basin occupied by the Great Lakes was created by glaciation, and its physical features and hydrology differ greatly from regions not exposed to Pleistocene ice sheets. In terms of earth history, the construction of the basin has only recently been completed. The five Great Lakes, with their outlets and approximate lake levels as they are today, probably date back less than 5,000 years. The processes of stream and shoreline erosion/accretion have made moderate changes in the original topography, but the slight changes are significant in the origin and development of coastal estuaries wetlands.

Prior to the Pleistocene Ice Age, the Great Lakes were non-existent; the area was dissected by well-developed valleys and several major streams. When the continental ice cap developed to a thickness of 2-3 km in northeastern Canada, it spread southward into the present Great Lakes region. Tremendous amounts of bedrock were eroded and the debris entrained in the ice mass. As the ice sheets slowly melted and retreated progressively northward, this entrained debris was released and vast irregular deposits of till were laid down on the scoured bedrock surface. Occasionally blocks of ice were also entrained in the till and eventually formed the kettle lakes and bog wetlands of the upland areas adjacent to the Great Lakes. The earliest of these lakes were narrow bodies of water ponded between the ice fronts and the topographic divides to the south. The water of these first lakes spilled southward through various discharge routes to the Mississippi River system. Although the general trend of the ice retreat was northward, several readvances of the ice margin occurred during the waning stages of glaciation. In general, the lakes expanded in size during this period of retreat, but on some occasions new and lower outlets to the north were uncovered by the melting glaciers which reduced their size. Once the lakes became established, three additional types of stream and shoreline processes provided favorable sites for wetlands: (1) delta formation, (2) estuary formation, and (3) sand bar/dune formation creating coastal lagoons. Although the gross configuration of the Great Lakes has been little altered since their glacial development, the above processes have established many favorable sites for wetlands. Except where bedrock is exposed or protective works constructed, the glacial or lacustrine overburdern comprising the shores is still vulnerable to changes which can work to the benefit or destruction of coastal wetlands.

Kettle Lake Wetlands. One of the most characteristic types of lakes in the glaciated upland areas adjacent to the Great Lakes was formed by the incorporation of ice blocks in the material that washed out from a melting ice front. The glacial outwash, consisting of sand, gravel, and silt, was derived from the drift or moraine underlying or bordering the ice. As the mass of ice melted, a basin was left in the drift, and if the basin penetrated below the water table, a body of water known as a *kettle lake* came to occupy the site of the original ice block. The kettles are extremely variable in shape and size; some are less than 30 m across while others, such as Trout Lake, Wisconsin, have a diameter of nearly 5 km (Hutchinson 1957). In general, the depth of kettle lakes does not exceed 50 m (Flint 1971). Bogs are the most common wetlands in kettle lakes.

Kettle lakes and other northern basins protected from wind and poorly drained may become bog lakes. They first become fringed by floating mats of sedge vegetation growing inward to encroach upon the open water; this change is accompanied by a drop in pH. The succession then continues as the mat covers the lake surface and sphagnum moss and ericaceous shrubs, such as leatherleaf and Laborador tea, become established. When growth exceeds decomposition, the lake basin begins to fill and peat deposits are formed. Ultimately a sequence of tree species, commonly tamarack followed by spruce, leads to a climax forest association.

Delta Wetlands. A stream reaching a body of standing water, such as the St. Clair River flowing into Lake St. Clair, at times builds a deposit or *delta*, composed of the stream's sediment load. These deposits are commonly the site of extensive wetland development. Not all rivers build deltas; deltas may be lacking at the mouths of streams which enter the Great Lakes because their mouths are so exposed to wave and current action that sediments are removed as rapidly as they are deposited. Some streams also lack deltas because they carry so little load. Although each delta has its own individual form, Strahler (1971) has recognized four basic outlines for deltas: (1) arcuate, triangular outline, (2) digitate, bird-foot type, (3) cuspate, tooth-shaped form and, (4) estuarine, drowned valley.

The typcial arcuate delta originates at an upstream apex and radiates lakeward by means of branched distributary channels to form a triangular shape. Sediments reaching the lakes from the distributary mouths are swept along the coast by wave-induced currents to form curved bars enclosing shallow wetland lagoons; the delta shoreline is thus arcuate in plan, bowed convexly outward. The digitate, or bird-foot delta, contains long extensions of its branching distributaries into open water. This type of delta requires a gently sloping lake bottom in front of the river mouth, such as Lake St. Clair, on which natural levees can be built up quickly. The cuspate or tooth-shaped delta is normally formed when the stream has a single dominant mouth. Sediment from this mouth builds the delta forward into deeper water while wave action sweeps the sediment away from the discharge to form a curving beach on both sides of the mouth, concave toward the lake. An estuarine delta commonly fills a long narrow estuary that resulted from drowning of the lower part of the river valley because of a rise in lake level. Estuarine deltas are characterized by depositional islands containing wetlands such as Ewing Island in the Maumee River near Rossford, Ohio.

Delta growth occurs when a stream enters a standing body of water as a jet or plume. The jet velocity is rapidly checked and sediment is deposited in lateral embankments (natural levees) in zones of less turbulence on either side of the jet, thus extending the stream channel into the lake. The stream repeatedly breaks through the embankments to occupy different radii (distributary channels) and in time produces a deposit in semi-circular form, closely analogous to the alluvial fans found at the base of mountain ranges. The natural levees serve to isolate shallow interdistributary pond and marshes containing fine muds and organic detritus or peat (Stanley and Swift 1976). The sediment structure of most deltas on the Great Lakes is produced by three sets of beds: (1) bottomset, (2) foreset, and (3) topset. Bottomset beds consist of fine-grained materials (silt and clay) carried farthest offshore and laid down on the bottom of the lake embayment into which the delta is being built. Foreset beds are somewhat coarser (fine sand) and they represent the advancing front of the delta and the greater part of its bulk; they usually have a distincly steeper slope (dip) than the bottomset beds over which they are slowly advancing. Topset beds lie above the foreset beds and are in reality a continuation of the alluvial plain of which the delta is the terminal portion. It is on the foreset beds that delta wetlands normally develop. Unlike deltas formed along the ocean, freshwater deltas do not contain aggregates of fine particles induced by electrolite flocculation (due to the dissolved salts in the sea). Therefore, fine particles are carried offshore in lakes and are not incorporated into the delta sediments.

Delta wetlands form a significant portion of the coastal wetlands in the Great Lakes region. Delta wetlands are gradational to embayment, estuary, river, and floodplain wetlands.

Freshwater Estuary Wetlands. The lower courses of several tributaries to the Great Lakes, particularly the more southerly lakes, are characterized by estuarine-type or drowned stream mouths. The flooded flat areas adjacent to these estuaries afford ideal sites for wetland development. The lower 24 km of the Maumee River, which flows into Lake Erie at Toledo, Ohio, and possesses the largest drainage of any Great Lakes tributary, is an excellent example of a freshwater estuary. The formation of this estuary on Lake Erie is the result of a series of geologic events related to Pleistocene glaciation. The flow of the Maumee River was reversed from its southwestern direction when the glacial lakes drained from the Erie Basin as the ice sheet melted, exposing a lower Niagara River outlet. At that time, river velocities were accelerated by the base-level lowering, and the Maumee Valley was cut deeply into lacustrine deposits, glacial tills, and bedrock. With the weight of the ice removed, the outlet eventually rebounded and produced a rise in lake level. The lake encroached up the valley and formed the present drowned stream mouth which is analagous in many ways to a marine estuary. Virtually all of the tributaries entering Lake Erie on the Ohio shore have estuarine-type lower reaches and attendant wetlands, where lake water masses affect water level and quality for several miles upstream from traditional mouths (Brant and Herdendorf 1972).

The Maumee River estuary begins near Perrysburg, Ohio, at the most downstream bedrock riffle. As the water enters the estuary from the river, its velocity abruptly dimishes except during major runoff events, causing sedimentation of suspended particles. The deposits have formed a series of elliptical islands which foster wetland formation. Similar deposits are found in the Sandusky River estuary and in the tributaries along the Michigan shore of Lake Michigan.

Coastal Lagoon Wetlands. In large bodies of water such as the Great Lakes, the shifting of sediments by nearshore currents (Fig. 21) can form basins where wetlands eventually develop. If sediments are deposited across the mouth of an embayment, a tributary outlet or a freshwter estuary, the blockage may result in the formation of a new pond or lagoon. Wave activity, too, has formed bars of sand and gravel, which likewise have closed off the mouths of embayments.

The usual way in which a lagoon capable of supporting a wetland is formed is by accretion of a bar across some irregularity or indentation of the coastline. The term bar is used here in a generic sense to include the various types of submerged or emergent embankments of sand and gravel built on the lake bottom by waves and currents. One of the most common types of bars asociated with wetlands in the Great Lakes is a spit. This feature is a sand ridge attached to the mainland at one end and terminating in open water at the distal end. Spits that have extended themselves across or partially across embayments are termed baymouth or barrier bars. Commonly the axis of a spit will extend in a straight line parallel to the coast, but where currents are deflected landward, resulting in the creation of a recurved spit or hook. Several stages of hook development may produce a compound recurved spit with a series of ponds separated by beach ridges. The ponds have provided excellent sites for wetland development along the Great Lakes.

Kormondy (1969, 1984) described wetland succession in beach ponds on a 6.4 km-long spit in Lake Erie known as Presque Isle near Erie, Pennsylvania (Fig. 22). Owing to a combination of its sandy shore and exposure to violent lake storms, this spit developed as a series of hooks with the establishment of numerous, fingerlike beach ponds over the past several thousand years. The ponds are created when an elevated bar of sand develops, thereby isolating a small portion of the lake; the ponds are seldom more than 200 m long, 20 m wide, and 1 m deep. Some of the ponds are destroyed in a few days, months, or years by subsequent storms which either breach the sand bar or blow enough sand to fill in the depression. The better protected ponds survive these geological processes only to be subject to a biological fate, wetland succession. A four-year-old pond is characterized by sparse pioneer vegetation, such as stonewort, algae, bulrushes, cattail, and cottonwood seedlings. At 50 years, filling has occurred in the basin and encroaching vegetation has reduced the open water portion to about half of its former area. The major vegetation then

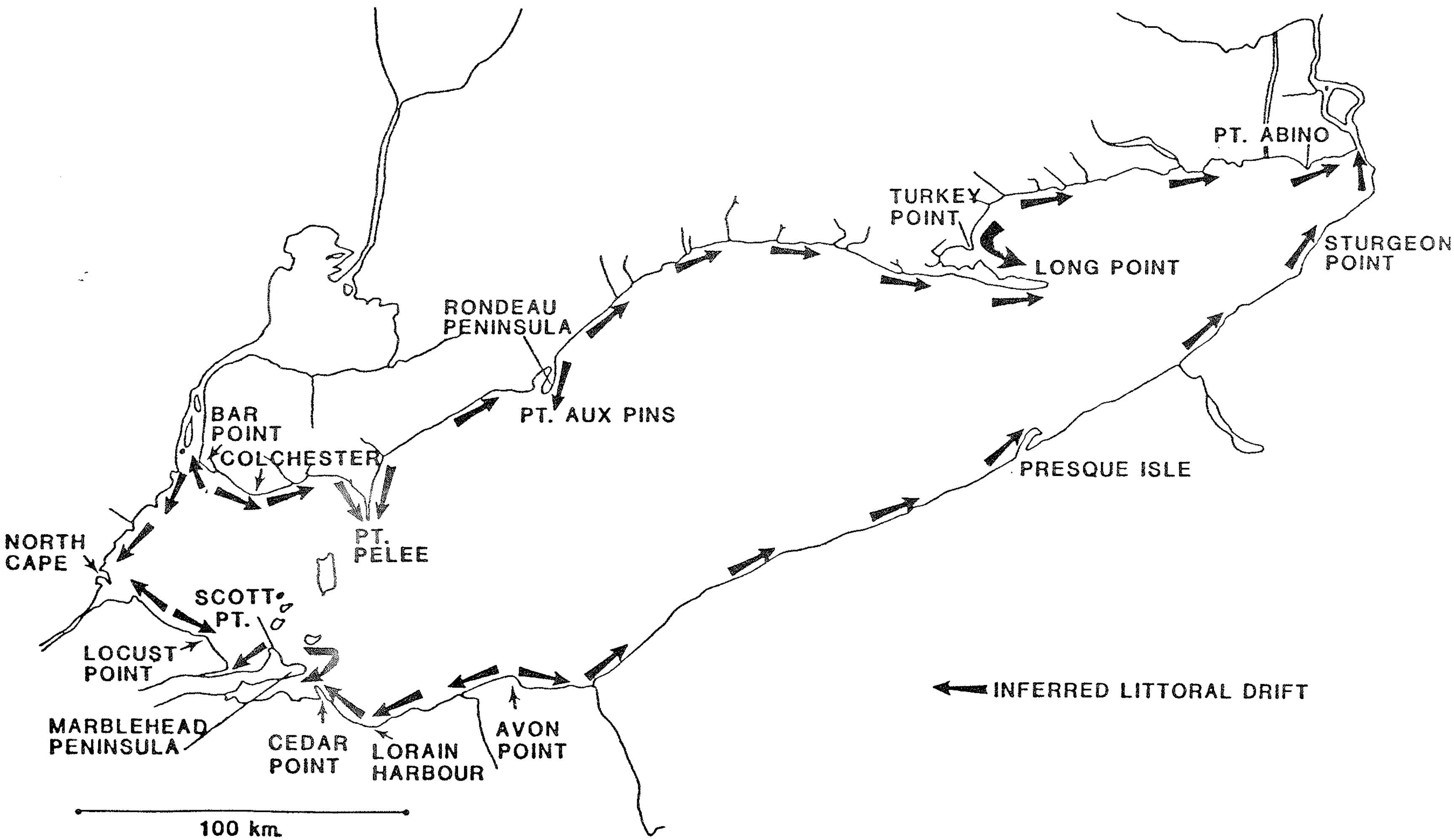

Figure 21. Dominant alongshore currents in Lake Erie.

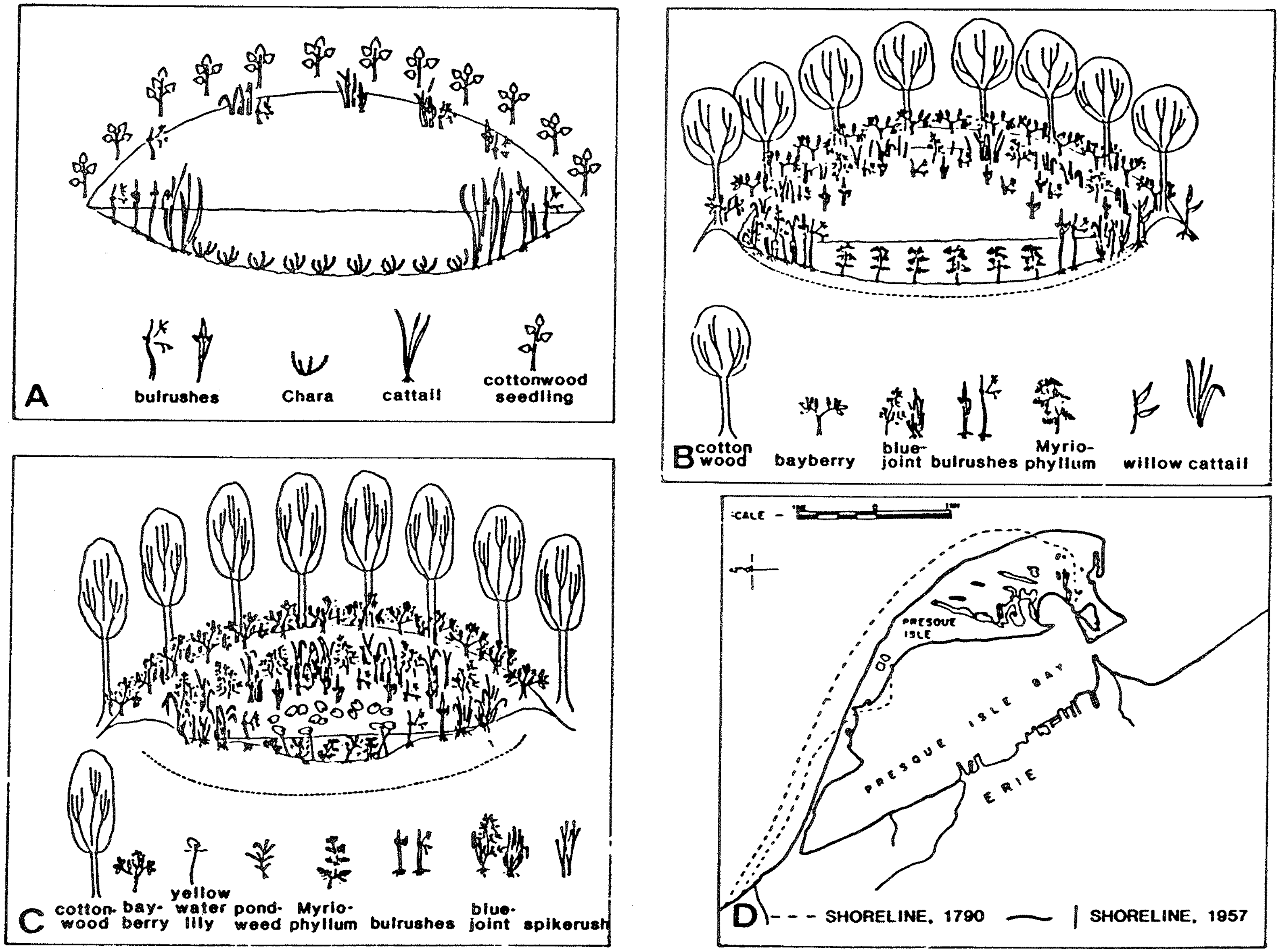

Figure 22. Wetland succession in a Lake Erie beach pond at Presque Isle, Pennsylvania: (A) 4 years old, (B) 50 years old, (C) 100 years old, and (D) progressive shoreline changes (after Kormondy 1969, 1984).

consists of water milfoil, cattail, bulrushes, bluejoint, willow, bayberry, and cottonwood. After 100 years the open water portion is almost obliterated and the vegetation has increased in complexity. The dominant forms then include water milfoil, pondweed, yellow water lily, bulrushes, bluejoint, spikerush, bayberry, and cottonwood. Sparseness of distribution and limitation of plant species mark the early ponds; increased density and heterogeneity characterize the older ponds, and the contrast is striking. From this analysis of succession, Kormondy concluded that the ponds or lagoons at the northeast end of Presque Isle are the youngest and that the spit has grown from the southwest because the ponds are increasingly older in that direction.

Geomorphic Processes of Lake Erie Estuaries

Old Woman Creek Estuary. Located on the most southerly reach of the Great Lakes, the mouth of Old Woman Creek provides an excellent example of a freshwater estuary (Fig. 23). The paleogeography and geomorphology of this estuary are discussed here to illustrate many of the features and processes common to Lake Erie estuaries. The hydrology of the estuary is driven both by Lake Erie and a 69 km^2 watershed. Old Woman Creek wetland occupies the lower estuarine portion of the stream. It is separated from Lake Erie by a narrow barrier beach at the stream mouth. The marsh itself is 30 hectares in area and extends about 1 km south of the lakeshore. It is approximately 0.34 km wide at its widest portion. Depths may reach up to 3.6 m in the inlet channel but for the major portion of its area it is less than 0.5 m deep. The wetland is mostly non-wooded, with emergent and floating-leaf plants bordered by a mixed hardwood forest on the steep banks. The American water-lotus is exceptionally well developed in this broad embayment on the north side of Star Island. The drowned mouth of the creek has been set aside since 1977 as a research and education preserve known as the Old Woman Creek National Estuarine Research Reserve. The Reserve, jointly managed by the National Oceanic and Atmospheric Administration (NOAA) and the Ohio Department of Natural Resources, features a public education center, research laboratories, housing for investigators, nature trails, and interpretive canoe trips. Old Woman Creek is the first reserve of this type on the Great Lakes.

Following the retreat of the Wisconsin glacial ice, Old Woman Creek excavated a deep channel through the till and softer lacustrine sediments. At one point along this channel was the future site of the creek's present mouth in Lake Erie. The Old Woman Creek channel is located over the deepest portion of the ancestral Huron River valley cut preglacially to depths of about 44 m in the Ohio Shale (Fig 24). The depth of the Old Woman Creek channel is great in comparison with what might be expected under current lake conditions and is the result of a lower lake level and thus lower base level of the creek at the time of the major erosion.

The valley of Old Woman Creek has two distinct channels. This bifurcation has preserved an isolated remnant of the lake plain in the vicinity of Star Island, around which the creek flowed to the east and west at various times (Fig 25).

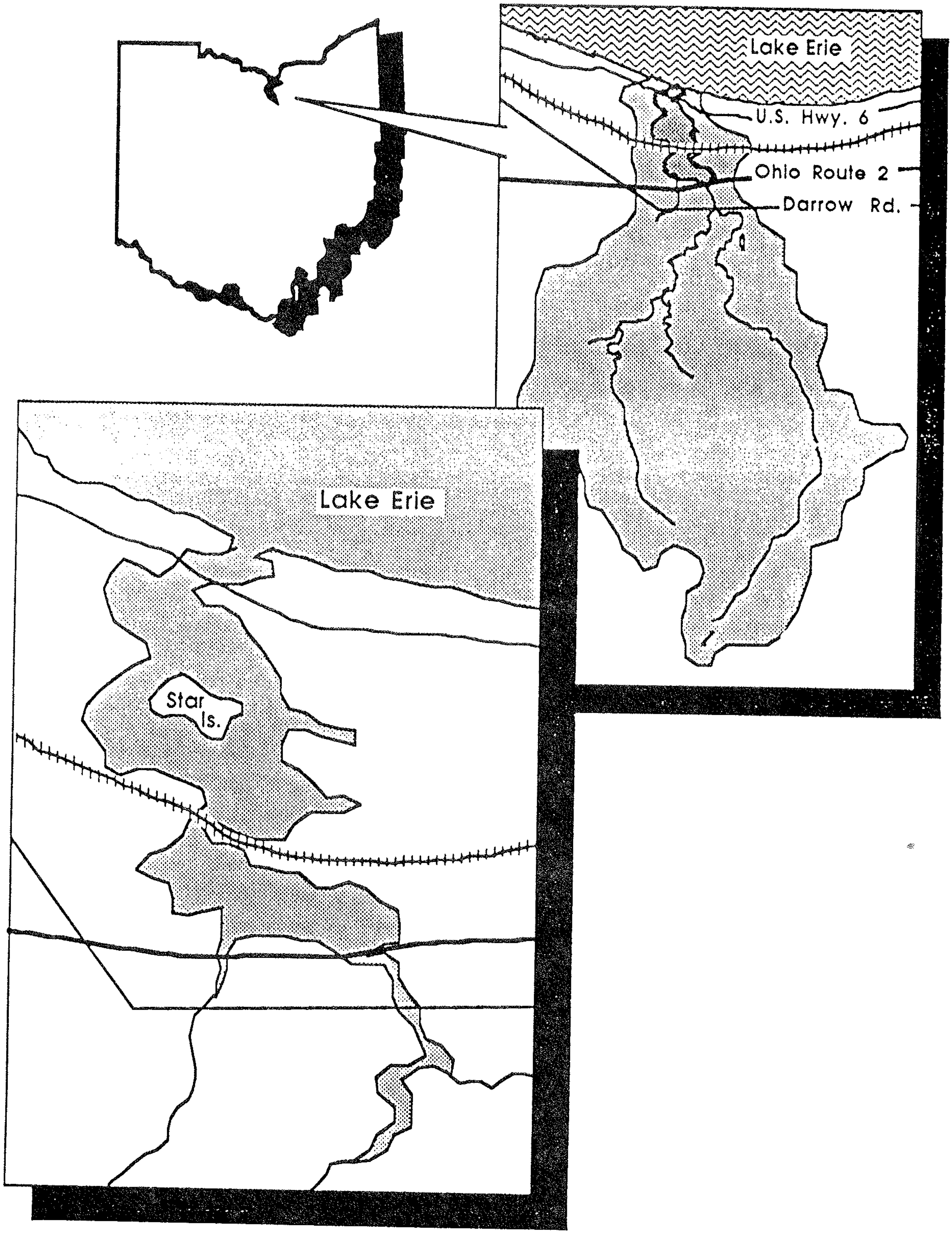

Figure 23. Old Woman Creek Estuary and watershed (after Reeder 1988).

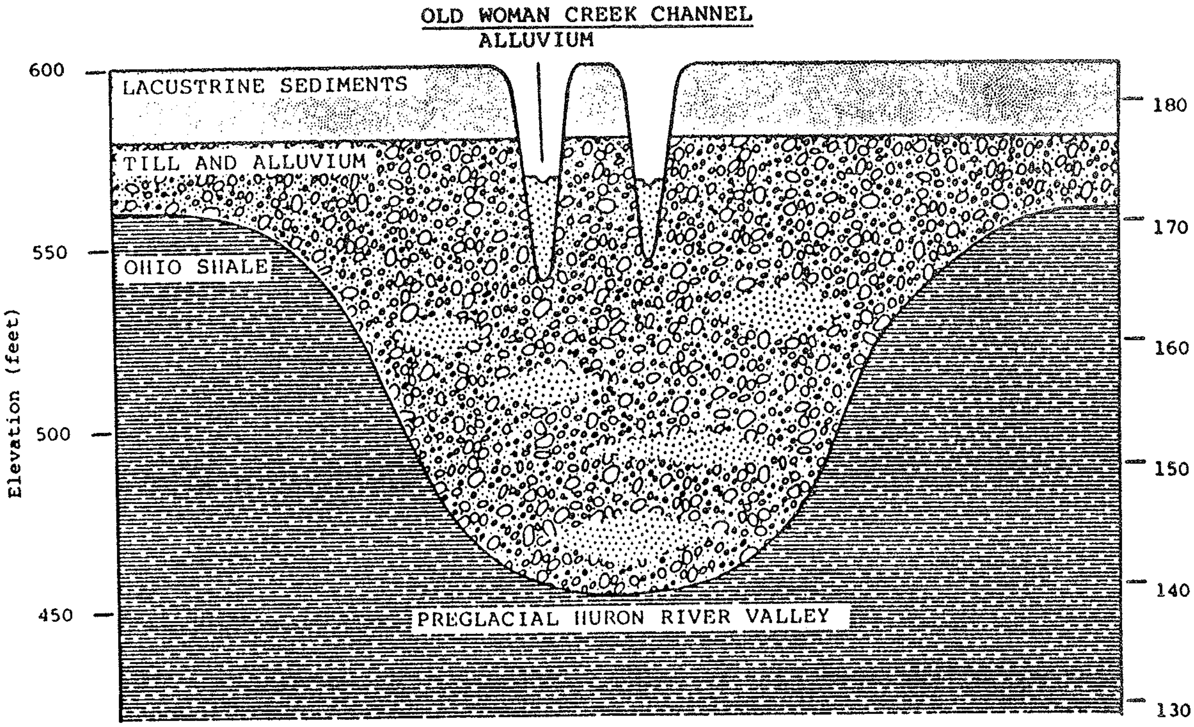

Figure 24. Geological cross-section of the Old Woman Creek estuary.

Figure 25. Flow patterns in Old Woman Creek Estuary in summer 1977 (after Buchanan 1983).

The erosional rather than depositional origin of Star Island can be inferred from the accordant height of the island with the surrounding uplands and the largely undisturbed lake plain sediments on the island.

After excavation of the Old Woman Creek channel near the present creek mouth in Lake Erie, the valley began to accumulate sediments as lake levels rose and the competency and capacity of the stream decreased. These accumulated sediments are shown as "Alluvium." Derived largely from erosion of the till and lake plain deposits above the estuary site, these sediments and their patterns of deposition reveal a detailed record of the conditions above and within the estuary since the glacial retreat (see Buchanan 1983).

At any given time, the primary control of the appearance of Old Woman Creek estuary is the level of adjacent Lake Erie. Both long- and short-term variations in lake level affect water levels in the estuary and thus may affect recent deposition, erosion, and biological processes. Even minor fluctuations in lake level on the order of a few centimeters can have profound effects in the estuary for two reasons: (1) the shallowness of the estuary makes it very responsive to fluctuations in water depth and (2) the elevation of the estuary floor is very close to mean lake level. Seiche events can be responsible for alternately exposing and flooding the entire floodplain in Old Woman Creek estuary. Several factors, however, tend to minimize the effects of seiche events on the long-term deposition of sediment in the estuary. First, most seiche events in Lake Erie are not directly transmitted into the estuary due to closure of the estuary mouth by the barrier bar. During recent years, the mouth of the estuary has been closed a majority of the time. If the duration and magnitude of these events are high, the likelihood of breaching the interceding barrier beach increases, allowing the estuary water level to fluctuate more directly with the lake. In addition, the effects of seiche events in the estuary are limited by other factors. The duration of a seiche event is short (generally less than a 14-hr period). Further, the magnitude of the water-level fluctuations transmitted into the estuary may not be sufficient to generate flow through the estuary channel capable of disturbing sediments previously deposited. Finally, there may not be an influx of texturally different sediment to record the event. Despite these minimizing factors, Buchanan (1983) believes that seiches are responsible for some of the erosional unconformities observed in the sediment record and may have provided opportunities for wind-generated wave action in the estuary to resuspend deposited sediment.

Of more significance to the size, depth and configuration of the estuary are long-term variations in lake level attributable to regional climatic factors such as precipitation, evaporation, and runoff. Ignoring for the moment the events of any particular year, a general trend from low water in the 1930s to high water in the 1980s can be readily observed. Water levels between 1860 and 1930 seem to have been on a slow decline, with average values intermediate between the 1930s and 1980s levels. On the basis of this cursory examination, more "terrestrial" conditions might be expected in the estuary in the 1930s and more "estuarine" conditions in the 1980s.

Thus, both the types of sediment and the nature of sediment deposition in Old Woman Creek estuary have varied greatly through time. The oldest sediments were deposited within the channel of Old Woman Creek and on the narrow floodplain across which the channel migrated about 8,000 years ago. These sediments exist at 6 m below the current estuary floor and consist of coarse to fine sands and silts deposited in the more swiftly flowing channel of the creek when the level of Lake Erie was much lower and the stream possessed a higher gradient. As the lake rose, the stream gradient of Old Woman Creek was reduced and the site of the estuary experienced increasing amounts of sediment deposition involving finer and finer sediments. As deposition progressed and the floor of the estuary rose in elevation, the size of the area over which the creek channel migrated increased, eventually to encompass and laterally enlarge the deep valley cut in the underlying lacustrine sediments and till by the early, erosive channel of the creek. Currently, only silts and clays are transported to and deposited in the estuary of Old Woman Creek (Buchanan 1983).

Within the last 100 years, the combined effects of rising lake levels and sediment deposition have decreased the water depth in the estuary to such a degree that shallow-water aquatic vegetation has begun to colonize its surface. The first indication of this colonization are zones of dark, organic-rich sediments with plant debris in the upper 1 m of cores recovered from the estuary. Using recent lake-level records and aerial photographs, Buchanan (1983) estimated that shallow water depths, between 15 to 30 cm, are necessary for such vegetation to flourish and that conditions such as these were present in the estuary between the 1920s and 1960s. More recent cores (Brian C. Reeder, personal communication) reveal a deeper, organic-rich layer, indicating even earlier low-water periods and high productivity in the estuary.

The sediment depositional rate in the estuary over the last 8,000 years has averaged 0.70 mm per year. This rate has been greatly accelerated in the last 100 years by agricultural development of the land surface within the drainage basin of Old Woman Creek. Current depositional rates in the estuary are estimated by Buchanan (1983) to be 10 mm per year on the basis of the nature and location of the dark, organic-rich zones.

Future of Coastal Marshes and Estuaries. Lake Erie is well known for its severe northeast and northwest storms and the resultant wave attacks and rapid fluctuations in water level at the shoreline. The high energy produced at the shore by these storms precludes the development of fringing coastal wetlands. Only where some type of natural or artificial protection is available against these harsh coastal processes (erosion, scour and rapid transport or deposition of beach material and sediments) can marshes become established and continue to exist. Settlements along the shore surrounding the western end of Lake Erie has greatly altered the natural shoreline. In the 1790s (see Kaatz 1955) much of the western basin shoreline was fronted by barrier beaches which protected lagoons and massive wetlands known as the "Black Swamp" (see Overview chapter, Fig. 8). Today these low shores are armed with stone dikes or protected with bulkheads. Sandy shores are now restricted to a few spits, such as Cedar Point, Ohio, Woodtick Peninsula, Michigan, and Point Pelee, Ontario, and places where littoral currents converge, such as Port Clinton and East Harbor, Ohio.

Based on these considerations, the coastal marshes of western Lake Erie fall into three categories, depending on the type of protection available to the wetland vegetation. As mentioned earlier, at one time the most important protection was that afforded by barrier bars (Fig. 26) or other natural features of the shoreline which formed quiet lagoons and coastal embayments. Very few natural wetlands of this type still exist in western Lake Erie. Until recently one of the best remaining examples was the lagoon ("east bay" of Sandusky Bay) stabilized by Cedar Point sand spit. However, during the record high water levels of 1972 and 1986, the bar was breached about 2 km from the base, severing the spit from the shore. In the past 15 years the spit has retreated over 800 feet into the bay resulting in the destruction of extensive wetland habitat. Other examples of natural-protection wetlands which still persist are those formed by rock-bound embayments in the islands region of western Lake Erie. Unfortunately, many of these embayments have been disturbed by the construction of small boat harbors.

Most of the lagoon-type coastal marshes, if they have not been drained or filled or engulfed by the lake, have been replaced by the second type: managed-waterfowl marshes which are now protected by earthen rip-rap dikes. The high wave energy of Lake Erie and the record high water levels of 1972-73 have taken a toll on the barrier beaches, necessitating the construction of armored dikes along much of the western basin shoreline. Large areas of wetlands are now protected in this manner by Federal, State and local agencies, as well as private shooting clubs.

The third type of protection is the natural isolation from lake storms provided by the estuaries of virtually all of the tributaries entering the western end of Lake Erie. At places such as the Maumee River, the estuarine aspects of the drowned river mouth extend upstream at least 15 km. Large wetlands have developed along most of the estuaries where disturbance has been minimal. Estuarine coastal marshes currently form the majority of the naturally protected wetlands bordering western Lake Erie.

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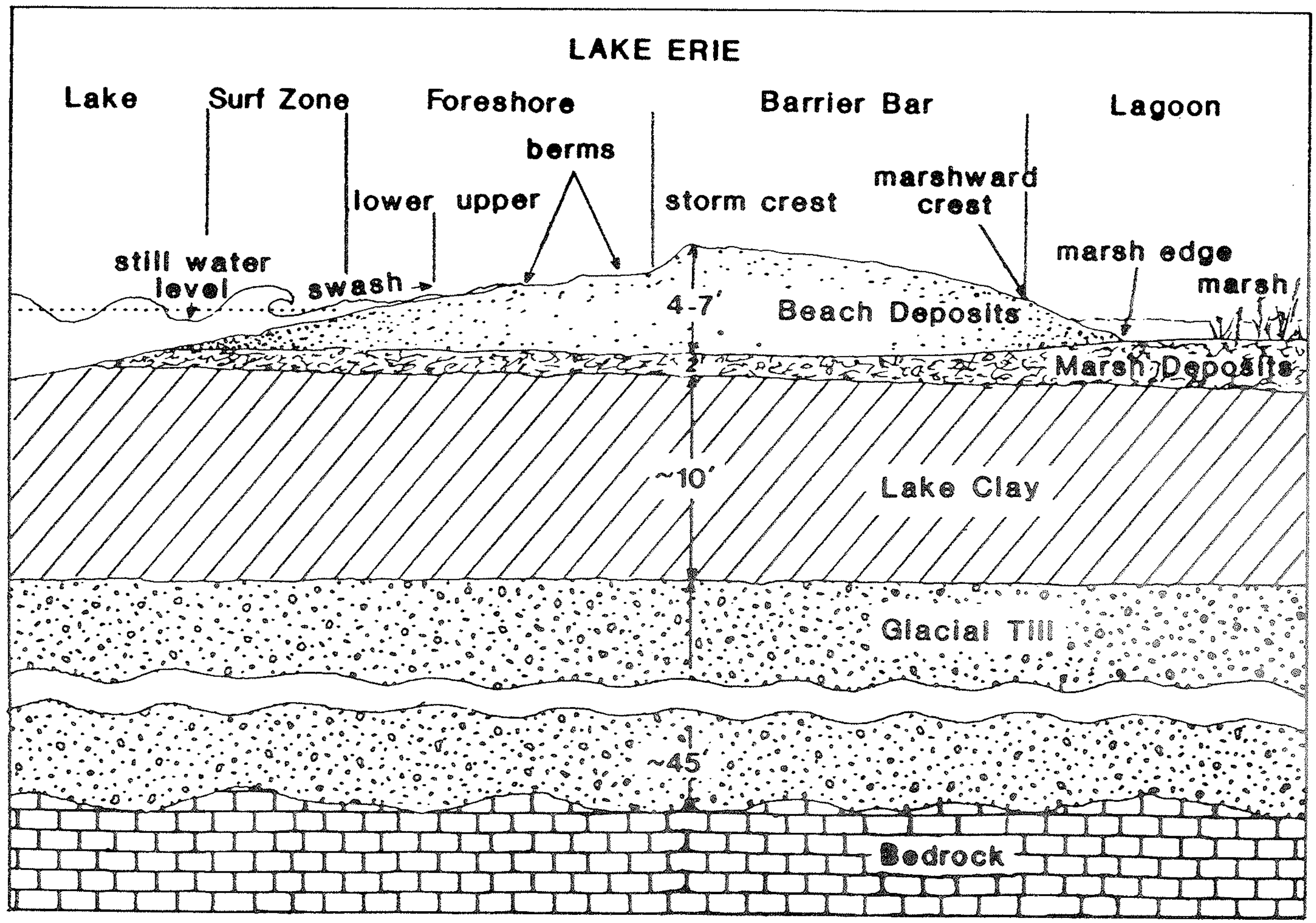

Figure 26. Typical cross-section of a Lake Erie barrier bar.

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THE EFFECT OF LAKE ERIE ON ITS TRIBUTARIES--RESULTING TRIBUTARY TRANSPORT MECHANISMS AND CONTRASTS WITH MARINE ESTUARIES

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INTRODUCTION

As it is with the other papers in this series, the objective of this paper is to present a summary of scientific and management issues, surrounding tributaries entering Lake Erie. The specific topics covered in this paper include the physical transport mechanisms of the Lake's tributaries, their coupling or interaction with Lake Erie and contrasts with marine estuary physics. The final purpose of this paper is to identify issues in the physics and transport realm to which attention should be directed in the following years.

Insofar as the last objective is concerned, one aspect of future research issues should be dealt with straightaway as it serves to establish the viewpoint of this paper: Within Lake Erie and, with the exception of perhaps Green Bay Harbor, for the most part all of the Great Lakes it is the case that no comprehensive field studies of the physics and transport of tributary confluence regions have occurred. In contrast, considerable published, verified knowledge about the physics of Lake Erie exists. Therefore, it is left to argue the points of this paper by implication which reduces the entire nature of this paper to suggestions for further research. A recent series of experiments in Sandusky Bay, a non-traditional tributary, provides the first and only pieces of solid evidence of some of the points raised here.

As a further clarification of the nature of this paper it is important to note that the confluence of these tributaries with Lake Erie is not an estuary as defined by Pritchard (1955), Cameron and Pritchard (1963), Hansen and Rattray (1966), Dyer (1973), Officer (1976), and McDowell and O'Conner (1977). There is no mixing of salt and no propagation of solar/lunar driven tide waves. Yet there are estuary transport analogies within Lake Erie tributaries and it will be the goal of this paper to show when analogous activity occurs and when it doesn't occur. The uniquely different transport mechanisms help to further frame the research issues.

Much of the information in this paper is abstracted from specifically cited references; there are, however, a number of fundamental documents which by their comprehensive nature serve as source works. These include the "Project Hypo" report (Burns and Ross, 1972), the special issue entitled "Lake Erie in the Early Seventies" (J. Fish. Res. Board Canada, Vol. 33) and most recently and importantly, the special issue entitled "Lake Erie Binational Study" (J. Great

Lakes Research, Vol. 13C4, edited by F.M. Boyce et al., 1987). Finally, Brandt and Herdendorf (1972) first suggested analogies to marine estuaries while this author and Herdendorf and co-workers attempted a first effort (Bedford et al., 1983) at collating Lake Erie physical effects on tributary confluence transport as primarily summarized from the thesis work of D. Lindsay (1981).

THE LAKE ERIE/TRIBUTARY SETTING

Lake Erie itself, as noted in previous papers, contains three basins, the Western, Central, and Eastern Basins, (Fig. 1) separated by two sills. Also, from Fig. 1, the islands separating the Western and Central Basins also define two channels for hydraulic flow, the Pelee Passage and the South Passage. The Lake is shallow, particularly in the Western Basin, which along with the Lake's southwest to northeast orientation makes it particularly susceptible to storm activity. As will be seen, the Lake response to storms is a controlling factor in confluence mixing and transport.

Figure 2 delineates the major tributaries entering Lake Erie with numbers referring to the tributary names and associated hydraulic data as extracted from Bedford et al. (1983), the United States Geological Survey Water Basin characteristic file and Brandt and Herdendorf (1970). The last two columns in Table 1 are based upon the estimation procedures developed by Brandt and Herdendorf (1970). Several items of note: 1.) Tributary No. 4 is the Sandusky Bay/River system which is completely anomalous in its structure compared to the other tributaries, 2.) Old Woman Creek, just east of the Huron River (No. 5), is an Estuarine Preserve but is not carried in the USGS Computerized Water Basin file; and 3.) The Detroit River, also not listed in the USGS Water Basin file, is considered the major tributary to the Lake.

In general, the river slopes are quite small, especially in the Western Basin and therefore, during non-storm periods, flows are quite small. Maximum tributary discharge occurs during and just after the spring "melt" season while a seasonal low flow occurs in the early fall. In general, the Detroit and Maumee Rivers contribute the largest load of water volume and sediment mass to the Lake; for example, Kemp et al. (1976) report that almost three million metric tons of sediment are transported to Lake Erie annually via these two rivers out of a total input (by mostly shore erosion) of 33 million metric tons.

Reversing flows have been persistently but aperiodically found in all these rivers except those near the center of the Lake, e.g. the Cuyahoga (Bedford et al. 1983), and it is the delineation of this activity and its origins that provides the key to understanding the similarities and dissimilarities between Lake Erie tributaries and marine estuaries.

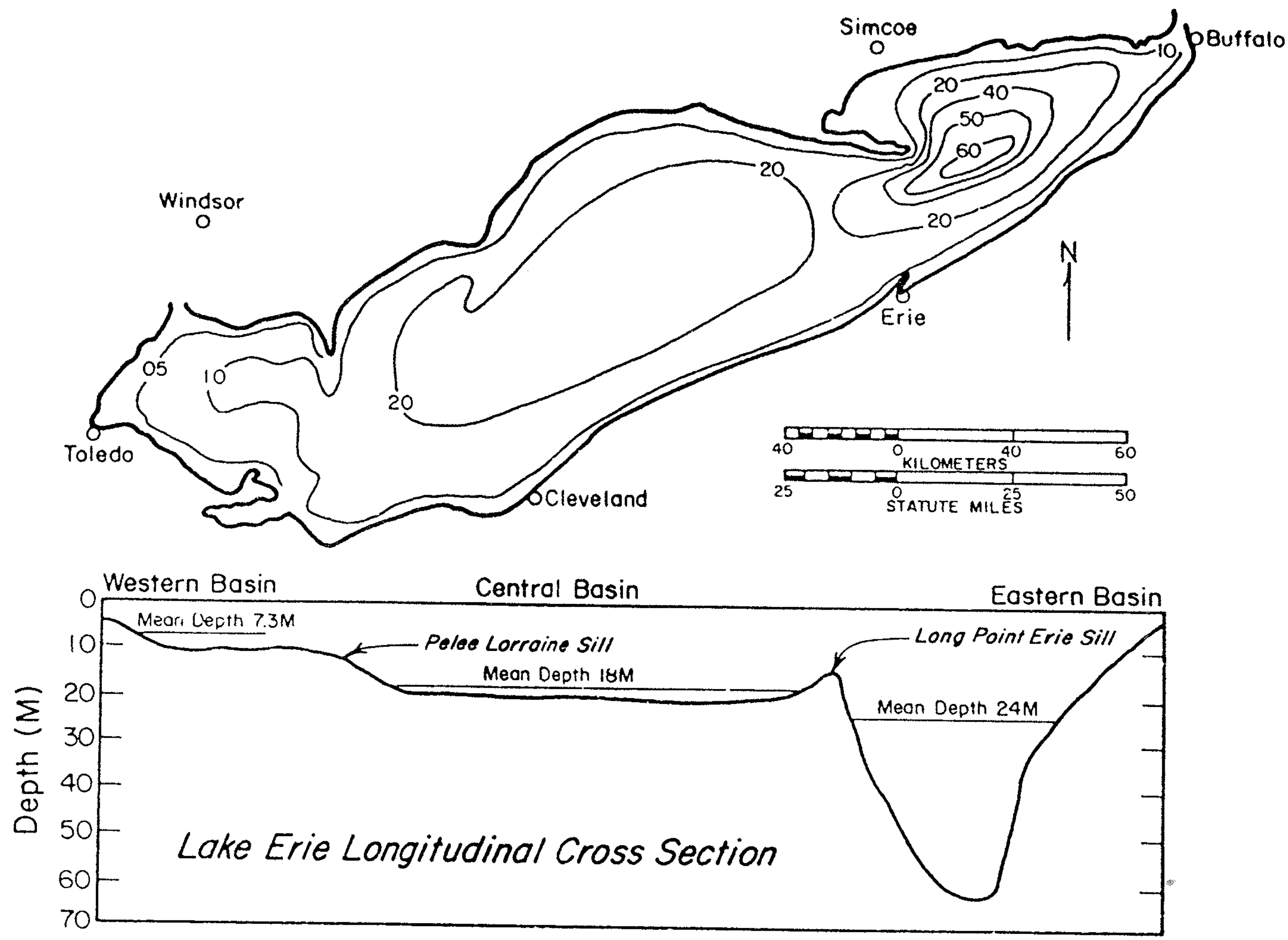


Figure 1. Lake Erie bathymetry (Bedford and Abdelrhman 1987).

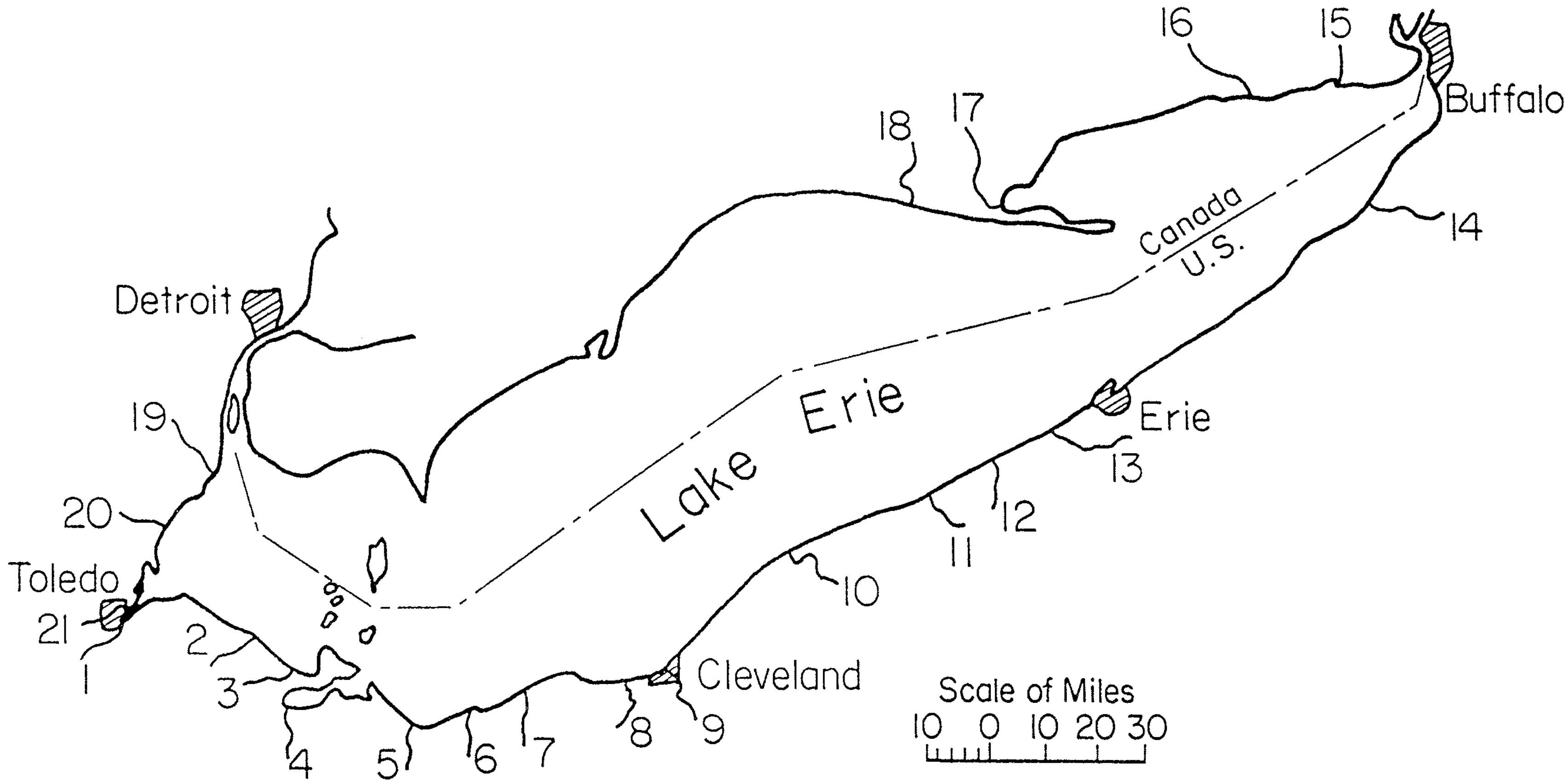


Figure 2. Tributary location map and identification numbers referenced to Table 1 (redrawn from Bedford et al. 1983).

Table 1. Mean flow and size data for the rivers indicated in Figure 2. (* data source, USGS Water Basin Characteristics File; + data source, Brandt and Herdendorf 1970).

ID#	Name and State	Mean* Annual Flow(cfs)	Q* 7,10 Low Flow (cfs)	Q* 7,10 High Flow (cfs)	Mean* Monthly Low Flow (cfs)	Mean* Monthl High Flow (cfs)	Bed* Slope (ft/mi)	Estuary+ Length (km)	Estuary+ Area (km^2)
1	Maumee, OH OH	445.7	93.7	54600	596.3 (Sept.)	10140 (March)	1.27	23.8	11.6
2	Toussiant, OH	N/A	N/A	N/A	N/A	N/A	N/A	16.1	3.9
3	Portage, OH	289.0	1.10	4710	26.7 (Aug.)	617 (March)	2.8	25.2	10.4
4	Sandusky, OH	975.0	12.2	14100	195.0 (Aug./ Sept.)	2470 (March)	4.03	24.8	5.3
5	Huron, OH	301.0	4.50	4390	47.3 (Oct.)	767 (March)	9.31	7.4	1.6
	Old Woman Creek	N/A	N/A	N/A	N/A	N/A	N/A	2.1	0.3
6	Vermillion, OH	261.0	0.10	4850	30.6 (Oct.)	777.0 (March)	6.99	2.4	0.3
7	Black, OH	324.0	3.70	4370	69.8 (Aug.)	859.0 (March)	6.69	6.6	0.9
8	Rocky, OH	241.8	1.40	3040	47.75 (Sept.)	580.0 (March)	9.45	0.8	0.1
9	Cuyahoga, OH	806	62.8	6070	305 (Sept.)	1712 (March)	7.13	7.2	1.0
10	Grand, OH	663.0	0.90	6780	107.0 (Aug.)	1631 (March)	1.45	5.3	0.8
11	Astubula, OH	155.0	0.00	1640	25.3 (Aug.)	348.0 (March)	12.8	2.8	0.3
12	Conneaut, OH	263.0	1.90	2850	64.6 (Aug.)	5680 (March)	7.04	2.0	0.2
13	Elk, PA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14	Cattaragus, NY	737.0	66.0	70.7	226.0 (Aug.)	1698 (March)	22.3	N/A	N/A
15	Welland Canal, Canada	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16	Grand, Canada	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
17	Big River, Canada	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
18	Big Otter, Canada	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
19	Huron, MI	407.0	40.50	2719	146.0 (Aug.)	842.0 (April)	2.3	N/A	N/A
20	Raisin, MI	648.0	38.18	7045	143.0 (Sept.)	1599 (March)	3.2	N/A	N/A
21	Ottowa, Canada	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

LAKE ERIE PHYSICS - AN OVERVIEW

Scales of Activity and Variability

An important requirement for understanding Lake Erie physics is its variability. It is extremely difficult if not impossible to identify physical characteristics of the Lake which are in some sense steady. The variability of Lake Erie extends over many decades of time and space with vertical spatial scales being quite compressed in contrast to the horizontal scales. Table 2 from Boyce (1974) and Bedford and Abdelrhman (1987) list all the physics and transport mechanisms extant in the Great Lakes and Lake Erie. What makes Lake Erie such a difficult area to study is that many of the mechanisms overlap in space/time structure and, therefore, it is very difficult to organize the controlled field programs necessary to validate hypotheses about the effect of one transport agent or another.

What is quite clear, however, is that several basic attributes of Lake Erie occur which are repetitively observed and fundamental to the understanding of the Lake. First, being so shallow, Lake Erie responds robustly to the annual thermal heating and cooling cycle (Schertzer 1987, and Schertzer et al. 1987). Second, in combination with the shallowness, thermal regime and orientation, the Lake quickly responds to the passage of storms, setting off an extremely complex variety of water surface and thermocline oscillations and corresponding velocities. Third, both free and forced responses exist for some time after the disturbance and surges, when they occur, are quite dramatic. Finally, during the interdisturbance or interevent time, transport is quite weak and exists against a backdrop of hydraulic flow established between the Detroit and Maumee River inflows and the Niagara River outflow.

Interevent times are often less than the time required for the previous event's disturbance responses to die away; therefore, the Lake is in a somewhat continuous cycle of impulsive storm forcing and response die away followed by another storm. Hence, a steady state description or explanation of gross Lake behavior based on ensemble averages is somewhat misleading. Nevertheless, the behavior of Lake Erie is summarized below from a long term average or ensemble average point of view. This summary will be followed by a discussion of episodic nature or climate of the Lake response to wind forcing.

Thermal Regime

From Project Hypo and the more recent works of Schertzer (1987) and Scherzter et al. (1987) much is known about the average thermal structure of the Lake. During the winter, ice cover exists over 90% of the Lake (Fig. 3) and effectively suppresses much wind driven circulation. After the ice break-up, wind mixing aids in distributing incident heat uniformly throughout the water column. This heating is relatively slow compared to the tributary water heating

Table 2. Summary of Lake Erie processes and scales; from Bedford and Abdelrhman (1987) after Boyce (1974).

A partial list of motions and their associated time and space scales (after Boyce 1974). Letters in parenthesis refer to the nature of the scale used. M, amplitude of motion; S, distance over which phenomenon varies significantly; P, period; T, time interval over which phenomenon varies significantly; C, wave speed; V, vertical particle velocity; H, horizontal particle velocity. The governing terms in the equations of motion and continuity are listed in column 6 according to the code: 1, time-dependent horizontal accelerations; 2, time-dependent vertical accelerations; 3, advective component of horizontal acceleration; 4, advective component of vertical acceleration; 5, Coriolis force; 6, pressure gradient force due to slope of free surface, 7, pressure gradient force due to slope of the thermocline; 8, pressure gradient force due to atmospheric pressure field; 9, variations in bottom topography; 10, wind energy/stress; 11, internal stresses arising from horizontal current shear; 12, internal stresses arising from vertical current shear; 13, friction against boundaries; 14, potential energy changes due to surface heating and cooling; 15, astronomical tidal-generaling forces due to sun-earth-moon gravitational potential field; 16, Potential energy changes due to temperature and salinity changes.

(1) Phenomenon	(2) Length Scale Horiz.	(3) Length Scale Vert.	(4) Time scale	(5) Velocity scale	(6) Dynamics major components
a. Wind driven surface gravitational waves	10 m(S)	1 m(M)	1S (P)	10 m/s(C) 1 m/s(V,H)	1,2,6,10
b. Surface gravitational waves – seiches	100 km(S)	10 cm(M)	2-10 h(P)	2 cm/s(H)	1,6,9,10
c. Short freely propagating internal waves	100 m(S)	2 m(M)	5 min(P)	2 cm/s(H)	11,2,7,10
d. Long propagating internal waves steered by topography	10 km(S)	2 m(M)	1 day(T)	50 cm/s(C)	1,5,7,9,10
e. Internal gravitational standing waves or seiches	10 km(S)	2 m(M)	16 h(P)	10 cm/s(H)	1,5,7,10
f. Surface wind drift	–	10 cm(S)	–	2 cm/s(H)	10,12
g. Coastal currents	10 km(S)	–	1 day(T)	10 cm/s(H)	all
h. Upwelling and downwelling	10 km(S)	10 m(M)	1 day(T)	<1 cm/s(V)	all
i. Wind driven horizontal circulation	100 km(S)	100 m(S)	1 day(T)	10 cm/s(H)	all
j. Geostrophic current	–	–	1 day(T)	3 cm/s(H)	5,6
k. Langmuir circulations vertical mixing of epilimnion	–	10 m(S)	1 h(T)	1 cm/s(V)	1,2,3,4,10,12,14, and others
l. Formation and decay	–	10-100 m(S)	1 mo(T)	–	10,12,14
m. Tidal waves:					
a) diurnal (kl,0.,P.)	Earth radius	–	1 day(T)	–	1,2,5,15
b) semidurnal (M_2,S_2,N_2)	Earth radius	–	1/2 day(T)	–	1,2,5,15

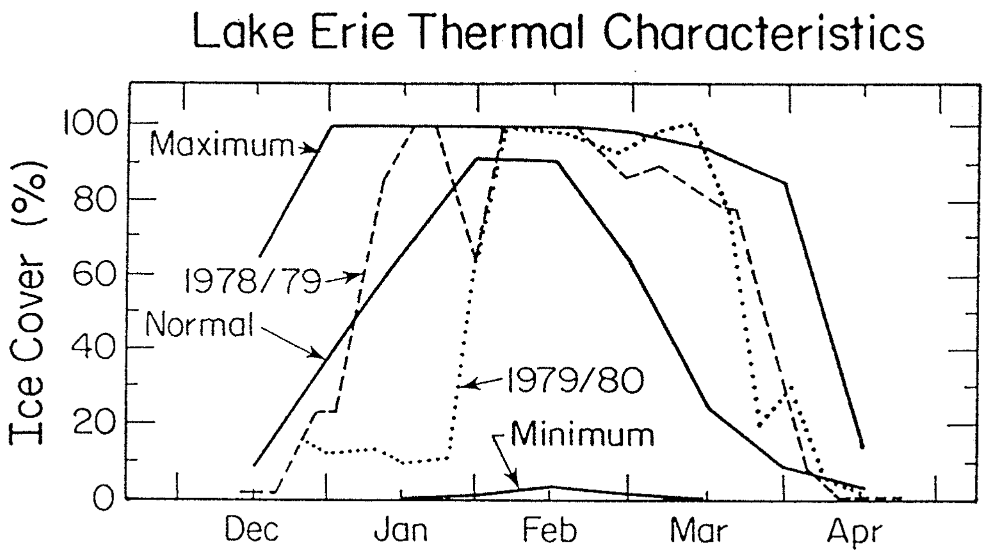


Figure 3. Thermal regimes of Lake Erie (redrawn from Schertzer et al. 1987).

(Schroeder and Collier 1966, Fraleigh et al. 1975, Herdendorf and Zapotosky 1977, and Bedford et al. 1983). Furthermore, the deeper Eastern Basin will lag the shallower Central and Western Basins in its response to heat input in the offshore deep water zones.

The spring-summer-fall heating-cooling cycle is marked by both vertical and horizontal temperature variation. The development of vertical temperature profiles is depicted in Fig. 4 (from Schertzer et al. 1987) and during the summer strong stratification is exhibited. The thermocline generally reaches its maximum vertical depth at 15-20 meters, a depth determined by a particular year's total heat and wind energy (mixing) input. Hypolimnetic waters generally have temperatures ranging from 5°-9°C. The thickness of the mesolimnion is a function of the severity of wind mixing with the deepest possible water column depth being achieved by mid-August (Schertzer 1987).

Vertical profiles during the fall return to homogeneity through storm induced de-stabilization. By mid-October homogeneous profiles are noted. In the fall it is noted that the Lake retains heat much longer than the overlaying atmosphere, thus, setting up unstable air/water temperature differences (Schwab 1978).

Horizontal variations in temperature are marked by thermal bar activity in the near-shore zone. Rodgers (1974) was among the first to investigate this phenomenon which is essentially an artifact of the freshwater density maxima at 4°C. The thermal bar is the offshore propagation of the 4°C isotherm as spring heating proceeds. Such offshore propagation results from the very shallow nearshore waters heating much quicker than the deeper offshore thermal waters. According to recent references in Schertzer et al. (1987), the offshore bar propagates to the mid-Basin and disappears by mid-May.

The presence of thermal density gradients affects the circulation and transport patterns, particularly the presence of ice cover, the temperature difference between the tributary and Lake Erie waters and the presence or non-presence of the thermocline. The interaction of the thermal and circulation fields is a particularly complex problem.

Persistent Circulation Features

A considerable body of knowledge of measured and modeled currents is available in the literature, and Table 3 (Bedford and Abdelrhman 1987) is an attempt to define the structure and classification of persistent circulation features. Model results are quite prevalent in verifying these regimes and of early note are the initial numerical model studies of Gedney and Lick (1972). Full three-dimensional model results, assuming no vertical acceleration (Haq and Lick 1975) have been performed for nonstratified conditions but a full three-dimensional simulation of Lake Erie, including full stratification effects, has yet to be done. Lam and Simon's (1976) two layer approach has provided insight to flow dynamics during stratification.

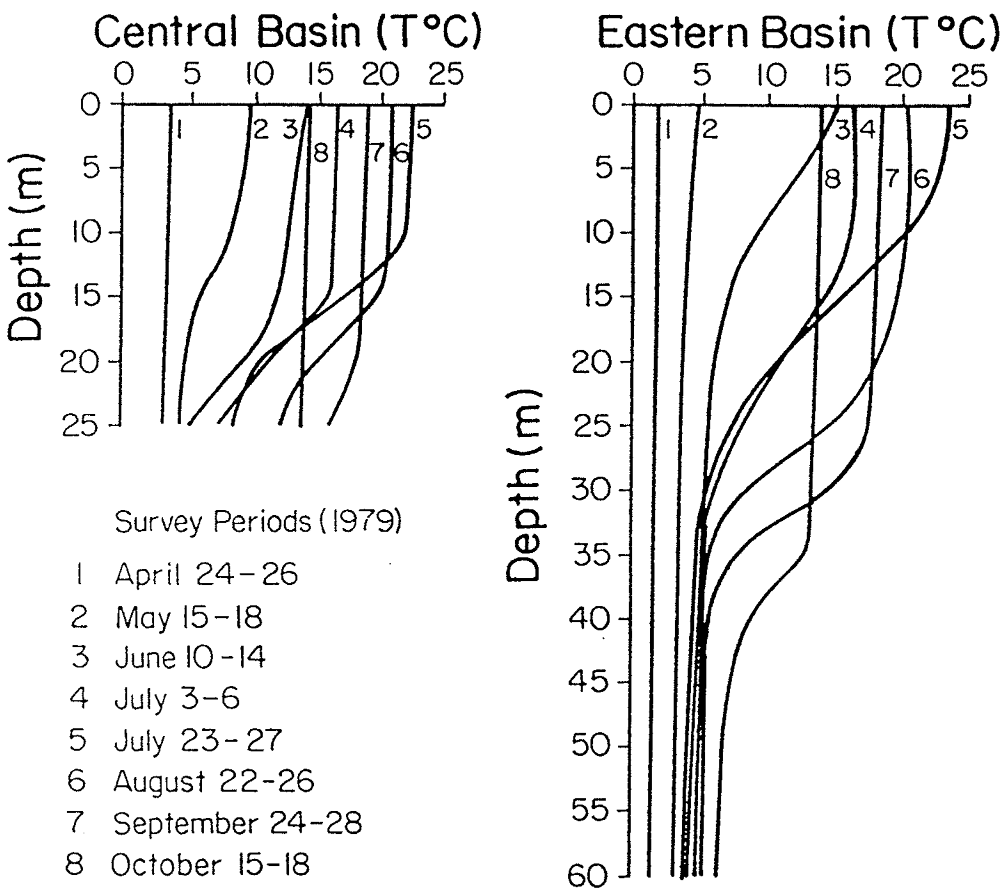


Figure 4. Development of Central Basin vertical temperature profiles (redrawn from Schertzer et al. 1987).

Table 3. General Lake Erie circulation categories and dominant processes; from Bedford and Abdelrhman (1987).

Location / Regime	Total Lake	Inshore Zone	Sill Zone	Western Basin	Central Basin	Eastern Basin
1. Ice Covered	m,j*	g	N.A.	j	m,j	m,j
2. Homogeneous, Non Storm Condition	N.A.	h,g	h,i	j,i	i,j	j,i
3. Stratified, Non Storm Conditions	N.A.	g,h,l h,i	c,d	c,d,i i,j	c,d,e i,j	c,d,e,
4. Homogeneous Storm Conditions	N.A.	a,b, g,h	h,b,i	b,a,i	i,j,b	i,j,b
5. Stratified, Storm Conditions	N.A. N.A.	a,b, g,h	c,d,e, i,h	a,b,i	c,d,e, i,j	c,d,e, i,j

* For process definition see Table 2.

Field observations of currents have not been as resolved as those observed in Lake Ontario during the International Field Year on the Great Lakes. However, good data do exist starting with Verber (1955). A review of the history of current data collection is found in the papers by Mortimer (1987) and Saylor and Miller (1987). The Saylor and Miller article, as well as articles by Schwab and Bennet (1987) and Boyce and Chiocchio (1987), provide a wealth of data about the persistent vertical and horizontal currents.

The essential nature of persistent circulation features is as a result of frequent wind impulses which relatively quickly (Haq and Lick 1975) spin the Lake up to a new circulation state. Saylor and Miller (1987) state that surface currents are a result of wind drift, while currents near the bottom are pressure gradient driven return flow. They go on to state that a quite complex suite of circulation gyres occurs whose simpler forms have been predicted by models (Saylor et al. 1980) and observationally confirmed (see Fig. 5) by Saylor and Miller (1987). It is noted that the gyres are often unstable with one or the other becoming dominant in the Central Basin. Such dominance is possible as a result of wind stress curl events. Of some note from the Saylor and Miller article is that stratification does not appear to be important in affecting current and gyre structures during episodes. Currents in the passages are a result of seiche activity, with Western Basin currents, in general, dominated by surface wind stress and the hydraulic influence of the Detroit and Maumee Rivers. Finally, as noted by Saylor and Miller (1987), in the nearshore zone a number of investigators have noted the thin bands of eastward flow in both northern and southern shores, and have noted the familiar Coriolis affected wind driven surface drift currents. The new evidence in Saylor and Miller (1987) does not change this picture.

THE EPISODIC NATURE OF LAKE ERIE

As mentioned, Lake Erie physics is particularly susceptible or responsive to storms. Due primarily to prevailing storm tracks (Irish and Platzman 1962) and shallowness, Lake Erie responds to the wind stress by a combination of free and forced mode oscillatory responses in water level and thermocline position which give rise to periodic velocity and current structures.

Forced Response Modes

The response of Lake Erie to the imposed wind stress as it is in contact with the Lake (i.e. during the passage of the storm) is called the forced mode. The most dramatic manifestation of this response is frequent and often dramatic storm surges. Water level increases occur downwind in the Lake with commensurate water level drawn down at the upwind end. Therefore, for winds from the southwest, water level increases at Buffalo will occur with drawdowns at Toledo. The opposite will occur for winds from the northeast. The Buffalo minus Toledo water level is called the set-up although this is a bit misleading in that the maximum positive surge amplitude above datum will occur some four

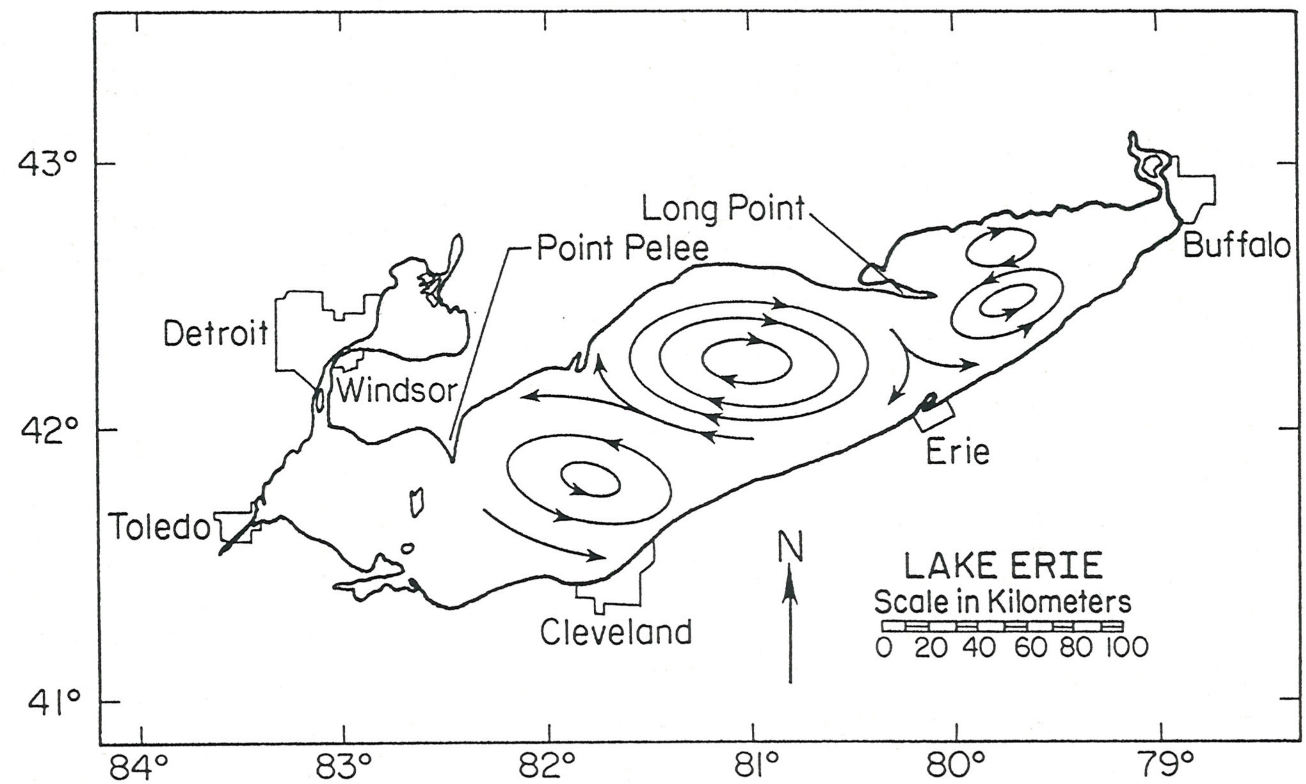


Figure 5. Schematic of proposed Lake Erie Central Basin circulation (redrawn from Saylor and Miller 1987).

hours or more before the corresponding maximum drawdown. Explanations for this vary, but have been offered by Rao (1968), Hamblin (1979) and Libicki and Bedford (1988) via the method of characteristics.

The statistics of surges are impressive and following the probability analyses of Irish and Platzman (1962) and Pore (1975) the following information is known (see Figs. 6a-6c, Tables 4 and 5). The water level at Buffalo exceeds the mean monthly water level by 3.5 feet at least once per year, while the same statistics hold for water drawdown at Toledo. Therefore, a maximum set-up of seven feet is exceeded roughly once per year. A set-up in excess of ten feet is equaled or exceeded every two years. The worst positive surge at Buffalo was 9.0 feet above the monthly average water level during the April 1979 storm (Hamblin 1979), while the worst positive surge in Toledo was 5.3 feet above the monthly average water level during April 1967. The worst negative surge at Toledo was 7.5 feet in March 1965, while the worst negative surge in Buffalo was 4.65 feet during March 1964. Extreme value/recurrence probabilities are presented in Fig. 6a. Commercial navigation is prohibited during extreme drawdowns in Toledo and freshwater intakes cannot function; therefore, surge forecasts are issued as necessary by the National Weather Service as based upon the model of Schwab (1978).

The origins of such storm surges are atmospheric pressure drops and wind shear stresses acting at the Lake's surface. Through the effect of large pressure drops and corresponding pressure gradients, a "suction lift" effect derived from hydrostatic pressure considerations is hypothesized to be one mechanism for creating surges. Harris (1957) examined such an occurrence on Lake Michigan. However, the effect is small for most large weather systems as the pressure gradients are small owing to the size of the storm over which the pressure drop occurs. For example, Dingman and Bedford (1984) analyzed the Lake Erie response to the January 1978 cyclone which had the lowest central pressure recorded for an extra-tropical cyclone observed over the Lake. The water level elevation increase due to the suction lift was 30 cm at most.

Shear stress is by far the most dominant mechanism in the creation of storm surges and two facets of the application of this shear stress to the Lake surface are critical in the development of large surge events: an air-water temperature instability and stress-band resonant coupling.

Originally discussed by Hunt (1958), it has since been recognized that the shear stress at the water surface is not only a function of the wind speed, but the air-water temperature difference as well. While Hunt's analysis was primarily empirical, Schwab's (1978) stability dependent formulation was based on well founded boundary layer methodologies and is now a commonly used procedure for making shear stress estimates. It should be noted that the drag coefficients for thermally unstable conditions are nearly twice as high as those for stable thermal regimes. This then explains to a large extent why the vast majority of very large surges occur during the late fall months (Fig. 6b and Fig. 7). The fall months are times when heat is retained in the Lake due to its slower heat conductivity relative to the atmosphere, and the passage of cold fronts can

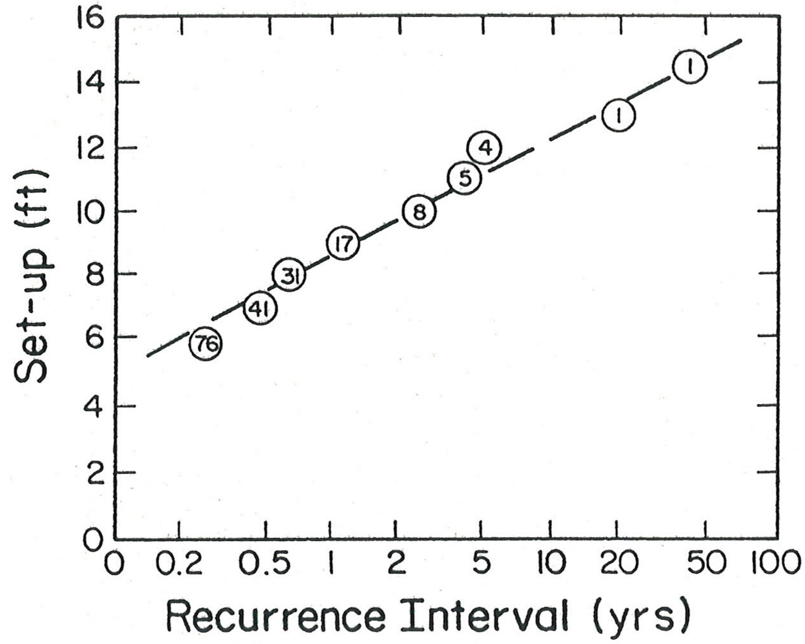


Figure 6a. Recurrence intervals for Buffalo-Toledo setups; circled numbers are number of cases for observed setup at one foot increments as of 1973 (redrawn from Pore et al. 1975).

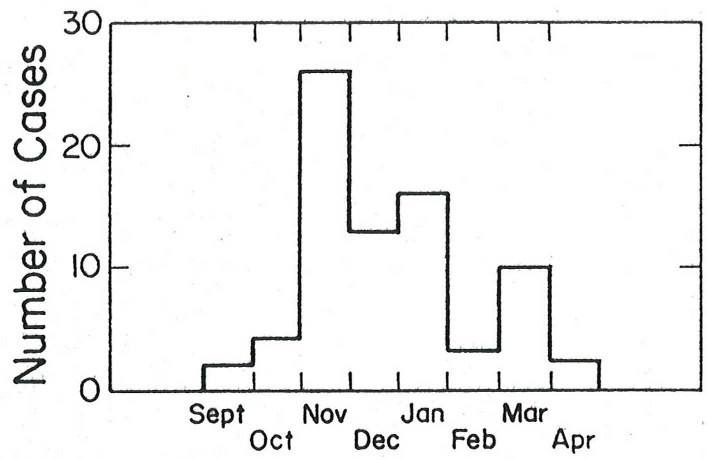


Figure 6b. Histogram of monthly setups in excess of six feet (redrawn from Pore et al. 1975).

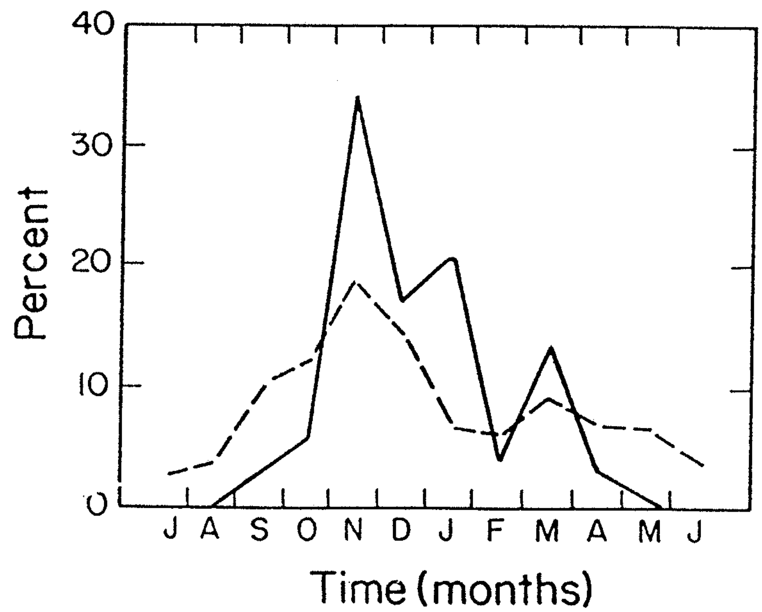


Figure 6c. Frequency distribution of six foot setups or greater (———) and severe storms (- - - - -) (redrawn from Pore et al. 1975).

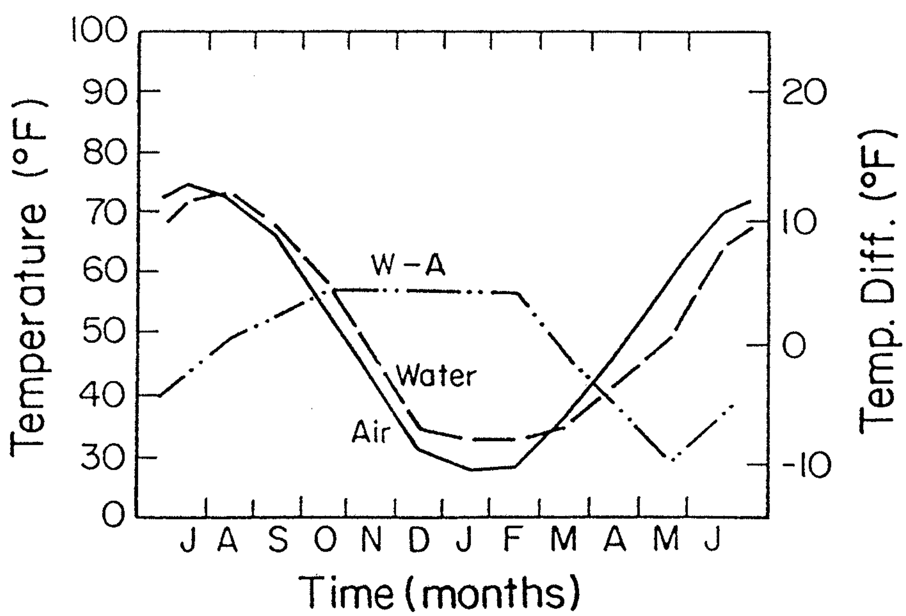


Figure 7. Monthly air and water temperatures for Lake Erie (redrawn from Hunt 1958).

Table 4. Average monthly and annual frequencies, positive storm surge at Buffalo, cases/year (from Pore et al. 1975).

Month	Storm Surge Heights (Ft) ≥2	≥3	≥4	≥5	≥ 6	≥7
JAN	2.31	1.06	0.41	0.16	0.09	
FEB	1.25	0.31	0.09	0.09	0.03	0.03
MAR	1.16	0.47	0.37	0.12	0.06	
APR	0.72	0.22				
MAY	0.15	0.06	0.03			
JUN	0.27	0.03				
JUL	0.18					
AUG	0.18					
SEP	0.70	0.21	0.09	0.03		
OCT	0.91	0.27	0.09	0.06	0.03	
NOV	2.85	1.33	0.48	0.1	0.03	
DEC	2.30	1.12	0.42	0.12	0.03	
Annual	12.98	5.08	1.98	0.79	0.27	0.03

Table 5. Average monthly and annual frequencies of negative storm surge at Buffalo, cases/year (from Pore et al. 1975).

Month	Storm Surge Heights (Ft) ≤-2	≤-3	≤ -4	≤-5	≤ -6	≤ -7
JAN	0.41	0.16	0.03			
FEB	0.16	0.03				
MAR	0.44	0.06	0.03			
APR	0.12					
MAY	0.03					
JUN	0.21					
JUL	0.03					
AUG	0.03					
SEP	0.12					
OCT	0.12					
NOV	0.18	0.03	0.03			
DEC	0.45	0.06				
Annual	2.30	0.34	0.09			

cause air quite colder than the Lake to pass over the surface. In the spring, the Lake takes longer to acquire heat and therefore the air is usually warmer; therefore instability plays less of a role in creating spring-time surges.

Another factor in the creation of excessive surge heights is resonance. Resonance conditions have been defined in various ways and are hypothesized to result from bands of low pressure or high shear stress traveling across the Lake with a speed equal to the free gravity wave speed for the Lake. This idea was suggested early on for pressure disturbances by Hunt (1950) to explain an anomalous surge in Lake Michigan arising from a convective storm.

Significant analytical attention has more correctly concentrated on the role of wind stress bands passing over the Lake. Initial attempts by Irish and Platzman (1962) to address this problem were somewhat flawed as they concentrated on defining the coupling through the position of the front in the weather system. The front is an ambiguous tracking measure. It remained for Rao (1967) to identify the proper tracking measure as the wind stress band and, noting that large pulses of stress can occur through either large winds or an air water temperature instability, defined resonance for Lake Erie as follows. For wind systems whose stress band width is less than the Lake's length, resonance occurs if the propagation speed of the stress band approximately equals the gravity wave speed. For Lake Erie this would be approximately 13.5 meters per second or 48.5 km/hr (30 miles per hour). For stress bands with a width longer than the Lake, resonance occurs when the time it takes the stress band to pass a stationary point equals the time necessary for a gravity wave to pass the length of the Lake. The resonance condition is frequently equaled because weather systems often travel with roughly that same speed.

The occurrence of resonance phenomena is perhaps not as frequent as previously thought. Extending Rao's (1967) work by use of more sophisticated computational algorithms, Libicki and Bedford (1988) demonstrated that the converging geometry of the shoreline near Buffalo was a far more important contributor in creating high surges than previously acknowledged. Pure resonance does occur and is marked by the presence of a high localized "flip" of the water surface near Buffalo. This flip is a brief localized pulse of water surface elevation which increases the water level 1 to 2 feet more than the elevation due to non-resonant geometry focused surges. Of the five worst surges in Lake Erie this flip was observed only once, in the April 1979 storm, and resulted in the highest amplitude ever recorded by over one foot. This storm surge was a resonant response; the other four worst surges were not resonant responses.

Free Mode Response

After passage of the stress event the potential energy stored in the surge is released and expressed as free oscillation gravity waves called seiches. The entire basin is activated by seiche activity. Following the lead of Csanady (1982), Csanady and Scott (1974) and Mortimer (1963), coastal jets and Kelvin waves can occur as well. Very little work has been done in Lake Erie in fully exploring this resulting nearshore activity. Since coastal jets and Kelvin waves might affect how tributary discharges are transported, more research will be required in this area.

The structure of seiche activity is widely known from observations made at the nine water level gauges surrounding the Lake and a number of one and two dimensional computational experiments. With the reviews by Mortimer (1987) and Hamblin (1987) providing the historical context, the following features are known. There are five longitudinal free modes in Lake Erie and as the initial modeling and spectral analyses of Platzman and Rao (1964a,b) showed the basin wide average periods are 14.1, 8.9, 5.7, 4.1 and 3.7 hours. A transverse mode was numerically speculated upon by Platzman (1963) and observed for the first time in the data by Dingman and Bedford (1984). The structure of these modes i.e. positioning of null oscillation lines, timing and phasing, volume transports etc. has been extensively researched. It has been initally shown by Platzman and Rao (1964a,b) that the seiches contain a counter clockwise progression of high water which is introduced by Coriolis activity. This amphidromic structure then results in phase lags between high water occurring at different points around the Lake. The first four amphidromic mode structures and phase relations are shown in Fig. 8 as redrawn from Hamblin (1987). These structures were calculated from model results. The fifth mode is weak. The transverse mode structure is also poorly defined, but portrayed (Fig. 9) from the modal analysis of Prater and Bedford (1982).

Platzman and Rao (1964b) used a one dimensional analysis to define typical water surface elevation, volume transports and cross section average current speeds. The one dimesional cross section average approach is particularly effective in summarizing the gross behavior of the seiche modes and Figs. 10a, b, and c contain these behaviors as redrawn from the 1964b reference. Implicit in these diagrams are several simple features of seiche activity. First, the relative amplitude of each successively higher mode is less than the fundamental mode, however, different amplitude modes are dominant in different parts of the Lake. For instance, the first, third and fifth modes are close to null east of Cleveland, while the maximum second mode amplitude excursion occurs at this point. By implication then, different tributaries along the Lake will be subjected to seiches of different period and amplitude, i.e., the second mode dominates the spectra of Cuyahoga River (No. 9, Fig. 2) elevation while the first mode dominates at the Maumee River (No. 1, Fig. 2).

A second feature is that water volume transports are generally maximum at null oscillation lines. Water volume transports therefore will also be different at different positions of the Lake. From Fig. 10b it can be seen that the first mode maximum transport occurs near Cleveland/Fairport, while the second mode maximum transport occurs near the Huron River (No. 5, Fig. 2) and Erie Pennsylvania. It is important to remember these transports are, in general, oscillating/periodic as are the elevations but are in general 90° out of phase with the elevation. The concept of maximum seiche excursion length (Sorenson 1978) associated with each mass transport mode is applicable but

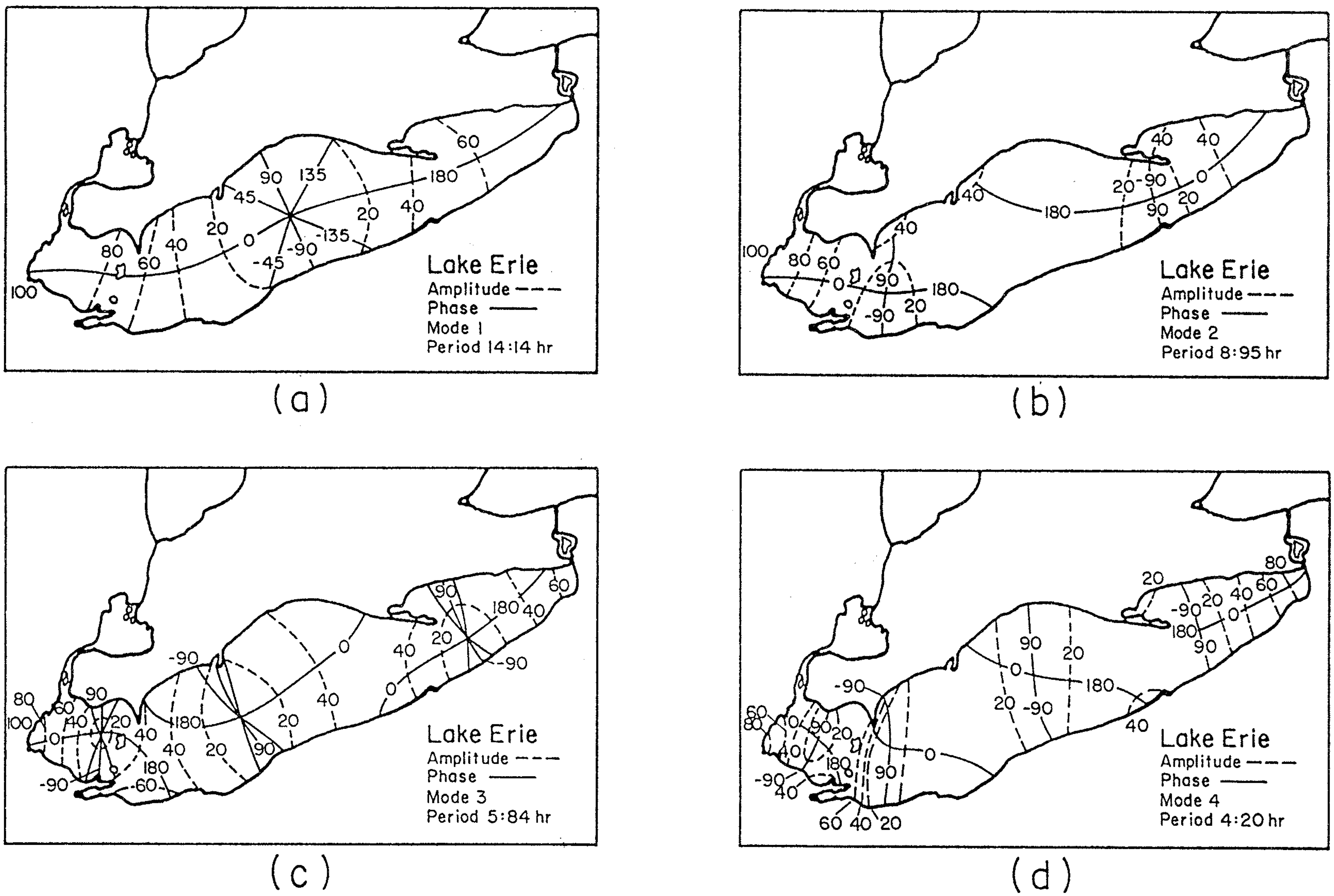


Figure 8. First four Lake Erie amphidromic mode structures (redrawn from Hamblin 1987).

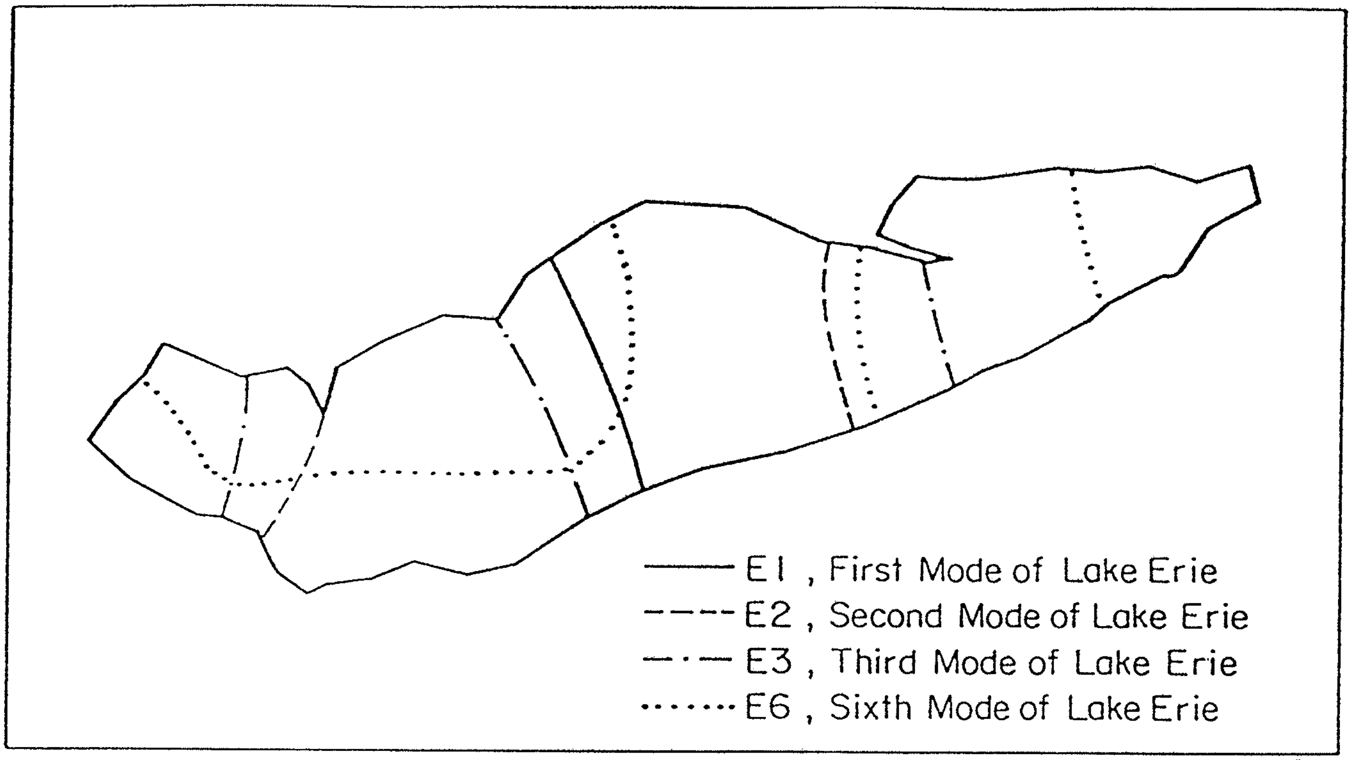


Figure 9. Lake Erie sixth mode null oscillation line (Bedford et al. 1988).

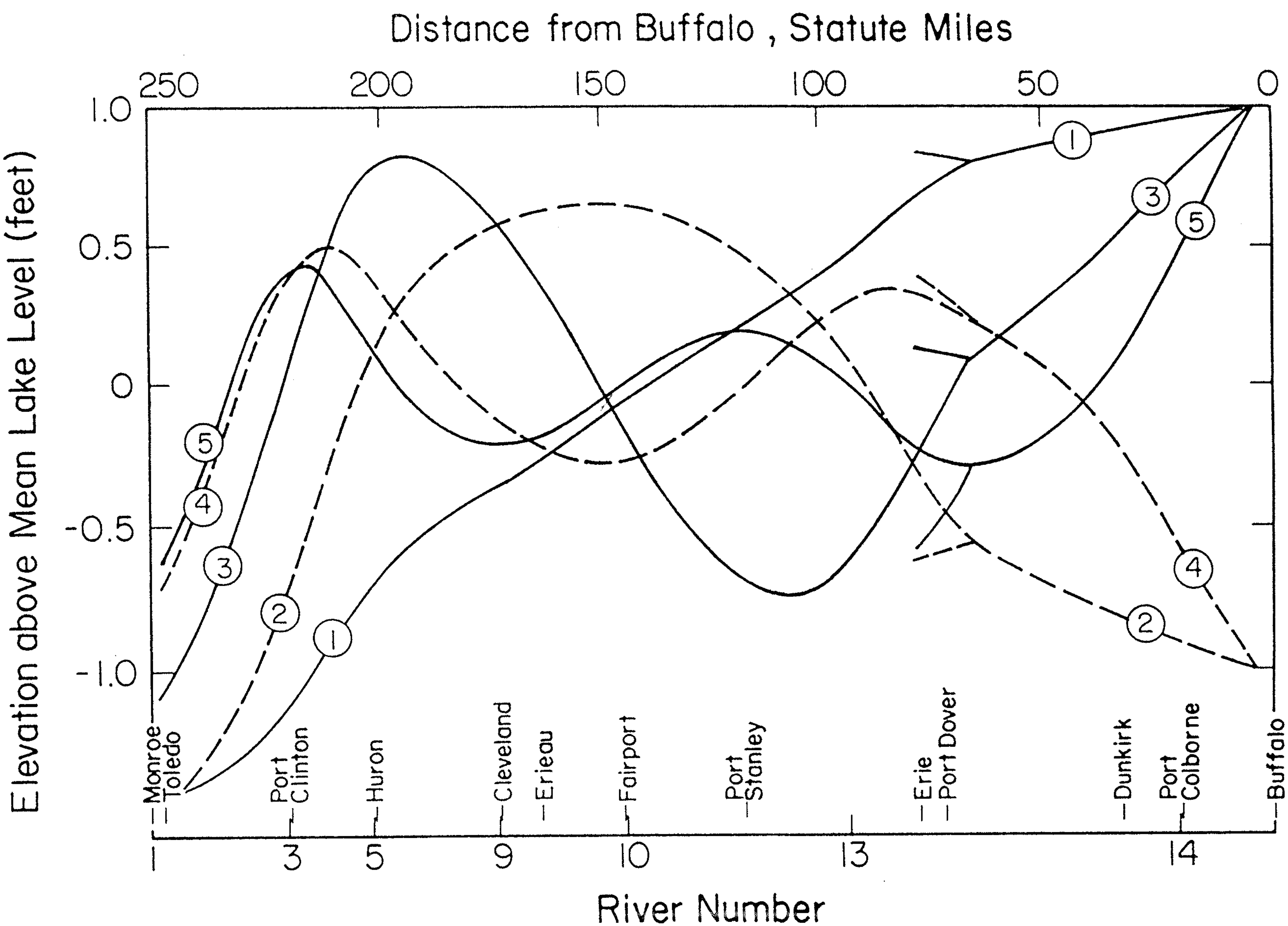


Figure 10a. Normalized Lake Erie water levels for the first five Lake Erie modes (redrawn from Platzman and Rao 1964b).

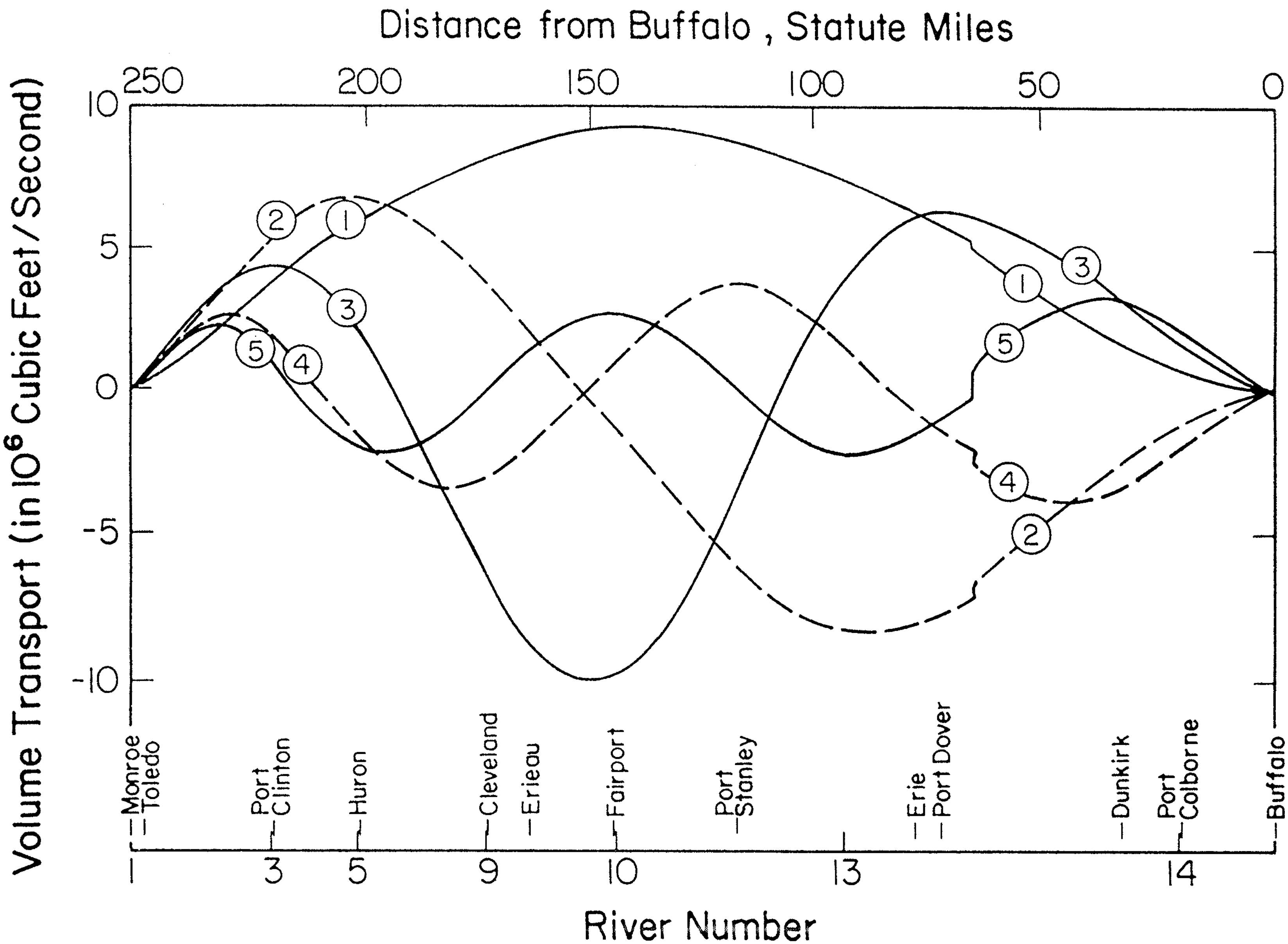


Figure 10b. Normalized water volume transports for the first five Lake Erie modes (redrawn from Platzman and Rao 1964b).

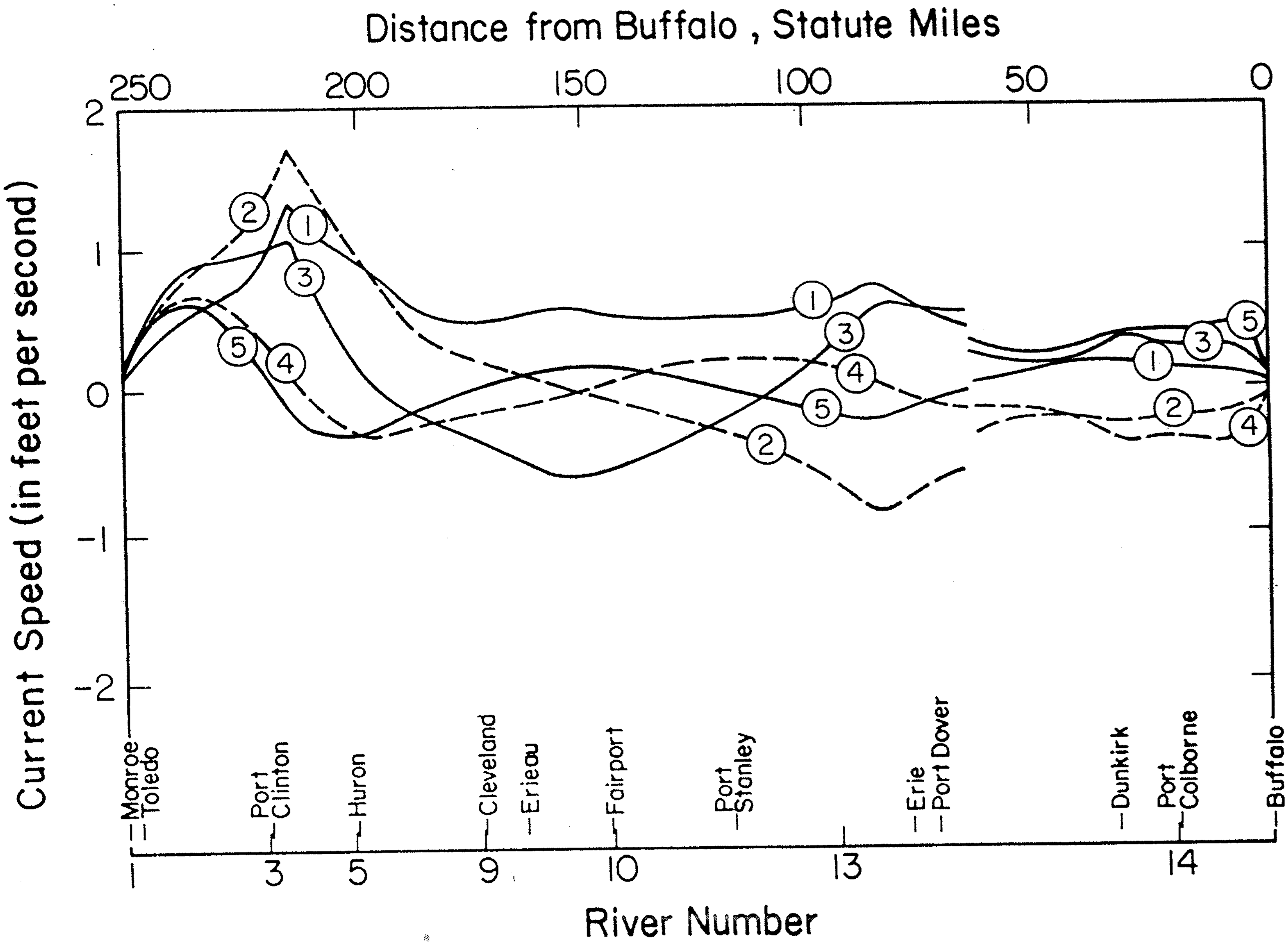


Figure 10c. Normalized current speeds for the first five Lake Erie modes (redrawn from Platzman and Rao 1964b).

has yet to be performed in detail for the Great Lakes with regard to tributary influences.

Finally, by dividing the mass transports by the cross sectional area, it is possible to estimate the average velocities due to each mode and in contrasting Figs. 1 and 10c, it is apparent that the sill areas very much affect the average velocities.

Recognizing that tributary positioning relative to seiche mode structure is critical in understanding the episodic and periodic nature of transport in these tributaries. Table 6 contains an estimate of the seiche mode amplitude for the tributaries labelled in Fig. 2. These elevations are referenced to the maximum amplitude observed in Toledo. It is possible from this list to infer that a number of the Rivers will have either positive or negative wave amplitudes propagating up the tributary with some flood waves, depending upon the initial surge height, containing enough momentum and energy to reverse the flow in the river. In essence, then, certain storms, by unleashing slow long period gravity waves in Lake Erie, give rise to the periodic reversing flow phenomena in certain Lake Erie tributaries. The question remains how analogous is this activity to estuaries and what are the implications of this behavior.

Since the decay modulus (Platzman and Rao, 1964b) for these seiches indicates an exponential decay of amplitude maxima, it is estimated that over four days of fundamental mode oscillation are required for full diminishment. Often, in the spring and fall storms arrive more frequently and therefore seiche activity persists. These seasons are expected to contain the highest probablity for the episodic tributary transport disruption due to flow reversals or flood wave propagation.

A SUMMARY OF ESTUARY TRANSPORT ATTRIBUTES AND A FIRST COMPARISON WITH LAKE ERIE TRIBUTARIES

From the early estuary overview works of Cameron and Pritchard (1963), Hansen and Rattray (1966), Dyer (1973), Officer (1976) and McDowell and O'Conner (1977) several features of estuary transport physics are fundamental and a comparison with Lake Erie tributaries physics serves as a starting point for selecting similarities and dissimilarities. First, estuaries contain salt with concentrations varying along the estuary from the freshwater head (concentration is zero) to the ocean receiving water (concentration is maximum). The longitudinal variation can have a low gradient such as when freshwater inflow and tidal velocity might be weak or can have a gradient so high as to give rise to a density interface. Dyer (1973) and Pritchard (1955) present schematics of the various types of salt water density structures that can exist, and although one may argue the merits of the details, it certainly is the case that such density gradients exist and are permanent features of estuaries. The sharpness of the vertical and/or horizontal salt gradient determines to what extent internal waves exist on the interface. Finally, depending on the severity of the freshwater discharge contrasted to the tidal momentum, the saltwater

Table 6. Identification of modes of oscillation which may affect flow patterns in the rivers of Lake Erie. Elevation ranges have been non-dimensionalized by the maximum observable displacement at Toledo, Ohio, shown in Fig. 2.

River ID#	Modes at Mouth	Elevation Range
1	1	1.0
	2	0.8
	3	0.72
	4	0.47
	5	0.40
	6	--
2	1	0.87
	2	0.70
	3	0.20
	6	--
3	1	0.8
	2	0.50
	4	0.23
	5	0.23
	6	--
4	1	0.57
	3	0.33
	4	0.23
	5	0.33
	6	--
5	1	0.50
	2	0.03
	3	0.47
	4	0.03
	6	--
6	1	0.3
	2	0.27
	3	0.50
	4	0.07
	5	0.07
	6	--
7	1	0.26
	2	0.33
	3	0.5
	5	0.3
	6	--
8	1	0.27
	2	0.30
	3	0.47
	5	0.17
	6	--
9	1	0.2
	2	0.4
	3	0.4
	4	0.1
	5	0.13
	6	--
10	2	0.4
	3	0.07
	6	--
11	1	0.3
	3	0.3
	4	0.2
	6	--
12	1	0.33
	3	0.33
	4	0.2
	6	--
13	1	0.43
	3	0.27
	4	0.27
14	1	0.6
	2	0.6
	3	0.5
	4	0.4
	5	0.33
	6	--
15	NA	NA
16	1	0.57
	2	0.5
	3	0.33
	4	0.1
17	NA	NA
18	1	0.3
	3	0.3
	4	0.2
	6	--

Table 6. Continued.

River ID#	Modes at Mouth	Elevation Range	River ID#	Modes at Mouth	Elevation Range
19	1	1.0			
	2	0.8			
	3	0.72			
	6	--			
20	1	1.0			
	2	0.9			
	3	0.72			
	4	0.47			
		0.40			
21	1	1.0			
	2	0.8			
	3	0.72			
	4	0.47			
	5	0.40			
		--			

interface may move up or down the estuary. Figs. 11a-e are schematic representations of the possible density structure (as well as velocity structure) of estuaries where dense water results from salinity and freshwater is assumed lighter than salt water.

The velocity structure of estuaries has also been schematized in the early works of Pritchard (1955) and Dyer (1973). Dyer's ideas also appear in Figs. 11a-e and even in these highly schematized portrayals, the simple interactions between freshwater discharge, tidal velocity, density shoreline, and to some extent bathymetry reveal quite complicated flow structures. For the most part, the most intuitive structure is the flow reversal introduced periodically by the tide. It is persistent for most estuaries and results in considerable longitudinal and vertical differences in velocity. Indeed, as the schematics suggest, it is quite possible to have flows going in opposite directions at the same estuary position (eg. Fig. 11d, 11e). Such intense flow gradients result in shear, a primary source of energy, mixing, entrainment and sediment resuspension.

With these simple schematic outlines of estuary physics the question becomes whether there are any analogs to the Lake Erie tributary physics and if so is there observational evidence upon which to confirm these analogies.

With regard to the density structure, Lake Erie tributaries do not contain salt in sufficient concentration to affect the flow structure. However, it is the case that given the freshwater density vs. temperature curve and its maximum at 4°C, the effect of thermally induced density differences is quite possibly pronounced. This is particularly the case when tributary waters, being shallower, heat and cool more quickly than Lake Erie water during spring and fall seasons respectively. The possible consequences are as follows. Starting with water at O°C during ice cover the tributaries would warm more quickly and would reach density maximum more quickly. Therefore, for a brief time in the spring tributary waters would sink below Lake waters at the confluence only to have this reversed with further heating of the tributary waters and Lake's waters having reached their density maximum later on. It is hypothesized that tributary waters would then be less dense and more readily flow over the Lake water. This effect would obviously diminish as heating reached equilibrim during early summer.

Somewhat the reverse situation would occur during the fall; tributary waters losing heat more rapidly would be more dense and "flow under" the Lake's water at the confluence. Again, a brief interchange would occur as the tributary waters would go through density maxima before the Lake's waters. Indeed such an annual cycle of density structures could be considerably more complex than the estuary case and far more ephemeral as it is driven by meteorological and climatic circumstances. In contrast, the salt content in the ocean water is fixed and doesn't vary seasonally according to the weather. Both the estuary and confluence density structure are similar, in that freshwater inflow at the head plays a strong role in determining the position of the interface longitudinally in the channel and the degree of "tilt" in the interface. Observational evidence is summarized in the next section.

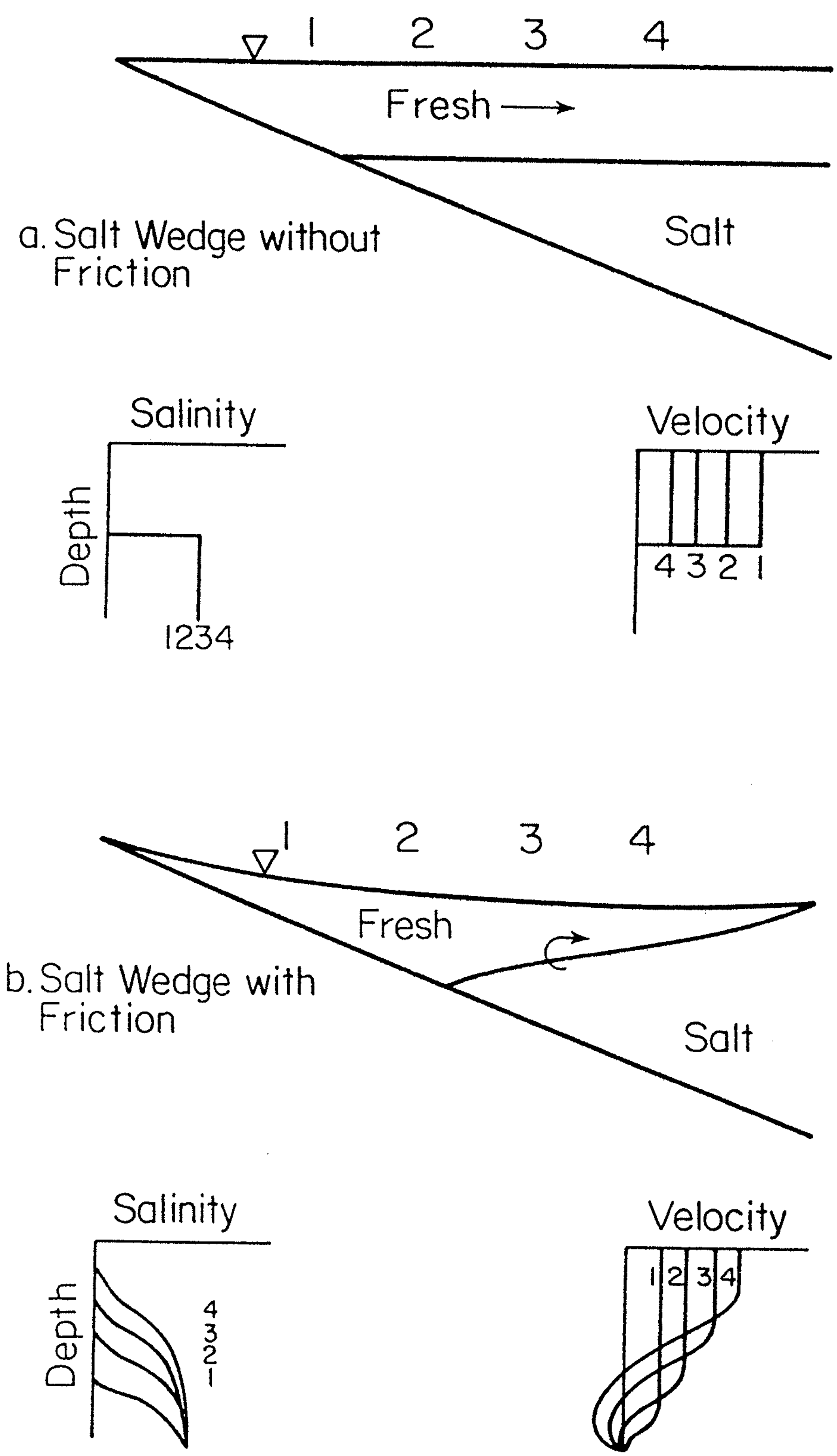


Figure 11a-e. Schematics of the five estuary density and velocity structures defined from Dyer (1973).

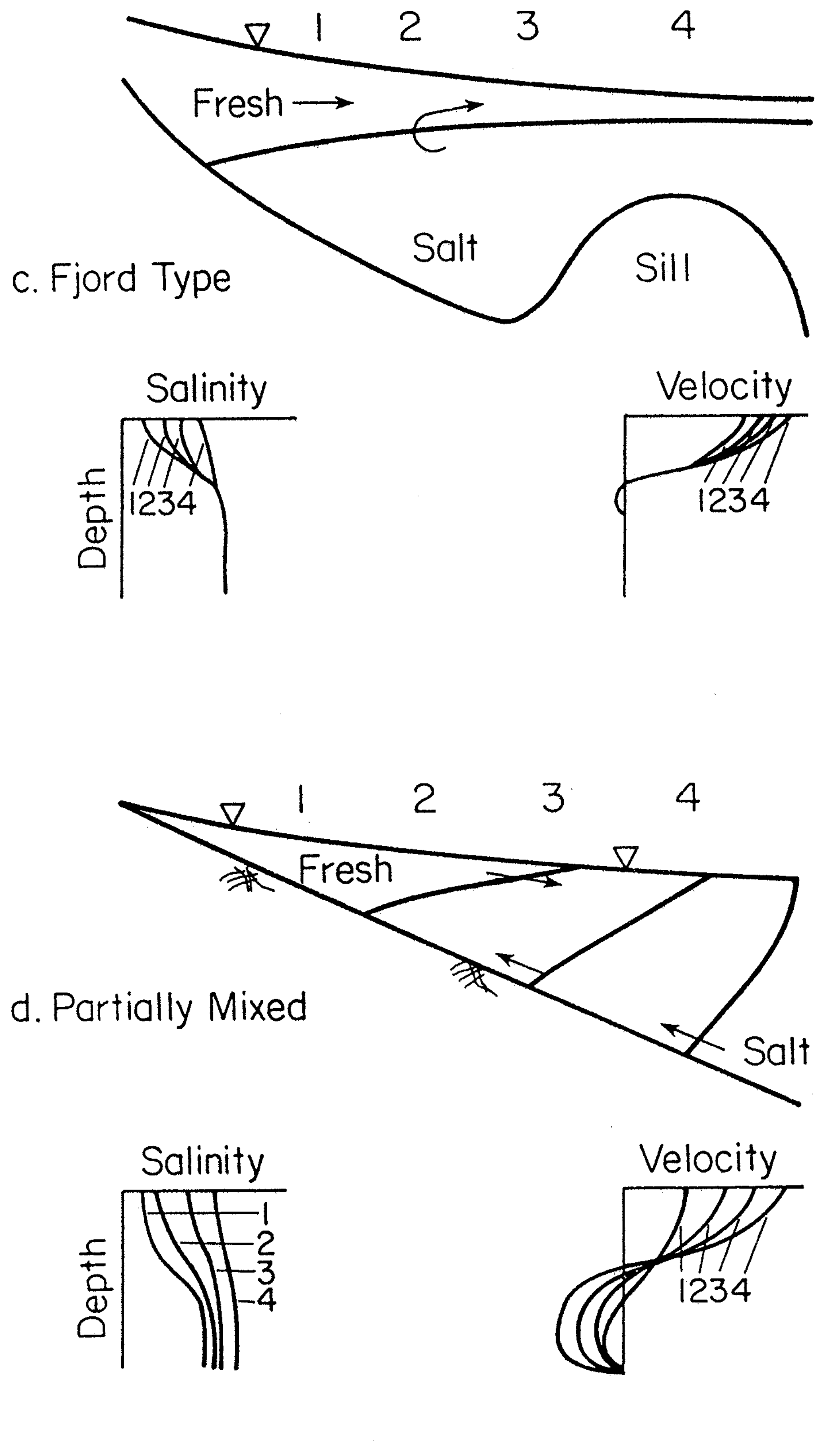


Figure 11. Continued.

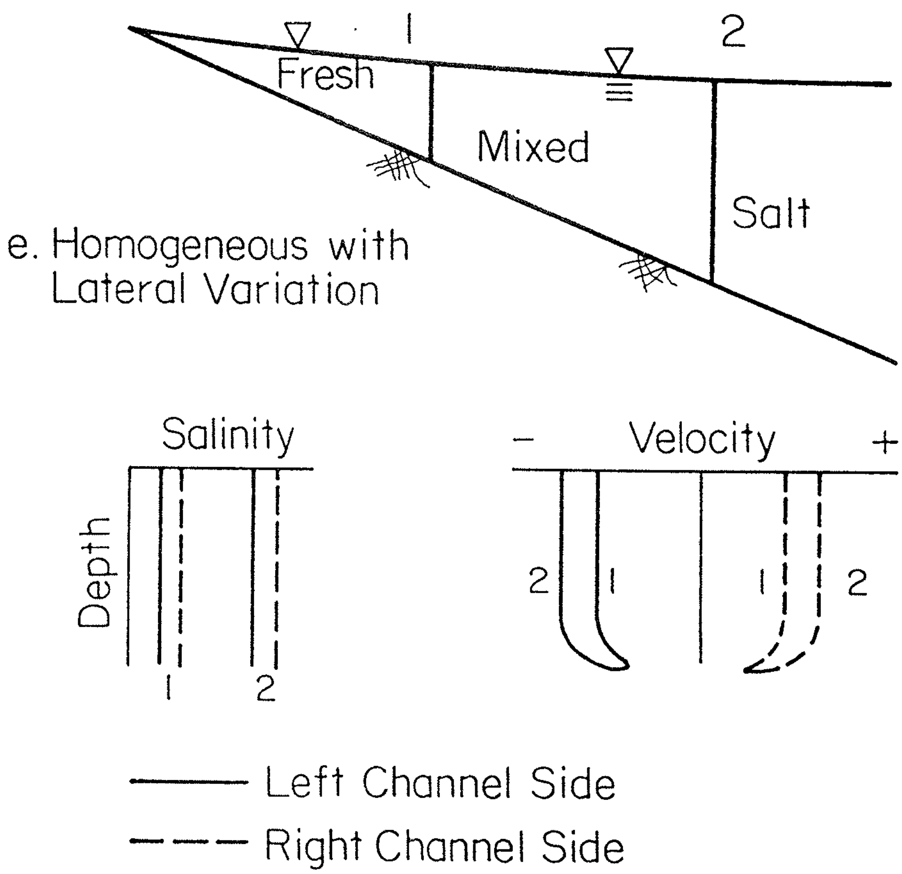


Figure 11. Continued.

Insofar as the water surface elevation changes are concerned, it is clear that long waves propagate up and down the Lake Erie rivers; the period and mode structure is quite complex in that up to five wave modes with periods as low as 3 hours may be propagated within the tributary. These wave events result from surges and seiches which are weather dependant and not persistent. The tide waves have a clear frequency and amplitude structure which is modulated by solar and lunar activity with periods of longer than one half day; therefore, the periodic pulses are less frequent or complex in estuaries, but are persistent.

In the Lake's tributaries, it is hypothesized that flood waves propagating upstream can do so without disrupting the lakeward tributary flow. This would especially be the case for non-stratified conditions where the tributary discharge momentum was more substantial than the weak channel flow induced by a weak slow moving floodwave. In contrast, strong flood waves resulting in storm surges could cause complete flow reversals in the tributary. Again these occurrences are climate dependent, episodic and are not persistent.

With these simple contrasts in mind can any observational evidence be cited to substantiate the hypothesized tributary Lake Erie interactions.

OBSERVATIONAL EVIDENCE

Observational evidence of these activities is not coherent, comprehensive nor thorough; particularly as regards circulation and velocity features. Temperature data, which is easily measured, exists and indicates that certain of the density features discussed do exist. Schroeder and Collier (1966) presented temperature data for the Cuyahoga River (Figs. 12a-c) which show the downstream variation of temperature for a fall condition (Oct. 21, 1964). The graphs do suggest compliance with the hypothesized variation. The Maumee River Bay and Lake interaction has been thoroughly investigated for dredging activities (Fraleigh et al. 1975) and from an International Joint Commission initiated study (Pollution from Land Use Reference Group, PLUARG) on how the winter melt affected the Lake Erie nearshore region (Pinsak and Meyer 1976, Herdendorf and Zapotosky 1977, for example). Fig. 13 is a plot from Fraleigh et al. (1975) showing the seasonal variation in water temperatures. Clearly the Ottawa River/Lake Erie behavior is as suggested earlier, but the Maumee River behavior is not consistent with the hypothesis. It should be noted, however, that in the Maumee River the lake effect intrudes to over 20 km upstream and since the Maumee River sampling point was well within this Lake Erie/confluence mixing zone, the Maumee River data are not representative of the freshwater tributary inflow temperature.

Detailed evidence abounds on the tributary water level disturbances in Lake Erie. Most of it is anecdotal until the early work of Brandt and Herdendorf (1972). Detailed probabilities of each tributary's water level structure and response to surges have not been done. Yet, the fact remains that the tributary water level disturbances were well enough known that USGS put their

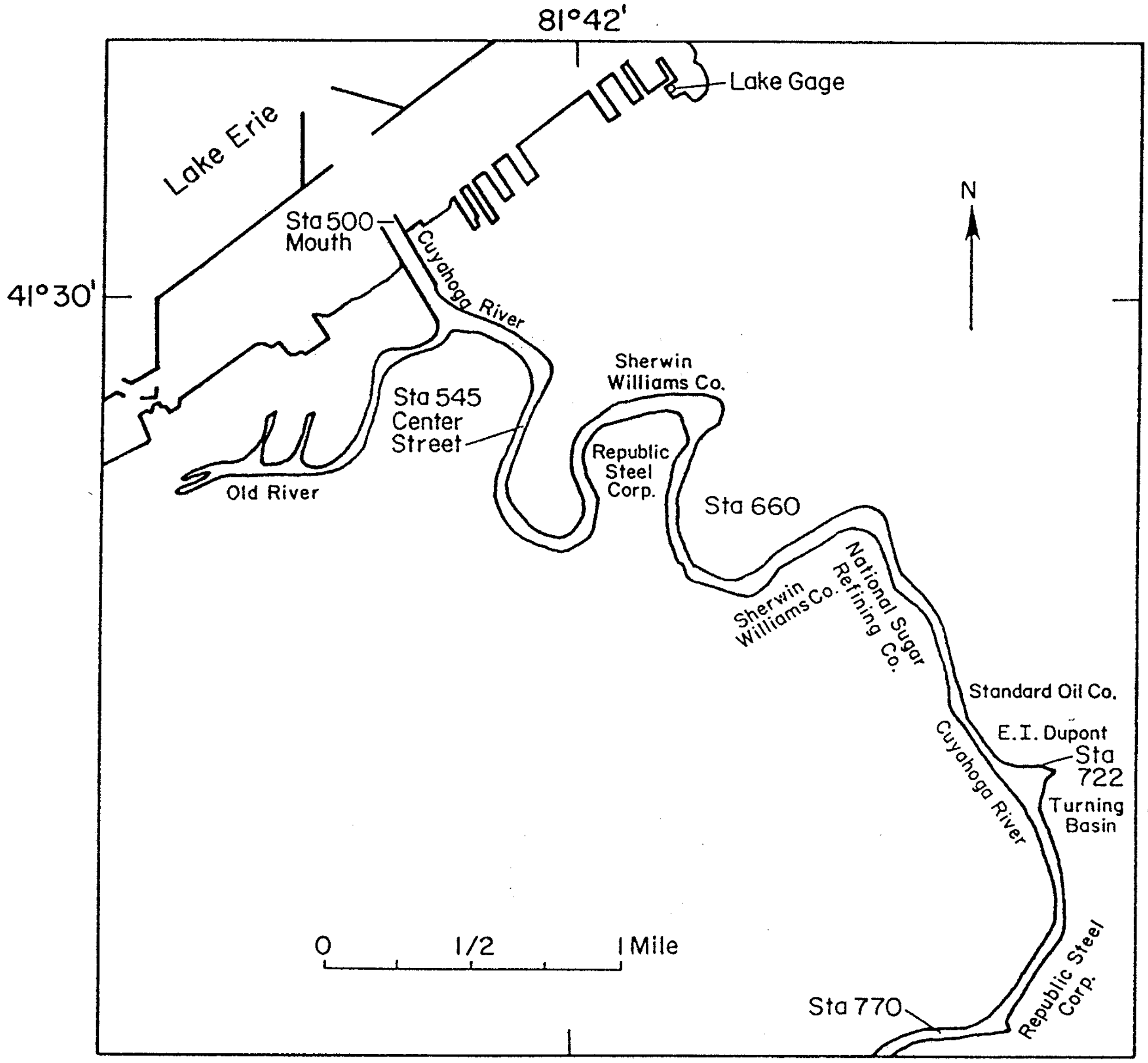
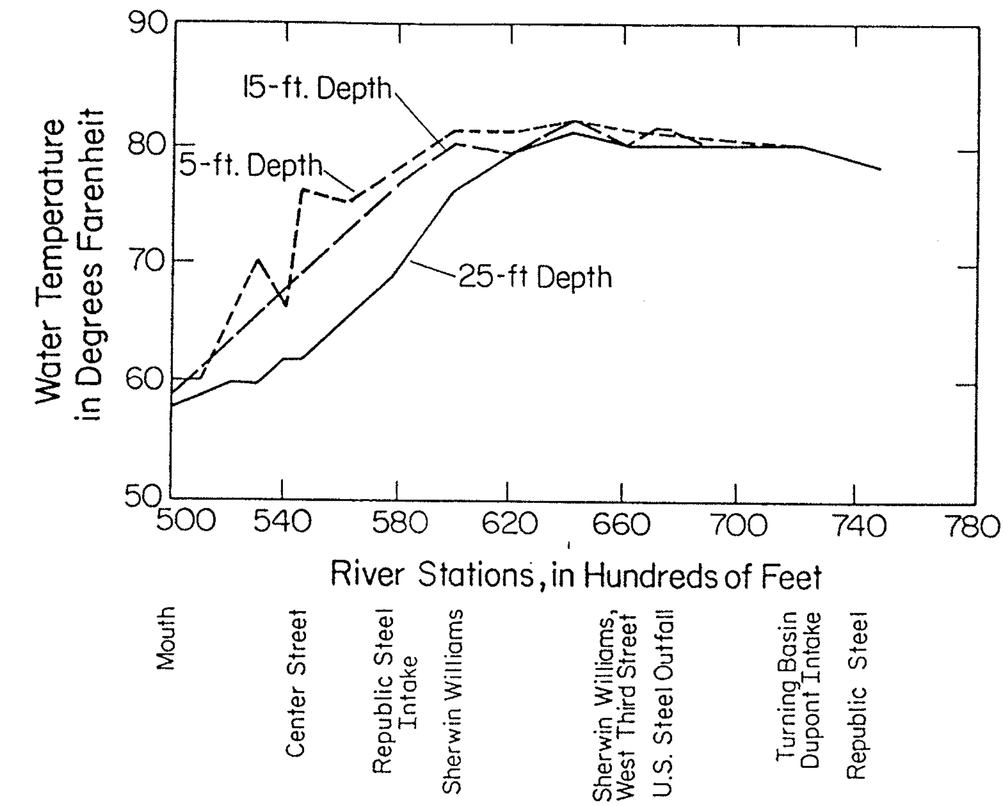


Figure 12a. Station definition map of the Cuyahoga River (redrawn from Schroeder and Collier 1966).

Figure 12b. Water temperature vs. station distribution in the Cuyahoga River at three depths, October 21, 1964 (redrawn from Schroeder and Collier 1966).



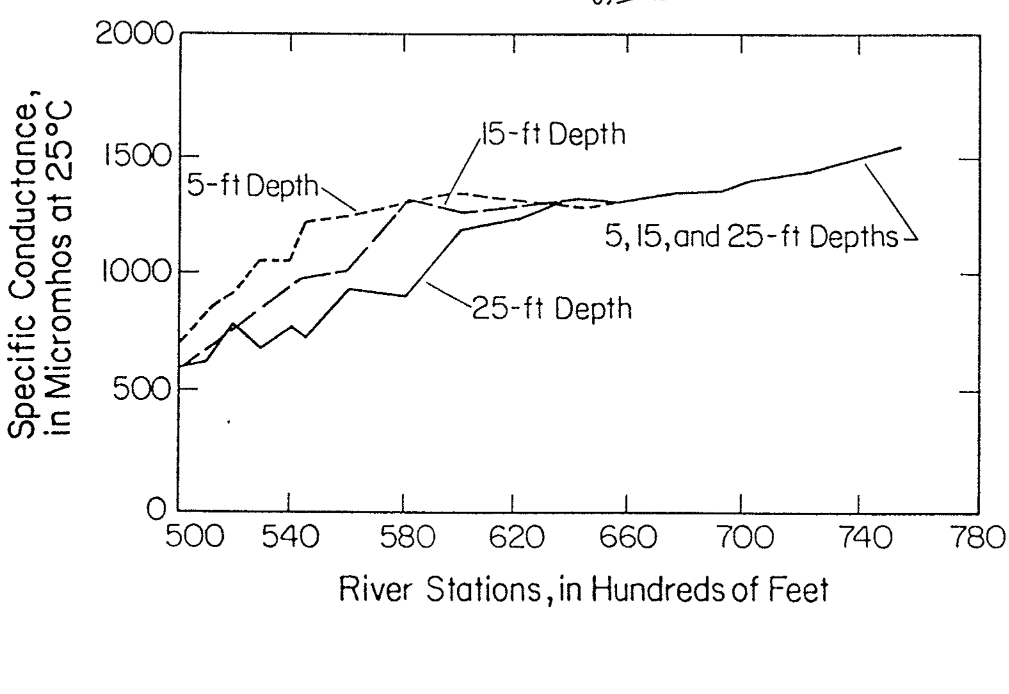


Figure 12c. Specific conductance vs. station distribution in the Cuyahoga River at three depths, October 21, 1964 (redrawn from Schroeder and Collier 1966).

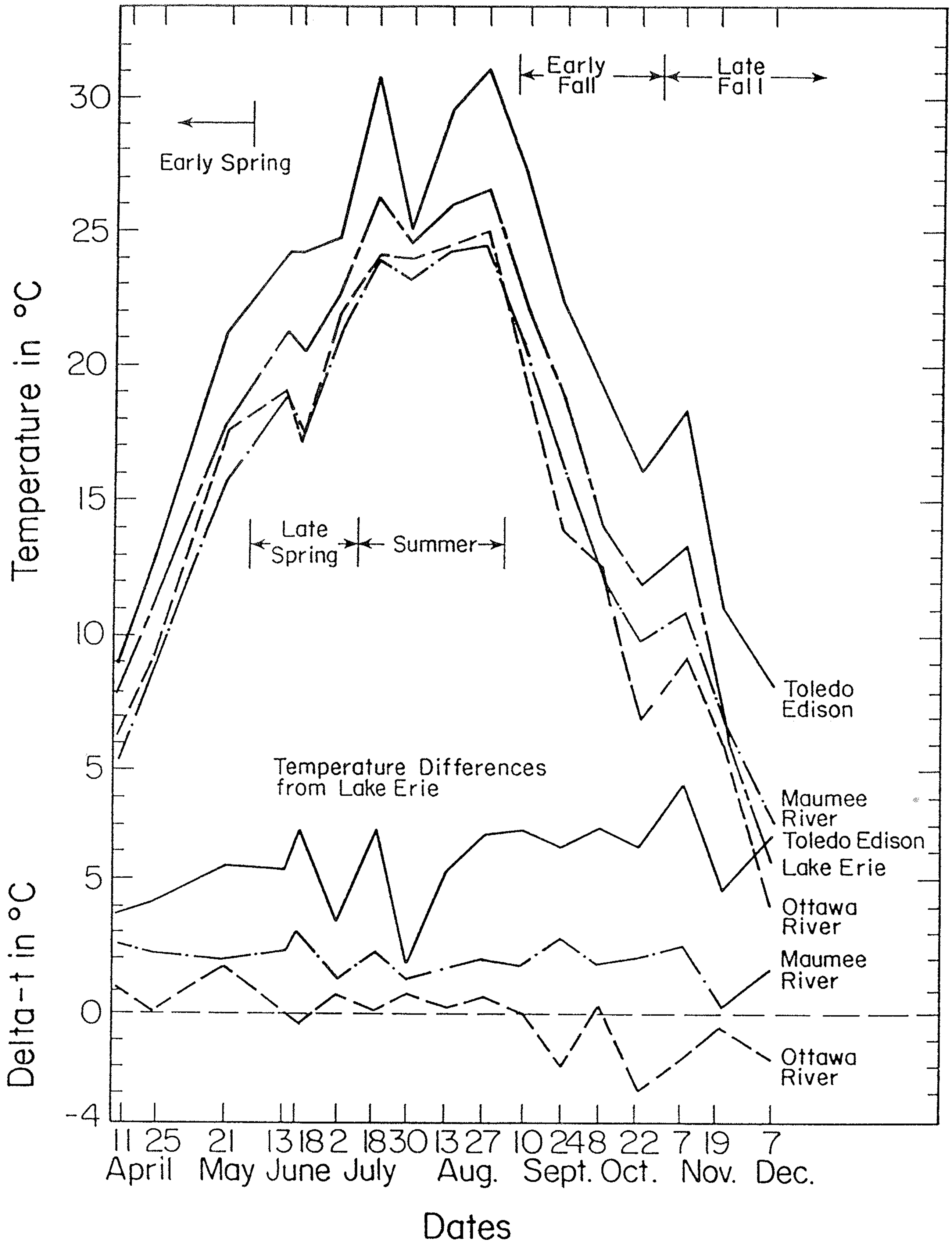


Figure 13. Maumee Bay/Ottawa River temperature variation over the year 1974 (redrawn from Fraleigh et al. 1975).

operational discharge and water quality gages enough upstream to be away from the flood wave/flow reversing behavior. In the case of the Maumee and Sandusky River these gages are over 30 kilometers away from the Lake's edge.

Velocity/current data in these confluence and mixing zones do not exist. Anecdotal information is all that is available, however Pinsak and Meyer (1976) a "flow persistance" diagram for the Maumee River. It is indeed disappointing that velocity data are not to this day routinely collected simultaneously with the ubiquitously collected water quality data.

SANDUSKY RIVER/BAY - AN ANOMALOUS TRIBUTARY

The Sandusky River/Bay tributary system has been extensively sampled from a water quality point of view and recently enough precision was obtained in the data to allow a coupled hydrodynamic and transport model of velocity, chlorides and sediments to be verified. As a result, several of the hypothesized transport issues can, at least, for limited time periods of data, be substantively addressed. The work referred to here is principally based on the author's modeling as found in Lee and Bedford (1988a,b), Bedford et al. (1988), Bedford and Mark (1988) and Lyon et al. (1988). These models are predicated on the data collected by P. Richards and D. Baker at Heidelberg College (Richards and Baker 1982). It is unfortunate that the Sandusky Bay confluence is entirely anomalous in contrast to all of the other tributary confluences in Lake Erie (or most of the rest of the Great Lakes for that matter). With reference to Figs. 14a,b the Bay is shallow, on the average being 2-7 meters in depth, and only the presence of the shipping channel at the confluence allows depths to attain 7 meters or more. The Bay is subjected to wind waves and wind-driven circulation. It is located at the null oscillation line of the second Lake Erie seiche mode and itself contains two free oscillation modes with the first being 7.1 hours (Prater and Bedford 1982) and the second being 3.0 hours which is coincident with the sixth Lake Erie mode. Fig. 15 shows the position of these modes. It is noted in Fig. 14 that the USGS loading data gage is in Fremont, Ohio some 29 km upstream of the confluence on to the perceived "Lake Erie effect."

The model detailed in the above papers was a combined two dimensional, free surface nonlinear hydrodynamic and transport model which incorporated the effects of: erosion and deposition from a multilayer bed; wind waves including air-water temperature effects; the time varying flow from the Sandusky River; and Lake Erie water levels. The time and space variations of currents, water levels and chloride, sand, salt and clay concentrations were predicted.

The conditions simulated (Figs. 16a-e) included two storm induced river discharge events and a six foot setup Lake Erie surge event. As can be seen, the water levels varied continuously at Marblehead throughout the entire simulation period, June 1 - July 16, 1981.

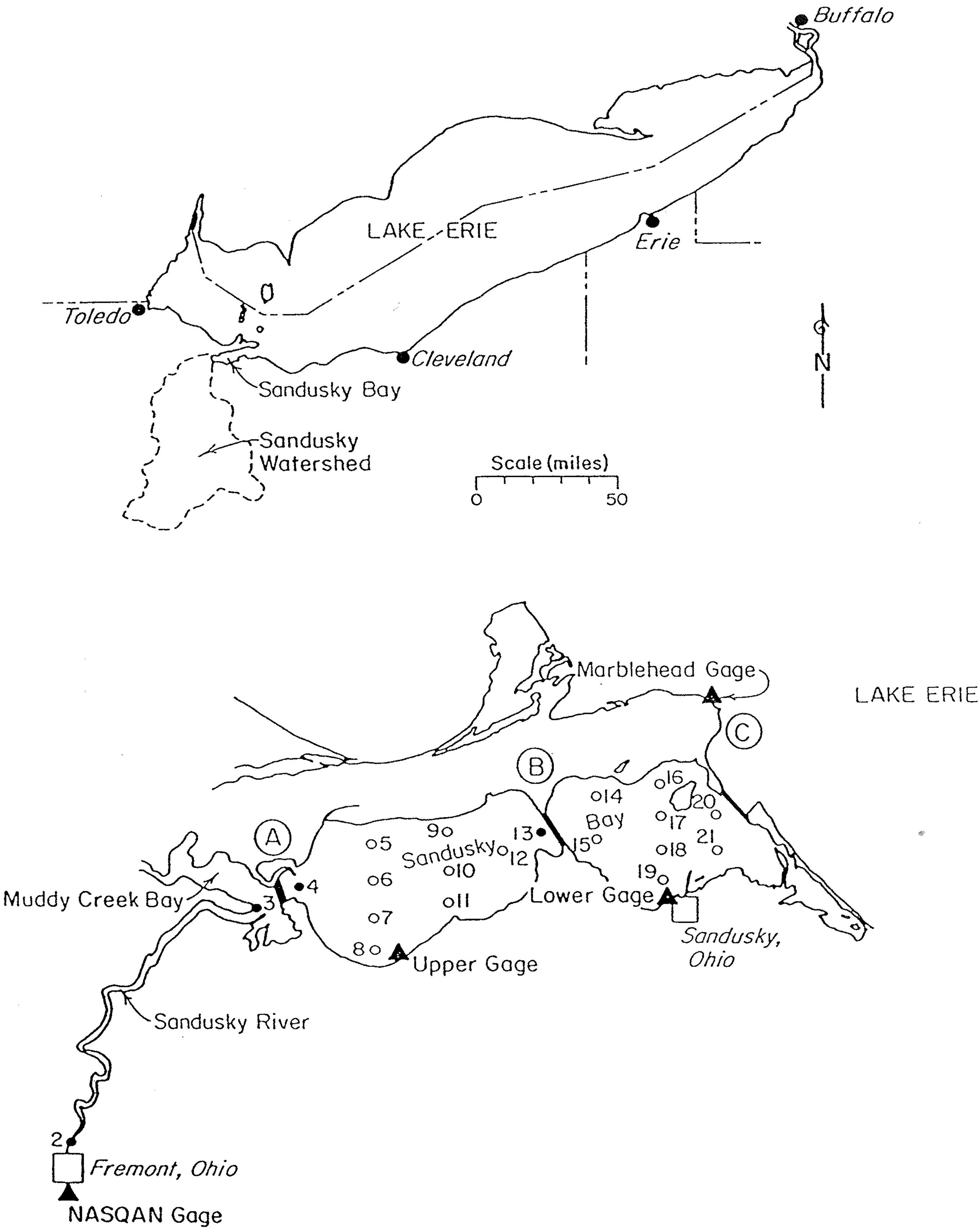


Figure 14. Sandusky Bay and transect location and data collection station definition map (Bedford and Mark 1988, and Richards and Baker 1982).

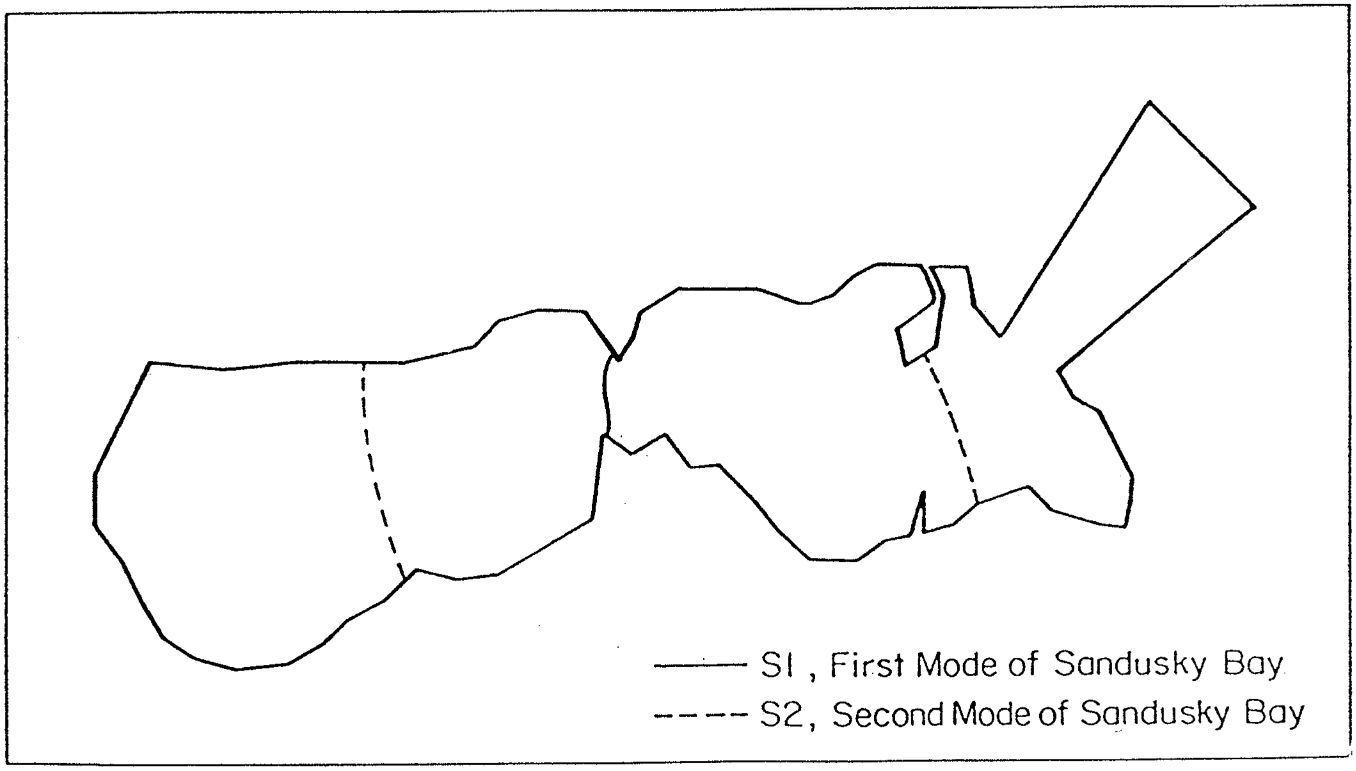


Figure 15. Null oscillation lines for the first (7.0 hour) and second (3.1 hour) Sandusky Bay free oscillation modes (Bedford et al. 1988).

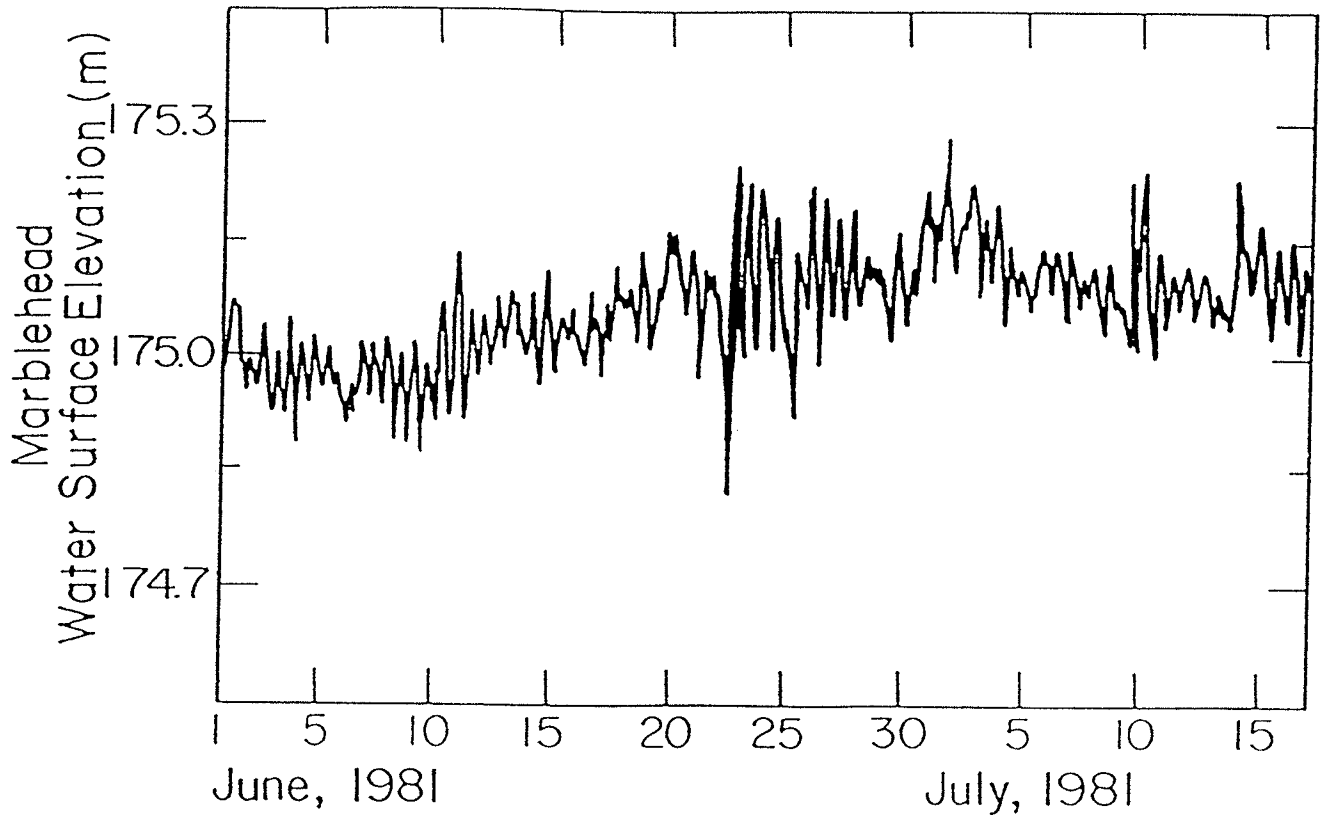


Figure 16a. Marblehead water level time series (Bedford and Mark 1988).

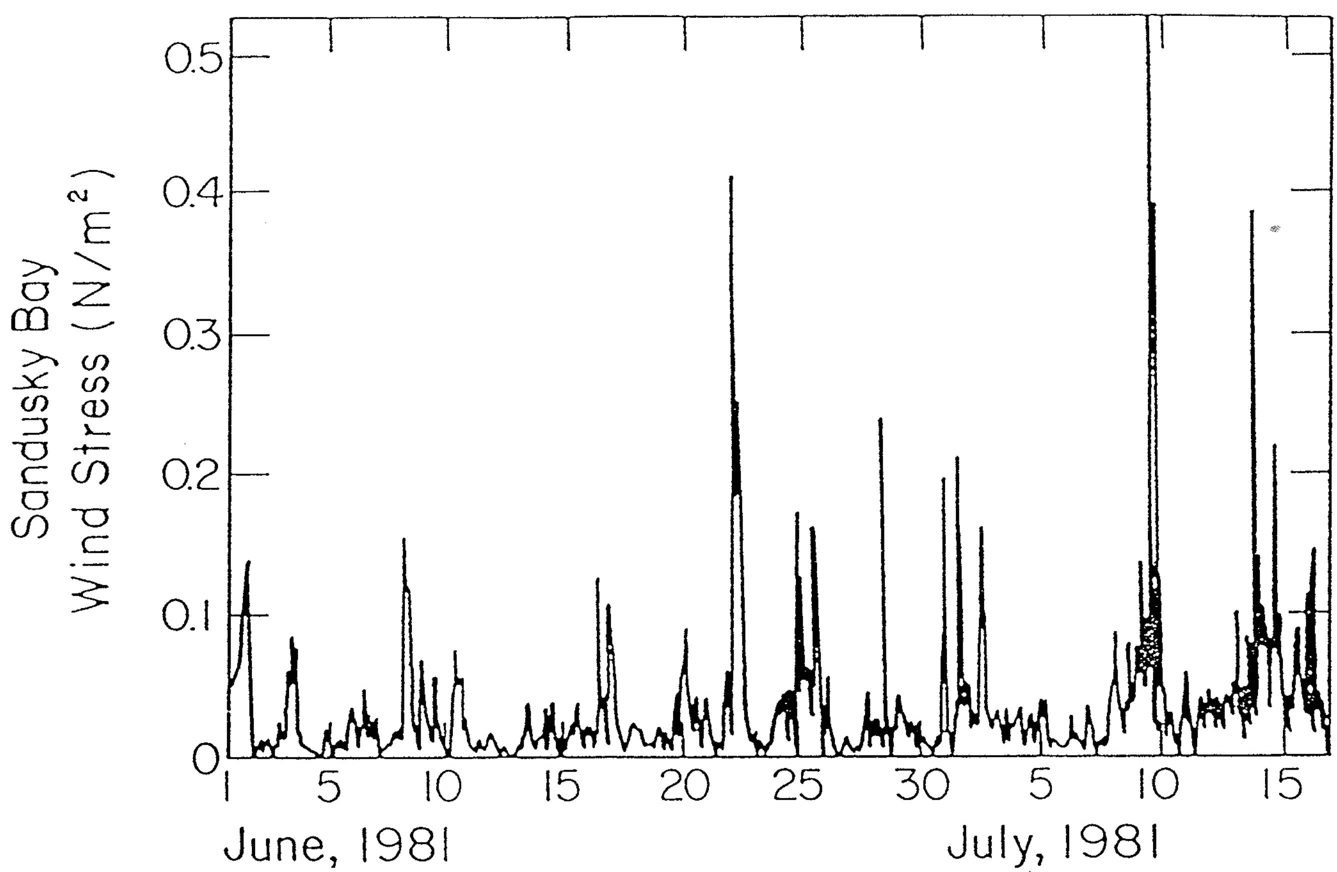


Figure 16b. Sandusky Bay wind shear time series (Bedford and Mark 1988).

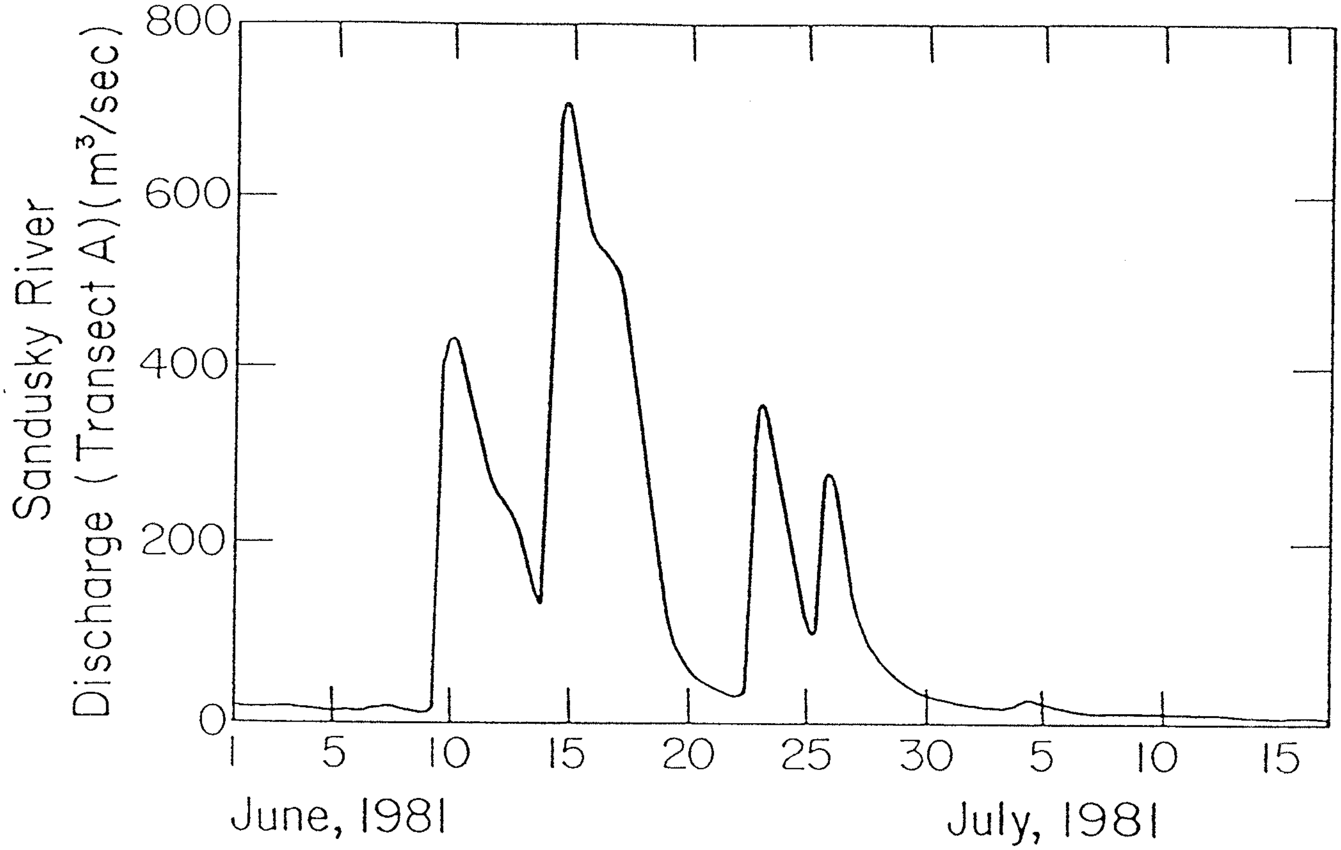


Figure 16c. Sandusky River discharge inflow time series (Bedford and Mark 1988).

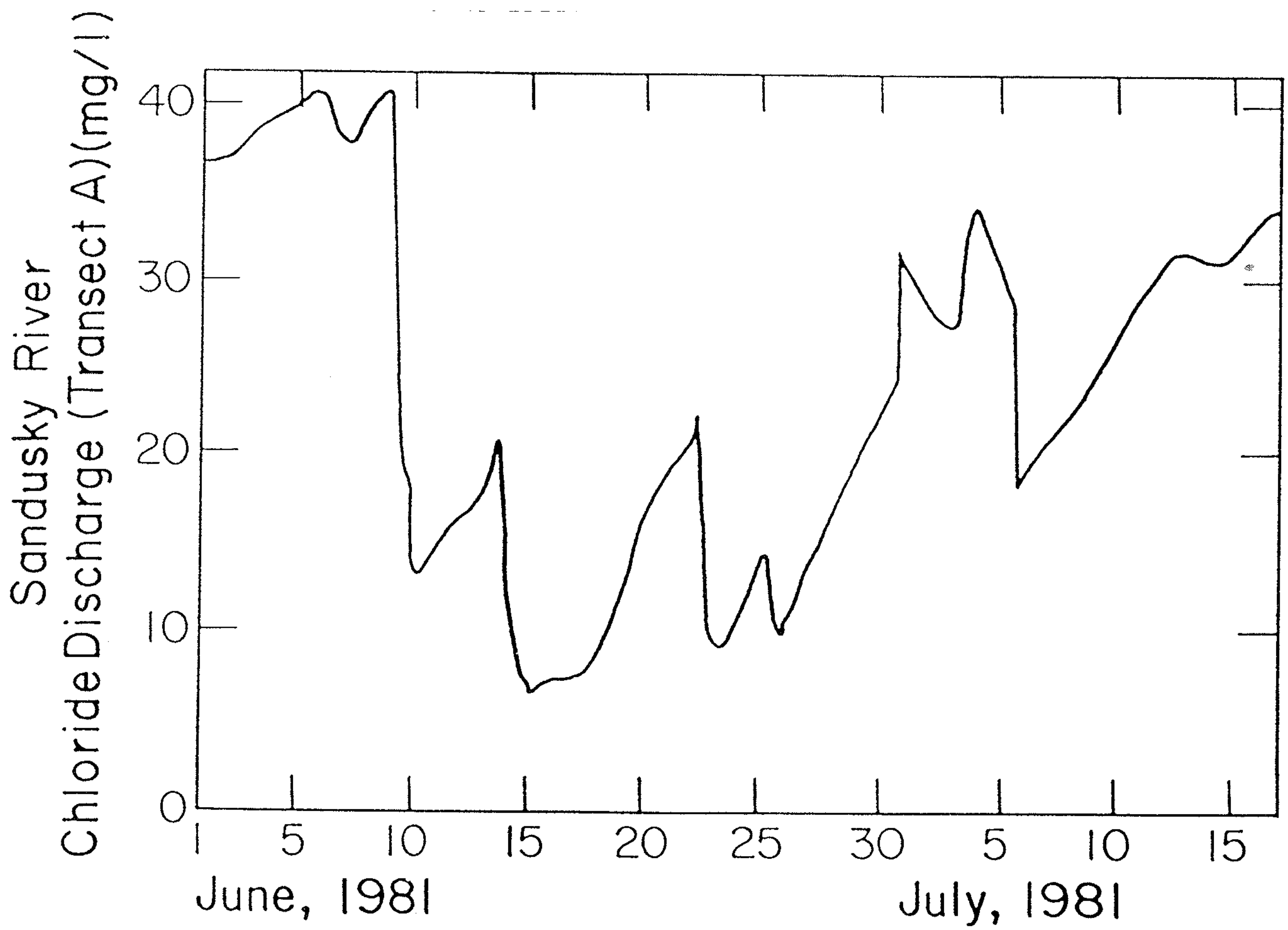


Figure 16d. Sandusky River chloride inflow time series (Bedford and Mark 1988).

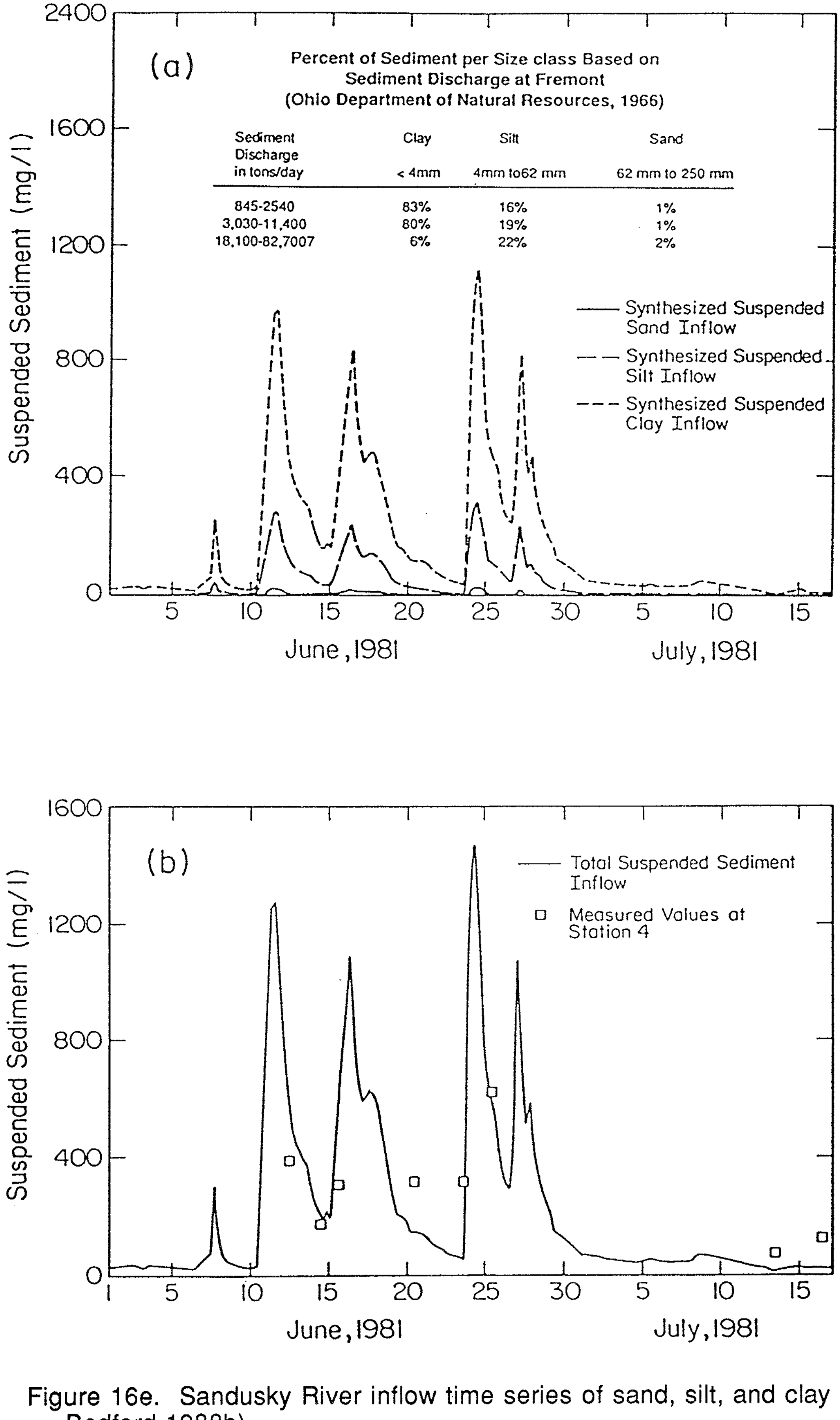


Figure 16e. Sandusky River inflow time series of sand, silt, and clay (Lee and Bedford 1988b).

From the results presented in the papers, a few directly speak to the hypotheses suggested here. The most important aspect of all is that Lake Erie water level fluctuations occurring, at the confluence never die away and propagate disturbances into the Bay. Fig. 17 is a plot of sediment fluxes (mass/area/time) at the three transects and it is quite clear that the tributary confluence, Transect C is subject to oscillating fluxes where material alternately enters and leaves the Bay. Indeed, some of these events are entire flow reversals which result in daily average fluxes being entirely into the Bay from the lake. Fig. 18 shows this for daily average chloride loads. It is also noted that the fluxes vary periodically at Transect B as well, while Transect A suffers no such lake induced reversal.

A second general area of similarity is in the sorting, deposition and scouring behavior of the sediments. Based upon the model simulated results in Bedford et al. (1988) and Lee and Bedford (1988b), Table 7 summarizes the total deposition of sediments in each size class in the Upper and Lower Basin as well as the total flux past each transect during the simulation. It is noticed that the Upper Bay, which is not affected by the Lake Erie seiches to any extent, is a net deposition zone for clays with extrapolated annual accumulation rates on the order of four centimeters per year. The western portion of the Lower Basin continues to be a net clay deposition zone, but in general the entire Lower Basin just transmits material through from Transect B to Transect C. The seiching effect of the Lake coupled with the Bay's natural oscillations keeps the material generally in suspension. A significant sand deposit occurs in the Lower Basin east of the Johnson Island - Sandusky second mode null oscillation (Fig. 19) and is hypothesized to exist because of sand in the Lake Erie littoral drift near the confluence being brought into the Bay during flow reversals and surges as well as the seiching which prohibits the settling of clay and silt particles in the confluence. This behavior is quite consistent with the recent summaries of estuaries' sediment transport and hysteresis effects by K. Dyer (1988).

Finally, estuaries have turbidity maxima that are arranged across the channel which are high concentration bands of sediment and it appears that there is one in Sandusky Bay as well. Fig. 20 contains a computed plot showing excessive shear/scour rates in the zone around the Lower Basin second mode null oscillation line, while Fig. 21, developed from June 1981 Landsat data by Lyon et al. (1988) clearly shows this maxima and its close correspondence with the null oscillation line. It should be noted that although no further hypothesis testing about this maxima can occur at this time, it is more than coincidence that it occurs where it does; not only because the null oscillation line for the Sandusky mode is the point of maximum velocity energy which is required for entrainment, but perhaps more importantly, it is the maximum in-Bay extent of the horizontal transport of the second Lake Erie mode, a nine hour mode with a 2.5 km half excursion length. Since the null oscillation of this second Lake Erie mode passes just east of the Sandusky Bay confluence this excursion distance represents a primary source of entrainment and mixing energy for the sediments.

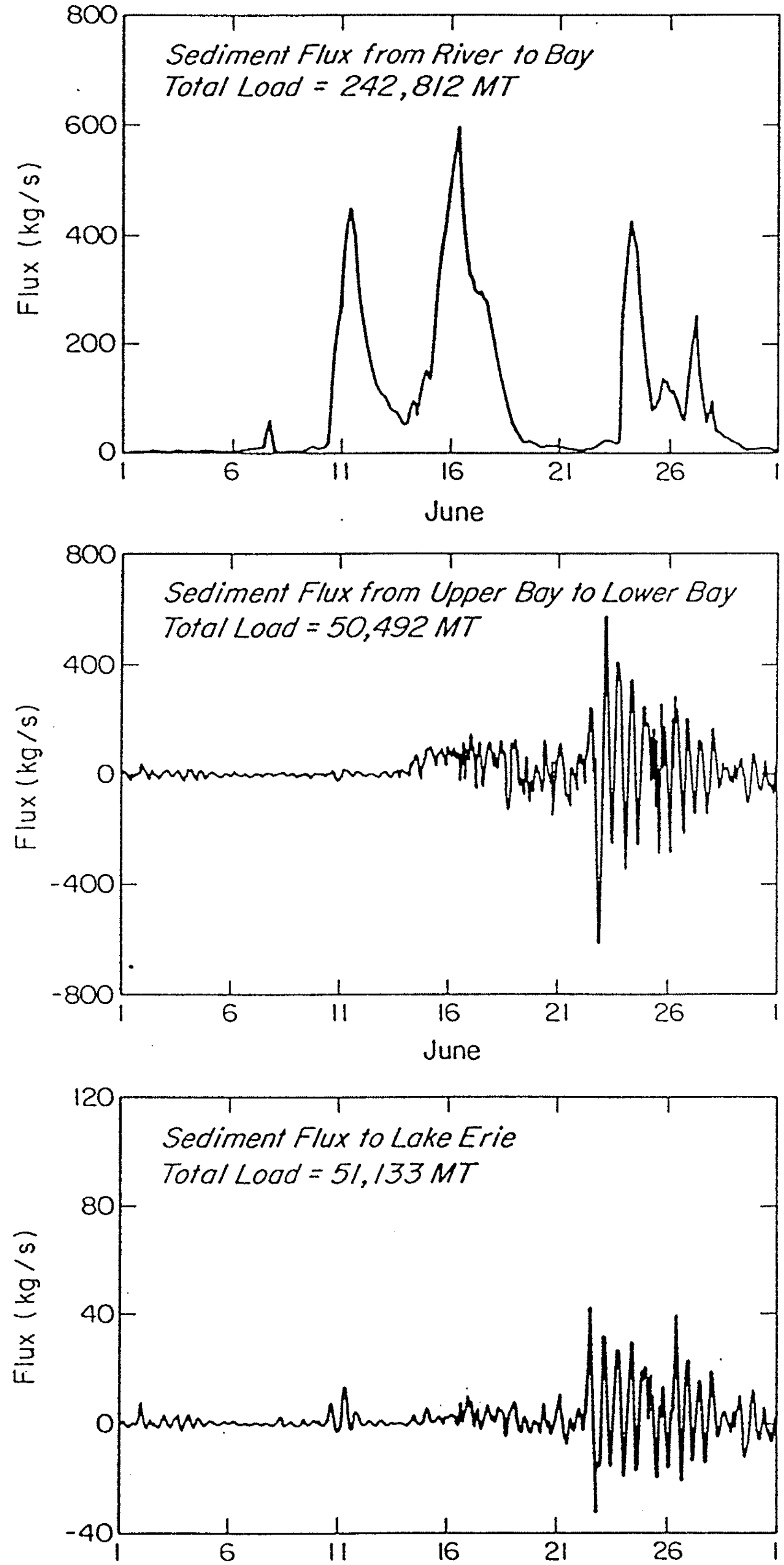


Figure 17. Sediment flux time series at three Sandusky Bay transects.

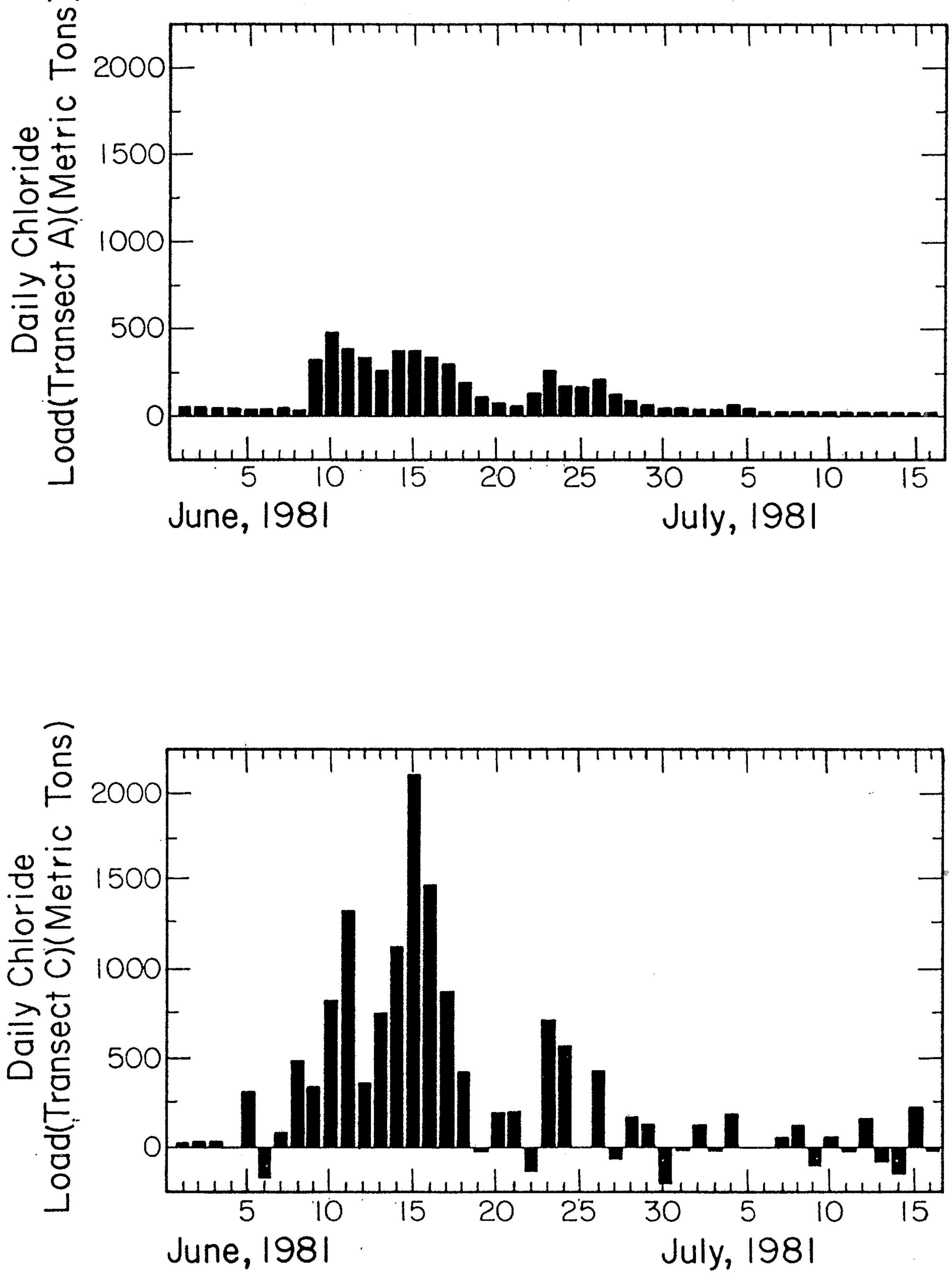


Figure 18. Daily average loads of chloride in Sandusky Bay at Transects A and C (see Fig. 14).

Table 7. Total sediment load passing each transect in Sandusky Bay for period June 1 - June 30, 1981 (Bedford et al. 1988).

TRANSECT (FIG. 14)	TOTAL (METRIC TONS, MT)	SAND (MT)	SILT (MT)	CLAY (MT)
C	51,133	13,659 (26.7%)	6,047 (11.8%)	31,427 (61.5%)
B	50,494	- 573 (-1.1%)	1,615 (3.2%)	49,450 (97.9%)
A	242,812	8,200 (3.4%)	57,213 (23.6%)	177,399 (23.0%)
FREMONT	372,194			

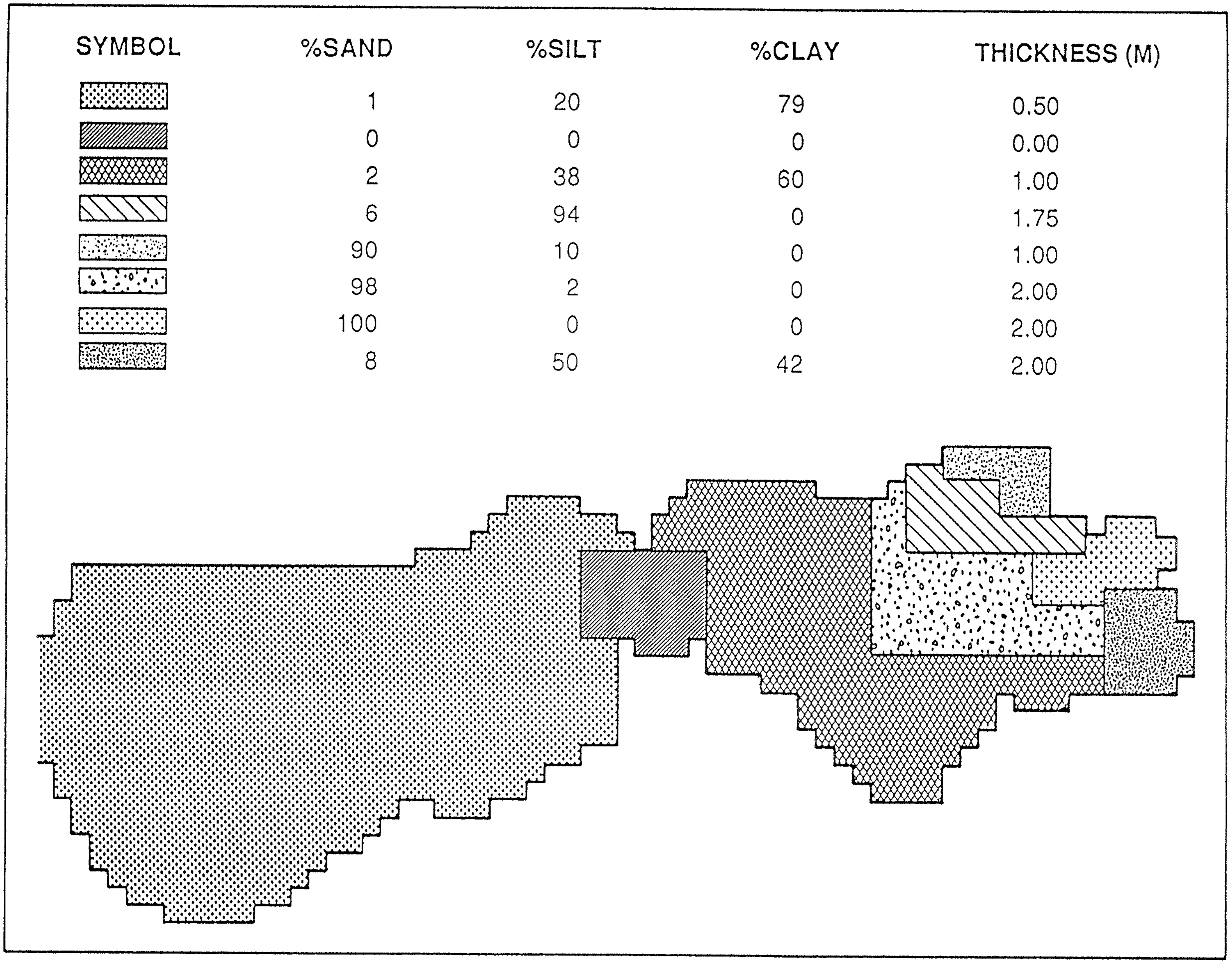


Figure 19. Bottom sediments distribution for Sandusky Bay (Lee and Bedford 1988b).

Net Erosion and Deposition of Sediment

June 1 - July 13, 1981   Time 0:0:0

Deposition (kg/m^2)	Erosion (kg/m^2)
-24.0364 to 16.02426	+24.1273 to 16.08492
-16.0242 to 8.01214	+16.0849 to 8.04247
-8.01214 to 0.00000	+8.04247 to 0.00000

Max. Increase in Sediment Thickness = 10.9 cm

Max. Decrease in Sediment Thickness = -12.4 cm

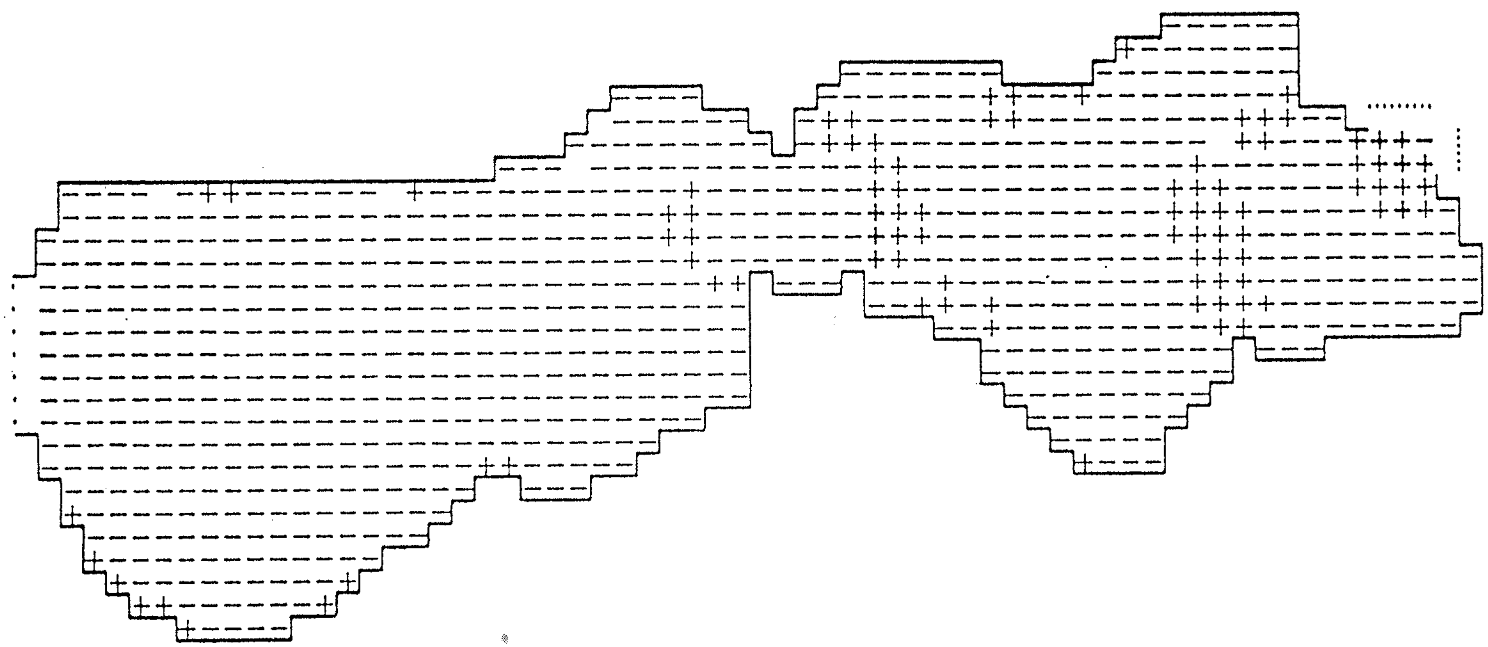


Figure 20. Net scour/deposition in Sandusky Bay, June 1 - July 13, 1981 (Bedford et al. 1988).

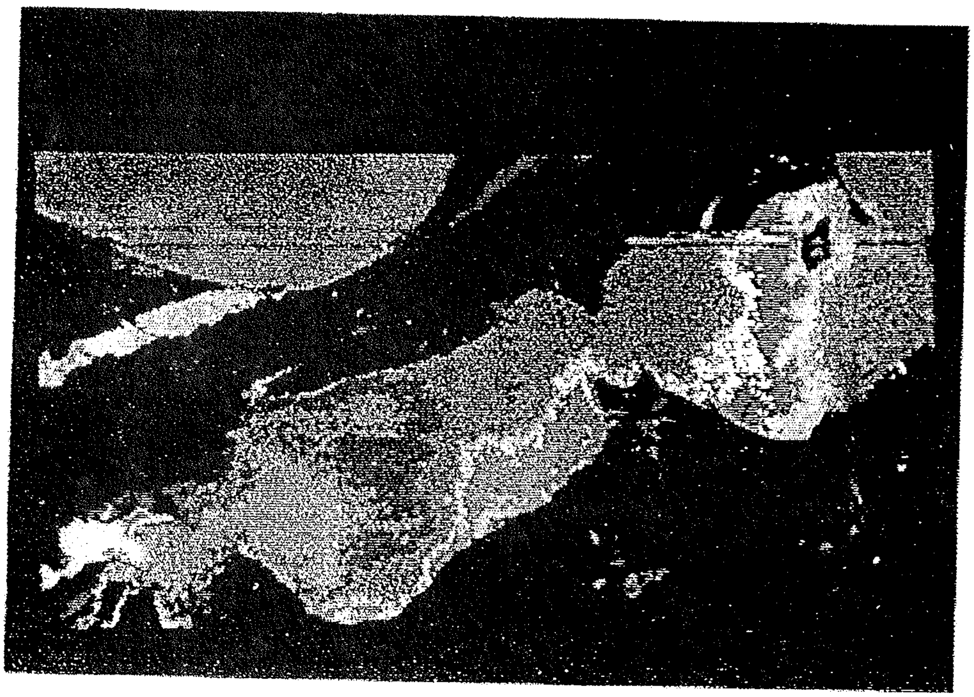


Figure 21. Landsat satellite image of Sandusky Bay, June 28, 1981 (refer to Lyon et al. 1988 for details).

MANAGEMENT ISSUES

The clear scientific issues arising from this brief review center on doing the clearly organized scientific observations required to delineate the transport behavior of the tributary confluence zone. Such work just doesn't exist; even the Sandusky Bay experiments suffered from having no current-meter data to go along with the other water quality data. This absence should never be allowed, as in-situ water quality data collected in the absence of current data have no context and are of dubious value.

Table 7 exposes the first, and in many ways, the most basic management issue. In order to manage the Great Lakes water quality as per the U.S.-Canada Water Quality Agreement of 1978, the International Joint Commission requires that monthly pollution loads be obtained from tributaries entering the Lake. In response, a large network of operational data collection devices are positioned on the Lake tributaries, but are located quite far away from the confluence. The central question becomes as follows: "What is the relationship between the load measured at the gage versus what actually enters the Lake at the confluence." Clearly, for the limited data summarized in Table 7, sediment loads, a principal transport agent for toxic substances, are less in quantity and far different in grain size distribution than those measured at the operational data collection site. The question then becomes whether these load differences are significant or important.

A final management question becomes "What happens to the confluence fluxes issuing to the Lake's nearshore zone? Do they pass through the near shore zone or does the Lake Erie Kelvin wave/shore parallel current activity 'pin' the effluent near the shore into beaches, wetlands," etc.

Clearly tributary confluences, while not estuaries, have every bit the complexity of marine estuaries and are not just simple steady jets entering quiescent receiving waters; they should be accorded scientific respect.

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REMOTE SENSING OF SUSPENDED SEDIMENTS AND WETLANDS IN WESTERN LAKE ERIE

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ABSTRACT

Two research projects have demonstrated the value of remote sensor measurements of estuarine and lacustrine resources. Benefits included a better understanding of water characteristics as measured by remote sensors, a methodology for measuring some characteristics of non-point sources of sediment, and a methodology for quantification of wetlands over time. Results provide insight on transport of sediment from bays or estuaries to the nearshore zone, and the loss of wetlands due to natural and human events.

INTRODUCTION

The two studies presented here focus on problems faced by Lake Erie ecosystems. These problems include non-point sources of pollution, and loss of wetlands. Two methodologies were used to provide information on the problems. Each approach illustrates how remote sensor data can be used to evaluate these problems, and complement traditional measurement technologies.

To address the problem of non-point sources of sediment required information from a combination of sources including remote sensors and model simulations. Categorizations of satellite data allowed evaluation of total suspended sediment concentrations in the Sandusky Bay/Estuary area. Four satellite images displayed trends in the measured on-site data and distribution of water colorants. Satellite data were compared to the results of a hydrodynamic and water quality model. Satellite derived images of relative or absolute suspended sediment concentrations could be interpreted as a tracer for some water quality and hydrodynamic conditions. Results from satellite data and models had similar concentrations of sediment and distribution of those concentrations. Comparisons also indicated new areas to be evaluated in continuing remote sensor and modeling efforts.

The change in quantity of wetlands versus Lake Erie water levels was determined from measurements on historical aerial photographs (1935 to 1980). Analysis indicated there has been a loss of approximately 700 ha of wetlands before 1950. The loss was tied to impoundments on the Huron River, and decreased nourishment of the Pointe Mouillee delta and estuarine wetlands from riverine sources. Rising Lake Erie water levels were found to negatively influence the remaining amount of wetlands in undiked areas (1950 to present). The total amount of wetlands followed the water level conditions, and since 1958 the totals have remained about the same at any particular water level. This methodology of measurements from historical aerial photographs and determination of local hydrological conditions has proven useful in other Great Lakes for quantifying change in these estuarine and lacustrine wetlands.

BACKGROUND

Improved measurement technologies are required to supply data on rivers, estuaries and lakes. Remote sensing data can provide a valuable contribution to inventory of resources, or assist the modeling of water resource characteristics. The combination of traditional and remote sensor measurement technologies and modeling methods can potentially supply information in a rapid, relatively lower cost, and less people-intensive manner that traditional approaches alone.

Methodologies employing satellite data have proven useful for Great Lakes applications. Great Lake problems often involve large area measurements, and necessitate repetitive coverage to address complex issues such as non-point sources of pollution. Other measurement problems require inventory and monitoring of estuarine and coastal wetlands. Remote sensor methods can supply historical and current inventories, and allow evaluations of long-term comparisons. They also supply measurements of water resource or terrestrial characteristics adjacent to wetlands resources, that are often involved in maintaining a wetland.

These examples illustrate some of the problems of Lake Erie and adjacent rivers and estuaries. Each addresses a problem and employs a remote sensor technology to supply data for analysis. The examples demonstrate remote sensor contributions to assessment of quantities of wetlands in Lake Erie, and use of satellite data to evaluate suspended sediment concentrations as an adjunct to modeling sediment transport through estuarine areas to the open Lake.

Remote Sensing of Lake Erie

Previous studies of Lake Erie have demonstrated the capability to measure water and wetland variables in combined remote sensing and on-site sampling experiments. These experiments were conducted by a variety of users, and for a variety of reasons. They can be grouped as a) evaluations of non-point sources of pollution, b) use of tracers to follow water currents, and c) evaluations of water quality.

Many efforts have evaluated remote sensor data as input to non-point studies. Monteith et al. (1981) used land cover statistics from computer categorizations of satellite data for comparisons of water quality sampling and composition of watershed land cover classes. Similar approaches have worked to evaluate tillage practices from residue cover in fields. Categorized Landsat

Thematic Mapper data demonstrated good separability of no-plow, chisel-plowed land, and moldboard plowed fields (Schaal 1986). This method of measuring tillage practices promises to be an accurate and cost-effective approach. It is hoped that the monitoring of fall and spring tillage conditions could be used to quantify implementation of erosion-reduction practices. Further work is being conducted by Terry Logan, John Lyon, and Andy Ward of OSU, and Gary Schaal of Ohio Department of Natural Resources. This effort is focused on improving our knowledge of measuring differences in tillage practices from spaceborne sensors, and is funded by NASA through the OSU Center for the Commercial Development of Space.

Erosion of shorelines and bluffs also contributes a lot of sediment to the Lake through coastal processes. This phenomenon has implications for water quality due to the contribution of glacial deposits which are also a source of phosphorus. Several studies on the Canadian side of Lake Erie focused on these phenomena (Bukata et al. 1975 and 1976, Coakley 1976, Haras and Tsui 1976a). The studies have mapped the location of erosion prone shores to provide for management (Haras and Tsui 1976b). Black and white infrared photographs were used as a basemap, and engineering data were recorded as an overlay. The resulting book is a detailed source of coastal conditions in both photo and narrative forms.

Other studies have used remote sensing to characterize the transport of suspended sediments, and used sediment as a tracer of water circulation patterns. Lake Erie has several prominent, coastal features. To study their genesis and understand the opportunities for protection and management, satellite and aircraft data were found to be useful. Bukata et al. (1975 and 1976) identified the common orientation of longshore drift and movement, and deposition areas of entrained materials. Of particular note was the location where opposite currents meet and deposition has formed coastal landforms. These include Pointe Pelee, where a vortex or gyre of sediment-laden water has been recorded from the air and space, and Turkey Pointe and Pointe Rondeau where offshore transport can be seen from satellite data.

Other authors have employed NOAA Environmental satellite measurements of lake thermal and sediment conditions to supply detail on surface circulation patterns. Sea Surface Temperature (SST) studies of Lake Erie demonstrated some of the prevailing areas of offshore transport as identified in the studies above. In the Long Point Bay and estuarine wetlands area in Ontario, transport and water quality conditions were sampled with Landsat and Coastal Zone Color Scanner data by LeDrew and Franklin (e.g., LeDrew and Franklin 1986). Similar transport has been identified on Advanced Very High Resolution Radiometer data (AVHRR) by Lyon et al. (1988). NOAA Environmental satellite data have also been valuable in evaluations of lake ice cover (Assel and Lyon 1984), and have been used to examine ice spectra and ice movement by the Great Lakes Environmental Research Laboratory in Ann Arbor, MI.

Water quality evaluations have also been conducted with remote sensors. NASA participated in some data acquisition and analysis in the 1970's. Studies included airborne scanner measurements of Cleveland harbor (Raquet et al. 1977), and remote sensing inputs to quantification of non-point sources of pollution in the Maumee Bay area (Shook et al. 1975). Some Daedalus airborne (1985) multispectral scanner data were flown of the Lake St. Clair, Detroit River and the extreme Western Basin of Lake Erie. Lyon is currently working on this data set under Ohio Sea Grant funding (NA84AA-D-00079, R/EM-8). The expected benefits include a radiometric model of light interaction with water, adaptations of the model for use with satellite data, and production of maps of general water bathymetry (one meter increments) and general bottom type using remote sensor data, on-site sampling and the radiometric model.

The studies above demonstrate the use of remote sensor data in studies of Lake Erie. However, these projects generally restrict their analyses to one date or one time only. This approach will supply no temporal data, and limited assistance in analyses of frequently changing water characteristics. This makes the results of remote sensor experiments difficult to use in any operational application.

To further the application of remote sensor data in water resources requires multiple date evaluations. Remote sensor data are acquired by satellites each day, or by aircraft on a periodic basis. Data potentially provide high frequency sampling of water and wetland spectra. It remains to address each data type and format, and attempt to input data from each in an experiment.

Suspended Sediment and Non-Point Sources

To limit lake and estuary eutrophication it is necessary to reduce phosphorus inputs or loads. Contributions from urban sewage and phosphate detergents have been limited at great cost. To further reduce causes of eutrophication it is necessary to limit non-point sources of pollution such as sediment eroded from farm fields (Schaal 1986, Logan 1987).

Effective management of activities that contribute to sediment and phosphorus loadings requires more information than is currently available. Fundamental questions about sediment transport, resuspension, deposition, and forcing functions need to be answered (Verhoff 1980, Bedford and Abdelrhman 1987). Quantifying sediment transported form farm regions to the Lake is difficult. Traditional measurement technologies are inaccurate, qualitative, time consuming, and people intensive. New approaches answer these questions by effectively measuring the impact of farm erosion, and sediment loadings on Lake Erie.

This project focuses on measuring suspended sediment concentrations using on-site data collection and remote sensor techniques. We have developed a methodology for modeling surface suspended sediment concentrations carried by river runoff to Lake Erie estuarine and coastal areas. A combination of synoptic satellite data, on-site sampling and sediment concentration results from models potentially fulfills a need for more information to understand and calculate real loadings to the Great Lakes.

Quantities of Wetlands

Waves interact with long-term fluctuations of Great Lake water levels to influence the hydrology of wetlands on Lake Erie (Beeton and Rosenberg 1968, Bruce 1984). Long-term water fluctuations are related to climatic change and occur within a time range of 10-38 years (IGLLB 1973). Extremely high lake levels were experienced during the early 1950's, the early 1970's, and the mid 1980's. Extremely low lake levels were experienced during the 1930's and the early 1960's. The interval between periods of high and low lake levels varies, as does the length of high or low periods (IGLLB 1973). These changes in lake level will continue to occur, and their effects on coastal resources have received a minimum of study.

Fluctuations in Great Lake water levels have been found to influence the extent of coastal wetlands (Jaworski et al. 1979, Lyon 1980, Harris et al. 1981). High water levels alter the hydrological conditions in wetlands which can kill vegetation, or they destroy barrier beaches which protect the wetlands from wave action (Harris et al. 1981). In a study of seven different varieties of Great Lakes wetlands, a decrease of 29% of wetland area was found between the lowest and highest lake levels that were studied (Jaworski et al. 1979).

It is clear that long-term fluctuations in water level can cause an increase or decrease in total area of wetlands. Information concerning the effects of lake levels on wetlands and beaches is necessary for resource management, and a methodology for quantifying local effects is required to supply data for resource management.

To determine the change in the quantity of wetlands we analyzed current and historical aerial photos. The objectives included: 1) measurement of the extent of wetlands from historical aerial photographs, and 2) use of the measurements to understand cause and effect relationships between wetlands and water levels.

The utility of the mapping approach has been demonstrated in a study of the Straits of Mackinac area of Michigan. Along the Lake Michigan coast of the Straits, a lower quantity of wetland and beach area was found in years of high water levels (Lyon 1981, Lyon and Drobney 1984, Lyon et al. 1986). From the study of the Straits of Mackinac and others, there appears to be a direct relationship between lake levels, and the presence of wetland plant communities and beaches. To further test the hypothesis that water levels influence the presence of wetland areas required investigation of longer-term influences over a number of years and number of different lake levels, and different Great Lakes. A determination of the long-term effect of water level fluctuations on wetland communities in the Pointe Mouillee region was a further test of the concept.

METHODS

Suspended Sediments

The period June 1 to July 15, 1981 was studied due to the occurrence of four large storms. Research indicated that the major transport of sediment to the open lake occurs under storm flow conditions. An additional, important factor was the availability of water sampling (Richards and Baker 1982) and satellite data during this period (Fig. 1).

Satellite data were processed into products that could be interpreted for relative or absolute surface suspended sediment concentrations. Data products were developed in two ways (Lyon et al. 1988). a) Satellite data were computer categorized to produce a map of sediment concentration classes or types. b) The resulting class mean brightness values from satellite data were used in comparisons with on-site sampling of suspended sediment concentrations (mg/L). Analysis included regressions of brightness values with the on-site sampling data, and rank correlation analysis to demonstrate the capability of the categorizing algorithm to select spectrally distinct classes.

a) Suspended sediment concentration class types were developed from computer categorizations of satellite data. This procedure selected homogeneous areas of suspended sediment concentration classes with a clustering algorithm. The resulting sediment classes effectively divided Sandusky Bay into concentration classes and provided a map of their locations (Fig. 3, 5).

Two NOAA-AVHRR scenes were evaluated for their capability to supply spatial distribution of suspended sediment concentrations in the form of images. The scenes were acquired on June 26 and June 27, 1981 or one and two days after on-site sampling (Fig. 5). All five data channels were used to make the computer categorized products mentioned above.

b) Individual concentration measurements of sediment and satellite brightness values were used to generate regression models of the relationship. Twelve individual sediment sampling sites were compared to the average brightness of the red and near infrared reflectance of computer categorized class. Linear or multiple variable linear regression models were developed from brightness values and on-site sampling. Histograms and tests of normality indicated the distributions were normal, and that linear models were appropriate for the concentrations involved.

For Landsat images, on-site sampling stations were located on the lineprinter maps of the categorized scene. The brightness values of twenty-five picture elements or pixels (0.16 km^2) surrounding the sampling station were averaged and compared to sediment concentrations measured in the water. This has been shown to be a suitable area to average the spectral response of

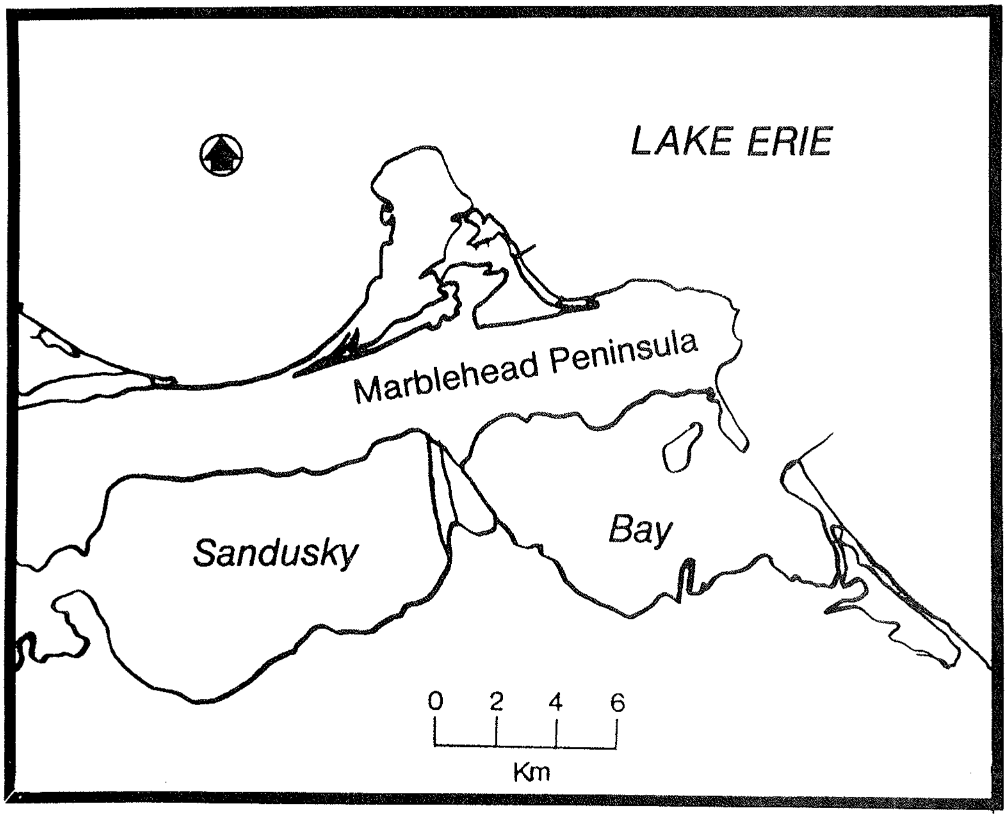

Figure 1. The Sandusky Bay, Ohio, study site.

water (Ritchie and Cooper 1987). Landsat channels 5 and 6 were shown to supply the most detail on sediment concentration conditions.

For AVHRR images, a single pixel (1 km^2) encompassing the sampling station was located, and the spectral characteristics of the categorized product were used for comparison with water samples. AVHRR channels 1 (red) and 2 (near infrared) provided the most useful data on sediment, and these data were used for later analysis.

A rank correlation, non-parametric Spearman Rho correlation test proved valuable for demonstrating that the cateogorization algorithms could recognize the sediment classes from satellite-measured brightness values. The test indicated that the categorizing algorithm distinguished sediment concentration classes based on their brightness, and there was a non-random association between on-site measures of sediment and computer generated classes.

Quantities of Wetlands

The historical distributions of wetland and beach areas were measured from aerial photographs acquired during periods of low water (1935, 1964), and high water (1973, 1978, 1980). Use of these photographs allowed a forty-year period for analysis, and several examples of each water level from different decades. The exact dates, scales and water levels are included in the results. This intensive sample of wetland areas and water levels was completed in the Pointe Mouillee area. For the inventory, only wetlands which were undiked and subjected to Lake Erie water levels were measured. Diked wetlands have been managed by flooding and accurate assessment of historical, hydrological conditions would be difficult (Fig. 2)

Boundaries of wetland and beach areas were interpreted and traced onto Mylar from enlarged aerial photographs. Area measurements were made with a planimeter, and corrected for actual photo scale to produce determinations of area.

Historic water level data were obtained for the area from the class 1 gage stations at Fermi Power Plant, Gibralter, Monroe, Michigan and Toledo, Ohio (NOAA 1978). When possible, daily levels were used instead of monthly averages, and the closest gage in operation was used for the water level value.

It is important to note that tides have a very small effect on the Great Lakes water levels. Wind or pressure generated events (e.g., seiches or storm surges), and long term changes in lake water levels from rainfall, create lake level fluctuations which influence hydrology of wetlands (IGLLB 1973).

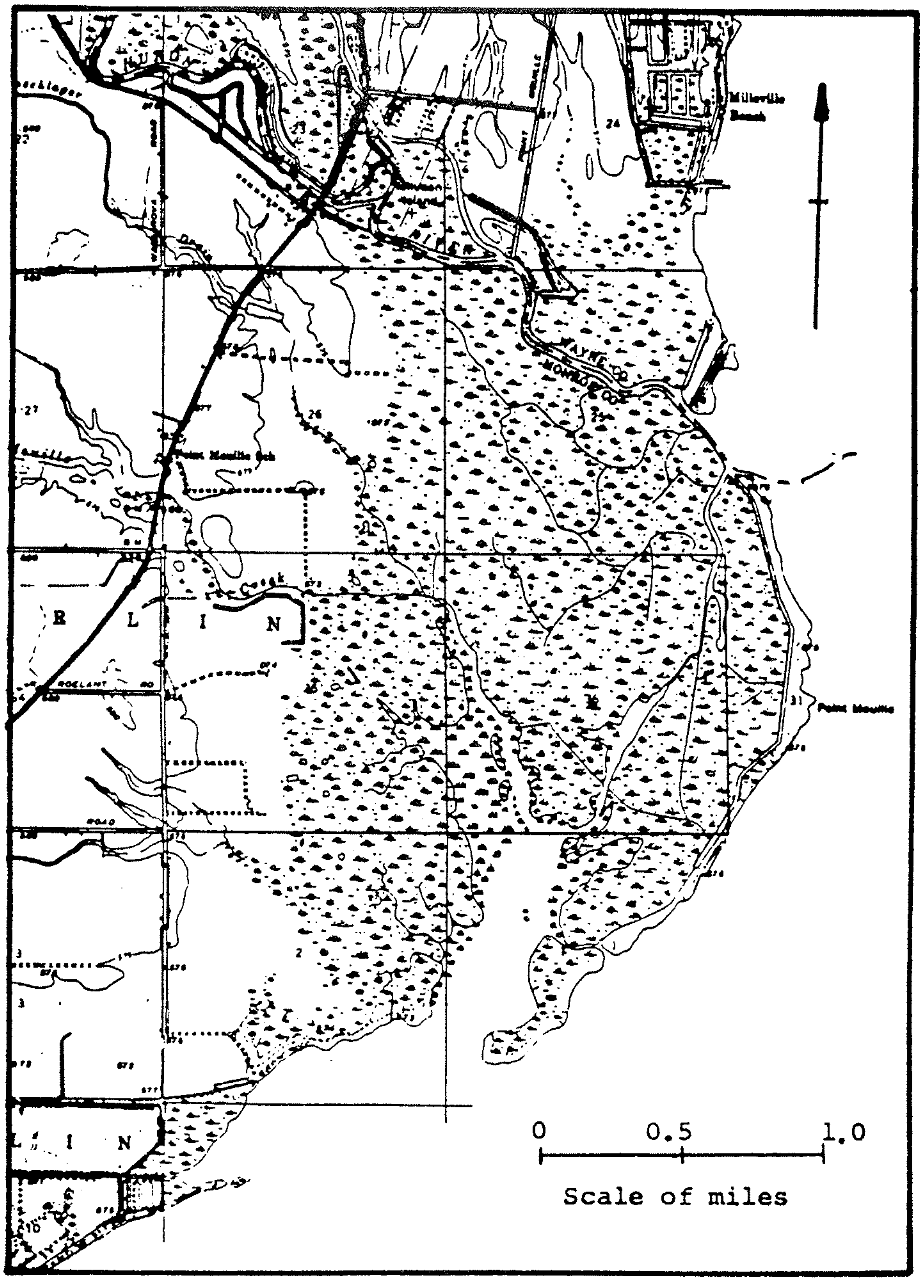

Figure 2. U.S.G.S. map of the Pointe Mouillee area from 1942. The area is in the Western Basin of Lake Erie. Original map scale was 1:62,500.

RESULTS

Suspended Sediments

Suspended sediment concentration measurements and satellite digital data products of Sandusky Bay, the nearshore region and open part of Lake Erie were compared during the June-July, 1981 study period. Calculations were completed using traditional, on-site sampling data, and raw brightness values and suspended sediment concentration categorization products from satellite sensors.

Work yielded good agreement between satellite data and on-site sampling (Lyon et al. 1988). A four day sequence of satellite and suspended sediment sampling demonstrated the basic concept and the proposed methodology. AVHRR and Landsat scenes from June 10, 26, 27 and 28, 1981 present the distribution of suspended sediment classes in Sandusky Bay (Figs. 3, 4, 5). Linear regression models of Landsat digital brightness values and suspended sediment concentrations showed a strong relationship (Table 1).

Non-parametric Spearman Rho tests also demonstrated a strong relationship between suspended sediment classes derived from AVHRR and Landsat satellite data, and on-site measurements.

These calculations and final results were compared with results from hydrodynamic and water quality models. General concentration class boundaries and general concentration levels simulated by the model were also demonstrated independently from categorized or enhanced satellite data.

Comparisons between satellite data and the results of hydrodynamic and water quality model runs (Lee 1986, Yen 1987) indicate several areas of agreement. Fig. 3 presents the July 28 Landsat categorized scene and the relative sediment concentrations contours from the model. Similar contour boundaries are indicated on the Fig. 4 and it is apparent that both data sources could produce similar results. All data sources indicated the plume (A) in the Upper Bay. It is important to note that both AVHRR and Landsat categorized scenes show this plume (Figs. 3, 5). Regressions of Landsat brightness values and on-site sampling from June 25 indicated this plume had clay concentrations ranging from 600 to 490 mg/L.

The satellite categorized scene and model results also identified lower concentrations area along the south shore of the Upper Bay (B). They also identified lower concentration areas along the north shore of the Upper and Lower Bay (C, 466 mg/L).

In the Lower Bay there were several areas of similarity. Large scale eddys can be identified (D) where Bay water and open lake water mix. Storm surges, seiches, and lake modes of resonance all can cause backflow and influx of open lake water into the Lower Bay (Lee 1986). The satellite categorizations

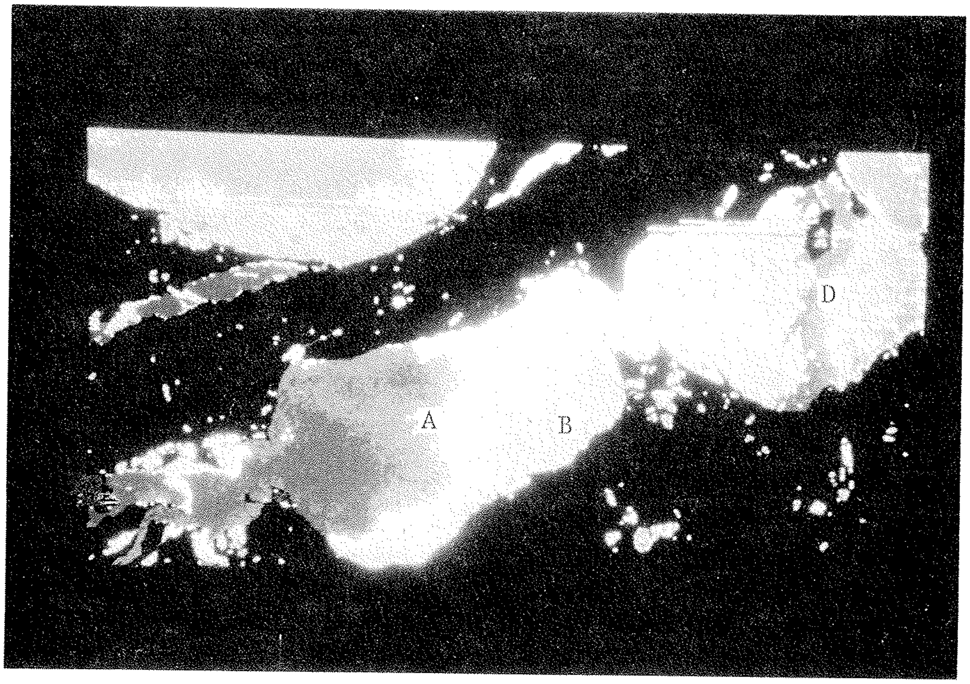

Figure 3. Categorized water colorant classes from the June 28, 1981 Landsat scene. Description of letter symbols is in the text.

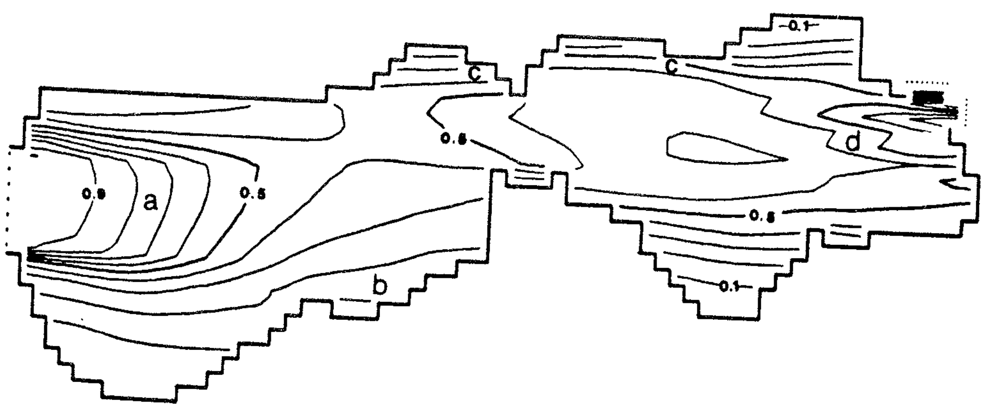

Figure 4. Results of hydrodynamic and water quality model simulations for the same time as Figure 2. The contour lines show proportional concentration of total suspended solids relative to 595 mg/L (after Lee 1986).

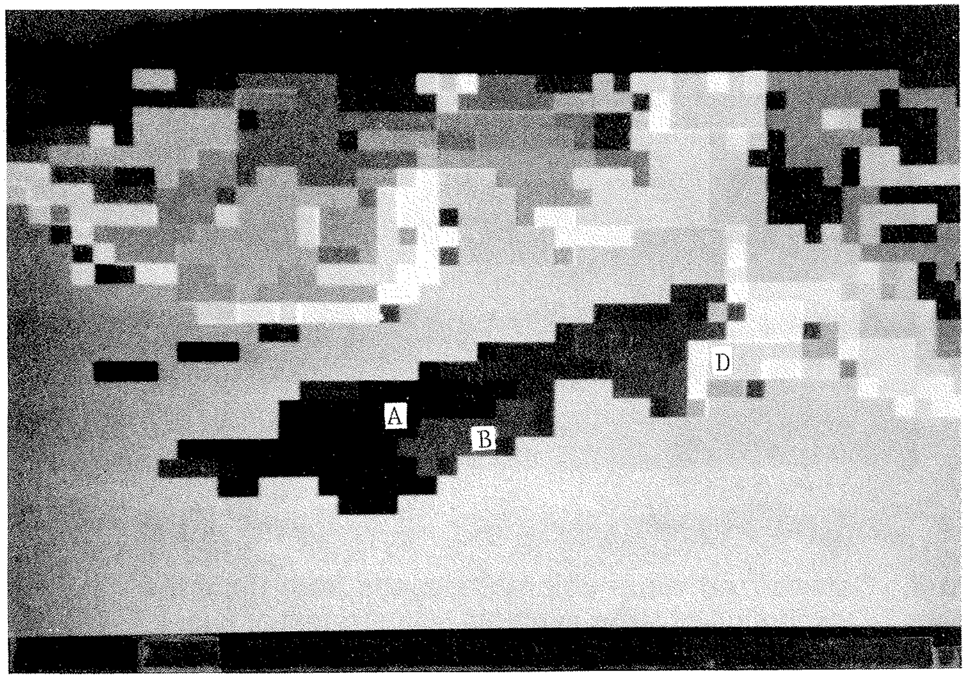

Figure 5. Categorized water colorant classes from the June 27 AVHRR scene.

Table 1. Results of regression analyses of Landsat digital brightness values for bands 5 (red) and 6 (near infrared) with on-site total suspended solids (n=12), and results of Spearman rho tests comparing the non-random assortment of on-site total suspended solids with categorized water colorant class from Landsat and AVHRR multiple channel data.

Date	Data Source		Linear Regression R2= , p>	Spearman Rho R= ,p>
June 10	Landsat			
	Categorized			0.86, 0.0124
	Raw data, bands	5 & 6	0.80, 0.0015	
		5	0.80, 0.0002	
June 12	On-site Samples Collected		-	-
June 25	On-site Samples Collected		-	-
June 26	AVHRR			
	Categorized			0.86, 0.0007
	Raw data, bands	1 & 2	0.87, 0.0003	
		1	0.80, 0.0002	
June 27	AVHRR			
	Categorized			0.78, 0.0072
	Raw data, bands	1 & 2	0.90, 0.0003	
		1	0.81, 0.0004	
June 28	Landsat			
	Categorized			0.93, 0.0001
	Raw data, bands	5 & 6	0.90, 0.0001	
		5	0.72, 0.0009	

display this as a change in water colorant classes over a short distance. The hydrodynamic and water quality model predicted some of this change.

Quantities of Wetlands

Results demonstrated: a) the recent, historical extent of wetlands in the study area (1935, 1011 ha, 2496 ac). b) The great fluctuation between low water and high water years, for example 1964 (173.64 m water level, 828 ha, 2045 ac) and 1973 (174.67 m water, 332 ha, 819 ac and 1980, 174.54 m, 203 ha, 502 ac). c) Area measurements indicated a decrease of approximately 700 ha of wetlands and beaches from 1935 to the 1950 period. The dates of photo coverage, scales, and water levels included: 1935, 1:30,162, 173.29-173.43 m; 1964, 1:20,556, 174.37 m; 1973, 1:41,605, 174.67 m; 1978, 1:24,130, 174.37 m; 1980, 1:24,771, 174.54 m. The 1935 photos had no date and it has been impossible to establish it. Hence, a range in water levels from May through September, 1935 were employed.

Analysis of the five sets of photos indicates there is a similar linear relationship between water levels and total undiked wetlands (Lyon et al. 1985). In general, higher lake levels result in lower quantities of wetlands. This result has been also demonstrated for Lake Erie wetlands at Long Point, Ontario (Whilliams 1985). Other studies have also found this relationship (Lyon 1981, Lyon et al. 1986) to be true.

An interesting result of this work was the loss in wetlands between 1935 and 1950. Figures 6 through 9 show the change in wetlands during this period (Green 1987). While Lake Erie water levels have been generally high since the 1970's, lake levels alone are not the explanation for this loss. Lake levels have varied from high to low since they have been recorded, and earlier accounts document the natural fluctuations of lake levels. Because weather conditions have not changed drastically since the 1920's or have lake levels, it is conceivable that the loss of sediment input to the Huron River delta or Pointe Mouillee has resulted in the decrease of total wetlands from 1935 to 1973.

This loss presumably resulted from the damming of the Huron River and entrapment of silt, sand and larger size particles (Greene 1987). The Pointe Mouillee area is the delta and estuarine wetlands of the Huron. The delta has been present since the retreat of the Wisconsin glaciation over four thousand years ago. The delta was largely intact until the 1920's or 1930's. Maps and accounts previous to that time record a delta of large size (Lyon et al. 1985). However, the early part of this century saw construction of seven or more dams on the Huron River, with documented decreases in transport of sediments to the delta area.

Figure 6. Aerial photo of wetland areas from 1937 (water level was 174.00 m).

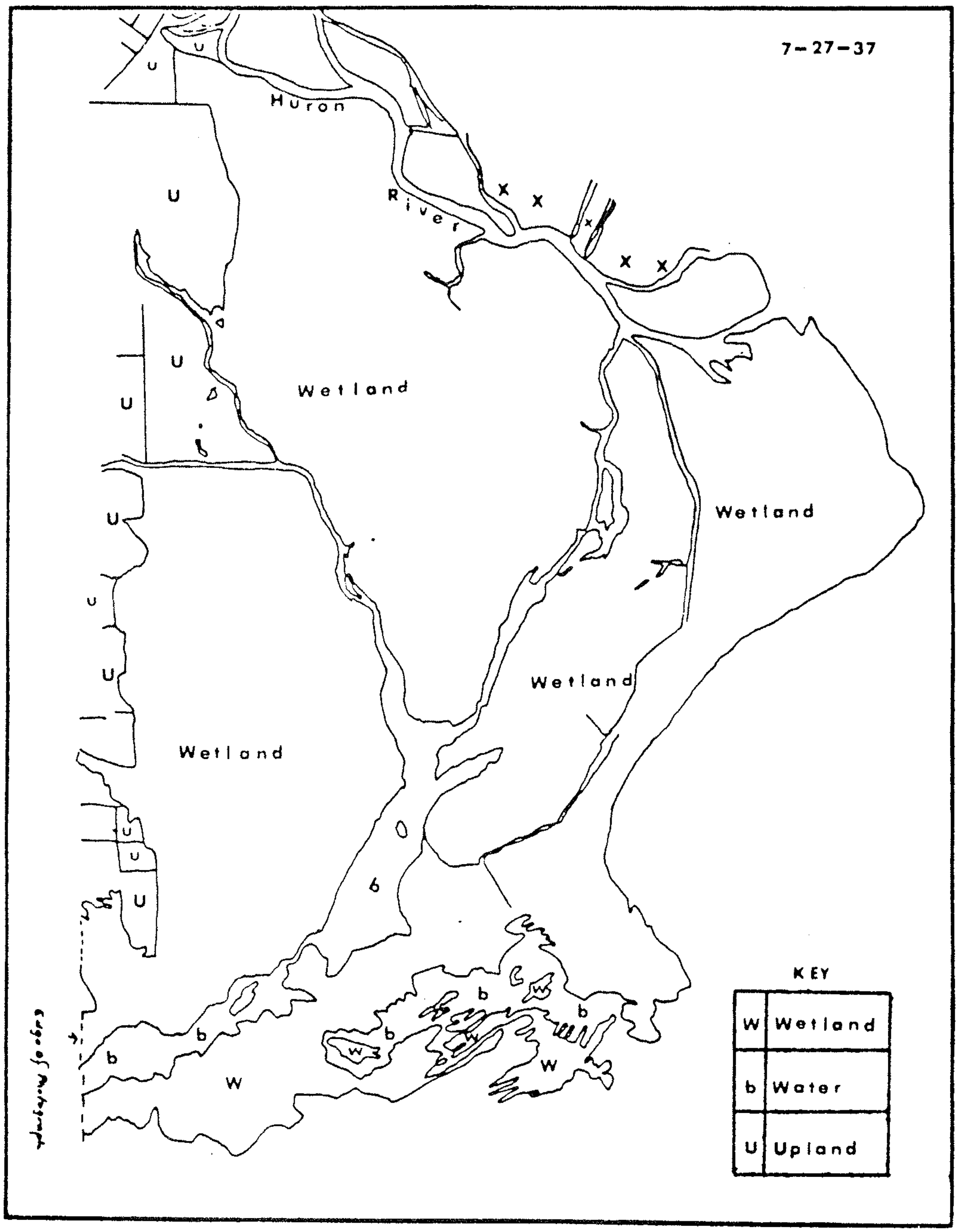

Figure 7. Interpretation of 1937 aerial photographs, Pointe Mouillee Area outside of the study area are shown as an 'x'.

Figure 8. Aerial photo of wetland areas from 1950 (water level was 173.92 m).

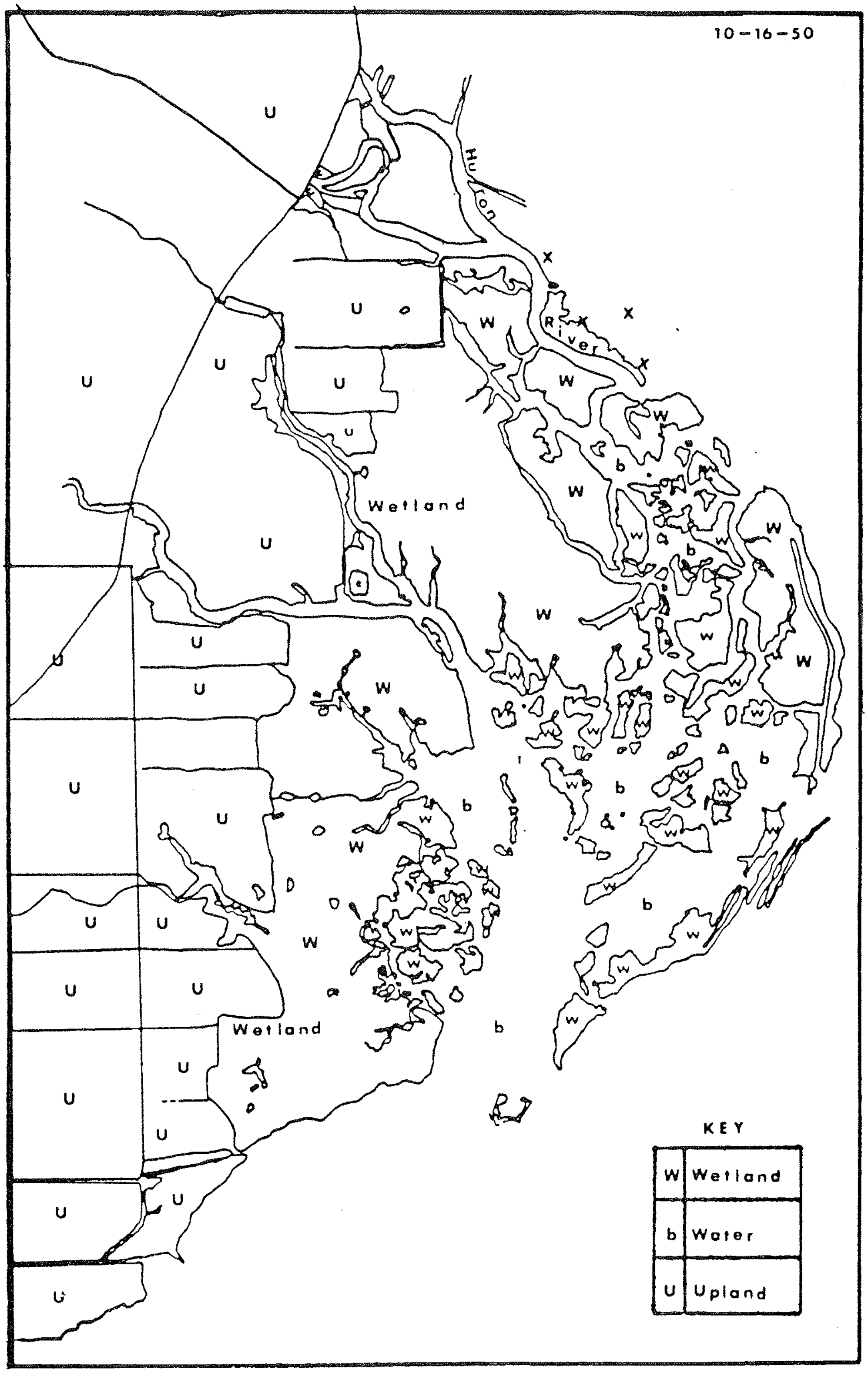

Figure 9. Interpretation of 1950 aerial photographs, Pointe Mouillee Area outside of the study area are shown as an 'x'.

DISCUSSION

Quantities of Wetlands

Record high Great Lakes water levels prompt questions concerning their influence on coastal resources and structures. One of the concerns is whether Lake water levels result in different quantities of wetlands and beaches. The results of this and other studies indicate there will be a decrease in available wetland and beach areas with increasing water level. However, the variable nature of precipitation input to the Lakes results in fluctuating water levels. This too results in variable quantities of wetlands.

The relatively constant presence of wetland and shore areas through time indicated that early seral communities have been maintained by fluctuations of water levels and flooding. Fluctuating water levels are a perturbation similar to fire in prairie, boreal forest or chaparral ecosystems. Low lake levels are historically followed by high lake levels which flood previously dry areas and kill non-wetland shrub and trees. Wetland plants recolonize these areas and wetland areas are maintained by the periodic disturbance of high water levels.

Suspended Sediments

Quantifying sediment transported from farm regions to the Lake is difficult. Traditional measurement technologies are inaccurate, qualitative, time consuming, and people intensive. New approaches can potentially answer these questions by effectively measuring the impact of farm erosion, and pollutant loadings on the Lake Erie.

Best Management Practices such as conservation tillage have been introduced to farms near Lake Erie tributaries to reduce farm-related erosion. To measure the implementation and future effects of Best management Practices (BMP) requires identification of sediment transport characteristics and the fate of the sediment. It is necessary to understand the various non-point source loading mechanisms, and to parameterize these loadings for use as input in management models.

The absence of an organized use of satellite and modeling methodologies results from the difficulty of analyzing several different data types and models. Often this combination of data is unavailable due to the cost of on-site sampling, the infrequency of aircraft or satellite coverage, and the difficulty of operating hydrodynamic and water quality models. The methodology proposed here can potentially overcome some of these difficulties and provide a basis for a future, operational methodology.

CONCLUSIONS

Estuary and nearshore areas experience a variety of changes, and have an influence on open lake systems. To better manage resources and model their behavior requires additional inputs of data. Remote sensor information can be very useful as an adjunct to traditional sources of data. The case studies presented here demonstrate the utility of remote sensing for both inventory and modeling. Both case studies and previous work demonstrated the value of remote sensor inputs to studies of estuarine and lacustrine systems.

There is great interest in the use of remote sensing technologies, and a need for operational applications of aerial and satellite data along with traditional measures. Potentially, a remote sensing approach can increase the accuracy of model determinations and reduce the costs associated with on-site sampling. Availability of daily remote sensor data can assist in providing more accurate estimates of water resources.

ACKNOWLEDGEMENTS

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CHEMICAL LIMNOLOGY AND CONTAMINANTS

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The chemical limnology of Lake Erie is a result of its morphometry and hydromechanics, and of the hydrological, topographical, geological, climatic and land-use characteristics of its watershed. Several of these characteristics have been presented already (Bedford, Herdendorf, Herdendorf and Krieger in this volume), but land-use and the contaminants derived from land activities need also to be noted because both have had a profound influence on the chemistry of Lake Erie since the advent of European settlement of the basin. This discussion will follow the route of the water from its precipitation onto the landscape, and its consequent movement with associated materials into the tributaries, on into the marshes and wetlands, and finally to the nearshore zone and open lake.

TRIBUTARIES

As previously discussed (Herdendorf), the natural characteristics of the Lake Erie basin vary greatly between the eastern and western ends of the lake. The southwestern and northern parts of the drainage are heavily agricultural, while a much greater proportion of the eastern two-thirds of the southern drainage is urbanized or forested. The nature of the soils also varies considerably. The combination of watershed sizes, soils, topography and land-use has influenced the kinds and amounts of various pollutants which enter the lake and affect its water and sediment chemistry.

Because of intensive row crop agriculture, the southwestern drainage contributes by far the greatest unit area losses of sediment and phosphorus, with average losses in some counties of 2.5 kg P per hectare per year (Internat. Joint Commission 1980). Because phosphorus, especially "bioavailable" phosphorus, has been shown to be the cause of much of the degradation of Lake Erie's water quality (Internat. Joint Commission 1980), a great deal of effort has been expended by both the U.S. and Canada to reduce the amount of phosphorus leaving the land and moving downstream to the lake. This effort is reflected in the 1983 Phosphorus Load Reduction Supplement to Annex 3 of the 1978 Great Lakes Water Quality Agreement between the two countries, and also in various reports on remedial programs (Honey Creek Joint Bd. Supervisors 1982, Great Lakes Phosphorus Task Force 1985, National Assoc. Conserv. Districts 1985).

Phosphorus arises from both point and nonpoint sources within the basin. While the amounts of phosphorus entering tributaries or the lake directly via point sources are computable from readily available data, attempts to quantify the amount entering from nonpoint sources have been complicated by the large annual variability in climate. Fig. 1 shows the annual precipitation occurring in the Sandusky Basin (the second largest U.S. watershed tributary to Lake Erie excluding the Detroit River) from 1976 through 1985. Discharge in the Sandusky River (Fig. 1) is much more variable from year to year than precipitation because of the dependence of discharge on soil moisture conditions and the intensity and duration of individual storms. Total phosphorus, which includes that bound to sediment particles and organic matter in storm runoff as well as that dissolved in the water, is even more variable than discharge (Fig. 1).

Thus, efforts to evaluate the effectiveness of programs applied to land management practices, such as conservation tillage demonstration projects in the Lake Erie basin (e.g., Honey Creek Joint Bd. Supervisors 1982, Nat. Assoc. Conserv. Districts 1985), through measurement of the amount of reduction in the loading of phosphorus to the lake, must be carried out over many years in order to "average out" the large annual and seasonal variations (Richards 1987. Furthermore, the loadings measured near the mouth of a single tributary, such as the Sandusky River, cannot be extrapolated to other watersheds in the basin, such as the Maumee, the Huron or the Cuyahoga, because of largescale effects of watershed size, as well as differences in land-use, topography and soil types, on the transport of sediments and pollutants (Baker 1988). It is, therefore, difficult to predict quantitatively the reduction in phosphorus loadings, and the loadings of associated pollutants, which will result from the implementation of best management practices on the land. Nevertheless, because rural nonpoint sources contribute 51% (in 1980) of the total phosphorus loading to Lake Erie (Yaksich 1983), much emphasis has been placed on such programs over the past decade. (Urban nonpoint sources in 1980 supplied 6%, point sources 27%, and Lake Huron and the atmosphere 16% of the phosphorus load (Yaksich 1983)).

Another major source of phosphorus is treated sewage effluent. The 1972 Great Lakes Water Quality Agreement established a standard of 1.0 mg total P/L to be met by all municipal point sources discharging more than a million gallons (3,800 m^3) of effluent per day (Great Lakes Water Quality Board 1985). Some of these point sources discharge into tributaries, while others discharge directly into Lake Erie along its shores or in its harbors. The Detroit plant is the single greatest source of phosphorus to Lake Erie via the Detroit River. The load from this facility has been reduced from 4,720 metric tons in 1975 to 789 metric tons in 1984. Table 1 shows the largest municipal wastewater treatment facilities discharging in the Lake Erie basin, their average annual flow rates and P concentrations, and their ranking among all Great Lakes Basin facilities. A target load of phosphorus to Lake Erie has been set at 11,000 metric tons per year (t/a). Because the load (estimated at 18,000 t/a in 1972) can only be reduced to 13,000 t/a if all municipal treatment plants discharge phosphorus at 1 mg/L, the remaining 2,000 t/a must be removed from the nonpoint sources (Great Lakes Water Quality Board 1985).

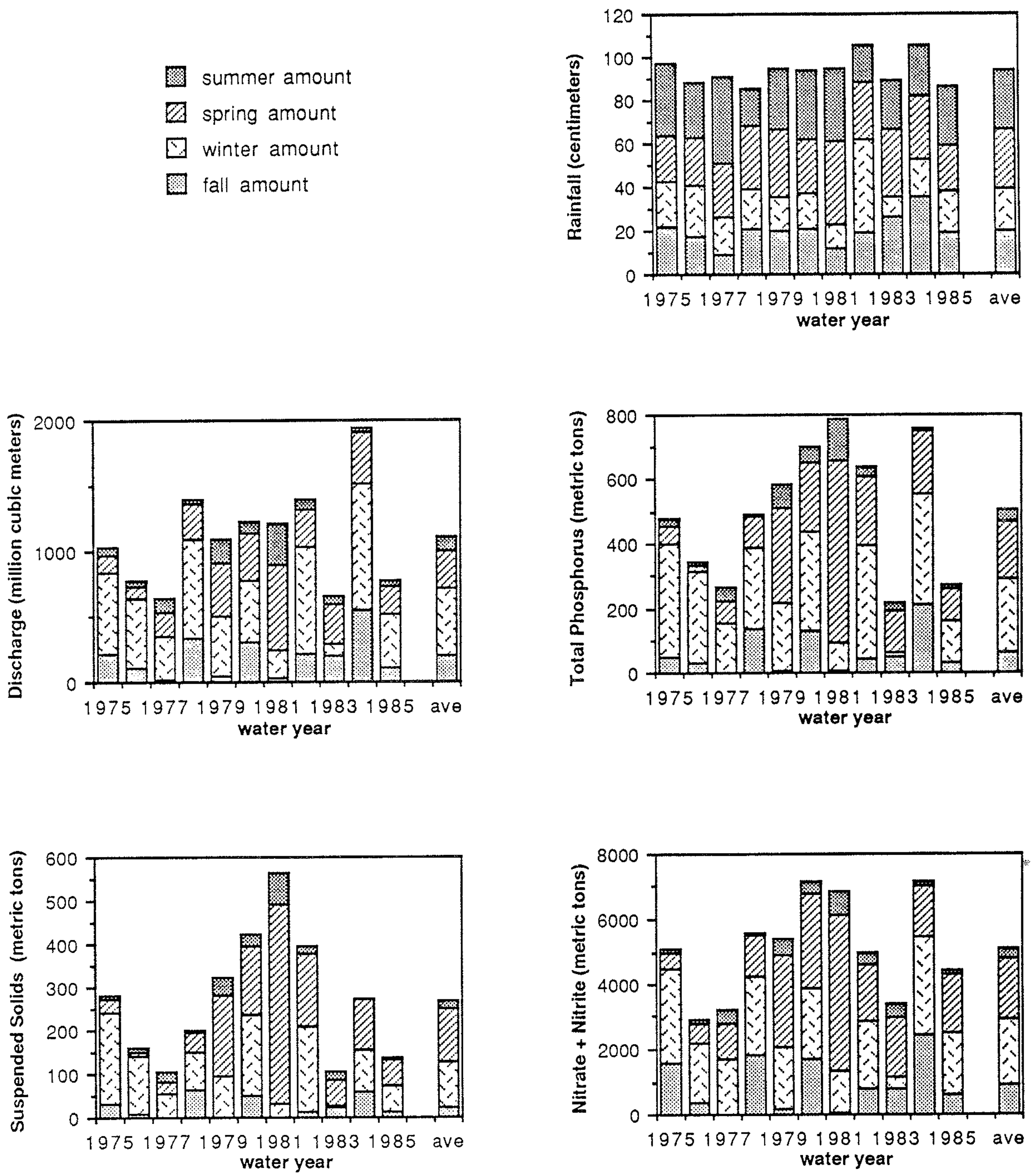

Figure 1. Annual variability and seasonal distribution of rainfall in northcentral Ohio and of discharge and loadings of total phosphorus, soluble reactive phosphorus, total suspended solids and nitrate+nitrite nitrogen in the Sandusky River at Fremont, Ohio (modified from Baker 1988).

Nitrate is another essential plant nutrient but not usually limiting to algal growth in Lake Erie. In fact, annual mean nitrate+nitrite concentrations have been increasing significantly over the last decade (Herdendorf 1984). Of more interest from the human health standpoint than from the standpoint of loading to Lake Erie, nitrate in drinking water supplies drawn from northwestern Ohio tributaries to the lake each spring exceeds the standard of 10 mg/L nitrate as N, above which nitrate has the potential to lead to methemoglobinemia in human infants as well as in some domestic animals (Ohio Coop. Ext. Serv. 1987). Nitrate in the Lake Erie watersheds derives from natural nitrogen fixation in the soil, water, and atmosphere, but also from faulty septic systems, urban sewage treatment effluent and from agricultural surface runoff and the effluent from drainage tiles, which are extensive beneath farm fields in the gently sloping, clayey soils of most of the southwestern drainage. The variability of its annual tributary loads is demonstrated in Fig. 1.

Agricultural herbicides used with corn and soybeans reach higher concentrations in rivers in northwestern Ohio than in rivers anywhere else in North America (Baker 1988). Their annual concentration pattern in streams is predictable: they always reach their highest concentrations in late spring or early summer in the first major storm runoff event following corn and soybean planting and then decline, at first rapidly, then more gradually to undetectable levels. Later storms usually give rise to brief increases in concentration (Baker et al. 1985). The height of the peak concentrations cannot be predicted, for herbicide concentrations, like those of phosphorus and sediment, are dependent largely on variable climatology. Atrazine, used with corn, and alachlor (Lasso™), used with corn and soybeans, both have reached peak

Table 1. Largest municipal wastewater treatment facilities in the Lake Erie Basin (Great Lakes Water Quality Board 1985).

Facility	1983 Average Flow Rate ($10^3 m^3/d$)	Annual Average P Concentration (mg/L) 1983	1984	Rank Among Great Lakes Facilities
Detroit, Michigan	2,646	0.79	0.85	1
Cleveland-Easterly, Ohio	502	0.69	0.33	4
Cleveland-Southerly, Ohio	349	0.69	0.80	7
Toledo, Ohio	315	1.30	1.09	9
Akron, Ohio	275	1.16	1.24	13
Erie, Pennsylvania	175	1.24	1.10	19
Fort Wayne, Indiana	135	0.83	0.69	25
Cleveland-Westerly, Ohio	133	1.52	1.15	26

concentrations near 100 µg/L (ppb) in some of the smaller tributaries to the lake (Baker et al. 1981, Baker 1988). Atrazine is known to be inhibitory to some native algae and vascular aquatic plants at the concentrations found in these watersheds; however, various studies have indicated that these effects are transitory and probably have no lasting effect on the composition or productivity of the aquatic plant communities (Krieger et al. 1988). Unlike atrazine, alachlor, which has a different mechanism of toxicity, apparently does not inhibit the productivity or alter the community structure of stream algae (Blake 1988). The toxic effects on algae and vascular aquatic plants of many of the other herbicides present together in storm runoff soon after planting are not known. Most insecticides are detectable for only brief periods if at all, at levels usually below 5 µg/L (Baker 1988), although slightly higher concentrations have on occasion been recorded in one western Lake Erie coastal marsh (Krieger, unpubl. data).

COASTAL WETLANDS

Most of the creeks and rivers debouching along the southwestern shore of Lake Erie possess "estuaries" (as defined by Brant and Herdendorf 1972), formed by a gradual rise in the lake level which drowned the lower tributary channels along with varying amounts of their floodplains. These riverine systems are also present along some other shores of the Great Lakes (e.g. Spain et al. 1969). The water in these wetlands is often a mixture of tributary and lake water and thus has an intermediate chemistry. Flow reversals are also frequent in at least the more lakeward portions of these systems. Hereafter in this report, these unique estuary-like systems will be called "riverine coastal wetlands" rather than estuaries because of their several major differences from true marine estuaries (Pritchard 1967). These wetlands most closely fit the Riverine System described by Cowardin et al. (1979), and most of them have areas which would be classified by them as Palustrine Systems.

The riverine coastal wetlands, which here include the freshwater estuary wetlands and parts of the delta wetlands as defined by Herdendorf (1987), differ from other coastal wetland systems of Lake Erie by deriving most of their water from one or more tributaries, with occasional major inputs of lake water via flow reversal. Examples include Old Woman Creek National Estuarine Research Reserve, the lower Maumee River, the lower Sandusky River and Sandusky Bay, and Big Creek Marsh (Fig. 2). Two other types of coastal wetland systems are also recognizable. One, the coastal lagoon wetlands (Herdendorf 1987), includes those marshes which derive their water mostly or entirely from the lake, being separated from it by a sand spit or a barrier beach. Examples are Sheldon Marsh just east of the mouth of Sandusky Bay and Point Pelee National Park, Ontario (Fig. 2). The other type is comprised of marshes which once were an integral part of riverine coastal wetlands but which have been diked and maintain a direct connection to the riverine system only via gates which may be controlled to maintain seasonally desired water levels. Examples of diked marshes include Winous Point Marsh on the northern and southern edges of upper Sandusky Bay, and Moxley Marsh on the southern shore of the bay (Fig. 2). Each of these three wetland types interacts differently with the lake and undoubtedly is different from the others in terms of its geochemical processes and biological communities. The recent ranges of selected physical and chemical variables are shown for representative marshes, Sandusky Bay and the western basin in Table 2. Herdendorf (1987) has examined our relatively meager understanding of the ecology of the various western Lake Erie wetland systems. This review focuses primarily on the riverine coastal wetlands.

Brant and Herdendorf (1972) determined that nine "estuaries" in the reach from the Maumee River to the Huron River account for 90% of the total estuarine area along the Ohio shore, related primarily ". . . to the relatively low, flat terrain in northwestern Ohio as opposed to the higher relief of the northeastern section of the state." Their lengths vary greatly from 0.8 km along the lower Rocky River, to 2.1 km along Old Woman Creek, 23.8 km along the Maumee River and 24.8 km along the Sandusky River.

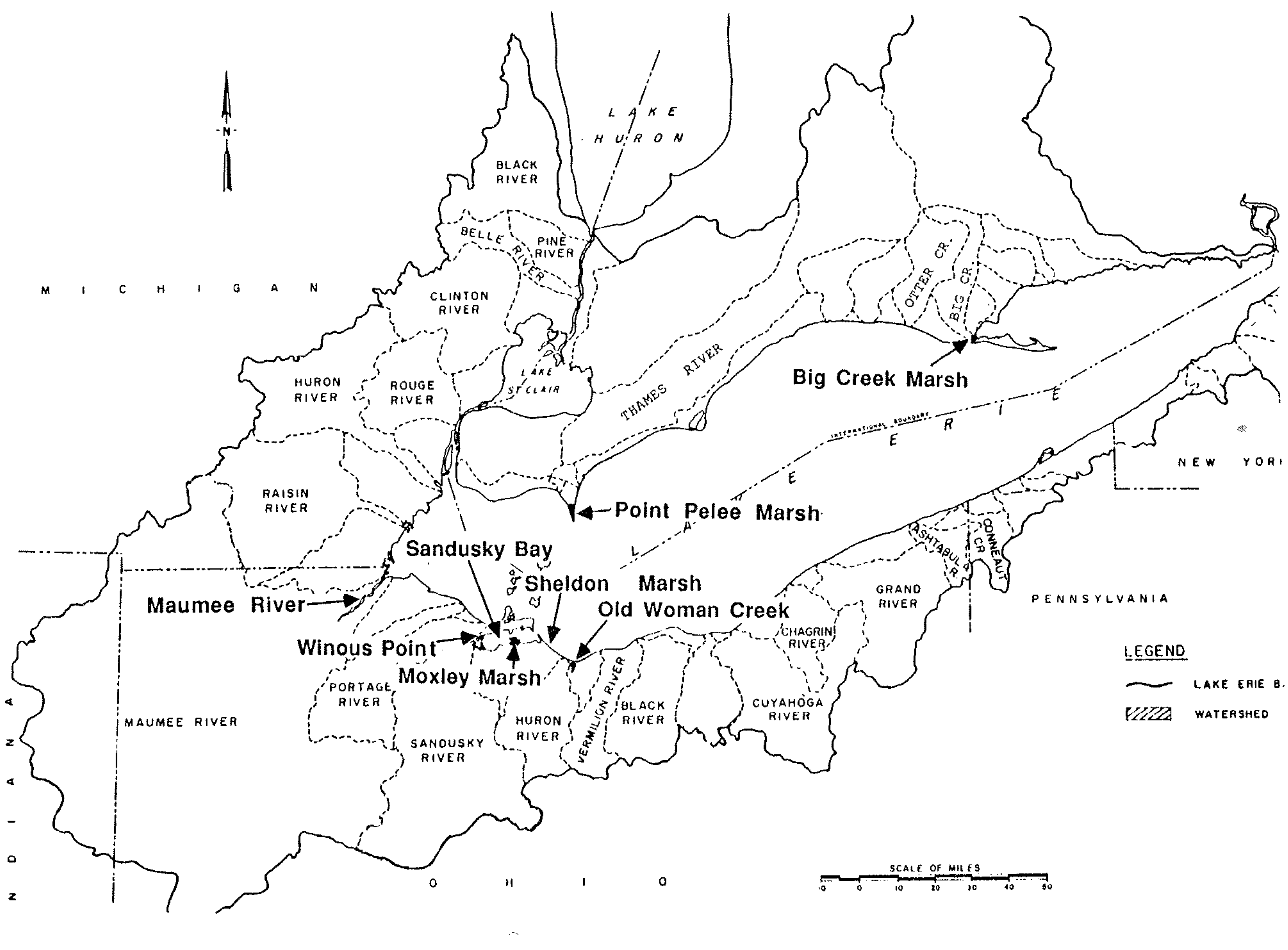

Figure 2. Locations of the Lake Erie coastal marshes cited in this review.

Table 2. Ranges of reported values of physical and chemical parameters from studies of western Lake Erie, Sandusky Bay, and selected marshes.

Parameter	Old Woman Creek Estuary[abc]	Sandusky Bay[d]	Lake Erie western basin[de]	Moxley Marsh[f]	Winous Point[f]
temperature, °C	0-31	12-29	12-25 (17.3)	13-25	14-32
turbidity	5-310 NTU			20-160 JTU	90-670JTU
total suspended solids, mg/L	27-576	8-975	<1-35 (19.9)		
Secchi depth, m	0.02-0.56	0-0.8	0.4-1.6 (0.80)		
spec. conductance µmhos/cm @ 25°C	176-715	232-644	217-368 (282)		
pH	7.4-8.8	7.0-9.5	7.0-8.8 (8.4)	7.2-7.7	7.4-8.3
dissolved O_2, mg/L	0.0-14.4	5.2-19.4	5.6-12.8 (9.8)		
total P, µg/L	60-600	40-500	20-80 (79)		
soluble reactive P, µg/L	<1-283	<1-70	<1-19	50-1,580	200-2,750
nitrate+nitrite N, µg/L	0-13.8	0.0-10.9	0.0-2.0 (0.3)	0.1-12	0.5-14
dissolved reactive silica, mg/L	0.01-11.7	0.02-9.9	0.1-1.1	7-15	5-13
chloride, mg/L	2.2-87.3	12.8-38.3	12.5-23.9	38-75	28-50
total iron, mg/L	0.6-33.6	0.2-14.0	0.1-1.1		
chlorophyll *a* (corrected) µg/L	-0.8-231	0-110	0-20 (13.5)		
atrazine, µg/L	ND-57[g]				
alachlor, µg/L	ND-45[g]				
carbofuran, µg/L	ND-8[g]				

[a] Krieger 1984
[b] Heath 1987
[c] Klarer 1988
[d] Unpubl. data for 1982 and 1983 from Richards and Baker (1985)
[e] Values in parentheses are means for 1967-1982 data; Herdendorf 1987
[f] Millie 1979 (3 dates except 6 dates for temperature; nitrate without nitrite; Hach kit data)
[g] Krieger (unpublished data)

The riverine coastal wetlands display a persistent chemical gradient (measured in parts per million rather than in parts per thousand as in marine estuaries). This gradient is the reverse of that in most true estuaries in that the highest concentrations are upstream, indicating a progressive dilution of tributary water with lake water in a downstream direction. During studies performed in the 1960s, specific conductance in the lower Cuyahoga River showed a nearly fourfold decrease from upstream to downstream, and the colder, less mineralized lake water intruded in some circumstances under the warmer, highly mineralized river water, the extent of intrusion being influenced by seiches, wind and changes in streamflow and lake level (Brant and Herdendorf 1972). In the 14-km (8.5-mile) long Sandusky Bay, which receives water from a 4,600 km^2 (1,770 sq. mi.) watershed, continuous recordings of specific conductance made on several dates while traversing its long axis revealed regions of "relatively constant" specific conductance separated by "relatively abrupt" transition zones, rather than a long, smooth gradient. The regions were interpreted to be "low flow river water and resident estuary water" (600-1,000 µmhos/cm), upper bay water (400-700 µmhos/cm), storm runoff water (200-400 µmhos/cm), and lake water (around 250 µmhos/cm) (Richards and Baker 1985).

A progressive decrease in specific conductance in a downstream direction has also been consistently measured in the much smaller Old Woman Creek Wetland (Krieger 1984, Heath 1987, Klarer 1988). Samples collected at 8-hr intervals for several weeks in 1987 near the mouth of the Old Woman Creek Wetland, draining a 69 km^2 watershed, revealed frequent dramatic oscillations in specific conductance which resulted from the alternate movements of lake water and marsh water past the sampling point (Fig. 3). In that ongoing study, from one to three samples are being collected at both ends of this wetland three times a day year-around and at least one sample per day is being analyzed for nutrients, suspended sediment and specific conductance (also pesticides at varying intervals) in order to measure quantitatively the exchange of water and materials between the lake and wetland and the transformation, trapping and release of materials by the wetland (Krieger and Baker 1988).

In a study of the movement of nutrients through the Old Woman Creek Wetland from March to October 1983, the first storm after spring planting produced the highest nutrient concentrations recorded during the study. During late spring and again after the first storm, the concentrations of soluble reactive phosphorus and nitrite+nitrate declined to undetectable levels (<0.1 and 10 µg/L, respectively), whereas dissolved silica stabilized after the first storm near 1 mg/L. All of the nutrient concentrations increased in the marsh upstream but not downstream in response to the later storms (Krieger 1984).

Similarly, the water chemistry of Old Woman Creek Wetland was studied before, during and after three storms in April and October 1984 and May 1985 (Klarer 1988). Three patterns of chemical changes in the storm water were noted over time, as shown in Fig. 4. Turbidity was employed as a marker for storm water from the tributary. (1) It was apparent that calcium (Fig. 4), magnesium, pH, total alkalinity, sodium, specific conductance, sulfate and chloride were diluted by storm runoff water. (2) However, soluble reactive phosphorus (Fig. 4), iron, copper, zinc, potassium and ammonia, because they were strongly correlated with turbidity, were considered to be associated with the sediment fraction of storm runoff. (3) Dissolved silica, nitrate (Fig. 4) and nitrite increased following the turbidity peak of storm events and were thus considered to be associated with increased interflow (groundwater and drainage tile flow) resulting from the storm (Klarer 1988).

In the Sandusky Bay system, a factor analysis performed on the physical and chemical data for five storms from 1981 through 1983 resolved four groups of highly correlated parameters: (1) phosphorus forms, nitrite+nitrate, dissolved reactive silica, iron, and Secchi depth (negative); (2) suspended solids and turbidity, and usually distance from river mouth (negative); (3) chloride and specific conductance, and usually chlorophyll *a*; (4) dissolved oxygen, oxygen saturation, and pH. The first two groups were combined in all but the first and by far the biggest storm, and the parameters (except Secchi depth and distance) increased in association with storm water (Fig. 5). Groups 3 and 4 were sometimes combined, and the parameters usually were lower in storm water as compared to resident bay water (Fig. 5) (Richards and Baker 1985).

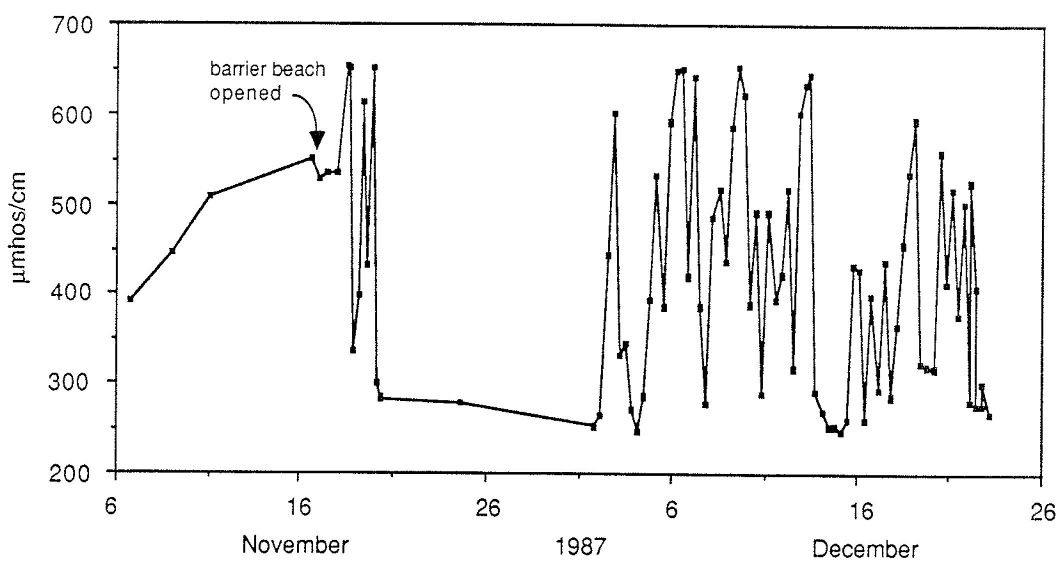

Figure 3. Oscillations in specific conductance (measured at 25°C) about 100 m upstream of the mouth of Old Woman Creek Wetland, revealing the frequent alternation of lake and marsh water masses in that region of the marsh (Krieger, unpubl.).

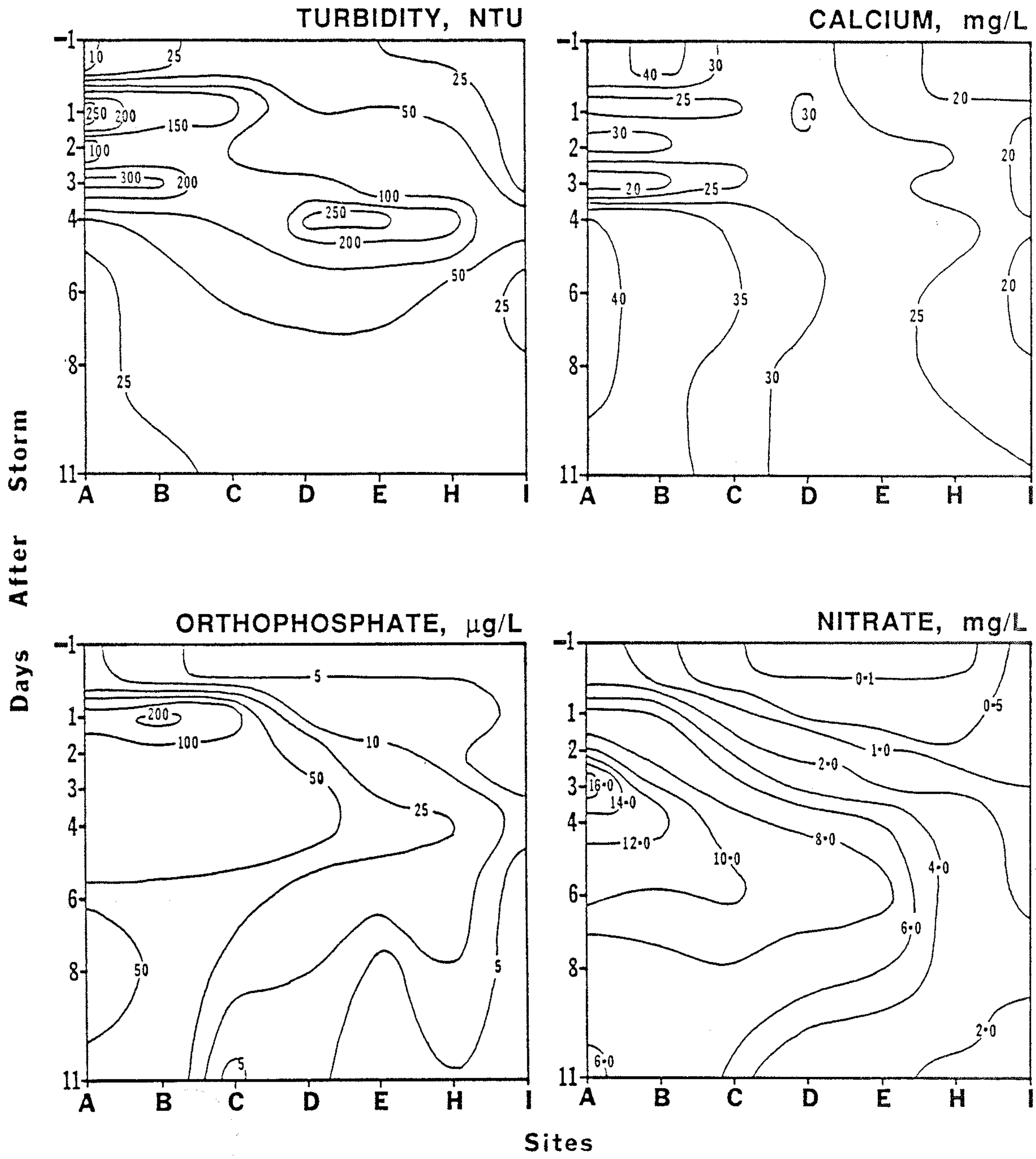

Figure 4. Temporal and spatial concentration patterns of turbidity, calcium, orthophosphate and nitrate following a May 1985 storm in the Old Woman Creek Wetland (modified from Klarer 1988). Site A is at the creek above the wetland, sites B-H are progressively downstream in the wetland, and site I is in the wave zone of Lake Erie about 100 m west of the wetland mouth.

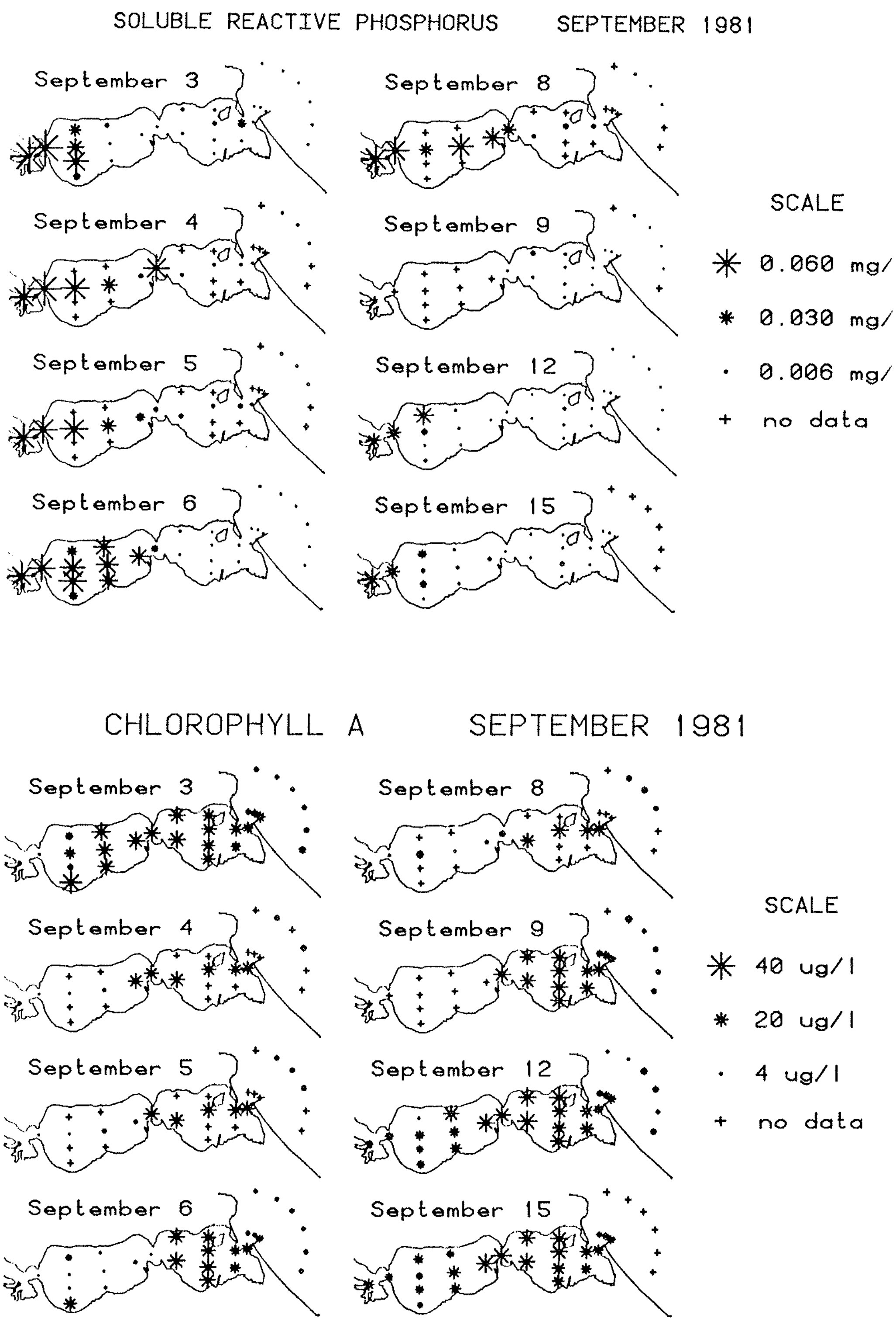

Figure 5. Concentration gradients in Sandusky Bay for soluble reactive phosphorus and chlorophyll *a* following a typical storm in September 1981 (modified from Richards and Baker 1985).

The spatial and temporal scales of the storm events in the two systems studied (Richard and Baker 1985, Klarer 1988) were near opposite extremes for Lake Erie riverine coastal systems but nevertheless those parameters which were included in both studies indicated the operation of similar processes. As might be expected the individual chemical parameters show essentially the same kinds of temporal patterns in the riverine coastal wetlands as they do in the upstream tributaries, but their concentration ranges are often narrower because of dilution of the river water by resident marsh water.

Dissolved oxygen concentrations, which can become limiting to freshwater fauna, vary widely over time and space in the few Lake Erie coastal wetlands studied (Table 2). The Old Woman Creek Wetland in the mid-1980's, when the lake was at record high levels, had mostly open water (without macrophytes) and a depth not exceeding 1.5 m except for a few locations in the stream channel where depths approached 2.5 m. One study undertaken during that period showed that dissolved oxygen declined to values below 4 mg/L on some occasions from mid-June into August in parts of the marsh, particularly in the deeper areas, when stream flow was near an annual low (Krieger 1984). A later study showed oxygen levels below 5 mg/L in October and as low as 3 mg/L in May in the same deep areas as the former study, while most of the open water areas had concentrations much higher than 5 mg/L (Klarer 1988). Heath (1987) found that during the summer, oxygen concentration was lower at a mid-marsh location than at either the inlet or outlet of the wetland, despite expectations based on increased productivity of the marsh community at that location. He noted, however, that because oxygen was measured early in the morning, the lower concentrations there may have been the result of greater nighttime respiration within the marsh community. He recorded maximum readings of 12.4-14.4 mg O_2/L at the three locations in December or April, and minimum readings of 0.0, 0.2 and 3.8 mg O_2/L between July and September. The mean values for 14 readings, 10 of which were between June and September, were 6.7-7.7 mg O_2/L, the lowest average being in the mid-marsh channel (Heath 1987). Oxygen values recorded in Big Creek Marsh, adjacent to Long Point Bay, were always above 5 mg/L when sampled in midafternoon monthly from April to November (Mudroch 1981).

Sandusky Bay (with a mean depth in the mid-1980s of about 2.6 m) had a mean dissolved oxygen concentration in 1972 and 1973 of 10.8 mg/L at the surface and 9.8 mg/L at the bottom, with a mean Secchi disk transparency of 4 cm (Lindsay 1976). In the early 1980s the mean saturation level of oxygen in the bay was 99.1%, compared with 91.7% near the surface of Lake Erie and 76.8% in storm water samples taken in the bay and lake (Richards and Baker 1985). These high mean oxygen concentrations in the bay and nearshore area of the lake are in part due to the ability of wind frequently to mix the water completely from top to bottom because of the great surface to depth ratio. The lower oxygen levels noted in the leading portion of storm water in both Sandusky Bay and Old Woman Creek Wetland (Richards and Baker 1985, Klarer 1988) were attributed to reduced algal productivity in the storm water (i.e., few algae present compared to the resident marsh or bay water) or perhaps increased biochemical oxygen demand (Klarer 1988).

Pesticide occurrences and concentrations in Lake Erie riverine coastal wetlands follow the same seasonal patterns as in the tributaries. In a study of pesticides in Old Woman Creek Wetland from March to October 1983, as noted above in Lake Erie tributaries, the first storm after spring planting (that year in June) produced the highest concentrations of herbicides throughout the marsh that were measured during the study. In part the high concentrations resulted because the large volume of the storm water replaced the resident water in the marsh, and also because the volumes of three other storms in July, August and October were so small that in those cases the storm water was trapped in the upper reaches of the wetland and did not flush it. In the same study, the five herbicides alachlor (Lasso™), atrazine (AAtrex™), linuron (Lorox™), metolachlor (Dual™) and metribuzin (Sencor™, Lexone™) attained a combined concentration of 28 µg/L (ppb), of which atrazine accounted for 11 µg/L. Atrazine and metolachlor persisted at detectable levels for the duration of the study (Krieger 1984).

A later study conducted over three years (1985-1987) showed peak concentrations of atrazine and alachlor, as well as other herbicides over five times higher than in 1983, the result of differences in storm timing, intensity and duration from year to year. The study also showed in both a lower Sandusky River marsh and Old Woman Creek Wetland that peak herbicide concentrations are very similar from the stream channel to the edge of the marsh several hundred meters away, indicating that the storm water and resident marsh water become thoroughly mixed transversely (Fig. 6). Thus, the highest concentrations are not restricted to tributary channels, and the extensive beds of emergent aquatic plants toward the marsh edges are exposed during their growing season to the highest herbicide concentrations (Krieger 1986, Krieger unpubl.).

Only recently have attempts been made to understand the functional role of Great Lakes coastal wetlands in processing sediments, nutrients and other pollutants entering them from their watersheds. Klarer (1988) estimated the role of Old Woman Creek Wetland in reducing the amounts of various chemicals delivered from the creek to the lake by computing output/input ratios from the average concentration values for each storm. The comparison was performed while acknowledging three assumptions which did not always apply: (1) that all of the storm water moved through the wetland and into Lake Erie, (2) that the storm water mass was equally sampled at all sites, and (3) that all flow through the wetland was unidirectional. Corrected to 100% chloride concentration to account for dilution of storm water in the marsh, the ratios indicated a reduction between input and output of 32%-53% of soluble reactive phosphorus entering in storms, 46%-71% of nitrate, and 44% to 54% of silicate. Some of these nutrients potentially were converted to other forms which may have then moved unmeasured into the lake.

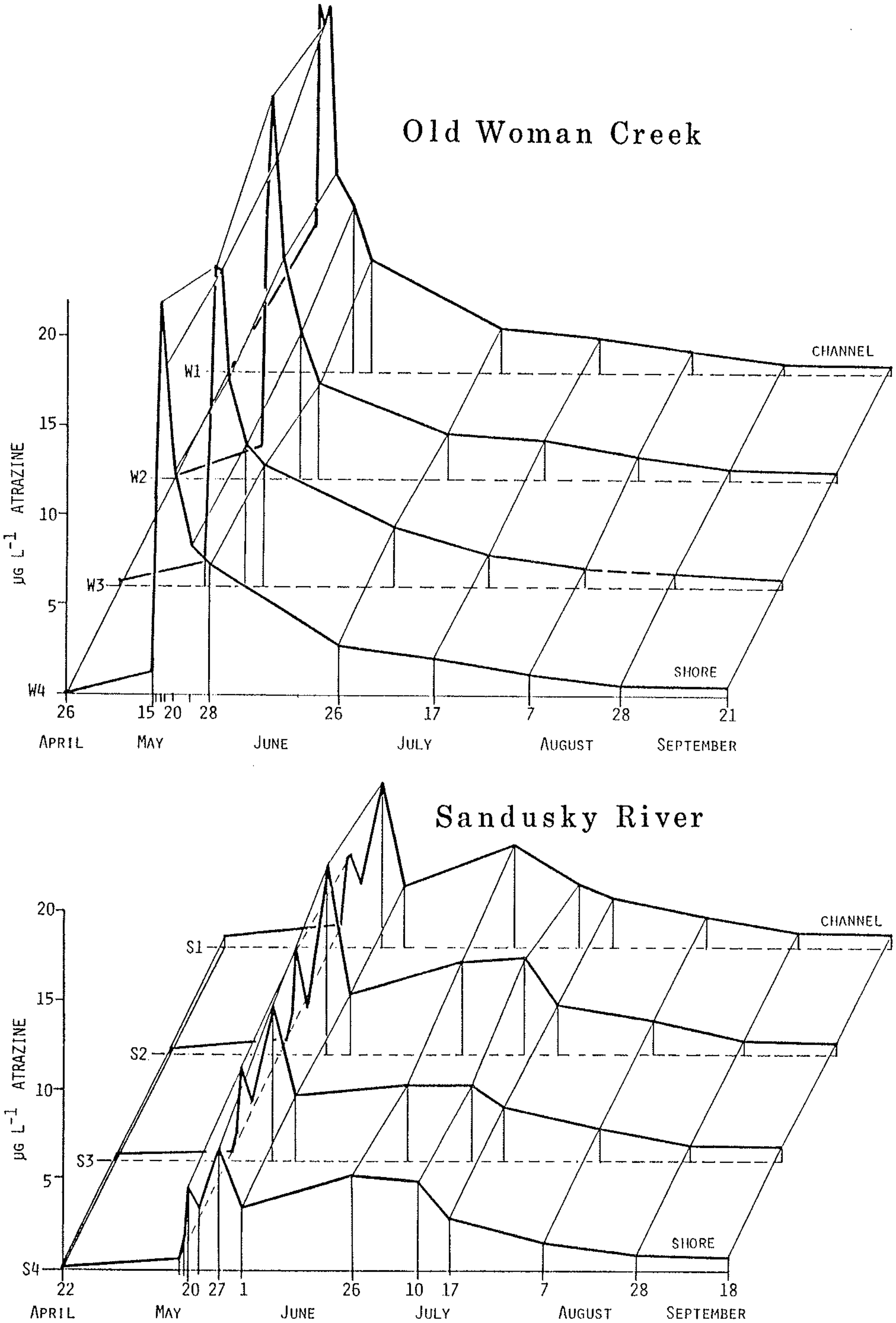

Figure 6. Changes in the concentrations of atrazine from April to September 1985 at four stations along a transect in Old Woman Creek Wetland (W1-W4) and a lower Sandusky River marsh (S1-S4). Stations W1 and S1 were in the stream channel; W4 and S4 were about 10 m from shore (Krieger 1986).

Richards and Baker (1985) estimated pollutant loadings from storms at several progressively downstream locations in Sandusky Bay. For a major (25-year recurrence) storm in June 1981, they estimated that the load of total suspended solids declined 46% between a continuously monitored discharge site on the lower Sandusky River (above lake level) and the head of Sandusky Bay. Most of the river below the discharge site is at lake level and is bordered by a narrow band of marshes and wetlands which might serve to dilute the storm water and trap or process some proportion of the pollutants. They estimated that in this river segment the total phosphorus load increased by 2%, soluble reactive phosphorus declined 43% and nitrate+nitrite declined 29%. Their calculations took into account a 42% increase in the watershed area below the monitored site, but the calculations for the bay did not account for frequent flow reversals noted at mid-bay (pers. observ.). Between the head and the middle constriction of the bay (Fig. 2), they calculated the loss of a further 38% of the original total suspended solids load as well as 74% of the total phosphorus load, 22% of soluble reactive phosphorus, and a gain of 8% in the nitrate+nitrite load. At the mouth of the bay, the original storm load as measured in the river was left with only 3% of the suspended solids, 14% of the total phosphorus, 23% of the soluble reactive phosphorus and 49% of the nitrate+nitrite, by their calculations.

The other four storms studied, all much smaller than the first, showed loads at the bay mouth which were only 1%-10% of the river load for suspended solids, 7%-24% for total phosphorus, 4%-10% for soluble reactive phosphorus, and 2%-31% for nitrate+nitrite. The decrease in loading from the river mouth to the lake was at least partly a function of storm water volume and the difference between the storm water and bay water concentrations (Richards and Baker 1985). Although the load reduction calculations were admittedly crude estimates, they served to show the effectiveness of the bay in trapping the materials transported into it via storm water.

Lake Erie riverine coastal wetlands probably serve as net sinks for sediments. Buchanan (1982) estimated from core samples that the sedimentation rate in Old Woman Creek Wetland was 0.76 mm per year prior to agricultural development at the beginning of the nineteeth century, and that the rate has increased by 13 times to about 10 mm per year at present.

Heath (1987) was the first to investigate the mechanisms of transformation of phosphorus forms in a Lake Erie riverine wetland and the transfer of phosphorus between the particulate and dissolved phases to the bacterioplankton and phytoplankton. He concluded that in Old Woman Creek Wetland, phytoplankton growth was not limited by phosphorus availability, on the basis of nutrient addition bioassays, but was probably nitrogen limited, at least in mid-summer. Furthermore, the phosphate turnover time was usually more than 20 minutes, whereas in phosphorus-limited communities it is often less than 5 minutes. He also noted that the particulate N:P ratio was less than 10 in the wetland rather than near 20 or greater as it is in phosphorus-limited systems. Whereas in phosphorus-limited communities soluble reactive phosphorus (SRP) often reaches undetectable levels (<1 µg/L), Heath (1987) found that SRP in Old Woman Creek Wetland rarely fell below 5 µg/L. This contrasts with the findings of Krieger (1984), who one year earlier had found SRP near detection limits in the wetland for most of June and occasionally in October. Klarer (1988), who sampled the same year as Heath (1987), reported that SRP was below 5 µg/L in the more downstream parts of the same wetland following an October storm whose runoff waters did not penetrate the downstream areas. Table 2 indicates that SRP in tributary systems of widely differing sizes falls below 1 µg/L and that its maximum values, and those of several other substances, are progressively less as size increases from small wetlands to large embayments to western Lake Erie. Confirmation of this apparent relationship by future values obtained from other riverine coastal wetlands would be suggestive of a progressively greater capacity to assimilate these substances in systems of increasing size, perhaps primarily through greater dilution. Nitrate shows the same relationship with size of system as SRP and total P, but the detection limit for nitrate is typically 100 times higher than for SRP. Thus, the data currently available to not permit a comparison of the lower limits of SRP and nitrate.

Based on changes noted in the distribution and metabolism of phosphorus components between upstream and downstream regions of the wetland, Heath (1987) concluded that it "greatly ameliorated" the availability of phosphorus to Lake Erie phytoplankton. The reduced availability of phosphorus was accomplished by increasing the proportions of particulate and soluble forms of phosphorus from which phosphate was only slowly released if at all. He showed that the sediments act as both a phosphorus sink (under aerobic conditions) and as a phosphorus source (under anaerobic conditions). Uptake by the sediments was shown to involve both ion-exchange sorption to surfaces and uptake by biota associated with the sediments (Heath 1987).

Mudroch (1981) assumed a complete mixing of discharged and receiving water and calculated that a complete discharge of the 850-ha Big Creek Marsh into Long Point Bay would increase the organic nitrogen concentration by 0.004 mg/L (ppm) and the total phosphorus concentration by <0.001 mg/L. This would amount to 0.017 g of total nitrogen/m^2/yr and 0.0008 g of total phosphorus/m^2/yr exported to the bay. It is unlikely, however, that these discharges occur because, as Mudroch (1981) noted, Big Creek courses along the northern border of the marsh, which has no other outlet to the bay. Thus, it is likely that most Big Creek water flows directly past the marsh and into the lake, and in the likely absence of frequent seiches or storm surges which would empty and refill the marsh, much of the marsh water probably has a residence time measurable in months rather than the 4 days assumed by Mudroch (1981). Nevertheless, as she concluded, "it is obvious that the marshes contribute very little to the nutrient loading of [Lake] Erie" (Mudroch 1981, p. 33).

Within six lower Great Lakes marshes in Canada, including Big Creek Marsh, Mudroch (1981) noted a high positive correlation between the annual loading of total N and the above-ground biomass production of *Typha latifolia* (cattail). Most of the N present in the marsh water was organic N. "All of the marshes showed a high capacity to retain nutrients and metals" (Mudroch 1981, p. 40).

Coastal marsh sediments and their chemistry probably strongly influence the marsh water chemistry. This is partly because the surface sediments in these very shallow systems are easily resuspended into the water column by wind, particularly where no emergent or floating-leaved macrophytes are present to prevent or dampen waves. Sediment resuspension permits sediment pore water, which is often anoxic (without oxygen) and contains various reduced chemical constituents, to mix with the oxygenated water column. Furthermore, fresh sediments entering the wetland serve as the vehicle for many pollutants (e.g., phosphorus, heavy metals and various persistent organics such as pesticides) adsorbed to the sediment surfaces.

The annual suspended sediment (total suspended solids) load for the Sandusky River above lake level was shown in Fig. 1. These values include the sediment resuspension from the bed surface of the finer silts and clays with the onset of rising storm flow (Baker 1988) but do not take into account the saltational, sliding or rolling downstream migration of bedload materials (Leopold et al. 1964) during freshets, which is believed to be a negligible proportion of the total sediment loading to the lake.

Frizado et al. (1986) examined the mineralogy of Old Woman Creek Wetland sediments and concluded that they most probably derived from glacial till, glacial lacustrine sediments, and soils. Because of differential transport and deposition of the source components, the surface deposit in the wetland contains fewer carbonate minerals, fewer clay minerals, and more quartz than the original source material. "After burial of the estuarine sediments, the post-burial or diagenetic processes become operative. The concentrations of most trace elements are higher in the interstitial waters than in the overlying water. Therefore, the sediments will act as a source of trace elements to the estuarine waters" (Frizado et al. 1986). These workers stopped short of measuring the actual contribution of trace elements from the sediments. They did measure several heavy metals in the sediments, which had a pH ranging from 7.0-8.7 with a maximum value within the upper 10 cm of sediment. Iron and manganese were the most abundant of the elements they analyzed in interstitial water, usually above 200 ppb. Cadmium, chromium and lead were usually below 15 ppb, cobalt usually below 30 ppb, copper below 50 ppb and nickel usually below 74 ppb. The interstitial concentrations of sodium, potassium, magnesium and calcium were very similar to the average concentration of the overlying surface water.

Big Creek Marsh was found to have "no large differences" in concentrations of magnesium, calcium, sodium, potassium, manganese and phosphorus in surface sediments except for high concentrations of calcium in an area covered by a dense growth of *Elodea*. It was surmised that the calcium may have come from calcium carbonate precipitation on the plants (Mudroch 1981). The pH in Big Creek Marsh sediments fell in a narrow range, between 6.9 and 7.0. Surface sediment concentrations of lead, copper, nickel, chromium and zinc were lower than those in the surficial sediments of Lake Erie, but elevated concentrations of arsenic and mercury were found in the part of the marsh most affected by inflow from Big Creek, which Mudroch (1981) associated with agricultural residues.

Heavy metals have been detected in the water column by the analysis of unfiltered water samples. Richards and Baker (1985) cited evidence that total iron in Sandusky Bay storm water is strongly sediment bound, but they also found evidence of a dissolved component. Copper was less strongly associated with storm runoff than iron, and it appeared to be entering the bay primarily in the spring. Other metals were rarely detected. In Old Woman Creek Wetland, Klarer (1988) noted that the concentrations of iron, copper, zinc and manganese increased at the onset of storm runoff events and then quickly declined. All of these metals appeared to be strongly associated with suspended sediment inputs as measured by turbidity.

LAKE ERIE

It is far beyond the scope of this review to address adequately the chemical limnology and contaminants of the harbors and open waters of Lake Erie. Excellent books (Rousmaniere 1979, Burns 1985) and extensive government reports (e.g., Internat. Joint Commis. 1980; Great Lakes Water Quality Board 1985, 1987; Herdendorf 1984; Lesht and Rockwell 1987) have been written which bring together an exhaustive body of scientific evidence to explain the nature and extent of the problems brought about by the nutrient enrichment of the lake from point and nonpoint sources, and by the presence of persistent toxic substances from primarily point sources. The fate, distribution and biological effects of many of the hundreds of organic chemicals now residing in the sediments or water of Lake Erie (refer to the overview in this volume by Herdendorf and Krieger) are poorly understood or are unknown, both from the standpoint of individual compounds and combinations of interacting compounds.

The problems of nutrient and toxic chemical contamination of the lake have long histories, and remedial programs were developed on a large scale in both Canada and the U.S.A. only in the late 1960s and 1970s. Progess in reducing the severity of contamination has, for most substances, been accomplished; but only through legislation and enforcement, as well as through continued scientific investigation into the sources and results of contamination, can this progress be continued and expanded. Recent trends for only two of the many problems -- annual oxygen depletion in the central basin, and persistent toxics in sediments and fish -- are briefly summarized here.

Late summer oxygen depletion to the point of anoxia in the central basin was first documented in the late 1920s and progressively became more extensive and more prolonged over the next four decades as phosphorus inputs to the lake continued unabated. Excessive bioavailable phosphorus, from the sources described earlier, permitted increasingly greater production of algae in the open lake (the phytoplankton) and along shore (see Monaco and Lorenz, this volume), accompanied by changes in algal species, filter clogging and taste and odor problems in water supplies, and increased turbidity. The increase in phytoplankton production, which can be measured chemically as chlorophyll *a* concentration (e.g., Fig. 5), permitted a large increase in the production of the zooplankton as well as a change in its composition (see Klarer, this volume), which in turn provided more food for the fish and other animals which feed on the zooplankton. The increase in algal production further led to visible "blooms" of algae from spring on into the fall each year. Mats of algae washed onto beaches in large quantities, presenting aesthetic and odor problems.

The annual spring bloom of algae was followed by a "crash" or sudden decline in the amount of algae in the lake as their nutrients (especially silica, phosphorus and nitrogen) were used up. The algal crash led to a similar crash of the zooplankton. This annual bloom-and-crash cycle provided large amounts of organic matter which settled to the lake bottom. Thus, with the continued increase in phosphorus inputs over the decades, the annual deposition of organic debris on the lake bottom increased. As these materials were decomposed by respiring microorganisms, the demand for dissolved oxygen during the summer in the lower depths of the lake increased as well. It is during the same season that thermal stratification of the lake takes place. This stratification prevents the surface water layer (the epilimnion), rich in dissolved oxygen, from mixing with and replenishing the oxygen in the layer of deeper and dark waters of the lower depths (the hypolimnion).

Once the summer stratification begins, the oxygen in the hypolimnion cannot be replenished until the fall overturn destroys the thermal structure and mixes the upper and lower water masses. For at least the past half century, all of the oxygen in part of the shallow hypolimnion of the central basin (variable from 2.7 m to 7.7 m thick, June-August; Lesht and Rockwell 1987) has been consumed by respiratory demand, leaving an anoxic area of greater or lesser extent (Fig. 7). The seasonal oxygen depletion has had a profound effect on the fish and invertebrate community structures of the central basin (see the reviews by Johnson and Klarer, this volume). Severe oxygen depletion rarely occurs in the shallow western basin because wind action in most years prevents hypolimnion development, but anoxia in that basin has been reported to have had devastating effects on the biota (Britt 1955). Anoxia has not been recorded in the open waters of the deep eastern basin, which is the least productive of the three basins and whose thick hypolimnion contains sufficient volume to meet the demands for oxygen.

Although phosphorus loading reductions to the lake have been achieved, the goal of restoring aerobic conditions in the hypolimnion of the central basin has been elusive. "Despite the documented decreases in point source phosphorus loadings to Lake Erie, oxygen depletion rates continued to increase through the 1970s and have now stabilized, fluctuating between 3.2 and 3.7 mg/L per month" (Great Lakes Water Quality Board 1987, p. 86). In 1985 the stratified period was longer than normal, with an anoxic hypolimnion

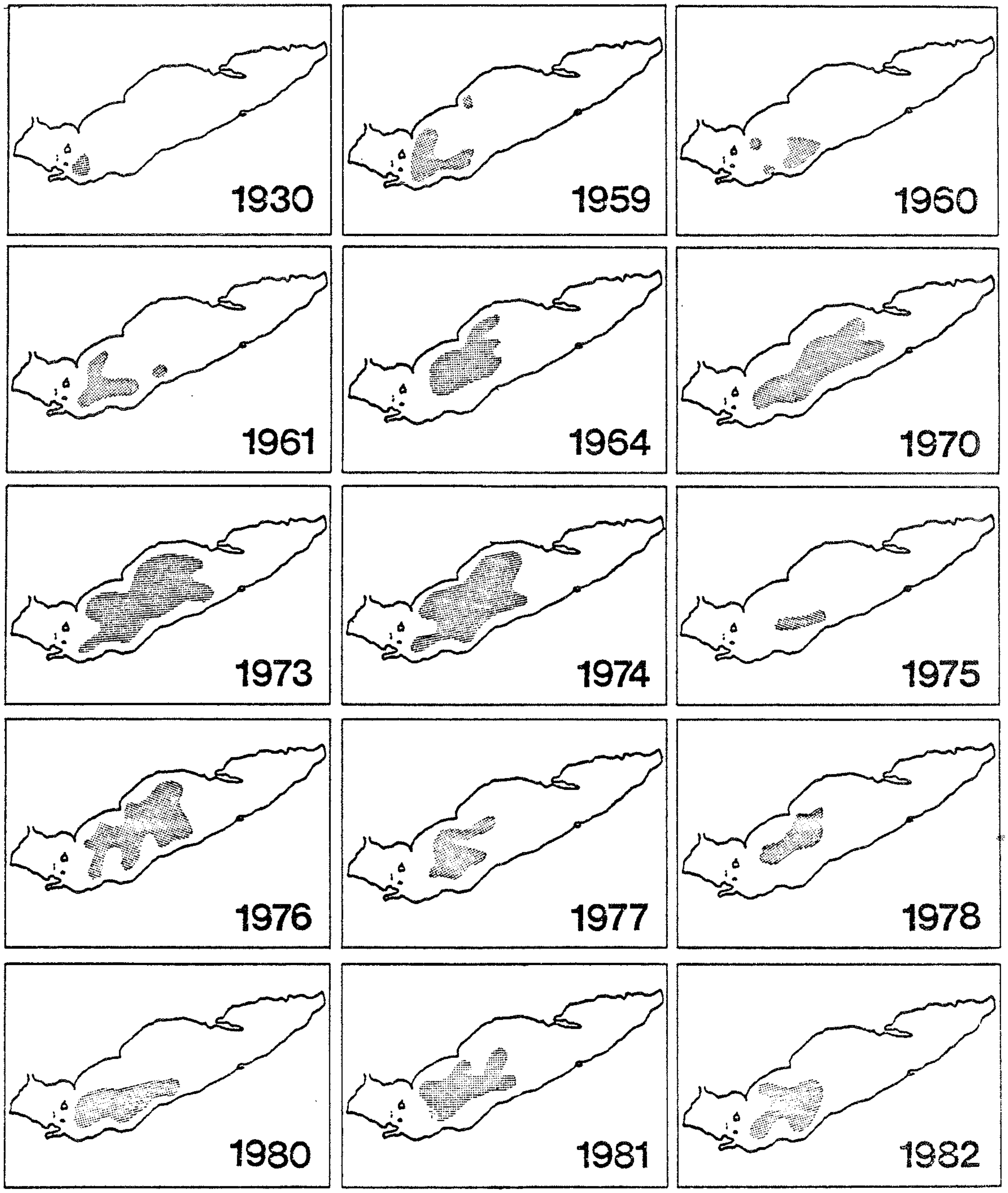

Figure 7. Areal extent of summer anoxia in the hypolimnion of the central basin of Lake Erie (Herdendorf 1984).

from late August through mid-September and a depletion rate of 3.7 mg/L per month (Great Lakes Water Quality Board 1987).

Phosphorus concentrations in the open waters of Lake Erie vary widely and have not decreased in the same proportion as the load reductions, partly because bioavailable phosphorus is released from sediments via regeneration in anoxic sediments and subsequent wave resuspension. However, evidence of slowly declining phosphorus concentrations is manifested by the large reduction in basin-wide blooms of planktonic blue-green algae in western Lake Erie as well as in reduced massive growths of attached green algae (*Cladophora*) between the mid-1960s and the present. Basin-wide blooms have been absent in recent years, and the open lake phytoplankton has decreased in abundance and reverted to a more mesotrophic species composition (Great Lakes Water Quality Board 1985).

On the basis of Secchi depth and the average total or particulate phosphorus and chlorophyll *a* concentrations in the surface waters, the trophic status has been determined for different regions of Lake Erie (Fig. 8). Most of the western basin and Sandusky Bay, Presque Isle Bay, and the southern nearshore zone of most of the central basin are classified as eutrophic, while most of the rest of the lake is considered mesotrophic. An area in the middle of the lake straddling the central and eastern basins is oligo/mesotrophic. The trophic regions shown in Fig. 8 are general and vary according to the exact classification scheme used. A discussion of the effects on classification of the seasonally dynamic variables used, and of the differences among the several indices that have been used, is found in Lesht and Rockwell (1987).

Baumann and Whittle (1988) have placed the problem of selected persistent organic contaminants in Lake Erie into perspective with the other Great Lakes in their recent compilation and interpretation of evidence collected by both the U.S. and Canadian governments. Analyses of whole-fish tissues from Lake Erie show a gradual decline between 1979 and 1985 in body burdens of DDT (dichlorodiphenyltrichloroethane), whose use was banned in both countries in 1970-1972 (Fig. 9). DDT may be approaching an equilibrium level which ". . . may be maintained primarily by inputs from sediment sinks and from airborne deposition" (Baumann and Whittle 1988).

Fish from Lake Erie have also shown a gradual decline in PCB levels since 1979 (Fig. 9). Much of the present input of PCBs to the lake is from atmospheric deposition (Baumann and Whittle 1988). Fig. 10 shows the lakewide distribution of PCBs in surface sediments in the early 1970s. In the 1980s the highest PCB concentrations are in the western basin and coincide with inputs from the Detroit River (Great Lakes Water Quality Board 1987).

PAHs (polynuclear aromatic hydrocarbons) are produced from incomplete combustion of organic matter and by a number of industrial processes. Two PAHs, fluoranthene and benzo(*a*)pyrene (B(*a*)P), are found in especially high concentrations in the sediments of the lower Black River, Cleveland Harbor, the Buffalo River and eastern Lake Erie and have been linked to carcenogenicity in

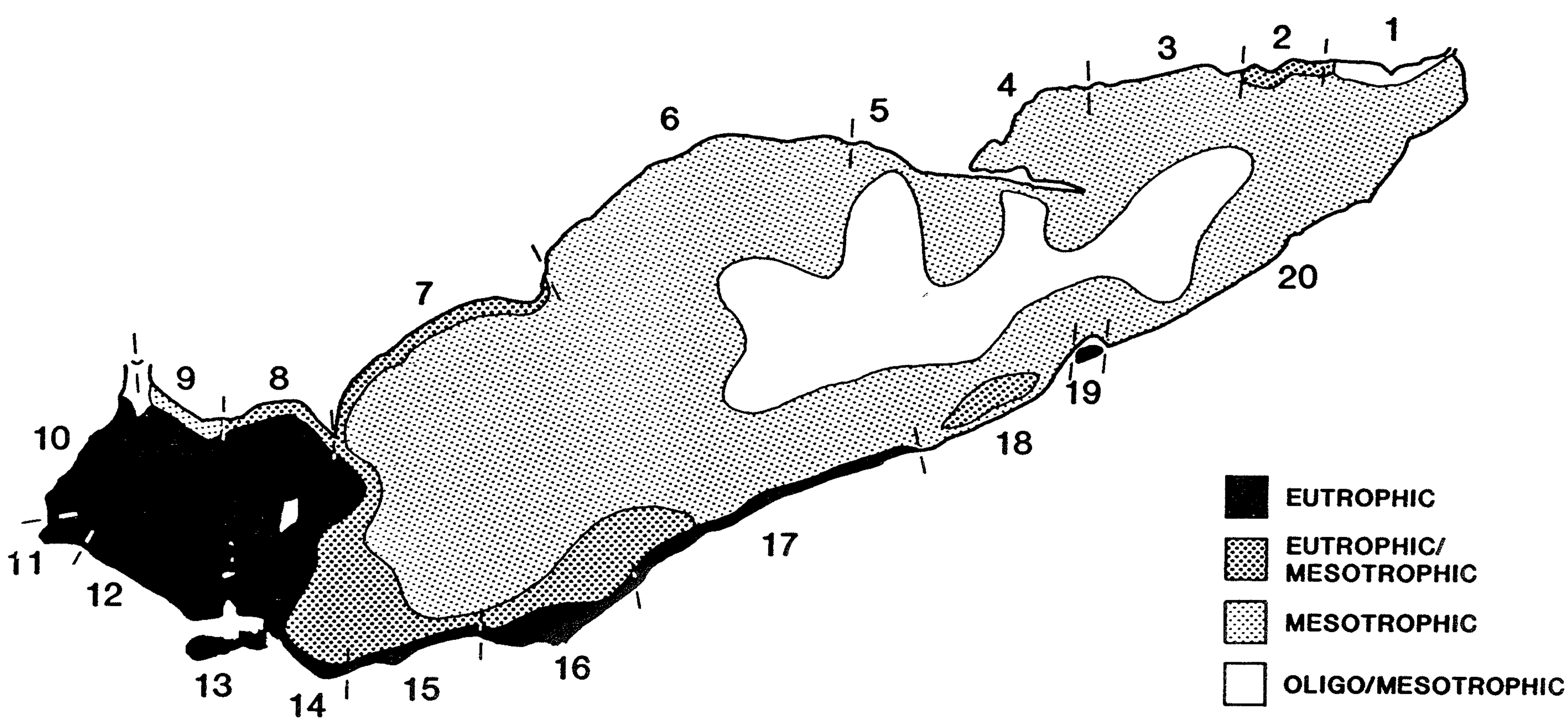

Figure 8. Trophic status of regions of Lake Erie (Herdendorf, unpubl.)

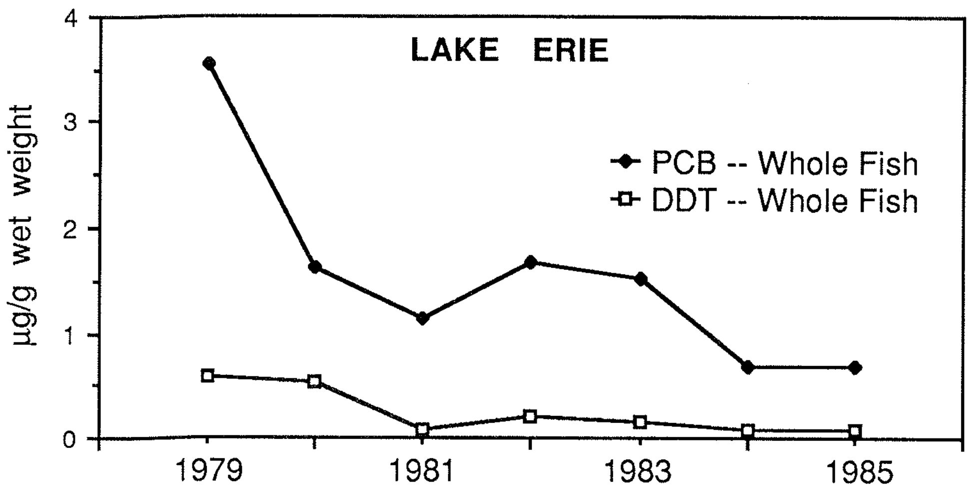

Figure 9. Trends for whole-fish tissue burdens of DDT and PCBs in Lake Erie (modified from Baumann and Whittle 1988).

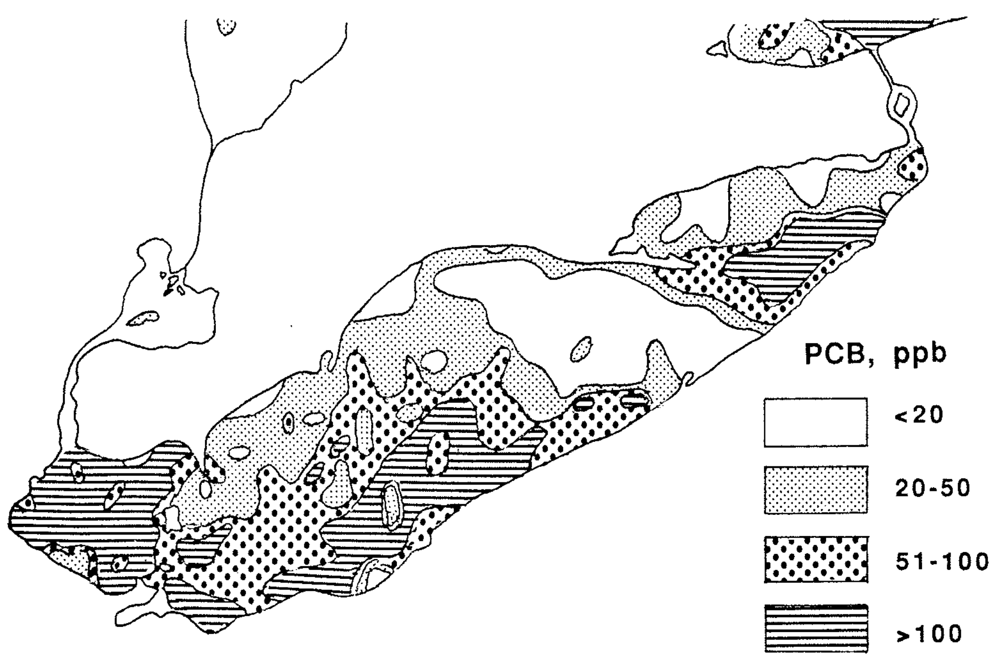

Figure 10. PCB concentrations (ppb=µg/kg) in surface sediments of lakes Erie and St. Clair and the southernmost parts of lakes Huron and Ontario in the early 1970s (PLUARG 1978).

fish. At all three of these locations where fish studies have been conducted, high frequencies of various kinds of tumors have been found in resident fish, especially bottom feeding species. Whole brown bullhead from the Black River, 84% of whose population had "either early tissue changes in the neoplastic process or more advanced lesions", contained over 1 ppm of fluoranthene and over 5 ppb of B(*a*)P (Baumann and Whittle 1988).

In summary, the pollution of Lake Erie has resulted gradually over many decades from intentional abuses as well as from an ignorance of the ecological processes operating in the lake basin. Only by determining and understanding the continuing nonpoint and point source pollution problems in the individual watersheds, the role of the coastal wetlands in ameliorating pollutants, and the ultimate response of the lake itself to various kinds of pollution, can we hope to restore the water and sediment quality of Lake Erie. Progress is being made, but many research and management needs remain. Many of the needs have been detailed in the annual reports of the International Joint Commission (e.g., PLUARG 1978, Internat. Joint Commission 1980, Great Lakes Water Quality Board 1985, 1987). The remaining Lake Erie coastal wetlands may play an important role in trapping, processing and releasing nutrients and other contaminants to the lake. This role needs to be measured quantitatively in order to understand their value as buffer zones between the tributaries and the lake. Furthermore, the transformational processes in the wetlands which are thought to be important in reducing the bioavailability of nutrients or the toxicity of persistent industrial organics to the lake biota need to be deciphered and quantified.

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PLANKTON AND MACROINVERTEBRATES

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The chemistry of water is reflected by the biotic communities living in it. The changes in the nutrient levels previously outlined by Herdendorf and Krieger (this volume) and Krieger (this volume) caused a marked change in the planktonic and benthic communities of Lake Erie.

Increased phosphorus inputs into Lake Erie have caused both an increase in phytoplankton numbers and a shift in species dominance since the early 1900's (Nicholls, 1981). Davis (1964) reported that total phytoplankton numbers have increased steadily from 1920 to 1963 based on daily phytoplankton counts performed by the Cleveland Division of Water. In addition to higher algal numbers, the annual duration of the peak periods has increased while the periods of minimum numbers have become less pronounced. The diatoms *Melosira granulata* and *Stephanodiscus* sp. dominated the late summer phytoplankton populations in the nearshore regions of Lake Erie in the early part of the century (Chandler, 1940). They have since been replaced by the blue-greens *Aphanizomenon*, *Oscillatoria*, and *Microcystis* (Kline, 1981).

The changes in the phytoplankton cited above resulted in changes in the zooplankton, since these planktonic animals utilize the phytoplankton as a food source. Total zooplankton numbers have risen over the past 50 years and there has been a marked shift in relative importance of individual species. The copepods *Acanthocyclops vernalis* and *Leptodiaptomus siciloides* and the cladoceran *Chydorus sphaericus* have exhibited sharp increases in both abundance and distribution over the last 40 years (Gannon, 1981). The large calanoid copepod *Limnocalanus macrurus*, which was quite abundant in 1929, had all but disappeared by 1968. *Limnocalanus*, a cold water species, avoided the high surface water temperatures by moving into the bottom waters during the summer months. Increased nutrient locading and the resulting anoxia in the botom waters, however, made this summer refugium uninhabitable for this species. This anoxia contributed to the decline of *Limnocalanus* (Gannon and Beeton, 1971).

The benthic fauna in the western basin during the 1930's was classified as a *Hexagenia* (Mayfly)/ *Oecetis* (Caddisfly) association (Shelford and Boesel, 1942). In 1953 the *Hexagenia* population crashed, going from 400/meter^2 in the early 1950's to 1/meter^2 in 1965 (Britt et al., 1973). *Oecetis* also showed a decline in total numbers, although it was not as dramatic. Again anoxia from accelerated eutrophication was believed largely responsible (Britt, 1955). The population in the western basin now would be considered a Tubificidae/

Chironomidae association. During the last 30-40 years pollution tolerant species have increased in importance in Lake Erie. Tubificid worms have increased ten-fold (Pliodzinskas, 1978), chironomid larvae four-fold, and Sphaeriidae (fingernail clams) two-fold in the western basin of the lake (Carr and Hiltunen, 1965). The tubificid *Branchiura sowerbyi,* a pollution tolerant species, was first reported in the Lake Erie watershed in 1947 in the Portage River and by 1959 was well established in the western basin of the lake (Britt et al., 1973). Pollution sensitive species in the amphipods, caddisflies, and naiad clams have become more restricted in their range in Lake Erie and their population numbers greatly reduced during the same period (Carr and Hiltunen, 1965). The estuarine areas of the Maumee, Raisin, and Detroit Rivers and the adjacent areas of nearshore Lake Erie were polluted prior to 1929 (Wright et al., 1955). These areas had benthic faunas in the 1920's dominated by the tubificid worms and chironomid larvae which today are the major groups found throughout the western basin of Lake Erie (Carr and Hiltunen, 1965).

Drs. Herdendorf (this volume) and Krieger (this volume) have described the distinctive geological and chemical features of freshwater estuaries. Early work on the phytoplankton of the estuarine portions of rivers, however, has suggested that these populations were of lake origin (Sullivan, 1953). The origins of the zooplankton found in these estuarine areas have not been addressed. The purpose of this paper is to investigate whether the planktonic communities in estuarine areas are merely an extension of lake populations, or if they are unique and controlled by factors other than those regulating lake populations. If the estuarine populations are unique, then it adds evidence for defining the estuarine portions of rivers draining into the Great Lakes as distinctive habitiats and worthy of study in their own right.

Studies on the benthic macroinvertebrate communities in river mouth areas have concentrated on their roles as pollution indicators (e.g. Brown, 1953), but have not compared the estuarine and nearshore lake benthic communities. A second goal of this paper is to determine if there are similarities between the benthic macroinvertebrates in the estuaries and in the nearshore zone of Lake Erie.

Information on the benthic macroinvertebrates of the estuarine areas of Lake Erie is very limited (Table 1). A survey of the nearshore zone of Lake Erie during 1978-79 revealed a community dominated by tubificid worms, chironomid larvae, and sphaeriid clams (Krieger, 1981). Other studies on the benthic fauna in the central and western basins of Lake Erie have reported similar results. The few studies undertaken on estuarine faunas have found a similar pattern, although the relative proportion of the chironomid larvae is greater and the proportion of the sphaeriid clams is smaller. In the Old Woman Creek estuary the filter feeding sphaeriid clams were not reported. This is probably due to lack of a suitable substrate. Rhodes and Young (1970) reported that high densities of deposit feeders (such as tubificid worms) rework the sediment surface, making it less suitable for filter feeders. Cones (1976) reported that the filter feeding sphaeriid clams were observed most frequently in sandy areas where deposit feeders were less dominant. In the Old Woman Creek estuary the bottom substrate is almost exclusively silt-clay and is very

Table 1. Relative composition of benthic macroinvertebrates at selected sites in the Lake Erie Basin.

Site	Oligochaeta Tubificidae	Diptera Chironomidae	Mollusca Sphaeriidae	Diptera Ceratopogonidae	Diptera Chaoboridae	Bryozoa
Lake Erie, Nearshore Central Basin 1979 (Krieger 1981)	Dominant	Common	Common	Not Observed*	Not Observed	Not Observed
Lake Erie, Nearshore Western Basin 1979 (Ontario Min. Environ. as cited in Steane and Cooper 1981)	Dominant	Common	Common	Not Observed*	Not Observed	Not Observed
Lake Erie, Western and Central Basins 1974 (Britt et al. 1980)	Dominant	Common	Common	Not Observed	Not Observed	Not Observed
Lake Erie, Nearshore Western Basin-Locust Point 1972-1974 (Cones 1976)	Dominant	Common	Present	Not Observed	Not Observed	Not Observed
Sandusky Bay 1972-1974 (Lindsay 1976)	Dominant	Dominant	Present	Present	Present	Present
Old Woman Creek 1983	Dominant	Dominant	Not Observed	Present	Present	Present
Turtle Creek 1985 (O.D.O.T. 1987)	Dominant	Dominant	Present	Not Observed	Present	Not Observed
Toussaint River 1985 (O.D.O.T. 1987)	Dominant	Dominant	Present	Not Observed	Present	Present

Dominant = Greater than 30% of population
Common = Between 10 and 30% of population
Present = Less than 10% of population
Not Observed = Not reported in study cited

* Barton and Hynes (1978) report Ceratopogonidae in the Lake Erie wave-zone.

flocculent. This substrate coupled with the dominance of the deposit feeders would certainly seem to preclude the sphaeriid clams.

Although the dominant organisms are similar at both lake and estuarine sites, there are some marked differences in the benthic fauna. The biting midges, Family Ceratopogonidae, were found in the estuarine areas and not in the open lake. However, Barton and Hynes (1978) reported that these organisms were found infrequently (less than 10% of the samples) in the wave-zone (shallower than 2 meters) of the lake. *Chaoborus*, in the Family Chaoboridae, was also reported from estuarine areas while it was not reported from the open lake, even in the wave zone. Carr and Hiltunen (1965) reported that several *Chaoborus* were found in the western basin of Lake Erie at stations immediately lakeward of the Maumee River mouth. The location of these stations coupled with the total absence of *Chaoborus* from all others sites in the western basin suggest that these organisms may have been carried into the lake from the Maumee River. Finally bryozoans have been routinely observed in the estuarine areas while they have not been reported from Lake Erie proper. Pennak (1978) characterized this group as preferring relatively unpolluted backwater areas, with little or no water movement. They grow attached to sunken logs, rocks, or vegetation. They are found scattered throughout Old Woman Creek estuary during the late summer months. The high turbulence in Lake Erie would exclude this group from the open lake.

From the benthic macroinvertebrates it appears that although the communities are similar, there are distinct differences in species composition. Further study is necessary to determine if this is universal in estuarine areas along Lake Erie, or if this is just an artifact from sampling only four relatively natural estuaries.

Lake Erie phytoplankton have a bimodal distribution pattern with peaks in late winter / spring and in late summer / early autumn (Kline, 1981). The first peak is dominated by diatoms, first the pennates *Fragilaria*, *Diatoma,* and *Asterionella* (Hohn, 1969), and then the centrics *Stephanodiscus* and *Skeletonema* (Kline, 1981). The blue-greens *Aphanizomenon* and *Microcystis* are the major algae during the second peak (Kline, 1981).

The pattern shown in the Old Woman Creek estuary during 1980 was noticeably different (Fig.1) (Klarer, 1983). There was no winter peak. This, however, may reflect more the shallowness of the estuary, since in many areas, ice formation extended through the water column into the sediments. Immediately after ice break-up there was a marked rise in population numbers. The peak was most evident at the mouth, where the resident dominant *Cyclotella* was augmented with an influx of lake species, primarily *Fragilaria* and *Asterionella.* The latter two genera were not common further back in the estuary. A second peak in May and early June was dominated by *Cyclotella* and the chrysophyte *Cryptomonas*. The diatoms *Cyclotella*, *Nitzschia*, and *Melosira* successively dominated the estuarine flora during the third peak in July. The final peak occurred in October / November when the mouth was closed and the estuary was isolated from Lake Erie by the formation of a barrier

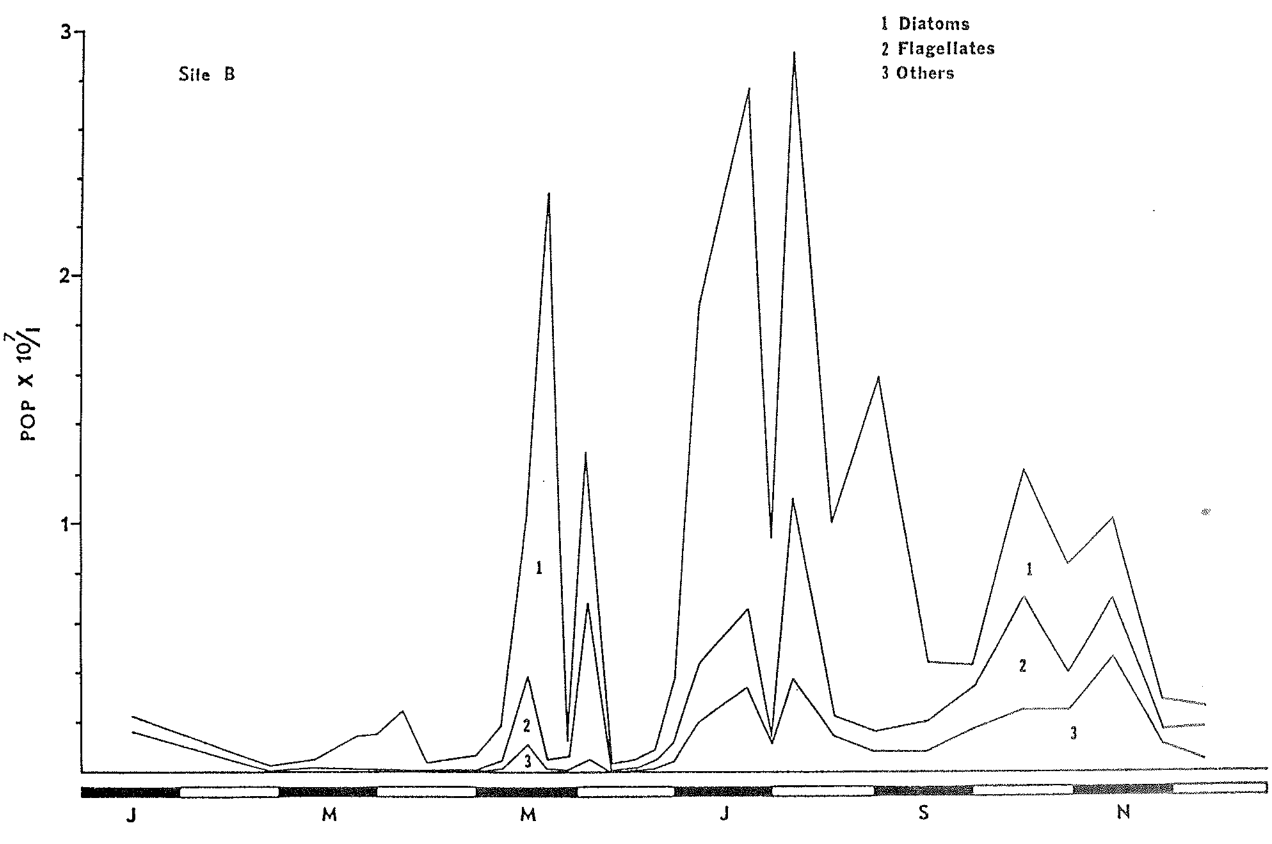

Figure 1. Seasonal population numbers of the phytoplankton in Old Woman Creek estuary during 1980. (from Klarer, 1983)

beach. The flora was dominated by the diatom *Melosira*, the chrysophyte *Cryptomonas*, and the blue-green *Gomphosphaeria*.

The sharp decline in population numbers corresponded to increased turbidity levels (Fig. 2) suggesting that storm events were flushing the estuarine algae into Lake Erie. During June turbidity levels were high and algal populations were low, again suggesting that storm events were a major factor in controlling phytoplankton populations in Old Woman Creek estuary.

Because of these initial findings, a study on the role of storm events in controlling phytoplankton populations was undertaken in 1985. The preliminary data analysis confirms the role of storm events in regulating phytoplankton numbers (Fig. 3). Total algal numbers declined with increasing turbidity, as was predicted from the earlier work. The sharp rise in population numbers following the storm is interesting and not unexpected. With the influx of storm water comes an influx of nutrients (Klarer, 1988). This nutrient rich environment would allow the population to increase faster than under pre-storm conditions, when nutrient levels were lower.

The flora in the estuary was distinctly different from the algal flora in Lake Erie. Although many species were found in both areas, Klarer (1985) reported 49 new records for the Lake Erie basin out of a total of 363 species identified in Old Woman Creek. Even with algal species that were found in both the estuary and the lake, the relative importance of the species in each area was different. The dominant lake species, when present in the estuary, were largely confined to the mouth portions of the estuary. *Stephanodiscus binderanus* seemed to be a good indicator of lake water influx into the estuary because it was not observed in the estuary during periods when the mouth was closed and the estuary was isolated from the lake. It was most frequently observed at the mouth site, and was never found in a site removed from the lake when it was not present in much greater numbers at the mouth. The blue-green dominants of the lake, *Aphanizomenon* and *Microcystis* were only infrequently recorded in the estuary. The estuarine dominants were largely confined to tributary mouths or the very nearshore zone of Lake Erie (Kline, 1981). The only exceptions were *Cryptomonas erosa* and *Rhodomonas minuta*, which seemed to be found lake wide (Munawar and Munawar, 1976).

A plankton study in Sandusky Bay during 1973-1974 (Herdendorf, 1975) presents a different picture. Here the seasonal pattern was more similar to that reported in the open lake. Three peaks were observed in Sandusky Bay, April, July, and October. *Aphanizomenon* dominate the latter two peaks, while *Skeletonema* and *Melosira* dominated the April peak. *Asterionella* and *Diatoma* were also very important components of the algal flora of Sandusky Bay. This similarity may be quite misleading. The dominant algae reported during the 1973-74 study period were the same as those reported by Chandler and Bodenlos in a 1938 study. It appears that except for a decline in *Scenedesmus*, the phytoplankton has not changed over a nearly 40 year period. Based on these phytoplankton similarities it could be suggested that the environmental conditions of Sandusky Bay have not changed greatly over this time. During the same period, the lake phytoplankton have undergone

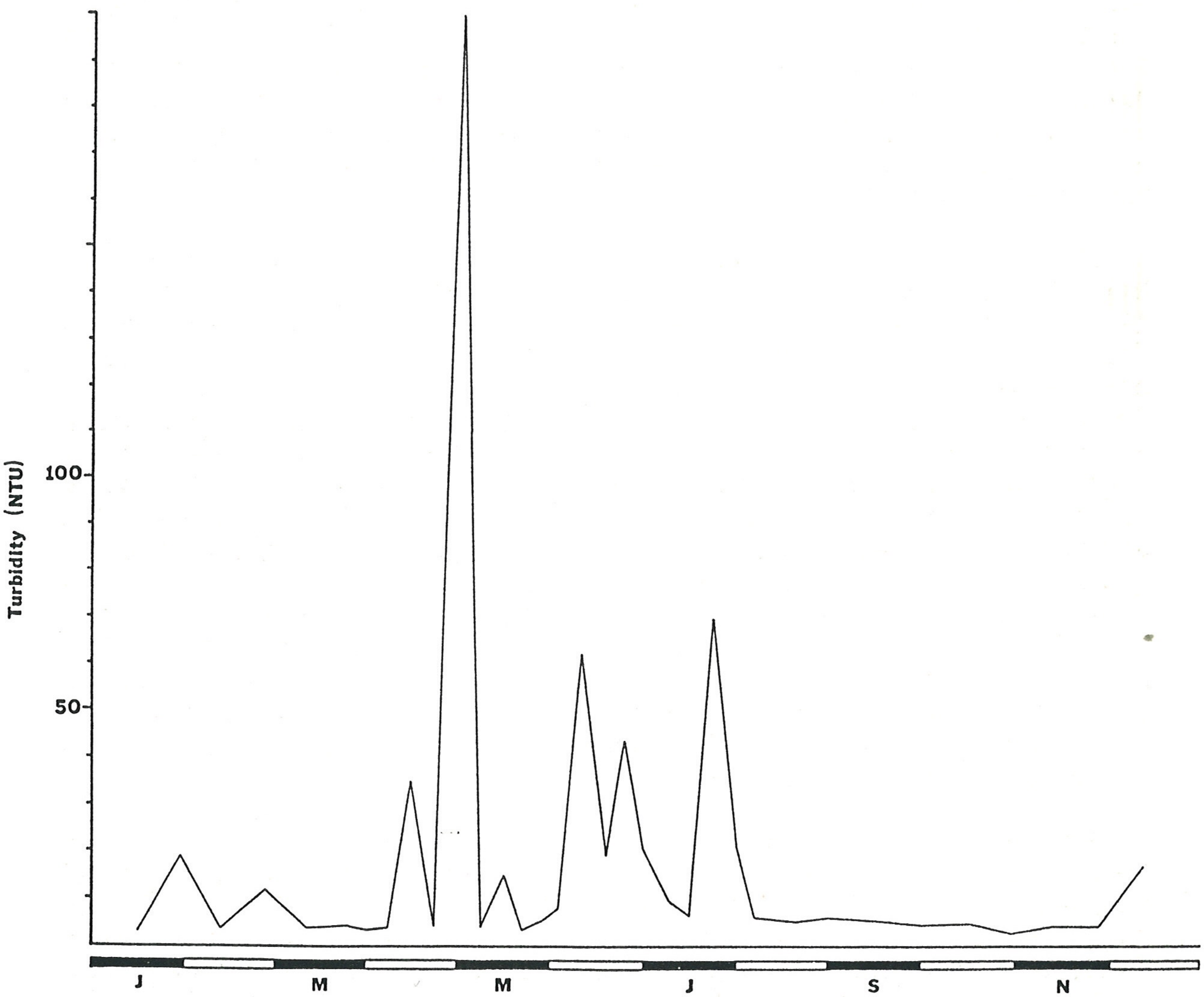

Figure 2. Seasonal pattern of turbidity (measured in NTU's) in Old Woman Creek estuary during 1980. (from Klarer, 1983)

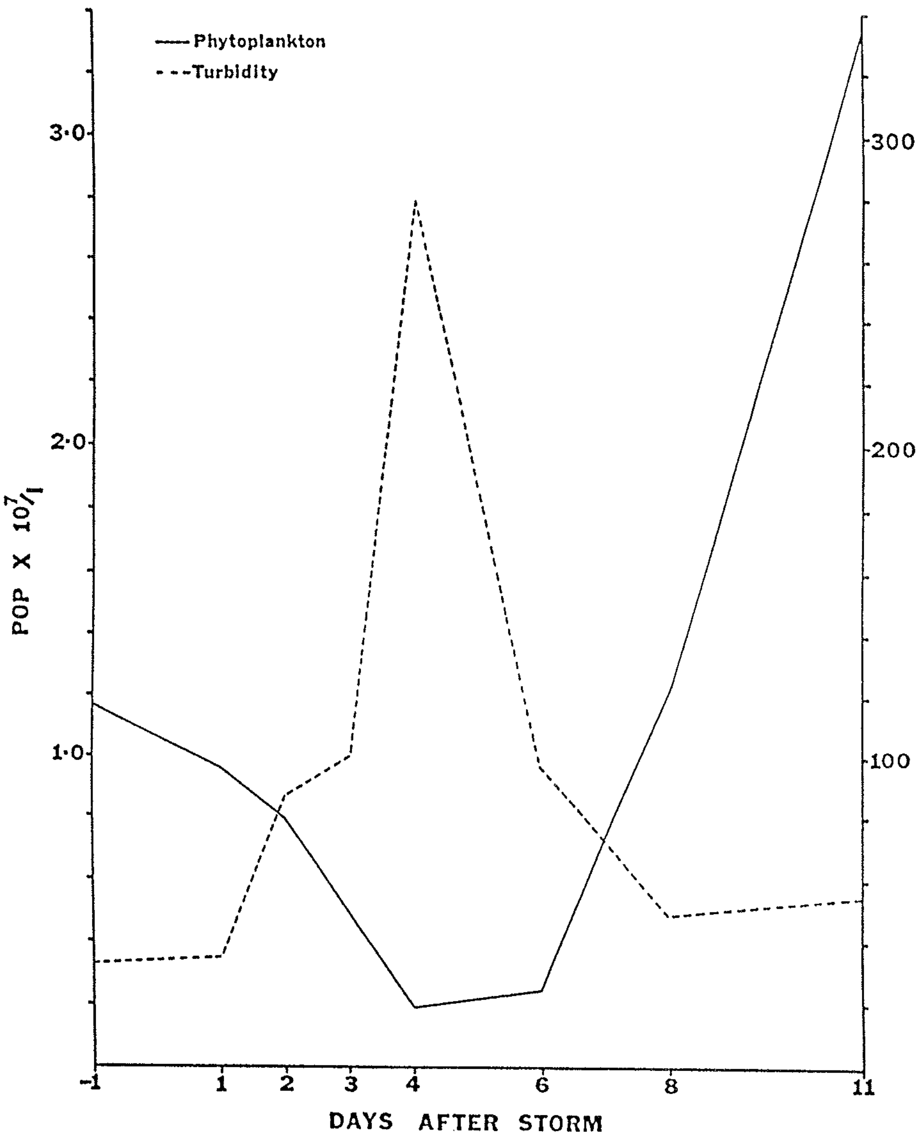

Figure 3. Changes in phytoplankton population numbers and turbidity (measured in NTU's) following a storm event in May, 1985.

major changes. This implies that Sandusky Bay is not just an extension of Lake Erie, but supports a biota distinct from that of the lake.

Although both Sandusky Bay and the downstream portions of Old Woman Creek can be considered estuaries, they each have distinctly different phytoplankton populations. A major cause of this dissimilarity is the infrequency of storms large enough to flush Sandusky Bay (Richards and Baker, 1985). The storm flushing which seems to regulate phytoplankton in Old Woman Creek is not a major factor in Sandusky Bay. Further studies of other estuarine areas may help elucidate the factors that control plankton population numbers and succession in estuarine areas.

Little is known of the zooplankton community structure or dynamics in the estuaries and coastal wetlands adjoining Lake Erie. Krieger (1985) examined the zooplankton community of Old Woman Creek estuary and determined that this community was distinctly different from the community in the adjacent Lake Erie wave zone. These two communities had different species compositions as well as different distribution patterns by common species. The population at the mouth was a transitional community with shared species from both the lake and estuary.

The estuary was dominated by the cyclopoid copepods *Acanthocyclops vernalis* and *Tropocyclops prasinus mexicanus* and the cladoceran *Diaphanosoma birgei.* All of these species were recorded from the wave zone, but in much reduced numbers. At the mouth and in the wave zone of Lake Erie, *Diacyclops thomasi* was an early summer dominant. This species was also found in the estuary, but at much lower numbers and with a more restricted seasonal distribution pattern. Other lake species recorded in the estuary in reduced numbers included the calanoid copepod *Eurytemora affinis*, and the cladocerans *Chydorus* sp., *Daphnia galeata mendotae*, *Eubosmina coregoni*, and the mucronate Bosminidae. The calanoid *Skistodiaptomus pallidus* and the cladoceran *Moina micrura* were not recorded in the wave zone, although both were frequently reported in the estuary.

The rotifer populations have only briefly been examined in Old Woman Creek estuary. There are also marked differences between the estuary and lake populations. In the estuary *Brachionus* spp. are very important during the summer months, while in Lake Erie *Conochilus* is the dominant genus and *Brachionus* is only infrequently observed. During the summer months *Polyarthra* sp. is important in both areas.

In addition to determination of seasonal patterns Krieger (1985) examined the role of a storm event in regulating population numbers (Fig. 4). Like the phytoplankton, zooplankton numbers dropped following the storm event. However, the marked rise in population numbers following the storm that was observed in the phytoplankton was not observed in this community. This may reflect the longer generation time of the zooplankton. Immediately following the storm event the population numbers of the wave zone zooplankton rose. This rise was apparently caused by the wash-in from the estuary as population levels of *Acanthocyclops*, *Tropocyclops*, and *Diaphanosoma* rose in the wave

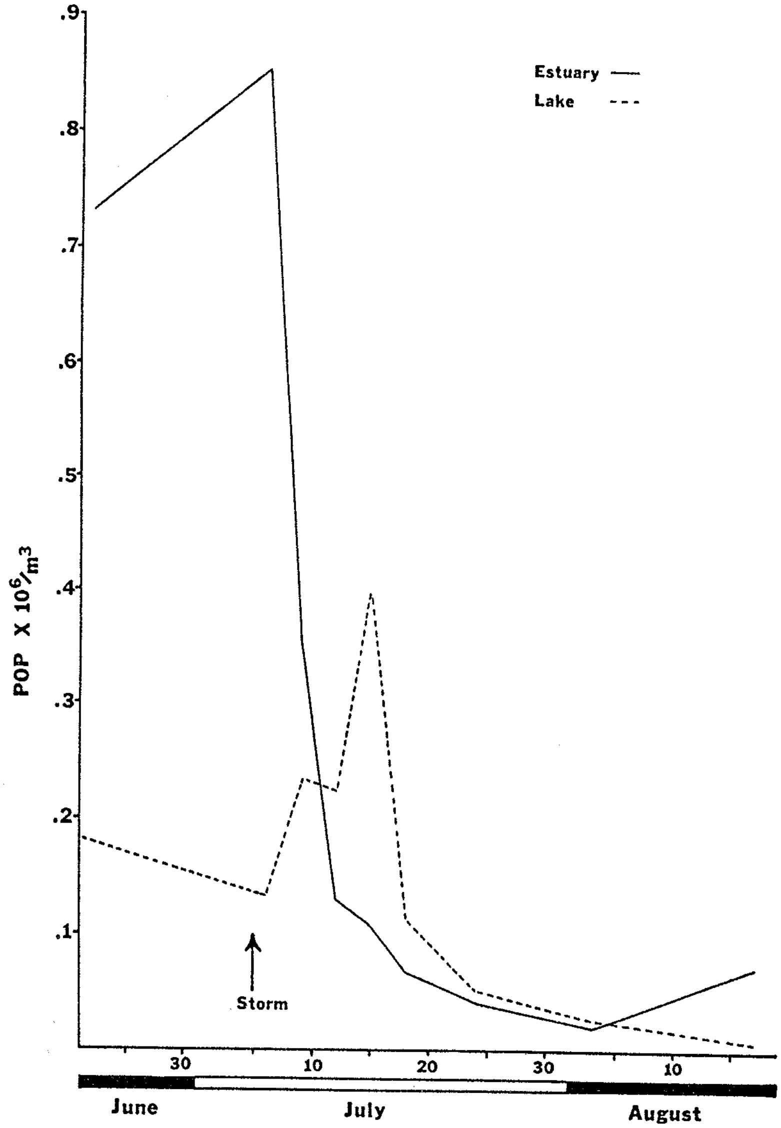

Figure 4. Changes in zooplankton population numbers in Old Woman Creek estuary and the adjacent nearshore zone of Lake Erie following a storm event in July 1984. (From Krieger, 1985)

zone. All three genera were dominant in the estuary immediately prior to the storm. Although population numbers decreased sharply in the estuary following the storm, there was no marked change in relative species abundance.

The available data suggest that the estuarine areas are unique and distinct from Lake Erie proper. Although the macroinvertebrate populations seem to be quite similar in both the lake and estuary, certain groups, particularly the Chaoboridae and the Bryozoa seem to be confined to estuarine areas. Both the phytoplankton and zooplankton populations are distinct from their lake counterparts. However, the information is particularly sparse and further work is necessary. In addition, comparative studies between these estuaries and other Lake Erie coastal marsh types must also be addressed before the freshwater estuarine system can be properly defined.

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THE GROWTH DYNAMICS AND ECOLOGY OF THE MAJOR LITTORAL ALGAE OF LAKE ERIE

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INTRODUCTION

The littoral zone of Lake Erie forms an interface between the land and open water. This area is an important component of the Lake ecosystem due to its dynamic community structure and associated high productivity. The most conspicuous organisms found on the rocky substrates and structures are the attached macroscopic filamentous algae. The three dominant epilithic algae with respect to biomass are *Cladophora glomerata* (L.) Kutz, *Ulothrix zonata* (Weber and Mohr) Kutz, and *Bangia atropurpurea* (Roch) Ag. The areal, vertical and seasonal distribution of these algae is an interest to ecologists and managers.

The purpose of this paper is to provide an overview of the distributions and interspecific ecology of these algae. Although all three species may be found throughout the Lake Erie basin most of the information presented focuses on western Lake Erie where the largest extent of colonizable bedrock substrate exists. A much larger amount of information is presented for *Cladophora* because it is the most studied and the most abundant of the major filamentous algae colonizing the rocky shores of the lower four Great Lakes (Lorenz and Monaco, In Press).

The information presented draws from six years of field studies and laboratory experiments conducted by the authors and from the studies of numerous other investigators. Our work was based out of the Ohio State University's Stone Laboratory located on South Bass Island in western Lake Erie. In addition, the facilities and support of the Center for Lake Erie Area Research and the Ohio Sea Grant Program enabled this work to be conducted.

Previous studies of the littoral algae in the Island Region include the distributional surveys of Pieters (1901), Tiffany (1937), and Taft and Taft (1971); the work on photosynthesis of McMillian and Verduin (1953); and the comprehensive study of Taft and Kishler (1973). Recently, distributional and ecological investigations of the filamentous algae have been performed by Lorenz (1981), Monaco (1985), and Lorenz and Monaco (In Press). Studies in the Great Lakes on the nutrient requirements of *Cladophora* have been by Gerloff and Fitzgerald (1976), Lin (1977), Mantai (1978) and Auer and Canale (1980, 1982 a, b). The influence of light and temperature on photosynthesis has been reported by Storr and Sweeney (1971), Wood (1975), and Graham et al. (1982). The general ecology of *Cladophora* has been discussed by Bellis and McLarty (1967), Herbst (1969) and Shear and Konasewich (1975). The distribution of *Ulothrix* in the Great Lakes has been studied by Herbst (1969), Moore (1978), Garwood (1979), Parker (1979) and Kirby and Dunford (1981). Recent investigations have explored the influence of phosphorus, light and temperature on the distribution of *Ulothrix* (Parker and Drown 1982, Auer et al. 1983, and Graham et al. 1982). Reports on *Bangia* in the Great Lakes include Kishler and Taft (1970), Breyman (1974), Lin and Blum (1977), Garwood (1982), Sheath and Cole (1980), Blum (1982), and Lowe et al. (1982). A special issue of the *Journal of Great Lakes Research* (8: 1982) contains the largest collection of literature on the littoral algae.

HISTORICAL PERSPECTIVE

Prior to the late 1960's, the attached algal communities of the littoral zone were characterized by a brief annual dominance by *Ulothrix* during the early spring and then by *Cladophora* the remainder of the growing season (Garwood, 1982). *Bangia* is a recent invader from marine environment into the Great Lakes (Kishler and Taft 1970, Damann 1979). Presently, all three algae are widely distributed in the lower four Great Lakes.

Historically, *Cladophora* has been the most abundant of the major filamentous algae in Lake Erie. The prolific growth of this alga results in standing crops of 100-300 g dry weight/m^2 of substrate, with a maximum filament length of approximately one meter (Lorenz and Herdendorf 1982, Monaco 1985). The dislodgement of filaments and subsequent deposition of large windrows of algae on the shoreline has resulted in nuisance conditions. However, *Cladophora* plays an important role in the ecology of the nearshore region by supporting diverse and abundant populations of epiphytes and browsing organisms (Lorenz 1981, Lowe et al. 1982).

Cladophora has been present in the Laurentian Great Lakes since the earliest recorded information (Bailey, 1847). The distribution of *Cladophora* in Lakes Huron and Michigan has been shown to be controlled by phosphorus levels and its abundance has increased in response to cultural eutrophication (Auer et al., 1982). In Lake Erie, *Cladophora* is only nutrient limited in the eastern basin (Millner et al., 1982). Phosphorus is not limiting to *Cladophora* growth in the central and western portions of Lake Erie, nor in Lake Ontario (Lorenz 1981, Polcyn 1973).

Early records from western Lake Erie indicate that present day distribution of *Cladophora* is similar to the distribution reported in the late 1800's to early 1900's (Wood 1872, Pieters 1901, Taft and Kishler, 1973). The impression received from talking with lifetime residents along the Lake Erie shoreline is that abundance of the "moss" may have reached peak levels between the mid 1940's to the mid 1960's. Present day abundance is reported not to be as "bad" as it was a few decades ago. These observations are generally based on shoreline accumulations that can be influenced by current and wind patterns as well as actual abundance.

Ulothrix is a common alga that occurs within all five of the Great Lakes. It is the dominant littoral alga in Lake Superior. The slick, slimy feeling filaments of *Ulothrix* are unbranched and much smaller than *Cladophora*. Filament lengths normally are not greater than four cm in Lake Erie. *Ulothrix* generally grows throughout western Lake Erie in the same areas that support *Cladophora*.

Bangia was first observed in Lake Erie at Buffalo Harbor in 1964 (Lin and Blum, 1977). The geographical distribution of *Bangia* extended to the Island Region by 1969 (Kishler and Taft, 1970). *Bangia* is now present throughout Lake Erie, and has been observed to be increasing in distribution in all of the Great Lakes except Lake Superior where no populations have been observed (Sheath and Cole, 1980). The alga's reddish-brown color is due to the presence of the photosynthetic pigment phycoerythrin. Filaments of *Bangia* are unbranched and average four to six cm, with a maximum of 12 cm.

It is theorized that *Bangia* migrated into the Great Lakes from the intertidal region of the Atlantic Ocean via the St. Lawrence Seaway (Lin and Blum 1977), Garwood 1979, Graham 1982). The work of Geesink (1973) and Sheath and Cole (1980) have shown that the marine species *Bangia fuscopurpurea* and the freshwater species *Bangia atropurpurea* are both adaptable to either a freshwater or marine environment. Breyman (1974) suggested that the increasing salinity (as total dissolved solids) of the Great Lakes, particularly along the shorelines and harbors, may have contributed to the establishment of *Bangia*. The invasion of other halophilic organisms into the Great Lakes may occur if the chemical composition of the nearshore region continues to increase in halides (Beeton 1961, Lin and Blum 1977).

Recent evidence indicates that *Bangia* is not the only filamentous alga to invade the Great Lakes shores from the marine environment. Ultrastructural studies on mitotic divisions, reproductive cells, and habitat preference all suggest that *Cladophora* and *Ulothrix zonata* invaded from the marine environment many years ago (Graham, 1982). Ultrastructural studies have shown that *Cladophora* and *Ulothrix zonata* are in the Ulvaphyceae and are much more phylogenetically similar that previously thought (Sluiman et al. 1980, Hoops et al. 1982, Floyd et al. 1985). This phylogenetic relationship of *Ulothrix zonata* and *Cladophora* may explain the similar habitat preference of the two species and why *Ulothrix zonata* distribution is different from other freshwater *Ulothrix* species.

AREAL DISTRIBUTION

Field surveys over a large portion of western Lake Erie were conducted to provide a comprehensive data base on the areal and vertical distribution of *Cladophora* during the peak biomass periods in late June of 1981, 1982, and 1983. The presence or absence of *Ulothrix* and *Bangia* was also recorded. Twenty-five sites were investigated that consisted mostly of bedrock and included shoreline areas, island shelves, and submerged reefs.

In western Lake Erie only three percent of the lake bottom provides adequate substrate for the epilithic algae, with largest extent of colonizable area in the Island Region (Verber, 1957). Much of the western basin shoreline in the United States portion of Lake Erie is low-lying, consisting of unconsolidated sediments and the Canadian shoreline has steep erodable bluffs. Colonizable substrates include exposed bedrock and cobbles which occur along most of the island shorelines. Many of the islands have steep vertical bedrock shorelines to the west and gently sloping shelves on their eastern shores. Suitable substrate is also available on the isolated peaks of open-lake bedrock reefs.

Cladophora, *Ulothrix*, and *Bangia* commonly occur throughout the Lake Erie basin generally wherever a firm substrate with little net sedimentation is present. Where suitable substrate exists, *Cladophora* biomass ranges from trace amounts to over 200 g dry wt/m^2. The Island Region consistently produces the largest amount of biomass.

VERTICAL DISTRIBUTION AND TEMPORAL ABUNDANCE

The littoral zone of western Lake Erie is a high energy, dynamic environment that is subjected to wide variations in environmental conditions that affect both the vertical zonation and seasonal distribution patterns of the algae. The littoral zone is composed of three components based on water level: the infralittoral zone (the region below mean water level), the eulittoral zone or splash zone (the wave influenced zone extending approximately 20 cm below to 20 cm above the mean water level) and the supralittoral zone (the region above the eulittoral zone that is influenced by spray of the waves) (Fig. 1). Although the littoral habitat may be segmented into specific zones, the distribution of the algae is much more complex due to the heterogeneity of the shoreline and the endless diversity of microhabitats.

Ulothrix - Soon after the ice disappears a sparse colonization of *Ulothrix* appears along the waterline. By early April, when surface water temperatures are near 4° C, *Ulothrix* has become well established forming a distinctive green band along with water's edge. The vertical distribution of *Ulothrix* expands with the fluctuation and slowly rising water levels of the spring. During this period of rapid *Ulothrix* growth, several distinct bands of the alga are noted on vertical substrate resulting from massive sporulations and rapid colonization of the zoospores along the fluctuating waterline.

The vertical distribution and seasonal abundance of *Ulothrix* peaks near late April when water temperatures are approaching 10°C. The alga reaches a maximum depth of 1.0 to 1.5 m where it occurs as scattered patches. Spatial distribution of *Ulothrix* varies greatly on a local scale from 100% coverage to not present in similar adjacent areas. Maximum filament length of 3-4 cm occurs just below the surface. As water temperatures increase above 10° C and daylength increases, the abundance and vertical extent of *Ulothrix* begins to decline. *Ulothrix* is generally not evident after May, although it has been observed in a few locations as late as July. *Ulothrix* returns to the lower eulittoral zone in the fall as water temperatures decline below 10° C. The early colonization and dominance of *Ulothrix* in the upper littoral zone during the spring is the result of the alga's capability to survive at low temperatures. The optimum photosynthetic temperature for *Ulothrix* is 5° C (Auer et al. 1983, Graham et al. 1986).

Bangia - Sparse patches of *Bangia* appear in the upper portion of the eulittoral zone in April, above the heavily colonized zone of *Ulothrix*. *Bangia* increases in abundance and vertical distribution during May when lake temperatures are in the range of 6-16° C, reaching peak levels in June. The red alga occupies the substrate above *Ulothrix* in the eulittoral and low supralittoral zones in the early spring. The alga intermingles and partially replaces *Ulothrix* by June, extending its vertical distribution to the waterline.

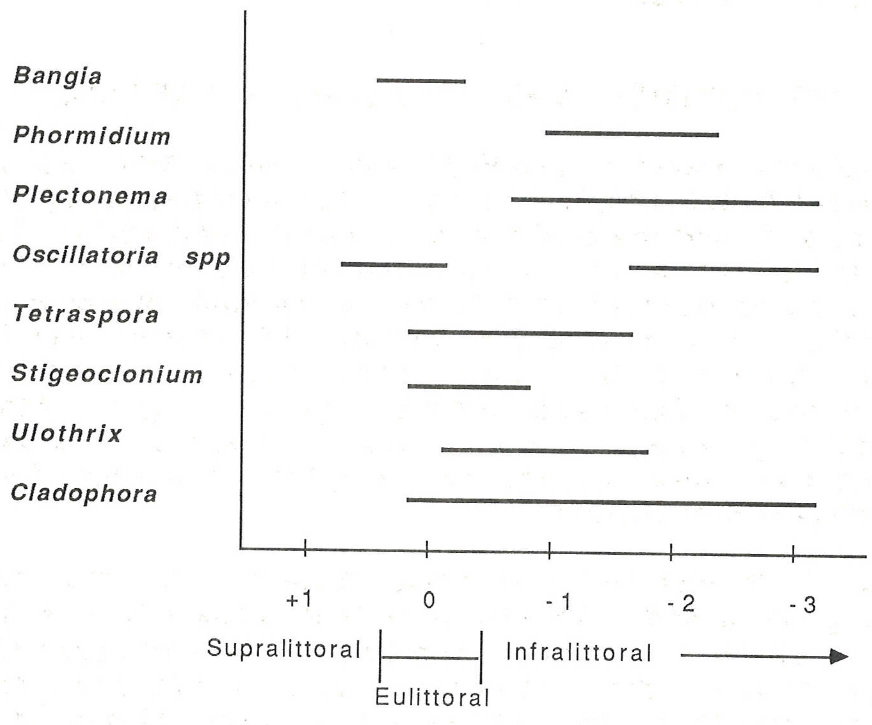

Figure 1. General zonation pattern of major attached algae in western Lake Erie.

The distribution of *Bangia* is much more irregular than that of *Ulothrix* or *Cladophora*. Bangia is normally the uppermost algal component in the vertical zonation pattern (Fig. 1). Populations of *Bangia* decline during the summer but remain present until the fall when a resurgence of growth occurs.

Bangia is most abundant on wave exposed vertical substrate such as breakwalls, steep shorelines, and boulders where it can find suitable habitat that is not in direct competition with *Cladophora*. *Bangia* does not colonize areas with gently sloping horizontal splash zones.

Cladophora - *Cladophora* overwinters in the crevices along the shore and in the infralittoral zone under the ice as 1-3 cm filaments. Observations under the ice during the winter indicate *Cladophora* is capable of minimal winter growth. Herdendorf observed in February of 1988 dense patches of *Cladophora* with filament lengths of about 2 cm in 4 m of water off South Bass Island using a remote controlled submersible with an underwater video camera (Pers. Comm., 1988). In mid-April, when temperatures are near 5^o C *Cladophora* is usually observed at depths of 0.5-1 m as 0.5-3 cm green filaments arising from brown holdfasts that have overwintered. The greatest concentration of filaments in the spring is in crevices and along edges of rocks. As temperatures rise above 10^o C the density and distribution of *Cladophora* expands shoreward into the eulittoral zone, previously occupied by *Ulothrix*. From May through June *Cladophora* biomass continues to increase reaching maximum levels in late June to early July. The maximum standing crop collected in western Lake Erie during our study was 240 g dry wt/m^2 (Monaco, 1985). Standing biomass varies greatly from year to year.

The optimal temperature range for *Cladophora* production based on laboratory findings is 13-17^o C (Graham et al. 1982). Where substrate is not limiting the maximum depth of *Cladophora*, colonization is limited by light. In the turbid western basin the maximum depth of colonization varies from 1.5-7.0 m (Lorenz et al. In Review). Field and laboratory observations indicate that 50 μE/m^2/sec is the minimal light value for colonization (Monaco, 1985). Optimum light levels for *Cladophora* are between 300-600 μE/m^2/sec (Auer et al. 1983).

As the *Cladophora* population of the infralittoral zone grows in the spring, the environment of previously barren bedrock changes into one of a dense, productive meadow. Peak biomass occurs in late June and early July. The presence of the extensive *Cladophora* beds greatly increases the available surface area and provides a habitat for a wide variety of organisms.

During July and August the standing crop of *Cladophora* in the infralittoral zone declines to short (0.5-2.0 cm) brown holdfasts. The loss of biomass is most prominent during periods of rough water, although, during July the slightest disturbance dislodges filaments. From August to mid-September the infralittoral zone does not support *Cladophora* growth. During this period of the summer *Plectonema wollei* and *Phormidium* sp. commonly occur entangled on the *Cladophora* stubble at depths of 1 m and greater. On the east side of South

Bass Island in July, *Tetraspora lubrica* colonizes the shallow (0.5 m) denuded rocks previously colonized by *Cladophora*.

In sharp contrast to the infralittoral zone, *Cladophora* thrives in the eulittoral zone from its initial colonization in May through the summer. The eulittoral population does show signs of stress in August and may become patchy in distribution for some areas. In mid-September to October the *Cladophora* in this zone undergoes massive sporulation, resulting in large apical areas of the filaments with empty cells (sporangia) which appear as whitish tips on the filaments. Soon after this sporulation a fall resurgence of *Cladophora* colonization in the infralittoral zone occurs. The fall colonization extends to approximately 1 m of depth which is less than the vertical distribution in the spring. *Cladophora* remains present in both the infralittoral and eulittoral zones into December. Both *Bangia* and *Ulothrix* also have a fall colonization with similar distributional patterns to that of the spring.

INTERSPECIFIC ECOLOGY

In Lake Erie, *Cladophora* is the dominant competitor of the filamentous algae in the littoral zone by virtue of its physical attributes which include, tenacious holdfasts, robust thalli, and relatively rapid growth rate. Also, *Cladophora* is the only one of the three major algae that can colonize at depths greater than two meters. The seasonal abundance and vertical zonation of *Cladophora*, *Ulothrix*, and *Bangia* in western Lake Erie can be explained by examining influences of temperature and light on the physiological tolerance of the algae. The adaptation of each species to a unique range of environmental parameters enables each alga to compete successfully in the littoral zone. *Bangia* and *Ulothrix* possess characteristics of opportunistic species. *Ulothrix* colonizes and grows very early in the spring before *Cladophora* growth begins. *Bangia* also begins growth early in the season and for the most part colonizes areas which support marginal growth of *Cladophora*.

The bimodal seasonal distribution pattern of *Ulothrix*, with colonization in the early spring and late fall, is the result of its ability to photosynthesize effectively at low temperatures. When lake temperatures increase the competitive edge shifts to *Cladophora* and *Bangia*, which have higher temperature optimums. As the temperature approaches 10^{o} C *Cladophora* begins to invade the previously occupied *Ulothrix* substrate and *Bangia* invades from the zone above. The vertical zonation that develops in late spring, with *Bangia* above *Cladophora*, allows both species to coinhabit the littoral zone. The decline of *Cladophora* in the infralittoral zone in mid-summer is the result of high temperature and light levels causing respiration to be greater than the gross photosynthesis, creating a negative energy balance for the alga (Lorenz, 1981). The physiological ability of *Bangia* to withstand desiccation has allowed it to invade and become successfully established in a habitat above the two original species (Garwood, 1982).

The littoral algae are very important to the ecology of the nearshore region, particularly *Cladophora* due to its abundance and characteristics. The rough, relatively mucilage free cell wall of *Cladophora* provides an excellent substrate for epiphytic organisms, particularly diatoms (Lowe et al. 1982). At peak biomass in late June many of the *Cladophora* filaments are obscured by the dense epiphytic population. This community is possibly stimulated by the release of nutrients from the senescing *Cladophora* cells (Lorenz 1981, Millner et al. 1982). The abundant epiphytic organisms in turn provide the base for a diverse invertebrate community. McMillan (1951) reported the combined photosynthetic rate of *Cladophora*, *Ulothrix*, and periphytic diatoms was 567 mg C/m^2/day during the growing season. This rate is comparable to that obtained by Cody (1972) for the phytoplankton present in the same area.

The macrophyte dominated littoral zones of lakes have long been known as important nursery areas for numerous aquatic species. With the destruction of most of the macrophyte areas in western Lake Erie (Stuckey, 1970) the *Cladophora* beds may be providing one of the few refuges for an important community that is having its habitat destroyed. The growth dynamics of *Cladophora* closely coincides with the reproduction of many aquatic organisms.

MANAGEMENT AND FUTURE RESEARCH

The capability of *Cladophora* to bioaccumulate a wide variety of substances provides an excellent means to monitor certain pollutants. Many substances such as PCB's, pesticides, and trace metals which are present in the lake environment near the detection limit, may be better assessed at the higher concentrations found in *Cladophora*. The sessile nature of the alga may provide site-specific information and the capability to continuously monitor the environment, enabling the documentation of pollution episodes not otherwise observed.

Cladophora has the potential to be utilized in monitoring water quality. Its presence in the upper Great Lakes is a positive indicator of nutrient enrichment and might be utilized as a quick and inexpensive way to survey large areas of shoreline for nutrient sources. Our work provides baseline data on the 1979-1983 *Cladophora* conditions in western Lake Erie upon which future trends can be based. The decline in phosphorus loading to the lake cannot be translated to a similar decline in concentrations or quantities of total phosphorus measured within the lake. No significant change in western basin total phosphorus concentrations has occurred for the past 12 years (Herdendorf, 1983). This can be partially explained by phosphorus releases from the sediment through wave suspension and anoxic regeneration. If improvements are to show up in the lake they should be detected first in western Lake Erie where the largest decrease in loadings has occurred. If these decreased concentrations are great enough a reduction in *Cladophora* biomass may occur, which would help assess management strategies.

The vertical colonization of *Cladophora* in western Lake Erie is limited due to the availability of light. Lorenz et al. (In Review) have developed a model to predict the deepest depth of *Cladophora* colonization based on a 50 $\mu E/m^2/sec$ light limiting regime. Growth responses of *Cladophora* to light intensity may be exploited by lake managers to limit *Cladophora* infestations. Water intakes have been clogged by *Cladophora* in Lakes Michigan and Erie (Poston and Gamet, 1964). If intakes are designed for placement below the predicted depth of growth, intake fouling may be minimized. Conversely, artificial reefs could be placed at depths appropriate for *Cladophora* colonization, thus increasing the productivity of the reef.

The increase in turbidity of western Lake Erie over the past century that has contributed to the decline of aquatic vascular plants (Stuckey, 1970) has probably decreased the total colonizable substrate available for *Cladophora*. If in the future the turbidity of the basin decreases in response to decreased nutrient loadings the quantities of *Cladophora* may increase due to expanded vertical distribution. An interesting phenomenon to investigate is to determine if, and how, the recent increase in lake levels affects both the vertical and geographical distribution of *Cladophora*.

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WESTERN LAKE ERIE AQUATIC AND WETLAND VASCULAR-PLANT FLORA: ITS ORIGIN AND CHANGE

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The aquatic and wetland vascular-plant flora of the open water, marshes, and swamps of the southwestern shore and the area about the islands in western Lake Erie represents one of the most diverse and extensively studied floras in Ohio and the Great Lakes region (Fig. 1). As early as 1836, the versatile genius, but often much criticized naturalist, Constantine S. Rafinesque noted after a 3-day stay in 1826 that the shore of Lake Erie near Sandusky represented a locality of "great botanical interest" (Rafinesque, 1836a, p .80; 1836b, pp. 28-29). Writing on the sources of the Ohio flora, August D. Selby and J.W.T. Duvel (1899) singled out the Lake Erie region with its inlets, marshes, and beaches as one of four distinct floristic regions of Ohio. This floristic region continued to be recognized by John H. Schaffner (1932) when he outlined nine phytogeographic regions for Ohio. The Lake Erie shoreline flora constituted one region and the islands and Sandusky Bay area formed a second.

HISTORICAL REVIEW

The aquatic and wetland vascular-plant flora was first thoroughly inventoried for the area during the summer of 1898 by Adrian J. Pieters (1901) of the United States Department of Agriculture, Washington, D.C. This study, conducted as part of the United States Fish Commission's systematic investigation of the Biology of the Great Lakes, was undertaken to determine factors controlling the primary source of food in the Great Lakes, with particular emphasis on providing a greater amount of food for fish (Stuckey 1988). Pieters recorded 95 species from six study localities: Put-in-Bay Harbor, East and West Harbors, Upper Sandusky Bay, Portage River, and Cedar Point. His paper has since come to be regarded as a classic from the viewpoint of the methods employed, the results obtained, and the morphoecological classification of the plants in relation to their growth habits and environment. Pieters' study was the most comprehensive field investigation of aquatic-wetland vascular plants that had been conducted to this date in the United States. It constituted the second aquatic plant systematic field survey in the country, the first having been performed on a much smaller scale in Lake St. Clair, also by Pieters (1894).

The first comprehensive inventory of both aquatic and terrestrial vascular plants of the island and Sandusky Bay area was prepared by Edwin L. Moseley, a science teacher in Sandusky High School from 1889 to 1914. His *Sandusky Flora* (1899) accounted for 612 species of vascular plants for the islands and nearly 1300 species for the region, many of which were unknown elsewhere in Ohio at the time.

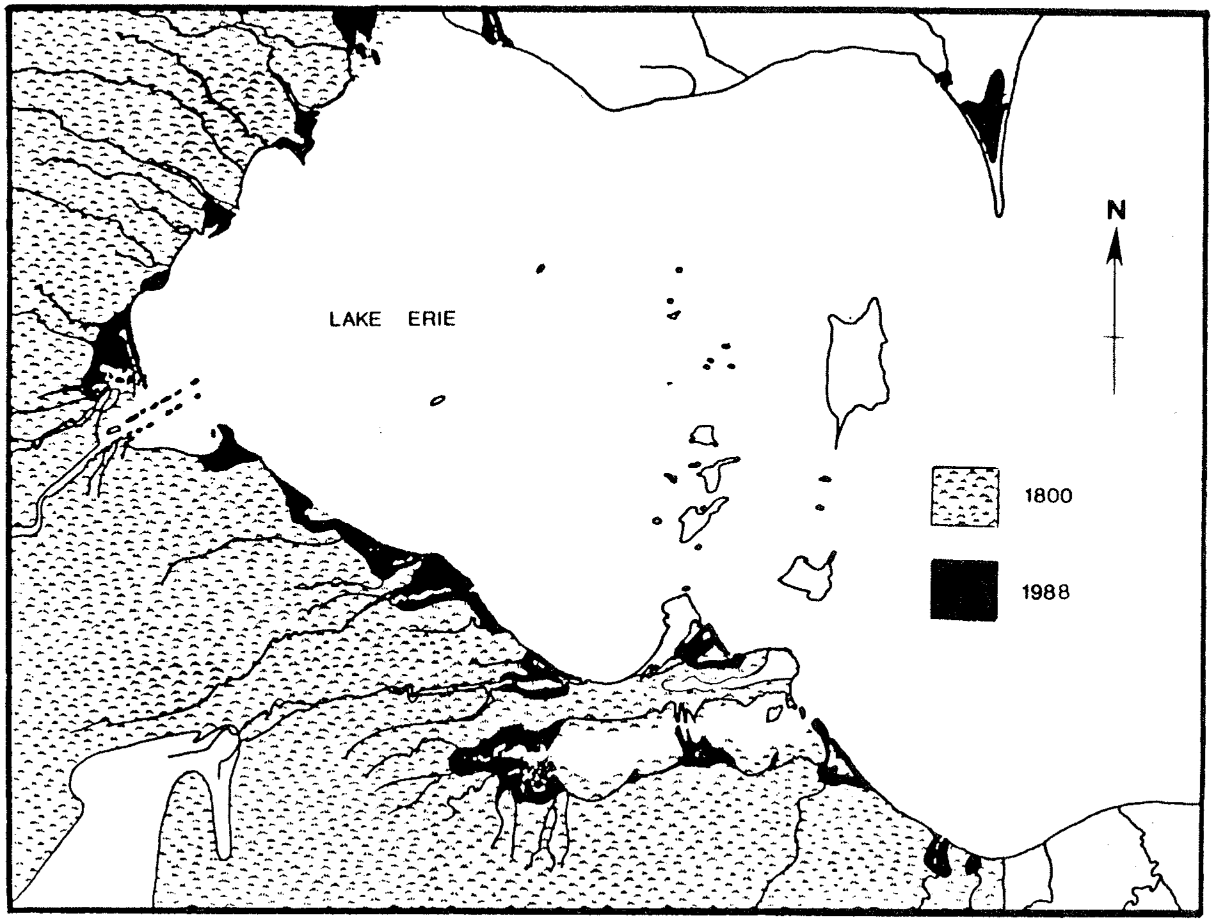


Figure 1. Map showing extent of wetlands bordering western Lake Erie in 1800 compared to distribution of coastal marshes and swamps in 1984 (from Herdendorf 1987, p. 139).

With the establishment of the Lake Laboratory by The Ohio State University at Sandusky in 1896, then at Cedar Point in 1903, and at Put-in-Bay by 1918, William A. Kellerman, Otto S. Jennings, John H. Schaffner, and Paul B. Sears of the University's Department of Botany continued to study the flora. An important contribution was a list of the plants of Cedar Point by Kellerman and Jennings (1904), while the major study by Jennings (1908) was an ecological classification of the vegetation of Cedar Point. Sears (1916) studied the relationship between evaporation and plant zonation in the marsh at Cedar Point. Perhaps the most significant botanical publication from the Laboratory was a flora of the Erie Islands with an annotated catalogue of 818 species of terrestrial and wetland vascular plants prepared by Earl L. Core (1948). He also resurveyed the aquatic and wetland flora at the same localities where Pieters studied, but left his results in an unpublished manuscript (Core, 1949). These studies were conducted while Core was a visiting teaching and research botanist at the Stone Laboratory of The Ohio State University from 1938 to 1941, and 1949.

Since 1966, I have studied the flora of the region and have completed an extensive manuscript on the vascular-plant flora of the islands in western Lake Erie which has been studied from the viewpoint of its origin, history, and change (Stuckey and Duncan, 1977; *see also* Cooper and Herdendorf, 1977). Over 860 species of vascular plants growing spontaneously have been verified for the islands. In addition, eight graduate students under my direction completed masters theses on various types of floristic analyses in the western Lake Erie region, and reports prepared by other students on special projects also add to the extensive data base. These studies, when combined, result in a checklist of the vascular plants for Erie and Ottawa Counties that totals over 1333 taxa (Stuckey and Carr, 1979). This 100+ year history of the flora of western Lake Erie provides an excellent data source from which to make comparisons of the past flora with the present flora to determine the kinds of changes that have occurred and the possible factors that are involved in effecting these changes (Stuckey, 1986b). In addition, these studies contribute data for analyzing the origin, movements, and phytogeographical affinities of the aquatic and wetland flora of western Lake Erie.

At least 300 species of aquatic and wetland vascular plants have been identified from western Lake Erie at 35 study localities (partial lists of plants in Tables 1, 2, 5, and 6; list of localities in Table 3, map showing study localities in Fig. 2). The large number reveals that a great diversity of species occurs here, and makes this flora a particularly important one for investigation. This great floristic diversity exists primarily because of the natural changing water levels over various substrates creating varied habitats which are available for plant colonization, and the continued natural and man-influenced changes to which these habitats are subjected. The habitats may be grouped into two types: (1) the aquatic comprising the open water of the lake, bays, and ponds, where species that are suspended, rooted submersed, and/or floating may grow; and (2) the vegetated wetlands along the shoreline creating marshes, which are predominately of herbaceous species (graminoids and forbs), and swamps

Table 1. List of scientific names in the text, with equivalent common names.

Scientific Name	Common Name
Azolla	floating water fern
Butomus umbellatus	flowering-rush
Ceratophyllum demersum	coontail, hornwort
Decodon verticillatus	swamp loosetrife
Elodea nuttallii	waterweed
Epilobium hirsutum	great hairy willow-herb
Hibiscus palustris	marsh marigold
Lycopus europaeus	European water horehound
Lythrum salicaria	purple loosestrife
Myriophyllum spicatum	Eurasian water milfoil
Najas marina	spiny naiad
Najas minor	minor naiad
Nuphar advena	spatterdock
Nymphaea tuberosa	white water-lily
Polygonum coccineum	swamp persicaria, swamp smartweed
Potamogeton crispus	curly pondweed
Potamogeton pusillus var. *tenuissimus*	small pondweed
Potamogeton richardsonii	Richardson's pondweed
Rorippa sylvestris	creeping yellow cress
Sagittaria latifolia	arrowhead
Sparganium eurycarpum	bur-reed
Typha angustifolia	narrow-leaved cat-tail
Typha latifolia	common cat-tail, broad-leaved cat-tail
Vallisneria americana	wild celery, tape grass, eel grass

Table 2. List of common names used in the text, with scientific equivalents.

Common Name	Scientific Name
American elm	*Ulmus americana*
arrowhead	*Sagittaria latifolia*
ashes	*Fraxinus* spp.
barnyard grass	*Echinochloa* sp.
beggar-ticks	*Bidens* spp.
bittersweet nightshade	*Solanum dulcamara*
black mustard	*Brassica* spp.
blue-joint grass	*Calamagrostis canadensis*
broad-leaved cattail	*Typha latifolia*
bulbous cress	*Cardamine bulbosa*
bulrushes	*Scirpus* spp.
bur-reed	*Sparganium eurycarpum*
buttonbush	*Cephalanthus occidentalis*
Canada thistle	*Cirsium arvense*
cat-tails	Typhaceae, a family of plants including the species *Typha angustifolia* and *T. latifolia*
coontail	*Ceratophyllum demersum*
cord grass	*Spartina pectinata*
cottonwood	*Populus deltoides*
curly pondweed	*Potamogeton crispus*
cursed crowfoot	*Ranunculus sceleratus*
dogwoods	*Cornus* spp.
duckweeds	Lemnaceae, a family of plants, including the genera *Lemna, Spirodela*, and *Wolffia*
elderberry	*Sambucus canadensis*
Eurasian water milfoil	*Myriophyllum spicatum*
European water horehound	*Lycopus europeaus*
false-nettle	*Boehmeria cylindrica*
false pimpernel	*Lindernia dubia*
ferns	Polypodiaceae, a family of fern plants
flat-stemmed pondweed	*Potamogeton zosteriformis*
flexed naiad	*Najas flexilis*
floating water fern	*Azolla* sp.
flowering-rush	*Butomus umbellatus*
Fries' pondweed	*Potamogeton friesii*
forbs	Species of broad-leaved dicot plants
fringed loosestrife	*Lysimachia ciliata*

Table 2. Continued.

Common Name	Scientific Name
golden ragwort	*Senecio pauperculus*
graminoids	Species of narrow-leaved monocot plants
grasses	Gramineae, a family of plants
grass-like pondweed	*Potamogeton gramineus*
great hairy willow-herb	*Epilobium hirsutum*
hard-stemmed bulrush	*Scirpus acutus*
hedge-nettle	*Stachys palustris*
large-leaved pondweed	*Potamogeton amplifolius*
leafy pondweed	*Potamogeton foliosus*
marsh cress	*Rorippa palustris* (*R. islandica*)
marsh marigold	*Caltha palustris*
minor naiad	*Najas minor*
monkeyflower	*Mimulus ringens*
narrow-leaved cattail	*Typha angustifolia*
nettles	Urticaceae, a family of plants, including the genera *Laportea* and *Urtica*
nodding smartweed	*Polygonum lapathifolium*
obtuse spike-rush	*Eleocharis obtusa*
panic grasses	*Panicum* spp.
pikerelweed	*Pontederia cordata*
pinkweed	*Polygonum pensylvanicum*
pondweeds	*Potamogeton* spp.
prairie grass	*Phragmites australis* (*P. communis*)
purple loosestrife	*Lythrum salicaria*
ragweeds	*Ambrosia* spp.
reed canary grass	*Phalaris arundinacea*
reed grass	*Phragmites australis* (*P. communis*)
Richardson's pondweed	*Potamogeton richardsonii*
river bulrush	*Scirpus fluviatilis*
Robbins' pondweed	*Potamogeton robbinsii*
roses	*Rosa* spp.
rushes	*Juncus* spp.
sago pondweed	*Potamogeton pectinatus*
sedges	Cyperaceae, a family of plants, including the genera *Carex, Cyperus, Eleocharis, Scirpus, Scleria, Rhynchospora*, and other genera
skunkcabbage	*Symplocarpus foetidus*

Table 2. Continued.

Common Name	Scientific Name
silver maple	*Acer saccharinum*
skullcap	*Scutellaria epilobiifolia, S. lateriflora*
slough grass	*Spartina pectinata*
small pondweed	*Potamogeton pusillus*
smartweed	*Polygonum* spp.
soft-stemmed bulrush	*Scirpus validus*
spatterdock	*Nuphar advena*
spike-rush	*Eleocharis* spp.
spotted touch-me-not	*Impatiens capensis*
spring cress	*Cardamine douglassii*
stiff water crowfoot	*Ranunculus longirostris*
strict-leaved pondweed	*Potamogeton strictifolius*
swamp buttercup	*Ranunculus septentrionalis*
swamp mallow	*Hibiscus palustris*
swamp milkweed	*Asclepias incarnata*
sweet clovers	*Melilotus* spp.
sycamore	*Platanus occidentalis*
three-square	*Scirpus pungens* (*S. americanus*)
umbrella sedges	*Cyperus* spp.
Walter's millet	*Echinochloa walteri*
water lotus	*Nelumbo lutea*
water-marigold	*Megalodonta beckii*
water-plantain	*Alisma plantago-aquatica*
water smartweed	*Polygonum coccineum*
water star-grass	*Heteranthera dubia*
waterweed	*Elodea canadensis*
white-stemmed water milfoil	*Myriophyllum exalbescens*
white water lily	*Nymphaea tuberosa*
wild carrot	*Daucus carota*
wild celery	*Vallisneria americana*
wild rice	*Zizania aquatica*
willows	*Salix* spp.

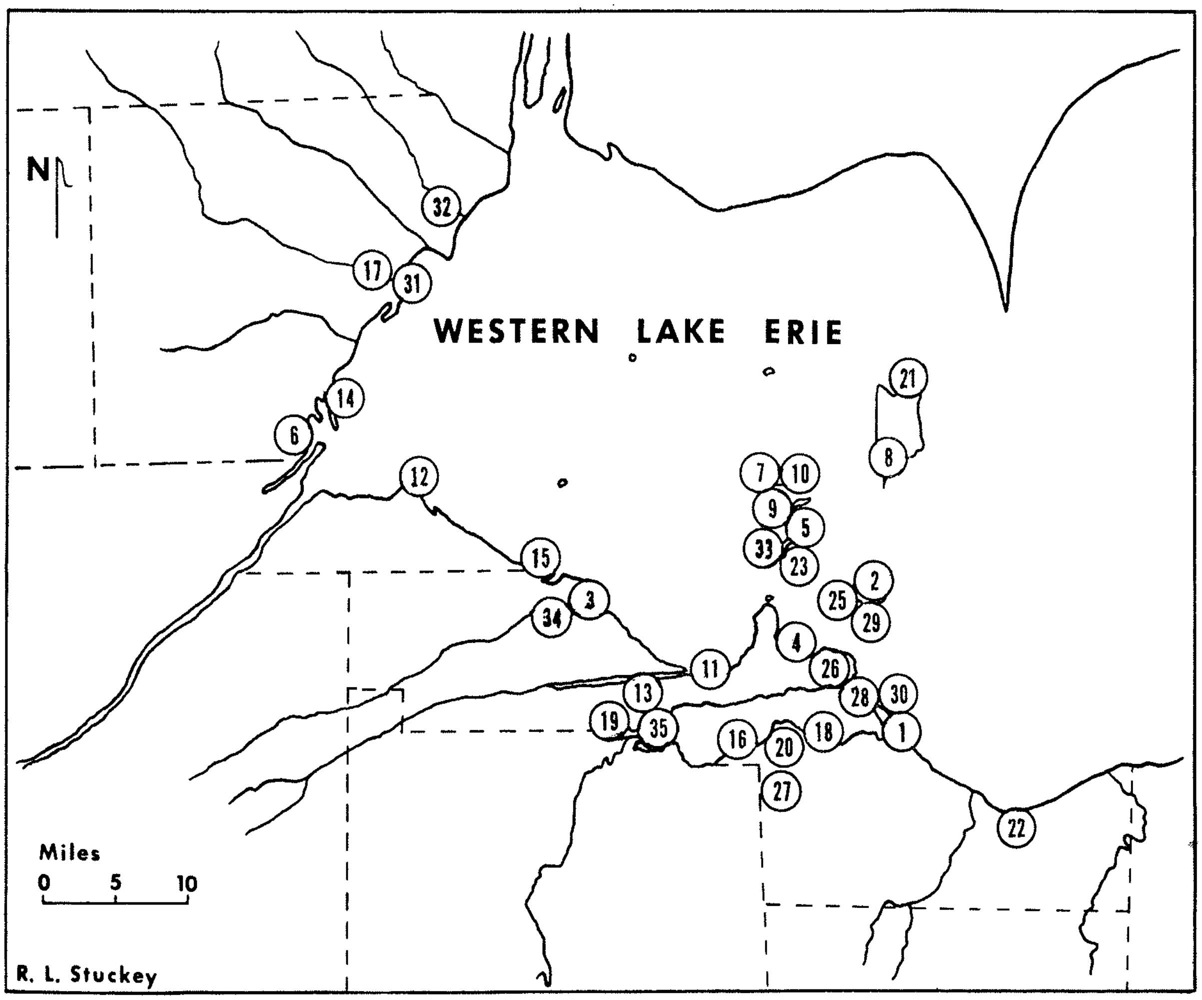


Figure 2. Map of western Lake Erie showing study localities by Ronald L. Stuckey and associates (1967-1987).

Table 3. List of study localities in the marshes of western Lake Erie (1967-1987).

1. Big Island Wetland (Lower Cedar Point), Erie County
2. Carp Pond, Kelleys Island
3. Davis-Besse Nuclear Power Plant Marsh (Navarre Marsh), Ottawa County
4. East Harbor State Park, Ottawa County
5. East Point, South Bass Island
6. Erie State Game Area, Monroe County, Michigan
7. Fox's Marsh, North Bass Island
8. Fox's Pond, Pelee Island, Canada
9. Haunck's Pond, Middle Bass Island
10. Honey Point and Smith's Pond, North Bass Island
11. Lakeview Park, Port Clinton, Ottawa County
12. Little Cedar Point Marsh, Lucas County
13. Little Portage Wildlife Area Marsh, Ottawa County
14. Luna Pier, Monroe County, Michigan
15. Magee Marsh, Lucas County
16. Maples (Levis Marsh), Erie County
17. Monroe, Monroe County, Michigan
18. Moxley's Marsh, Erie County
19. Muddy Creek, Ottawa County
20. Neilsen's Marsh, Erie County
21. North Pond, Pelee Island, Canada
22. Old Woman Creek Estuary, Erie County
23. Perry's Victory Monument Marsh (now destroyed), South Bass Island
24. Put-in-Bay Harbor, South Bass Island
25. Quarries (shallow pools and mudflats) on Kelleys Island
26. Quarries (shallow pools and mudflats) on Marblehead Peninsula
27. Resthaven Wildlife Area (Castalia Prairie): also fen habitat, Erie County
28. Sand Point Marsh, Marblehead Peninsula, Ottawa County
29. Seaway Marina (Kelleys Pond), Kelleys Island
30. Sheldons Folly, Erie County
31. Sterling State Park, Monroe County, Michigan
32. Swan Creek at Old Port, Monroe County, Michigan
33. Terwilligers Pond, South Bass Island
34. Toussaint Creek Wildlife Area, Ottawa County
35. Winous Point Marsh, Ottawa County

characterized with mostly woody species (trees and shrubs). In these habitats, depending on water-levels, plants of all growth forms: floating, suspended, submersed, floating-leaved, and emersed (emergent) may be present. This aquatic-wetland flora has not remained stable, and drastic changes have occurred during the past century.

Other contributions toward an understanding of the aquatic-wetland flora of western Lake Erie, not cited elsewhere in this paper, have come from Albright (1966), Campbell (1982), Davis (1969), Herdendorf (1987), Jones (1983), Marshall and Stuckey (1974), Stevenson (1983), Stuckey (1976a), Van Wey (1983), and Wood (1966).

ORIGIN OF THE FLORA

Since the retreat of the Wisconsinan glacier from the western basin of Lake Erie about 14,000 years B.P., the shallow waters and barren sand-mudflats along the southwest shoreline have been the site for the colonization of pioneer plants. From that time on until the present, while the lake basin was filled to different levels of water, these pioneer aquatic and wetland species native to the North American continent have been migrating into the area. They have come from the east, the south, and the west, while the northern region was still covered with ice. These geographically distinctive species comprise about 52+% of the aquatic-wetland flora, based on a total of 300 species (Tables 4, 5). The species are generally rare, occasional, or sometimes common in the present-day flora and occur primarily in the open water and marshes. Of these sub-groups, the western element contains 16%, the highest percentage, while the eastern and southern are similar with 12+% each. A distinctive western-southern prairie component and southeastern fen-prairie element comprise about 10% of the flora (Foos, 1971; Hurst, 1971; Stuckey and Denny, 1981). An additional 2% account for one endemic variety and five known hybrids. Most of the species belonging to these geographical elements occur in open, wet, naturally disturbed sites on mud flats, rocky or sandy shores, in shallow ponds and embayments, and marshes. These places are representative habitat types and environments that were available and most extensive at the time of the retreat of the Wisconsinan glacier. Being able to survive under warming temperatures and higher humidity where changing, open, wet, and naturally disturbed habitat conditions prevailed, these species continue to live in the disturbed shoreline habitats today as they did 12- to 14,000 or more years ago. The aquatic-wetland flora of western Lake Erie, therefore, is unique because of the survival of these relic habitats with these geographically distinctive species.

The largest single floristic element is composed of widespread species. This element comprises about 36% of the aquatic-wetland flora of the western basin of Lake Erie. These species commonly occur in the most general and most frequently encountered kinds of wetland habitats, not only in western Lake Erie, but also elsewhere throughout most of the continent. They are very tolerant species able to survive many kinds of natural and artificial disturbances, in addition to pollutants that may enter the water and substrate.

Table 4. Numbers and percentages of aquatic-wetland vascular plants in the open water, marshes, and swamps of western Lake Erie according to general geographical affinity.

Geographical Affinity	Number of Species	Percentage Based on 300 Species	Geographically Distinctive Species
Widespread	109	36%	
Western	49	16%	
Eastern	37	12+%	
Southern	37	12+%	152 52%
Southeastern-Southwestern (Fen-Prairie)	29	10%	
Endemics and Hybrids	6	2%	
Nonindigenous	33	11%	
Total	300	100%	

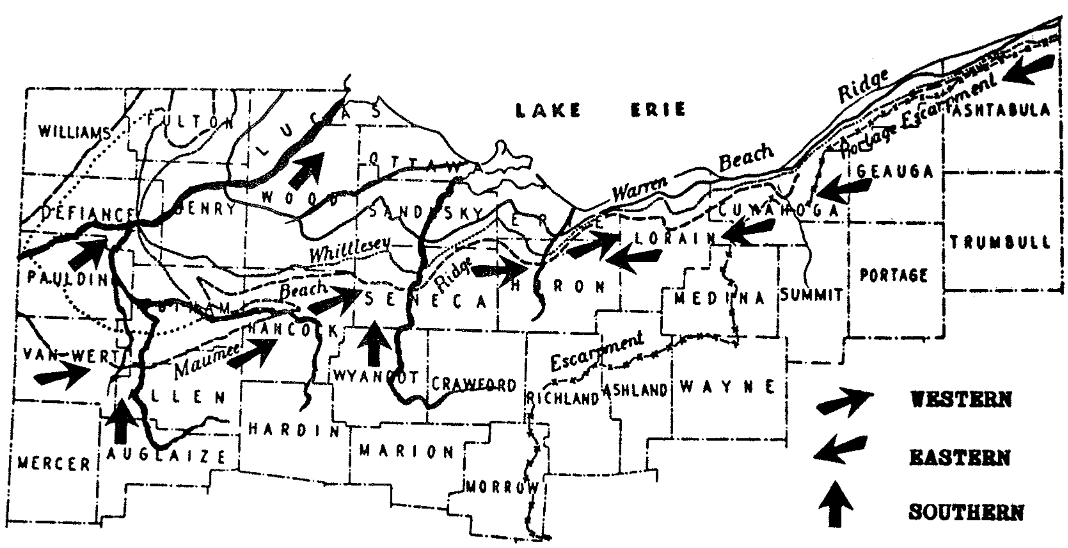


Figure 3. Map of northern Ohio showing suggestive migration routes of western, eastern, and southern species into western Lake Erie (base map from Ohio Geological Survey in Herdendorf 1987, p. 32).

Table 5. Geographically distinctive aquatic-wetland species in western Lake Erie (52+%).

Western Species (16%)

Atriplex patula
Calamagrostis canadensis
Calamagrostis inexpansa
Carex aquatilis
Carex atherodes

Carex buxbaumii
Carex pauciflora
Carex stricta
Carex viridula
Cicuta bulbifera

Cyperus engelmannii
Eleocharis elliptica
Eleocharis palustris
Elodea nuttallii
Gentianopsis procera (*Gentiana p.*)

Juncus alpinus
Juncus articulatus
Juncus balticus
Juncus nodosus
Lobelia kalmii

Lycopus uniflorus
Lysimachia thyrsiflora
Megalodonta beckii
Myriophyllum exalbescens

Najas flexilis
Nuphar variegatum
Nymphaea tuberosa
Phragmites australis (*P. communis*)
Polygonum amphibium

Potamogeton amplifolius
Potamogeton filiformis
Potamogeton gramineus
Potamogeton natans
Potamogeton praelongus

Potamogeton richardsonii
Potamogeton robbinsii
Potamogeton zosteriformis
Potentilla anserina
Potentilla fruticosa

Ranunculus pensylvanicus
Rorippa palustris var. hispida
Rumex maritimus
Sagittaria cuneata
Salix amygdaloides

Salix candida
Scirpus acutus
Scirpus fluviatilis
Scutellaria epilobiifolia
Triglochin palustre

Eastern Species (12+%)

Betula pumila
Bidens coronatus
Carex garberi
Carex lacustris
Carex lupulina

Cladium mariscoides
Eleocharis geniculata (*E. caribaea*)
Eleocharis intermedia
Eleocharis olivacea
Eleocharis smallii

Najas gracillima
Nuphar advena
Peltandra virginica
Polygonum hydropiperoides
Polygonum sagitatum

Pontederia cordata
Potamogeton friesii
Potamogeton perfoliatus var. bupleuroides
Potamogeton strictifolius

Table 5. Continued.

Eastern Species (12+%), continued

Erechtites hieracifolia
Gentianopsis crinita (*Gentiana c.*)
Hibiscus palustris
Hypericum boreale
Hypericum kalmianum

Iris versicolor
Juncus canadensis
Juncus effusus
Ludwigia alternifolia

Rumex orbiculatus
Salix lucida
Scirpus cyperinus
Scirpus expansus

Scirpus hattorianus
Scirpus purshianus
Scirpus smithii
Scirpus torreyi
Zizania aquatica

Southern Species (12+%)

Amaranthus tuberculatus
Ammannia robusta
Amphicarpa bracteata var. *bracteata*
Amphicarpa bracteata var. *comosa*

Boltonia asteroides
Carex frankii
Carex hyalinolepis
Carex lurida
Carex muskingumensis

Cyperus inflexus
Echinocystis lobata
Eclipta alba
Euphorbia humistrata
Hibiscus laevis (*H. militaris*)

Hypericum mutilum
Justicia americana
Iris brevicaulis
Iris virginica

Leucospora multifida
Lophotocarpus calycinus
Lycopus rubellus
Lippia lanceolata
Ludwigia palustris
Nelumbo lutea

Pilea fontana
Phystostegia virginiana
Polygonum pensylvanicum var. *durum*
Polygonum scandens

Rorippa sessiliflora
Rotala ramosior
Rumex altissimus
Rumex verticillatus
Salix nigra

Samolus parviflorus
Saururus cernuus
Sicyos angulatus
Strophostyles helvola

Table 5. Continued.

Southeastern-Southwestern (Fen-Prairie) Species (10%)

Agalinus purpurea
Carex crawei
Ceratophyllum echinatum
Cyperus diandrus
Eleocharis compressa

Eleocharis quadrangulata
Eleocharis rostellata
Eragrostis frankii
Fimbristylis autumnale
Helenium autumnale

Hemicarpha micrantha
Juncus brachycephalus
Juncus torreyi
Liatris spicata
Lysimachia quadriflora

Lythrum alatum
Parnassia glauca
Prosperpinaca palustris
Pycnanthemum virginianus
Rhynchospora capillacea

Sabatia angularis
Sagittaria brevirostra
Sagittaria graminea
Sagittaria rigida
Salix rigida

Satureja arkansana
Scirpus pendulus
Solidago ohioensis
Solidago riddellii

Endemics and Hybrids (2%)

Juncus x *alpiniformis*
Juncus x *nodosiformis*
Juncus x *stuckeyi*
Lycopus x *sherardii*
Polygonum pensylvanicum var. *eglandulosum*
Typha x *glauca*

Table 6. Nonindigenous aquatic-wetland species in western Lake Erie (11%).

Armoracia rusticana
Azolla caroliniana
Butomus umbellatus
Echinochloa crusgalli
Echinochloa walteri

Epilobium hirsutum
Iris pseudacorus
Juncus gerardii
Lycopus asper
Lycopus europaeus

Lysimachia nummularia
Lythrum salicaria
Mentha alopecoides
Mentha gentilis
Mentha piperita

Solanum dulcamara
Solanum nigrum
Typha angustifolia

Myosotis scorpioides
Myriophyllum spicatum
Najas marina
Najas minor
Nasturtium officinale

Phalaris canariensis
Polygonum orientale
Polygonum persicaria
Potamogeton crispus
Potentilla paradoxa

Ranunculus bulbosus
Rorippa sylvestris
Salix alba
Salix fragilis
Salix purpurea

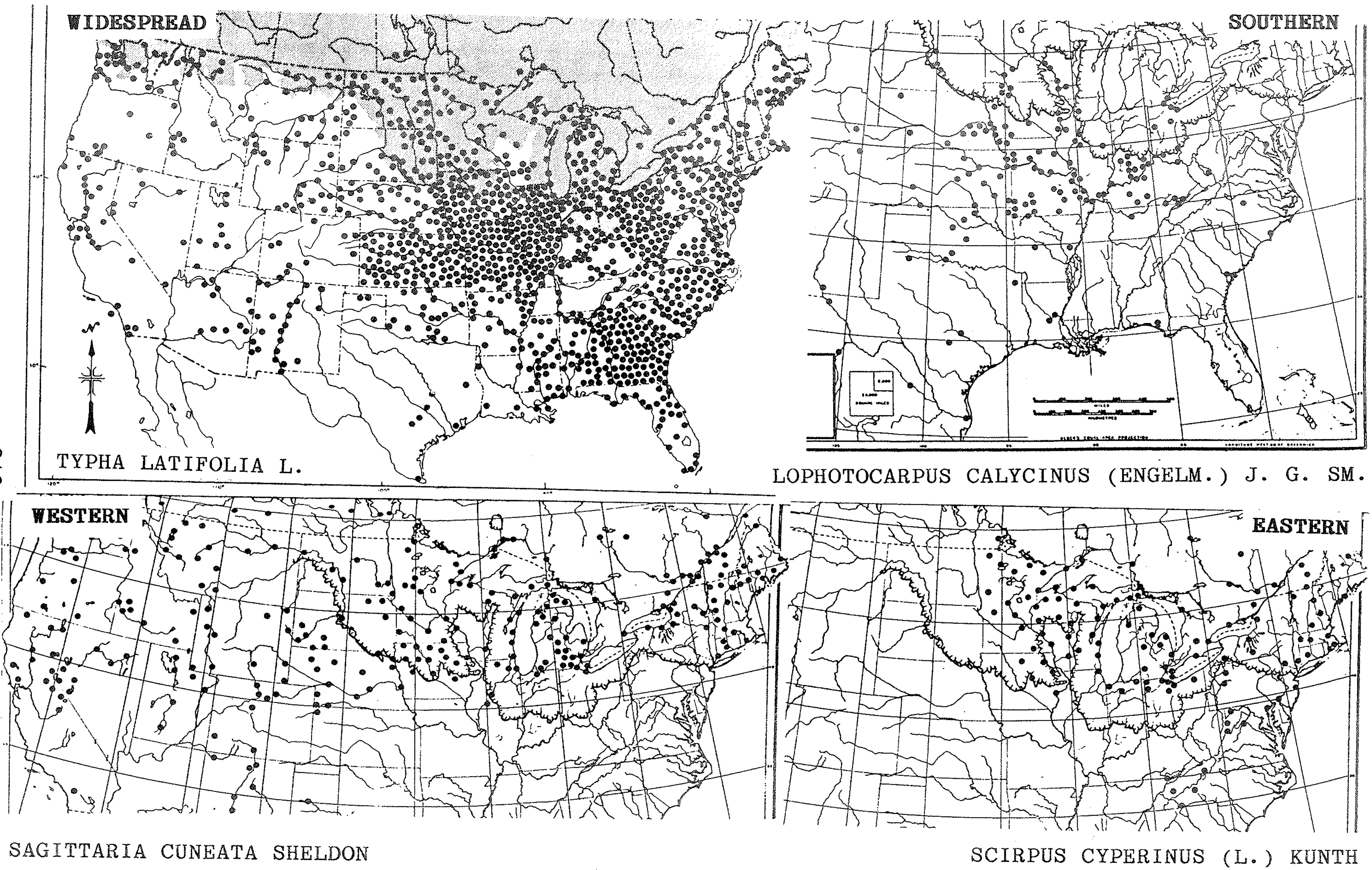


Figure 4. Four maps of portions of North America, representing by dots the distribution of a widespread species, *Typha latifolia*; a western species, *Sagittaria cuneata*; an eastern species, *Scirpus cyperinus*; and a southern species, *Lophotocarpus calycinus.*

Another important floristic element is composed of foreign or nonindigenous species (Table 6). With the arrival of European immigrants, plants from Europe, and to a lesser extent from other continents and other parts of North America, have invaded western Lake Erie during the past 100 or more years. The species have moved into those sites that have been severely disturbed and changed by mankind, such as in artificial ponds, in reservoirs, along dikes, and in gardens and lawns of beachfront property. The nonindigenous or foreign element of 11% is not high when considering those species able only to live in aquatic and wetland habitats. When foreign species of drier habitats invade the wetland environment, as frequently occurs, then the percentage of this element rises sharply, as is discussed in more detail later in this paper.

The Canadian botanist Marie-Victorin (1938) has provided a plausible explanation for these geographical distribution patterns seen in pioneer species, particularly those of aquatic and wetland habitats. In an attempt to explain the presence of isolated western or Cordilleran species in northeastern Canada, he wrote that those species must have moved eastward across an "unforested belt that must have existed along a receding ice-front, as a kind of side-walk extending from the Rockies to the Gulf of St. Lawrence" (p. 554). This idea of a "Sidewalk Hypothesis" applies equally well to any pioneer aquatic and wetland species where they occur in wet, open, disturbed habitats, such as along riverbanks, shores of lakes, and wetland sites disturbed or created by man. The "Sidewalk Hypothesis" may appropriately be applied to species common in the Rocky Mountains which range nearly continuously eastward north of the Wisconsinan glacial boundary to the shores of the Great Lakes or all the way to the wetlands of the east coast. Equally applicable, the "Sidewalk Hypothesis" may explain the resulting migration patterns of the eastern species that have moved westward into the Great Lakes region and northward into Canada; and the southern species which have migrated northward along rivers with disturbed shores and mudflats to, or somewhat northward beyond, the southernmost limit of the Wisconsinan glacial boundary (Figs. 3, 4). The nonindigenous or foreign species have spread also via remnants of the glacial sidewalk, particularly in disturbed sites along rivers and shores of natural lakes and ponds, and in artificially formed wetlands and reservoirs. The idea of pioneer wetland species migrating from one geographical area to another along a receding ice front has been discussed in the literature at least ten years earlier than Marie-Victorin, by Svenson (1927), and since then by Field and Coddington (1980), Iltis (1965), Stuckey (1972), Stuckey and Denny (1981), and Vesper and Stuckey (1977). The terms "side-walk" or "Sidewalk Hypothesis" have only been used once, and that was in one of Stuckey's papers (1972, p. 376).

CHANGES IN THE FLORA

Taken from three approaches, the changes in the aquatic and wetland vascular-plant flora of western Lake Erie have occurred (1) in species composition during the past nearly 100 years (long-term changes), (2) in sizes of populations of species over the past 20 years (short-term changes), and (3) because of the invasion of nonindigenous species (Stuckey, 1979a).

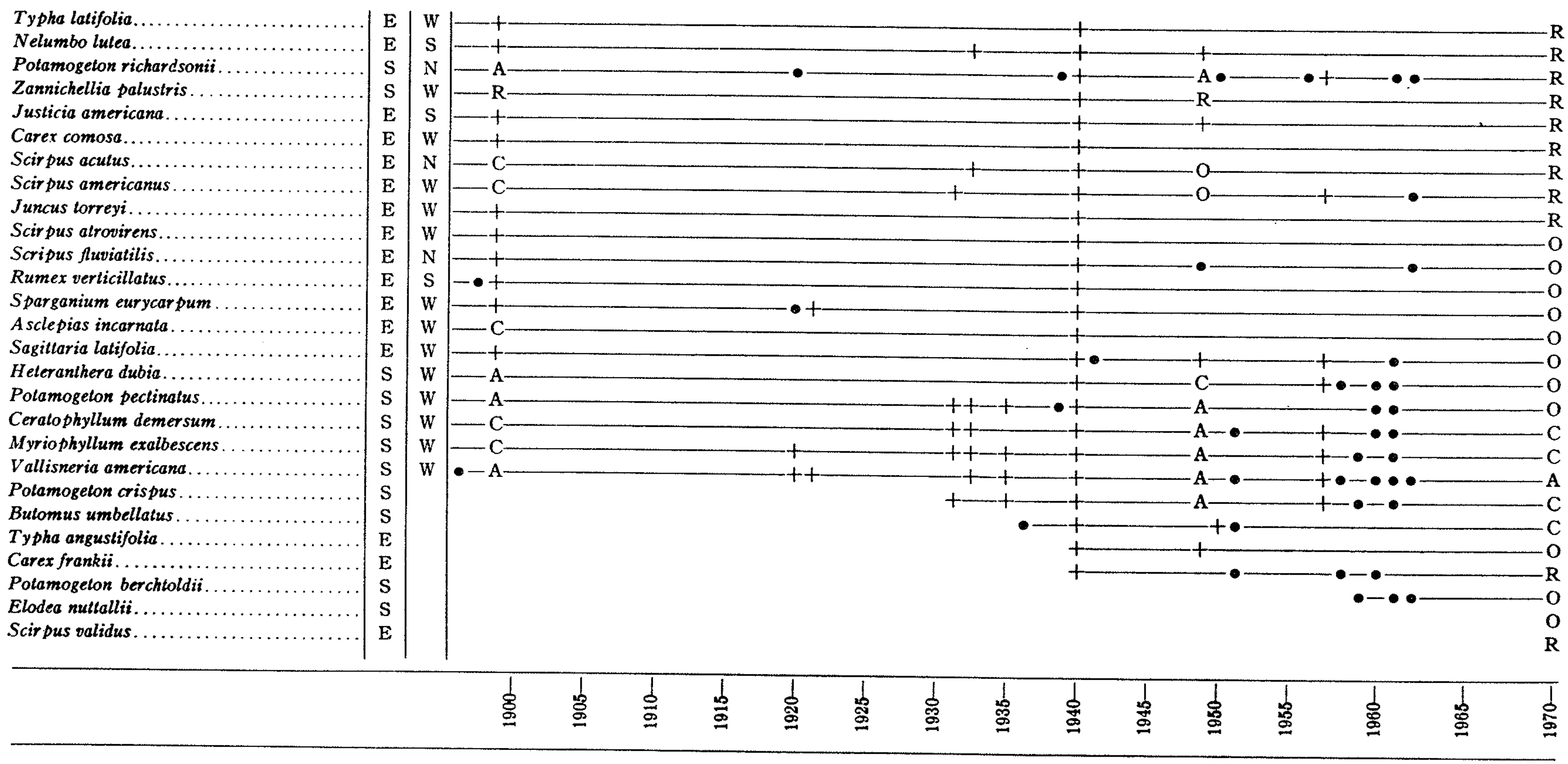
Long-Term Changes

In the open water of the lake and large bays, species of aquatic vascular plants are few and limited mostly to the rooted submersed ones, such as wild celery, sago pondweed, Richardson's pondweed, Eurasian water milfoil, and water star-grass. These species along with coontail, waterweed, small pondweed, curly pondweed, and the submersed form of the flowering-rush are the major submersed species in the bays and shallow water near the shoreline. The flora of the ponds shows considerable diversity. In addition to having most of the species already mentioned, small floating plants such as the duckweeds form dense mats in quiet, stagnant water. In some places the floating water fern, *Azolla*, also forms dense, often reddish mats. Species with large floating leaves, white water-lily and the large yellow-flowered water lotus, are not common, but where they do grow they may form extensive colonies, as does the large emersed-leaved, yellow-flowered spatterdock. Emersed species with showy flowers or large distinctively shaped leaves, such as cat-tails, bur-reed, flowering-rush, arrowhead, water plantain, swamp mallow, water smartweed, iris, and pickerel-weed, line the edges of the ponds often in segregated zones. Prominent also along the edges of ponds are various graminoids, species of grasses, sedges, and rushes.

As an aid to describing changes in the flora, it has been useful to organize the species into three categories, (1) those that are common and widespread in their range, (2) those that are northern, which occur primarily from Lake Erie northward, or are generally north of the glacial boundary, and (3) those that are southern, which exist from Lake Erie southward, or are usually south of the glacial border. Drastic long-term changes have been discussed and analyzed for the aquatic-wetland species of the bays and ponds (Stuckey, 1971, 1978, 1979c). In Put-in-Bay Harbor, Pieters (1901) recorded 40 species of aquatic-wetland vascular plants in 1898. Of these 40, eight species were never reported in later surveys, and five of those eight are northern in distribution. By 1968, 70 years later, 20 of these 40 species, or 50%, had disappeared (Table 7 Figs. 5, 6, 7). Of these 20, 11, or 55% are northern in distribution (Table 8). Considering only those species which are suspended or submersed and living entirely in, or surrounded by water, 22 of the original 40, 15 of these 22 have been lost. Ten of these 15, or 67%, are northern species (Table 8). In at least two categories, the original flora had a 55% and 67% majority of northern species. In general, these northern species are more common in cool, deep, clear, well-oxygenated or oligotrophic waters north of Lake Erie, but being on the southern edge of their range in Lake Erie and in northern Ohio, they are

Table 7. Documented changes of vascular aquatic flowering plants during 70 years in Put-in-Bay Harbor, Lake Erie, Ohio, compiled from the literature and herbarium records (from Stuckey 1971).

	Growth Habit[2]	Geographical Distribution[3]	1898 Pieters (1901)	Stehle (1923); Kennedy (1923)	1924 Krecker (1924)	1931 Shawver (1931)	1933 Tiffany (1934, 1937)	Krecker (1939)	Core (1948)	1949 Core (1949)	1957 Stansbery (1961)	1967 Stuckey
Potamogeton amplifolius	S	N	+									
Potamogeton friesii	S	N	O									
Potamogeton praelongus	S	N	+									
Potamogeton perfoliatus	S	N	+									
Megalodonta beckii	S	N	+									
Najas guadalupensis	S	S	A									
Scirpus expansus	E	S	+									
Carex aquatilis	E	W	+									
Potamogeton filiformis	S	N	R						+			
Potamogeton gramineus	S	N	C						+			
Potamogeton natans	S	N	+						+			
Sagittaria rigida	E	N	C						+			
Potamogeton nodosus	S	S	+				+		+			
Nuphar advena	E	S	C		+	+			+			
Potamogeton pusillus	S	W	A						● +	A		
Potamogeton foliosus	S	W	+	●					+	+		
Nymphaea tuberosa	E	S	+			+			+	+		
Elodea canadensis	S	W	C	+		+	+	+	+	C	+	
Najas flexilis	S	N	A				+	+	+	A	+	
Potamogeton zosteriformis	S	N	A			+	+	+	● +	C	●	



1. Abundance values as given in or inferred from the literature for the data between 1890-1966, and as determined by Stuckey in the 1967-1970 study (see text):
   A = Abundant
   C = Common
   O = Occasional
   R = Rare
   \+ = Present (Used when abundance values are not known)
   ● = Herbarium specimen record (known herbarium specimenscited in Table 2 are available for most of the 1898 records of Pieters (1901), the 1939-1941 records are of Core (1948), and the 1967-1970 records of Stuckey)

2. Growth habit:
   S = Sumbersed aquatic species
   E = Emersed (or large floating-leaved) aquatic species

3. Geographical distribution (see text):
   N = Northern
   S = Southern
   W = Widespread

Corrections and Changes for Table 7

Changes of Vascular Aquatic Flowering Plants during 70 Years in Put-in-Bay Harbor

1. *Najas guadalupensis* was rediscovered in Put-in-Bay Harbor in 1978 by Michael Glorioso, and has been seen there nearly every year since. *Elodea canadensis* is also still present in the Bay.

2. *Myriophyllum exalbescens* is an indigenous species and was last known from Put-in-Bay Harbor in July 1946, based on herbarium specimens obtained by Robert B. Gordon and by H. E. Simmons.

3. *Myriophyllum spicatum* is a nonindigenous species that was first discovered in Put-in-Bay Harbor in June 1952 as represented by specimens obtained by W. Hintz and by A. McQuate at the Stone Laboratory. The species apparently had invaded just before that time, and is probably the second in abundance only to *Vallisneria americana* in Put-in-Bay Harbor.

4. *Potamogeton berchtoldii* is considered to be conspecific with *P. pusillus*, and the information for these two taxa should be combined. The species is abundant in Put-in-Bay Harbor, particularly during years when the water is very clear during the spring and early summer.

5. *Nelumbo lutea* has disappeared from Squaw Harbor.

Floristic Changes in Squaw Harbor (1938 - 1968)

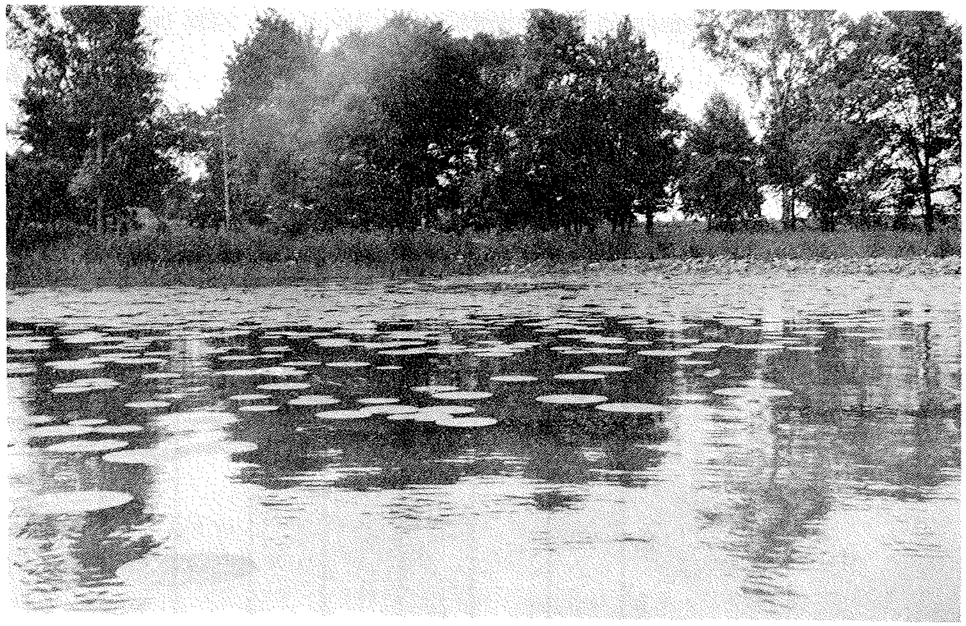


Figure 5. **1938**. Aquatic plants in Squaw Harbor, Put-in-Bay, looking toward the southwest shoreline. Floating-leaved plants are in the foreground, and dense zones of cat-tails and sedges are in the background (photograph by Clarence E. Taft, Summer 1938).

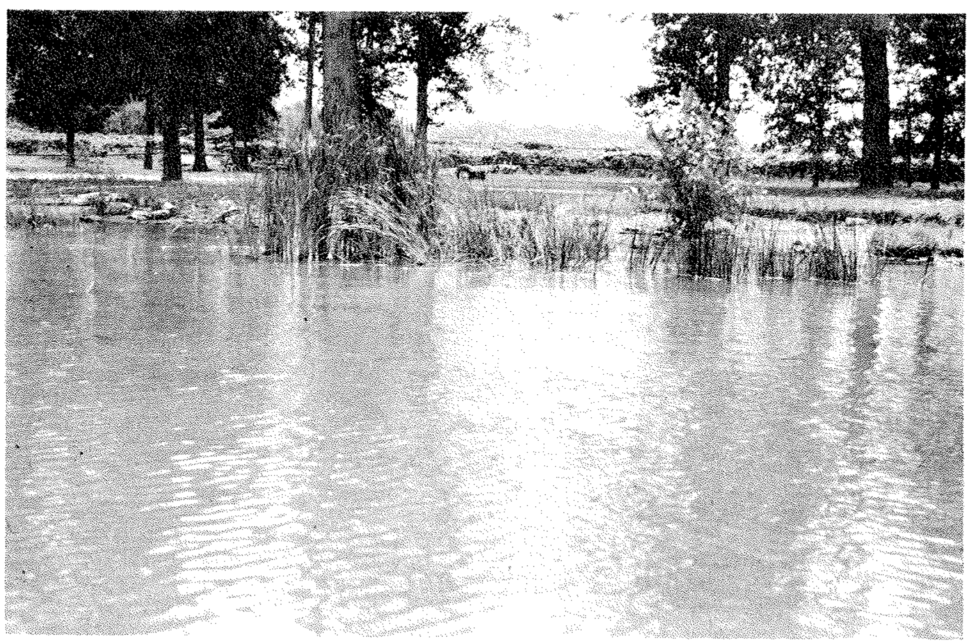


Figure 6. **1968**. Aquatic plants in Squaw Harbor, Put-in-Bay, looking toward the southwest shoreline. Floating-leaved plants are absent from the foreground and only a few remaining cat-tails and sedges remain in the background. All of these plants disappeared from this location by the summer of 1970, following a rise of higher water level in early 1969. (photograph by Ronald L. Stuckey, 8 August 1968).

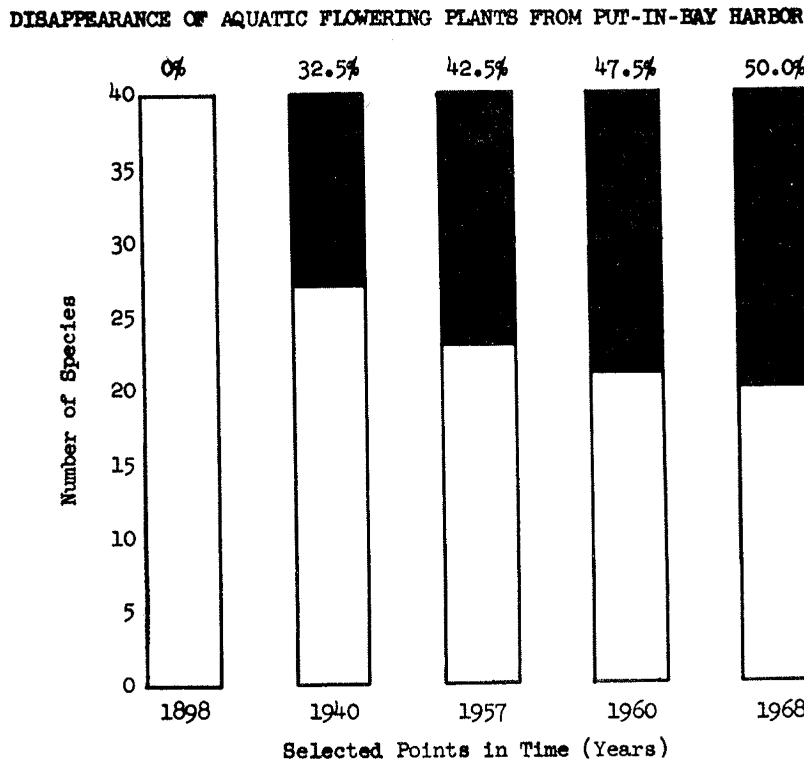


Figure 7. Graph showing loss in numbers and percentages of species from Put-in-Bay Harbor from 1898 (0% lost) to 1968 (50% lost).

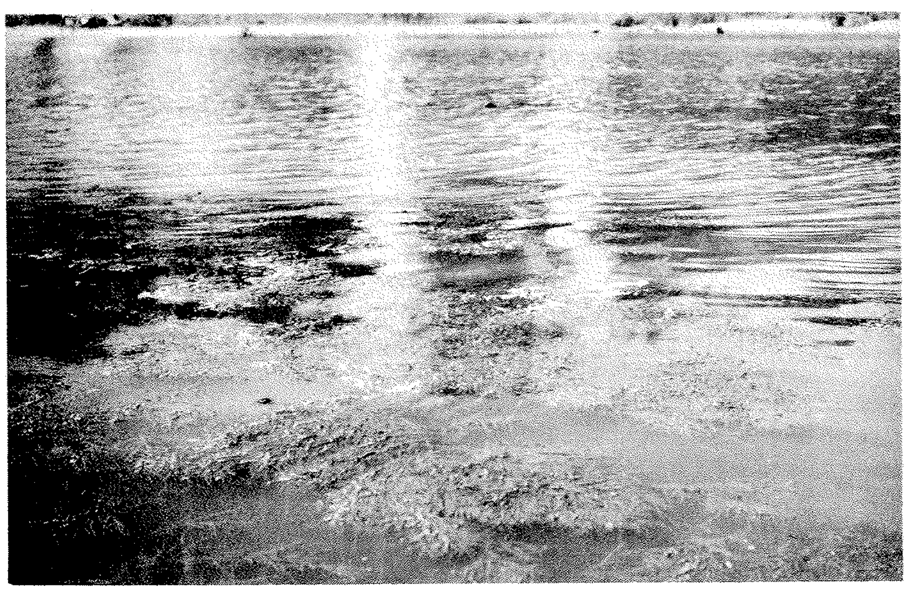


Figure 8. **1974**. *Potamogeton pectinatus* (sago pondweed) in very turbid water at Old Woman Creek Estuary, Erie County (photograph by John H. Marshall, summer 1974). The plant body shows a crown of leaves on the upper portion of the stem. These leaves fan out near the water surface which allows them to receive a maximum of exposure of light in turbid water situations (Langlois 1954, p. 101-102).

more sensitive to changes in their environment. The loss of these species has probably occurred in Put-in-Bay Harbor owing to a combination of factors, including gradual warming, increased turbidity, and decreased oxygen content of the waters. Significant additional changes have come about by dredging critical portions of the Harbor, construction of steel retaining walls, increase use of the Harbor by motor boats, soil run-off from the nearby grape vineyards, and the dumping of domestic sewage into the Harbor. These modifications that have increased the turbidity of the water must be taken into consideration as possible factors that have, independently and interrelatedly, in part or in total, been responsible for the 50% loss in species composition. Those species that have disappeared are the sensitive northern species with narrow ecological tolerances which are intolerant to drastic alterations of their habitat.

To the contrary, of the original 20 species that survived in Put-in-Bay Harbor, 14, or 70% have widespread distributions (Table 8). These widespread species occur in warm, shallow, turbid, more poorly oxygenated waters. They are species with wide ecological tolerances, and can be expected to occur and survive in those waters considered to be more eutrophic or contain more foreign chemicals or pollutants (Fig. 8). In addition to the 20 surviving species, only five submersed aquatic species, *Potamogeton crispus, P. pusillus var. tenuissimus, Elodea nuttallii, Butomus umbellatus,* and *Myriophyllum spicatum* are believed to have invaded Put-in-Bay Harbor in the past 40 years (Table 7). Thus, it is clearly evident that the amount of species diversity, as well as entire biomass, as represented by aquatic vascular plants in Put-in-Bay Harbor, has been drastically reduced to fewer numbers of species, and of those that survive, only five, *Potamogeton crispus, Vallisneria americana, Myriophyllum spicatum, Ceratophyllum demersum*, and *Butomus umbellatus* can be considered common or abundant in the Harbor today. Only two of these, *V. americana* and *C. demersum*, were in the original 40 reported by Pieters. The other three are recent invaders from foreign countries.

The magnitude of the depletion of the submersed and unattached floating aquatic vascular plants at Put-in-Bay Harbor is well illustrated when compared with a similar flora of the isolated ponds on the islands in Lake Erie. Based on the original records, 30 species of these plants occurred in the Bay and in the ponds, with five of them common to both habitats. Of the 10 species that were restricted to the ponds, all continue to survive there today, whereas only five of the 15 that were restricted to Put-in-Bay Harbor continue to survive; the remaining 10 that inhabitated only the Bay have disappeared (Table 9). Several of the ponds on the islands have been destroyed to build marinas and housing developments. Of the isolated ponds that still remain, floristically they are essentially the same today as they were 80 years ago, influenced by the human population mostly by surface wash from nearby once-cultivated fields and vineyards. Most of the submersed species ever known in the area still survive in these ponds, which represent one of the few survival sites for this segment of the flora. By contrast, it is evident that the changes brought about by human activity in a bay environment, such as in Put-in-Bay Harbor, have had a profound influence in bringing about the decline of the submersed aquatic flora.

Table 8. Summary of the geographical distributions of the original 40 species of vascular aquatic plants in Put-in-Bay Harbor (summarized from Table 7).

Total Number of Species That	General Geographical Distributions			
	Northern	Southern	Widespread	Total
Disappeared before 1940	5	2	1	8
Disappeared before 1949	9	4	1	14
Disappeared before 1967	11*	5	4	20*
Have survived since 1898	3	3	14*	20*
Total number of submersed species that				
Disappeared before 1967	10*	2	3	15*
Have survived since 1898	1	0	6	7

* Important numbers given in the text.

Table 9. Summary of the abundance and changes among the submersed and the unattached floating vascular aquatic plants on the islands in western Lake Erie since about 1900.

Total Number of Species	Ponds Only	Bays Only	Bays + Ponds	Total
Present today	14	6	8	28*
Recently established	4	1	3	8
Disappeared since 1900	0	10*	0	10*
Disappeared since 1940	0	4	0	4

* Important numbers given in the text.

The loss in species has been the most severe in Put-in-Bay Harbor, and not as drastic for Sandusky Bay and East Harbor, where Pieters and Moseley studied, and where similar comparative studies have been conducted (Lowden, 1967, 1969; Moore, 1973, 1976). Calculations show a loss of 36% of the aquatic and wetland species for the upper portion of Sandusky Bay and 25% for East Harbor. Both locations still contain areas of open water and marshes where man has affected the flora to a lesser extent than in Put-in-Bay Harbor. The percentage is lowest at East Harbor, because this area was private marshland with little human use prior to 1945. Since then, much of the area has been developed into a state park. If, for each of these three localities, the numbers of rare (or endangered) species, which probably are the most vulnerable to man's activities, are added to the numbers of species already lost, the percentages of lost and endangered species would rise considerably, ranging from 42% to 70%. This calculation was made 20 years ago, and since then the percentages essentially have not changed. Sixty rare species have been identified from East Harbor State Park (Stuckey, 1988).

Similar magnitudes of change in the aquatic flora have been demonstrated in small lakes heavily used by man in New York, Ohio, and Iowa (Crum and Bachman, 1973; Forest, 1977; Judd and Taub, 1973; Lowden, 1967, 1969; Moore, 1973, 1976; Volker and Smith, 1965), and changes to a lesser extent in other more isolated, less used lakes in New York, Iowa, Wisconsin, and Ontario have been documented (Brady and Lamb, 1976; Bumby, 1977; Crum and Bachman, 1973; Dale and Miller, 1978; Harmon and Doane, 1970; Lind and Cottam, 1969). In Lake East Okoboji, Iowa, for example, between 1915 and 1961, 26 of an original 44 species, or 60% of the aquatic flora had disappeared (Volker and Smith, 1965). At the time of the original surveys in Put-in-Bay Harbor and Lake East Okoboji, these bodies of water had in common 18 submersed species. In both lakes, 11 of these have disappeared, and of these 11, eight are northern species characteristic of cool, clear-water lakes (Table 10). Five of the submersed species that have survived in both lakes are common widespread species. One northern species, *Potamogeton richardsonii* has continued to survive in both lakes, but is rare at both localities (Table 11).

A study of 15 bodies of water in states from New York to Iowa north to southern Canada and northern Michigan, reveals that among submersed and suspended species, anywhere from 44% to 86% of them have disappeared from the more southern lakes which are more heavily used for industry and recreation than are the northern lakes, which had only 12% to 30% loss of the submersed aquatic species (Stuckey, 1981a). In Douglas Lake, Michigan, and Lake Temagami and Teapot Lake, both in northern Ontario, no species were reported lost as determined from recent surveys (Haynes and Hellquist, 1978; Dale 1986; and Garton 1984). These three rather isolated far northern lakes are little used by human populations, and consequently they have remained diverse in species of aquatic vascular plants. The pattern noticed in many of the localities already studied is obviously repeatable. The percentages of species lost or predicted to be lost in the future already reveal the drastic and potentially drastic effect that human activity has on sensitive aquatic ecosystems.

Table 10. Summary of the geographical distributions of the submersed vascular aquatic plants that have disappeared from both Put-in-Bay Harbor and Lake East Okoboji.

Species	Geographical Distribution
Megalodonta beckii	northern
Najas flexilis	northern
Potamogeton amplifolius	northern
Potamogeton friesii	northern
Potamogeton gramineus	northern
Potamogeton natans	northern
Potamogeton praelongus	northern
Potamogeton zosteriformis	northern
Potamogeton nodosus	southern
Potamogeton pusillus	widespread
Elodea canadensis	widespread

Table 11. Species of aquatic plants that have continued to survive in both Put-in-Bay Harbor and Lake East Okoboji.

Species	Geographical Distribution
Ceratophyllum demersum	widespread
Potamogeton foliosus	widespread
Potamogeton pectinatus	widespread
Sagittaria latifolia	widespread
Zanichellia palustris	widespread
Potamogeton richardsonii	northern

Consequently, these changes should be taken as warnings if man intends to maintain high floristic diversity in ponds, lakes, bays, and marshes.

"In North America, species are considered to be most sensitive to pollution when at the extremes of their geographic range" (Haslam, 1978, pp. 358-359). This statement is based on two studies by Stuckey; the first one demonstrating the loss of the sensitive northern lake species from the southern edge of their range in Put-in-Bay Harbor (Stuckey, 1971) and the second one stating the loss of the sensitive southern river species from the northern edge of their range in the Ottawa River of northwestern Ohio (Stuckey and Wentz, 1969). Species that are on the edge of their range are under stress from many ecological parameters, such as climatic, nutrient, substrate, and when pollutants are added to the system, along with other changes that may occur in the habitat, these narrowly ecologically tolerant or sensitive species can no longer compete in the altered environment. Ultimately, they die out more easily along the margin of their geographical range.

Before the coming of the European settlers, the marshes behind the sand and gravel beaches were much more extensive than they are today. Originally in wet places in shallow, clear water, vast stands of tall grasses, such as wild rice, prairie or reed grass, blue-joint grass, and cord or slough grass dominated. Sedges were also plentiful, including spike-rushes, hard- and soft-stemmed bulrush, river bulrush, and three-square. Broad-leaved cattail was then much more extensive than the rare, nonindigenous, narrow-leaved cat-tail (Stuckey and Salamon, 1987). Plants with large showy flowers, such as the yellow water lotus, white water-lily, spatterdock, swamp mallow, pickerelweed, and arrowhead grew in large colonies and gave color to the marsh. Scattered throughout the marshes, among the cat-tails and sedges, were water plantain, monkeyflower, swamp milkweed, hedge-nettle, skullcap, and marsh cress. On the exposed mudflats were annuals: false pimpernel, beggar-ticks, cursed crowfoot, obtuse spike-rush, and several species of umbrella sedges. In the clear open water in great abundance were submersed species: wild celery, waterweed, white-stemmed water milfoil, stiff water crowfoot, flexed naiad, and many species of pondweeds. An example of the decline in abundance of large showy perennial species can be seen by comparing the abundances given for 28 species selected from the flora of Moseley (1899) with their present-day abundances. Two-thirds or 18 of 28 species (67.5%) show a decline in abundance during this century (Table 12).

The water of the marshes and most of the bays has become quite muddy and turbid within the past century. These conditions have come about by (1) the extensive erosion of the soil in the once-forested uplands of the watershed, (2) the dredging, diking, and drainage of large portions of the marshes for private, industrial, agricultural, and wildlife areas, (3) the building of docks and retaining walls that in combination with dredging channels have changed shorelines in many of the bays which are now used for commercial or recreational purposes, (4) the introduction of carp, a species of fish that uproots and destroys aquatic plants and contributes to the overall continued turbidity by stirring the bottom silt and keeping it in suspension (Anderson, 1950; Giltz and Myser, 1954; King and

Table 12. Abundance of selected emersed (emergent) species of aquatic-wetland flowering plants as reported by Moseley (1899) compared to their present day abundance.*

Species	Moseley's Note on Abundance	Present Abundance in Western Lake Erie
1. Species That Apparently Have Declined in Abundance (native species)		
Zizania aquatica	abundant	rare
Acorus calamus	frequent	rare
Eleocharis smallii (E. Palustris)	frequent	rare
Rumex orbiculatus	frequent	rare
Scirpus cyperinus	frequent	rare
Calamagrostis canadensis	frequent	occasional
Iris versicolor	frequent	occasional
Nuphar advena	frequent	occasional
Pontederia cordata	frequent	occasional
Sagittaria rigida	freguent	occasional
Spartina pectinata	frequent	occasional
Decodon verticillatus	common	occasional
Nymphaea tuberosa	common	occasional
Rorippa palustris	common	occasional
Rumex verticillatus	common	occasional
Scirpus acutus (S. validus)	common	occasional
Scirpus fluviatilis	common	occasional
Typha latifolia	common	occasional
2. Species That Apparently Have Retained About the Same Abundance (native species)		
Hibiscus palustris	frequent	common
Polygonum coccineum	frequent	common
Alisma plantago-aquatica	common	common
Asclepias incarnata	common	common
Nelumbo lutea	[common]	common
Sagittaria latifolia	common	common
Scirpus atrovirens	common	common
Scirpus pungens (S. americanus)	common	common
Sparganium eurycarpum	[common]	common
Phragmites australis (P. communis)	frequent	abundant

Table 12. Continued.

Species	Moseley's Note on Abundance	Present Abundance in Western Lake Erie
3. Species That Apparently Have Increased in Abundance or Invaded the Area (mostly nonindigenous species)		
Phalaris arundinacea	infrequent	common
Solanum dulcamara	frequent	common
Typha angustifolia	scarce	abundant
Hibiscus laevis (H. militaris)	at Toledo in 1865	occasional
Lophotocarpus calycinus	[one location]	occasional
Lythrum salicaria	not reported	abundant
Butomus umbellatus	not reported	common
Echinochloa walteri	not reported	common
Epilobium hirsutum	not reported	occasional
Lycopus asper	not reported	occasional
Lycopus europaeus	not reported	occasional
Rorippa sylvestris	not reported	occasional
Iris pseudacorus	not reported	rare
Peltandra virginica	not reported	rare

* The species selected are mostly showy, dominant perennials. Eighteen of 28 native species (categories 1 and 2) or 67.5% have declined in abundance from 1900 to the present time. An additional 14 mostly nonindigenous species (category 3) have apparently increased in abundance or invaded the area since about 1900.

Hunt, 1967). These physical changes, silted conditions, and continued high turbidity levels reduce the amount of light penetrating into the water and bring about a situation in which submersed sensitive species of open, clear waters are eliminated or are drastically reduced in numbers. These submersed species are the more sensitive, mostly northern species with narrow ecological tolerances that normally inhabit clear, cool, well-oxygenated waters. Examples of these are large-leaved pondweed, grass-like pondweed, Robbins pondweed, flat-stemmed pondweed, Fries pondweed, strict-leaved pondweed, white-stemmed water milfoil, flexed naiad, water marigold, and in some places the wild celery (Stuckey 1975b). With the loss of these species and others, species diversity is drastically reduced. A comparison of a list of submersed species, as taken from Moseley (1899) with those submersed species present today, reveals that 10 of 28 species have never been present in surveys conducted during the past 20 years. Three submersed species, *Myriophyllum exalbescens, Potamogeton natans*, and *P. zosteriformis* have not been located since 1972 or earlier, making a total of 13 of 28 species, or 46% of the species in the submersed aquatic flora, that apparently have disappeared (Table 13).

Surviving are only a few tolerant native submersed species, such as coontail, sago pondweed, leafy pondweed, small pondweed, waterweed, stiff water crowfoot, and water star-grass. These turbid conditions provide favorable habitats for the invasion of tolerant European species, such as Eurasian water milfoil, curly pondweed, minor naiad, and flowering-rush. These foreign species are on the increase. Mainly because of the physical changes in the marshes, coupled with the ever-changing water-level conditions of Lake Erie, most of the grasses and sedges mentioned above are also becoming scarce and even the wild rice may now be extirpated. The species with large showy flowers, doubtlessly reduced in numbers of plants from 100 years ago, undergo considerable fluctuation in size of individual populations today because of the changing water-level conditions. In years of low water, when dikes artificially maintain the marshes and mudflats, bulrushes, arrowhead, swamp mallow, reed canary grass, barn-yard grass, panic grasses, and narrow-leaved cat-tail flourish. In many places during years of low-water level, narrow-leaved cat-tail is dominant, almost to the exclusion of all other species. On newly created dikes, the nodding smartweed, pinkweed, Canada thistle, sweet clovers, ragweeds, wild carrot, black mustard, and reed canary grass dominate during the early years following construction. In the marshes, Walter's millet has been planted for wildlife food, and several European invaders, flowering-rush, purple loosestrife, bittersweet nightshade, great hairy willow-herb, and European water horehound, are spreading and increasing in numbers. In some places acres of purple loosestrife now dominate to the exclusion of most other species (Figs. 9, 10).

The swamps, dominated by woody species, occur in small units in the low wet areas along the lake shore. These small areas of wooded vegetation are all that remain of the more extensive swamps that once prevailed in the shallow water to damp soil habitats extending from the marshes and grading into drier sites containing the beech-maple forest. The most extensive swamp, the Black Swamp, encompassed the Maumee River watershed, or nearly all of

Table 13. Abundance of submersed species of aquatic flowering plants as reported by Moseley (1899) compared to their present day abundance.

Species	Pre-Dominant Habitat	General Range	Moseley's Note on Abundance	Present Abundance in Erie and Ottawa Counties
Armaracia aquatica	lake & river	eastern U.S.	rare	extirpated
Potamogeton strictifolius	lake	northern	+Not reported	extirpated
Potamogeton robbinsii	lake	northern	scarce	extirpated
Potamogeton praelongus	lake	northern	scarce	extirpated
Megalodonta beckii	lake	northern	scarce	extirpated
Najas gracillima	lake	northern	one locality	extirpated
Potamogeton friesii	lake	northern	infrequent	extirpated
Potamogeton amplifolius	lake	northern	infrequent	extirpated
Potamogeton gramineus	lake	northern	frequent	extirpated
Potamogeton perfoliatus	lake	northern	frequent	extirpated
Potamogeton zosteriformis	lake	northern	common	extirpated
Potamogeton natans	lake	northern	common	extirpated
Myriophyllum exalbescens	lake	northern	common	extirpated
Najas guadalupensis	lake	widespread	infrequent	rare
Najas flexilis	lake	northern	common	rare
Potamogeton richardsonii	lake	northern	abundant	occasional
Potamogeton foliosus	lake & river	widespread	scarce	occasional
Potamogeton illinoensis	lake	widespread	frequent	occasional
Ranunculus longirostris	lake	widespread	frequent	occasional
Elodea canadensis	lake & river	widespread	common	occasional
Potamogeton pusillus	lake & river	widespread	infrequent	common
Potamogeton pectinatus	lake & river	widespread	abundant	common
Utricularia vulgaris	lake	widespread	frequent	common
Heteranthera dubia	lake & river	widespread	common	common
Ceratophyllum demersum	lake & river	widespread	common	common
Potamogeton nodosus	lake & river	widespread	common	common
Vallisneria americana	lake & river	widespread (eastern U.S.)	common	common
Zannichellia palustris	lake & river	widespread	rare	occasional
Ceratophyllum echinatum	lake	widespread (eastern U.S.)	not reported	rare
Elodea nuttallii	lake	widespread (eastern U.S.)	not reported	rare
*Butomus umbellatus**	lake & river	n. eastern U.S.	not reported	common
*Myriophyllum spicatum**	lake & river	eastern U.S.	not reported	common
*Potamageton crispus**	lake	widespread	not reported	common
*Najas minor**	lake	eastern U.S.	not reported	occasional
*Najas marina**	lake	widespread	not reported	rare

\+ A specimen was obtained by Mr. Adrian J. Pieters from Sandusky Bay, 31 August 1898 (US).

* Nonindigenous species; species marked extirpated have not been located since 1972 or earlier; those marked rare have been recorded from only one or two localities.

northwestern Ohio. Most of the Black Swamp has since been drained by tile and ditches creating the best agricultural section of Ohio, and one of the most productive in the nation (Kaatz, 1955). In the swamp, trees consisting of willows, cottonwood, sycamore, silver maple, and ashes dominate. Formerly, American elm was more prevalent, but most of these trees have since been destroyed by the dutch elm disease. Shrubs are mostly dogwoods, elderberry, willows, buttonbush, and roses. Diversity of herbaceous flowering plant species in the swamp is generally low. Among the more common occurring ones during the summer season are nettles, false-nettle, fringed loosestrife, and spotted touch-me-not. In the spring season, herbaceous species are more plentiful, and they bloom before the leaves emerge on the woody plants. Selected examples are skunk-cabbage, marsh marigold, swamp buttercup, spring cress, bulbous cress, and golden ragwort. Ferns can sometimes be quite plentiful.

Short-Term Changes

Short-term changes in the size of populations of aquatic and wetland plants in western Lake Erie are explainable, in part, because of the effect of fluctuating water-levels on these plants. Within the past 20 years, in 1973 and 1986, the waters of Lake Erie have twice been at an all time record high. This high water level occurs about every 15 years, but the interval has varied from 10 to 20 years since the turn of the century (Fig. 11). Thomas H. Langlois (1945, p. 98) in his book, *The Western End of Lake Erie and Its Ecology*, commented briefly on the "backward and forward movement of vegetational zones along the shores." According to him, this movement of vegetation results from Lake Erie's high and low water cycles. Consequently, if aquatic vascular plants are sensitive or tolerant to these changes in water levels through time, then local changes in species composition, such as increase in numbers of certain species and the disappearance of other species should be evident in those ponds and marshes whose water levels are controlled by the level of Lake Erie. Indeed, this phenomenon is occurring, and after observation of it for the past 20 years, particularly in Carp Pond along the north shore of Kelleys Island, one can now comprehend what Langlois meant by his statement.

By selecting 10 large, dominant, showy-flowered, mostly rhizomatous, perennial aquatic vascular plants, the effect of high water can be demonstrated (Table 14; Stuckey, 1976b). The three species, *Typha angustifolia, Sagittaria latifolia,* and *Sparganium eurycarpum* at the top of the list in Table 14, are the most drastically affected by a sudden rise in water-level (Figs. 12, 13, 14). These are emersed species which grow in shallow water or on mudflats and spread by rhizomes, tubers, or stoloniferous rhizomes. They usually form narrow to broad zones around the edge of nonwooded ponds, particularly in those ponds which have broad, very gently sloping shorelines. Of the 10 species in this list, these three are the most sensitive to a sudden rise in water-level at some critical period, most probably in the spring of the year when water-levels may rise 1 to 2 or more feet. Consequently, these plants, which have no vegetative mechanism to allow for survival in the newly created deeper water habitats, may be partially or totally eliminated from a pond or marsh. This

Invasion of Purple Loosestrife into Cat-Tail Marsh

Figure 9. **1952**. A solid stand of *Typha angustifolia* (narrow-leaved cat-tail) in marsh along south shore of Sandusky Bay at the Maples, formerly called Levis Marsh (photograph by Maurice Giltz, taken during study by Giltz and Myser, 1954; from the collections of David H. Stansbery, Museum of Zoology, The Ohio State University).

Figure 10. **1978**. A stand of *Typha angustifolia* (narrow-leaved cat-tail) which has been invaded by *Lythrum salicaria* (purple loosestrife) during high water of the early 1970's in marsh along south shore of Sandusky Bay at the Maples, formerly called Levis Marsh (photograph by Mark Reinking, August 1978).

Table 14. Selected rhizomatous perennial aquatic vascular plants of Lake Erie marshes and their sensitivity to high waters.

Species	Common Name	Sensitivity Change
Typha angustifolia	narrow-leaved cat-tail	most sensitive
Sagittaria latifolia	arrowhead	least tolerant
Sparganium eurycarpum	bur-reed	
Hibiscus palustris	swamp mallow	
Pontederia cordata	pickerelweed	intermediate
Decodon verticillatus	swamp loosestrife	sensitivity
Polygonum coccineum	water smartweed	
Butomus umbellatus	flowering-rush	
Nuphar advena	spatterdock	most tolerant
Nymphaea tuberosa	white water-lily	least sensitive

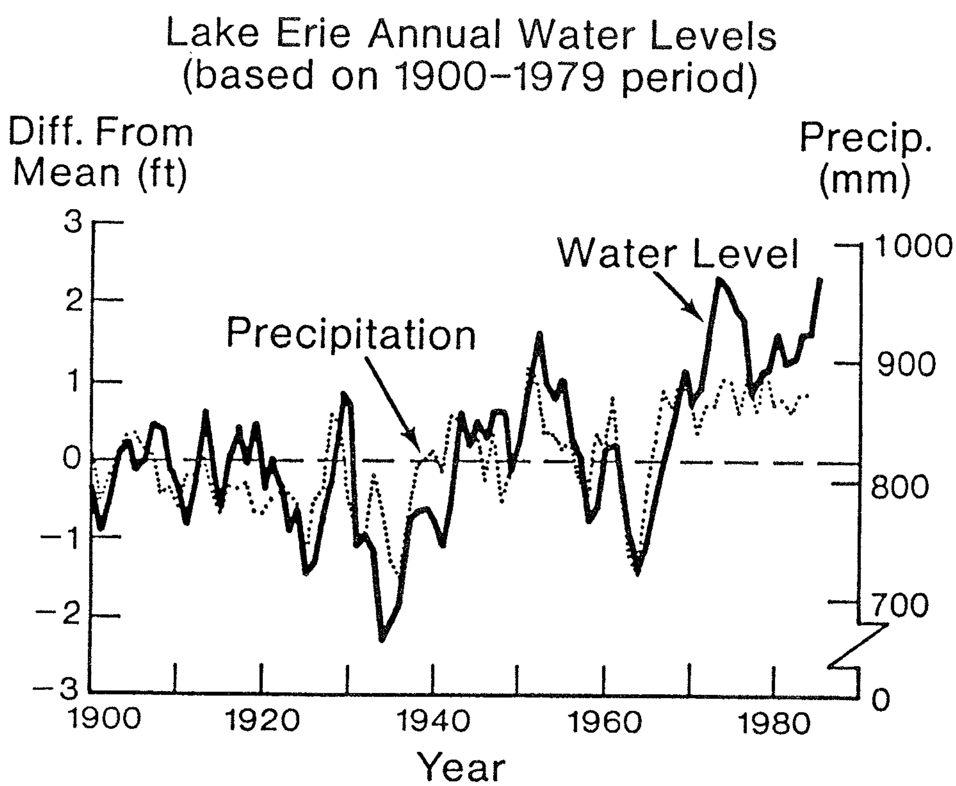


Figure 11. Comparison of Lake Erie annual water levels (from F. Quinn, Great Lakes Environmental Research Laboratory, NOAA; Carter 1986).

Figure 12. **1969**. Dead *Typha angustifolia* (narrow-leaved cat-tail) killed by high water of 1969 at Magee Marsh (Crane Creek State Park) (photograph by Marvin L. Roberts, September 1970).

Figure 13. **1974**. Partially dead *Typha angustifolia* (narrow-leaved cat-tail) killed by high water of 1973 in marsh west of Port Clinton (photograph by Jane L. Forsyth, 16 September 1974).

Figure 14. **1976**. Recovered *Typha angustifolia* (narrow-leaved cat-tail) two years later, in marsh west of Port Clinton, near the same site as Figure 13 (photograph by Jane L. Forsyth, 20 July 1976).

elimination is particulary evident in those ponds with steep banks and little or no adjacent gently sloping mudflats, or with surrounding woodlands with a closed canopy where the red wave-lengths of light penetrate very little to the forest floor. In ponds with gently sloping available mudflats, or very shallow water, and not surrounded by swamp forest, these species will re-establish there in new zones. If high water-levels are maintained, the trees in the adjacent swamp forest will die over a period of several years and the canopy of the forest will eventually become open. Under an open canopy, the red wave-lengths of light reach the mudflats of the swamp forest floor and the zones of emersed herbaceous aquatic plants return under the dead trees. During this entire time of high water, the species really have survived, but only as seeds in the mud. These seeds evidently have the ability to germinate once a sufficient amount of red light reaches the substrate surface, and the moisture and temperature conditions are optimum (Wesson and Wareing, 1969 a, b). For example, broad-leaved cat-tail, *Typha latifolia*, once a common species of the western Lake Erie marshlands about 1900, but now very rare in the marshes because of a large die-off in the 1930's, suddenly reappeared on mudflats created by high water extending into new areas during the mid 1970's, where previously there were lawns and fields. These plants must have germinated from seeds that had been buried in the soil for 40 or more years.

Those species that are quite tolerant to a sudden rise in water level have apparently developed vegetative mechanisms which allow them to survive under these conditions. *Hibiscus palustris* grows in clumps which may in fact enlarge and form numerous adventitious roots on the stems below the surface of the water. These roots are closer to a larger supply of oxygen, and hence may explain why this species can withstand limited rising water level conditions. Compared to the next two species, *H. palustris* is probably the least adapted to survive changes in water levels. Dead or partially living colonies have been noted under these conditions, and some colonies even spread to adjacent mudflats, exhibiting a pattern similar to the extremely sensitive species mentioned earlier. *Decodon verticillatus* reproduces vegetatively by layering. The stems arch over into the water, the stem tips take root, and new shoots develop and anchor themselves in the mud. These new plants can continue the same process and large areas of a marsh can be colonized in this manner. *Polygonum coccineum* forms long floating stems with broader, shorter leaves that are somewhat arrow-shaped. These floating stems, often seen up to 12 or sometimes 20 feet long, develop adventitious roots and young aerial plants at the nodes along the floating stem. When the water-level lowers, these stems drop to the mud, take root, and the young plants can soon become established by extending out new slender rhizomes. Soon the species can colonize the mudflat.

Those species most tolerant of high water levels and which usually continue to survive under such conditions are *Butomus umbellatus, Nuphar advena*, and *Nymphaea tuberosa*. *Butomus umbellatus*, the only nonindigenous species in the selected list, is most striking in that it changes from a stout, erect, flowering, or capable of flowering plant on the mudflat to a submersed form with limp three-angled leaves which lacks the ability to flower. *Nuphar advena* and

Nymphaea tuberosa usually show an increase in the size of colonies after two or three years of higher water level. These species have broad leaves that are either projecting above or are floating on the water. Their leaves are kept in these positions by the continuous growth of the petioles year after year while at the same time compensating for the higher level of the water (Arber, 1920, p. 31). *Nymphaea tuberosa* has invaded some portions of ponds that have two or more feet of water, where previously these places were dry or mudflats. While water levels remain high, these colonies of *N. tuberosa* continue to expand in size. These two species of waterlilies, being quite tolerant of high water levels, survive only in those ponds that continually have water. They disappear from ponds that become dry for a period of several years, indicating that these two species are quite sensitive to drying conditions (Schaffner et al., 1904, pp. 164-165).

The disappearance of certain species and increase in abundance of other species during high water times is usually only temporary, and when water levels lower, exposing shorelines and mudflats, these species will return, many of them having survived as seeds in the mud and sediments for many years (Figs. 15-23). The composition of the seed bank and its relationship to the early flora that appears following lowering of water levels in Lake Erie wetlands is just beginning to be studied (Siegley, 1986; Siegley et al., 1988), and much more investigation needs to be conducted. Other species survive as small isolated vegetative colonies on mudflats or in shallow water near the edge of ponds. The dynamic and fluctuating water level conditions that occur in the Lake Erie marshes provide a major explanation for the great diversity of species in these marshes, compared to lakes, reservoirs, and other marshes inland in Ohio that generally have stable water levels and fewer kinds of substrates. Stabilization of water levels by diking and drawdowns in segments of Lake Erie's marshes, for example, also reduces the diversity of the aquatic and wetland flora (Meeks 1963, 1969).

If the selected 10 species listed in Table 14 were arranged in a pond, they would occur in a zonation pattern in which the species most sensitive to high water would occur around the edge on the mudflats or in shallow water. Often a zone of *Typha angustifolia* occurs on the outer edge of the pond and to the inside of this zone is *Sagittaria latifolia* and *Sparganium eurycarpum*, usually occurring together along with the mudflat form of *Butomus umbellatus*. All three of these species may occur in zones separated one from another. Moving into slightly deeper water would first be *Hibiscus palustris* then *Decodon verticillatus* and then *Pontederia cordata*. In the deepest water near the center would be *Nymphaea tuberosa*, and in slightly shallower water, *Nuphar advena* would occur. Because of the morphological versatility of the nonindigenous *Butomus umbellatus*, it can be expected in almost any position in the pond. In view of great disturbances brought about by man through dredging, diking, and draining, naturally occurring ponds and marshes are nearly impossible to find in Ohio. Therefore, it is now virtually impossible to see these idealized aquatic vegetation zones, but where remnants of these zonation patterns do occur, the position of these selected species in the zonation scheme correlates quite well with the behavior of these species when they come in contact with a sudden

Figure 15. **1966**. Carp Pond with zones of emersed wetland plants on mudflat (photograph by Ronald L. Stuckey, July 1966).

Figure 16. **1968**. Carp Pond with zones of emersed wetland plants in very shallow water (photograph by Ronald L. Stuckey, 9 August 1968).

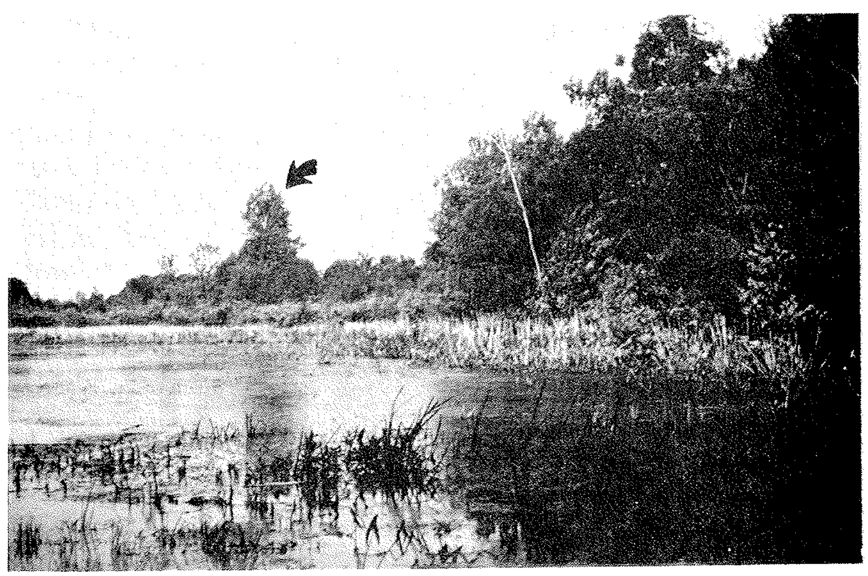


Figure 17. **1969**. Carp Pond showing loss of emersed wetland plants following a rise of water in the winter and spring (photograph by Thomas Duncan, 14 August 1969).

Arrow points to indicator tree that is living, figures 15, 16, 17.

Figure 18. **1975**. Carp Pond at time of highest water level, with emersed wetland plants absent and some trees now dead (photograph by Randall Snodgrass, August 1975).

Figure 19. **1978**. Carp Pond after high water has receded; several colonies of *Nymphaea tuberosa* (white water-lily) have invaded; emersed species have recolonized along sandy shore in foreground (photograph by Ronald L. Stuckey, August 1978).

Figure 20. **1979**. Carp Pond with water level lowered and *Nymphaea tuberosa* (white water-lily) covering large areas of the pond (photograph by Ronald L. Stuckey, August 1979).

Arrow points to indicator tree that is dying, figure 18; dead in figures 19, 20.

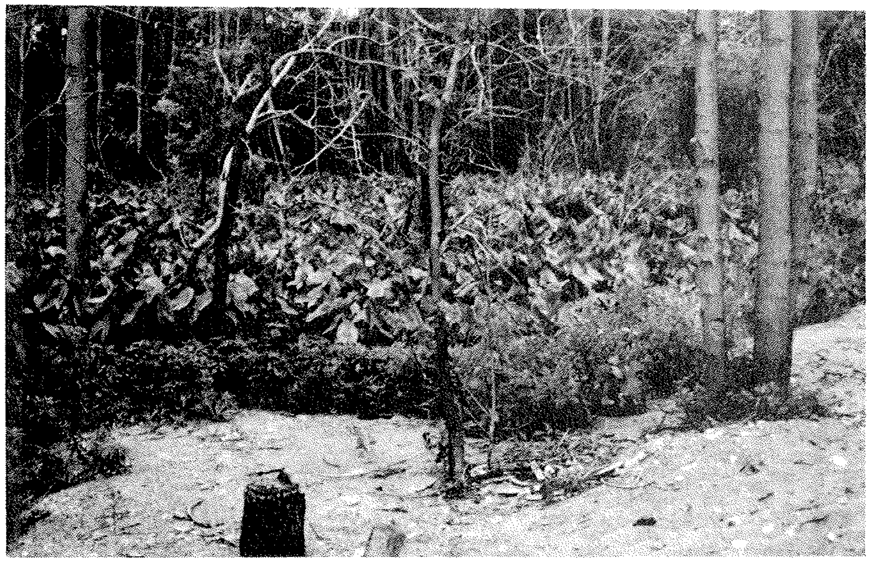


Figure 21. **1978**. Carp Pond showing reformation of zone of *Sagittaria latifolia* (arrowhead) under partially dead trees where sunlight (red portion) reaches mudflat and seeds of herbaceous species germinate and begin to form new zones (photograph by Ronald L. Stuckey, August 1978).

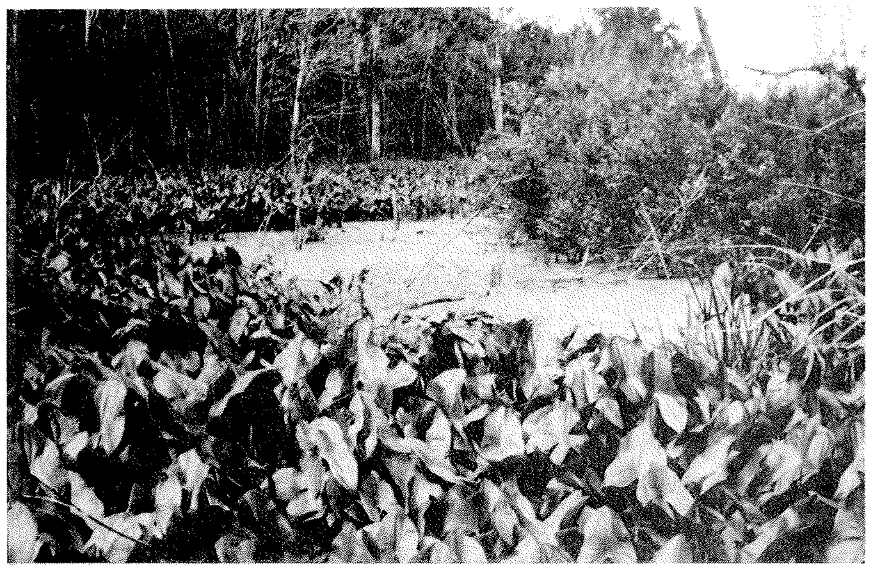


Figure 22. **1979**. Carp Pond showing reformation of zone of *Sagittaria latifolia* (arrowhead) on mudflat in open area away from the woody vegetation (photograph by Ronald L. Stuckey, August 1979).

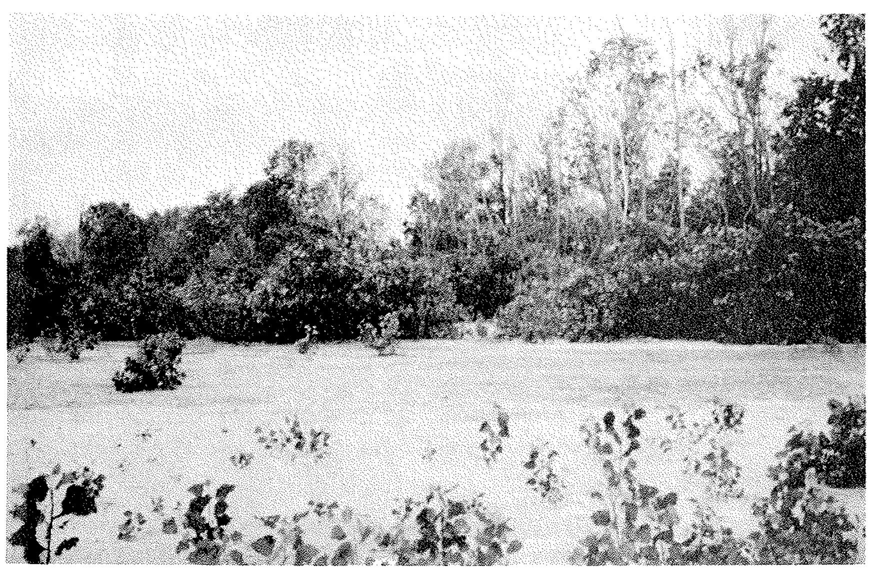


Figure 23. **1979**. Carp Pond at about the same position as Figure 16, where *Populus deltoides* (cottonwood) is the dominant species.

rise or change in water level. The effects of Lake Erie's high water are also demonstrated in such phenomena as lawns becoming marshes, cat-tail marshes becoming ponds, and tree covered sand and gravel beaches becoming barren beaches or severely wave-washed shorelines.

INVASION OF NONINDIGENOUS SPECIES

The invasion of nonindigenous species constitutes a third major kind of change in the aquatic and wetland flora of western Lake Erie (Stuckey, 1970b). As a whole the vascular-plant flora of the state of Ohio contains approximately 24% (599 of 2,518) nonindigenous species, a percentage which reveals the large influence that human activity is having on the flora of an area that large. In the marshlands of western Lake Erie even higher percentages of nonindigenous species are known, particularly in those marshes where considerable disturbances and changes by man have taken place. Representative percentages of nonindigenous species at sites studied are: 18% (24 of 131 species) at Fox's Marsh on North Bass Island (Pilatowski, 1987), 26% (71 of 273 species) at Old Woman Creek (Marshall, 1977), 27% (97 of 364 species) at Winous Point (Lowden, 1967, 1969), and 36% (46 of 128 species) at Perry's Victory Monument Marsh (Stuckey, 1975a). At all of these locations considerable influence by human activity is evident owing to the building of dikes and roads which provide ideal sites for species of drier habitats. It is in these drier habitats where nonindigenous terrestrial species invade. Many of these species are considered to be "weeds" that have followed man from his European homeland.

On newly constructed dikes which have been built to retain the marshlands in place and control water levels, the percentage of nonindigenous species on the upper portion of the dikes is known to be as high as 55% (43 of 78 species) recorded by Bartolotta (1978). In these sites Canada thistle, sweet clovers, ragweeds, wild carrot, black mustard, and various grasses dominant during the early years following construction. In the wetlands proper, the number of nonindigenous species is fewer, but most of these are particularly aggressive species. Walter's millet has been planted for wildlife food. Submersed species such as *Myriophyllum spicatum*, *Najas minor*, and *Potamogeton crispus* inhabit ponds and open water areas of the marshes to the exclusion of the native species, while populations of emersed species, such as *Butomus umbellatus* (Fig. 24), *Epilobium hirsutum* (Fig. 25), *Lycopus europaeus* and *Lythrum salicaria* (Fig. 26) continue to expand, eliminating the native wetland species that are more desirable as food and cover plants for wildlife. In some places acres of *Lythrum salicaria* (purple loosestrife) now dominate to the exclusion of most other species (Balogh, 1986; Stuckey, 1981b; Thompson, et al. 1987). This species should be eliminated wherever seen, not only because it can outcompete all of the other species in the marsh and destroy the species diversity of the marsh, but it is also the law in Ohio to eliminate spontaneous populations.

Studies of the distributional and life histories of these foreign species provide information that may be useful to predict their future behavior and to

Examples of Invading Species

Figure 24. *Butomus umbellatus* (flowering-rush) at Perry's Victory Monument Marsh, Put-in-Bay (photograph by James S. Pringle, July 1975).

Figure 25. *Epilobium hirsutum* (great hairy willow-herb) at Perry's Victory Monument Marsh, Put-in-Bay (photograph by James S. Pringle, July 1975).

Examples of Invading Species

Figure 26. *Lythrum salicaria* (purple loosestrife) at Moxley's Marsh, west of Sandusky (photograph by Ronald L. Stuckey, 12 July 1975).

Figure 27. *Lycopus asper* (western water horehound) at Luna Pier, Michigan (photograph by William H. Anderson, 14 September 1968).

establish measures that would need to be implemented to bring them under control. Distributional histories have been prepared for some of the nonindigenous species of the western Lake Erie marshes: *Butomus umbellatus* (Core, 1941; Stuckey 1968a), *Epilobium hirsutum* (Stuckey, 1970a), *Lycopus asper* (Fig. 27; Stuckey 1969). *Lycopus europaeus* (Stuckey and Phillips 1970), *Potamogeton crispus* (Stuckey, 1979b), and *Najas minor* (Wentz and Stuckey 1971).

SUMMARY: MAINTAINING THE DIVERSITY

The aquatic and wetland vascular-plant flora of western Lake Erie represents a flora of great diversity, certainly the most diversified in the state of Ohio and the Great Lakes and perhaps equally diverse with many other wetlands in the United States. This diversity has been maintained over the years by the natural changing water-levels of Lake Erie, creating open water areas and extensive mudflats, marshes, and swamps. A high floristic diversity is one measure revealing that the wetland is of high quality. With the coming of European man and the various activities he has conducted in the wetlands, noticeable changes in the flora have occurred during the past 100 years that are now being documented. In selected wetlands where man's activity has been particularly intense, species diversity has decreased to the extent that at least half of the native species have disappeared and one-fourth to one-third of the flora is nonindigenous. Stabilization of the water-levels through diking and ditching also creates a lower diversity of native species in the wetlands. These floristic changes certainly are bringing about a reduced diversity in the native wetland species, and consequently the quality of the marshes and swamps as a whole are degraded and lowered.

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LAKE ERIE WETLANDS: FISHERIES CONSIDERATIONS

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HISTORY

Many scientists (Langlois 1954; Trautman 1957, 1977, 1981; Regier et al. 1969; Van Meter and Trautman 1970; and Hartman 1972, 1973) have reviewed the composition of Lake Erie fish communities and the history of their exploitation and responses to environmental changes and cultural stresses. They have recorded approximately 138 species of fishes in Lake Erie and its tributaries, at least 40 of which are presently or have formerly been of significant commercial or recreational value. Lake Erie supports a greater diversity of fish species and a higher biomass of fish per unit area than any of the other Great Lakes. The diversity and abundance of fishes in the lake is attributable to its southernmost position in relation to the other Great Lakes, its relatively warm, shallow, nutrient-rich waters, and its variety of aquatic habitats, in particular an extensive coastal marsh system surrounding the western end of the lake (Langlois 1954; Trautman 1957, 1981; Van Meter and Trautman 1970). The original native fish communities of Lake Erie were characterized by a predominance of coldwater and coolwater species, including: lake sturgeon (Table 1 contains all scientific names of fish used in this paper), lake trout, lake whitefish, lake herring, northern pike, muskellunge, and blue pike. Many warmwater species, such as white bass, white crappie, black crappie, largemouth bass, and smallmouth bass, were also abundant.

The original Lake Erie wetlands were vast in size and created a system of interrelated macrophyte communities which in turn provided a variety of important habitats for fish species. They functioned in various combinations as feeding areas, shelter, and spawning substrate depending on the fish species. These wetlands also acted as a buffer for floods and in many cases a trap for their load of nutrients and silt. This function helped to keep the nearshore waters low in turbidity and reduced siltation. Such conditions are necessary to species requiring clear water and clean sand or gravel substrates (Raphael 1980). Lake Erie water levels have historically fluctuated, but the impact on wetlands was minimal. As water levels decreased the marginal wetlands simply moved further into the lake, and when water levels rose, the wetlands moved inland.

The fish community in these wetlands was apparently quite diverse although early detailed studies are lacking. Approximately 47 species of fish are or once were associated with the coastal marshes of Lake Erie (Table 2). This assemblage was made up of fish which used the wetlands for a variety of

Table 1. Common and scientific names of fish referenced in this paper.

Common Name[1]	Scientific Name[1]
Alewife	*Alosa pseudoharengus*
Banded Killifish	*Fundulus diaphanus*
Bigmouth Buffalo	*Ictiobus cyprinellus*
Black Bullhead	*Ictalurus melas*
Blackchin Shiner	*Notropis heterodon*
Black Crappie	*Pomoxis nigromaculatus*
Blacknose shiner	*Notropis heterolepis*
Black Redhorse	*Moxostoma duquesnei*
Bluegill	*Lepomis macrochirus*
Blue Pike	*Stizostedion vitreum glaucum*
Bluntnose Minnow	*Pimephales notatus*
Bowfin	*Amia calva*
Brook Silversides	*Labidesthes sicculus*
Brook Stickleback	*Culaea inconstans*
Brown Bullhead	*Ictalurus nebulosus*
Central Mudminnow	*Umbra limi*
Channel Catfish	*Ictalurus punctatus*
Common Carp	*Cyprinus carpio*
Creek Chub	*Semotilus atromaculatus*
Emerald Shiner	*Notropus atherinoides*
Fathead minnow	*Pimephales promelas*
Freshwater Drum	*Aplodinotus grunniens*
Gizzard Shad	*Dorosoma cepedianum*
Golden Redhorse	*Moxostoma erythrurum*
Golden Shiner	*Notemigonus crysoleucas*
Goldfish	*Carassius auratus*
Grass Pickerel	*Esox americanus vermiculatus*
Green Sunfish	*Lepomis cyanellus*
Iowa Darter	*Etheostoma exile*
Johnny Darter	*Etheostoma nigrum*
Lake Chubsucker	*Erimyzon sucetta*
Lake Herring	*Coregonus artedii*
Lake Sturgeon	*Acipenser fulvescens*
Lake Trout	*Salvelinus namaycush*
Lake Whitefish	*Coregonus clupeaformis*
Largemouth Bass	*Micropterus salmoides*
Logperch	*Percina caprodes*
Longnose Gar	*Lepisosteus osseus*
Muskellunge	*Esox masquinongy*
Northern Pike	*Esox lucius*
Orangespotted Sunfish	*Lepomis humilis*
Pugnose Minnow	*Notropis emiliae*
Pugnose Shiner	*Notropis anogenus*
Pumpkinseed Sunfish	*Lepomis gibbosus*

Table 1. Continued.

Common Name[1]	Scientific Name[1]
Quillback	*Carpoides cyprinus*
Rainbow Smelt	*Osmerus mordax*
Rainbow Trout	*Oncorhynchus mykiss*
Rock Bass	*Ambloplites rupestris*
Sea Lamprey	*Petromyzon marinus*
Shorthead Redhorse	*Moxostoma macrolepidotum*
Silver Chub	*Hybopis storeriana*
Silver Lamprey	*Ichthyomyzon unicuspis*
Silver Redhorse	*Moxostoma anisurum*
Smallmouth Bass	*Micropterus dolomieui*
Spottail Shiner	*Notropis hudsonius*
Spotted Gar	*Lepisosteus oculatus*
Spotted Sucker	*Minytrema melanops*
Tadpole Madtom	*Noturus gyrinus*
Trout-perch	*Percopsis omiscomaycus*
Walleye	*Stizostedion vitreum*
White Bass	*Morone chrysops*
White Crappie	*Pomoxis annularis*
White Perch	*Morone americana*
White Sucker	*Catostomus commersoni*
Yellow Bullhead	*Ictalurus natalis*
Yellow Perch	*Perca flavescens*

[1]Nomenclature according to Robins et al. (1980) except rainbow trout according to Robins (1988)

purposes including spawning, refuge during their juvenile stages, and feeding areas. Twenty-eight of these fish are considered obligate wetland species during one or more of their life stages, and others are facultative in their wetland use.

The temporal dynamics of this community were complex, since use tended to be seasonal as well as diel. For example, species such as northern pike used the wetlands for spawning at ice-out. The adult northern pike tended to leave the marshes as the vegetation increased while the young continued to use the area as a nursery. In midsummer the juveniles left to avoid low water periods, warm water and occasional low nighttime oxygen concentrations. Based on recent knowledge gained about white crappie (Leckie

1980; Durfey 1986) they also used the areas for spring spawning with the adults continuing to make feeding forays into the wetlands during the evening.

The community was probably mostly composed of benthivores, detritivores, and omnivores with piscivores using these areas for periodic feeding bouts. Generally, fish using wetlands later in the summer were the more tolerant species, able to function in dense vegetation, higher water temperatures, and periodic low oxygen. Thus, the reproductive and feeding guilds of fish using the wetlands were highly variable, regulated by season and time of day, and required ready access to and egress from the wetland.

Coastal wetlands provided a diverse habitat of open water and submergent, floating, and emergent vegetation. Our research (Petering and Johnson, The Ohio State University, unpublished data) indicates that larval fish are somewhat selective within this diversity with crappie (*Pomoxis* sp.) and gizzard shad being found primarily in open water and minnows (Cyprinidae) and sunfish (*Lepomis* sp.) being found in vegetated areas. Wetlands also provided a continuum, both of water depth extending into the open lake and laterally along the shoreline. This was important because when populations were faced with catastrophic events such as reduced oxygen, draining, flooding, siltation, and high water temperatures, they could seek refuge by moving into the deeper water just off shore or laterally into more hospitable environs.

Because the original Lake Erie wetlands provided a continuous habitat, the flow of genetic information was unimpeded, even among members of obligate wetland users. This flow of genetic information was presumably important as it allowed new adaptations to be "communicated" along an extensive geographical area. Thus, marginal wetlands provided a "sidewalk," a concept introduced and discussed by Stuckey (1972) in relation to plant migration. This "sidewalk" provided fish not only a path for genetic information but also a means for invading species to expand along the coast without ever leaving the wetland habitat.

CURRENT CONDITIONS

A general reduction of many of the original fish populations mentioned previously has occurred lake-wide. Intensive commercial exploitation of the originally abundant salmonid, esocid, and percid populations was largely responsible for significant depletions or extirpations of these populations. In addition, the introduction or invasion of exotic species such as sea lamprey, alewife, rainbow smelt, carp, goldfish, and white perch, which compete with or alter the habitats of native species, have deleterious effects on many native populations. Cultural development of the Lake Erie region resulted in the alteration or elimination of essential habitats and spawning areas as a result of agricultural siltation, industrial waste discharge, draining and filling of marshes, and channelization or damming of tributaries used by lake-run spawners. Limnological changes associated with a climatic warming trend and increasing

Table 2. Fish associated with coastal marshes of western Lake Erie.[1]

Species[2]	Importance[3]	Abundance[1] Pre-1900	Present
Longnose Gar*	?	A	C
Spotted Gar*	E	C	R
Bowfin*	?	A	U
Gizzard Shad	P	U	A
Central Mudminnow*	?	A	C
Northern Pike*	R	A	U
Muskellunge*	E	A	R
Grass Pickerel*	?	A	C
Common Carp*	C,R	C	A
Goldfish*	C	U	C
Golden Shiner*	P	A	C
Pugnose Minnow*	E	U	R
Emerald Shiner	P	A	A
Spottail Shiner	P	A	A
Blackchin Shiner*	E	C	R
Blacknose Shiner*	E	C	R
Pugnose Shiner*	?	U	R
Fathead Minnow*	P	R	C
Bluntnose Minnow	P	A	A
Bigmouth Buffalo	C	U	C
Quillback	C	C	C
Shorthead Redhorse	C	A	C
White Sucker	C	A	A
Spotted Sucker	?	A	U
Lake Chubsucker	E	A	R
Channel Catfish	C,R	A	C
Yellow Bullhead*	C,R	C	C
Brown Bullhead*	C,R	A	C
Black Bullhead*	C,R	A	A
Tadpole Madtom*	?	C	U
Banded Killifish*	E	A	R
Brook Stickleback*	?	A	C
White Bass	C,R	A	A
White Perch	?	O	A
White Crappie*	R	A	A

Table 2. Continued.

Species[2]	Importance[3]	Abundance[1] Pre-1900	Present
Black Crappie*	R	A	C
Rock Bass	R	A	C
Smallmouth Bass	R	A	C
Largemouth Bass*	R	A	C
Green Sunfish*	R	A	C
Bluegill*	R	A	C
Pumpkinseed Sunfish*	R	A	C
Yellow Perch	C,R	A	A
Logperch	?	A	C
Johnny Darter	?	A	A
Iowa Darter*	?	C	R
Freshwater Drum	C,R	C	A

[1]Based on Trautman (1957,1981), Van Meter and Trautman (1970), and unpublished data of Ohio Department of Natural Resources and Ohio State University, School of Natural Resources, Center for Lake Erie Area Research and F.T. Stone Laboratory; abundance relative to Lake Erie in general: A = abundant; C = common; U = uncommon; R = rare; O = absent

[2]Nomenclature according to Robins et al. (1980). Scientific names found in Table 1

[3]Demonstrated economic or legal importance only: R = recreational; C = commercial; P = known prey use; E = endangered and legally protected (Ohio Department of Natural Resources); ? = importance not known (or formerly important but currently of unknown importance due to greatly decreased numbers)

* = Entirely or largely dependent on aquatic vegetation or marsh habitats

cultural nutrient loading resulted in accelerated eutrophication and accompanying dissolved oxygen depletion, increased plankton densities, and increased deposition of organic sediments (Langlois 1954; Beeton 1961; Regier et al. 1969; Verduin 1969; Hartman 1972, 1973; Regier and Hartman 1973).

Cultural stresses in Lake Erie are greater than in the other Great Lakes because of the relatively small size and volume of the lake and the extensive agricultural and urban-industrial development in its watershed. Such stresses continue to affect the lake, although they are now strictly regulated and partly abated or reversed by scientific land use, water quality, and fisheries management practices. The coldwater salmonid component of the original fish communities of the lake has been largely eliminated, and remaining valuable coolwater species such as yellow perch and walleye are abundant despite heavy exploitation. Warmwater species such as gizzard shad, common carp, spottail shiner, channel catfish, brown bullhead, white bass, and freshwater drum comprise the largest and most stable component of the fish communities of the lake. Common carp, channel catfish, and white bass are currently important commercial and recreational fishes. Other warmwater species such as largemouth and smallmouth bass and white and black crappies have declined in abundance due to a combination of intense exploitation and habitat loss. Species favored by the warmer, more turbid condition of the lake, including gizzard shad and freshwater drum, have proliferated, yet have minimal current economic values (Trautman 1957, 1981; Regier et al. 1969; Hartman 1972; Van Meter 1973). In general the lake community has become less diverse and dominated by species more tolerant of declining water quality.

As shoreline areas began to be developed for agriculture, urban living, and industry, the extensive Lake Erie wetlands were drained, a process extensively discussed by other papers in this document. As dikes were built, the wetlands were "backstopped." As a result, the normal fluctuations of the lake water level had devastating impacts on the remaining wetlands with high water levels creating deep, turbid submerged bottomlands with little vegetation. As a response to that impact, many wetlands (over half of the existing wetlands in Ohio waters) had to be revegetated by diking former wetland areas to allow water level control. Most of those dikes were created by federal and state agencies and by private clubs, all interested primarily in establishing or protecting much needed waterfowl habitat. The decline in abundance since 1850 of many fish populations dependent on coastal marshes as adult habitats or spawning and nursery areas has been largely attributed to the original draining and filling of marshes and to the inaccessibility of much of the remaining marsh area to such populations due to the presence of dikes or other control structures (Trautman 1957; Hartman 1973).

The wetlands of western Lake Erie no longer function as a single and integrated system. Instead of the contiguous buffer and ecotone between the open lake and terrestrial environments the wetlands are now isolated islands of vegetation separated by open water and, in many cases, dikes. Most runoff from surrounding land is no longer caught and filtered by wetlands, either because the wetlands have been lost or because most diked wetlands are completely isolated from the local watersheds.

Just as the introduction or invasion of exotic species had an effect on the lake as a whole, it has also had an impact on wetlands. No species illustrates this fact better than the common carp. Turbidity levels, already increased by changing land-use practices and wave action on shorelines formerly protected by wetlands, were increased further by the feeding actions of the common carp. This caused a reduction of light penetration and decrease of species diversity and biomass of vegetation (Crivelli 1983). In response the managers of diked marshes have attempted to exclude the common carp with a series of grates covering the entrances to their marshes. The expected result of this practice is a drastic reduction of adult fish movement of all species into and out of the wetland. The reduction of northern pike populations in western Lake Erie is partly attributable to this exclusion (Herdendorf 1987).

The changes in the Lake Erie wetland community are predicted to impact fish species differently, depending on the level of wetland use. Unfortunately, no broad data base exists to measure these losses. Those fish which are facultative marsh users, such as gizzard shad, quillback, white sucker, white bass, white perch, channel catfish, and yellow perch, can adjust to the loss of wetland continuity; they can modify which wetland areas they use. Their loss in numbers is hard to correlate with wetland loss. Reduction in numbers of obligate users such as northern pike, longnose gar, bowfin, bullheads, and crappies, should be easier to prove and may be greater than predicted by a linear relationship, since the loss of wetland continuity is more than a loss of habitat - it is a loss of communication. Isolated populations of obligate wetland fish may have, with the loss of their "sidewalk", a more limited gene pool with little opportunity to import fresh genetic information. These populations are also faced with periodic catastrophic events such as reduced oxygen, draining, flooding, siltation or toxic substance influx which they cannot easily escape, either because of dikes or because they are reluctant to enter open water to search for the next isolated wetland.

With wetlands becoming generally more hostile environments, we predict that, in much the same way as the lake fish community in general has reacted, the wetland fish community will be reduced in diversity and dominated by more tolerant species. That prediction can be tested specifically in some research we recently conducted comparing diked and undiked marshes in western Lake Erie and summarized in the following case study.

CASE STUDY: WINOUS POINT MARSHES

In 1982 we initiated studies supported by the Sea Grant Program (R/ER-1) to compare a 102 hectare diked marsh with an undiked bottomland immediately outside the diked area. The location chosen for the research was Winous Point Shooting Club, a private hunting club located at the head of Sandusky Bay. The diked marsh is characterized by relatively high water levels in the fall and winter, followed by a water drawdown in spring to encourage growth of aquatic vegetation. The only deep water left at that time is in a canal along one side of the marsh which has a maximum depth of 2.5 meters. The dominant submerged vegetation is water milfoil (*Myriophyllum spicatum*) with some sago pondweed (*Potamogeton pectinatus*) and curlyleaf pondweed (*P. crispus*). The emergent community is characterized by pickerelweed (*Pontederia cordata*) with some arrowhead (*Sagittaria latifolia*) and rushes (*Juncus* spp.) and bullrushes (*Scirpus* spp.). On the exposed mudflats we find swamp rosemallow (*Hibiscus palustris*), narrow leaf cattail (*Typha angustifolia*), and threesquare (*Scirpus americanus*) predominating. Floating leaf vegetation is mostly water lotus (*Nelumbo lutea*) with some white water lily (*Nymphaea tuberosa*). The submerged bottomland is actually the upper end of Sandusky Bay, an area called Muddy Creek Bay. It is mostly unvegetated with sparse beds of sago pondweed, an island of narrowleaf cattail, and small beds of water lotus.

These two systems are both very different from original Lake Erie wetlands. The diked marsh provides a good mix of aquatic vegetation although it is much less diverse than former wetlands. It only allows access by fish two times each year -- in the fall when the marsh is flooded and in the spring when the marsh is drained. The submerged bottomland on the other hand, while technically a wetland because of its water depth, is practically devoid of vegetation. It is also at the mouth of rivers which are used for spawning, so pelagic fish might be expected in the spring as they pass through to spawning areas upstream.

We have been sampling these two habitats for six years, using trapnets and seines for adult fish and push nets for larvae. We have also examined the potential immigration and emigration of adult fish between the diked marsh and the open bay. We have identified 27 species from the diked marsh while 42 species were captured in the undiked bottomland (Table 3). Trapnets, the most extensively used sampling equipment, were fished a total of 4,079 hours in both systems combined and captured 59,713 fish representing 44 different species.

Of the 44 species sampled only two, golden shiner (only one fish sampled) and banded killifish, were unique to the diked marsh. On the other hand, 16 fish species were unique to the undiked bottomland (Table 3). However, many of the species (e.g., the lampreys, alewife, rainbow trout, and the suckers) are considered pelagic, not wetland fish. This fact points out the unique open water aspect of the undiked bottomland. In order to evaluate the uniqueness of these two habitats as wetlands one should limit the analysis to fish characterizing wetlands.

Of the 47 fish species previously identified as wetland species (Table 2), we sampled 30. Of the 17 species not sampled, six are nearly extirpated from western Lake Erie: lake chub sucker, pugnose shiner, pugnose minnow, blackchin shiner, blacknose shiner, and Iowa darter. These species plus most of the other eleven not sampled in our study share one common habitat requirement, vegetated areas with clear water. That combination is no longer readily available in Lake Erie wetlands. There were only two of these "wetland" fish species, golden shiner (only one fish) and banded killifish sampled in the diked marsh exclusively, while six of these species were sampled exclusively in the undiked bottomland (longnose gar, spottail shiner, quillback, tadpole madtom, rockbass, and logperch). This would seem to argue further that the diked marsh is not providing an accessible and unique habitat for wetland fish and that the open and mostly unvegetated bottomland is functioning in some fashion as an important wetland habitat.

The most abundant fish sampled tended to be the same species in both systems; e.g. gizzard shad, common carp, goldfish, brown bullhead, and white crappie. These fish tend to be tolerant of adverse water quality conditions. The Ohio Environmental Protection Agency (OEPA 1987) has classified 82 fish as to

Table 3. Fish sampled from Winous Point marshes.

Species	Fish Abundance[1] Diked	Undiked	Feeding[2] Guild	Vegetation[3] Required?	Clear Water[3] Required?	Organic Substrate Required?
Silver Lamprey		R	P	no	yes	avoided
Sea Lamprey		R	P	no	yes	avoided
Longnose Gar	R	U	P	preferred	preferred	no
Bowfin	U	U	P	preferred	preferred	no
Alewife		R	V	no	no	no
Gizzard Shad	A	A	O	no	no	no
Rainbow Trout		R	I/P	no	yes	no
Rainbow Smelt		R	I	no	no	no
Common Carp	A	A	O	no	no	yes
Goldfish	A	A	O	yes	no	yes
Golden Shiner	R		I	yes	yes	yes
Silver Chub		R	I	no	yes	avoided
Creek Chub		R	G	no	no	no
Emerald Shiner	R	U	I	avoided	yes	no
Spottail Shiner		C	I	no	preferred	avoided
Fathead Minnow	U	U	O	no	no	no
Bigmouth Buffalo	R	U	I	no	no	yes
Quillback		A	O	avoided	preferred	yes
Silver Redhorse		R	I	no	yes	no

Table 3. Continued.

Species	Fish Abundance[1] Diked	Undiked	Feeding[2] Guild	Vegetation[3] Required?	Clear Water[3] Required?	Organic Substrate Required?
Black Redhorse		R	I	no	yes	no
Golden Redhorse		R	I	avoided	no	no
White Sucker	R	C	O	tolerated	no	no
Spotted Sucker		R	I	no	yes	no
Channel Catfish	R	U	O	avoided	no	no
Yellow Bullhead	R	R	I	yes	preferred	no
Brown Bullhead	A	A	I	preferred	preferred	yes
Black Bullhead	A	C	I	no	no	yes
Tadpole Madtom	R	R	I	yes	preferred	yes
Trout-perch		U	I	avoided	no	no
Banded Killifish	C		I	yes	yes	no
Brook Silverside	C	C	I	no	yes	no
White Bass	U	C	P	no	yes	no
White Perch	C	A	I	no	yes	no
White Crappie	A	A	I/P	preferred	no	no
Black Crappie	A	C	I	preferred	preferred	no
Rockbass		U	C	no	preferred	no
Green Sunfish	C	R	C	preferred	no	no
Bluegill	C	U	I	preferred	preferred	no
Orangespotted Sunfish	C	U	I	no	no	no

Table 3. Continued.

Species	Fish Abundance[1] Diked	Undiked	Feeding[2] Guild	Vegetation[3] Required?	Clear Water[3] Required?	Organic Substrate Required?
Pumpkinseed Sunfish	C	C	I	yes	preferred	yes
Walleye		R	P	avoided	yes	avoided
Yellow Perch	R	C	P	yes	yes	no
Logperch		R	I	yes	yes	avoided
Freshwater Drum	U	C	C	no	preferred	no

[1]If no letter appears in the column, no individual of that species was sampled.
A = Abundant - Present in 71% or more of our samples.
C = Common - Present in 29-70% of our samples.
U = Uncommon - Present in 11-30% of our samples.
R = Rare - Present in 10% or less of our samples.

[2]Feeding Guilds are patterned after Karr et al. (1986).
P = Piscivore
V = Invertivore
I = Specialist Insectivore
O = Omnivore
G = Generalist
C = Carnivore

[3]These habitat preference characteristics were summarized by the author from Trautman (1981).

their tolerance of low water quality. While most of these fish are stream species, 18 species were sampled in our study. Fifteen of the categorized species that we sampled are rated as moderately or highly tolerant of low water quality, while only three are rated as intolerant. Of these three intolerant species, brook silversides were sampled in both the diked and undiked systems while the other two, silver and golden redhorse were sampled in the undiked wetland. This fact indicates that both habitats are severely modified and that the diked system is not enhancing survival of species intolerant of poor water quality. There was one species, however, sampled from the undiked system which is considered endangered in Ohio; the silver lamprey.

As predicted previously, there were few piscivores taken in the study. Of the eight sampled fish species considered, at least at some stage of their life to be fish eaters, only three were found in the diked marsh. Increased turbidity makes sight feeding a difficult feeding strategy. Durfey (1986) found that white crappie had significantly less food in their stomachs in the upper, turbid end of a reservoir than did the fish in clearer water. The clear water also produced faster growing fish.

As another means to assess the interaction of the diked marsh with Lake Erie we monitored the immigration and emigration of fish with the protective grates removed. In one year 2,434 fish entered the marsh and 1,740 left. Most of these fish were gizzard shad. It would appear that the diked marsh is not a net exporter of fish to the lake. In another attempt to measure the isolation of the diked wetland we measured lengths of white crappie, black crappie, and common carp, captured inside and outside the diked wetland. In all cases the lengths of the fish were smaller inside the diked marsh. This again indicates that the diked marsh is isolated and also that high densities of fish have reduced the growth rates of these species in the diked marsh. White crappie, in particular, show this effect since most fish in the marsh are too small (under six inches) to eat fish while the white crappie in the open water are much larger and able to eat young fish of several species. This fact casts serious doubt on the diked marsh functioning as an effective nursery area. Ironically, the screens placed to restrict entrance of common carp into the marsh have apparently allowed young fish to enter but prevented adults from leaving, resulting in higher catch-per-unit-effort of common carp inside the diked marsh than in the undiked bottomland.

Our sampling of larval fish indicates that ten identifiable groups or species use the diked marsh for spawning while 12 groups use the submerged bottomland or surrounding areas (Table 4). The only groups or species using the diked marsh exclusively are the bullheads and the brook silversides. In the undiked wetland we find exclusive use by the suckers, channel catfish, yellow perch, and walleye. In cases where both systems produce the same fish larvae groups and densities can be estimated, the diked marsh does not consistently produce more of any group, while the undiked bottomland consistently produces more white bass/white perch, freshwater drum, and shiners.

To summarize our case study in regards to the predictions made previously, the fish found in both systems seem to reflect the loss in diversity predicted and also represent species which are more tolerant of adverse water quality conditions than those fish not found but which might be expected to be present. The systems also seem to be dominated by fish specializing in feeding on invertebrates rather than fish which use other fish as prey. The primary method of creating wetlands which have a good diversity of wetland plants has been diking. These data indicate that, while this habitat may be quite acceptable to wildlife species capable of crossing the dikes, such as waterfowl and furbearing mammals, the Lake Erie fish community is not significantly affected by this marsh. The diked marsh fish community is not particularly unique and fish are isolated from the larger lake-wide community. There is also no indication that the diked wetland provides unique or advantageous nursery areas for fish. It is important to remember that our study looked at only one representative from

Table 4. Summary of larval fish sampled in Winous Point marshes and their relative abundance.

Species or group	Diked Marsh	Undiked Bottomland
Carp/Goldfish	Present	Present
Gizzard Shad	Present	Present
White Bass/White Perch	Present	More Abundant
White/Black Crappie	Present	Present
Sunfish (*Lepomis* spp.)	Present	Present
Freshwater Drum	Present	More Abundant
Fathead Minnow	Present	Present
Brown/Black/Yellow Bullhead	Present	Absent
Minnows (*Notropis* spp.)	Present	More Abundant
Suckers (*Catostomus* spp.)	Absent	Present
Channel Catfish	Absent	Present
Yellow Perch	Absent	Present
Walleye	Absent	Present
Brook Silversides	Present	Absent

each type of marsh system. We cannot at this time extend our conclusions to other marsh units within Winous Point Shooting Club, and certainly not to other locations in Lake Erie.

THE FUTURE

We must first expand our knowledge about current fish communities in wetlands of all types around Lake Erie. The classification system used in this paper to make decisions about wetland function needs to be refined, made more quantitative, and made easily applicable to other wetlands, much as the OEPA has developed its biological criteria for evaluating streams and rivers.

The problem of low water quality in western Lake Erie wetlands is not easily solved. Massive changes in land-use practices and nutrient inputs will help. The managers of diked marshes need to find other methods to restrict populations of common carp and goldfish. The screens are not effective and poisoning the fish, while effective for a short time, reduces the community of fish to pioneer species and eliminates the possibility of establishing unique and high quality communities. We have been investigating the use of northern pike as a predator to reduce numbers of these fish. We have found that the northern pike prefer to prey on common carp and goldfish (Navarro 1988) but we have not conducted experiments which will provide conclusive evidence that water quality will improve in the presence of these predators.

Wetland loss is still underway in western Lake Erie, although at a slower pace. Attempts to mitigate that loss by providing a wetland at another location are difficult. This is especially true, as illustrated in our case study, if the wetland is to be accessible to fish. In particular, states which have more natural wetland than is left in western Lake Erie may wish to carefully examine their policies to prevent the loss of contiguous wetland areas.

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TOWARD AN OHIO COASTAL MANAGEMENT STRATEGY

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I have been asked to speak about an Ohio Coastal Management Strategy. Most the presentations that you've heard so far today have been technical in nature. My presentation will be a bit different as a strategy is more policy oriented. Also I am not going to limit myself to just wetlands and estuaries.

I've been with the Ohio Department of Natural Resources for about 14 years working on coastal management issues. One of the goals in the Department 14 years ago was to develop a federally approved coastal management program. Ohio still has not been able to get a federally approved program. It is my hypothesis that one of the reasons Ohio has had difficulty with coastal management and other Lake Erie issues is that a ready constituency has not been developed on lake issues. A reason for that is the lack of a public sense of stewardship for Lake Erie. The hypothesis states that a difference exists in the perception of Lake Erie by the people from the State of Ohio from that of the other coasts by residents of those states. On the other coasts, most beaches are held as a public resource. If people can get to the beach, they walk the entire length of the beach, fish, swim, or sunbathe. Through this enjoyable experience, the residents of those states have the opportunity to develop a sense of stewardship. On the Great Lakes, a different situation exists. The beaches are held by the upland owner and are a private resource. If you want to go to a beach, you have to go to a public park. Once you arrive at that park, you are restricted to the boundaries of that park. You cannot walk the entire length of the beach but must remain within the park. It is difficult, then, for people from around Lake Erie to enjoy it. Without this experience of Lake Erie, the public in general doesn't develop the sense that it's a public resource and needs to be protected. Therefore, we have a lesser degree of stewardship for Lake Erie and less support for our initiatives.

One thing I want to emphasize today, however, is that Lake Erie and the Great Lakes are very important to the region. The Great Lakes literally and figuratively form this region. The Great Lakes are the cornerstone of our economy. From a national perspective, 95 percent of the fresh surface water of the U.S. is in the Great Lakes (International Joint Commission, 1985). Seventy percent of the domestic raw steel in the U.S. is produced in the Great Lakes region. Fifty-six percent of domestic machine tool establishments are in the Great Lakes states (Great Lakes Commission, 1985). This is partly the result of the quality of the water and the dependability of the lakes, the low-cost water transportation, and the location of the resources. The Lakes are significant for our economy and significant for the quality of life of the people in the Great

Lakes states (Center for the Great Lakes, 1984).

Lake Erie is also very important to Ohio for a number of reasons. First, Lake Erie is important as a water supply. Ohio utilizes approximately 4 percent of the 110 billion gallons per day that flow past our shores. This water supply is particularly important to the electric utilities that use nearly 3/4 of the withdrawal from Lake Erie or about 3.2 billion gallons per day (Ohio Department of Natural Resources, 1982).

Commercial navigation is also an important aspect of Lake Erie. In 1979 before the recession, 98 million tons of goods passed in and out of the Ohio Lake Erie ports. It is important to note that 90 percent of that total tonnage was in four commodities, iron ore, limestone, coal, and grain (U.S. Department of Army, 1982). The low-cost transportation on the Lakes is important for our steel, power, coal, and agricultural industries. In 1985 after the recession, the tonnage had decreased to 65 million tons in and out of the Ohio Lake Erie ports. However, this still means 8,800 jobs in Ohio and $210,000,000 in wages to Ohio's economy (Ohio Department of Transportation, 1988).

Recreational boating is very popular on Lake Erie. Nearly 1/4 of all the boats registered in Ohio list Lake Erie as their primary area of use, 80,000 out of 320,000 (Ohio Department of Natural Resources, 1987a). An Ohio Sea Grant study estimated that the recreational boating industry generated about $133,000,000 to the economy of eight shoreline counties in 1980 (Wenner, 1982).

The fishery in Lake Erie has always been important to Ohioans. The great story recently is the walleye fishery. Ohio has proclaimed Lake Erie as the walleye capital of the world. In 1975 sport fishermen took only 112,000 walleye from Lake Erie. In 1986, sport fishermen took over 4.4 million walleye from Lake Erie. That is a 4,000 percent increase in 11 years (Ohio Department of Natural Resources, 1987b). The Lake Erie walleye fishery has been estimated to be worth over $100,000,000 in 1981 (Hushak et al., 1984).

Similar types of increases have been seen in the number of charter boat captains. In 1975, there were 46 charter boat captains operating in Lake Erie. In 1987, 998 charter boat captains were registered (Ohio Department of Natural Resources, 1987c).

As you can see, the water in Lake Erie is working for us in Ohio. Ohioans have shown a renewed interest in Lake Erie in the last 10 years. Associated with that new interest is a great increase in development along the Lake Erie shoreline. Unfortunately, this development has impacts on the wetlands and estuaries. We are seeing a great deal of marina development, condominium development, commercial development, and in Toledo, Cleveland, and Sandusky, office and hotel development.

The perceived clean water and the improved fishery are working in Ohio to create a sense of stewardship. The people are getting out on the lake, seeing the clear water, and enjoying the fishing. An example of this heightened sense of stewardship for Lake Erie is demonstrated by the 10,000 signatures in support of a water quality initiative that were collected last January at a boat show.

The revitalization of Lake Erie is providing a base for the revitalization of our economy. In the 60's if you were for the environment, it seemed that you had to be against economic development. Now we realize that as we take environmental quality seriously, we build the underpinnings of a strong economy for the future. Without the commitment to the environment over the last 15 years, we in the Great Lakes region would be in trouble today. The improved water quality has been providing us with dividends. Therefore, economic development cannot be built without a healthy environment.

In regard to issues and management problems on Lake Erie, the issues over the last 14 years really have not gone away. If anything, the list has increased. The highest priority issue has been and is water quality in the lakes. While the public has perceived improvements in water quality and thinks that the lakes have been cleaned up, we are not out of the woods on water quality. The issues of toxics in the lakes, contaminated sediments, the conventional pollutants such as phosphorus and nitrate, point and non-point source pollution abatement programs, and combined sewer overflows need to be addressed.

If property owners along Lake Erie are asked what the issues are, they will automatically bring up flooding and erosion. High lake levels have occurred on the Great Lakes since 1972. In some cases, these high lake levels have directly caused problems with inundation. However, most of the damage from high lake levels is caused during storm events. Lake Erie is on a northeast and southwest axis. Whenever high, sustained winds occur over a period of 12 to 24 hours, a wind set up can occur on the lake. This can be quite damaging in the western basin as the landside is very low and flat and without any bluff. Flooding in the western basin can occur up to two miles inland during a storm event from the northeast.

Erosion is also a serious problem along the shoreline, especially in the central basin where there are high bluffs. A survey was done of the damages between 1972 and 1976 due to shore erosion and flooding. It was found that there were about $65 million dollars in property losses in the Ohio shoreline counties in those four years. The shoreline property owners spent an additional $34 million dollars in trying to protect their properties (Bedford et al., 1978). One storm alone in 1972 caused $22 million dollars in damages (Carter, 1973).

With shore erosion, we are in a "catch 22" in Ohio. Most of the Ohio Lake Erie shoreline is fairly heavily developed. The most common means of addressing the erosion problem has been to build shore erosion control structures. Shoreline residents protect their property rather than retreat from the shoreline. The consequence of armoring the shoreline is that the source of sand which builds beaches is eliminated. Ohio geologists have found that in some parts of the shoreline the property owners have been very successful at slowing down shore recession. The consequence of that effort is that the source of supply for our sand beaches is decreased. The long-term implication is that the beaches will get smaller, the offshore profiles will become steeper, and larger shoreline structures will have to be constructed. In the future, either we will have to build larger structures or find sources of material for beach nourishment (Carter, 1986).

If you ask people who don't live on the shoreline what the issues are, they will talk about water quality. The next issue that they bring up, however, is public access. People who do not live on the shoreline automatically think that access is a major issue. They want to go boating and fishing, view the shoreline, and have access to the beaches. Most of the communities along the Lake Erie shoreline have a park or some sort of access facilities. However, most of these facilities are set up only to handle local demand. In addition, most of the shoreline is privately held. Where the local governments have parks, they also have difficulty maintaining their beaches due to the high lake levels and the severe erosion problem. Often, the local parks are in a state of disrepair.

Fluctuating lake levels are also a concern. Low lake levels occurred in the 1930's. Lake levels set record highs in the 1950's. At that time the Department of Natural Resources was created. One of the original five divisions was a Division of Shore Erosion. In 1964 the levels returned to near record lows. With low levels a reference was sent to the International Joint Commission to study the ways to mitigate the low lake levels. Also, the Division of Shore Erosion was disbanded. In 1972 lakes returned to the high stages and set record high levels again. The low level IJC reference soon became a high lake level reference (IJC, 1976). The lakes stayed above their average in the 1970's and returned to record high levels in 1985 and 1986. Over the last 16 years the Great Lakes have given the other coasts some excellent case examples of the impacts of sea level rise and examples of what to do and not to do.

The wetlands and estuaries are important parts of the Lake Erie system. As the previous speakers have pointed out, dramatic changes in the wetlands and estuaries have occurred since settlement of the area. There have been both direct and indirect impacts on the wetlands, the direct impacts being the development along the shoreline and draining of the wetlands. Indirect impacts include the increased sediment load into the wetlands and estuaries which retards vegetation growth, and the shoreline development which blocks the retreat of the wetlands as the lake levels rise. Some natural impacts have also occurred. As the lake levels rise many of the protective barrier beaches are breached. As this occurs, the wetland vegetation rapidly succumbs to the energy of the lake. The wetland areas become open water.

Dredging is another issue on the lake. The majority of the dredging on the Great Lakes occurs on Lake Erie because it is so shallow. At one harbor alone, 1.1 million cubic yards of material were dredged in 1987 (Ohio Department of Natural Resources, 1988). This probably represents about 10 percent or so of all the material dredged on the entire Great Lakes by the Corps of Engineers. One of the issues with dredging is the disposal of contaminated sediments. The programs to date have provided for the sediments to be disposed of in confined disposal facilities. This program is intended to protect the quality of the water and to insure that these sediments do not re-enter the water column. The confined disposal facilities, however, have been built in the nearshore areas and estuaries along Lake Erie. This, then, is a trade-off between protection of water quality and protection of nearshore habitat.

Another issue on the Great Lakes is water diversion and consumptive uses of water. In 1981 the governors and premiers of the Great Lakes states and provinces and other parties became very concerned about water diversions from the Great Lakes. The Powder River Coal Company proposed a coal slurry pipeline to the Great Lakes region. A second pipeline from the Great Lakes to Gillette, Wyoming was proposed for freshwater feed for the pipeline (Council of Great Lakes Governors, 1985). Also, the International Joint Commission recently conducted a study on consumptive uses in the Great Lakes. The IJC found that consumptive uses may double to 8,400 cfs by the year 2000, which would impact the levels and flows of the Great Lakes (IJC, 1985).

The last issue I want to address is the complexity of government in the Great Lakes region. There are many layers of government, which makes it very difficult to manage the lakes. In Ohio the primary agency to manage the landside activities is the local level of government. Ohio is a strong home-rule state. The Ohio General Assembly is hesitant to give state authority which would diminish local government autonomy. We have many regional agencies managing shoreline activities such as ports and conservancy districts. Several state agencies manage different aspects of Lake Erie resources. There are also different federal agencies managing resources. Several interstate bodies have been established to develop policies on the Lakes' resources, such as the Great Lakes Commission, the Great Lakes Fishery Commission, and the Council of Great Lakes Governors. The International Joint Commission was established pursuant to the 1909 Boundary Waters Treaty to advise the federal governments on policies for the Great Lakes.

Given the issues, the state is developing strategies to address these issues. In general, state government is the key to implementing the variety of policies on the lakes.

In Ohio a major initiative on Lake Erie was recently announced: the establishment of the Lake Erie Office. This was modeled after an initiative in Michigan, the Office of the Great Lakes. The purpose of the Lake Erie Office is to provide a focus among state agencies for Lake Erie, to coordinate the activities of state agencies in order to insure their consistency, to be a "One Stop Shop" for questions and information on Lake Erie, to act as an advocate for Lake Erie, to educate the people on the value of Lake Erie as a natural resource, and to work on developing a constituency for Lake Erie.

The first item on the agenda for the Lake Erie Office is to create a state coastal management plan. This plan will essentially be a compilation of the existing statutes and regulations on how we currently manage Lake Erie. The state coastal plan will be a major step towards the background document necessary for a federally approved coastal management plan.

The Lake Erie Office was also given a legislative agenda for 1988. Three bills were put on that agenda. A bill limiting phosphates in household detergents which are sold in the Lake Erie basin was passed in March. The Great Lakes Charter bill, which establishes the programs necessary to meet the objectives of the Great Lakes Charter, was also passed in March of 1988. The Great Lakes Charter is a non-binding agreement which was signed by the Great Lakes governors and premiers in 1985 and sets out water resource management programs to protect the Great Lakes from diversions out of the basin and manage consumptive uses in the basin. The Charter bill addresses the issue of consumptive uses, amends Ohio's water diversion law, and establishes a water withdrawal registration program. The third bill is the coastal management legislation. This bill will establish a program in the statutes and addresses the problems of flooding, erosion, access, and submerged lands leasing. While we are optimistic that the coastal management bill can be passed, the limiting factor is the time that is left in the General Assembly.

The Lake Erie Office has also been charged with overseeing the development of the remedial action plans. There were 42 Areas of Concern designated by the International Joint Commission around the Great Lakes. These Areas of Concern exhibit persistent water quality problems. For each Area of Concern, the states and local governments are to develop remedial action plans. Four remedial action plans are being developed for Lake Erie tributaries in Ohio, including the Maumee River, Black River, Cuyahoga River, and Ashtabula River.

In the future, the Lake Erie Office will be overseeing the implementation of the Great Lakes Toxic Substances Agreement and the Great Lakes Protection Fund. The Great Lakes Protection Fund will be an endowment fund from state and private sources of $100,000,000. It is estimated that the fund can earn $10,000,000 a year which will be provided to the Great Lakes states to implement various parts of the toxics agreement. Legislation should be introduced next year to raise Ohio's portion of the $100,000,000 endowment.

The Lake Erie Office will be working to implement a Lake Erie Land Trust. The trust will be a nonprofit organization which will allow the private sector to become involved in acquisition projects. Priorities for the trust will be public access and protection of environmentally sensitive areas.

Ohio is working to develop the nonpoint programs as called for in the Clean Water Act. The assessment plans and management plans are being developed. After having several demonstration programs in Ohio, we are looking forward to funds to implement our nonpoint programs.

There is a saying that if you want to see where people's priorities are, look at where they spend their money. In the last two capital budgets we have been allocating monies for Lake Erie. The funds have gone towards developing public access at our state parks with construction of a marina and beaches, and acquisition of additional areas. We have also worked cooperatively with local officials on access projects and marina development. In 1987 we acquired a 2,000 acre wetland parcel for about $2.6 million. This acquisition laid the ground work for the Ohio Wetlands Fund in our capital budget for 1989-90. The Ohio Wetlands Fund will be used primarily for acquisition.

The Ohio Department of Natural Resources is developing an Ohio Wetlands Priority Conservation Plan. This plan will outline the status of wetland protection efforts in the State of Ohio and will outline future initiatives for wetland protection.

In 1984, Ohio initiated the Lake Erie Access Program. This program will work with local governments to try to improve local facilities into facilities that will meet more regional and statewide needs. The current focus of the Lake Erie Access Program is boating access and shoreline fishing (Ohio Department of Natural Resources, 1984).

The Ohio Coastal Resource Management Project (OCRMP) has established a citizen's task force on coastal issues. OCRMP is a nonprofit organization in Ohio which was organized to promote improved coastal management. The citizen's task force will be publicizing its recommendations for improved coastal management this coming December.

The last point on the strategies I want to make is on cooperation. No longer can a state or local government solve all the issues that it must address. Local and state governments are currently confronted with problems that go beyond our boundaries. The challenge over the years to come will be to see how inventive we are at figuring out new ways to cooperate and confront problems. The cooperation has to be between all levels of government, between the U.S. and Canadian federal governments, between the U.S. government and the states, between the eight Great Lakes states, and between the Great Lakes states and provinces.

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ISSUES AND MANAGEMENT PROBLEMS -- A CANADIAN VIEW

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THE NORTH SHORE

The Canadian shore of Lake Erie is markedly different from the United States shore in terms of municipal and industrial development. The shore land use is predominantly agricultural. The IJC Lake Erie Water Level Study (IJC 1981) gives the following distribution of shoreline length: Residential, 164 miles; Commercial/Industrial, 8 miles; Agricultural/Forest, 145 miles; Other, 19 miles; Recreational and Public Lands, 62 miles.

Three significant topographical features are the sites for major national or provincial parks. The only significant river mouth is that of the Grand River at Port Maitland. Except for scattered groups of summer cottages and a succession of small communities, the shoreline is in its natural state. In common with the south shore, episodes of severe shore erosion continue to move the bluff further inland.

The major marshlands are associated with the three major projections into the lake at Long Point, Rondeau Point and Point Pelee, and the estuary of the Grand River. In most cases these marshlands are protected by incorporation into a national or provincial park. In total, there are ten Provincial parks distributed along the Canadian shore.

FLUCTUATING WATER LEVELS

One of the important characteristics of Lake Erie is the fluctuation of annual mean water levels through a range of about five and one half feet. The time period between these highs and lows varies from 10 to 30 years, which is the reason people forget the past extreme events. These fluctuations are completely natural and are related to several successive years of above or below normal precipitation.

Major damage to shore property results from a combination of high lake levels and wind storms that create even higher local water levels as well as shore eroding wave energy. Property damage is caused by a combination of inundation and erosion.

Periods of low water levels create serious problems for commercial navigation and recreational boating. Additional harbour dredging is required or the ships must carry less than full loads. High water levels permit ships to carry increased loads.

The reduced flows out of the lakes associated with low water levels also reduces the production of hydro power.

It is technically feasible to regulate the lake levels by building suitable engineering works, but in addition to the cost of the works there are significant disbenefits to other users of the lake such as hydro-power and navigation. The downstream property owners also would be injured by the negation of the storage effect of the lakes resulting in much higher fluctuations in outflow.

Another disbenefit, of special interest to this seminar, is the impact of lake level regulation on wetlands bordering the lake. It is claimed that the habitat in these areas is best maintained in what has been called a "pulse stable" regime. In other words, wetland habitat is most productive in transition from one level to another. A constant lake level would create a permanent shoreline with a sharp demarkation between the water and land with very dense vegetation of both the submerged aquatic plants and the terrestrial plants without the highly variable range of marshlands.

A major initiative to address these concerns is the IJC Reference on Fluctuating Water Levels in the Great Lakes. This binational study will consider a wide range of possible remedial measures. For several of the most promising measures the study will determine the environmental and economic benefits and disbenefits to each of the stakeholders.

EUTROPHICATION

Lake Erie is dead! That was the catch-phrase of the 60s which initiated the massive IJC study of the lower lakes and led to the signing of the Great Lakes Water Quality Agreement (GLWQA) of 1972. While this catch-phrase was a massive overstatement, it caught the public's attention and generated the required political pressure to move governments to action. Today, the Great Lakes are better monitored and understood than any other major water system. They have been the recipient of a multi-billion dollar reclamation effort between two sovereign nations including eight States and two Provinces.

The massive reduction in phosphorus loading to lake Erie, and the lake's response is one of the great success stories in environmental management. But the job is not finished! The target levels of loading of total phosphorus to the basin of Lake Erie cannot be achieved by controlling the effluents of point sources like waste treatment plants and industries alone. Non-point sources such as agriculture and other land use activities also must be controlled.

The GLWQA still is in force. Canada and the United States have agreed to an apportionment of the further phosphorus load reduction required. Canada's share of the 2000 metric tons/year (mta) reduction target is 300 mta. The phosphorus management plan to achieve that goal includes a major federal/provincial, agricultural/environmental initiative called SWEEP. This thirty million dollar, five year program will reduce the phosphorus load to the Lake Erie basin by 200 mta. It also will reduce soil erosion and keep the nutrients in the fields where they can contribute to agricultural production.

The introduction of "conservation tillage" is the main thrust of SWEEP. This involves a series of educational and financial incentive programs, along with research and pilot scale studies to identify the best technology for the particular soil conditions in southwestern Ontario. Mathematical models will be used to determine the basin-wide reduction in phosphorus load.

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LAKE ERIE MANAGEMENT ISSUES

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The major Lake Erie environmental management problems are, from our point of view:

1) Eutrophication, in terms of excess algal growth and oxygen depletion in the bottom waters of the Central Basin.

2) Use impairments in the geographic Areas of Concern. The use impairments range from nuisance conditions to degraded biological populations and to fish consumption warnings due to toxics.

3) Toxic contaminants in fish which result in fish consumption advisories (catfish and bullheads at present).

4) Habitat loss is a fourth environmental problem, but one where EPA has not been intensely involved until recently.

A major management challenge is to bring together the many governmental and non-governmental organizations necessary to address these environmental problems on a systematic basis. The one document that provides an overall management approach to the problems is the U.S./Canada Great Lakes Water Quality Agreement. Its role was strengthened in 1987 when the U.S. Clean Water Act was amended to make specific reference to the Agreement and to require USEPA to provide support and to report annually to Congress on progress being made in its implementation. The Great Lakes National Program Office (GLNPO) has responsibility for coordinating the U.S. efforts under the Agreement and the Clean Water Act. The coordination includes EPA programs in Regions 2, 3 and 5, as well as the other Federal agencies involved in Great Lakes activities.

The Agreement itself was strengthened in 1987 through amendments that added management features. Specific reporting schedules were established and the Parties to the Agreement agreed to meet twice a year to review progress and plan implementation. This will mean the need to organize the Great Lakes States and other Federal agencies into a U.S. team. Two new provisions in the Agreement deserve special mention:

1) Remedial Action Plans are called for to address impaired uses in the geographical Areas of Concern.
2) Lake Management Plans are called for to address critical pollutants in the open lakes.

The Geographic Areas of Concern are designated areas where beneficial uses are impaired. (The uses range from aesthetic to human health and to the health of the biota.) The designation of the areas and preparation of plans started several years ago under the leadership of the International Joint Commission's Water Quality Board, but were officially incorporated into the Water Quality Agreement in 1987. A major purpose of the plans is to establish a clear consensus statement of the environmental problem and its causes, together with a clear statement of the key action steps needed to solve the problems. No such plans existed for these areas. Bringing together the myriad of concerned organizations to prepare such plans is proving to be a major management challenge. However, once brought together within a positive framework, representatives of the organizations, particularly public interest groups, are providing a tremendous amount of creative energy.

Lake Management Plans (LMP's) are a new provision within the Water Quality Agreement that reflect our success in developing the Lakewide Management Plan for Phosphorus Load Reductions. In the case of phosphorus, a joint U.S. and Canadian effort was successful in: establishing a lakewide target load; calculating the load reductions that would result from full compliance with point source requirements; and agreeing on the further reductions needed to meet the target. Based on this, each country developed load reduction plans relying heavily upon reduction of nonpoint sources.

Lake Management Plans are not intended to be complete ecological plans addressing things like fisheries management or habitat issues. Rather, they are aimed directly at critical pollutants. This narrowed focus is intended to result in action plans for prompt control of specific pollutants. Habitat and fisheries management are issues that may be revisited in the future when the two countries have had some experience with the more narrowly focused plans. Several current efforts will be utilized as we address LMP's. They include the Green Bay Mass Balance Study, the Lake Michigan Toxic Strategy and the Lake Ontario Toxic Plan. GLNPO and our Canadian counterparts will be holding a Workshop in the fall to address LMP's from a bi-national point of view.

Returning to immediate Lake Erie problems, we are reviewing the progress being made in implementing the Phosphorus Load Reduction Plans in the U.S. and Canada. Because the plans rely heavily upon reduction of nonpoint sources, many governmental agencies must be involved at the Federal, State and local levels. On the U.S. side we have managed to reach agreement on how to monitor and estimate the rate at which nonpoint source practices are being adopted, now we must gather and evaluate the information, and if necessary modify the Phosphorus Load Reduction Plans. It is important to maintain our efforts in this area to ensure that we not allow a return to the eutrophic state of Lake Erie in the 60's and 70's.

Thank you for inviting me to be with you today. It has provided me with valuable information on the state of Lake Erie both currently and historically.

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