STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
RALPH J. BERNHAGEN, CHIEF

REPORT OF INVESTIGATIONS NO. 58

SYNOPTIC SURVEY of WATER PROPERTIES in the WESTERN BASIN of LAKE ERIE

by

Robert P. Hartley
Charles E. Herdendorf
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COLUMBUS
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INTRODUCTION

The following report is the result of a cooperative effort by the Division of Wildlife and the Division of Geological Survey, Ohio Department of Natural Resources. Although these two Divisions have dissimilar objectives, they have a common interest in acquiring greater knowledge about the characteristics of Lake Erie water.

The Division of Wildlife is engaged in research on the management and propagation of desirable fish populations. Investigation of habitats is essential to this research. Therefore a knowledge of the physical and chemical features of the water, both permanent and transient, is of vital importance.

The Division of Geological Survey is primarily interested in the origin, transportation, and deposition of shore and bottom sediments. Water is the carrier and water movement determines the pattern of distribution of the sediments. Thus the physical characteristics of the water are directly related to sedimentation.

Field personnel consisted entirely of Division of Wildlife and Division of Geological Survey employees. The laboratory measurements were made by the personnel of the Fish Management Section, Division of Wildlife.

Helpful criticism of methods and results was given by Mr. Jerry Manz of the Ohio Division of Wildlife, Mr. John Hyland formerly of the Ohio Division of Water, Mr. David Papier of the Ohio Department of Health, Dr. George Whetstone of the U.S. Geological Survey, and Dr. G. K. Rodgers of the Great Lakes Institute, University of Toronto.

STUDY PURPOSE

The main objective of this study has been to determine the feasibility and value of a synoptic survey of some physical characteristics of the water in Lake Erie. The attainment of the main objective depended upon the determination of the existence of separate and distinct water masses within a lake basin. If such masses existed, were their properties sufficiently uniform, yet amply different from those of adjacent masses, so that they could be mapped intelligibly? If the masses could be mapped, then it might be possible to determine their origins and their paths of movement. Successive studies could provide some insight into the stability of mass-movement patterns and could also provide a basis for detailed water-movement studies.

The need for a different approach to the detailed studies of water movements has been demonstrated by attempts which have been plagued by severe shortcomings. Most work has been done by (1) using drift bottles and cards, or (2) making direct current measurements. Both methods are far from adequate, the first because of wind influence and unknown paths of movement, and the second because of the necessarily limited knowledge of simultaneous movement elsewhere.

It was decided that the initial survey should be simple and rapid, covering a wide area as synoptically as possible. The simplicity of the survey was accomplished by establishing the factors believed to produce the most useful information for the least time involved. The factors were: (a) turbidity, (b) hydrogen-ion concentration (pH), (c) conductivity, and (d) temperature of the water. The samples were also limited to a number which could be analyzed in a relatively short time.

STUDY LOCATION AND GENERAL DESCRIPTION

Western Lake Erie, west of a line between Point Pelee and Cedar Point, was selected as the area in which to conduct the survey (fig. 1). The selection was made for several reasons. Western Lake Erie, west of the islands, is a natural basin. It contains most of the spawning grounds for the more important fishes and is the area of major fishing endeavor. It is also the recipient of large influxes of water (each with different properties) from the Detroit River, the Maumee River, and the central basin of the lake. The area of the western basin is also relatively small, being less than 1,300 square miles. All of these features indicated the western basin as the ideal area in which to conduct a water study of this type.

The western basin is extremely shallow, averaging only 24.2 feet below datum (Verber, 1950). West of the Bass Islands it does not exceed 34 feet. The maximum depths within the study area have been found in the interisland channels. Just north of Starve Island Reef (fig. 11), is a small depression with a maximum depth of 67 feet and south of Gull Island Shoal is another depression 54 feet deep. Elsewhere these depths are not approached.

Topographically, the western basin bottom is monotonously flat, except for the sharply rising islands and reefs in the eastern and central part. The shoreward-rising slopes on the south and west mainland shores are exceedingly gentle, while those along the north shore are comparatively very steep.

The central basin of Lake Erie, east of the islands, into which the western basin drains, averages about 60 feet in depth and covers an area of about 6,000 square miles. It has a maximum depth of 84 feet.

The lake bottom in the study area is predominantly mud or a mixture of silt and clay (Verber, 1958). Sand and gravel is abundant only near the shores and around some reefs. Bedrock, mainly dolomite, comprises the islands and reefs, but exposures are scarce in the west half of the basin.

The western basin is subject to extreme short-term fluctuations of lake level, especially during storm periods. Fluctuations of six feet or more within a period of a few hours are fairly common at Toledo. The fluctuations are nearly always wind induced. Extreme rises are caused by strong northeast winds and extreme falls in level are caused by westerly winds. Wind-produced fluctuations give rise to ensuing periodic rises and falls called *seiches.* The seiche having the greatest amplitude has a period of about 14 hours. This is the natural longitudinal period of that part of the lake east of the islands.

Winds are especially effective in the western basin in stirring of the water and the bottom-surface materials. This, along with inflow of turbid streams, results in higher turbidities than elsewhere in Lake Erie.

The western basin receives more than 95 percent of the drainage into Lake Erie via the Detroit and Maumee Rivers. The flow of the Detroit River averages about 176,000 cubic feet per second and the flow of the Maumee averages approximately 8,400 cubic feet per second. These values have been obtained from discharge records compiled by the Ohio Division of Water (1953) and by the U.S. Army Corps of Engineers Lake Survey, Detroit, Mich. (personal communication, W. T. Laidly, Aug. 14, 1959).

SURVEY METHODS

The Division of Wildlife provided three vessels for the survey, *Explorer, Investigator, and Inspector.* The Division of Geological Survey provided its research vessel, *SE-1.*

Sampling stations were previously established on a two-mile grid, resulting in a total of 300 stations (fig. 1). Stations were allotted to each vessel so that all sampling could be accomplished within a period of eighteen hours. Although the station locations were determined by dead reckoning, accuracy was within acceptable limits because of the proximity of charted land and navigation markers. Water samples were taken at each site at the pre-established depths of five feet below the surface and at two feet above the bottom. The upper samples are herein referred to as "surface" and the lower as "bottom" samples. In water less than ten feet deep, only one sample was taken, at a depth of five feet. This procedure was followed at all stations except some of those occupied by the *SE-1.* The water sampler was lost at station 33, so that only surface samples could be taken at stations 34 through 79. Otherwise all samples were taken with Kemmerer water samplers.

Water samples were retained in four-ounce-capacity bottles made of glass or polyethylene. The bottles were carefully cleaned and rinsed with distilled water beforehand. Each bottle was again rinsed at the time of sampling with the water that was being sampled. The bottles were filled completely with the sampled water so that no air remained. All samples were refrigerated at once to minimize chemical and biological activity, and were kept under refrigeration until the time of analysis. Those samples around the island area taken from the *Inspector* were frozen upon return to the laboratory and remained frozen until the day of analysis.

Temperatures, to the nearest degree Fahrenheit, were read on most of the water samples at the time of sampling. In addition, bathythermograph measurements were made on a four-mile grid to determine the existence of thermal stratification and the areal distribution of water temperature (fig. 9). On those measurements where hysteresis occurred, the traces with the sharpest and smoothest curves were read.

Dissolved oxygen and alkalinity determinations were conducted at the time of sampling for those samples taken from the *Explorer.* The results are not included in this report.

The survey was made on June 23, 1963, and all samples were taken between 0400 and 2300 hours Eastern Standard Time. The lake was calm. The wind was light and variable with a maximum velocity of 10 mph from the northeast in the late morning near the Ohio shore. The sky was clear and visibility was excellent.

Another sampling cruise with the *SE-1* was made on May 28, 1964, to test the consistency of the measurements obtained from the earlier survey. Surface sampling was done at one-mile intervals with an underway-scoop device that was designed for the survey. The survey was conducted from 0900 to 2000 hours Eastern Standard Time along a 125-mile course that was planned to give a general covering of the western end of Lake Erie (fig. 8). The day before the survey the wind was moderate, 10 to 25 mph, from the southwest to northwest, and the day of the survey the wind was light, 4 to 12 mph, from the northwest to north. The water level was falling at the time of the survey.

The May 1964 survey differed from the earlier survey in that all measurements were made in the field at the time of sampling; water samples were not retained. The field method was used in an attempt to eliminate error introduced by sample storage. Conductivity and temperature of the surface water were the only factors considered in this survey. Specific conductance measurements were taken with an Industrial Instruments RB-2 portable conductivity meter. This meter gives values in micromhos per cm referred to 25 C.

LABORATORY METHODS

All water samples were returned to the Sandusky

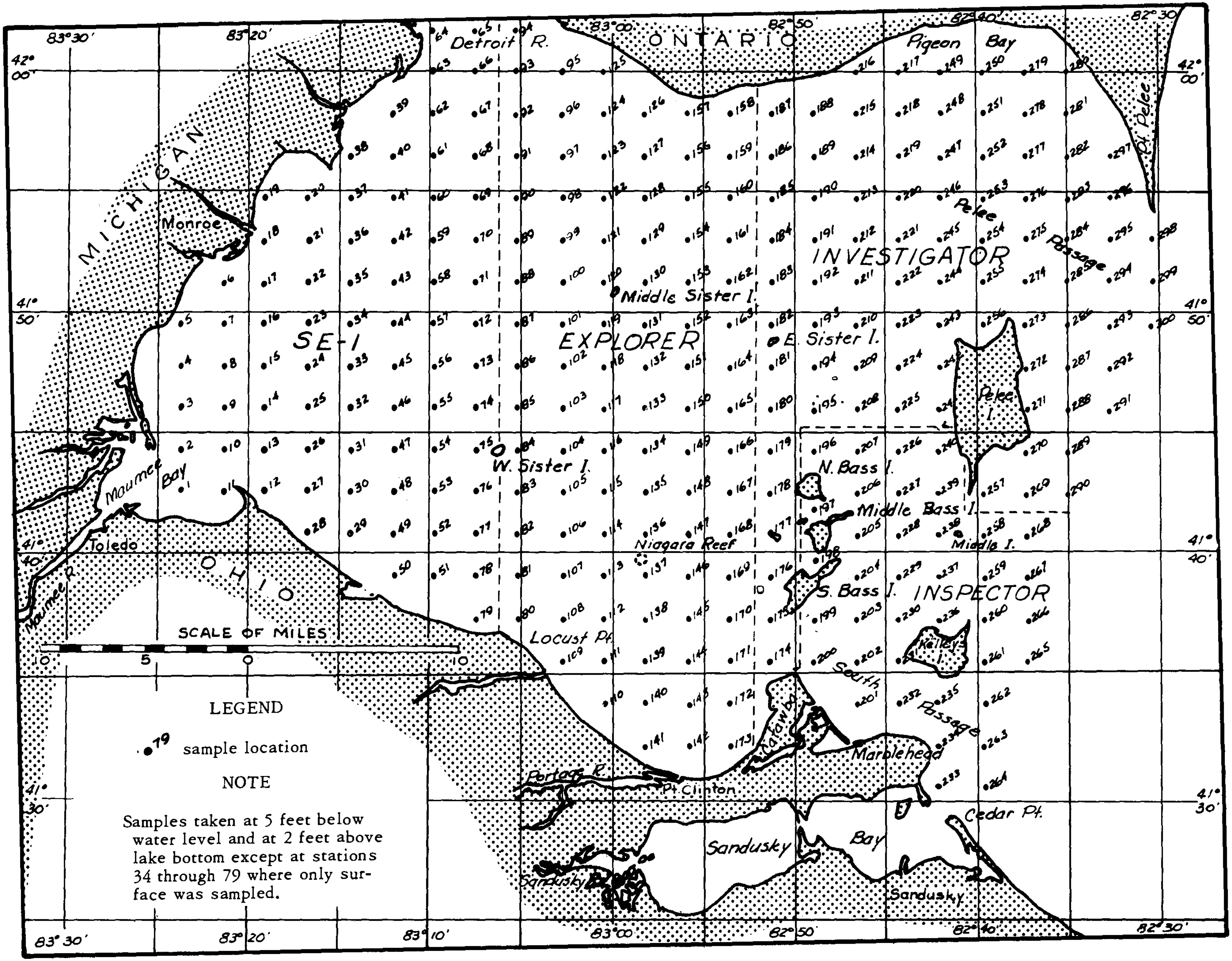

Figure 1. - Water sampling stations in western Lake Erie on 23 June 1963.

office of the Division of Wildlife. The Fish Management Section, Division of Wildlife, began analyses on June 24, 1963, the day following the sample collections. The analyses were completed June 26.

All of the samples were kept under refrigeration until the day of analysis, when they were allowed to reach room temperature.

Turbidity values were obtained with a Hellige turbidimeter according to procedures set forth by Welch (1948). With this instrument the values are equivalent to the parts per million of silica (fuller's earth) required to produce the same condition of turbidity in distilled water.

Hydrogen-ion concentration (pH) was determined for each sample with a Beckman Zeromatic pH meter.

Conductivity (specific conductance) of laboratory samples was measured with an Industrial Instruments model RC 16B2 polyster cell with conductivity bridge and platinum electrodes. Measurements were reduced to micromhos per cm at 25 C according to the procedures listed in the eleventh edition of "Standard Methods for the Examination of Water and Wastewater", 1960.

The results of the laboratory analyses were plotted on charts of the western basin of Lake Erie, using U.S. Army Corps of Engineers Lake Survey Chart 39 as a base. The values of each factor were contoured in order to establish the areal patterns if such existed.

RESULTS OF THE SURVEY

TURBIDITY

The turbidity values are shown as contours in figures 2 and 3. The surface turbidity values as shown in figure 2 are probably more reliable indicators of actual conditions than those shown for bottom turbidity in figure 3. Extremely high values for bottom turbidity may be due to stirring of bottom sediment by the sampler or to local rapid blooms of plant life.

Surface turbidity values (fig. 2) show a pattern for June 23 indicating movement of water from the Detroit River south and southeastward. The higher values were obtained south and west of a line running from southern Pelee Island southwest to Niagara Reef, thence northward to the Detroit River. The highest values were found along the Michigan and Ohio mainland shores. It appears, for that day, from surface turbidity values, that water from the Monroe-Toledo area moved southeastward along the Ohio shore and northeastward through the island area.

Bottom turbidity values (fig. 3) showed patterns similar to those on the surface, except that extremely high values were recorded north and northwest of the Bass Islands. These high values, as noted above, may have been caused by stirring of the bottom with the sampler or by unusual organic content.

The least turbid water in the western basin on June 23, 1963, appeared to be in the northeast quarter of the basin. This may have been caused by a recent influx of water from the central basin through Pelee Passage. However, it seems more likely that turbid water from the Michigan-Ohio shores was simply not moved, or had cleared before it moved, into the area. It should be noted that turbidity along the north shore was generally much less than along the other shores.

Turbidity values, as obtained for this survey, are not now considered reliable indicators of water movement or actual habitat conditions. Substantial changes may have occurred during sample storage. Aquatic growth during storage, and precipitation of compounds due to temperature reduction are factors which could have greatly affected the measurements.

HYDROGEN-ION CONCENTRATIONS

Figures 4 and 5 show the contours of pH values for the surface and bottom samples, respectively. Figure 4 indicates that a band of surface water with a pH greater than 9.0 extended southward from the west side of the Detroit River mouth. In contrast to this, another mass, originating in the center of the Detroit River, extended southward and fanned out into the northwestern part of the basin. This water had pH values less than 8.5.

Samples taken in the Bass-Kelleys Island area showed the lowest pH values (less than 8.0), indicating a possible influx of central-basin water at the time of the survey.

Bottom pH values (fig. 5) were not greatly different from those on the surface. The island area again showed the lowest values. Although bottom samples were lacking in the strip south of the Detroit River mouth, a few samples east and west indicate that a band of high values may have existed similar to those at the surface.

The bottom pH values, like those on the surface, indicate that there might have been a movement of water from the west side of the Detroit River southward toward the Ohio shore. Also indicated is an influx of water into the southern-island area from the central basin.

The hydrogen-ion concentrations obtained from this survey are of doubtful value for any purpose where exactness is required. The values seem unusually high in light of the values obtained over the years by other agencies (Rodgers, 1962, and Ohio Div. of Water, 1953). Values above pH 8.5 have been rare.

Errors are introduced quickly in pH measurements by many factors, both *in situ* and in the sample. Some

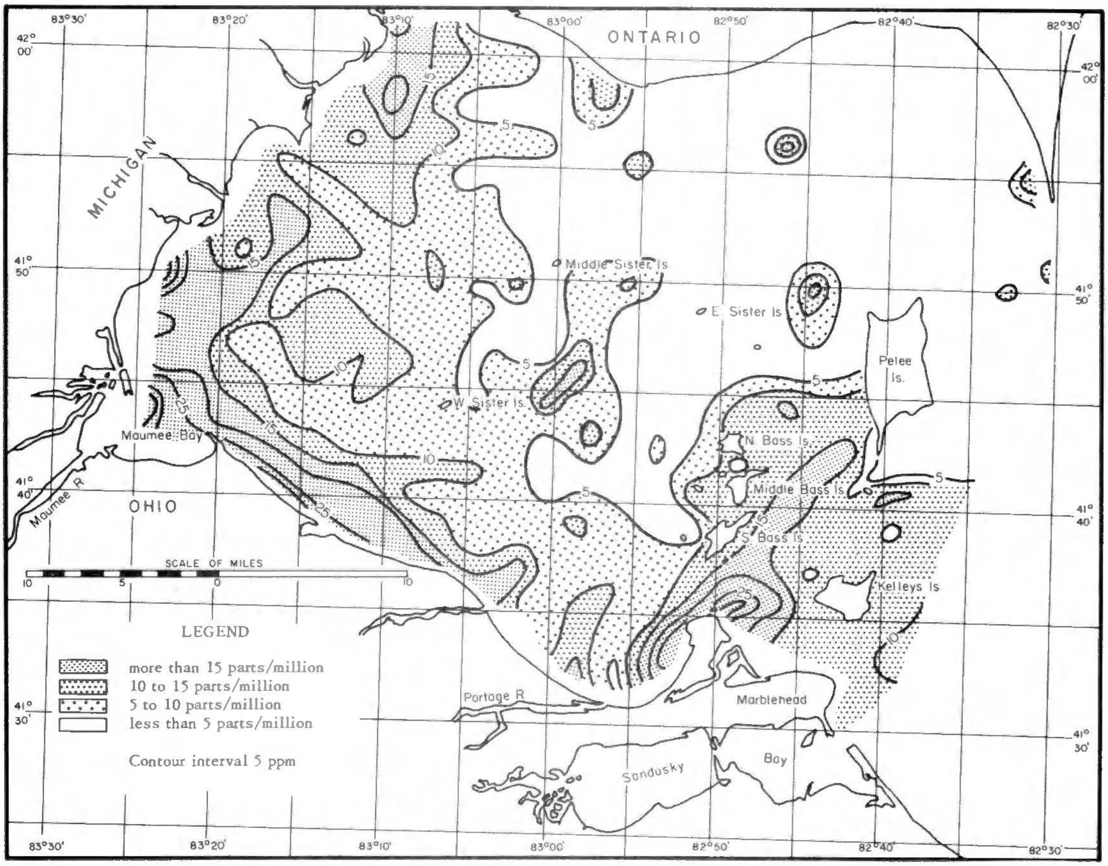

Figure 2. - Turbidity of surface water in western Lake Erie on 23 June 1963.

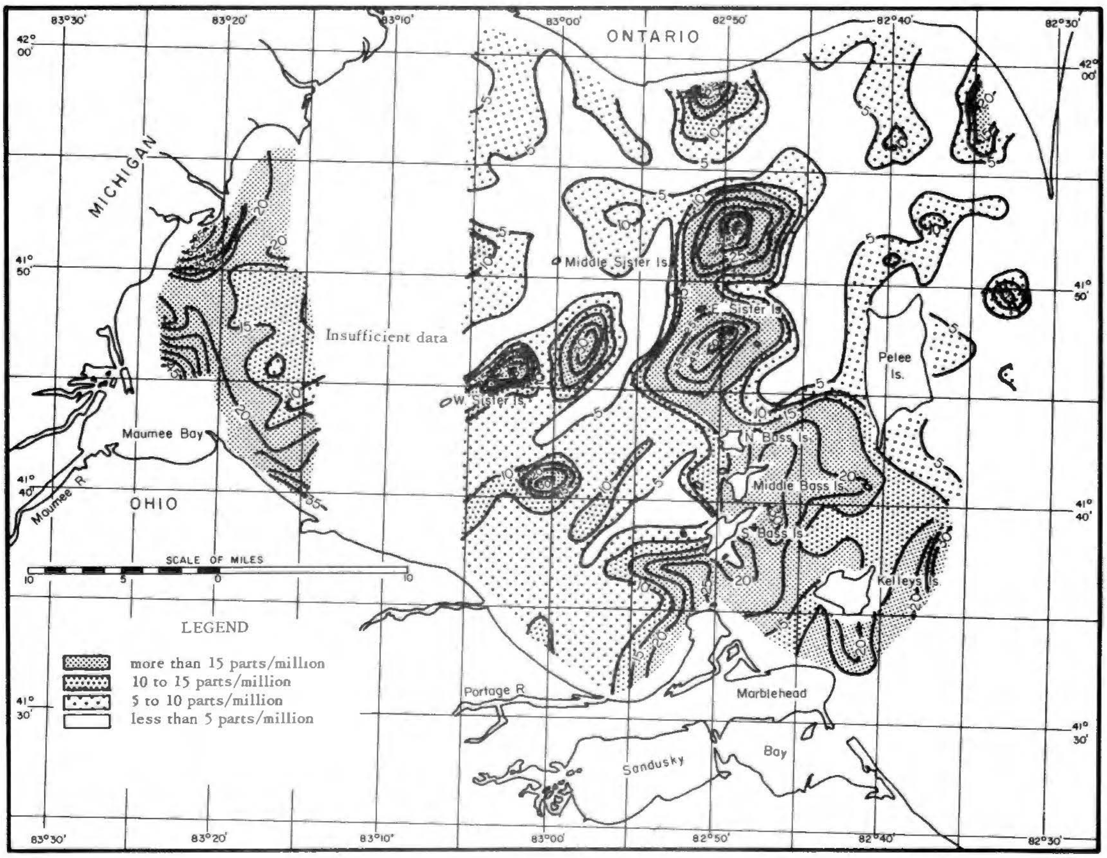

Figure 3. - Turbidity of bottom water in western Lake Erie on 23 June 1963.

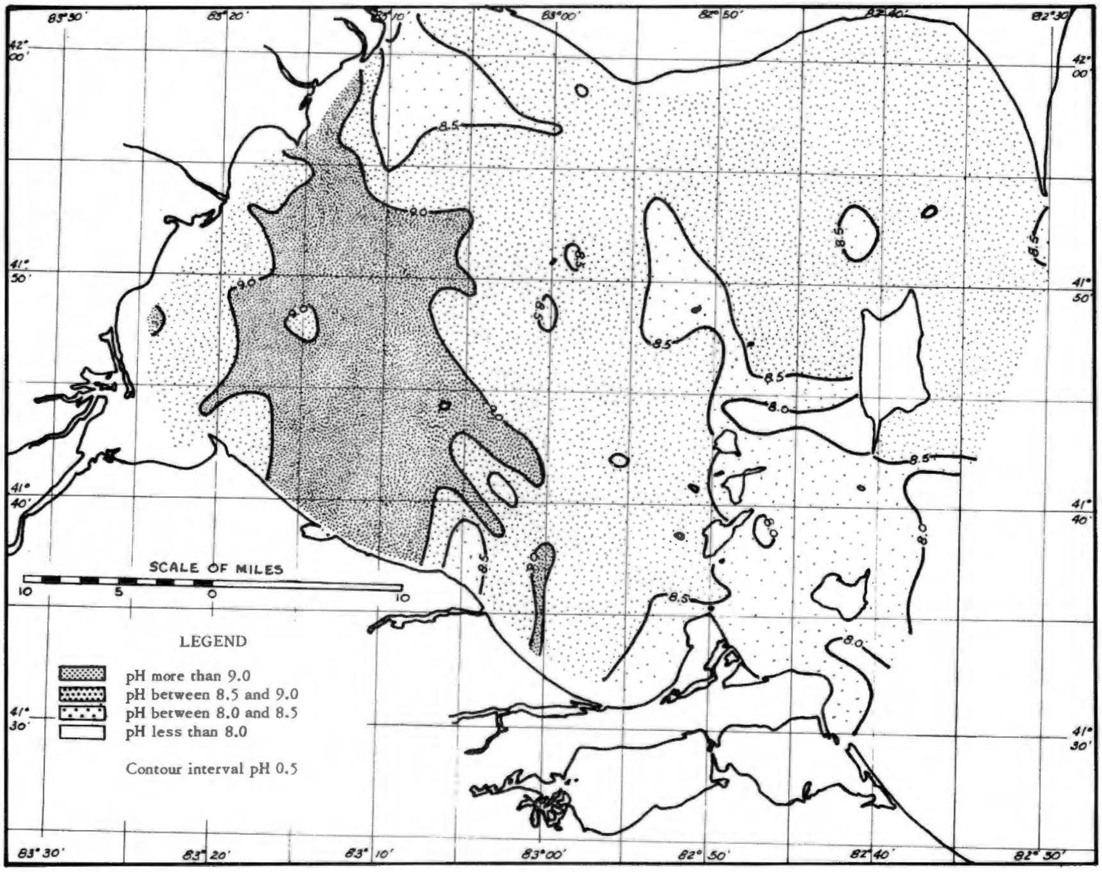

Figure 4. - Hydrogen-ion concentration (pH) of surface water in western Lake Erie on 23 June 1963.

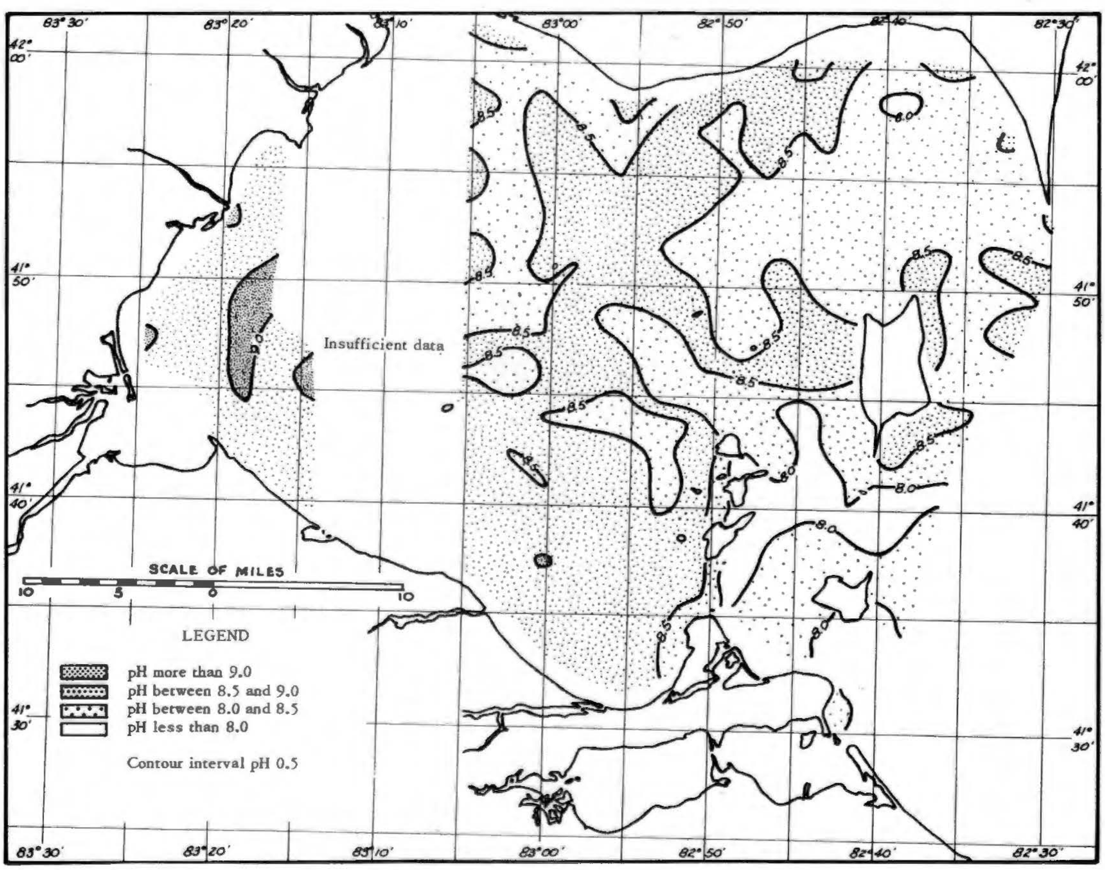

Figure 5. - Hydrogen-ion concentration (pH) of bottom water in western Lake Erie on 23 June 1963.

of the factors are temperature changes, air in sample jars, aquatic life, light conditions, wind, the amount of reactive elements, and agitation of the samples. The time of sampling is even a factor. Verduin (1962) states that the highest pH values are usually observed at about 1500 hours and the lowest values at about sunrise. The sampling for this study spanned those times. All the samples with pH values greater than 9.0 were taken late in the day, while those samples from the island area with pH values less than 8.0 were taken during the morning hours.

In light of the above considerations, the reliability of the pH values is questioned. However, they do indicate patterns of water movements apparently similar to those indicated by other components.

CONDUCTIVITY

Figures 6 and 7 show the conductivity (specific conductance) values for surface and bottom waters respectively, contoured at an interval of 25 micromhos per cm. Definite patterns are shown which appear to be related to individual water masses.

Conductivity of the surface samples ranged from 149 micromhos per cm west of Niagara Reef to 471 on the west side of the mouth of the Detroit River. In general the lower values were obtained in the Bass-Kelleys Island area while the higher values were found along the Ohio and Michigan mainland shores.

A band of relatively lower surface conductivity values extended southward from the Detroit River to the Ohio shore, and a similar band extended eastward from the Detroit River along the Canadian shore to the vicinity of the north end of Pelee Island. This indicates that the Detroit River water had moved along paths similar to these bands (fig. 6).

The highest conductivity for a surface sample was found on the west side of the Detroit River mouth. This water was also apparently moving southward. The pattern indicated that it may have joined with higher conductivity water from the Maumee River which apparently had been moving southeastward along and near the Ohio shore.

Another mass of surface water with higher conductivity existed on the west side of the islands, while, simultaneously, water of apparent low conductivity was found within the southern-island area. This could be interpreted as an indication that water from along the Ohio shore was moving northward on the west side of the islands. As will be shown later, however, the values for the southern-island area are probably erroneous because of freezing during storage.

A strikingly similar pattern is shown by the

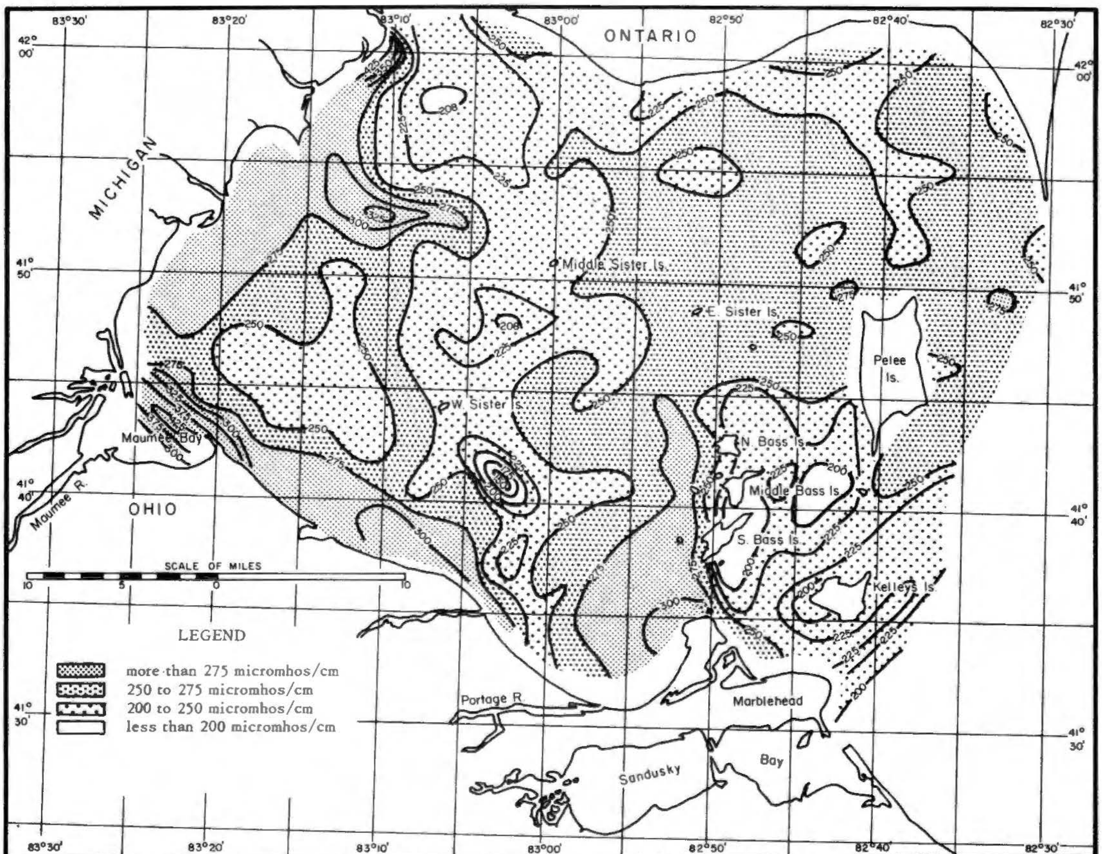

Figure 6. - Conductivity of surface water in western Lake Erie on 23 June 1963.

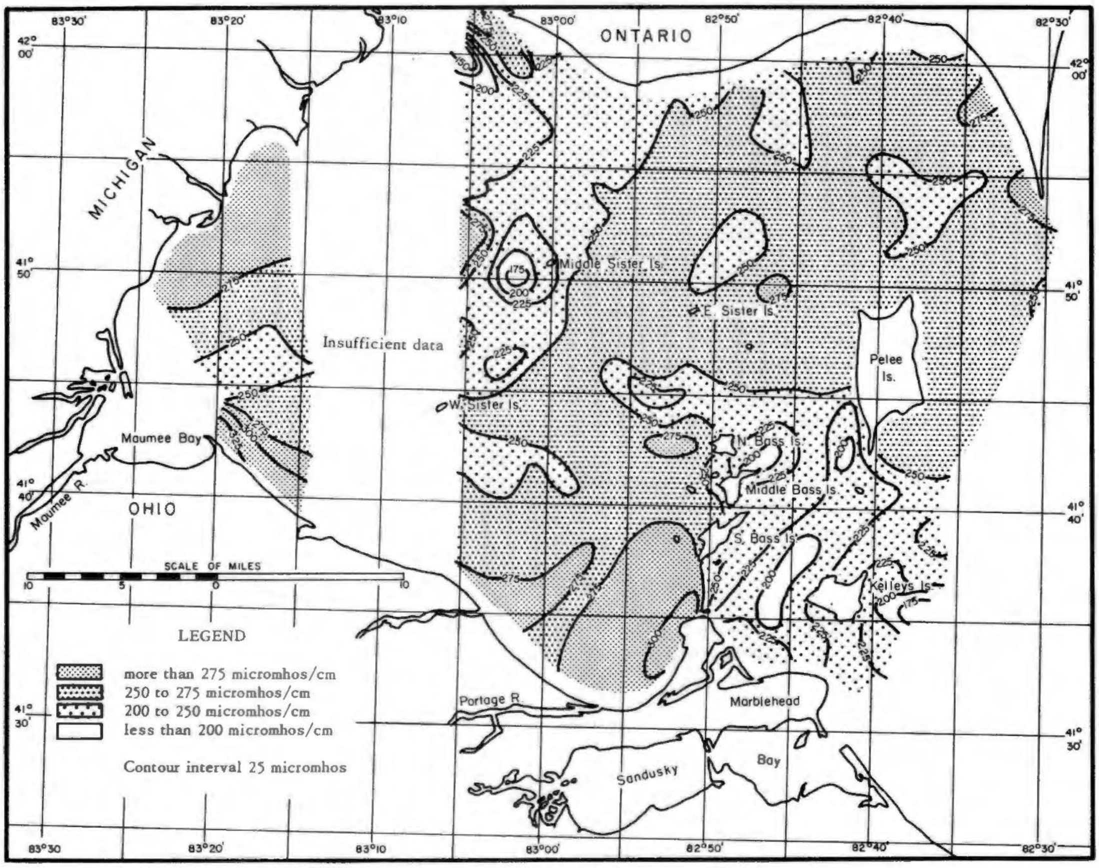

Figure 7. - Conductivity of bottom water in western Lake Erie on 23 June 1963.

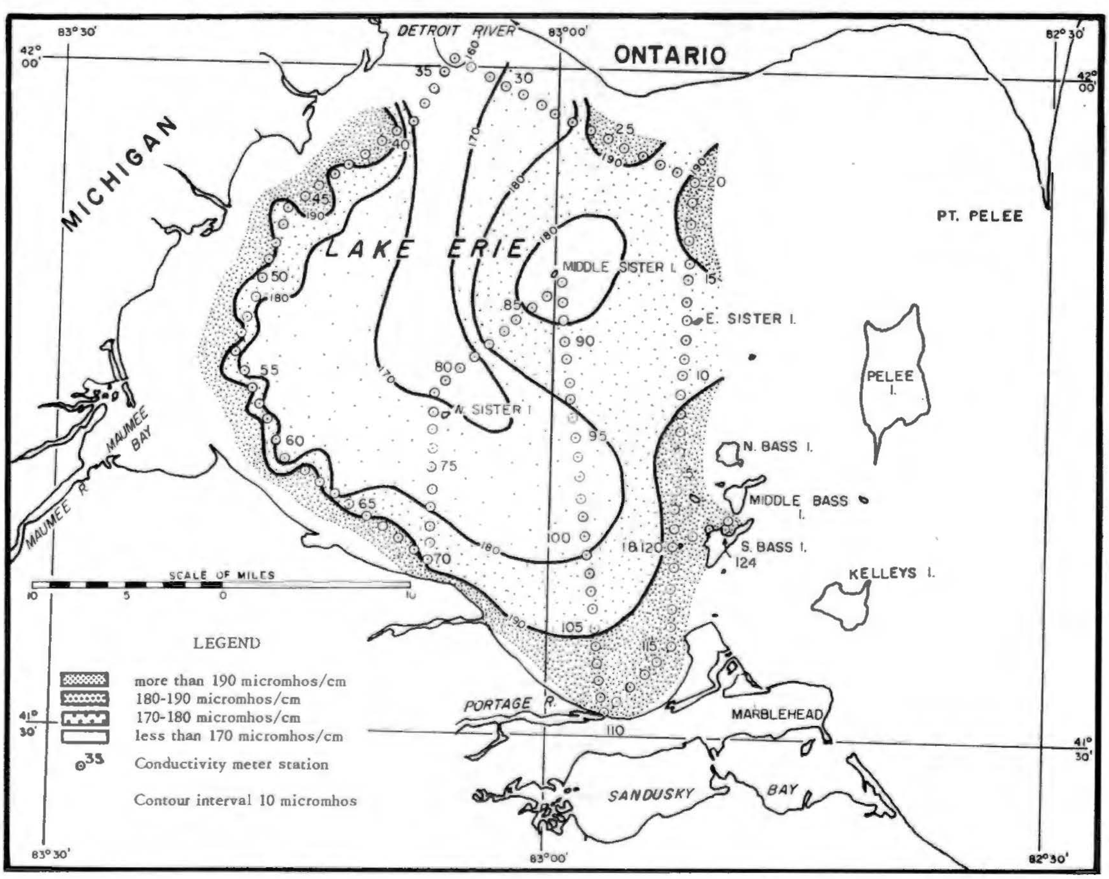

Figure 8. - Surface conductivity of western Lake Erie on 28 May 1964.

bottom-water conductivity values. Unfortunately, there are no samples from much of the important band south of the Detroit River mouth. Adjacent samples, however, indicate a pattern probably existed similar to that of the surface. There is some indication that the bottom water from the Detroit River may not have reached as far south as the surface water.

Surface conductivity of western Lake Erie was measured in the field during a cruise of the *SE-1* on May 28, 1964. The measurements were taken at the time of sampling with a portable conductivity meter. The values were somewhat lower than those of the survey of June 1963, but the variation patterns were similar (fig. 8). The highest values were again found on the west side of the Detroit River mouth, near Monroe, Michigan. Another mass of highly conductive surface water was present along the Ontario shore, but water of low conductivity, apparently the midchannel flow of the Detroit River, was found southeast as far as West Sister Island. High conductivity values west and southwest of the Bass Islands may be the result of a combined nearshore flow of Detroit River and Maumee River water that turned northward at Catawba Island during a period of falling water level at the time of the survey.

Figure 8 indicates that on May 28, 1964, the water masses were present and were moving in patterns that correspond well with the data obtained from the survey of June 23, 1963. The similar results of the two surveys tend to substantiate a consistency of flow patterns within western Lake Erie.

Rodgers (1962), reports conductivity values comparable to those of our survey for four cruises during the summer and fall of 1961, the lowest values being south and southeast of the Detroit River mouth. Beeton (1963) reports that in August 1960, the lowest conductivity was in the main outflow of the Detroit River channel and that the low-conductivity water fanned out southeasterly, roughly following the distribution of surface temperatures. He also states that Detroit River waters have lower conductivity than waters along both shores. The results of our survey substantiate this.

It was suspected that the freezing of some of the water samples affected the conductivity. The following brief experiments were performed to check the effects. A water sample was divided into three parts and stored for two days. One part was frozen, one was cooled to 4 C, and the third was stored at room temperature of about 23 C. A conductivity of 301 micromhos per cm at 25 C was read immediately after sampling. Two days later, the cooled sample had a conductivity of 316 at 25 C, the sample at room temperature was 313 at 25 C but the frozen sample measured 269 micromhos per cm at 25 C. Freezing had reduced the conductivity by about 40 micromhos, while cooling and no cooling had had virtually no effect.

A correction of about + 40 micromhos, if applied to the southern-island area samples, puts the values in the expected range and in the range of values expected in central Lake Erie water. This can still be interpreted as indicating an insurgence of water from the central basin into that area.

TEMPERATURE

Bathythermograph recordings made on June 23, 1963, indicate that a weak thermocline developed after noon in the upper water of the western basin. The thermocline showed at nearly all stations after 1200 hours, but none was shown at those stations occupied before 1100 hours. In total, more than half of 76 stations showed thermal stratification. The bathythermograph recordings are included in a compilation by Herdendorf (1963).

The thermocline did not show the classic sharp break in temperature, but ranged between 1 F and 5 F drop per 5 feet water depth. The maximum drop in temperature occurred just below the surface in late afternoon. This may have been the beginning of the development of a true thermocline. However, it is more likely that the stratification on June 23 was diurnal, disappearing during the night and reappearing the following day. Extended periods of very calm weather, low seiche activity, and warm air are needed to develop a true thermocline in the western basin.

Temperatures of the surface water, ranging from 66 F to 75 F, at the times of sampling, when plotted on a chart, show a pattern similar to that of surface conductivity. These values cannot be considered synoptic because of heat absorption during the survey hours, which probably changed the surface temperature by as much as 3 F. However, the surface temperatures do indicate that the colder Detroit River water was split, south and southeast, upon entering the basin.

Temperatures, to be considered synoptic, had to be obtained from a zone in which the temperature change during the day was negligible. If such a zone existed, it could not be in the upper diurnally heated layers, nor in the bottom waters where sediment-water heat exchange might have occurred. The ten-foot depth was chosen as that depth most nearly approaching the ideal for the day of the survey, because the temperature values were uniform from a few feet above to a few feet below this depth.

The water temperatures from bathythermograph recordings, at the ten-foot depth have been plotted and contoured in figure 9. The pattern shows a definite southward movement of the relatively cold Detroit River water. It also indicates a northward flow of warmer water west of the islands and an apparent insurgence of cooler water from the central basin into southern-island channels and into Pelee Passage northeast of Pelee

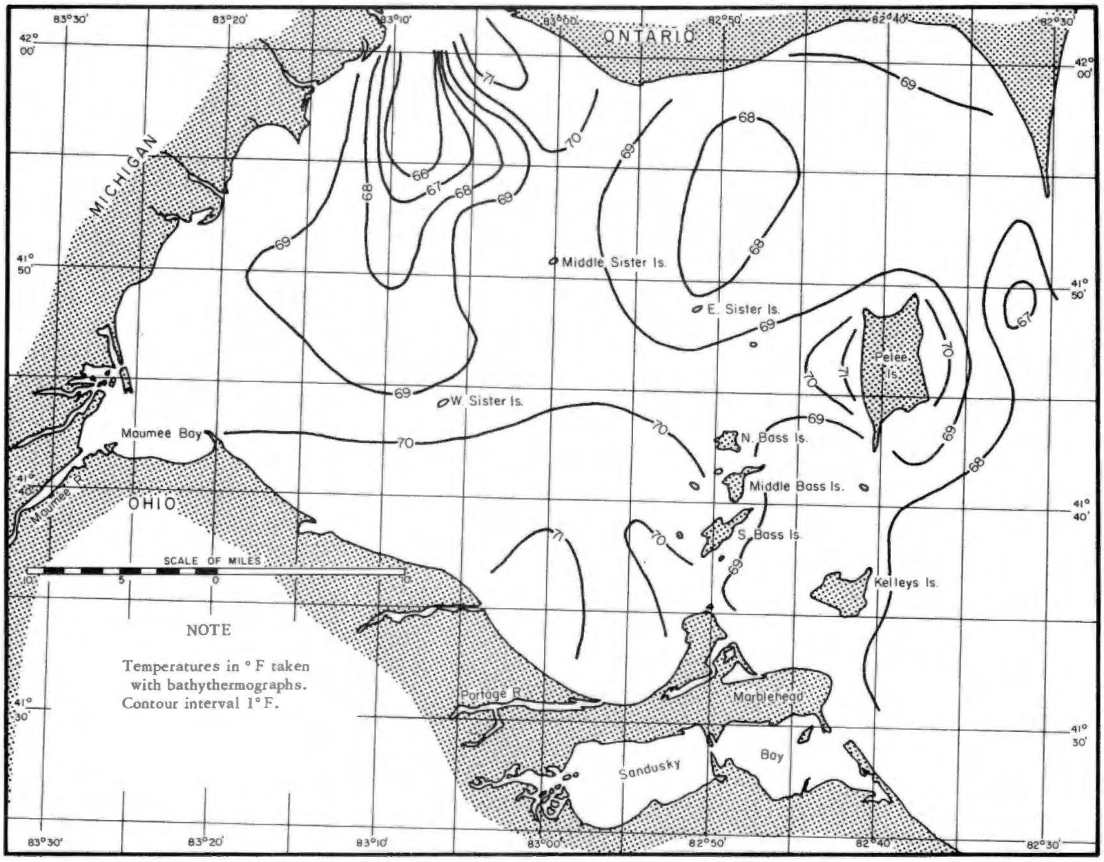

Figure 9. - Water temperatures at 10-foot depth in western Lake Erie on 23 June 1963.

Island. There are no temperature measurements for that day from the central basin, but central-basin water is ordinarily cooler in summer than western-basin water.

Although temperatures are subject to change in a relatively short time, they are probably more useful in the western basin than elsewhere in Lake Erie as evidence of mass water movements, because of the great volume of cold water which moves into the basin from the Detroit River. The cold water is apparently warmed considerably before it leaves the western basin. In addition to providing the basis for temperature mapping, the magnitude of the warming is an indication that much of the water may stay in the western basin for a long time before passing into the central basin.

Beeton (1963) reported that in August 1960:

> "Detroit River was extended from the river mouth almost to the Bass Islands as a forked tongue of cooler water. The major mass extended southward almost to Marblehead while a smaller mass protruded into Pigeon Bay."

It is assumed that he meant Catawba instead of Marblehead.

WATER COLOR

Color determinations were not made during the present survey, but some observations are worthy of note. The main flow of the Detroit River, at its mouth, was pale green and apparently clean, while the west side of the river was brown to dark brown, containing all sorts of debris and sewage. The pale color of the main flow graded, with perceptible boundary, southward into the usual green color of unroiled water in the western basin. The brown color of the western side persisted all along the Michigan shore, sharply divided from the green water to the east. The brown color faded gradually southward along the Michigan shore to the vicinity of Monroe. The color then intensified again and graded into the characteristic reddish-brown if the Maumee River flowage. The color maintained its sharp division from the main body of the lake southeastward to about halfway between Maumee Bay and Locust Point. In this area the reddish-brown color faded into green and color boundaries disappeared.

Color would apparently be a valuable component of water studies. In this study the pattern was apparently similar to that of surface conductivity, which was to be expected.

WATER LEVELS AND WEATHER

A graph of lake-surface elevations at Sandusky for three days preceding the survey is shown in figure 10. Also shown are hourly wind velocities from U.S. Weather Bureau records at Sandusky.

A wind set-up and ensuring seiche (longitudinal) are shown for June 20 and 21. After about 1200 hours on June 22 the lake was not disturbed significantly by seiche activity. A few seiches, each approximately 3 hours in period, may have been the transmitted effects of transverse seiches of the central basin or of some oscillation of Sandusky Bay.

The last significant change in water level attributable to seiche movement, prior to the survey, was a rise of about 0.2 foot between 0500 and 1200 hours on June 22, after which levels were relatively stable. A relict effect of this rise may be reflected in the conductivity and temperature values which seem to denote an influx of water into the southern-island area from the central basin.

There was a rise in water level during the survey beginning at about 1400 hours on June 23 that reached a maximum at about 2200 hours. The Sandusky gage recorded a rise of 0.24 foot. The U.S. Lake Survey gage at Marblehead recorded a rise of 0.25 foot between 1440 and 2230 hours. Measurements made in the island area should have reflected the maximum effect, if any, of the rise. The southern-island area part of the survey had been completed before the rise. However, the *Investigator* was working the Pelee Passage area between 1400 and 1900 hours. The temperature measurements (fig. 9) in that area indicate an influx of central-basin water, which is to be expected with a rise in water level.

Winds were very light preceding the study period and did not exceed 11 mph at Sandusky after 0200, June 21. The "land and sea breeze" effect caused northerly and southerly winds to alternate on June 22 and 23. Estimated velocities within the western basin during the study were somewhat less than those recorded in Sandusky and did not exceed 10 mph and were generally less than 5 mph.

Both water levels and winds indicate that the survey was carried out at an ideal time, when disturbing influences were at a minimum.

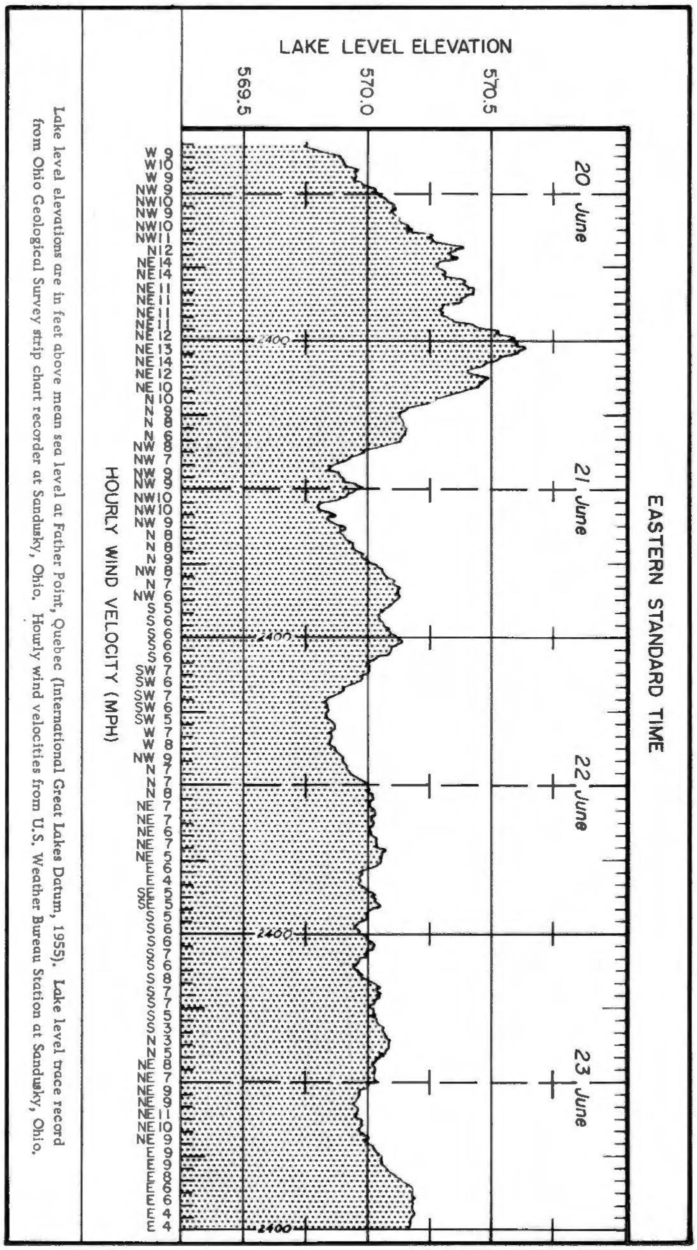

Figure 10. - Lake levels and wind velocities at Sandusky, Ohio, 20 June through 23 June 1963.

CURRENT MEASUREMENTS

During the spring of 1963 the Division of Geological Survey made several field studies of currents in the spawning areas of western Lake Erie. Most of the work consisted of measuring current velocities and directions with an Ekman meter for extended periods at each of several stations, the locations of which are shown in figure 11. Additional current studies were made during the summer of 1964 to correlate conductivity patterns with measured water movements.

The quantity of information gained in the current studies was not sufficient to establish any definite patterns. Some of the measurements, however, are consistent with the apparent water movements. A brief summary of the results of the current studies follows.

Niagara Reef

Measurements made during a seven-hour period on April 16, 1963, indicated currents existed on Niagara Reef which were controlled by seiche activity and deflected by the wind. Currents at 10.0 feet depth moved northwestward at an average velocity of 0.14 ft per sec with a maximum of 0.23 ft per sec. At a depth of 5.0 feet the direction was similar and velocities averaged 0.24 ft per sec. Wind speed varied between 10 and 20 mph from the south to southeast. Water level was rising.

Toussaint Reef

Measurements made during a five-hour period on May 4, 1963, on Toussaint Reef showed currents at a depth of 5.5 feet averaging 0.23 ft per sec and moving east to southeast. The maximum velocity was 0.26 ft per sec. The wind was southwest to south-southwest between 5 and 10 mph.

Currents on Toussaint Reef were probably activated by seiche action and deflected somewhat by the wind and bottom topography. Water level was falling at the time.

Starve Island Reef

Measurements were made at approximately half-hour intervals at a depth of 8.0 feet on Starve Island Reef for 24 hours beginning at noon, May 2, 1963. For the first 7 hours the current was west to west-southwest with an average velocity of 0.27 ft per sec, and

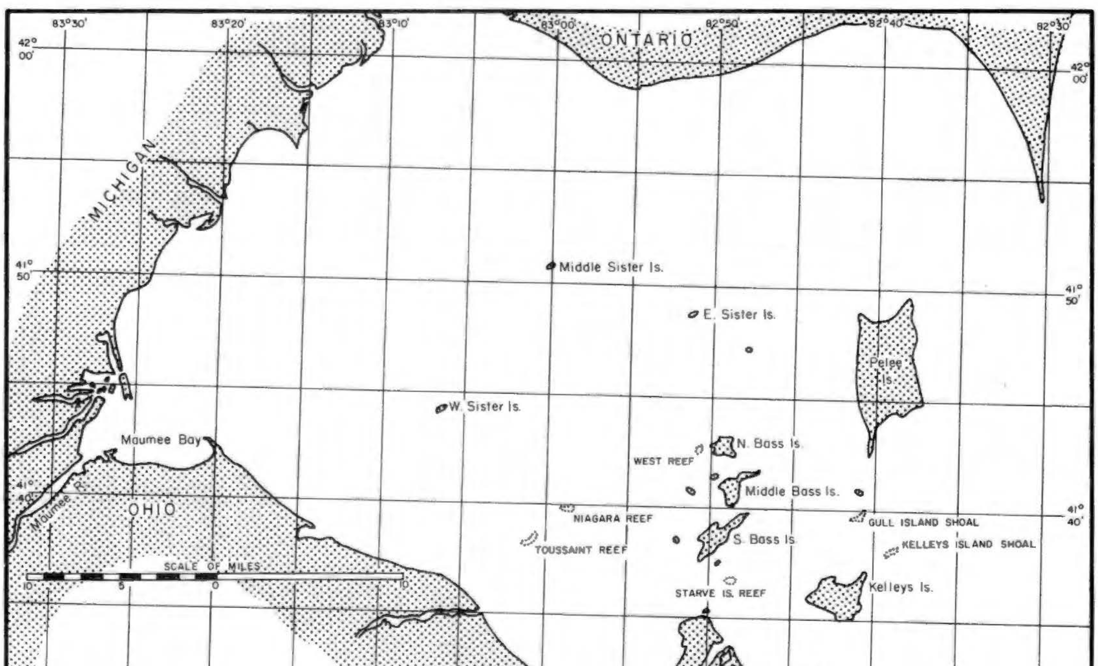

Figure 11. - Map showing locations of reefs on which currents were measured--spring, 1963.

a maximum of 0.34 ft per sec. The wind was southwest to southeast at 5 to 10 mph and the water level was rising.

For the next 8 hours the current was essentially east-northeastward at an average speed of 0.26 ft per sec and a maximum of 0.36 ft per sec. The wind was south to southeast at 0 to 5 mph. Water level was falling.

For the next 9 hours the current was again westerly with an average velocity of 0.10 ft per sec and a maximum of 0.24 ft per sec. The wind was south to southwest at 5 to 15 mph and the water level was rising.

The currents on Starve Island Reef were primarily seiche controlled. During periods of high seiche amplitude and during storm periods it appears that the current velocities could easily surpass 2.0 ft per sec.

Gull Island Shoal

Gull Island Shoal was occupied for 22 hours beginning at 1000 hours on April 18, 1963. For the first 6 hours the current was essentially south-southwestward at an average velocity of 0.20 ft per sec and a maximum of 0.29 ft per sec at 9.0 feet water depth. Water level was falling and the wind was northeast to east at 5 to 10 mph.

For the next 8 hours, during a rising water level, the current was northwestward averaging 0.29 ft per sec with a maximum of 0.84 ft per sec. During the period the water level was rising and the wind increased from 5 mph (east-southeast) to 25 mph (east-northeast). The maximum current velocity coincided with maximum wind velocity.

During the next 8 hours the current was southeastward at an average speed of 0.35 and a maximum of 0.70 ft per sec. Water level was falling. For the first half of the period the wind was northeast 10 to 20 mph. During the last half the wind was southwest 15 to 20 mph.

The currents on Gull Island Shoal were controlled by the longitudinal seiche and apparently were deflected by the wind and bottom topography. They were essentially at right angles to the long axis of the reef. Current velocities were fairly high and quite capable of moving sand-size sediments. Under other conditions much higher velocities than those measured at this time could be anticipated. Velocities up to 2.0 ft per sec would not be unexpected during storm periods.

Kelleys Island Shoal

Current measurements were made at half-hour intervals on Kelleys Island Shoal over a 24-hour period beginning at noon on April 24, 1963, at 10.0 feet water depth. The wind was variable and under 10 mph throughout the period.

Unlike the currents at other stations, the current here was seldom in the same direction for any length of time. Instead, the directions progressed clockwise around the compass. The first measurement at noon showed an easterly moving current. At 1700 hours it was southward, at 1830 it was westward, at 2230 northward, and at 2400 it was again easterly. At 0730 hours the following day it was moving southward. The average velocity for the 24 hours was 0.15 ft per sec. The maximum was 0.47 ft per sec. Velocities were somewhat higher in the easterly quadrants.

Current velocities and directions were apparently related to seiche activity, although it was slight during the period. The clockwise change of current direction may have resulted from seiche activity along axes other than the longitudinal axis of the central basin.

West Reef, North Bass Island

Currents were measured at depths of 4.0 and 7.0 feet on West Reef at alternate half-hour intervals for 24 hours beginning at 1400 hours on May 6, 1963. Currents here were of very low velocities and moved northward throughout the period. The maximum velocity was 0.31 ft per sec, near the lower limit of accuracy of the Ekman meter. The wind throughout the period was light and variable.

The extreme calm during this period allows no reasonable conclusions regarding currents on West Reef. However, it does seem likely that currents are not of the magnitude here as at other reefs, and that northerly movements may dominate.

Between Middle Sister Island and West Sister Island

The results of the June 1963 and May 1964 surveys indicated a southerly flow of midchannel Detroit River water between Middle Sister Island and West Sister Island. To correlate the flow patterns obtained from the conductivity measurements with actual water movements a current-meter station was established midway between the two islands. The station was visited twice during July 1964. Currents were measured sequentially, using one Eckman meter at depths of 2.0, 15.0 and 25.0 feet at half-hour intervals for four hours beginning at 1100 hours on July 1, 1964, and for seven hours on July 8, 1964, beginning at 0930. On July 1 the wind was moderate, 10 to 19 mph from the southwest. On July 8 the wind was light, 4 to 14 mph from the north-northeast.

For the first hour on July 1 the currents were southwesterly and of low velocities at all depths. At about 1200 hours the direction changed to south-southeast at all depths and increased slightly in velocity for the remainder of the study period. The highest recorded velocity was 0.15 ft per sec at 25.0 feet. On July 8 the current at all depths was moving in an average southeasterly direction. The average velocity at 2.0 feet was 0.26 ft per sec, at 15.0 feet it was 0.06 ft per sec and at 25.0 feet it was 0.10 ft per sec. The maximum velocity was 0.46 ft per sec at 2.0 feet.

The data collected from this station appear to further substantiate the conductivity patterns of the Detroit River flow. The velocities were only moderate but the fact that the direction of flow was nearly always southerly is significant. Another important factor is the similarity of direction at all three depth which again may be indicative of Detroit River flow.

DISCUSSION

WATER MASSES AND MOVEMENTS - COMBINED ANALYSIS

The water survey of June 23, 1963, in the western basin of Lake Erie demonstrated that water masses can be mapped, particularly those created by major inflowing streams. Observations of all of the measurable factors produced results which give reasonably good charted patterns.

Figure 12 shows the general paths of water movement at all levels as interpreted from the combined analyses of all factors. Although the interpretations for the northeast quarter of the basin are admittedly weaker, because of the lesser variations in values for that area, the case is stronger for the remaining part of the interpretation. Values for pH, turbidity, conductivity, and temperature, together with color observations, indicate a dominating southward movement of most of the Detroit River water, some of which must have reached the Ohio shore. The center main flow of the river separated flows on either side which showed higher values for all factors, with the west side showing the highest.

Conductivity, turbidity, and temperature values indicate an eastward movement along the Ohio shore from Maumee Bay to the island area and then northward along the west side of the island area. All factors, except turbidity, indicate a northwestward flow of water from the central basin into the southern-island area. Temperatures indicate some recent inflow from the central basin in Pelee Passage.

Emphasis must be placed on the fact that the interpretation is based on the results of a one-day survey. The hazards of the interpretation are well known to the writers. We are dealing with a highly mobile subject which is easily changed by a wide variety of forces. Also the pattern we see may be the result of more than one set of previous water movements. Keeping this in mind, a comparison was made between this survey and previous water movement studies in the western basin.

COMPARISON WITH PREVIOUS WATER MOVEMENT STUDIES

Harrington (1895), in a rather crude survey of the Great Lakes currents, using drift bottles, mapped the surface currents of western Lake Erie (fig. 13). He used very few bottles, some of which were not found until months after release. In some respects his map is similar to ours. The Detroit River flow, according to Harrington, was split south of the river mouth. Part of the flow went south-southwest toward Maumee Bay, while the major part apparently went eastward directly to Pelee Passage. He does not indicate what happened to that part of the flow which went to the Maumee Bay area, but one must assume it moved from there eastward. He shows a flow pattern to the east splitting, with part moving out north of the islands and part through the southern-island area. Inflow from the central basin moved between Kelleys and Pelee Islands, through the Bass Islands. All of this resulted in a clockwise current around Pelee Island.

The major discrepancy between our work and that of Harrington is in interpretation of flow in the southern-island area, where we show no eastward flow, which obviously requires that the outflow from the western basin moves out the Pelee Passage. Consistent with our study, he also indicates *most* of the outflow through Pelee Passage.

Olson (1950) made a study of currents in western Lake Erie in 1948 and 1949 using drift cards. The flow patterns (fig. 14) he obtained by this method are quite inconsistent with those obtained in our survey, with the exception that both his and our patterns show most of the western-basin water moving out through the Pelee Passage. He divides the flow from the Detroit River into three parts, which he calls the "Colchester Convergence," the "Pigeon Bay Drift," and the "Pelee Passage Drift." This of course implies that all of the Detroit River flow stays along the north shore, passing into the central basin via Pelee Passage. He also states this as a conclusion. His areas of "Michigan Shore Drift" and "Maumee Flowage" have shown flow during our survey, but he admittedly has little data in the southern part of the basin. According to Olson there is a to-and-fro motion of the water in the southern-island area and, like Harrington, he shows a clockwise movement around Pelee Island, called the "Pelee Island Gyre."

Comparing our work with that of Olson then, there is agreement that most of the water passes out through Pelee Passage and that there is a drift of Detroit River water along the north shore. Also our study does not conflict with his "Pelee Island Gyre."

We are at variance with Olson's "Michigan Shore

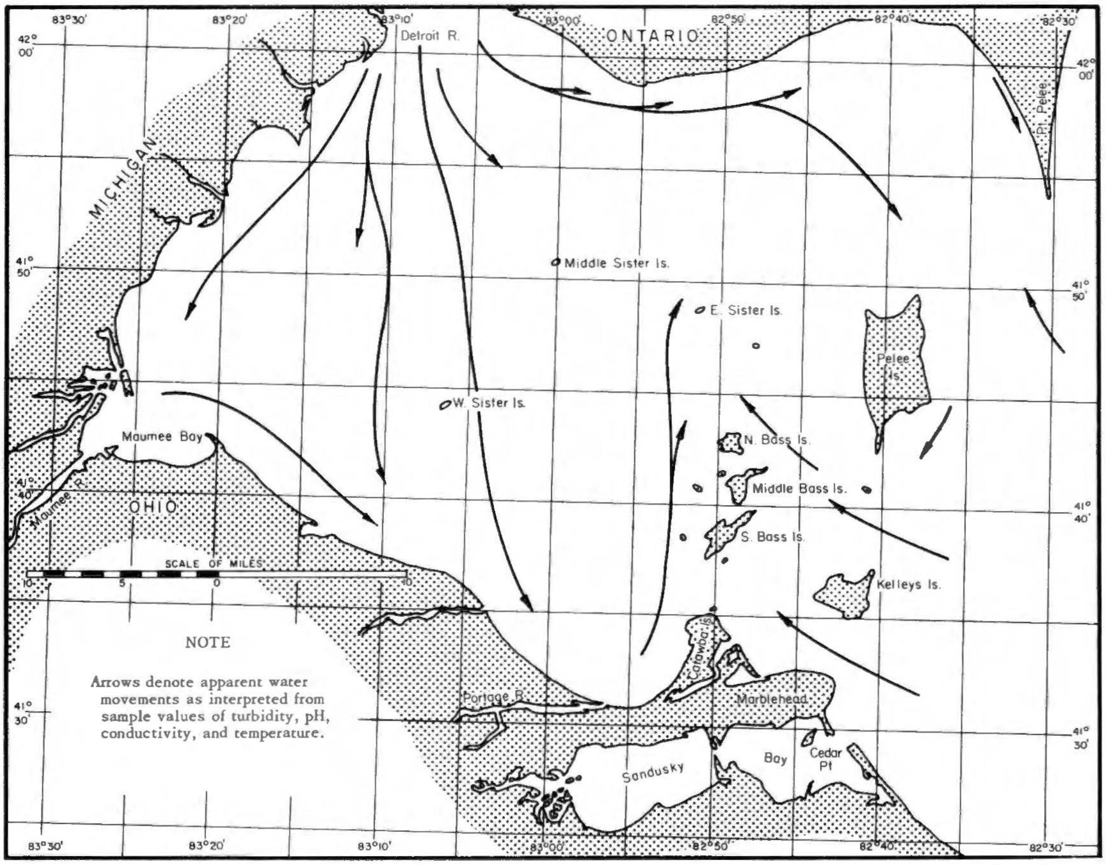

Figure 12. - Water movement in western Lake Erie on 23 June 1963.

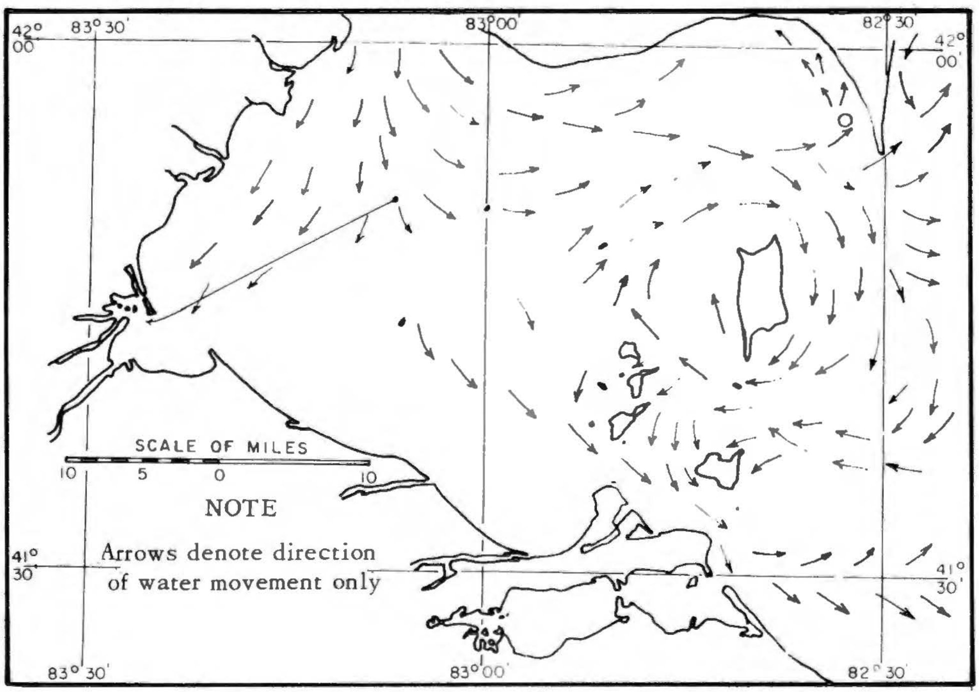

Figure 13. - Water flow patterns in western Lake Erie according to Harrington (1895).

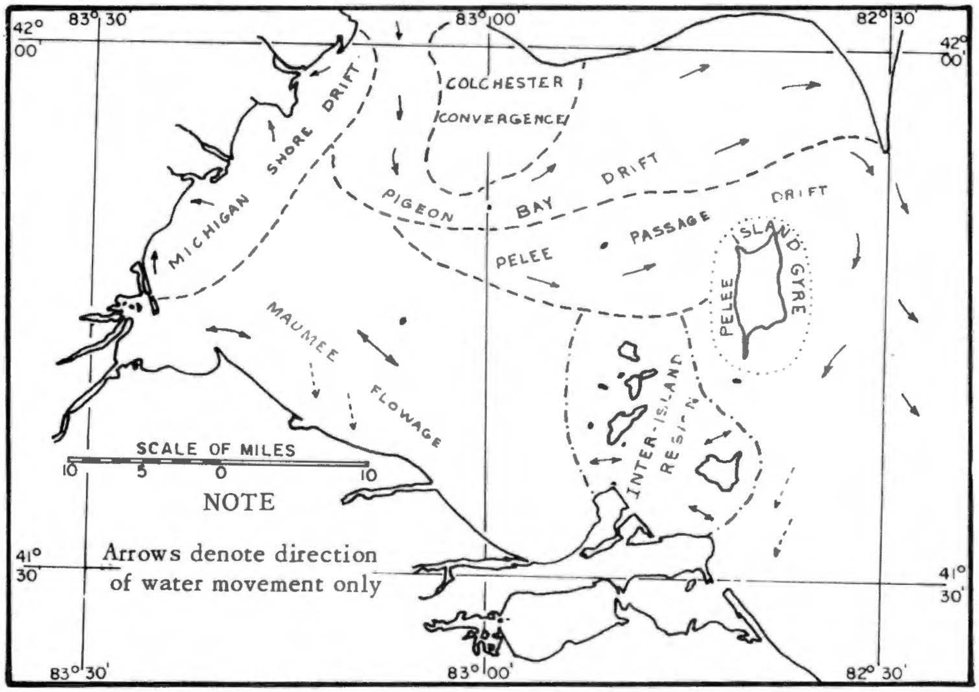

Figure 14. - Current and water mass patterns in western Lake Erie according to Olson (1950).

Drift," "Maumee Flowage," and his "Inter-Island Region." He could not show definite dominating flow patterns in these areas. He also states that:

> "in no case will there be a 'crossing-over' of Maumee and Detroit River waters" and, "it is obvious that water from the Maumee must go through the South Passage or possibly through the islands and that only the Detroit River water can flow through the Pelee Passage."

This is almost opposite to our findings, which indicate that the Detroit River main flow moved southward and part of it reached the Ohio shore, combining then with the Maumee River water to turn northward west of the islands. It must be remembered however, that his patterns cover weeks or months of time, while ours are the patterns of a single day.

Wright (1955) studied the currents of western Lake Erie in 1928 with drift bottles. He draws no conclusions, but states that the currents are not constant and are highly dependent upon the wind. Without knowledge of the winds at the time, it is not possible to compare his data with ours with any confidence. Suffice it to say that bottles released near the Ohio and Michigan mainland shores went southward and most bottles released just west of the Bass Islands went northward.

Verber (1953a, 1953b), through the use of drift cards and direct current measurements, concluded that a rotational movement of water exists in western Lake Erie. Measurements, mainly in Pelee Passage, indicate a larger outflow than inflow and vice versa in the southern channels. He also indicates a northward flow east of the islands. This is consistent with the results of our study.

An anonymous article in the "Engineering News-Record" (1956) reported three separate flowages in the Detroit River near Detroit. Midchannel clean water was bounded by water on both sides with very high coliform counts. This is an indication that three masses discharge from the river, and this agrees with our findings. Beeton (1963) indicates the possibility of the existence of three masses when he states that "conductance probably was higher along both shores of the river mouth" in August 1960.

Langlois (1954), in his exposition on western Lake Erie, does not go into detail on water movements. He suggests that turbid water from the south-shore streams can affect the entire basin. He theorizes that high turbidities are caused mainly by stream injection, and he states that Verduin (1951) accepts this theory and indicates that river water may spread out over or under the lake as a thin layer of different density. Langlois also states that southern water is much more turbid than northern (Detroit River) water. He cites Andrews (1948) as showing:

> "a displacement of southern water mass by violent persistent northeastern wind, with the silty water pushed toward the north channel."

Halicki (1956) includes a map, in a bacteria study, showing lake currents in the western end. He implies that the patterns are taken from works of Olson and Verber, although they do not appear similar. He has a pattern showing the Portage and Sandusky River discharges moving northwestward to near Middle Sister Island and then turning eastward. He also shows Maumee water joining the Portage flow near Port Clinton. Much of the pattern seems highly unlikely, especially that of the Sandusky River.

CONCLUSIONS

The synoptic study has demonstrated that a dense pattern of water sampling and analyses, carried out in a short time, can be valuable in determining the existence and shapes and movements of water masses. This was the main objective of the study.

From the standpoint of reliability of data, some conclusions can be drawn regarding the relative values of the different factors used in this study, as follows:

1. Hydrogen-ion concentration, as also indicated by other workers, is not a good indicator of separate water masses because it is subject to diurnal and other changes. It may be useful in delineating major inflow, such as the Detroit River.
2. Turbidity may be useful as an indicator of separate masses if used in conjunction with other factors. Turbidity of samples may be subject to considerable change during storage because of biologic and chemical action.
3. Conductivity is apparently a reliable indicator of water masses. Conductivity does not change appreciably in sample storage at temperatures above freezing. Measurements of samples that have undergone freezing and thawing show greatly reduced conductivity.
4. Water temperatures are reliable indicators of water masses if the water is nearly homothermous vertically. The temperatures just below the zone of surface heating should be used in mapping. Surface temperatures are not good indicators because of diurnal heating.
5. Water color is apparently a useful factor in mapping water masses, although this was not used in detail in this study.

Water masses and their locations may change considerably, depending upon time and conditions during and preceding a survey. On June 23, 1963, during and after a 2-day period of calm, our study indicates that:

1. The main (midchannel) flow of the Detroit River moved primarily southward and may have reached the Ohio shore.
2. Some of the main flow and that from the east side of the Detroit moved eastward near the Canadian shore.
3. The flow along the west side of the Detroit moved southward along the Michigan shore.
4. The Maumee River flow moved eastward near the Ohio mainland shore and then northward along the west side of the islands.
5. Most of the flow into the central basin was through Pelee Passage.
6. Most of the flow from the central basin into the western basin was through the southern-island area.
7. The most highly contaminated water, as indicated by surface conductivity and turbidity, was at the west side of the mouth of the Detroit River, Maumee Bay, and around Catawba.
8. The cleanest water, also indicated by surface conductivity and turbidity, was in the main flow of the Detroit River and near the Canadian shore.
9. Water with high pH, extending south from the Detroit River mouth, probably was due to diurnal fluctuation caused primarily by photosynthesis.

Determination of water masses and their movements by the methods used in this study is probably dependent upon conditions during and preceding the survey. Storms and significant seiche activity can probably disrupt any pattern, in proportion to the magnitude of the disrupting influence. It is conceivable that in western Lake Erie there may be times when water properties are practically uniform throughout the basin. It appears then that surveys of this kind, to be of the most value, should be made during and after calm periods. Fortunately the present study was made at such a time.

LIMITATIONS OF THE STUDY AND FUTURE WORK

A study of this type has several limitations, the most important of which is the lack of synopticity. Although the survey was done as rapidly as possible, it was not really synoptic, in that the lake water was changing biologically, physically, and chemically, and was moving horizontally during the survey. The ideal synoptic quality can never really be achieved, but the method can be improved considerably by using more boats with advanced equipment.

Turbidity and hydrogen-ion concentration are probably subject to rapid changes at any one site during the day. Because of this, it is felt that future studies, if they are to be used to delineate water masses, should not include these data. However, if the data are to be used in the study of biological phenomena, they should be measured in the field at the time of sampling.

Future studies of this type should be done with electronic gear which, in the field, instantaneously records temperature, conductivity, and hydrogen-ion concentration. This would reduce or eliminate the error introduced by sample storage.

The number of sampling sites could be cut in half without a proportional loss of detail. This would also increase the synopticity by halving the allotted field time. More boats would, of course, further reduce the time.

Samples for later analysis should be held to a minimum. These samples should be analyzed for the content of stable compounds, such as chlorides, which can also be useful in determining mass water movements. Conductivity should be run as a check on field measurements.

Color of the water, according to a standard scale, should be noted at each sampling station, and sharp boundaries should be located.

Bathythermograph recordings should be made on a pattern similar to the one in this study.

Identical surveys should be made at least three times in one year; preferably in spring, summer, and fall. They should be run during periods of calm weather and low seiche activity which are, of course, difficult to anticipate.

With the proper equipment and careful planning, a survey similar to the present one could be accomplished in less than half the time, resulting in more useful, detailed, and reliable data.

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