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LIMNOLOGICAL SURVEY OF EASTERN AND CENTRAL LAKE ERIE, 1928-1929

SPECIAL SCIENTIFIC REPORT—FISHERIES No. 334

UNITED STATES DEPARTMENT OF THE INTERIOR
FISH AND WILDLIFE SERVICE

United States Department of the Interior, Fred A. Seaton, Secretary
Fish and Wildlife Service, Arnie J. Suomela, Commissioner
Bureau of Commercial FisheriesM Donald L. McKernan, Director

LIMNOLOGICAL SURVEY OF EASTERN AND CENTRAL LAKE ERIE 1928-29

by

Charles J. Fish
and
Associates

United States Fish and Wildlife Service
Special Scientific Report--Fisheries No. 334

Washington, D. C.
June 1960

ABSTRACT

Results of a cooperative survey of the central and eastern basins of Lake Erie in 1928-29 by the U. S. Bureau of Fisheries, New York State Conservation Department, Ontario Department of Game and Fisheries, Health Department of the City of Buffalo, and the Buffalo Society of Natural Sciences are presented in a series of papers. Physicochemical data include seasonal, vertical, and horizontal variations in temperatures, water movements, dissolved oxygen, carbon dioxide, phenolphthalein and methyl-orange alkalinity, pH, chlorides, and turbidity. The species composition, seasonal abundance, and distribution of micro- and macroplankton are discussed in detail. Special consideration is given to the influence of polluted river waters which flow into the lake.

It is concluded that the lake is remarkably free from chemical and sewage pollution. Evidence of pollution farther than 1 mile from possible sources was detected at only 2 stations. The nutrient level of Lake Erie is high and the lake should support large fish populations.

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FOREWORD

Any detailed account of the reasons for a 30-year delay in the publication of this report would be of questionable value. Suffice it to say that present research on Lake Erie, being conducted by Ontario, several state agencies, the Federal Government of Canada, and the U. S. Bureau of Commercial Fisheries, has demonstrated the value of the manuscripts included in this report. Comparisons between the observations of then and now have provided evidence of progressive eutrophication in Lake Erie. The manuscripts on microplankton and macroplankton are the most comprehensive that have appeared to date on plankton of the Great Lakes. Furthermore, the careful and detailed work of the 1928-29 surveys of the central and eastern basins of Lake Erie, plus the 1928-30 surveys of the western basin (Wright 1955), provide an invaluable basis for future limnological studies of the lake.

This report was edited by staff members of the Great Lakes Biological Laboratory, Bureau of Commercial Fisheries; many deteriorated figures were redrawn. In view of the obvious difficulties presented by the great time lag between preparation and publication, and since most of the authors could not be contacted, normal editorial criteria could not be followed. This enterprise was greatly advanced by the advice and assistance of Dr. Fish.

Alfred M. Beeton

GENERAL INTRODUCTION

Charles J. Fish, Director
Buffalo Museum of Science

The serious decline in certain fish populations in Lake Erie has made obvious the need for more extended knowledge of conditions affecting the fishery. To quote from a preliminary report (Fish et al. 1929): "For several years the rapid decline in the fish supply of the Great Lakes, particularly of Lake Erie, has been a matter of serious concern not only to the fishermen but to the American and Canadian governments, the states bordering on the lakes, and the many private organizations and individuals interested in preserving what was once one of the most productive bodies of water in the world.

"Obviously legislative action was necessary, but the problem is an international one, and intelligent legislation was not possible so long as the factors responsible for the decline were not known. Various explanations were advanced. Some claimed that Lake Erie was being overfished; others that chemical and sewage wastes from the cities were polluting the waters to such an extent that the fish were being wiped out. Some fishermen attributed the decline to sewage silt invading the spawning grounds and rendering whole areas unfit for the production of young fish. The possibility that a lack of food was responsible for the decline was also advanced. But so long as these claims remained unanswered there could be little grounds upon which to base restrictive legislation.

"Of one thing all are certain: the decline is due to man's influence, but how? As a large shallow lake Erie offers the greatest possibilities for rich animal and plant life; in fact, there is no lake in the world more favorable for the production of fish than this body of water under its normal conditions; and the records bear out this statement. One has only to refer to the large catches of former years to learn what a varied and extensive fish fauna Lake Erie is capable of supporting."

Lake Erie, with a drainage area of 34, 680 square miles and a continuous movement of water, offers unusual biological possibilities. A portion of the lake retains cold bottom water throughout the year, while the remainder, which constitutes a large percentage of the total area, offers conditions favorable for shallow water species requiring high summer temperatures. It is the shallowest of the Great Lakes, and is 240 miles long with an average width of about 40 miles. Having a total area of approximately 9, 633 square miles (exclusive of rivers), the lake divides itself into three natural sections (fig. 1).

The western section, which comprises less than one-eighth of the total area, has a maximum depth of 15 meters. A natural barrier formed by points extending from the two shores and two islands (Kelly Island and Pelee Island) separates this body of water from the rest of the lake. The waters of the Detroit, Maumee, and Sandusky rivers enter the lake in this area.

The middle two-thirds of the lake forms a second section extending from the islands to a shoal having a minimum depth of 13 meters and extending north and south across the lake just west of the 25-meter contour line, in the vicinity of Erie, Pa. This area, the widest part of the lake, forms a broad shallow basin with a maximum depth of 26 meters in its western portion. The greater part of the floor, sometimes referred to as the Great Plain, is exceptionally even. No major rivers enter here.

The eastern, or deep section, comprises the area investigated in 1928 and extends from Erie, Pa. to the entrance to the Niagara River. The most significant characteristics are the Deep Hole, having a maximum depth of 64 meters, and Long Point which exerts great influence on the circulation of the water mass in the eastern part of the lake. This point forms a shallow bay 15 miles wide at the mouth and some 20 miles in length, with a maximum depth of about 14 meters.

The Deep Hole is about 30 miles long and 20 miles wide at the 40-meter level. The bottom waters here are only slightly influenced by summer warming, that portion below 60 meters rarely attaining 5° C.

The bathymetrical chart (fig. 1) shows the bottom contours of Lake Erie. The approximate areas at the various levels and their percentage of the total surface area are given in table 1.

The 30-meter contour line designates the outer margin of the deep basin, which is limited to the eastern area, and forms only 9 percent of the total area of the lake. The Deep Hole, bounded by the 40-meter contour, comprises but 4.5 percent. The deeper portion of the western basin is indicated by the 25-meter contour with an area of approximately 593 square miles. The eastern area at this depth is approximately 1,013 square miles.

The lake empties into the Niagara River discharging 206,000 cubic feet per second at mean height (572.42 feet above the sea level). The discharge increases at a rate of 22,000 feet per second with each rise of 1 foot. There is an average rainfall of 34 inches in this region and an annual variation of the lake level of approximately 1 foot, the maximum being in June and the minimum in January (Uspensk: 1928).

Table 1. --Area of Lake Erie at different depths

Level (meters)	Area (square miles)	Percentage of lake
0	9,632.9	100.0
20	5,386.1	55.9
25	1,605.3	16.7
30	890.4	9.0
40	429.3	4.5
50	151.1	1.6
60	35.8	0.4

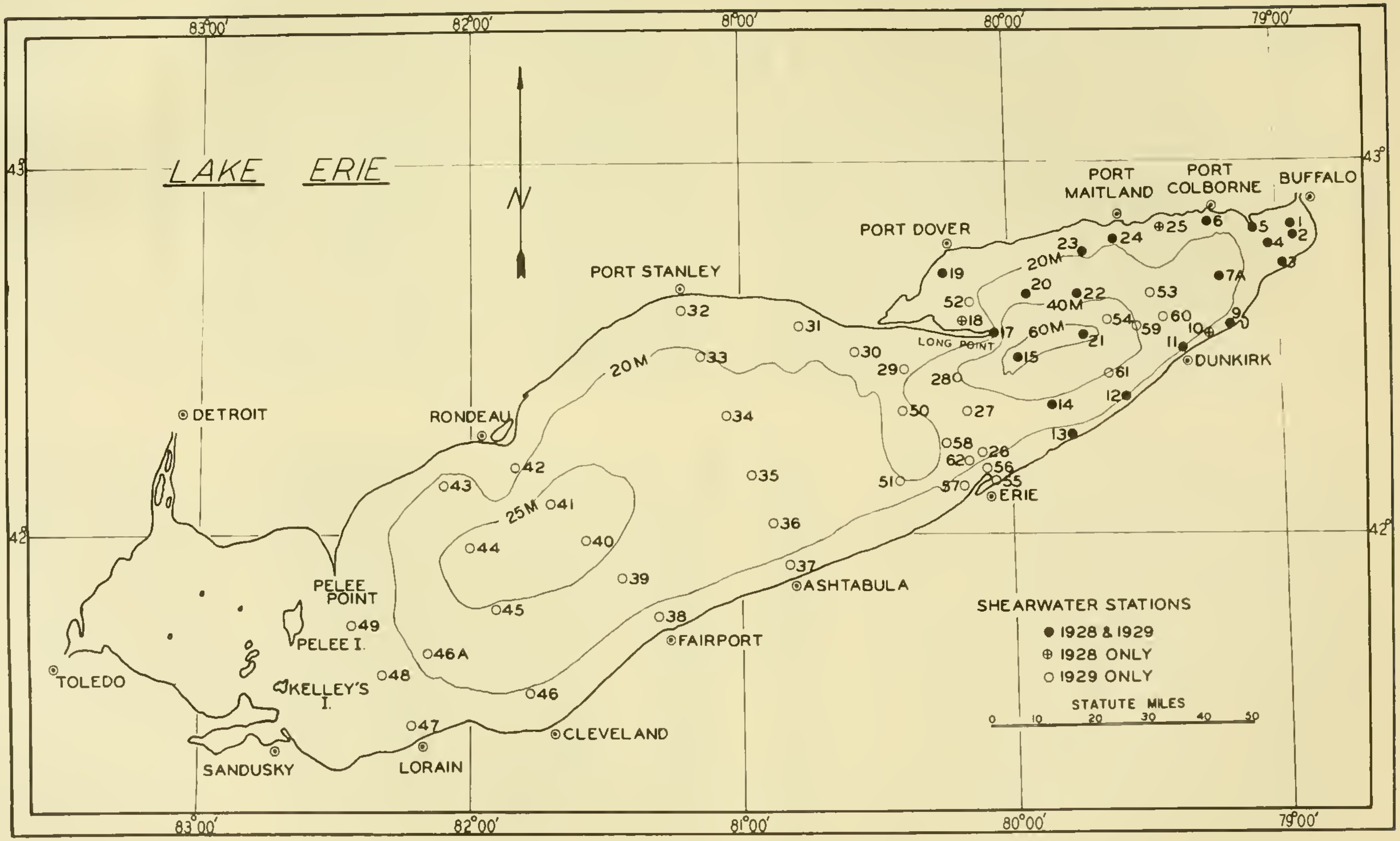

Figure 1. --Bathymetric chart of Lake Erie with 1928 and 1929 *Shearwater* stations.

PROGRAM AND ITINERARY

Charles J. Fish, Director
Buffalo Museum of Science

The need for correlation in limnological work has been recognized in planning the present program. Bigelow (1930) has expressed this need very well: "...in the further development of sea science the keynote must be physical, chemical, and biological unity, not diversity, for everything that takes place in the sea within the radius of any one of these artificially divorced sciences impinges upon all the rest of them." Unfortunately, much of the scientific data previously acquired could not be utilized in such a general problem as that concerning the natural economy of Lake Erie. Not until the interrelationships of the various factors are more fully understood can an application of these miscellaneous data be made. It was for this reason that the present survey was planned in such a manner that the staff functioned as a unit, concentrating on each particular area simultaneously.

In order to ascertain the cause for the decline in the fishery the investigations were designed to determine the significant physical, chemical, and biological conditions in the lake at the present time and the extent to which human interference has affected the natural environment of the animal population.

The work was carried on in 1928 under the joint auspices of the United States Bureau of Fisheries, the New York State Conservation Department, the Ontario Department of Game and Fisheries, the Health Department of the City of Buffalo, and the Buffalo Society of Natural Sciences. To the original five cooperating institutions, the Ohio Division of Conservation was added in 1929 when the area was extended to include a portion of Ohio waters.

The staff in 1928 consisted of the following investigators:

*Charles J. Fish, Director, Buffalo Museum of Science, Buffalo, N. Y.
*Charles B. Wilson, Macroplanktonologist, Westfield Normal School, Westfield, Mass.
Richard Parmenter, Hydrographer, United States Bureau of Fisheries
*Marie P. Fish, Ichthyologist, Buffalo Museum of Science, Buffalo, N. Y.
*Paul R. Burkholder, Microplanktonologist, Cornell University, Ithaca, N. Y.
Roger C. Williams, Chemist, City Health Department, Buffalo, N. Y.
Andrew M. Zillig, Bacteriologist, City Health Department, Buffalo, N. Y.
Reginald H. Pegrum, Topographer, Buffalo Museum of Science, Buffalo, N. Y.
Albert E. Allin, Asst. Ichthyologist, University of Toronto, Toronto, Canada
Willis L. Tressler, Asst. Microplanktonologist, University of Wisconsin, Madison, Wisconsin
Elizabeth L. Saunders, Scientific Assistant, Brown University, Providence, R. I.
*Vernon S. L. Pate, Artist, Cornell University, Ithaca, N. Y.

The staff in 1929 consisted of those designated by the asterisk in the above list and the following additional members:

Charles K. Green, Hydrographer, U. S. Coast & Geodetic Survey, Washington, D. C.
Casimir J. Munter, Chemist, Ohio State University, Columbus, Ohio
Arthur H. Louden, Asst. Ichthyologist, Queens University, Kingston, Ontario
Ralph M. Buchsbaum, Asst. Phytoplanktonologist, University of Wisconsin, Madison, Wisconsin.

In 1928 the investigations covered that portion of Lake Erie lying east of a line from the New York State boundary to Long Point. In this area of 1,701 square miles 23 stations were located and observations made weekly so far as possible, from July 26 to September 15. For this work the U. S. Bureau of Fisheries Steamer Shearwater, an 85-foot vessel of 95 gross tons, was used.

During the interval from June 15 to July 26, 1928, a modified program was substituted to cover the shallow area about the margin of the lake (fig. 2), the New York State gasoline launch Navette being used. These observations had not been planned and were arranged when unforeseen difficulties delayed the arrival of the larger vessel. The work, however, proved very desirable, for the marginal area formed a connecting zone between the open lake and the alongshore waters then being investigated on the

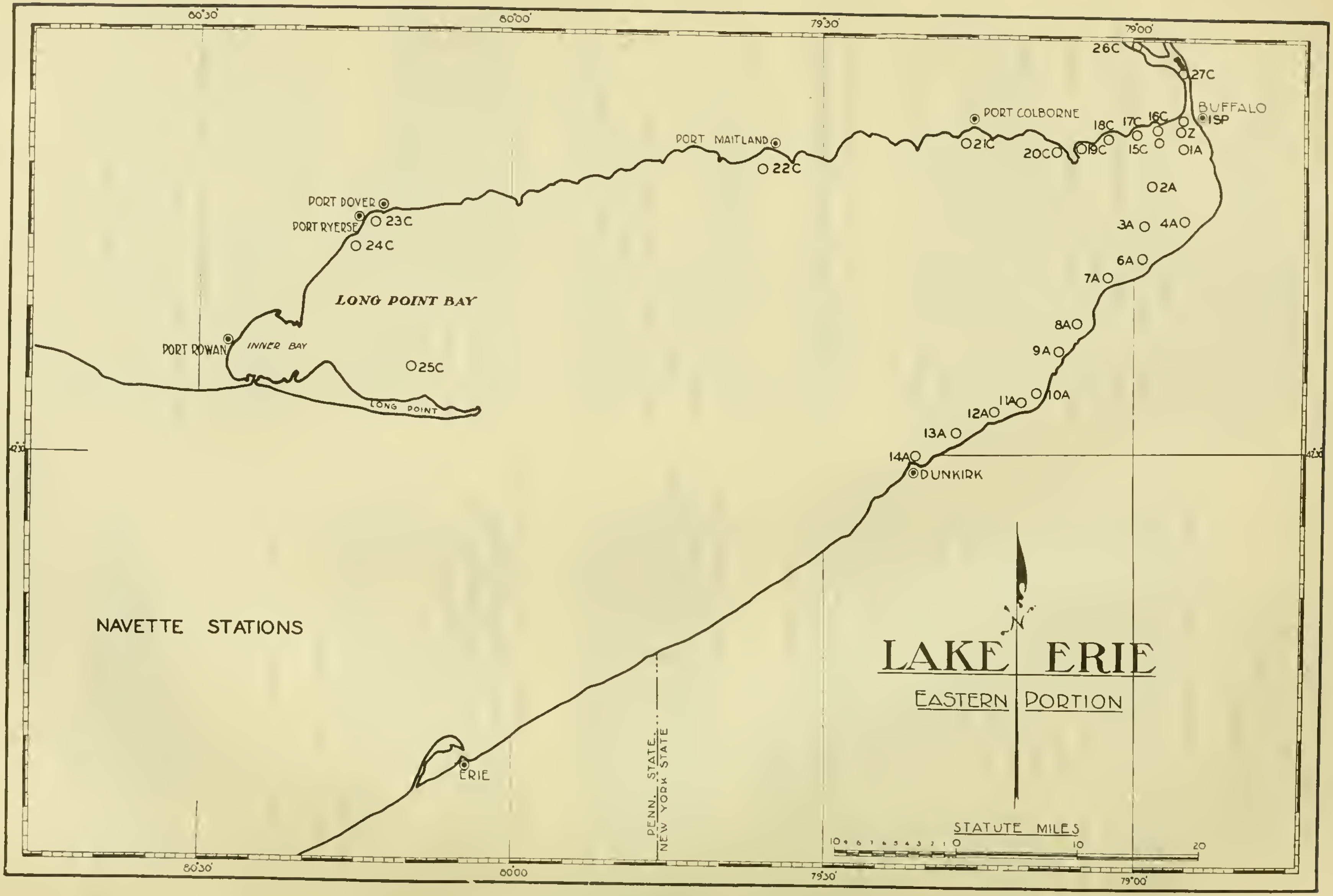

Figure 2. --Navette station, 1928

American side of the New York State Conservation Department and on the Canadian side by the Ontario Department of Game and Fisheries. The spawning grounds of several of the summer-spawning fish lie within this area.

Owing to the fact that there were no laboratory facilities on board the Shearwater during the first season, the work could be carried on only in reasonably calm weather. For that reason the 3-day cruises did not always take place as scheduled.

Due to increased vessel facilities and assistance from Ohio, the area in 1929 was extended to cover the entire lake with the exception of the region west of the islands in Ohio, which was being investigated by representatives of that state and the Federal Bureau of Fisheries. Station 49, located 3 1/2 miles east of a north and south line from Point Pelee, marked the western margin of the survey.

Four regular monthly cruises were made between May 15 and September 20 starting in each case as nearly on the first of the month as weather conditions permitted. These started at Buffalo and terminated at Put-in-Bay, requiring usually 15 days. All of the 50 fixed stations were occupied on each of these cruises. The intercruise interval was utilized for special observations and in returning to Buffalo after each cruise. In all 250 stops at stations and about 20 special stations for water samples at harbor entrances were made during the season and 4,435 statute miles covered.

It will be noted that in the eastern area the location and the numbers of the stations correspond with those of the previous year (table 2).

In the present report whenever a station number is referred to the cruise number is also given. In this system each station receives two numbers separated by a decimal point. The first designates the number of the cruise and the second the number of the station. Thus 05.06 would designate cruise 5, station 6; 06.06 would indicate the sixth cruise, station 6. The cruise numbers refer to Shearwater cruises only and are numbered consecutively and repeated in each of the two years (table 3). Navette stations are not given cruise numbers. The station number in this case is followed by an alphabetical letter which, except for the immediate vicinity of Buffalo, is "C" for stations along the Canadian shore and "A" for those along the American shore.

A third report covers the western section of the lake and includes an extensive bibliography (Wright 1955). Consequently, no attempt has been made at this time to present a review of former limnological investigations. Only references found necessary in the text are included in the present bibliography.

Table 2. --Shearwater stations, 1929

[Stations 1 to 24 are the same as the 1928 stations; stations 26 to 49 are additional regular stations of 1929 survey; stations 50 to 62 are additional stations occupied in 1929 for special work]

Station	Depth (meters)	Location		Position
		Latitude (North)	Longitude (West)	
1	6	42-52.5	78-55.0	Buffalo Intake Pier
2	11	42-48.0	78-55.8	Seneca Shoal
3	11	42-44.0	78-59.0	Off Eighteen Mile Creek
4	18	42-47.0	79-02.0	Mid-lake
5	11	42-49.5	79-05.5	Point Abino
6	16	42-51.0	79-15.0	Port Colborne
7	21	42-42.0	79-13.0	Mid-lake
9	14	42-34.5	79-10.0	Silver Creek
11	16	42-30.5	79-20.0	Dunkirk
12	22	42-23.0	79-34.0	Westfield
13	16	42-17.5	79-46.0	State line
14	37	42-22.0	79-50.0	Mid-lake
15	61	42-29.5	79-57.5	Deep Hole
17	21	42-33.5	80-02.5	Long Point
19	9	42-43.0	80-13.5	Ryetse
20	35	42-40.0	79-55.5	Long Point Bay
21	58	42-32.5	79-43.5	Mid-lake
22	37	42-40.0	79-43.5	Mid-lake
23	21	42-46.5	79-43.0	Tecumseh Reef
24	17	42-48.5	79-35.5	Port Maitland
26	20	42-14.4	80-06.2	Off Erie
27	29	42-20.7	80-08.8	Mid-lake
28	38	42-26.2	80-11.3	Off Long Point
29	18	42-27.9	80-23.0	Off Long Point
30	18	42-30.5	80-34.0	Off Clear Creek
31	17	42-34.9	80-46.5	Off Port Burwell
32	12	42-37.3	81-12.4	Port Stanley
33	20	42-30.0	81-08.3	Mid-lake
34	21	42-20.5	81-02.8	Mid-lake
35	22	42-10.7	80-57.5	Mid-lake
36	22	42-03.1	80-53.2	Mid-lake
37	17	41-56.6	80-49.4	Ashtabula
38	15	41-48.3	81-18.4	Fairport
39	23	41-54.3	81-26.3	Mid-lake
40	24	42-00.2	81-34.2	Mid-lake
41	23	42-06.2	81-42.0	Mid-lake
42	20	42-12.2	81-50.0	Off Rondeau Harbor
43	21	42-09.0	82-05.5	Off Rondeau Harbor
44	23	41-59.0	81-59.8	Mid-lake
45	23	41-49.2	81-54.3	Mid-lake
46A	20	41-42.0	82-09.4	Mid-lake

(Continued)

Table 2. --*Shearwater* stations, 1929 (Cont'd)

Station	Depth (meters)	Location		Position
		Latitude (North)	Longitude (West)	
46	18	41-35.6	81-46.7	Cleveland
47	12	41-30.4	82-12.8	Lorain
48	14	41-38.3	82-19.6	Mid-lake
49	13	41-46.6	82-26.3	Southeast Shoals
50	16	42-21.0	80-23.6	Mid-lake
51	23	42-09.7	80-24.6	Mid-lake
52	13	42-38.7	80-08.5	Long Point Bay
53	27	42-39.6	79-27.8	Mid-lake
54	52	42-35.4	79-37.7	Mid-lake
55	9	42-10.0	80-03.5	Erie
56	16	42-11.9	80-04.8	Erie
57	9	42-09.8	80-09.3	Erie
58	22	42-16.2	80-14.8	Mid-lake
59	37	42-34.5	79-30.8	Off Dunkirk
60	30	42-35.7	79-24.3	Off Dunkirk
61	41	42-26.5	79-37.5	Off Westfield
62	21	42-13.2	80-09.0	Off Erie

Table 3. --*Shearwater* cruises, 1929

Cruise number	Date	Cruise number	Date
1	May 15-28	5	July 22-27
2	June 2-19	6	August 3-20
3	June 22-27	7	August 26-28
4	July 2-15	8	September 3-19

PHYSICAL HYDROGRAPHY AND TEMPERATURE

Charles K. Green, Hydrographer
U. S. Coast and Geodetic Survey

CONTENTS

INTRODUCTION

The limited survey of the eastern portion of Lake Erie in 1928 disclosed the presence in this area of unusual hydrographic conditions. The 1929 program called for a more comprehensive investigation of these conditions and the extension of the survey to include the main body of the lake. As biological, chemical, and geological researches were equally important branches of the survey, it was necessary to make definite and regular cruises; and the Shearwater was therefore not available to maneuver solely in accordance with the needs of the hydrographer. Nevertheless, the general physical properties of the lake were well covered. The data obtained during the survey are included in this report in the form of tables and figures.

METHODS

The hydrographic apparatus, with the exception of the Secchi disc and the surface-current pole, was operated on a 1/4-inch galvanized iron wire and hand winch. The depths were obtained from a high-grade meter sheave which was hung from a davit about 7 feet from the quarter deck. This arrangement permitted the thermometers to be hoisted to the height of the observer's eye where they could be read quickly and accurately.

Negretti-Zambra and Richter-Wiese deep-sea reversing thermometers were used for water temperatures. Readings were made to 0.01° C. on the latter type and to the nearest 0.05° C. on the Negretti-Zambra instruments. All the thermometers had been standardized at the Bureau of Standards and stem corrections were applied to the readings when the correction was large enough to affect tenths of a degree. The results are tabulated to the nearest 0.01° C.

Throughout this report all temperatures are given in Centigrade, depths in meters, distances in statute miles, and velocities in statute miles per hour.

Transparency was determined by observations with a 20-centimeter white Secchi disc attached to a line graduated in meters. The depth, in meters and tenths, at which the disc disappeared from view is recorded as the transparency. The chemist made top and bottom turbidity determinations at each station also.

The standard Coast and Geodetic Survey current pole was used for surface-current measurements. This equipment consists of a 15-foot pole, 3 inches in diameter, and weighted with lead at one end so that it floats in an upright position with about a foot of its length showing above the surface. A graduated cotton line is attached to the pole by means of a simple bridle; the stray line is about 100 feet long. The line is so graduated in knots and tenths (or statute miles per hour and tenths) that the number of graduations passing out in 60 seconds, when the pole is free to drift with the current, gives the velocity directly.

A Price (Gurley) current meter was used for measurement of subsurface velocities. This instrument is accurate only when it is suspended from a dock or some other stable structure. If it is suspended from a boat, the vertical movement, even in a sea which may be called "smooth", increases the revolutions, and the greater the movement the greater will be the error. As subsurface velocities of the lake are low, the error thus introduced may be as much as 50 percent on choppy days. In a current of 1 or 2 m.p.h., the percentage of error due to vertical movement of the boat is small, but when we are dealing with velocities of only 0.1 or 0.2 m.p.h., the percentage error is obviously greatly increased. It was for this reason that the current pole and line were used in surface observations, as this method is practically free from the above-mentioned error. It may be possible to measure low-velocity subsurface currents accurately by placing the present type of meter between a specially equipped anchor and float, and allowing enough slack in the line to the boat to prevent vertical movement of the meter. Time and equipment did not permit such a procedure during this survey. Furthermore, an accurate knowledge of these low and variable velocities would be of value only in connection with an extensive current survey.

Subsurface current directions were measured with a direction indicator, which consists of a carefully balanced wheel, some 30 inches in diameter, suspended horizontally above the water and free to revolve easily on ball bearings, and a 7-foot vane which is supported horizontally and lowered to the required depth by two fine wires which are attached to opposite sides of the rim of the wheel (fig. 3). The vane, heading into the current, moves the wheel correspondingly by means of the wires. The direction is read on a stationary graduated circle attached to the axle of the wheel. An ordinary bicycle wheel makes an excellent indicator wheel. A lead-filled 1/2-inch pipe, split and flattened on one end to hold a 15-inch piece of sheet iron, serves as the vane. The wire is made up in carefully measured pairs of the various lengths necessary for the desired depths. A snap-hook is fitted to one end of the wire and a small ring to the other end. Two stiff wire rings are fitted through vertically drilled holes in the vane pipe, thus enabling the wires, which are snapped into these rings, to support the vane properly. As the wheel is usually some distance above the water, two light ropes, just long enough to span this distance, are fitted to opposite sides of the wheel rim and snap-hooks are bent on their lower ends. After the vane is lowered to the required depth, the upper (ring) ends of the wires are attached to the above snap-hooks at the surface of the water.

In operation of the indicator, care must be taken to lower the two ends of the vane simultaneously in order to prevent the wires from fouling each other. Also, it may be necessary to adjust the ropes, leading from the wheel to the wires, slightly in order that the wheel may remain perfectly horizontal. The gear is supported on a 2- by 4-inch outrigger to clear the ship's hull. The indicator gives satisfactory results when the current is greater than 0. 1 m. p. h.

The sequence of work upon arrival at a station was as follows: First, a sounding was taken to check the location. Second, top and bottom water samples for the chemist, top and bottom water samples for plankton study, bottom (mud) sample, air and surface water temperatures, and transparency were obtained. When chemist's samples had been taken the serial subsurface temperature measurements were begun. Upon completion of the above, the boat got under way at a slow speed and the 5-minute surface and bottom meter-net and the surface foot-net hauls were made. If the station was to be occupied for currents, the boat was anchored upon arrival and the net hauls made after weighing anchor.

The time spent at a station varied from 20 to 60 minutes, depending upon the depth and whether or not a thermocline was encountered, which necessitated several more temperature observations. When the boat was anchored for current determinations, the time of occupation was from 1 to 2 hours.

METEOROLOGICAL CONDITIONS

Weather conditions, as shown by Weather Bureau records, were about normal for the period of the survey except that the wind velocity was 9 percent above the average. In table 4, which gives comparative meteorological data, the figures are the means of the Cleveland and Buffalo readings. The water temperatures, with the exception of those for May, are the means of 37 selected stations fairly evenly distributed over the lake, and offer an opportunity to study the temperatures of the lake as a whole in relation to air temperatures. It should be kept in mind, however, that the water temperatures were taken during daylight hours only, while the air temperatures are from continuous day and night readings.

There were two general storms during the period of the survey when the wind velocity exceeded 54 m. p. h. One occurred on May 16 and the other on September 10. On 11 days, the velocity exceeded 40 m. p. h. All of these blows were from the west or southwest. The most stormy week of the survey was from September 10-17, when the average for the Buffalo daily maxima was 46 m. p. h. The physical effects of these storms on the waters of Lake Erie are taken up in detail in subsequent paragraphs.

The prevailing winds are westerly, and play an

Table 4. --Comparative meteorological data and mean water temperatures, summer of 1929

Month	Precipitation (inches)		Average wind velocity (m. p. h.)		Number of clear days		Mean air temperature (° C.)		Mean water temperature (° C.) 1929	
	Normal	1929	Normal	1929	Normal	1929	Normal	1929	Surface	Bottom
May	3.11	3.10	11.4	12.4	9	7	13.5	12.6	8.7	6.0
June	2.97	2.92	10.4	10.9	12	10	18.8	18.2	15.5	9.4
July	3.24	3.96	10.1	11.7	14	14	21.4	21.5	18.9	12.8
August	2.92	1.60	10.0	10.9	11	12	20.7	19.4	20.6	14.7
September	3.12	2.44	11.2	11.5	10	13	17.3	18.3	20.0	16.8
Mean	3.07	2.80	10.6	11.5	11.2	11.2	18.3	18.0	16.7	11.9

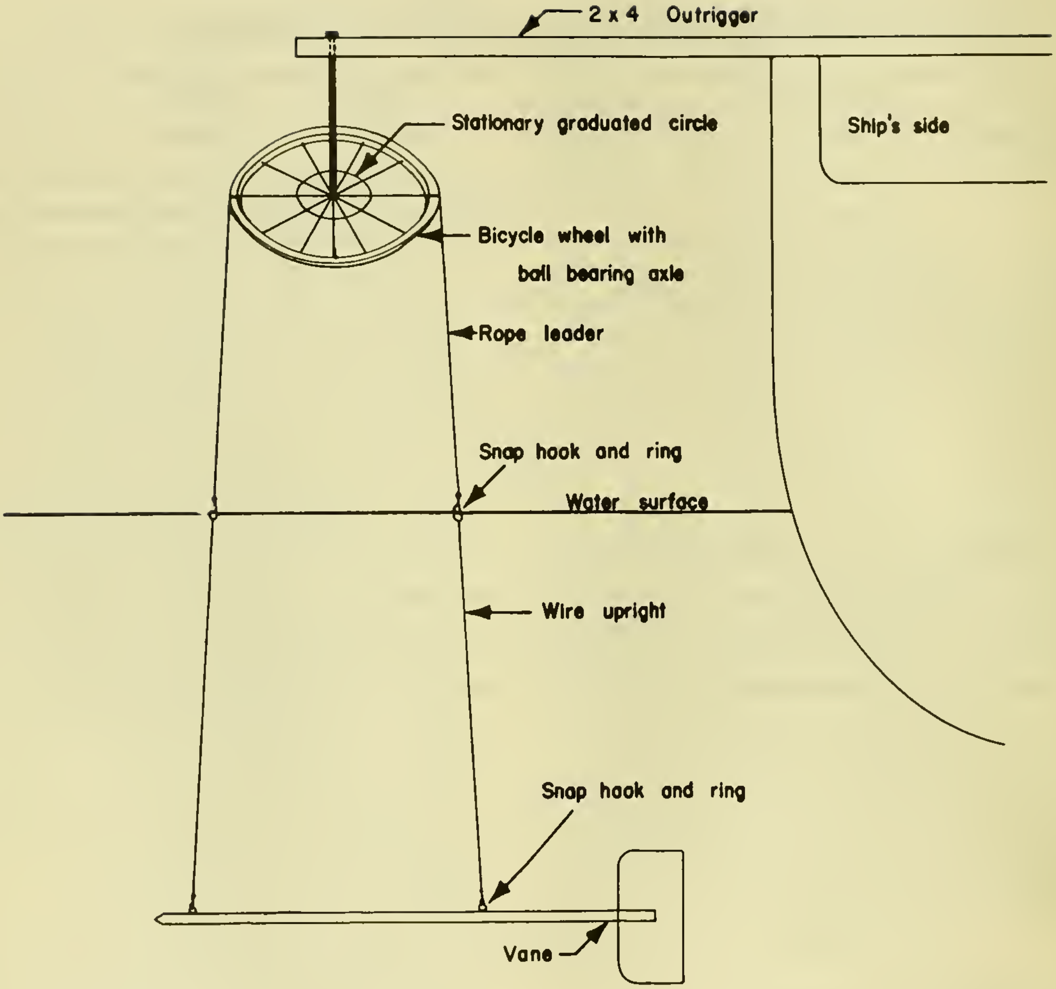

Figure 3. --Subsurface current-direction indicator.

important role in the circulation of the waters of the lake.

In February 1926 the monthly mean lake level reached the minimum for the past 50 years. The level was then 3 feet lower than it was during the period of the survey. The average lake levels in June and September 1929 were 1. 9 feet and 1. 4 feet, respectively, higher than the average stages of those months for the past 10 years. These variations in mean lake levels are principally the concern of the navigator and the city engineer, and only indirectly enter into the problems of this survey.

The maximum daily range of 4. 9 feet at the Buffalo gauge during the period of the survey occurred on May 16. The daily range of water level sometimes exceeds 8 feet in severe storms.

TEMPERATURES

Conditions at Time of Different 1929 Cruises

Cruise 1. --Field ice left Lake Erie earlier than usual in 1929. The last of the ice passed down the Niagara River May 2, 1929, although shipping opened at Buffalo on April 12. Thus the lake was free from ice at least 3 weeks earlier than in 1928, when ". . . . there was closely packed field ice extending from Buffalo as far as the eye could reach on May 15, and for several days thereafter" (New York Conservation Dept. , 1929, p. 46). Ice is nearly always present during April, and spring storms keep the water well mixed. Vernal warming becomes evident in May; and, although the regular cruises did not begin until the following month, 19 stations were occupied between May 17 and 28. The best values obtainable from these May observations for the temperatures of the whole lake are: surface, 8. 2°; bottom, 6. 0°. The distribution by sections was as follows: the Great Plain area, surface 8. 2°, and bottom 7. 2°; Deep Hole area, surface 7. 3°, and bottom 4. 8°; eastern area, surface 10. 9°, and bottom 7. 0°; Long Point Bay, surface 7. 7°, and bottom 4. 8°.

The coldest column of water was observed at station 01-27, at the southwestern edge of the Deep Hole. Here the surface was only 4. 8° and the bottom 4. 3°. The air temperature at this station was 6. 0°, and the wind northeast, force 4 (table 5). The little surface warming that had taken place here was destroyed by the wave action from this cold wind, blowing as it was from the cold waters of the Deep Hole.

During the last half of May, then, the lake was still cold, with but slight vertical temperature gradients and no thermocline. The last two conditions are conducive to vertical mixing; such a situation did not exist again until the middle of September, when the waters of the Great Plain were once more homothermous.

Surface-temperature changes of several degrees in 24 hours may be expected in the spring. During the afternoon of May 24, the sea was choppy and the air temperature was 8° C. at station 15 (Deep Hole), while the surface temperature was 5. 6°. The next day was bright and warm and the sea smooth. The afternoon surface temperature at station 15 was now 8. 3°--an increase of nearly 3° in 22 hours. On the second day, 5. 6° water was found at a depth of 6 meters. Such sudden changes were not observed after the thermocline was well established.

Cruise 2. --During the first half of June, the surface water was warmed at a considerable rate. The western end reached 20° C. by the 18th, whereas a month previous this area was only 8°. Cold surface water was confined to the area of the Deep Hole.

The mean temperatures for the lake on cruise 2 were: surface 15. 5° C. and bottom 9. 4° (table 4). The top and bottom isotherms for the lake are shown in 2° intervals in figures 4 and 5. The steep horizontal thermal gradient to the westward is partly due to the fact that the cruise commenced at the Buffalo end on June 7 and ended 12 days later at the western end, and partly due to the greater rapidity of warming in the shoaler western section of the lake. The lowest temperatures on this cruise were in the Deep Hole region where the surface was 10. 0° and the bottom 4. 4°. Temperatures were only slightly higher in the adjacent waters of Long Point Bay. Although surface marginal-zone temperatures of the Eastern area were uniformly around 13°, the bottom waters were slightly warmer along the southeastern shore. Station 02-12, which is only 1 1/2 miles off the south shore, proved an exception, with 6. 1° bottom water. The first thermocline was also encountered at this station, where the temperature dropped 3. 4° between 13 and 14 meters (table 6A).

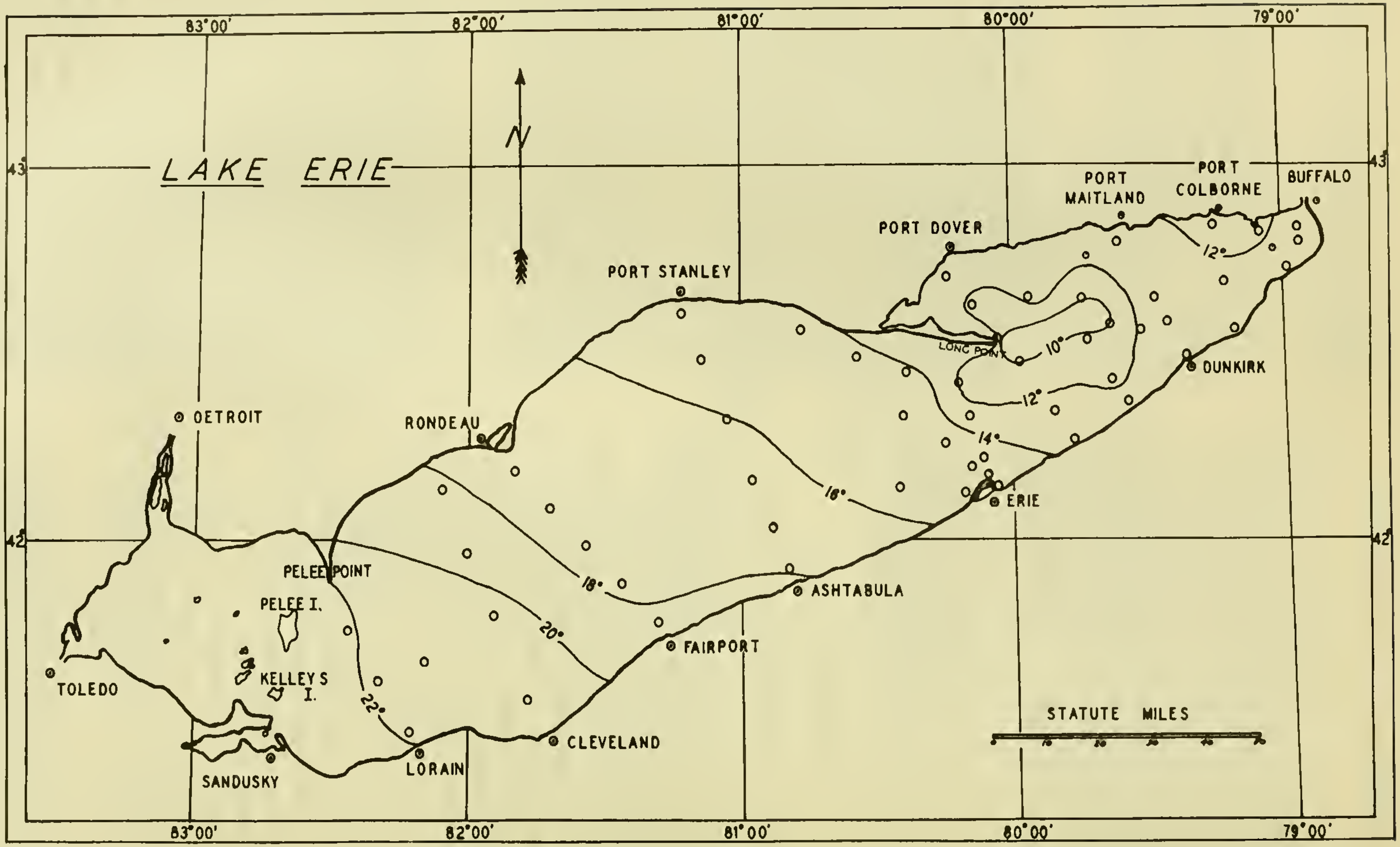

Figure 4. --Surface temperature distribution, cruise 2, 1929.

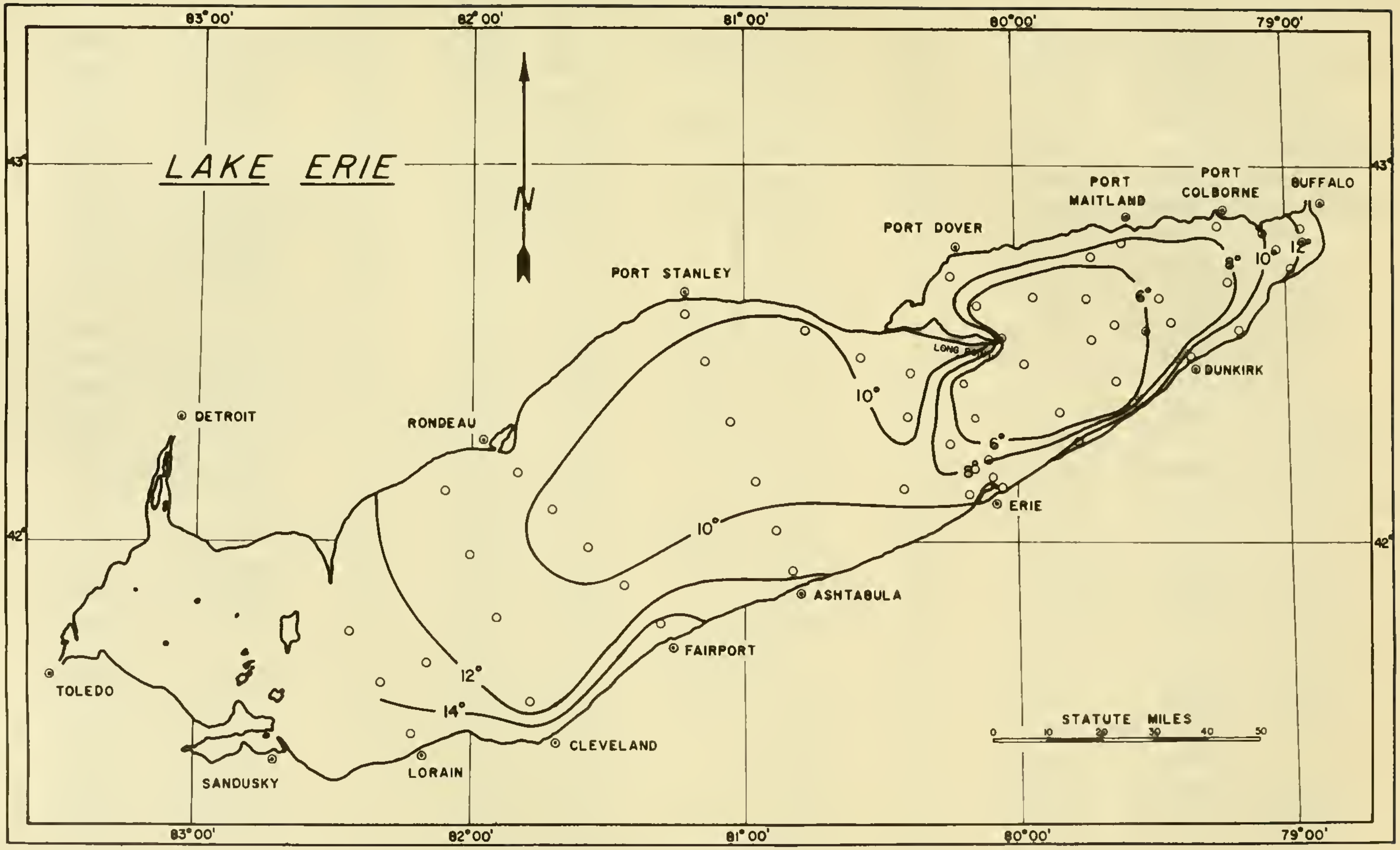

Figure 5. --Bottom temperature distribution, cruise 2, 1929.

Table 5. --*Shearwater* station data, 1929

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.) Air	Surface	10 meters	Bottom	Transparency (meters)	Wind and force	Sea	Sky
01	2	June 7	8:24- 9:14 a. m.	5 1/2	17	13.6	...	13.2	1.2	N-2	Choppy	Overcast
	4	July 2	8:30- 9:17 "	6	11	19.6	...	19.5	...	NW-3	do	Cloudy
	6	Aug. 3	9:30- 9:55 "	7	16	21.7	...	21.4	...	NW-4	Rough	...
	8	Sept. 3	10:45-11:12 "	6	23	20.5	...	20.3	5.1	W-3	Choppy	Hazy
02	2	June 7	9:45-10:25 "	12	18	12.6	12.3	12.3	1.2	N-1	Choppy	Overcast
03	2	June 7	11:00-11:28 "	9 1/2	18	13.9	...	13.6	1.2	N-1	Swell	Overcast
	4	July 2	10:25-10:52 "	12	12	19.8	...	19.5	1.8	NW-3	Choppy	Clear
	6	Aug. 6	9:20- 9:40 "	11	16	20.0	19.8	19.8	0.9	W-3	do	do
	8	Sept. 3	12:23-12:45 p. m.	11	22	20.5	20.4	20.4	5.2	W-4	do	Hazy
04	1	May 28	12:10-12:50 "	17	16	12.3	...	7.2	1.1	Calm	Smooth	Overcast
	2	June 7	12:00-12:35 "	17 1/2	19	13.5	...	11.2	1.1	NNE-2	Swell	Partly cloudy
	4	July 2	11:20-11:45 a. m.	18 1/2	14	19.5	18.9	18.7	2.0	N-1	Rippled	Clear
	5	July 27	12:58- 1:25 p. m.	18	22	21.2	...	17.1	5.3	...	...	...
	6	Aug. 6	10:05-10:35 a. m.	19	17	19.9	19.6	19.6	1.6	WxN-4	Rough	Clear
	8	Sept. 3	1:15- 1:35 p. m.	18	23	20.2	20.1	20.0	7.3	W-4	Choppy	Hazy
05	2	June 7	1:00- 1:40 "	13	20	11.5	...	9.5	1.0	N-1	Swell	Hazy
	4	July 2	12:10-12:35 "	10 1/2	14	19.5	...	18.5	1.8	WxN-2	Rippled	Clear
	6	Aug. 6	11:03-11:20 a. m.	11	17	20.0	19.6	19.6	1.7	WNW-4	Rough	Partly cloudy
	8	Sept. 3	2:05- 2:25 p. m.	11 1/2	23	20.2	...	19.7	2.7	WxS-3	Choppy	Hazy
06	2	June 7	2:35- 3:05 "	16 1/2	20	10.5	9.8	8.5	1.9	Calm	Swell	Overcast
	4	July 2	1:40- 2:03 "	16	13	18.0	...	16.9	1.1	W-3	Choppy	Clear
	6	Aug. 6	12:25-12:45 "	14 1/2	19	18.3	17.9	17.5	2.1	WxS-4	Rough	Partly cloudy
	8	Sept. 3	3:50- 4:30 p. m.	16	23	20.3	20.0	19.9	7.1	WSW-3	Swell	Hazy
07	2	June 7	4:05- 4:40 "	21 1/2	17	12.5	10.2	7.8	1.3	Calm	Swell	Partly cloudy
	4	July 2	3:08- 3:30 "	21	13	18.3	17.4	16.6	3.0	SW-4	Choppy	do
	5	July 27	11:32-12:00 "	22	22	21.0	20.9	10.9	6.0	SW-3	do	...

(Continued)

Table 5. --Shearwater station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.) Air	Surface	10 meters	Bottom	Transparency (meters)	Wind and force	Sea	Sky
07	6	Aug. 6	1:55- 2:25 p. m.	22	18	19. 5	19. 2	19. 1	2. 8	SW-4	Rough	...
	8	Sept. 4	10:00-10:25 a. m.	21	24	20. 4	20. 0	19. 3	10. 1	WxS-2	Rippled	Hazy
09	2	June 8	8:14- 8:44 "	12	13	13. 3	10. 5	10. 5	1. 4	NE-2	Choppy	Hazy
	4	July 2	4:30- 5:00 p. m.	15	12	19. 5	19. 5	18. 6	1. 8	SW-4	Rough	Partly cloudy
	6	Aug. 6	3:20- 3:45 "	14	19	20. 4	...	20. 2	1. 9	SW-4	Choppy	Cloudy
	8	Sept. 4	8:40- 9:05 a. m.	14	25	20. 2	20. 2	20. 2	9. 2	SW-1	Rippled	...
11	1	May 28	8:10- 8:40 "	14	18	9. 4	...	7. 3	1. 0	NW-1	Smooth	Overcast
	2	June 10	10:30-11:00 "	16	20	12. 5	9. 7	7. 5	1. 3	W-1	do	Hazy
	4	July 5	9:30- 9:55 "	17	20	19. 6	19. 3	19. 1	1. 3	SW-2	Swell	Cloudy
	6	Aug. 7	11:00-11:25 "	16 1/2	20	21. 2	20. 7	20. 6	2. 1	NxE-1	Rippled	Clear
	8	Sept. 4	7:15- 7:40 "	16	26	20. 3	20. 2	19. 9	9. 6	SxE-1	do	Hazy
12	2	June 8	4:50- 5:25 p. m.	24	17	12. 6	11. 8	6. 1	1. 4	NE-2	Choppy	Clear
	4	July 5	5:30- 6:00 "	20	21	18. 5	17. 7	17. 7	2. 5	SW-1	Swell	do
	6	Aug. 8	9:00- 9:45 a. m.	22	19	20. 4	20. 3	7. 4	2. 9	S-3	Choppy	Partly cloudy
	8	Sept. 5	12:30- 1:10 p. m.	21 1/2	24	21. 7	20. 4	10. 2	10. 1	NxW-1	Smooth	Hazy
13	1	May 24	12:10-12:25 "	16 1/2	11	8. 3	8. 1	7. 8	0. 9	SW-1	Swell	Partly cloudy
	2	June 12	9:00- 9:23 a. m.	16	20	13. 6	13. 4	12. 3	1. 5	WSW-1	Choppy	Cloudy
	4	July 8	3:30- 3:55 p. m.	17	18	20. 5	20. 1	18. 1	2. 2	WSW-2	do	Clear
	5	July 23	12:55- 1:15 "	16 1/2	25	20. 7	19. 4	13. 5	5. 4	WxS-2	do	Partly cloudy
	6	Aug. 10	9:50-10:35 a. m.	16	25	21. 1	20. 4	17. 1	5. 3	SW-2	Rippled	Hazy
	8	Sept. 7	2:05- 2:25 p. m.	16 1/2	24	21. 2	20. 6	19. 5	8. 0	E-2	Choppy	do
14	1	May 24	1:15- 1:55 "	38	8	5. 1	4. 7	4. 5	1. 0	NW-1	Swell	Clear
	2	June 12	10:00-11:00 a. m.	37	17	13. 9	13. 5	4. 7	1. 7	WxS-1	do	Cloudy
	3	June 25	2:45- 3:30 p. m.	36 1/2	19	19. 3	16. 8	5. 0	3. 1	W-3	Choppy	do
	4	July 8	1:20- 2:45 "	37	18	18. 2	17. 3	5. 3	3. 8	WSW-2	do	Clear
	5	July 23	2:00- 2:45 "	37	23	20. 6	19. 3	6. 4	5. 0	SSW-4	do	Partly cloudy
	6	Aug. 10	11:15-11:45 a. m.	37	24	21. 2	...	6. 0	5. 1	W-1	Smooth	Cloudy
	8	Sept. 7	1:00- 1:20 p. m.	37 1/2	23	20. 9	20. 7	11. 7	10. 5	ExN-2	Choppy	Hazy

(Continued)

Table 5. --*Shearwater* station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.) Air	Surface	10 meters	Bottom	Transparency (meters)	Wind and force	Sea	Sky
15	1	May 24	3:20- 4:30 p. m.	62	8	5.6	5.1	4.5	1.0	WSW-3	Choppy	Clear
	2	June 11	11:37-12:50 "	61	14	10.5	8.9	5.0	1.2	SW-3	Rough	Hazy
	3	June 26	11:05-12:45 "	62 1/2	19	18.0	11.5	4.8	4.0	WxS-2	Choppy	Cloudy
	4	July 8	10:30-12:10 "	61	18	15.9	14.1	4.9	3.8	SW-2	Swell	Clear
	5	July 23	4:15- 4:45 "	61 1/2	23	20.5	...	5.0	5.1	W-5	Rough	Squally
	6	Aug. 9	12:10- 3:30 "	61 1/2	21	21.0	20.0	5.2	5.8	SW-2	Swell	Clear
	7	Aug. 28	12:00- 2:00 "	61	17	20.5	20.1	5.3	...	NE-3	Choppy	Cloudy
	8	Sept. 7	11:05-12:20 "	61	21	20.8	20.7	5.5	9.9	ENE-3	do	do
17	1	May 25	10:35- 1:00 "	20	11	11.7	6.2	5.3	0.8	NE-1	Smooth	Clear
	2	June 11	10:16-10:58 a. m.	24	14	10.0	...	5.2	1.2	SW-3	Choppy	Hazy
	3	June 26	1:40- 2:50 p. m.	20	18	18.2	8.7	7.2	3.4	SxW-2	Rippled	Partly cloudy
	4	July 8	9:10-10:00 a. m.	18 1/2	19	15.1	13.2	10.7	3.6	W-1	do	do
	5	July 24	9:20-10:20 "	19 1/2	22	19.9	15.2	5.3	3.1	Calm	Swell	Cloudy
	6	Aug. 9	9:30-11:20 "	20 1/2	21	18.8	14.0	11.3	1.6	SW-2	Rippled	Clear
	7	Aug. 26	1:10- 3:00 p. m.	20 1/2	23	20.1	15.0	11.2	...	SW-3	Choppy	Cloudy
	8	Sept. 6	2:00- 3:40 "	20 1/2	24	21.0	18.4	16.4	6.8	W-2	do	do
19	1	May 25	7:45- 8:00 a. m.	9	10	8.0	...	7.4	0.8	NE-0	Smooth	Clear
	2	June 11	8:00- 8:23 "	9	15	12.8	...	9.5	1.2	SW-3	Choppy	Hazy
	4	July 6	5:20- 5:45 p. m.	8 1/2	18	14.5	...	10.8	1.5	SE-3	Rippled	Rain
	6	Aug. 8	5:30- 5:55 "	9	23	16.9	...	9.8	1.3	Calm	Smooth	Cloudy
	8	Sept. 7	7:25- 7:55 a. m.	9	20	20.4	...	20.4	7.6	E-2	Choppy	Rain
20	2	June 10	5:20- 6:00 p. m.	37	22	12.4	9.2	4.8	1.5	SW-1	Smooth	Clear
	3	June 27	8:45- 9:40 a. m.	34 1/2	17	17.6	10.6	5.8	4.7	SE-1	Rippled	Partly cloudy
	4	July 6	2:50- 3:40 p. m.	34	18	16.7	14.6	7.4	3.9	S-1	do	Cloudy
	5	July 24	4:10- 4:35 "	37	23	21.0	19.2	5.2	6.0	SSW-2	do	Overcast
	6	Aug. 8	3:20- 3:55 "	34	23	16.9	12.6	7.1	1.6	Calm	Smooth	Cloudy
	8	Sept. 6	12:00-12:30 "	36	26	21.4	20.3	6.6	7.8	SW-1	Rippled	do
21	2	June 8	2:00- 3:00 "	58	15	10.5	9.2	4.4	1.4	Calm	Swell	Clear
	3	June 27	10:35-11:30 a. m.	56	18	19.0	11.3	4.6	3.8	E-1	Rippled	do

(Continued)

Table 5. --Shearwater station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.) Air	Surface	10 meters	Bottom	Transparency (meters)	Wind and force	Sea	Sky
21	4	July 5	3:30- 4:10 p. m.	57 1/2	17	16.0	15.3	4.8	5.0	SW-2	Swell	Clear
	5	July 24	12:40- 1:25 "	57	23	21.1	...	5.2	6.5	SE-1	Smooth	Overcast
	8	Sept. 5	3:25- 3:45 "	57	26	21.2	20.5	5.4	11.3	Calm	do	Hazy
22	2	June 8	12:25- 1:10 "	37	12	10.2	9.2	5.2	1.4	Calm	Swell	Clear
	4	July 5	2:10- 2:35 "	36	18	16.0	15.2	8.3	3.5	SW-2	Rough	do
	5	July 24	3:05- 3:25 "	35 1/2	21	21.0	19.6	6.0	6.0	SSW-1	Smooth	Cloudy
	6	Aug. 8	1:35- 2:05 "	37	21	21.0	19.0	6.7	6.6	Calm	do	Partly cloudy
	8	Sept. 6	10:20-10:45 a. m.	37	24	21.2	20.5	8.4	9.6	SW-2	Rippled	Rain
23	2	June 10	3:35- 3:58 p. m.	21	20	12.1	9.3	6.2	1.9	Calm	Smooth	Clear
	4	July 6	1:10- 1:25 "	21	20	17.0	15.8	14.7	3.0	S-1	Rippled	Cloudy
	6	Aug. 7	4:45- 4:59 "	21	19	19.5	18.0	14.0	4.9	Calm	do	Clear
	8	Sept. 4	1:40- 2:05 "	21	26	20.6	19.6	16.1	10.3	WxS-1	do	Partly cloudy
24	1	May 27	2:20- 2:45 "	16 1/2	19	11.7	7.6	6.7	1.1	Calm	Smooth	Foggy
	2	June 10	2:30- 2:55 "	18	17	13.9	...	6.4	1.6	Calm	do	Clear
	4	July 6	11:30-12:10 "	17	20	16.2	14.7	13.7	3.0	SxW-1	do	Overcast
	6	Aug. 7	2:40- 4:00 "	17	20	17.1	14.6	13.7	2.6	Calm	do	Clear
	8	Sept. 4	12:25- 1:00 "	17	26	20.6	19.6	17.8	9.2	WxS-2	Rippled	Hazy
26	1	May 20	12:40- 1:50 "	21	6	9.9	5.8	5.4	0.6	NE-3	Choppy	Cloudy
	2	June 14	12:00-12:40 "	19 1/2	18	15.1	13.6	8.1	2.2	W-3	Rough	Partly cloudy
	3	June 25	8:10- 9:15 a. m.	20	23	20.7	17.8	5.8	4.6	NW-2	Choppy	Cloudy
	4	July 9	11:00-12:15 p. m.	20 1/2	24	18.9	16.4	6.1	3.9	WSW-4	do	Partly cloudy
	5	July 22	5:48- 6:25 "	19 1/2	22	20.9	19.5	8.2	6.3	E-1	Smooth	Clear
	6	Aug. 13	8:45- 9:25 a. m.	20 1/2	20	22.2	20.8	9.8	3.4	E-1	do	do
	8	Sept. 9	9:25- 9:45 "	20 1/2	24	20.7	20.7	14.9	9.8	NE-2	Choppy	Cloudy
27	1	May 20	3:15- 4:15 p. m.	29	6	4.8	4.5	4.3	1.2	NE-4	Choppy	Partly cloudy
	2	June 12	3:10- 3:40 "	28	13	12.6	11.2	5.7	1.9	Calm	Smooth	Overcast
	3	June 25	10:10-10:50 a. m.	29 1/2	19	19.6	10.8	5.2	3.4	NW-2	Rippled	Rain

(Continued)

Table 5. --Shearwater station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.) Air	Surface	10 meters	Bottom	Transparency (meters)	Wind and force	Sea	Sky
27	4	July 9	1:15- 1:45 p. m.	28 1/2	20	18.2	16.5	5.7	1.9	W-4	Rough	Partly cloudy
	5	July 22	4:40- 5:00 "	28	24	20.7	19.4	11.6	6.1	E-1	Smooth	Clear
	6	Aug. 10	4:10- 4:45 "	29 1/2	22	21.5	20.0	7.6	5.5	W-2	Rippled	Cloudy
	8	Sept. 9	1:25- 1:45 "	29	23	21.1	20.7	10.1	7.4	NE-2	Choppy	Rain
28	1	May 22	9:35-11:45 a. m.	37 1/2	11	6.0	4.8	4.7	1.0	SW-1	Smooth	Clear
	2	June 12	1:35- 2:30 p. m.	35	13	11.7	9.5	5.2	1.3	Calm	do	Overcast
	3	June 25	11:45-12:45 "	40	19	18.6	11.3	5.4	3.3	Calm	Swell	Cloudy
	4	July 9	2:35- 3:05 "	37	20	18.0	17.4	6.0	3.1	WxS-5	Rough	Partly cloudy
	5	July 22	3:40- 4:10 "	36	23	21.6	19.6	6.7	6.0	N-1	Smooth	Clear
	6	Aug. 10	2:45- 3:25 "	39	24	21.0	19.0	5.4	5.5	W-2	Rippled	Cloudy
	8	Sept. 9	11:35-12:15 "	39	22	21.0	20.8	6.7	8.6	NE-2	Choppy	do
29	1	May 22	12:15-12:50 "	18	9	6.9	5.5	5.4	1.3	SW-1	Smooth	Clear
	2	June 15	1:00- 1:55 "	17	19	14.7	13.6	11.6	2.9	Calm	do	Hazy
	4	July 10	2:26- 2:50 "	18 1/2	19	18.6	15.2	11.2	2.8	WNW-4	Choppy	Clear
	6	Aug. 13	12:50- 1:20 "	18 1/2	20	21.0	19.9	13.6	6.1	E-1	Rippled	do
	8	Sept. 12	11:30-11:50a. m.	16	19	19.4	19.3	19.3	1.6	SSE-2	Choppy	Cloudy
30	2	June 15	3:08- 3:50 p. m.	18	20	14.7	12.8	10.4	3.3	Calm	Swell	Clear
	6	Aug. 13	2:10- 2:30 "	18	23	21.3	17.9	11.2	5.9	E-1	Rippled	do
	8	Sept. 12	12:55- 1:20 "	16 1/2	20	19.8	19.7	19.7	1.6	SE-2	Choppy	Cloudy
31	2	June 15	5:00- 5:35 "	17 1/2	20	14.7	13.7	9.6	5.2	Calm	Smooth	Clear
	4	July 10	4:55- 5:05 "	18	20	18.5	16.8	11.8	2.4	WNW-4	Choppy	do
	6	Aug. 13	3:50- 4:15 "	17	22	20.7	14.4	13.3	4.2	ESE-3	do	do
	8	Sept. 12	2:35- 3:00 "	16 1/2	21	19.6	19.6	19.3	1.0	SE-2	do	Cloudy
32	2	June 16	7:25- 8:20 "	12	17	14.9	10.4	10.4	4.3	SE-1	Smooth	Partly cloudy
	4	July 11	7:10- 7:35 a. m.	13	16	17.1	...	14.2	2.7	ExN-2	Rippled	Clear
	6	Aug. 15	7:03- 7:30 "	12	11	18.8	...	16.8	1.2	WxN-5	Swell	Squally
	8	Sept. 15	7:15- 7:35 "	12 1/2	10	18.9	...	18.9	1.9	SW-2	Choppy	Partly cloudy

(Continued)

Table 5. --Shearwater station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.)				Transparency (meters)	Wind and force	Sea	Sky
					Air	Surface	10 meters	Bottom				
33	2	June 16	9:25-10:25 a. m.	20	20	15.5	13.6	9.5	4.8	SE-2	Smooth	Partly cloudy
	4	July 11	8:30- 9:00 "	20	18	17.1	15.7	10.5	2.5	E-1	Rippled	Clear
	6	Aug. 16	7:40- 8:05 "	19	16	18.6	18.4	15.8	4.3	Calm	Smooth	do
	8	Sept. 15	8:30- 8:50 "	19 1/2	12	19.4	19.4	19.4	2.7	SW-1	do	do
34	2	June 16	11:30-12:15 p. m.	21	20	16.1	11.7	9.4	5.1	SE-1	Smooth	Cloudy
	4	July 11	10:10-10:35 a. m.	21	19	18.6	17.7	14.5	5.7	NE-3	Choppy	Partly cloudy
	6	Aug. 16	9:20- 9:45 "	21	19	19.8	19.6	16.6	6.6	NE-0	Smooth	Clear
	8	Sept. 15	10:10-10:30 "	21	13	18.7	18.6	18.6	3.7	SW-1	do	do
35	2	June 16	1:30- 2:05 p. m.	21 1/2	23	16.6	12.6	9.9	3.1	Calm	Smooth	Hazy
	4	July 11	11:49-12:48 "	22	19	19.4	18.5	10.6	5.9	NE-3	Choppy	Partly cloudy
	6	Aug. 16	10:55-11:25 a. m.	21 1/2	20	20.7	19.9	12.5	6.1	E-1	Smooth	Clear
	8	Sept. 15	11:55-12:15 p. m.	21 1/2	17	19.5	19.2	19.2	2.7	SW-1	do	do
36	2	June 16	3:10- 3:45 "	22	23	16.8	11.9	10.3	2.9	Calm	Smooth	Hazy
	4	July 11	1:49- 2:30 "	22	20	19.9	18.5	11.3	6.0	NE-3	Choppy	Clear
	6	Aug. 16	12:25- 1:00 "	22	20	21.1	19.9	16.4	6.2	E-1	Smooth	do
	8	Sept. 15	1:25- 1:45 "	22	20	19.5	18.9	18.9	2.9	SW-1	Swell	do
37	2	June 16	4:20- 4:50 p. m.	17	24	18.7	13.1	11.5	1.8	SE-1	Smooth	Cloudy
	4	July 11	3:15- 3:45 "	17	21	21.7	20.4	20.2	2.5	NE-4	Choppy	Partly cloudy
	6	Aug. 16	1:50- 3:00 "	17 1/2	21	21.6	20.4	20.4	4.1	Calm	Smooth	Clear
	8	Sept. 15	2:40- 3:00 "	17	20	20.2	19.6	19.6	2.0	SW-1	Rippled	do
38	2	June 17	12:00-12:30 "	15	23	18.8	16.5	16.5	3.5	W-1	Swell	Clear
	4	July 12	11:40-12:15 "	15	23	22.3	19.7	18.4	1.3	NE-0	Smooth	Overcast
	6	Aug. 17	10:25-11:10 a. m.	15	24	21.2	20.9	20.8	2.8	SW-3	Choppy	Hazy
	8	Sept. 16	10:20-10:45 "	15 1/2	23	19.6	19.6	19.6	2.4	SW-3	do	Clear
39	2	June 17	1:30- 2:05 p. m.	23	23	17.3	13.2	10.2	4.4	W-1	Smooth	Partly cloudy
	4	July 12	1:10- 2:00 "	23	21	20.3	17.8	10.1	6.0	NE-1	Rippled	Overcast

(Continued)

Table 5. --Shearwater station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.)				Transparency (meters)	Wind and force	Sea	Sky
					Air	Surface	10 meters	Bottom				
39	6	Aug. 17	12:10-12:40 p. m.	21 1/2	22	20.9	20.2	20.2	7.5	SW-3	Choppy	Clear
	8	Sept. 16	11:45-12:05 "	22	23	19.4	19.2	19.2	2.9	SW-4	do	do
40	1	May 17	12:10- 2:30 "	25 1/2	13	8.3	7.3	7.2	1.2	ENE-2	Swell	Partly cloudy
	2	June 17	3:10- 3:55 "	24 1/2	24	17.7	12.7	9.5	4.0	Calm	Smooth	Clear
	4	July 12	3:05- 3:45 "	24 1/2	23	20.6	17.4	10.9	6.4	NE-0	do	Overcast
	6	Aug. 17	1:40- 2:25 "	24 1/2	22	21.1	20.9	11.2	8.5	SW-2	Choppy	Clear
	8	Sept. 16	1:10- 1:30 "	24	23	19.6	19.5	19.5	5.1	SW-3	do	do
41	2	June 17	4:55- 5:40 "	22 1/2	23	17.1	13.2	9.7	4.3	Calm	Smooth	Clear
	4	July 12	4:40- 5:25 "	23 1/2	22	21.1	18.3	10.7	5.0	ExS-1	do	Partly cloudy
	6	Aug. 17	3:25- 4:10 "	24	22	21.0	20.0	12.2	3.9	SW-2	Swell	Clear
	8	Sept. 16	2:30- 2:50 "	23	23	19.4	19.2	19.2	4.2	SW-3	Choppy	do
42	2	June 17	6:30- 7:05 "	19	23	17.7	...	10.5	3.3	Calm	Smooth	Clear
	4	July 13	7:30- 7:45 a. m.	19 1/2	21	21.1	18.2	13.4	3.2	SSW-2	Choppy	do
	6	Aug. 17	5:20- 5:55 p. m.	20	21	21.1	20.5	12.3	5.5	SW-2	do	do
	8	Sept. 16	3:55- 4:15 "	20	23	19.8	19.6	19.5	3.7	W-4	Rough	Partly cloudy
43	2	June 18	8:10- 9:00 a. m.	21	22	18.0	12.1	10.3	5.5	S-0	Smooth	Clear
	4	July 13	9:25-10:05 "	21	23	21.7	19.5	11.7	2.9	SSW-3	Choppy	do
	6	Aug. 18	10:00-10:30 "	21	19	21.5	20.9	15.1	5.2	N-1	do	do
	8	Sept. 17	8:35- 8:55 "	21	13	19.7	19.7	19.7	4.0	SW-2	do	do
44	2	June 18	10:20-11:05 "	23	21	19.4	14.2	10.7	5.9	S-0	Smooth	Clear
	4	July 13	11:20-12:05 p. m.	23	22	21.5	18.8	11.6	5.8	SW-2	Choppy	Cloudy
	6	Aug. 18	11:50-12:20 "	23	24	21.7	20.6	14.9	8.3	Calm	Smooth	Clear
	8	Sept. 17	10:15-10:35 a. m.	23	16	19.6	19.6	19.6	7.2	SW-5	Rough	Gloomy
45	2	June 18	12:25- 1:05 p. m.	23	25	20.8	13.4	10.9	4.0	Calm	Smooth	Clear
	4	July 13	1:20- 1:50 "	22 1/2	22	21.2	18.0	10.8	6.3	SW-1	do	Overcast
	6	Aug. 18	1:35- 2:25 "	23	24	21.7	20.7	13.9	8.4	Calm	do	Clear

(Continued)

Table 5. --Shearwater station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.) Air	Surface	10 meters	Bottom	Transparency (meters)	Wind and force	Sea	Sky
46	2	June 18	2:55- 3:30 p. m.	18	25	21.3	...	11.2	3.4	Calm	Smooth	Clear
	4	July 13	3:30- 4:00 "	18 1/2	21	21.7	18.6	11.2	4.4	SW-5	Rough	Squally
	6	Aug. 18	4:00- 5:00 "	18 1/2	26	21.6	20.8	20.7	4.3	NE-1	Swell	Clear
	8	Sept. 19	8:20- 8:40 a. m.	17	8	18.8	18.8	18.8	2.5	SE-3	Choppy	Cloudy
46A	1	May 15	12:30- 1:30 p. m.	20 1/2	13	8.0	7.6	7.4	1.5	S-2	Smooth	Partly cloudy
47	2	June 19	7:10- 7:33 a. m.	12	23	21.6	...	17.0	1.1	W-1	Choppy	Partly cloudy
	4	July 15	11:20-11:40 "	11 1/2	22	21.5	20.6	20.6	2.2	E-3	Rough	Clear
	6	Aug. 19	10:15-10:45 "	12	22	21.2	...	21.1	1.1	E-1	Swell	do
	8	Sept. 19	11:10-11:30 "	12	11	18.8	...	18.8	1.3	SW-2	Choppy	Cloudy
48	2	June 19	8:40- 9:50 a. m.	14	23	21.1	...	13.5	1.8	W-1	Choppy	Partly cloudy
	4	July 15	12:50- 1:25 p. m.	13 1/2	18	21.1	...	17.7	4.5	E-4	Rough	Clear
	6	Aug. 20	12:00-12:30 "	14	20	21.7	21.2	21.2	2.0	E-1	Swell	do
	8	Sept. 19	12:30-12:50 "	14	13	18.7	18.7	18.7	2.8	SW-1	do	Cloudy
49	2	June 19	11:03-12:20 "	12 1/2	23	22.3	...	13.3	2.6	W-1	Swell	Partly cloudy
	4	July 15	2:35- 3:00 "	12 1/2	18	21.2	...	20.7	2.1	E-3	Choppy	Clear
	6	Aug. 20	1:40- 2:05 "	13	19	21.5	...	20.0	2.1	SE-2	do	do
	8	Sept. 19	1:55- 2:15 "	13	16	18.2	...	18.1	1.8	SW-1	Swell	Cloudy
50	1	May 18	2:00- 2:40 "	15	13	6.1	5.2	5.2	1.2	W-1	Swell	Overcast
	2	June 15	10:55-12:10 "	15	18	14.2	11.2	10.9	3.8	Calm	do	Hazy
	3	June 22	12:15- 2:15 "	14 1/2	23	20.5	13.2	9.7	5.5	Calm	do	Clear
	4	July 10	1:25- 1:45 "	16	21	19.3	17.3	12.9	4.5	W-4	Choppy	do
	5	July 22	1:50- 2:15 "	16	21	20.0	18.8	16.2	4.5	N-2	Rippled	do
	6	Aug. 13	11:25-11:50 a. m.	17	20	22.1	21.0	18.7	4.0	E-1	do	do
	8	Sept. 12	10:25-10:40 "	14 1/2	17	18.6	...	18.1	4.0	SSE-3	Choppy	Cloudy
51	1	May 22	3:10- 3:55 p. m.	23	14	11.3	8.4	8.3	1.1	SW-0	Smooth	Clear
	2	June 14	2:20- 2:55 "	23 1/2	18	15.0	12.6	8.8	2.3	SW-2	Swell	Partly cloudy
	3	June 22	9:30-10:50 a. m.	22	23	18.6	13.2	7.8	5.5	Calm	Smooth	Clear

(Continued)

Table 5. --Shearwater station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.)				Transparency (meters)	Wind and force	Sea	Sky
					Air	Surface	10 meters	Bottom				
52	1	May 25	8:50- 9:30 a.m.	13	10	7.7	4.8	4.8	0.8	Calm	Smooth	Clear
	2	June 11	9:00- 9:31 "	13 1/2	14	11.9	...	5.7	1.4	SW-3	Choppy	Hazy
	3	June 26	3:45- 4:05 p.m.	14 1/2	16	17.7	...	6.8	3.5	NNW-3	do	Squall
	4	July 8	7:50- 8:15 a.m.	12 1/2	18	13.3	...	11.2	2.1	W-1	Rippled	Partly cloudy
	5	July 24	7:45- 8:15 "	12	20	19.9	...	16.0	3.6	NW-2	do	Cloudy
	6	Aug. 9	8:25- 8:45 "	13	18	18.3	11.6	8.0	2.4	SW-1	do	Clear
	8	Sept. 6	4:35- 5:00 p.m.	14	24	21.1	20.0	16.7	9.2	W-1	do	Cloudy
53	1	May 27	12:25-12:55 "	28	17	10.1	7.6	6.5	1.0	NNE-1	Smooth	Rain
	2	June 10	12:17- 1:15 "	29	18	13.9	9.5	6.4	1.7	Calm	do	Clear
	3	June 27	1:30- 1:55 "	28	18	19.8	12.2	6.9	4.5	Calm	do	Partly cloudy
	4	July 5	11:20-11:45 a.m.	28	18	17.1	16.9	13.7	3.8	SW-4	Rough	do
	5	July 27	10:03-10:30 "	27	22	21.1	...	8.7	7.0	SW-2	Choppy	Hazy
	6	Aug. 7	12:45- 1:10 p.m.	27 1/2	20	21.4	20.1	19.3	6.6	Calm	Smooth	Clear
	8	Sept. 4	3:35- 4:00 "	26 1/2	24	21.2	20.2	16.1	9.2	WxS-0	do	Cloudy
54	1	May 27	4:45- 5:10 "	49	18	9.1	6.1	4.7	1.3	E-1	Smooth	Hazy
	2	June 8	11:05-11:35 a.m.	52	12	10.2	...	4.5	1.4	Calm	Swell	Clear
	3	June 27	12:05-12:35 p.m.	49	18	18.4	12.5	5.0	4.8	E-1	Rippled	Partly cloudy
	4	July 5	12:45- 1:25 "	53	19	15.2	14.6	5.0	3.4	SW-3	Rough	do
	5	July 24	2:00- 2:30 "	50 1/2	20	21.5	20.0	5.2	6.5	SSE-1	Smooth	Cloudy
	6	Aug. 8	11:55-12:50 "	52	22	20.5	19.8	5.8	6.8	N-1	Swell	Partly cloudy
	8	Sept. 6	8:55- 9:30 a.m.	53	23	20.9	20.6	5.4	12.3	SW-2	Choppy	do
56	2	June 14	10:20-11:27 "	16	17	14.6	13.6	8.7	2.0	SW-4	Rough	Partly cloudy
	7	Aug. 26	9:00- 9:45 "	16	21	21.0	20.4	20.0	...	SW-2	Choppy	Cloudy
58	4	July 10	11:20-12:00 "	22	25	19.6	17.8	6.0	3.6	WSW-2	Choppy	Clear
	5	July 22	11:40-12:10 p.m.	22	20	20.3	18.9	11.3	5.5	S-2	Rippled	do
	6	Aug. 13	10:00-10:25 a.m.	21	21	22.1	20.8	10.2	5.2	E-1	Smooth	do
	8	Sept. 12	9:00- 9:20 "	22	16	19.2	19.2	11.3	4.8	SSE-3	Choppy	Cloudy

(Continued)

Table 5. --*Shearwater* station data, 1929 (Cont'd)

Station	Cruise	Date	Hour	Depth (meters)	Temperature (° C.)				Transparency (meters)	Wind and force	Sea	Sky
					Air	Surface	10 meters	Bottom				
59	5	July 25	3:25- 4:05 p. m.	41 1/2	23	20.6	20.0	5.7	6.0	NE-3	Swell	Overcast
	8	Sept. 6	8:04- 8:12 a. m.	37	22	20.8	20.7	5.6	10.1	SW-2	Choppy	Partly cloudy
60	5	July 25	4:25- 4:50 p. m.	30 1/2	21	20.4	19.9	6.4	4.5	NE-3	Swell	Overcast
61	6	Aug. 8	10:15-10:45 a. m.	40 1/2	20	20.0	...	6.1	6.1	S-2	Choppy	Partly cloudy
	8	Sept. 5	1:55- 2:25 p. m.	41	26	21.0	20.4	5.8	10.6	Calm	Smooth	Hazy
62	8	Sept. 11	9:00- 9:30 a. m.	20 1/2	11	20.2	20.2	20.1	...	N-4	Rough	Cloudy

Table 6A. --Serial temperatures in 1929 at station 12

Depth (meters)	Temperature (° C.)			
	June 8 5:00 p. m.	July 5 5:30 p. m.	August 8 9:30 p. m.	September 5 1:00 p. m.
0	12.6	18.5	20.4	21.7
5	12.4	...	...	...
10	11.8	17.7	20.3	20.4
11	10.6	...	...	...
12	10.2	...	...	...
13	10.0	...	...	...
14	6.6	...	...	...
15	6.5	...	19.9	...
18	...	...	16.6	18.2
18 1/2	...	...	...	11.6
19	...	17.7	16.0	10.6
20	...	...	10.7	...
20 1/2	...	...	...	10.2
21	6.1	...	7.4	...
Cruise number	2	4	6	8
Air temperature (° C.)	17	21	19	24

Table 6B. --Serial temperatures in 1929 at station 14

Depth (meters)	Temperature (° C.) May 24 1:30 p. m.	June 12 10:30 a. m.	June 25 3:00 p. m.	July 8 2:00 p. m.	July 23 2:30 p. m.	Aug. 10 11:30 a. m.	Sept. 7 1:00 p. m.
0	5.1	13.9	19.3	18.2	20.6	21.2	20.9
5	4.8	13.7	19.1	...	...	...	...
9	...	...	17.4	...	...	...	...
10	4.7	13.5	16.8	17.3	19.3	...	20.7
11	...	...	13.0	...	...	...	...
12	...	...	11.6	...	...	...	...
15	4.7	9.3	9.9	16.3	...	...	...
17	...	...	...	11.4	...	...	...
20	4.6	6.3	...	7.2	13.4	17.8	...
25	4.6	4.7	5.3	...	11.4	12.4	...
26	...	...	...	...	10.3	9.8	...
27	...	...	...	...	...	8.8	...
28	...	...	...	...	7.7	7.2	...
29	...	...	...	...	...	6.8	...
30	...	...	...	...	6.4	6.6	...
31	4.5	...	...	...	...	...	...
35	...	4.7	5.0	5.3	6.4	...	...
36	4.5	...	...	...	...	6.0	11.7
Cruise number	1	2	3	4	5	6	8
Air temperature (° C.)	8	17	19	18	23	24	23

Table 6C. --Serial temperatures in 1929 at station 15

Depth (meters)	Temperature (° C.)									
	May 24 4:00 p. m.	May 25 2:30 p. m.	June 11 Noon	June 26 Noon	July 8 11:00 a. m.	July 23 4:30 p. m.	July 25 Noon	Aug. 9 2:00 p. m.	Aug. 28 1:00 p. m.	Sept. 7 11:30 p. m.
0	5.6	8.3	10.5	18.0	15.9	20.5	20.4	21.0	20.5	20.8
1	...	7.2	...	...	...	...	...	...	...	...
2	...	6.2	...	...	...	...	...	...	...	...
3	...	6.0	...	17.8	...	...	...	...	...	...
5	5.4	5.7	...	17.7	...	...	...	...	...	...
6	...	...	...	16.2	...	...	...	...	...	...
7	...	...	...	14.4	...	...	...	...	...	...
8	5.3	...	...	13.4	...	...	...	...	...	...
9	...	...	...	12.3	...	...	...	...	...	...
10	5.1	5.3	8.9	11.5	14.1	...	20.0	20.0	20.1	20.7
12	...	...	....	...	13.1	...	...	...	...	...
15	...	...	...	...	...	18.8	...	20.0	...	...
16	...	...	...	...	...	...	19.8	...	...	...
17	...	...	...	...	11.7	...	...	18.9	...	...
18	...	...	...	...	...	...	19.3	...	...	...
19	...	...	...	...	...	...	16.8	...	...	...
20	4.9	5.0	8.3	8.6	9.1	13.2	14.9	15.4	19.0	19.0
21	...	...	...	...	...	...	...	...	17.1	...
22	...	...	...	...	...	...	...	...	16.3	...
23	...	...	...	...	...	...	...	12.4	14.8	15.6
25	...	...	...	...	...	10.2	...	10.6	12.3	12.8
28	...	...	6.4	...	...	...	...	...	9.7	10.4
30	4.9	...	...	5.8	...	8.2	8.0	9.4	8.8	9.7
37	...	...	5.1	...	...	...	...	...	...	...
40	4.8	4.8	...	5.1	6.7	6.2	5.4	8.1	6.8	6.9
50	4.7	...	...	4.9	...	...	...	5.7	5.3	6.3
55	...	...	5.0	...	...	...	...	...	...	...
60	4.5	4.4	...	4.8	4.9	5.0	4.8	5.2	5.3	5.5
Cruise number	1	1	2	3	4	5	5	6	7	8
Air temperature (° C.)	8	17	14	19	18	23	21	21	17	21

Table 6D. --Serial temperatures in 1929 at station 17

Depth (meters)	Temperature (° C.) May 25 11:00 a.m.	June 11 10:30 a.m.	June 26 2:00 p.m.	July 8 9:30 a.m.	July 24 10:00 a.m.	Aug. 9 10:00 a.m.	Aug. 26 1:30 p.m.	Aug. 27 9:30 a.m.	Aug. 27 12:30 p.m.	Aug. 27 3:30 p.m.	Aug. 27 6:30 p.m.	Aug. 28 9:30 a.m.	Sept. 6 2:30 p.m.
0	11.7	10.0	18.2	15.1	19.9	18.8	20.1	19.7	19.8	20.2	20.2	19.5	21.0
1	10.2	...	...	...	...	...	...	...	...	...	...	...	...
2	9.0	...	...	...	...	...	...	...	...	...	...	...	...
3	7.7	...	17.4	...	...	...	...	...	...	...	...	...	...
4	7.3	...	12.3	...	...	...	...	...	...	...	...	...	...
5	7.1	...	11.6	...	...	...	19.5	...	...	...	...	...	...
6	...	...	10.6	...	...	16.8	18.8	...	...	...	...	...	...
7	...	9.2	...	...	...	...	15.8	...	...	...	...	...	...
8	...	...	9.6	...	...	...	15.7	...	...	...	...	...	...
9 1/2	...	...	...	...	17.0	...	...	...	...	...	...	...	...
10	6.2	...	8.7	13.2	15.2	14.0	15.0	19.3	...	19.7	...	19.5	18.4
10 1/2	...	...	...	...	11.5	...	...	...	...	...	...	...	...
11	...	...	...	...	8.0	...	...	...	...	...	...	...	...
12	...	7.8	...	...	6.5	...	...	...	...	...	...	...	...
13	...	...	...	...	6.2	...	...	...	...	...	19.4	...	...
14	5.5	...	7.5	...	5.8	12.2	14.3	...	...	...	19.4	...	17.8
14 1/2	...	...	...	...	...	...	...	...	...	19.1	...	...	...
15	...	...	...	...	5.4	...	13.9	19.1	...	17.5	16.4	19.4	17.6
15 1/2	...	...	...	...	...	...	...	...	...	13.9	...	...	...
16	...	...	...	...	5.3	...	13.6	18.9	...	12.4	14.1	18.9	17.4
16 1/2	...	...	...	...	...	...	...	...	19.0	...	...	...	...
17	...	5.2	...	...	5.3	...	13.4	16.9	16.8	11.9	13.5	17.0	16.7
17 1/2	...	...	...	10.7	...	...	...	...	12.0	...	...	...	...
18	...	...	...	...	5.3	11.5	12.0	13.0	11.7	11.5	12.6	16.7	16.4
18 1/2	...	...	...	...	...	...	...	12.9	11.1	11.4	12.6	16.5	...
19	5.3	...	7.2	...	...	...	11.2	...	...	...	...	...	16.4
20	...	5.2	...	...	...	11.3	...	...	...	...	...	...	...
Cruise number	1	2	3	4	5	6	7	7	7	7	7	7	8
Air temperature (° C.)	11	14	18	19	22	21	23	17	18	19	18	17	24

Table 6-E. --Serial temperatures in 1929 at station 20

Depth (meters)	Temperature (° C.)					
	June 10 5:30 p.m.	June 27 9:00 a.m.	July 6 3:00 p.m.	July 24 4:30 p.m.	Aug. 8 3:30 p.m.	Sept. 6 Noon
0	12.4	17.6	16.7	21.0	16.9	21.4
5	10.4	17.0	...	...	...	...
6	...	15.7	...	...	...	...
7	...	13.9	...	...	...	...
8	...	11.7	...	...	...	...
10	9.2	10.6	14.6	19.2	12.6	20.3
15	8.9	9.1	12.8	...	...	...
17	...	...	10.4	...	...	...
19	...	...	8.1	...	...	...
20	8.7	5.9	7.8	12.9	9.3	15.4
22	7.1	...	...	...	...	...
23	...	...	...	...	...	12.5
24	...	...	...	...	...	11.9
25	5.2	...	...	...	...	10.8
30	...	...	...	...	...	8.9
33	...	5.8	7.4	...	7.1	...
35	4.8	...	...	...	...	6.6
36	...	...	...	5.2	...	...
Cruise number	2	3	4	5	6	8
Air temperature (° C.)	22	17	18	23	23	26

Table 6-F. --Serial temperatures in 1929 at station 21

Depth (meters)	Temperature (° C.)				
	June 8 2:30 p.m.	June 27 11:00 a.m.	July 5 4:00 p.m.	July 24 1:00 p.m.	Sept. 5 3:30 p.m.
0	10.5	19.0	16.0	21.1	21.2
5	9.5	17.7	...	...	...
6	...	16.8	...	...	...
8	...	13.7	...	...	...
10	9.2	11.3	15.3	...	20.5
15	9.0	8.7	...	...	...
20	7.0	...	11.2	18.4	...
22	...	...	...	16.5	...
24	...	...	...	13.4	...
25	5.8	...	...	...	...
26	...	...	...	10.0	...
28	...	...	...	8.3	...
30	4.8	5.2	6.1	6.4	15.9
40	4.6	...	4.9	5.3	...
54	...	4.6	...	...	...
55	...	...	4.8	5.2	5.4
56	4.4	...	...	...	...
Cruise number	2	3	4	5	8
Air temperature (° C.)	15	18	17	23	26

Table 6-G. --Serial temperatures in 1929 at station 22

Depth (meters)	Temperature (° C.)				
	June 8 12:30 p.m.	July 5 2:30 p.m.	July 24 3:00 p.m.	Aug. 8 1:30 p.m.	Sepr. 6 10:30 a.m.
0	10.2	16.0	21.0	21.0	21.2
5	9.4	15.4	...	...	...
10	9.2	15.2	19.6	19.0	20.5
15	9.1	...	...	...	...
20	8.5	14.3	13.3	15.9	...
23	7.3	...	...	...	...
25	5.8	...	8.2	15.5	...
30	...	...	...	6.8	...
34	...	...	6.0	...	...
35	5.2	8.3	...	...	8.4
36	...	...	...	6.7	...
Cruise number	2	4	5	6	8
Air temperature (° C.)	12	18	21	21	24

Table 6-H. --Serial temperatures in 1929 at station 26

Depth (meters)	Temperature (° C.)						
	May 20 1:00 p. m.	June 14 Noon	June 25 8:30 a. m.	July 9 11:30 a. m.	July 22 6:00 p. m.	Aug. 13 9:00 a. m.	Sept. 9 9:30 a. m.
0	9.9	15.1	20.7	18.9	20.9	22.2	20.7
4	9.8	15.0	...	...	...	...	...
5	9.7	...	20.6	...	...	...	...
6	8.9	...	...	...	...	...	...
7	6.7	...	...	...	...	...	...
9	6.2	14.3	...	...	...	...	...
10	5.8	13.6	17.8	16.4	19.5	20.8	20.7
11	...	...	...	16.2	...	...	...
12	...	12.3	...	...	19.5	...	...
13	...	10.9	...	15.2	...	20.7	...
14	...	...	13.3	7.5	19.5	...	...
15	5.5	...	8.0	6.2	12.8	...	...
16	...	...	5.9	...	...	20.4	...
17	...	...	5.8	...	...	16.1	...
18	...	8.1	5.8	...	8.2	11.3	...
19	5.4	...	5.8	6.1	...	...	14.9
20	...	...	...	...	...	9.8	...
Cruise number	1	2	3	4	5	6	8
Air temperature (° C.)	6	18	23	24	22	20	24

Table 6-I. --Serial temperatures in 1929 at station 27

Depth (meters)	Temperature (° C.)						
	May 20 3:30 p.m.	June 12 3:30 p.m.	June 25 10:30 p.m.	July 9 1:30 p.m.	July 22 5:00 p.m.	Aug. 10 4:30 p.m.	Sept. 9 1:30 p.m.
0	4.8	12.6	19.6	18.2	20.7	21.5	21.1
1	4.7	...	...	...	...	...	...
2	4.7	...	...	...	...	...	...
3	4.7	12.2	...	...	...	...	...
4	4.6	...	...	...	...	...	...
5	4.6	...	19.4	...	...	...	...
7	...	...	14.2	...	...	...	...
9	...	...	11.5	...	...	...	...
10	4.5	11.2	10.8	16.5	19.4	20.0	20.7
14	...	10.0	...	...	...	...	...
15	4.5	...	8.8	14.0	19.1	...	...
16	...	9.1	...	...	...	...	...
17	...	...	...	12.8	...	...	...
18	...	8.3	...	...	...	...	...
20	4.4	5.7	7.0	9.1	14.2	...	...
22	...	...	...	6.2	...	...	...
25	4.3	...	...	...	...	...	...
26	...	...	...	...	11.6	...	...
27	...	5.7	...	5.7	...	...	...
28	4.3	...	5.2	...	...	7.6	10.1
Cruise number	1	2	3	4	5	6	8
Air temperature (° C.)	6	13	19	20	24	22	23

Table 6-J. --Serial temperatures in 1929 at station 28

Depth (meters)	Temperature (° C.)						
	May 22 10:00 a.m.	June 12 2:00 p.m.	June 25 Noon	July 9 3:00 p.m.	July 22 4:00 p.m.	Aug. 10 3:00 p.m.	Sept. 9 Noon
0	6.0	11.7	18.6	18.0	21.6	21.0	21.0
1	5.6	...	...	...	...	...	...
2	5.2	...	...	...	...	...	...
3	4.9	...	...	...	...	...	...
4	4.8	...	...	...	...	...	...
5	4.8	11.2	18.4	...	...	...	...
6	4.8	...	...	...	...	...	...
7	4.8	...	...	...	...	...	...
8	4.8	...	14.6	...	...	...	...
10	4.8	9.5	11.3	17.4	19.6	19.0	20.8
12	...	...	10.4	...	...	...	...
15	4.7	8.5	9.4	...	...	...	...
19	...	...	...	...	...	...	17.3
20	4.7	8.1	8.6	13.2	16.5	15.4	15.9
21	...	8.0	...	...	...	...	15.0
22	...	7.6	...	...	...	...	13.8
23	...	...	...	...	...	...	13.2
24	...	7.1	...	...	...	...	12.5
25	4.7	5.3	...	11.3	12.7	9.5	12.0
26	...	...	...	...	...	...	10.9
27	...	...	...	7.3	...	...	10.3
28	...	5.3	...	...	...	...	9.6
29	...	...	...	...	...	...	9.1
30	4.7	...	...	6.9	9.4	...	8.4
34	...	5.2	...	...	...	...	...
35	...	...	...	6.0	6.7	...	...
36	4.7	...	...	...	...	...	...
37	...	...	...	...	...	5.4	6.7
38	...	...	5.4	...	...	...	...
Cruise number	1	2	3	4	5	6	8
Air temperature (° C.)	11	13	19	20	23	24	22

Table 6-K. --Serial temperatures in 1929 at station 35

Depth (meters)	Temperature (° C.)			
	June 16 1:30 p. m.	July 11 Noon	Aug. 16 11:00 a. m.	Sept. 15 Noon
0	16.6	19.4	20.7	19.5
5	14.5	...	...	...
10	12.6	18.5	19.9	19.2
15	11.5	16.6	...	...
18	...	16.4	...	...
19	...	11.6	...	...
20	...	10.6	12.5	19.2
21	9.9	...	...	...
Cruise number	2	4	6	8
Air temperature (° C.)	23	19	20	17

Table 6-L. --Serial temperatures in 1929 at station 40

Depth (meters)	Temperature (° C.)				
	May 17 2:30 p. m.	June 17 3:30 p. m.	July 12 3:30 p. m.	Aug. 17 2:00 p. m.	Sept. 16 1:15 p. m.
0	8.3	17.7	20.6	21.1	19.6
3	...	14.9	...	...	...
5	7.3	...	...	...	...
10	7.3	12.7	17.4	20.9	19.5
12	...	12.5	...	...	...
15	7.3	11.5	16.4	20.3	...
18	...	...	16.2	...	...
19	...	...	15.2	...	...
20	7.3	...	11.9	20.3	...
21	...	...	...	14.3	...
23	...	9.5	10.9	11.2	19.5
24 1/2	7.2	...	...	...	...
Cruise number	1	2	4	6	8
Air temperature (° C.)	13	24	23	22	23

Table 6-M. --Serial temperatures in 1929 at station 52

Depth (meters)	Temperature (° C.)						
	May 25 9:00 a.m.	June 11 9:00 a.m.	June 26 4:00 p.m.	July 8 8:00 a.m.	July 24 8:00 a.m.	Aug. 9 8:30 a.m.	Sept. 6 5:00 p.m.
0	7.7	11.9	17.7	13.3	19.9	18.3	21.1
1	6.9	...	...	...	...	...	...
2	6.7	11.7	...	...	...	...	...
3	6.5	...	...	...	...	...	...
4	5.4	...	17.4	...	...	...	...
5	5.3	9.8	14.4	13.1	19.8	...	...
6	4.8	...	11.8	...	...	...	...
7	4.8	...	9.6	...	...	...	...
8	4.8	8.2	7.6	...	...	...	...
10	4.8	...	...	...	...	11.6	20.0
12	4.8	5.7	...	11.2	16.0	8.0	...
13	...	...	6.8	...	...	...	16.7
Cruise number	1	2	3	4	5	6	8
Air temperature (° C.)	10	14	16	18	20	18	24

Table 6-N. --Serial temperatures in 1929 at station 58

Depth (meters)	Temperature (° C.)			
	July 10 11:30 a.m.	July 22 Noon	Aug. 13 10:00 a.m.	Sept. 12 9:00 a.m.
0	19.6	20.3	22.1	19.2
10	17.8	18.9	20.8	19.2
12	16.8	18.9	...	...
13	15.3	18.5	...	...
14	14.3	14.5	...	...
15	8.6	13.6	...	...
16	6.1	...	...	...
17	6.1	12.6	...	...
20	6.0	11.3	10.2	11.3
Cruise number	4	5	6	8
Air temperature (° C.)	25	20	21	16

Table 6-O. --Serial temperatures in 1929 at station 61

Depth (meters)	Temperature (° C.)	
	Aug. 8 10:30 a.m.	Sept. 5 2:00 p.m.
0	20.0	21.0
10	...	20.4
20	19.1	20.0
25	18.9	16.6
26	17.7	15.5
27	...	14.6
28	14.2	11.7
29	10.9	8.2
30	8.7	6.9
32	6.2	...
39	6.1	...
40	...	5.8
Cruise number	6	8
Air temperature (° C.)	20	26

The Great Plain (central basin) now had an average surface temperature of 17° C., with cooler waters on the north shore than on the south shore. The central part of the plain was covered with bottom water of from 9.4° to 10°, while the 12° bottom isotherm included nearly all of the plain except the southern marginal zone from Sandusky to Ashtabula, where 17° bottom water was encountered 2 miles offshore from both Lorain and Fairport.

Thus June found about 80 percent of the whole lake area with bottom water under 12°. Surface warming had not yet been sufficient to build up a definite thermocline over any extensive area.

Cruise 3.--At the termination of cruise 2 and before the next regular cruise (4), the physical observations were confined to the Deep Hole area where the 6° C. bottom isotherm was determined. The horizontal shifting of the subsurface, cold-water mass of this area was observed in the 1928 survey. It was therefore considered advisable this year to determine the limits of 6° bottom water as frequently as the survey program would permit. The results of these determinations are discussed under "Water movements."

The mean surface temperature from 13 stations observed on cruise 3 was respectively 50 percent and 12 percent greater than the means of the same stations on cruises 2 and 4. As these cruises were progressively 2 weeks apart, it would be logical to expect that the mean for cruise 3 would be about equal to the average of the means of cruises 2 and 4, since the maximum surface temperature for the lake as a whole was not reached until August (table 4). But when one turns to the weather conditions, the reason for the excessive temperatures of cruise 3 is apparent. We find that on cruise 3 the stations were occupied during generally calm weather and the surface temperatures were not lowered by deep vertical mixing, whereas on cruise 4 they were occupied immediately following 3 days of stormy weather, and the surface temperature was lowered temporarily by mixing with the cold subsurface waters of this Deep Hole area.

An inspection of the means of the bottom temperatures of these stations gives a clearer picture of the seasonal warming. Here we find the mean for cruises 2, 3, and 4 to be 5.1°, 6.0°, and 7.8° C. respectively.

Cruise 4.--In July the mean lake temperatures were: surface 18.9° and bottom 12.8°. Table 4 shows that the maximum mean air temperature was reached during this month, although the surface water temperature continued to rise to a maximum in August.

The coldest surface temperatures were in Long Point Bay, where 13.3° C. water was encountered, with bottom readings of 11°. The cold bottom waters of the adjacent Deep Hole had flowed into this shallow bay, and the storms which occurred just prior to the occupation of these stations lowered the surface temperature considerably by vertical mixing. This condition is temporary as this bay is subject to wide thermal fluctuations, due to the movements of the cold-water mass of the Deep Hole. Probably the mean surface temperature for the whole month was lower in the Deep Hole region than it was in this area; but, due to the impracticability of frequent and simultaneous observations over the whole lake, the situation could not be verified.

The surface water of the eastern area was about 2° C. warmer on the southern and eastern sides than in the northern zone where there was 17° water. The surface water of the Deep Hole was 16° (fig. 6).

Two new and interesting thermal conditions were observed in the Great Plain on this cruise. As they still prevailed on cruise 6 (August), they are probably normal summer phenomena and must be of considerable biological importance. The first is the presence of comparatively cold surface water in the Port Stanley region; the second is the thin cold bottom layer extending over the greater portion of the Plain. The isotherms on figures 6 and 7 clearly show these conditions.

Although comprehensive temperature studies of the whole lake had not been made prior to the survey, it was generally believed that the waters of the Great Plain were nearly homothermous, as the greatest depth is only 25 meters and the area is frequently swept by strong winds.

The prevailing wind direction for July at Cleveland was south. One might expect the leeward shore to have higher surface temperatures, but observations showed the situation to be reversed. Temperatures were 17° C. off Port Stanley and 22° off Fairport and Ashtabula. On the day that these stations were

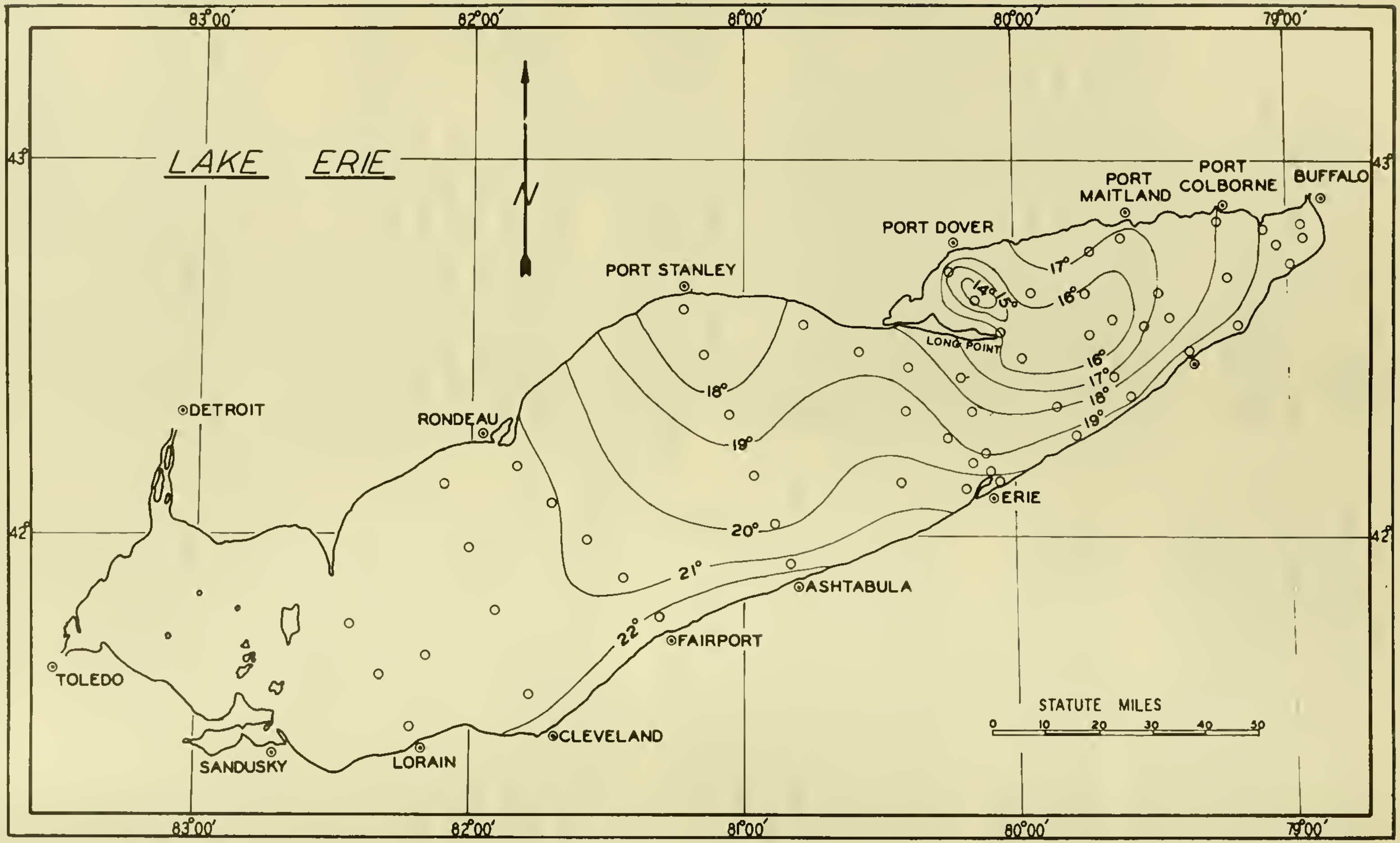

Figure 6. --Surface temperature distribution, cruise 4, 1929

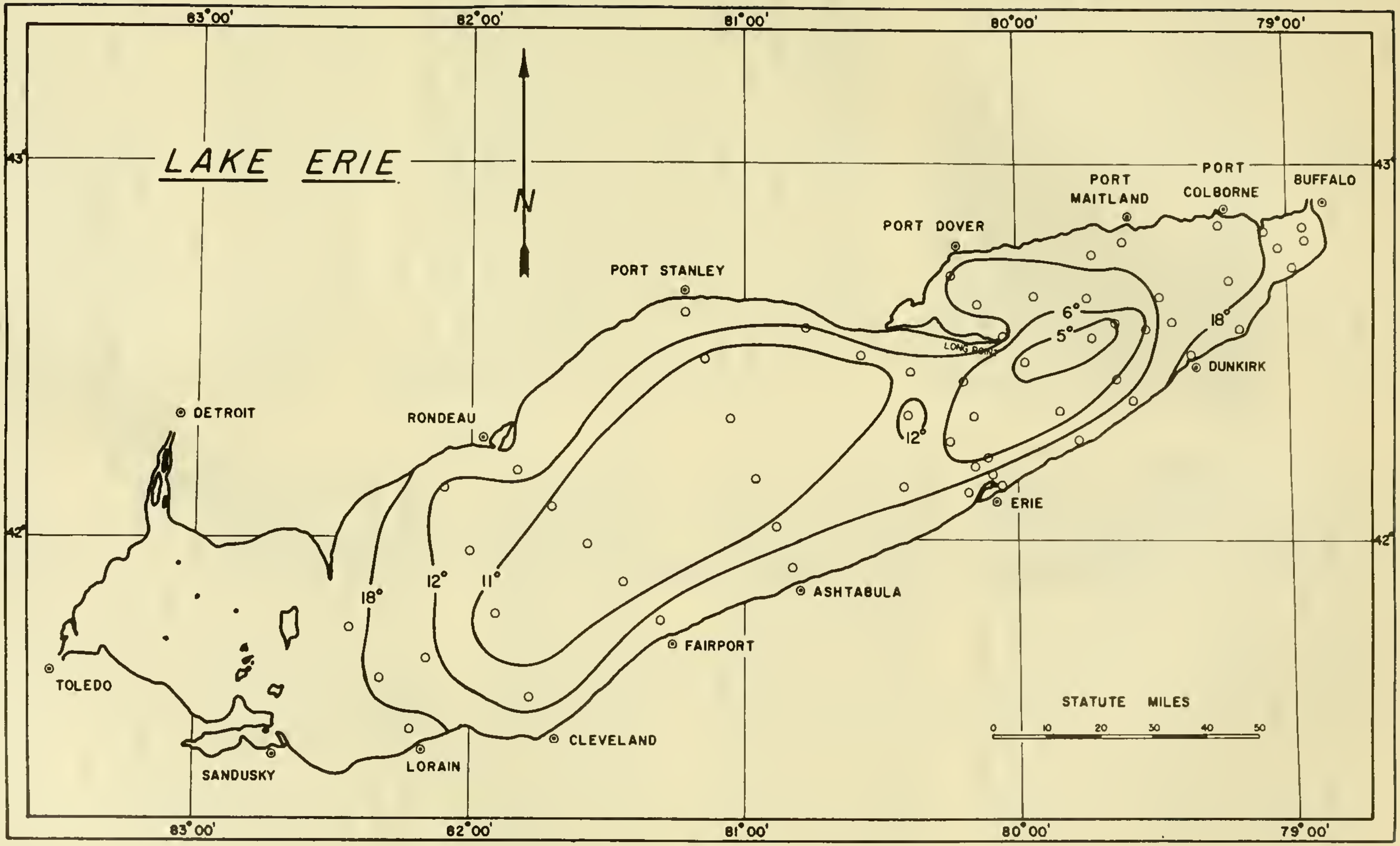

Figure 7. --Bottom temperature distribution, cruise 4, 1929

occupied, and on the preceding day, the wind was northerly and moderate, but not of sufficient duration to cause a complete reversal of the horizontal gradient on a body of water the size of Lake Erie. Furthermore, on cruise 6, when this area was observed immediately after two days of strong south and west winds, the colder water remained in the Port Stanley vicinity, as it did on cruise 4. Kettle Creek empties into the lake at Port Stanley, but on account of the small effluent, it is not a factor in regulating the lake temperature except in the local marginal zone. It is possible that south and southwest winds set up a greater wave action in this area than in other parts of the Great Plain, causing a more marked lowering of the surface temperature by deeper mixing.

Figure 8 shows graphically the temperature distribution on cruise 4 in the vertical section of the Great Plain from Port Stanley, Ontario, to Ashtabula, Ohio (stations 04-32 to 04-37). Both the lower surface temperature of the Port Stanley region and the layer of cold bottom water are clearly pictured. Figure 1 shows the location of this section, and table 6-K, station 35, gives the seasonal changes in the serial temperatures at that station.

The cold bottom layer, which covered the floor of the Great Plain included within the 20-meter depth curve, now had an average thickness of 4. 5 meters and ranged from 10. 1° C. in the deeper parts to 12° at the 20-meter curve. This cold water was insulated from the warmer upper layers by a thermocline of 4° change in a meter.

As may be seen from figure 7, in July about 45 percent of the total lake area was covered with bottom water having a temperature less than 12°. The thermocline was now established over the lake from Erie to Cleveland. Its average depth was 18 meters in the western part of this area and 14 meters in the eastern part. The greatest temperature difference in 1 meter was at station 04-26, where readings were 15. 2° at 13 meters and 7. 5° at 14 meters--a difference of 7. 7°. Two weeks later, on July 22, the thermocline at this same station was between 14 and 15 meters, where there was a difference of 6. 7°.

The surface temperatures in the Deep Hole area were comparatively low and the thermocline therefore was not so definitely established. At station 04-15, at the deepest part of the lake, the temperature dropped 5°C. from the 10-meter level to the 20-meter level, but at no depth was the difference as great as 1° to the meter.

Cruise 5. --The interval between regular cruises 4 and 6 was utilized in determining again the limits of the 6° C. water of the Deep Hole area. The mean surface temperature for 14 stations on this cruise was 20. 9°, as compared with 20. 8° for the mean of the same stations on cruise 6. This section of the lake is unique in that the thermocline occurs at widely different depths due either to oscillatory movements or upwelling of the cold Deep Hole water. Thus at station 05-17 (Long Point) there was a difference of 7. 2° between 10 and 11 meters; at station 05-14, there was a temperature drop of 2. 6° from 26 to 28 meters.

Cruise 6. --The mean of the observed surface temperatures for the lake reached a maximum in August at 20. 6° C. The mean bottom temperature for this cruise was 14. 7° (table 4). The north shore of the eastern area again had the lowest surface-water temperatures. As may be seen from the isotherms of figure 9, a horizontal gradient ranged from 17° along the north shore to 21° at midlake; the southern portion of the area was around 21°. Water temperature of 22° was found from Erie out to Northwest Shoal (station 50), and Port Stanley was again the region of the coldest surface water in the Great Plain. Here the water was between 18° and 19°, whereas the southern marginal zone was from 20° to 21°. An even horizontal gradient radiated from Port Stanley. West of the Fairport-Rondeau line the surface temperature did not vary more than 0. 3° from 21. 5°

The cold bottom waters of the Great Plain had shrunk to the extent that the 14° C. isotherm (fig. 10) covered only half the area that the 12° isotherm had included a month previous. The lowest temperature for this area was now 11. 2° as compared with a low of 10. 1° on cruise 4.

An excellent example of the role that the lake bottom contours play in the regulation of the thermocline depth was observed at stations 06-12 and 06-61, which are only 5 miles apart (fig. 1). At station 12, less than 2 miles off the southern shore at Westfield, the depth is 22 meters. Here the water was practically homothermous vertically from the surface to 15 meters, but dropped 1° per meter from that level to

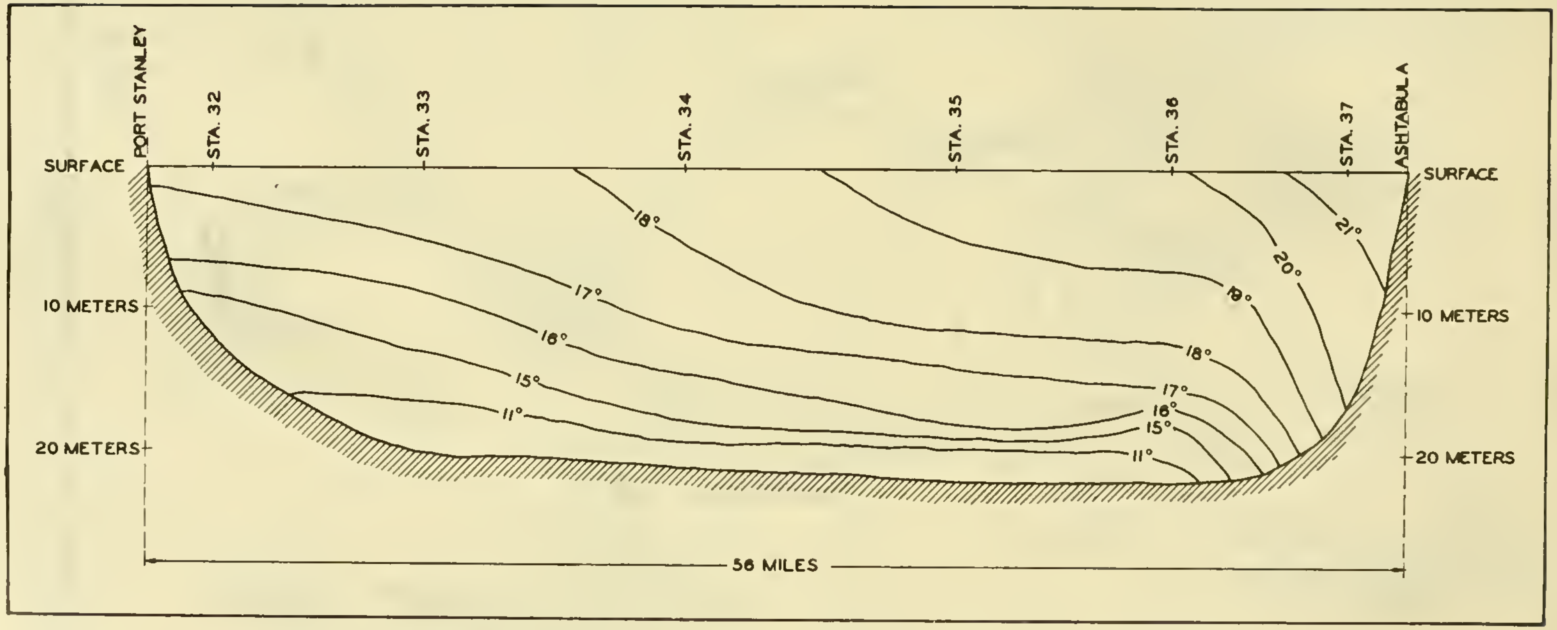

Figure 8. --Isotherms of vertical section, Port Stanley, Ontario, to Ashtabula, Ohio.

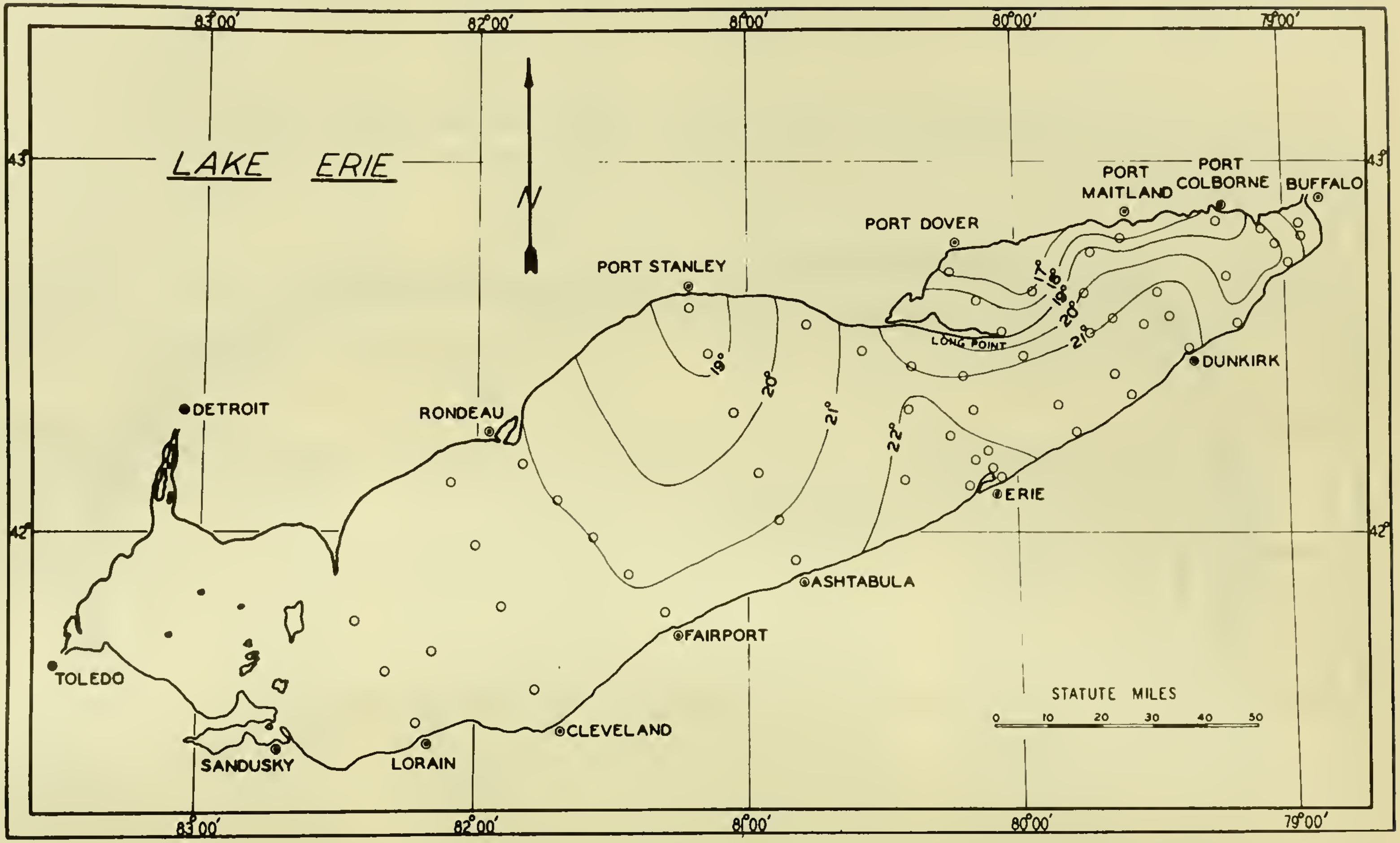

Figure 9. --Surface temperature distribution, cruise 6, 1929.

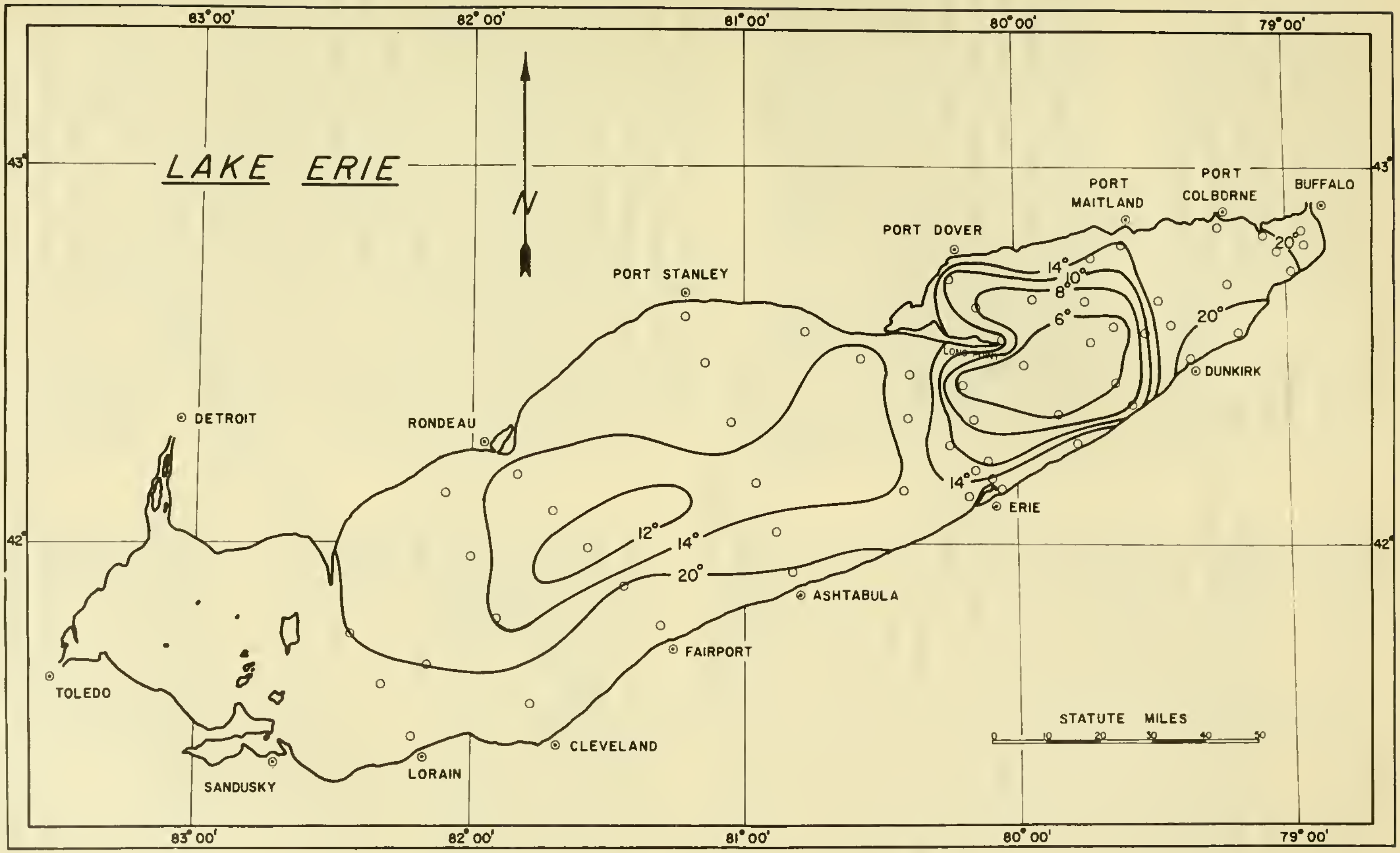

Figure 10. --Bottom temperature distribution, cruise 6, 1929.

19 meters, where a thermocline of 8.6° was encountered between the 19- and 21-meter levels (table 6-A, station 12).

Station 61 is directly offshore from station 12, and the depth is 41 meters. Here the vertical gradient was very slight down to the 26-meter level, where the temperature dropped rapidly to the 30-meter level. The temperatures in this discontinuity layer were as follows: 26 meters, 17.7° C.; 28 meters, 14.2°; 29 meters, 10.9°; 30 meters, 8.7°. As these two stations were occupied only 1 hour apart, they may be considered as being observed simultaneously, and we find the thermocline rising from the 28-meter level to the 19-meter level in conformity with the bottom slope. It is of interest that the thermocline level changed but 9 meters, although the difference in depth of water was 19 meters. In other words, position of the thermocline only tends to conform with the bottom. The bottom temperature of 17.1° (table 5) at station 06-13, only 1 mile off the south shore, indicates that the thermocline is limited at this season of the year to areas of greater depth than 16 meters, except where upwelling produces abnormal conditions.

The thermocline at station 06-26 was between 16 and 18 meters, where the temperature difference was 9.1° as compared with a depth of 13 meters on cruise 4 and 14 meters on cruise 5 at this station. The mean depth of the thermocline in the Deep Hole region, as obtained from 6 stations, was now 25 meters. In the Great Plain, the average thermocline depth was 20 meters--about 2 meters lower than in July.

Cruise 7. --Only 6 stations were occupied on cruise 7 as this interval was utilized in current observations.

At 2:00 o'clock on August 26 at station 07-17, there was an even vertical gradient from the surface down to 6 meters, where the temperature was 18.8° C. The temperature was 15.8° at 7 meters and the gradient was fairly even from that depth to the bottom, 20 meters (table 6-D, station 17). To collect more data on the shifting of the thermocline depth, the *Shearwater* was anchored on this station (17) from 9:00 a.m. to 7:00 p.m. on August 27. The record of the serial temperatures taken throughout the day is shown in table 6-D, station 17. The thermocline depth steadily rose from 17 meters to 14 meters between 9:30 a.m. and 6:30 p.m. The next day (August 28) at 9:00 a.m. the thermocline was between 16 and 17 meters, and was not nearly so well marked. The rise of 4° in bottom temperature in the past 15 hours indicated that the cold bottom waters were moving out of Long Point Bay and into the Deep Hole.

Thus the serial temperatures at this station establish beyond doubt that cold water wells up from the Deep Hole and flows into the comparatively shallow Long Point Bay. No other source can account for the temporary presence of cold bottom water in Long Point Bay. The bottom temperatures at station 52, which is in the center of the bay, on the successive cruises 4, 5, 6, and 8, were 11.2°, 16.0°, 8.0°, and 16.7° respectively--values that indicate that the bottom waters are in movement. The upwelling of cold water out of the Deep Hole and into Long Point Bay is depicted by the isotherms of figure 11.

Cruise 8. --The mean temperatures for the Septemper cruise--surface 20.0° C. and bottom 16.8°--indicate that the maximum surface temperature for the whole lake was reached during the latter part of August. The additional surface warming that took place during September was more rapidly transferred to the deeper layers by storms of greater intensities. Surface temperatures of the lake from Erie eastward were now between 20.2° and 21.7°, whereas those of the Great Plain ranged from 18.2° to 20.2° (fig. 12). Stations east of Erie were occupied prior to the storm of September 10 and 11, and those west of Erie after the storm. This timing accounts for the difference in the mean surface temperatures for the two sections of the lake on this cruise. The still fractionally colder surface water off Port Stanley was matched by a slightly colder area between Point Pelee and Lorain.

Cold bottom water was now confined to the Deep Hole region, where 12° C. water covered about 10 percent of the total lake area. The bottom waters of the entire Great Plain were close to 19°, and at no station in this area was the vertical differential over 0.6°.

It will be noticed from figure 13 that the cold bottom isotherms are crowded over to the south shore

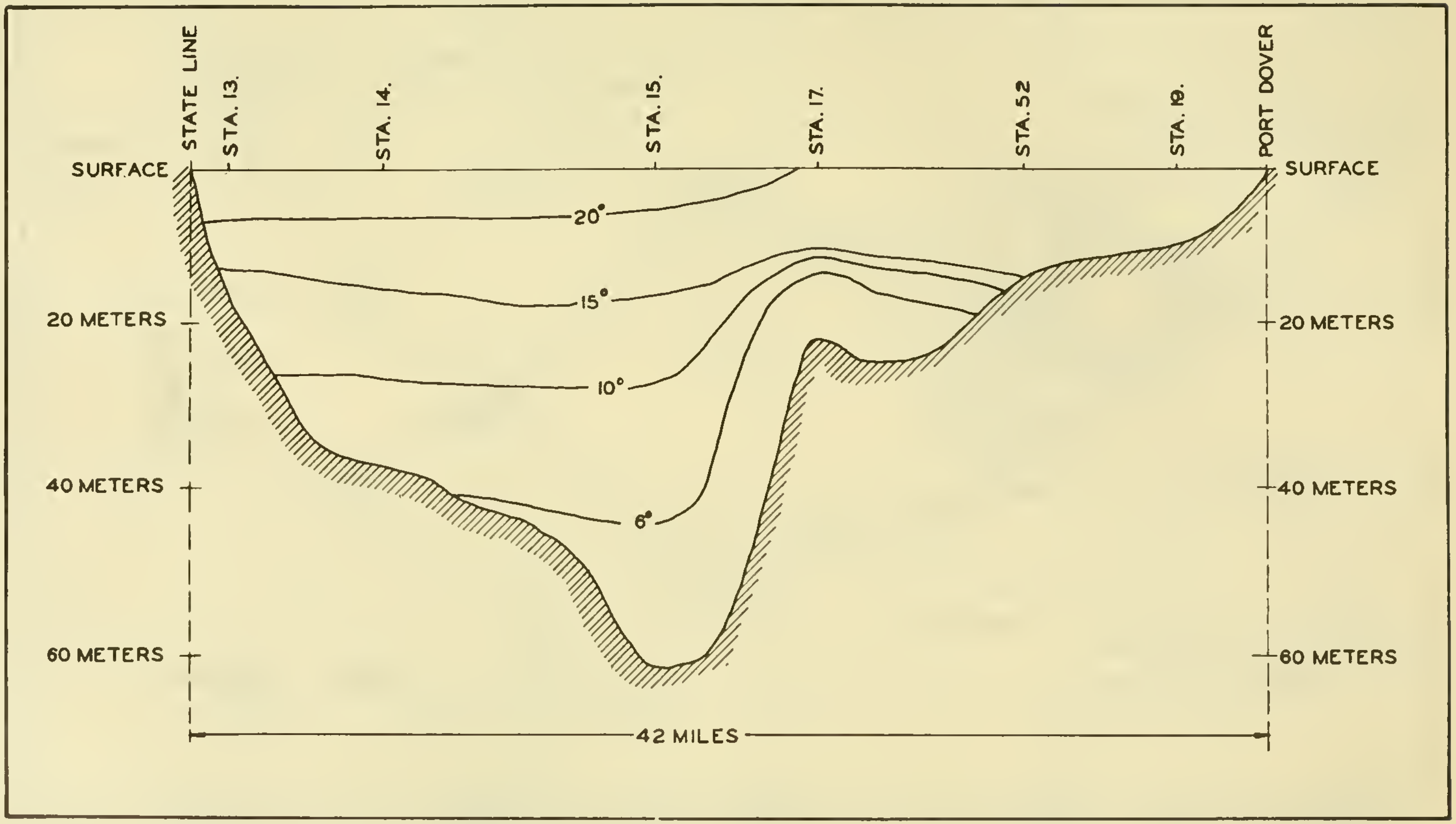

Figure 11. --Isotherms of vertical section, Port Dover, Ontario, to the New York-Pennsylvania State Line.

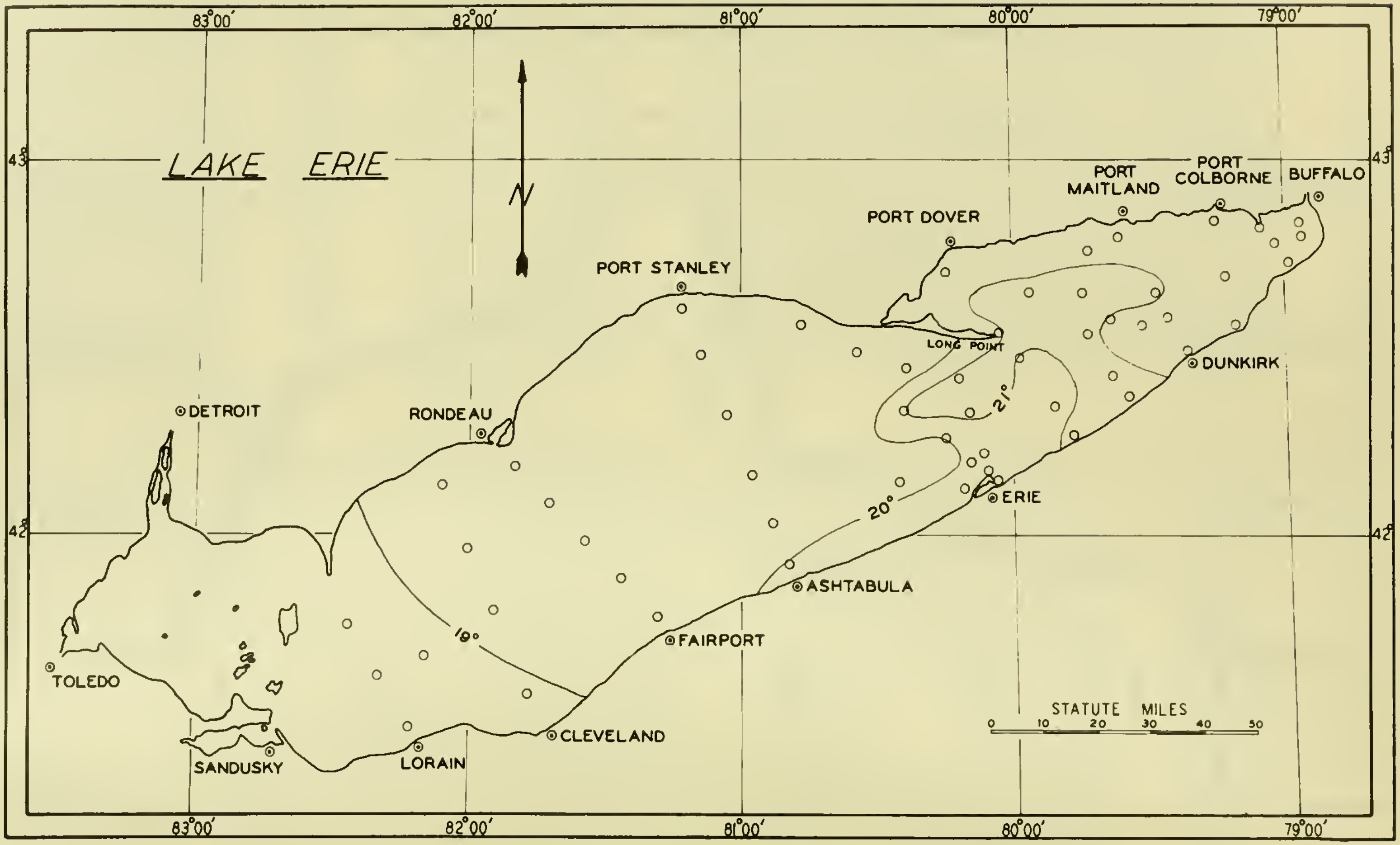

Figure 12. --Surface temperature distribution, cruise 8, 1929.

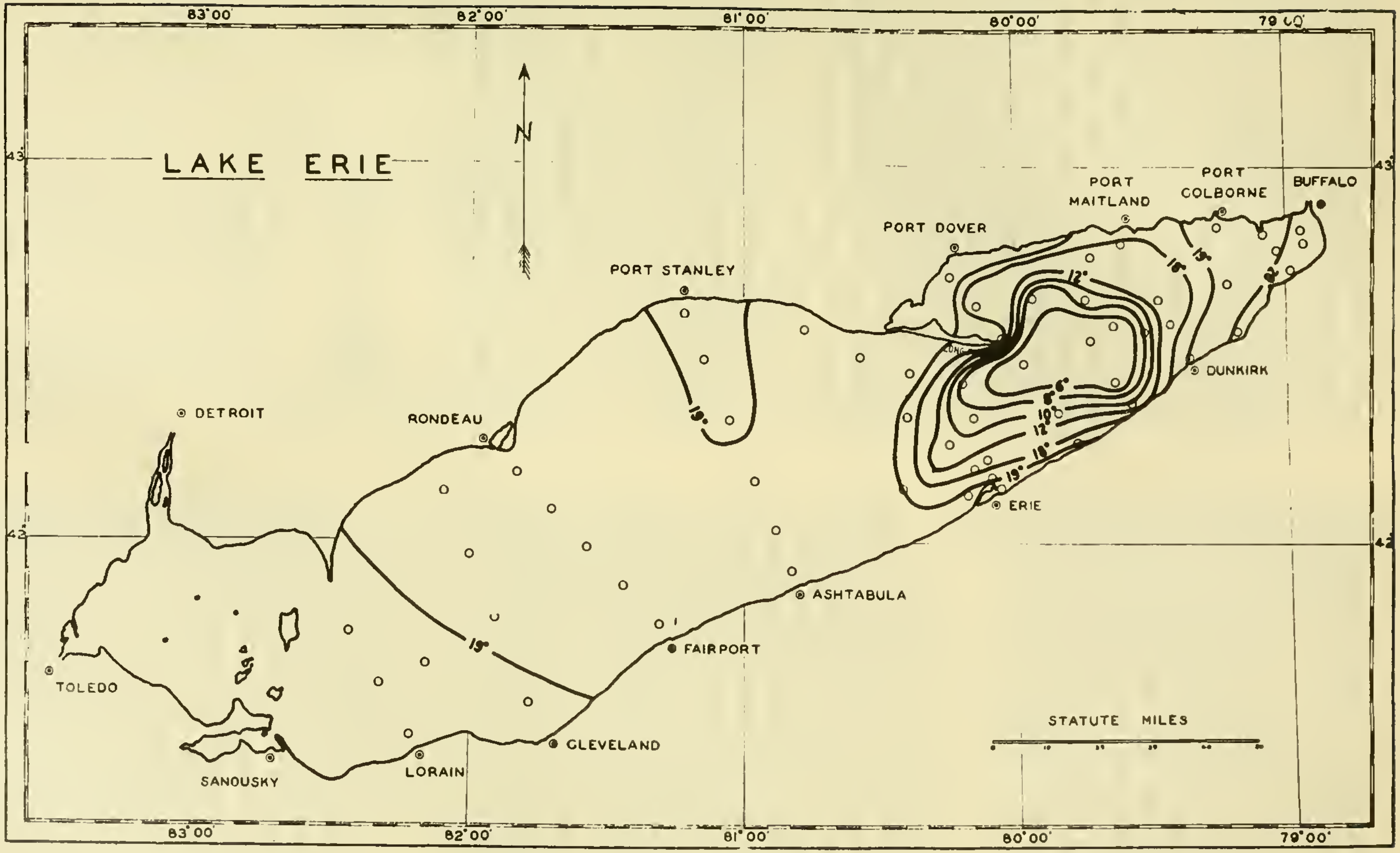

Figure 13. --Bottom temperature distribution, cruise 8, 1929.

at station 08-12, 13 miles southwest of Dunkirk, and that this station had the most intense thermocline of the season. Here the temperature at 18 meters was 18.2° and at 18.5 meters only 11.6°--a difference of 6.6° in 0.5 meter. These readings were taken on a calm, smooth day, and their correctness established beyond doubt by readings with different thermometers. (Indeed all marked thermoclines observed during the season were checked by observations with a different set of thermometers.) The depth of the thermocline at station 08-61 was 28 meters. The relation between stations 12 and 61 in this respect was almost identical with the conditions on cruise 6.

Temperatures in 1928

The 1928 program did not extend west of Long Point and therefore did not include the western limit of the Deep Hole, or any of the Great Plain area. There were, however, three regular cruises when stations 1 to 24 were occupied for physical data. During this period the mean surface temperature was 1.3° C. above that of the same stations on the corresponding cruises of 1929, but the mean bottom temperature was only 0.4° above the mean in 1929. The average of the mean of temperatures at the surface, at the 10-meter level, and at the bottom was 1.0° above the mean in 1929. The area under consideration appears to have received a little more heat up to September 1 in 1928 than in 1929. The data are not sufficient, however, to permit a definite conclusion.

On August 16, 1928, during calm weather, surface temperatures were fractionally over 24° C. in Long Point Bay, whereas during the corresponding time in 1929 the surface water of this area was between 18° and 19°. The surface temperature of a given area is subject to great fluctuation due to varying weather conditions and that general thermal values are obtained only by averaging many stations, or by the means of frequent observations at the same station over a considerable period. The high surface temperatures in Long Point Bay on the above date were caused by the calm, clear weather of that day and by the light easterly winds of the four preceding days. The warm surface water was slowly carried to leeward while the cold bottom waters moved to windward. The low-velocity winds caused no great vertical mixing. The presence at this time of 5° bottom water 10 miles east of Dunkirk is evidence that the movement took place.

As the prevailing winds are from the west, one would expect to find warmer surface water along the American shore and in the Buffalo region. This expectation was met on four of the seven regular cruises during the two summers. On two of the cruises, the horizontal gradient was slight, and on only one the warmer water was in Long Point Bay and along the north shore.

The remarkable thermocline at station 17 was first observed on July 31, 1928 (table 7 gives the thermocline data on 11 days during the two seasons). The wide range in depth and the fact that on half the observations no thermocline existed show that the cold waters of the Deep Hole were in motion vertically as well as horizontally. It is significant that on the three cruises when thermoclines were observed at station 12 (table 6-A) there were none at station 17 (table 6-D). These stations are on opposite sides of the Deep Hole, and lie along a northwest-southeast line.

The shifting thermocline at station 17, and the great horizontal movements of the cold water mass observed in 1928, were witnessed again in 1929, and undoubtedly represent normal summer conditions.

Table 7. --Thermocline data at station 17 (Long Point)

Date	Depth of thermocline (meters)	Temperature change in 1 meter (° C.)
1928		
July 31	14-15	7.8
Aug. 16	17-18	6.5
1929		
May 25	none	...
June 11	none	...
June 26	3-4	5.1
July 8	none	...
July 24	10-11	7.2
Aug. 9	none	...
Aug. 26	6-7	3.0
Aug. 27	17-18	5.1
Sept. 6	none	...

Summary of Temperature Observation

The mean temperatures for the whole lake for the period of the 1929 survey (May 15 to September 19) were: surface, 16.7°; bottom, 11.9°; and mean air temperature, 18.0°. The average number of clear days per month was 11.2, which is normal for this period (table 4). As the normal mean air temperature during this period is 18.3°, the amount of heat received by the lake this summer was probably close to normal. The annual heat budget, as derived from the maximum-minimum means, can not be determined, as the survey did not cover the period of minimum temperature.

Birge, Juday, and March (1928) in their comprehensive investigations of Lake Mendota have shown that approximately 8 percent of the heat budget of that lake is absorbed by the bottom mud. This heat is returned to the water mass in winter and in early spring. Lake Mendota is comparatively small, but its maximum depth (24.5 meters) is the same as that of the Great Plain of Lake Erie. As Lake Mendota has a much smaller percentage of water over 20 meters than Lake Erie and a different thermal cycle, no direct comparison is attempted. Nevertheless, the absorption and subsequent release of heat by the upper stratum of bottom deposits must be an appreciable factor in the thermal cycle of Lake Erie. When bottom water of the marginal zone reaches a temperature of 1° or 2° C., it is slowly warmed by the bottom and becomes heavier as it approaches 4° (temperature of maximum density). This heavier water tends to move to greater depths; and in areas such as those that surround the Deep Hole, where the slopes are steep, the movement may be of importance in preventing physical stagnation in the deep waters of the lake during the cold months.

From available data, the following estimate is made of the probable time that maximum mean temperatures were reached:

Air.	July 15-30
Surface water	August 10-20
10-meter level	August 20-30
Bottom water	Sept. 20-Oct. 5
Surface of bottom mud. . .	October 15-30

The highest surface temperature observed in 1929 was 22.3° C. at station 4-38 on July 12. The day was calm and smooth and the air temperature was 24°.

To aid in visualizing the thermal changes that took place during the season, temperature graphs have been prepared of the water columns at stations 15 and 40. Figure 14 shows the graphs for station 15, the deepest part of the lake. It will be seen from this figure that the water column was practically homothermous on May 24. By June 11, vernal warming had penetrated to a depth of 30 meters, and on June 26 a thermocline was evidenced between 5 and 10 meters. The surface, at 18° C., had warmed 12° in a month. The strong winds that swept this area during the first week of July broke down the thermocline above 10 meters; and on July 8 the column of water was divided into two fairly even gradients, from the surface to 20 meters and from 20 meters to the bottom. The wave action due to strong winds lowered the temperature from the surface to 7 meters, and raised it from 7 meters to 20 meters (crossing of the curves for June 26 and July 8).

The closely parallel curves for July 25 to September 7 depict the normal thermal condition of the area for this time of the year. The upper layers are thoroughly mixed down to 20 meters, where a broad discontinuity layer is encountered between that depth and 30 meters; the temperature drop in this 10-meter stratum is about 10° C. From 30 meters to the bottom (60 meters), the gradient is uniform. The bottom temperature gradually increased from 4.5° on May 24 to 5.5° on September 7. The temperature here probably never exceeds 6.0°.

The graphs for station 40 (fig. 15) are based on table 6-L. The cycle of the thermocline is of sufficient interest to warrant the careful inspection of these curves. Station 40, as may be seen from figure 1, is in the deepest part of the Great Plain, and is typical for this large area.

On May 17, the water was cold and homothermous from a depth of 3 meters to the bottom and the surface was only 1° C. warmer than the rest of the column. On June 17, the bottom temperature had risen 2° and the surface 9°, and the vertical gradient was steep in the upper 10 meters. By July 12 continued surface warming and convectional mixing changed the upper portion of the vertical gradient to the extent that the differential was now only 5° between the surface and 19 meters. The thermocline was first observed on this date when the temperature dropped 3.3° from 19 meters to 20 meters. August 17 found the upper water mass well mixed; the warm-water column with less than a degree of differential reached from the surface to the thermocline at the 20-meter level. A difference in temperature of 6.0° was now found between 20 and

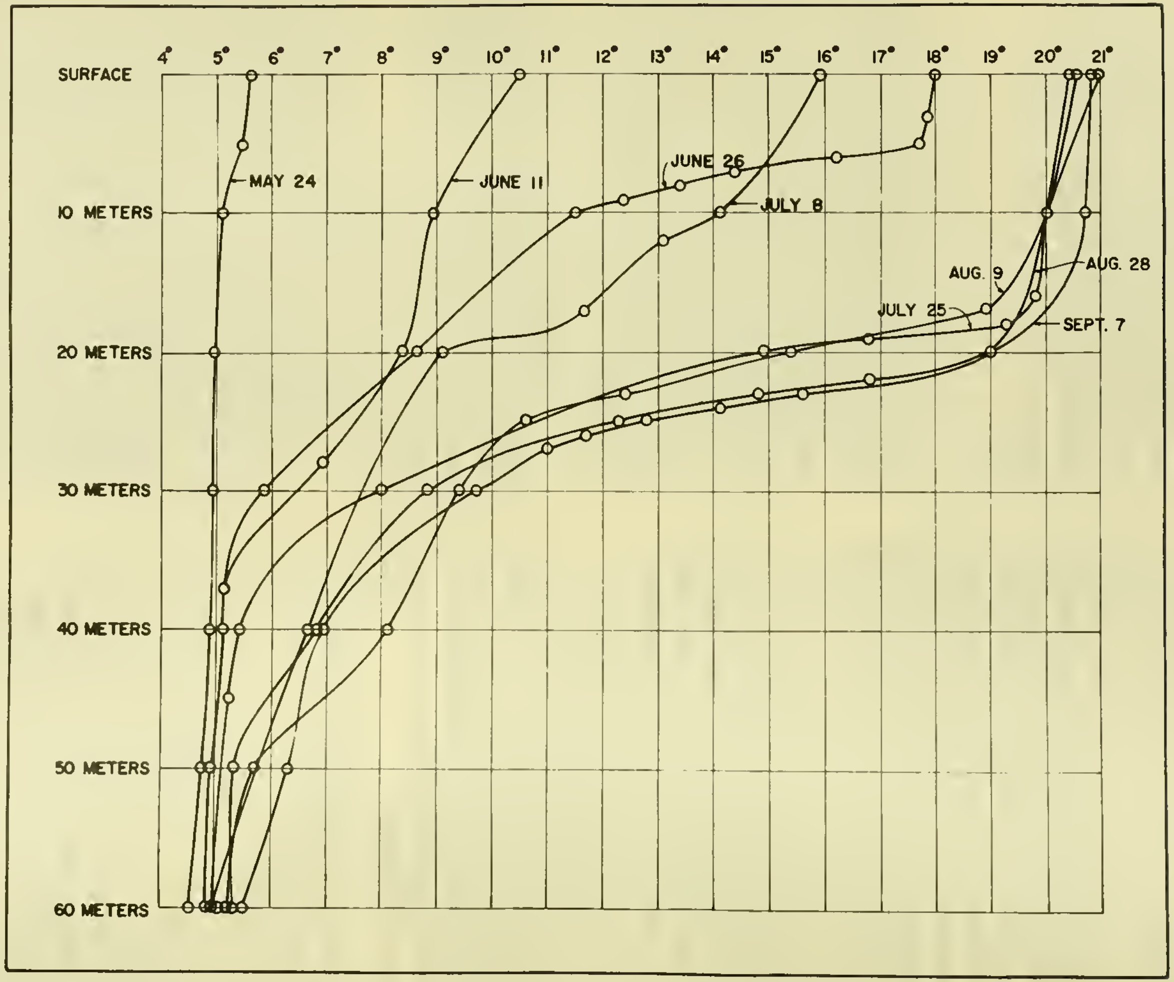

Figure 14. --Temperature graphs of water column at station 15, 1929.

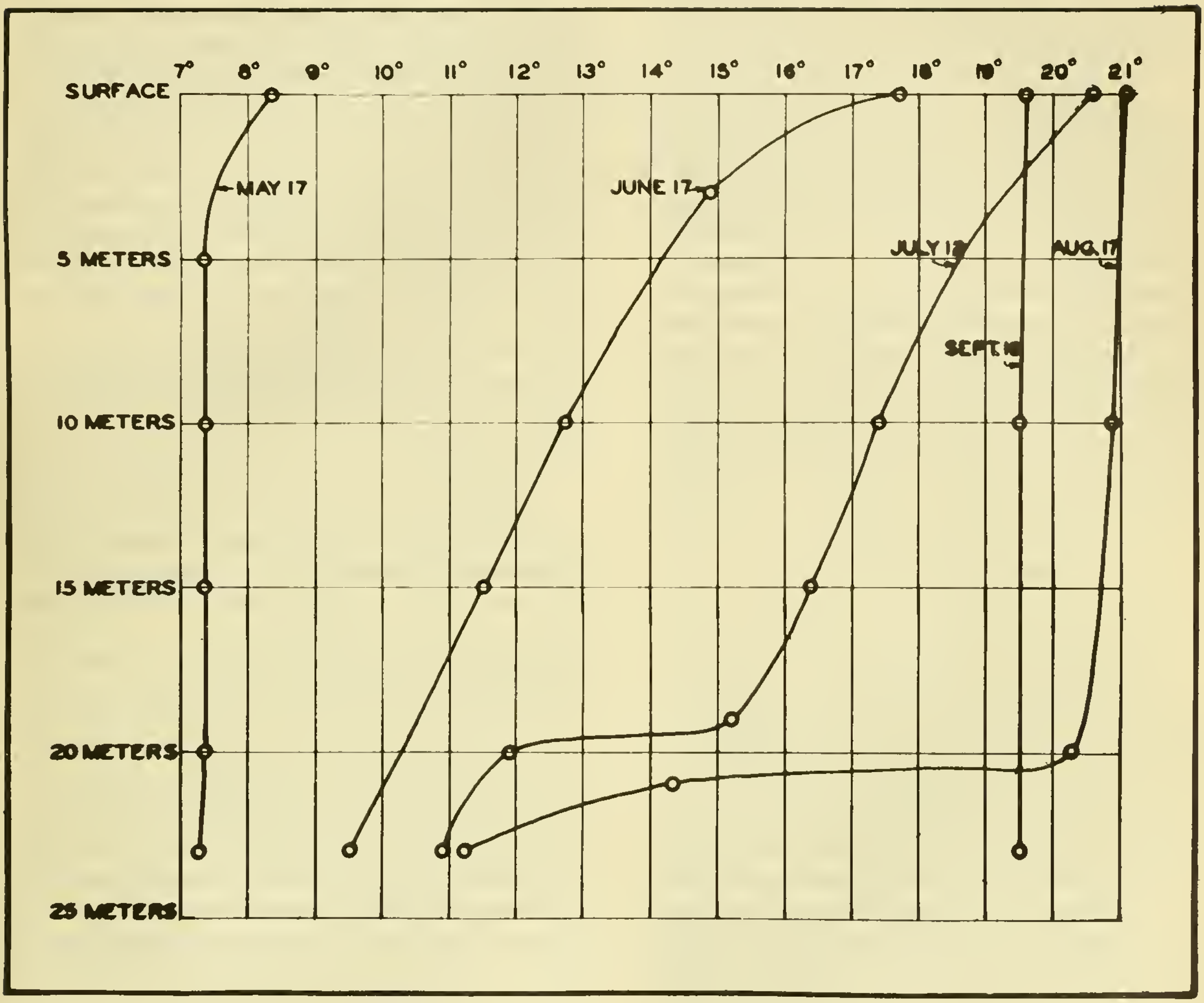

Figure 15. --Temperature graphs of water column at station 40, 1929.

21 meters. Strong winds (maximum velocity, 54 m.p.h.) during the first half of September caused seas of sufficient size to break down the thermocline completely and place the Great Plain in a homothermous condition again, as shown by temperatures at this station September 16, when the water from top to bottom was about 19.5°.

The life of the thermocline in the Great Plains was certainly less than 3 months and probably not over 2 months. It is probable that the thermocline does not form in this area in years of frequent and severe summer storms. When this occurs, it is not likely that bottom temperatures under 17° C. will be encountered during the summer. In such years, cold water in summer would be limited to about 10 percent of the area of the lake, whereas in favorable years it may remain in 50 percent of the bottom area. It may be stated, then, that the frequency and intensity of summer storms control the extent of cold bottom water which, in turn, may limit the habitat of cold-water communities of the lake.

WATER MOVEMENTS

Currents

During the period of the survey, the average effluent of the lake was, in round numbers, 240,000 cubic feet per second, computed as in Bulletin 37, U. S. Lake Survey. This amount was above normal, due to the prevailing high lake level. If the flow, in passing down the lake, were confined to the upper 4 meters, it would have an average velocity of 0.097 m.p.h. at the restricted cross section between Erie and Long Point. However, the depth affected is probably greater than 4 meters, and although the velocity at the surface in the middle of the "stream" would be greater than the average velocity of the section, it is not likely that this natural eastward flow ever greatly exceeds 0.1 m.p.h., except near the inlets and outlets.

Along the Atlantic Coast local winds set up surface currents having velocities of about 1 1/2 percent of the wind velocity.[1/] Lake Erie is a large body of water and should have somewhat similar wind effects. If so, a 67-mile wind would set up a current of 1.0 m.p.h. The average summer wind velocity, as obtained from continuous readings, is about 11 m.p.h. which would theoretically set up a current of 0.16 m.p.h. As the prevailing wind direction is southwest, the resulting current would be approximately east by north (deflectional effect of earth's rotation on currents is to the right in the northern hemisphere). This is also the direction of the general flow of the lake. Consequently, there is a prevailing easterly movement of the surface waters, the velocity of which may reach 1.0 m.p.h. during severe protracted storms. Not all of the average wind is from the southwest, however, and therefore only a portion of the average velocity of the 0.16 m.p.h. is in an easterly direction. Furthermore, the water of the lake, being confined, does not have a uniform velocity in any given wind. A wind blowing along the longitudinal axes of the lake would of course cause stronger currents in the restricted Erie--Long Point section than in the more open portions of the lake.

Temperatures in the Great Plain indicate that the natural eastward movement is mainly confined to the middle one-third of the plain. Temperatures were fractionally higher in this longitudinal belt than in the adjacent waters on either side, and it is believed that the origin of the slightly warmer "stream" is the warm, shoaler waters of the western section.

The general eastward movement of the surface waters is not, of course, continuous and is even reversed during easterly blows, so the net prevailing velocity is probably not more than 0.1 m.p.h. It would, at this rate, require 3 months for the water particles to pass from the Detroit River to the Niagara River. This velocity is not easily measured under ordinary field conditions. As only part of the easterly flow passes down the Niagara, there is a prevailing westerly return movement of the waters below the frictional depths.

The Shearwater anchored for current observations on 25 occasions during the summer of 1929. Six of these observations were made at station 15 (Deep Hole) and 9 at station 17 (Long Point) where, with the exception of the inter-island channels of the western section, the strongest currents of the lake are encountered.

When the lake level of the eastern portion is altered, either by winds or by barometric-pressure differentials, water is forced to pass around Long Point in the adjustment of the level of Long Point Bay.

1/ Current Tables, Atlantic Coast, U. S. Coast and Geodetic Survey, Washington, 1930.

Station 17 lies about 1/2 mile NNE of the end of Long Point and it was here that the maximum current was measured.

As may be seen from the current data (table 8), the observations were scattered over a period of 4 months and included widely separated stations. Although the data are not sufficient for a detailed study of the currents, they do show that velocities over 0.5 m.p.h. are not frequent. Currents with estimated velocities of from 1 to 3 m.p.h. were witnessed in the narrow entrance channel to Erie Harbor, but they are the result of local topography and such velocities were not found in the open waters of the lake.

On August 7 and 8 the wind was calm to moderate easterly, and on August 9, light and from the southwest. At Buffalo the Weather Bureau records show that the wind velocity did not exceed 14 m.p.h. during these 3 days; yet on the latter date surface currents of 0.60 and 0.38 m.p.h. were observed at stations 17 and 15, respectively. These velocities were the greatest encountered, and their respective directions were 94° and 50° true.

During the night of August 27-28 there was a fresh northeast wind in the Long Point region which gradually subsided by the afternoon of the 28th. At 1:00 p.m. on the 28th the surface current was 0.25 m.p.h. at station 15 and its direction of 70° true was almost directly into the wind. Both this current and those of the preceding paragraph (on August 9) were plainly seen by watching slightly submerged drift particles while the boat was at anchor and the correctness of their directions is assured.

The above examples of relations between observed currents and weather are especially mentioned to show that the current velocity is not always in direct proportion to the wind velocity at a given time and that the current direction may, in fact, be against a strong local wind of several hours' duration. The Weather Bureau records at Buffalo and Cleveland (about 50 and 100 miles, respectively, distant from the Deep Hole region) show that the strong northeast wind of the Long Point region on August 28 was more or less local and was not of sufficient duration to reverse the direction of the current set up by the general southwest winds of August 26. It is impossible, therefore, to predict local currents in Lake Erie from wind conditions alone.

Fishermen state that the strongest currents are often encountered during the following periods of calm weather, and that they generally occur during summer, when the average wind velocity is at a minimum. Whether their views are actually true, or whether summer merely offers more opportunities for witnessing currents, is problematical. It is during these months, however, that the lake is subjected to large and rapid thermal changes that cause movements of the water mass. Summer is also the season of thunderstorms, which are usually accompanied by differences in barometric pressures and are therefore another source of water movements.

Fishermen reported current velocities of sufficient strength to interfere with the setting of nets in the vicinity of the Port Maitland entrance buoy on August 7. It so happened that the Shearwater occupied station 24 (entrance buoy) at the time of the reported currents, and as a slight easterly set was discernible at the buoy, the boat was anchored for observations. The surface current was found to be 0.30 m.p.h., 75° true, and there was no measurable bottom current. The weather was calm and the sea smooth on this date, but strong southwest winds had prevailed on the 4 preceding days. Currents may have been stronger elsewhere in the vicinity, for they were reported as having seriously interfered with the handling of nets.

The Dunkirk, Port Dover, and Port Stanley fishermen agree in their affirmation of the occurrence of strong currents in the lake. Their occupation should particularly qualify them as authorities in this regard, but they have no instruments with which to measure the velocities and their estimates vary greatly. An officer of the Erie-Port Dover passenger ferry stated that they do not encounter strong currents on their regular run around Long Point. It appears that a current which is "strong" to the fishermen may not be so considered by the navigator.

Averages computed from table 8 show that the surface current at station 15 (6 observations) had a mean velocity of 0.19 m.p.h. and at station 17 (9 observations) 0.26 m.p.h. The prevailing direction of the current was east and the wind was southwest at both stations.

Current observations in 1928 were confined to station 15 (Deep Hole) where a maximum surface current of 0.63 m.p.h., 99° true, was observed on

Table 8. --Current observations, Shearwater, 1929

Station	Date	Current velocity (miles per hour)		Current direction (degrees, true)		Wind and force	Sea	Observations with pole (P) meter (M)
		Surface	Bottom	Surface	Bottom			
14	July 8	0.00	0.00	...	...	SW-2	Rippled	P
15	May 25	.00	...	...	...	Calm	Smooth	P
15	June 26	.05	...	180	...	W-2	Rippled	P
15	July 8	.37	...	105	...	SW-2	do	P
15	July 25	.07	...	80	...	W-4	Choppy	P
15	Aug. 9	.38	.30	50	275	SW-2	Rippled	M
15	Aug. 28	.25	.00	70	...	NE-3	Choppy	M
17	May 25	.53	.17	83	157	Calm	Smooth	M
17	June 26	.08	...	300	...	SW-2	Rippled	P
17	July 8	.13	...	305	...	W-1	do	P
17	July 24	.00	...	...	...	Calm	Smooth	P
17	Aug. 9	.60	.15	94	145	SW-2	Rippled	MP
17	Aug. 26	.38	.00	70	...	SW-3	Choppy	M
17	Aug. 27	.00	...	...	...	N-3	Rough	P
17	Aug. 28	.30	.15	178	178	NE-3	Choppy	M
17	Sept. 6	.31	.22	95	350	SW-2	do	M
24	Aug. 7	.30	.00	75	...	Calm	Smooth	M
37	Aug. 16	.00	.00	...	...	Calm	do	M
40	May 17	.00	.00	...	...	SW-2	Choppy	M
40	July 12	.14	...	310	...	NE-1	Smooth	P
46-A	May 15	.00	.00	...	...	S-2	do	M
48	June 19	.06	...	65	...	W-1	Rippled	P
49	June 19	.06	...	125	...	W-1	do	P
50	June 22	.24	.10	205	305	Calm	Swell	MP
56	Aug. 26	.27	.00	45	...	SW-3	Choppy	M

July 30. As this measurement was made with a current meter, the value is probably excessive. General westerly winds had prevailed during the 3 preceding days.

Since the subsurface current observations shown in table 8 were made with a current meter suspended from a boat, the tabulated values are too high (see under "Methods"). One can only state, then, that subsurface currents were witnessed at stations 15 and 17, and that the velocities were less, probably by as much as 50 percent, than the tabulated values. That the bottom waters are not physically stagnant is also apparent from the fact that the coldest bottom temperatures were sometimes found to the eastward and sometimes to the westward of station 15, the deepest part of the lake.

From the observed data and information collected verbally during the survey, it may be concluded that current velocities exceeding 1 m. p. h. are extremely rare in Lake Erie.

Subsurface Movements of the Deep Hole Waters

The movement of the bottom water of the Deep Hole was first witnessed during the 1928 survey when the eastern limit of 5° C. water advanced 20 miles from July 27 to August 15 and then returned, 2 weeks later, to the west. This eastward movement was greater than was observed during the 1929 survey and is all the more remarkable because of the comparatively small area of cold water remaining in August.

Table 9 gives the area included within the 6° C. isotherm on each of the 1929 cruises when the limits were located, and also shows the relative position of the cold-water mass. The 6° isotherm was arbitrarily chosen as the most suitable temperature to show these movements graphically. The 7° and 8° isotherms would have the same general shape and would include but slightly greater areas during the summer months. Isotherms of less than 6° do not include a sufficient area, especially in the 1929 season, when the bottom temperatures were slightly higher than in 1928. Additional 1929 stations were therefore selected to permit a more accurate development of the 6° curve.

There is an area of 300 square miles in which the bottom temperature on all of the 1929 cruises

Table 9. --Area and position of 6° C. bottom water in 1929

Cruise number	Date	Area (sq. miles)	Position
1	May 18-27	1, 290	Normal
2	June 8-15	900	Normal
3	June 25-27	790	Westward
4	July 5-10	570	Westward
5	July 22-27	500	Eastward
6	Aug. 8-13	430	Slightly westward
8	Sept. 5-12	410	Slightly eastward

remained below 6°, regardless of whether the cold-water mass extended to the eastward or to the westward. The boundary of this area of "perpetual" cold water is approximately the 40-meter depth curve, and its center is shown by the (+) in figure 16. When the 6° water is more or less evenly distributed (horizontally) about this center, its position is herein called "normal, " and when the distribution is eccentric, the position is termed eastward or westward. Due to summer warming, the area of 6° bottom water in September was only one-third as great as in the latter part of May (table 9). Therefore the movement of the cold water as shown by the eastward and westward limits on the various cruises is subject to correction according to this seasonal shrinkage. Cruises 4 and 5, 1929, were only 2 weeks apart and, as the area did not change greatly during that interval, the 6° isotherms of these cruises were chosen as best depicting the actual movement and are shown in figure 16, laid down over the depth curves. The curve of cruise 2 is also shown as an example of the normal position of the cold-water mass, although the area on cruise 2 was 80 percent greater than that on cruise 5. When the cold water was eastward (cruise 5) the southwest portion of the isotherm lay approximately on the 40-meter curve but on cruise 4, when the cold water was westward, the northeast portion lay along the 40-meter curve. Similarly, the aforementioned area of "perpetual" cold water was not crossed by the 6° isotherms on any of the cruises.

The isotherms of figure 16 show a horizontal movement of 16 miles in 2 weeks on the west side and 5 miles on the east side. This was the maximum movement measured in 1929. The 1928 survey did not include the western limits of the cold water, but the eastward limit on August 15, 1928, is shown in

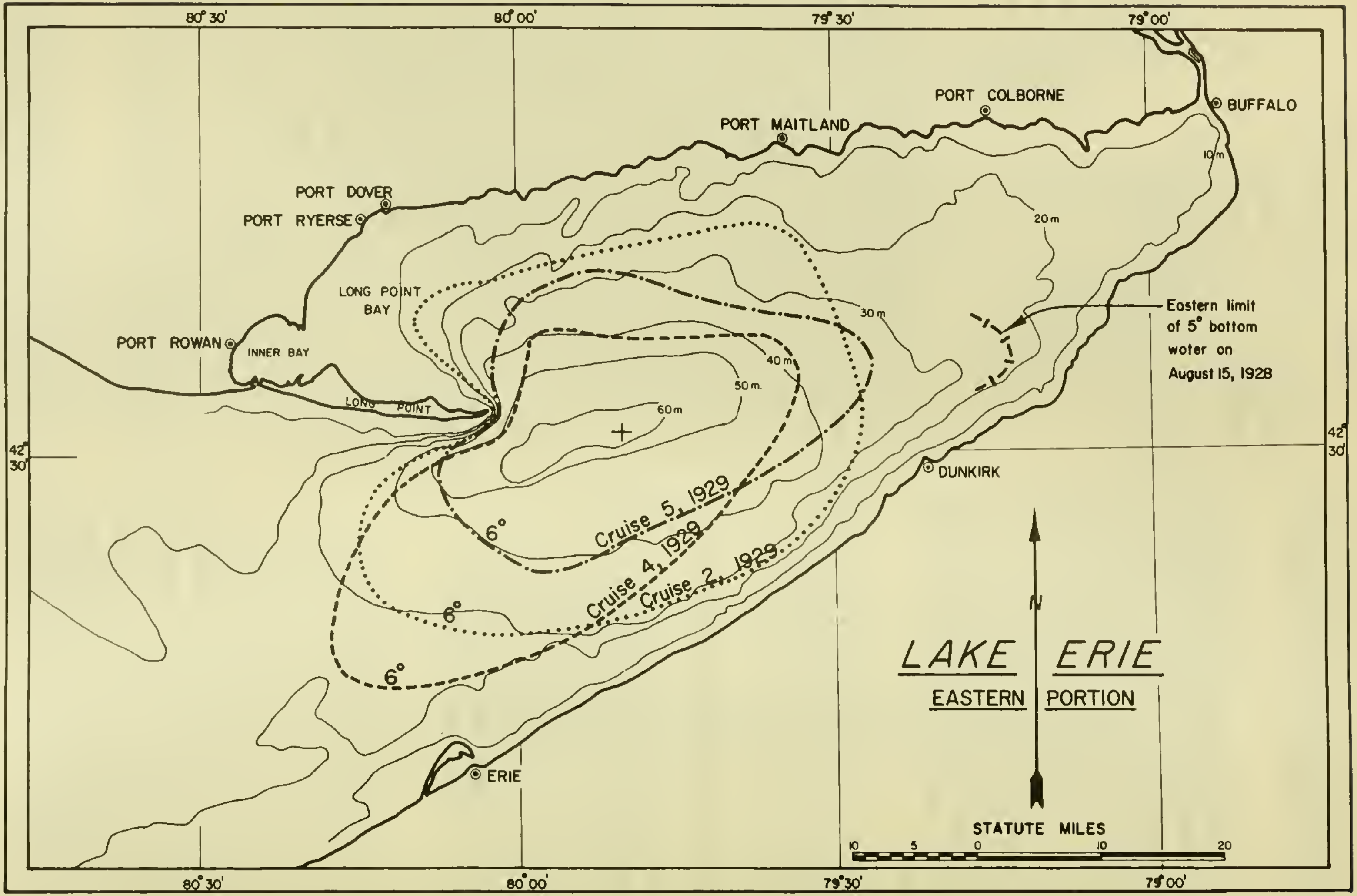

Figure 16. --6° bottom isotherms, cruises 2, 4, and 5, 1929

the figure. The curves for the other cruises are omitted to avoid confusion.

It seems apparent that these water movements were caused or at least influenced by the wind effect on the lake level. Figures 17 and 18 have been prepared in an effort to establish this relation. The relative positions of the cold water on the various dates of observation are shown with the graph of the lake level at Buffalo. The daily means were used in plotting the lake-level curve, and the comparatively large and sudden fluctuations caused by high winds of short duration are apparent only insofar as they affected the means.

Figure 17 shows the cold water to be in its normal position on August 1, 1928, and the lake level to be uniform until the 10th, when easterly winds caused a drop of 0.7 ft. in the 2 following days (minimum on August 12). Three days later, although the lake level had risen 0.6 ft., the cold water was eastward (see limit in fig. 16). Apparently the great eastward movement was the result of the lowering lake level at Buffalo, but we do not know when the movement started or when the maximum eastward limit was reached. We do know, however, that the cold water returned to the Deep Hole during the latter part of the month, even though the mean level at Buffalo had fallen slightly since the observations of the 15th.

Figure 18 shows that the cold water was to the westward (see fig. 16, cruise 4) on July 6-10, 1929, after the lake level had been raised by the strong southwest winds of the preceding 8 days. The water was probably in westward movement soon after the 40-m.p.h. southwest wind of June 28 and was held to the westward by the week of strong winds. After July 10, the wind was variable and moderate until the 18th, and during this period the cold water undoubtedly returned to its normal position. On July 19 and 20, the wind at Buffalo was easterly and there was a marked lowering of the level of the eastern end of the lake. Three days after this lowering, the cold water was observed to be eastward (fig. 16, cruise 5). By August 2, the cold water had probably returned to its normal position and was then set in motion to the westward by the strong southwest winds of August 3-4, which raised the lake level at Buffalo materially. On August 6 the wind died down and on the 7th and 8th blew from the east, causing the level at Buffalo to fall rapidly. This lowering of level apparently caused the cold water to reverse its direction, for its position on August 8-12 was once more nearly normal. It is believed that the cold water was moving from the westward to the eastward between August 6 and 14, and that the observations were taken when a nearly normal position was reached.

Unfortunately, the data are not sufficient to plot the daily position of the cold water and we are forced to interpolate between observations. The actual observations, however, seem to justify the following conclusions. During the summer a cold-water mass normally lies in the Deep Hole below the discontinuity layer. Winds of short duration, even though they have a high velocity and cause wide but temporary fluctuations in the lake level at Buffalo, do not alter the position of this cold water materially. But when the lake level at Buffalo is raised over a period of 2 or 3 days, even though the total rise does not exceed 0.5 foot, the cold water is depressed to the westward, and remains westward so long as the surface of the lake has an upward gradient to the eastward. When the outside forces subside and the surface of the lake returns to a horizontal position, the cold water returns to its normal position and remains there until the outside forces again build up a gradient on the lake. An upward gradient to the westward causes a similar but opposite movement of the cold water. Because the movements are slow, a lag exists between the maximum or minimum lake level and the maximum limit of cold-water movement. The much colder and therefore heavier waters below the discontinuity layer are returned to the Deep Hole by gravity and, as this is an actual movement of the water mass, it is probably a source of the surface currents so often witnessed during periods of comparatively calm weather. A uniform period of oscillation is not evident in these movements, although it can not be stated that an oscillatory movement does not exist.

That the bottom water is often in motion is well known to the fishermen. During the summer of 1929, the fish tug George V raised whitefish nets from the bottom in 19 fathoms near station 53 (midlake) and found them to be foul with old paper, leaves, green slime, and other drift material. A small sample of this twine was later examined by John Van Oosten, of the Bureau of Fisheries, and although it had completely dried out, particles of paper (printed matter) and leaves were found in abundance.

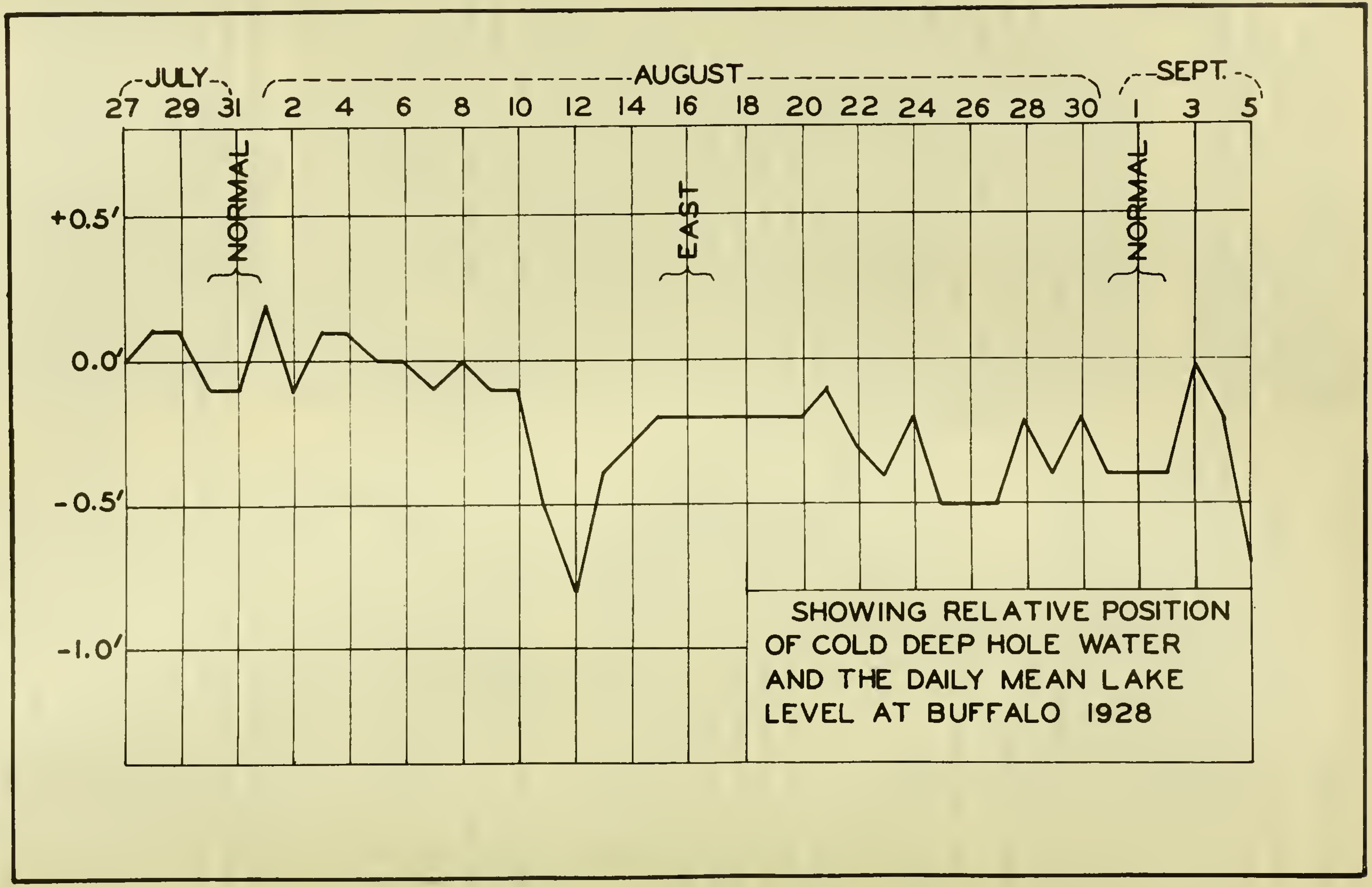

Figure 17. --Buffalo daily mean lake level and relative position of cold water, 1928.

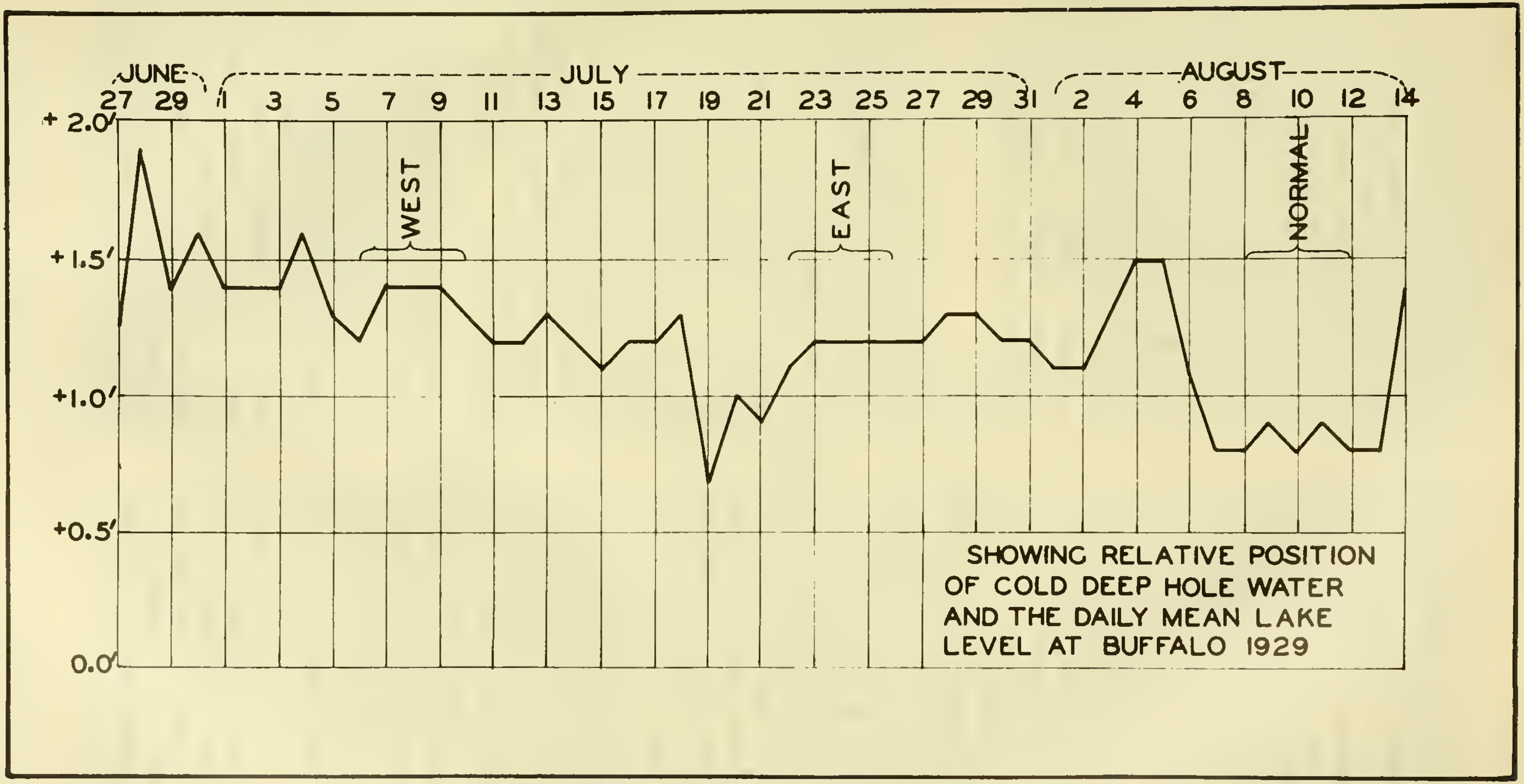

Figure 18. --Buffalo daily mean lake level and relative position of cold water, 1929.

Oscillations

Winds and barometric-pressure gradients disturb the equilibrium of an enclosed body of water and when violent, they exert impulses that set up oscillations, or seiches, within that body. Strong winds on Lake Erie are often, but not always, accompanied by steep east-west barometric gradients. When the storm center is northeast of Buffalo, the isobars are normal to the east-west axis of the lake and form a downward pressure gradient from Toledo at the west end to Buffalo at the east end. Such a condition tends to augment the effects of the westerly wind on the lake level at Buffalo. When the storm center is northwest of Buffalo, however, the isobars are parallel to the east-west axis of the lake, although the general wind direction over the whole lake may be southwest. In this situation, the barometric pressure is not a direct factor in changing the level at Buffalo. As an example, at 8:00 a. m. on November 21, 1928, a low pressure area northwest of Buffalo caused no east-west pressure gradient on the lake. At this instant the wind at Buffalo was southwest 40 m. p. h. This storm caused the lake level to rise 3. 1 feet in 5 hours, at the eastern end of the lake. Comparison of the Weather Bureau records of strong westerly winds and their effects on the lake level at Buffalo, indicated but little difference in the amount of "pile-up" when an east-west pressure gradient does or does not exist. The wind, therefore, seems to be the principal factor in producing the impulses which set up the main east-west oscillation in the lake.

There are several seiche areas in Lake Erie, and each has its own definite boundaries and period. Furthermore, the impulses of one area are transferred to adjacent areas, where they tend to amplify or dampen the oscillations occurring. Thus the system is extremely complicated. This overlapping of the seiches is readily apparent from the continuous graphs at any of the several gauges on the lake. Krecker (1928) has discussed the seiches of the western part of Lake Erie, and has prepared graphs of local oscillations in the vicinity of Put-in-Bay, Ohio.

Henry (1900) has concluded that this primary oscillation is stationary rather than progressive, and has prepared an excellent graph showing the wind effect on the lake level. The period of the oscillation has been discussed by Hayford (1922). As some additional information was obtained this season, a further discussion seems advisable at this time.

Figure 19 shows the lake-level graphs at three stations and the wind at Buffalo for the period May 1-17, 1929. The full line, broken line, and the dash-dot line are the respective level curves at Buffalo, New York, Port Stanley, Ontario, and Put-in-Bay, Ohio. The left-hand scale is the lake level in feet (0 equals 572. 8 feet above mean sea level). The wind at Buffalo is shown by a dotted line, with the scale in miles per hour at the right. Buffalo is at the extreme eastern end of the lake; Put-in-Bay is on South Bass Island, 30 miles from the western limit of the lake; and Port Stanley is less than 10 miles east of the line midway between the east and west limits of the lake. The curve for Buffalo is from the U. S. Engineers' gauge; that for Port Stanley is from hourly heights from the Department of Marine and Fisheries, Canada; and the one for Put-in-Bay is from hourly and half-hourly staff readings. The wind curve is from the hourly readings of the U. S. Weather Bureau.

It may be seen that the lake-level curves are close together until 2 a. m. May 16, when the level at Buffalo commenced to rise rapidly while the Put-in-Bay level fell correspondingly under the influence of westerly winds of high velocity. The maximum level at Buffalo and the minimum at Put-in-Bay were reached between 11 a. m. and 12 noon on the 16th, and during the following 6 hours the level fell 4. 9 feet at Buffalo and rose 3. 5 feet at Put-in-Bay. From 10 a. m. May 16 until 6 a. m. May 17, there were no observations of the level at Put-in-Bay; but it is readily seen that the maxima at Buffalo occur approximately at the times of the minima at Put-in-Bay, and vice versa. The figure shows excellently the original impulse set up by a westerly wind of high velocity and the resulting east-west oscillation which continues even though the wind subsides.

The oscillations at Buffalo (full line) and Port Stanley (broken line) from May 7 to 11 are shown in figure 20. The lake level at Buffalo rose about 1 foot under the influence of a west wind which reached a maximum of 40 m. p. h. on May 7, 1929. From this date to May 11, the wind was light and variable and therefore did not greatly distort the period or amplitude of the east-west oscillation occasioned by the impulse of May 7. The study of 180 of these more or less undisturbed oscillations at Buffalo showed the mean period for one complete oscillation to be 14. 1 hours. Henry (1900) referred to this oscillation as having a period of from 12 to 16 hours, and Hayford

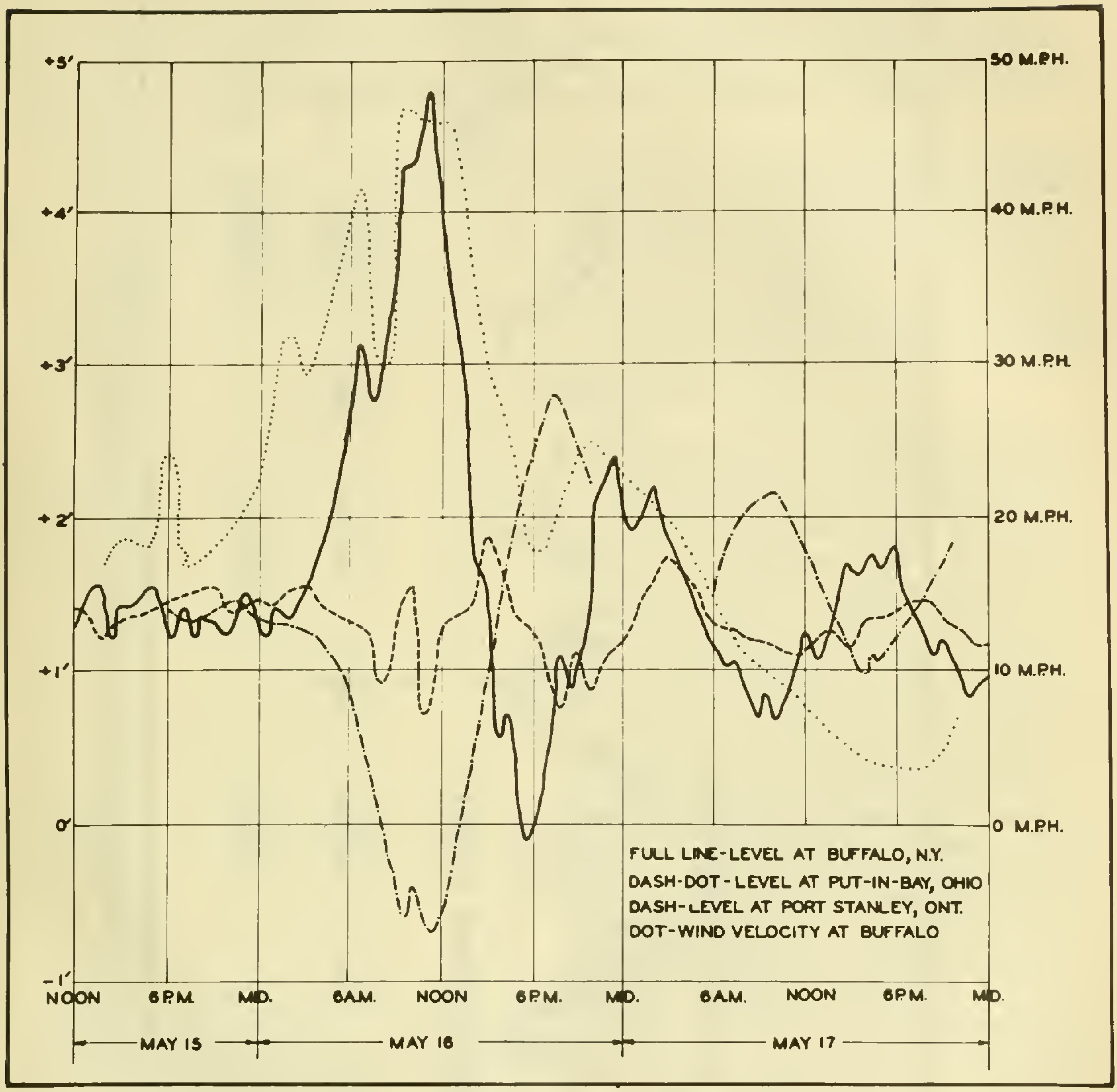

Figure 19. --Lake-level graphs at Buffalo, New York, Port Stanley, Ontario, and Put-in-Bay, Ohio.

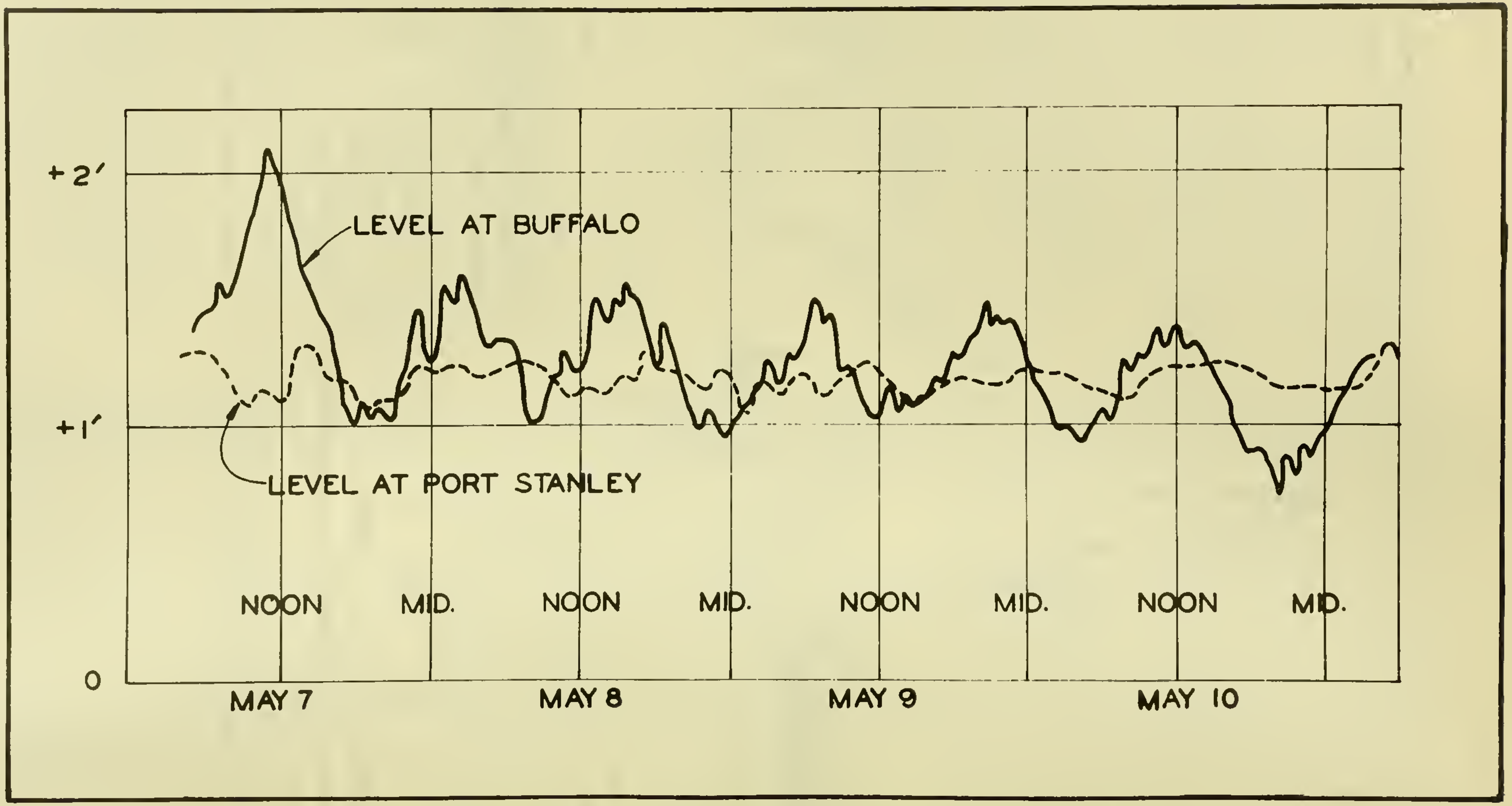

Figure 20. --Lake-level graphs at Buffalo, New York, and Port Stanley, Ontario.

(1922) gave a value of 13. 1 hours. Since Hayford's value was derived from 28 cases and included overlapping periods under new wind influences, it is believed that 14. 1 hours is nearer the true period for the lake. Table 10 gives the number of complete oscillations and the corresponding period for that number of observations. The mean period of 14. 1 hours was derived from this table.

Table 10. --Observed periods of the primary east-west oscillation on Lake Erie

Period (hours)	Number of oscillations observed
12. 8	5
13. 0	5
13. 1	10
13. 2	4
13. 3	13
13. 4	4
13. 6	6
13. 7	3
13. 8	7
13. 9	18
14. 0	17
14. 1	9
14. 2	5
14. 3	2
14. 4	7
14. 5	12
14. 6	15
14. 8	13
14. 9	6
15. 0	10
15. 4	5
15. 5	4

When a prolonged westerly wind blows acceleratedly, the lake level at Buffalo tends to rise until the maximum wind velocity is reached. In this situation the time interval of the initial rise at Buffalo may greatly exceed 7 hours (half the period of oscillation); but after the wind reaches a maximum velocity and begins to subside, a half period of approximately 7 hours soon obtains and continues until distorted by a new wind impulse.

Examination of the Port Stanley graphs (figs. 19 and 20), reveals that two main oscillations are taking place. One is the north and south, and the other the 14-hour, east-west oscillation. The computed period of the north-south oscillation is about 2. 5 hours, and the mean of 90 observed periods from the Port Stanley gauge (May and August 1929) is 2. 7 hours. Hayford gives a period of 2. 6 hours for the north-south oscillation at Cleveland.

The east-west 14-hour oscillation is clearly evidenced on the Port Stanley graphs and has an amplitude of approximately one-third that of the Buffalo curve. The most peculiar feature of the curves at Port Stanley is the apparent lag of 3 hours in this oscillation from the Buffalo graph. The lag is not only apparent in the two figures submitted, but is found to be constantly present in comparisons of the available graphs for the two places.

If the oscillation is "stationary, " as the graphs of Buffalo and Put-in-Bay most assuredly indicate, one might expect the maxima and minima at Port Stanley to occur simultaneously with the maxima and minima at either Buffalo or Put-in-Bay, depending on whether the nodal line of this oscillation is east or west of Port Stanley. Additional graphs of the lake level at stations some 30 miles on either side of Port Stanley would undoubtedly enable us to fix the position of the nodal line and to arrive at the source of the 3-hour lag. In the absence of such observations, three possible reasons for the lag are suggested. First, the 14-hour period at Port Stanley may be from a different seiche area which happens to have the same period as the primary east-west oscillation. An examination of the chart, however, fails to disclose the presence of any such area. Furthermore, the lag is always approximately 3 hours, regardless of whether the time interval between maxima happens to be greater or less than the mean period of 14. 1 hours. We may assume, then, that the Port Stanley oscillation is definitely associated if not identical with the main east-west oscillation. Second, since the volume of water is alternately increased and decreased on each side of the nodal line, there is an actual periodic east and west movement of water back and forth across the nodal line. During the half period when the level is rising at Buffalo, the water is in eastward movement across the nodal line. Now if inertia causes a lag in this water movement, or, in other words, if it continues eastward for some time after the maximum elevation is reached at Buffalo, then the average level of the waters east of the nodal

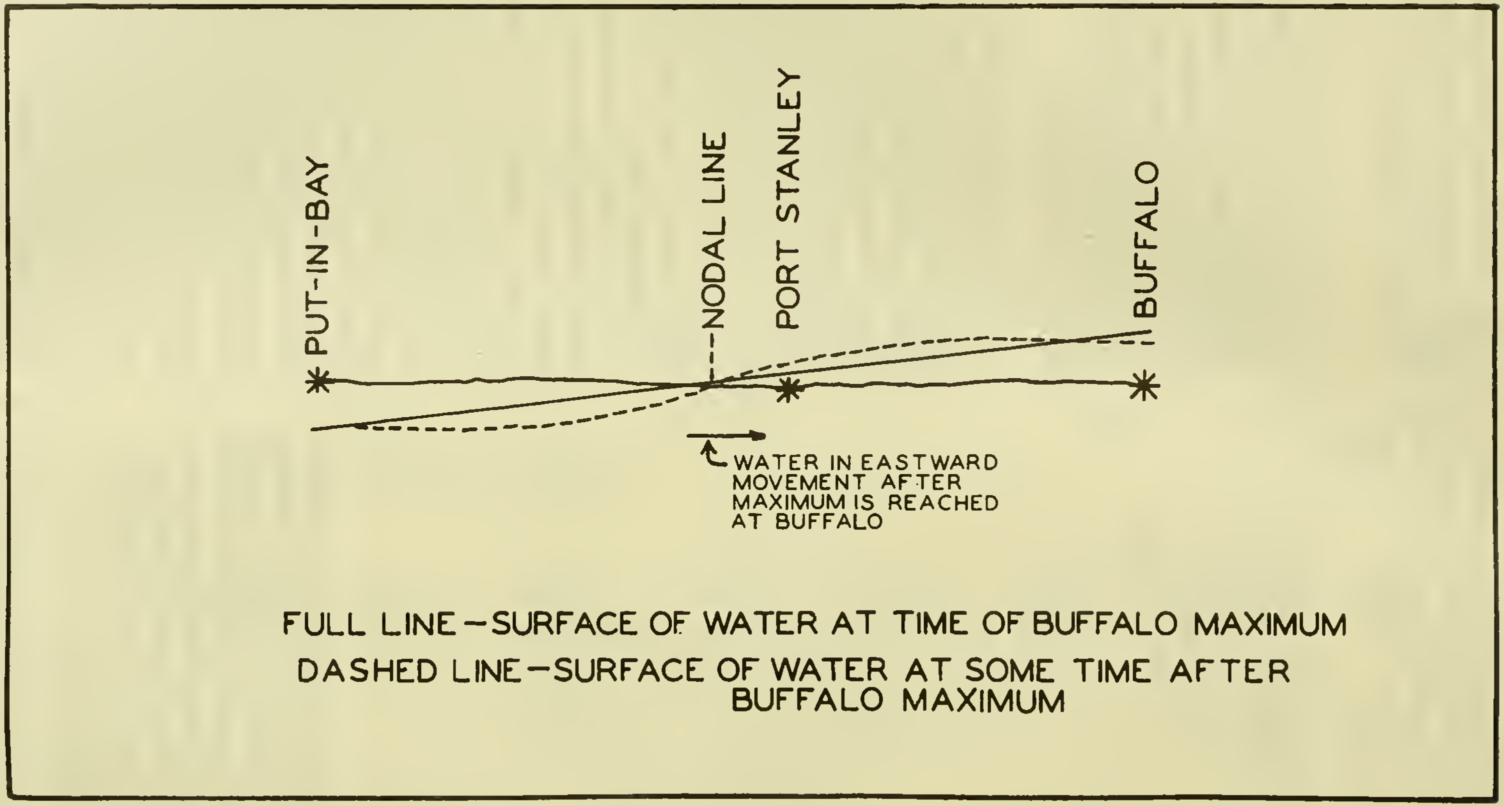

Figure 21. --Possible form of surface slope in 14-hour oscillation, Lake Erie.

line must continue to rise for some time even though the level at Buffalo is falling. Thus the level at Port Stanley would reach a maximum some time after the Buffalo maximum (always assuming the nodal line to be west of Port Stanley), and this would also account for the larger observed amplitude than might be expected near the nodal line. Figure 21 illustrates the foregoing suggestion. Third, the 14-hour oscillation may give rise to a progressive wave originating from either Long Point or the point at Rondeau Harbor which upon reaching Port Stanley would cause the delayed maxima and minima.

It is frankly admitted that the true cause of the lag is not known, and that the problem will no doubt remain unsolved until additional field observations are made.

The presence of two primary seiches, or oscillations, is well established. The best available values for their periods are 14.1 hours for the lengthwise (east-west), and 2.7 hours for the crosswise (north-south) oscillations. These values are believed to be correct within 0.2 hour.

TRANSPARENCY

The Secchi-disc readings for all of the stations are listed with the station data (table 6). The maximum reading of 12.3 meters was obtained at station 54 on September 6, 1929, after several days of comparatively calm weather; and the minimum readings of 0.6 meter occurred at station 26 on May 20, 1929. On both occasions the sea was choppy and the sky cloudy. The maximum and minimum values during the 1928 survey were 10.5 and 2.0 meters.

The monthly means of the readings over the whole lake in 1929 were: June, 2.5 meters; July, 3.3; August, 4.1; September, 6.1; and the mean of the 19 stations occupied in May was 1.0 meter. Thus the mean transparency increased as the season advanced.

The decrease in transparency following a period of stormy weather is well illustrated in the September observations. During this month we find a mean of 8.5 meters for the stations east of Erie, Pa., and a mean of only 3.0 meters for the remainder of the lake. The observations over the eastern part were taken during the following moderate to calm weather, and those of the western part following a week of very stormy weather.

The marginal zones of the lake are usually very muddy during and immediately following onshore storms, and the line of demarkation between the muddy water and the deeper, clear water is often very sharp. This line of demarkation runs parallel with, and 1-4 miles from, the shore line, depending on the depth of water. As only a few of the stations are near the shore, observations were seldom made in muddy water. Aside from the seasonal increase, it is evident that both the quantity of plankton and the amount of bottom silt held in suspension during the following storms are the primary factors controlling the transparency.

The most favorable situation for high readings at a given station was a clear day with the sun 2 or 3 hours from the meridian and when the observation was taken on the lee and shady side of the boat. The light rays reflected from the surface did not then interfere with vision. At a favorable position, the transparency was as much as 10 percent greater than at an unfavorable position.

DISTRIBUTION OF SOME CHEMICAL VALUES IN LAKE ERIE

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CONTENTS

INTRODUCTION

In the course of the general biological survey of Lake Erie, an inquiry into certain chemical conditions of the waters was made for the purpose of determining the natural lake conditions and the extent to which these may have been affected by domestic sewage and industrial wastes from the various cities and harbors along the shores. During the summer of 1928 analyses were made upon samples of water taken from some 20 different stations occupied monthly by the U. S. Fisheries Steamer Shearwater in that part of the lake east from a line connecting Long Point and the Pennsylvania-New York state line. In the second season, i.e. 1929, operations were extended to cover practically the entire lake and analyses were carried out monthly on samples collected from about 60 stations in the open lake and from many harbor waters.

In 1928 the samples were collected and the field analyses were made by the writer. The major part of the laboratory work was, however, performed by Roger Williams, Buffalo City Chemist, and his assistant, Albert Reiser. In 1929 the collection and analysis of the samples was executed by Casimir J. Munter, Assistant in the Department of Chemistry, Ohio State University.

During the survey the following determinations were made: albuminoid ammonia, free ammonia, nitrate nitrogen, dissolved oxygen, phenolphthalein alkalinity, methyl-orange alkalinity, hydrogen-ion concentration, chloride, and turbidity.

METHODS

For the nitrogen analyses, a 1-liter sample of water was collected from the intermediate depth of each station in July, and from both the surface and bottom in August and September, 1928. Samples were obtained by lowering a 1-liter glass stoppered bottle in a special frame to the desired depth. The bottle was then filled by working a double tripping device which opened and closed the sample in situ. The samples were kept in these bottles on ice until analyses could be made in the laboratory.

Water samples for all other analyses in 1928 were taken with a Greene-Bigelow water bottle. In 1929 the surface samples were obtained with the Kemmerer sampler and the subsurface samples were collected with the Greene-Bigelow bottle. The methods of analysis were employed as recommended by the American Public Health Association's Standard Methods of Water Analysis (1925).

PRESENTATION OF THE DATA

The vertical, horizontal, and seasonal distribution of the chemical values obtained in the two years will be presented in this paper with attention focused primarily upon what are considered "normal conditions" of the open lake. Data obtained in rivers and harbors are treated in the light of their contrast with the open lake conditions in the paper by C. J. Munter entitled Chemical Observations on Pollution.

For purposes of the present discussion, the data obtained in both years are utilized. The nitrogen determinations of the first season and the oxygen, carbon dioxide, pH, total alkalinity, chloride, and turbidity figures for the second year are selected for treatment in detail. Results of all the analyses for the second year may be found in the appended tables 13 and 14.

Nitrogen Compounds

Since nitrogen is a constituent in the proteins of both plants and animals, it is one of the most important elements in the aquatic environment. That the utilization of available nitrogen in the growth

Table 11. --Average nitrogen content in eastern Lake Erie, summer of 1928

Date	Mean depth of samples (meters)	Albuminoid ammonia (p. p. m. of N)	Free ammonia (p. p. m. of N)	Nitrate (p. p. m. of N)
July 29-Aug. 1	10	0.070	0.014	0.150
Aug. 28-Sept. 3	0.5	0.089	0.015	0.107
	20	0.086	0.014	0.140
Sept. 12-14	0.5	0.090	0.030	0.126
	17	0.093	0.013	0.148

processes of lake organisms may appreciably reduce the amount of ammonia and nitrates in solution has been shown by Domogalla, Juday, and Peterson (1925). Examination of the nitrogen content of eastern Lake Erie in the summer of 1928 shows moderate amounts of albuminoid ammonia, free ammonia, and nitrates. The results of the analyses are recorded as parts per million of nitrogen in table 11.

There was a fairly uniform distribution of albuminoid nitrogen with perhaps a slight preponderance in the Buffalo region (fig. 22). The lowest figure recorded is 0.06 p. p. m. at a depth of 20 meters in July and the highest is 0.117 p. p. m. at the surface of station 03 in August. Throughout the summer there was a gradual increase from an average of 0.070 p. p. m. in July to 0.088 in August and 0.092 in September. These data indicate an increase in organic matter with advance of the season.

The free ammonia content was somewhat lower than recorded for other lakes by Domogalla, Juday, and Peterson (1925). The range in Lake Erie was from 0.005 to 0.038 p. p. m. The means of the observations suggest a marked increase at the surface in September. The ammonia content at intermediate depths in July averaged 0.014 p. p. m. In August, at the surface, it averaged 0.015 p. p. m. and in September there was in increase to 0.030 p. p. m. In August there was about the same concentration of ammonia at both the surface and bottom, but in September there was more than twice as much at the surface.

The region along the southern shore from Dunkirk to Buffalo appears richer than the other areas examined (fig. 23). Increases are conspicuous in late summer, especially at the surface. The relatively low concentration of ammonia at the bottom is peculiarly different from what might have been expected in the light of analyses on the Wisconsin lakes.

Nitrates were relatively more abundant than the free ammonia and albuminoid nitrogen. The results of the nitrate analyses (fig. 24) indicate a fairly uniform horizontal distribution. There was some reduction, however, in the surface nitrate, which may be due to its utilization by plankton.

The greatest concentrations occurred at intermediate depths in July when 0.20 p. p. m. was recorded at a number of stations. The minimum quantity of 0.08 p. p. m. was found at the surface of station 15 in August. The average for all stations in July was 0.15 p. p. m., in August 0.123 p. p. m., and in September 0.137 p. p. m.

The free ammonia content was greater at the surface than at the bottom and increased toward autumn. Nitrates were more abundant at the bottom than at the surface and also showed autumnal increase. The albuminoid ammonia was about the same at the surface and bottom, and changed little during the summer.

Dissolved Oxygen

The dissolved oxygen content throughout the summer months was relatively high. Analyses of the surface samples indicate a high percentage saturation at all stations in open lake waters. The mean percentag saturation at the surface in the summer of 1929 was 94.9. The bottom mean for the summer was 83.3 per cent. These figures are higher than those obtained in the eastern area during the preceding summer when th

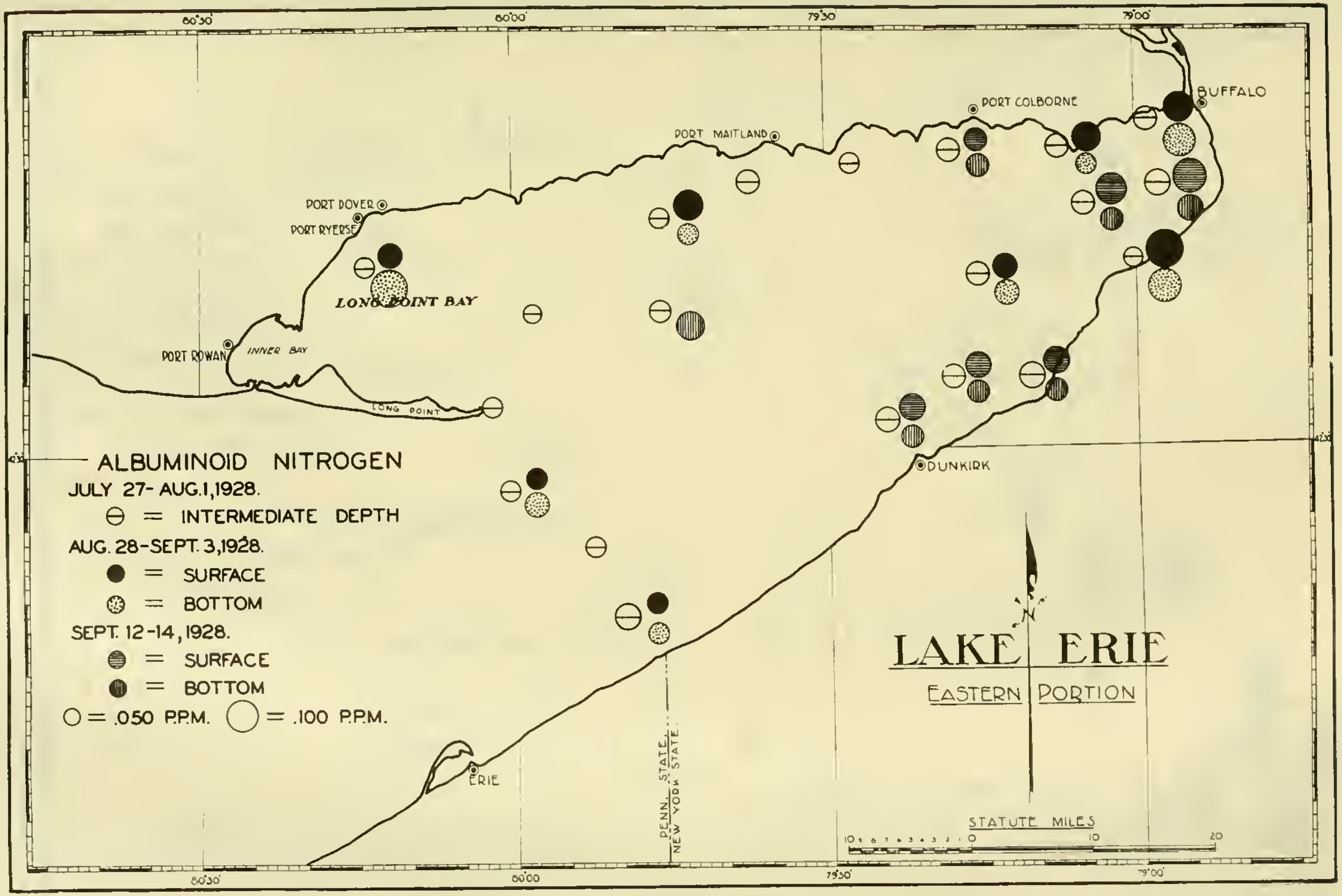

Figure 22. --Albuminoid nitrogen expressed as parts per million.

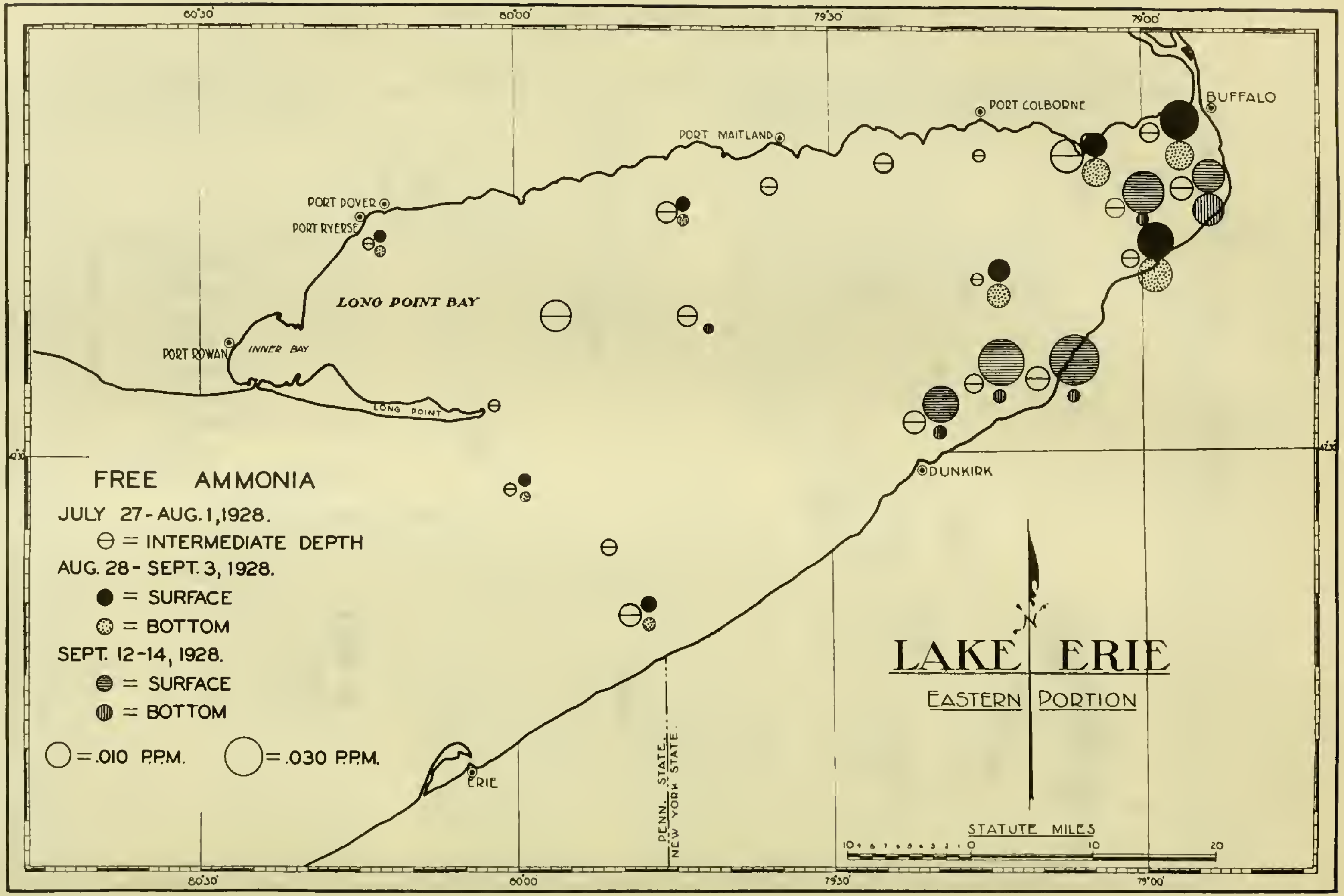

Figure 23. --Free ammonia nitrogen expressed as parts per million.

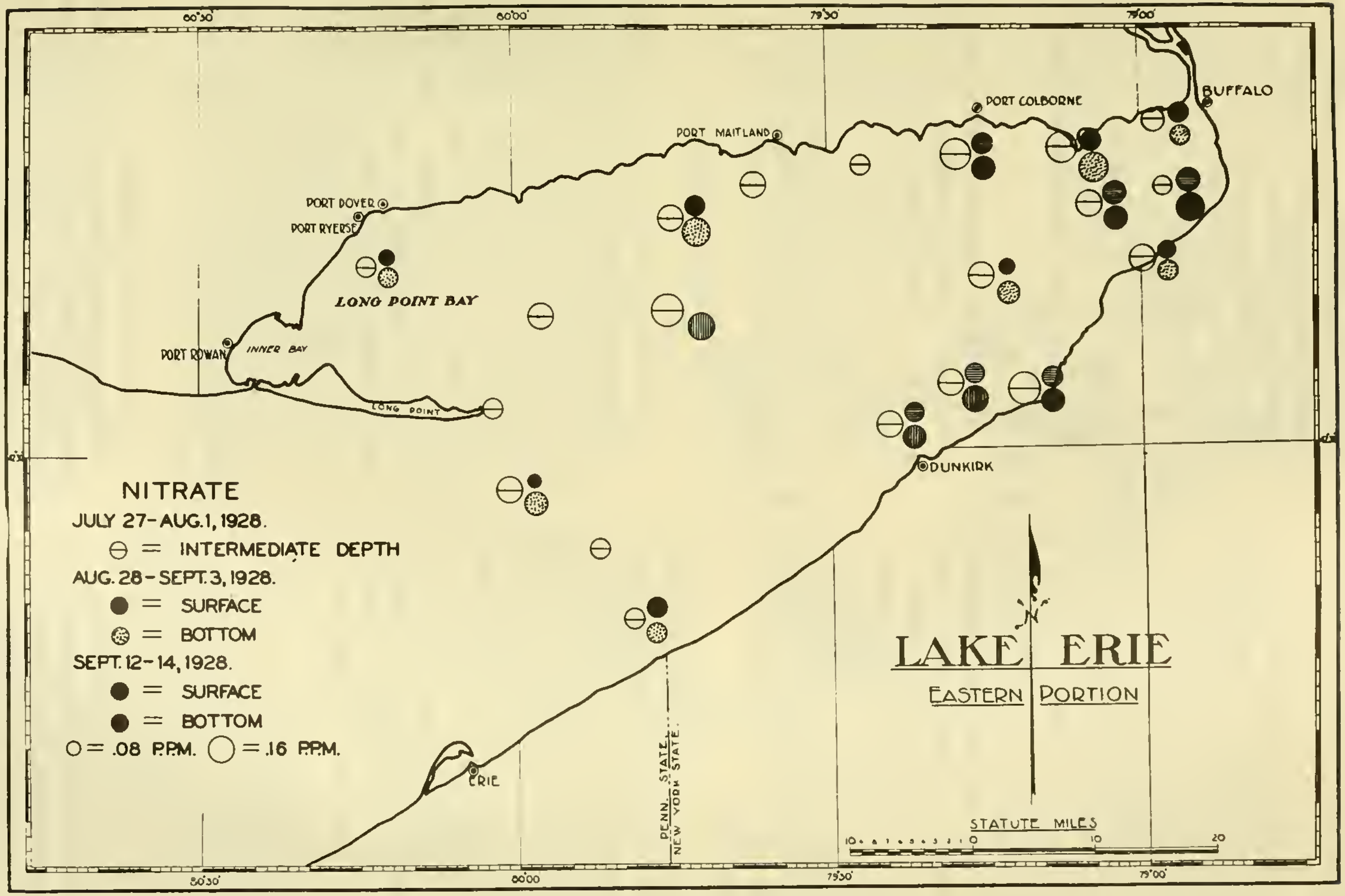

Figure 24. --Nitrate expressed as parts per million of nitrogen.

surface saturation averaged 81.5 percent and the bottom 72.5 percent. In spite of these differences the figures are of such similar order as to point to the same general conclusion that the lake possesses a high degree of oxygen saturation.

The oxygen content from station to station throughout the lake, June-September, may be seen at a glance in figures 31-34. At nearly every station the surface saturation was above that at the bottom. In June there was a low oxygen content occurrence near Buffalo; surface and bottom saturation ran around 60 percent. Rarely did the surface saturation ever drop below 90 percent. The bottom, however, was almost always less saturated than the surface. That the bottom water, shut off from direct contact with the atmosphere and in many cases below the photic zone, did not run even lower in its oxygen content suggests that there may be relatively little organic decomposition in the lake. The lowest oxygen concentration usually occurred in regions of considerable depth, where presumably there was less chance for vertical mixing as well as photosynthetic activity because of lower light intensity and the lower temperatures characteristic of the hypolimnion.

Supersaturation was observed at about one-half meter below the surface. In June there was a supersaturated area in the western part of the lake. Supersaturation occurred during July and September in the surface waters of the Long Point region (figs. 25 and 26). To be sure the figures never ran very high, 105 percent being the maximum for July. Active photosynthesis probably produced the high oxygen content. In this region, too, there are currents which may have affected a certain amount of vertical mixing of the stratum so that with rise in temperature, there may have resulted a certain amount of supersaturation.

The lowest oxygen saturation in the open-lake waters was found at the bottom in August at two western stations, 41 and 42, where the percent saturation dropped to 44 and 52 respectively. At all other times and places reduction in the oxygen of bottom waters in the western area and in the region of the Deep Hole off Long Point usually ran between 60 and 70 percent. The areas of oxygen concentration below 81 percent near the bottom may be seen in figure 29. Further discussion of the variations in oxygen will be made in connection with the treatment of carbon dioxide.

The oxygen saturation of Lake Erie has not shown great extremes. Its supersaturation does not anywhere approach the figures obtained in certain other lakes, such as Lake Mendota where Birge and Juday (1911) found 150 percent saturation a common condition in the epilimnion. On the other hand, its bottom oxygen reduction does not approach that for Lake Mendota where the bottom water may become void of oxygen in July. Lake Erie would seem to approximate more nearly an entirely different type of lake, such as Cayuga in central New York State. The waters of this lake showed in July, 1927, a saturation of 104.1 percent at the surface and 83.4 percent at the bottom where the depth was 63 meters (Burkholder 1931).

The oxygen conservation in Lake Erie appears to be due to the general oligotrophic character of the body of water. Photosynthetic activity apparently never reaches a peak sufficient to highly supersaturate the epilimnion. Its processes of decomposition are only moderate in amount and hence the hypolimnion does not dip to a minimum oxygen content such as is found in lakes richer in organic materials.

Carbon Dioxide

The dissolved carbon dioxide of natural waters is of importance chiefly because of its effect upon the alkaline reserve and the pH of the environment, and because it is a raw material used in photosynthesis. The sources of carbon dioxide are: (1) the atmosphere which contains 3 parts per 10,000; (2) the processes of fermentation and decomposition in the lake; and (3) drainage from the watershed. When the free carbon dioxide is exhausted, the algae have recourse to the half-bound carbon dioxide and in this way draw upon the bicarbonates. This situation is present in the epilimnion of Lake Erie, since in both the summer of 1928 and in 1929 no free carbon dioxide was found in samples taken near the surface. In the bottom waters, however, free carbon dioxide occurred frequently.

In the tables and discussion, the carbon dioxide figures are presented in two forms, the positive and the negative carbon dioxide. The positive carbon dioxide is the actual free dissolved carbon dioxide present, expressed as parts per million. The negative carbon dioxide is an expression of the amount of carbon dioxide which would have to be added to convert

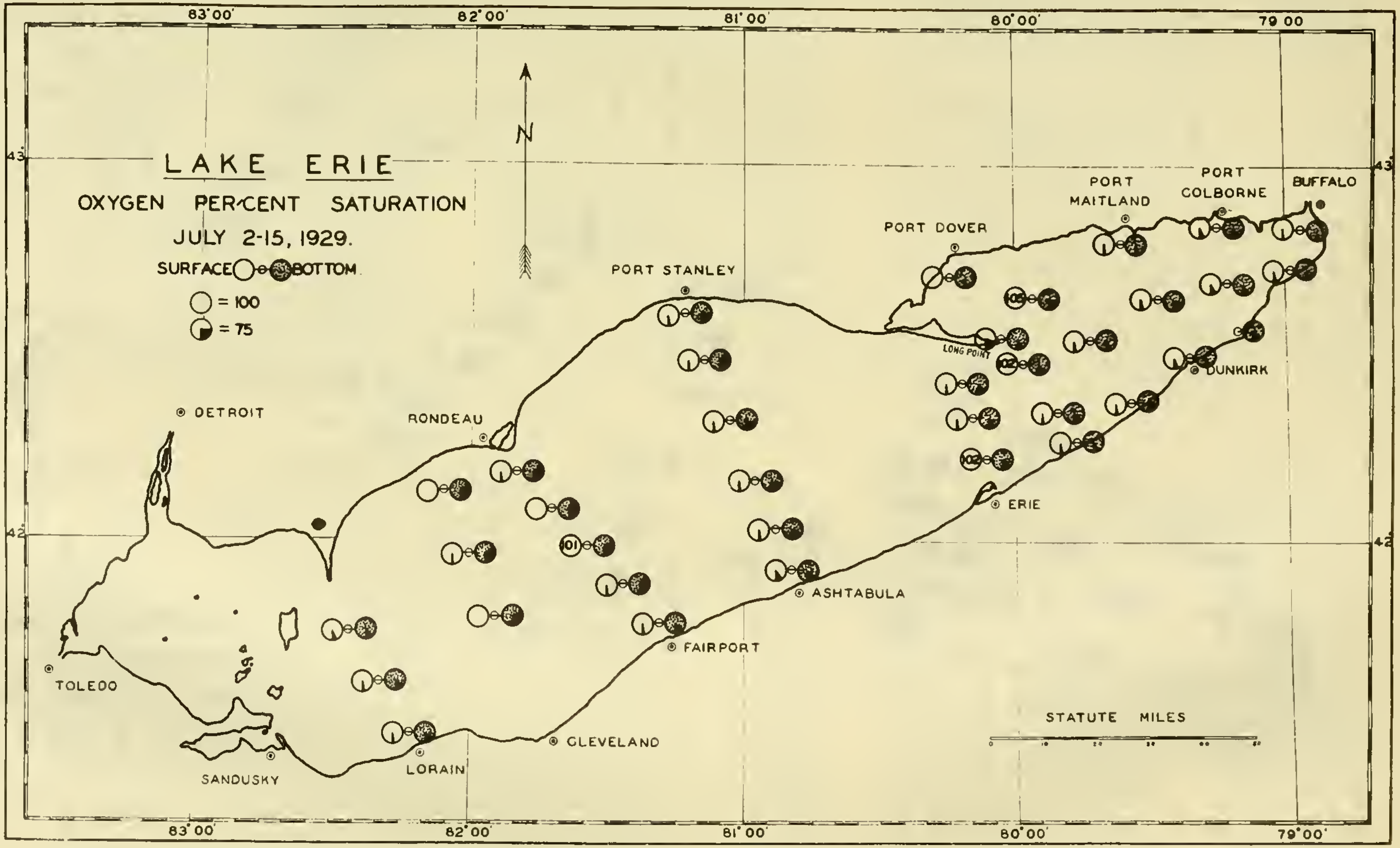

Figure 25. --Oxygen in terms of percent of saturation at the surface and bottom in July, 1929.

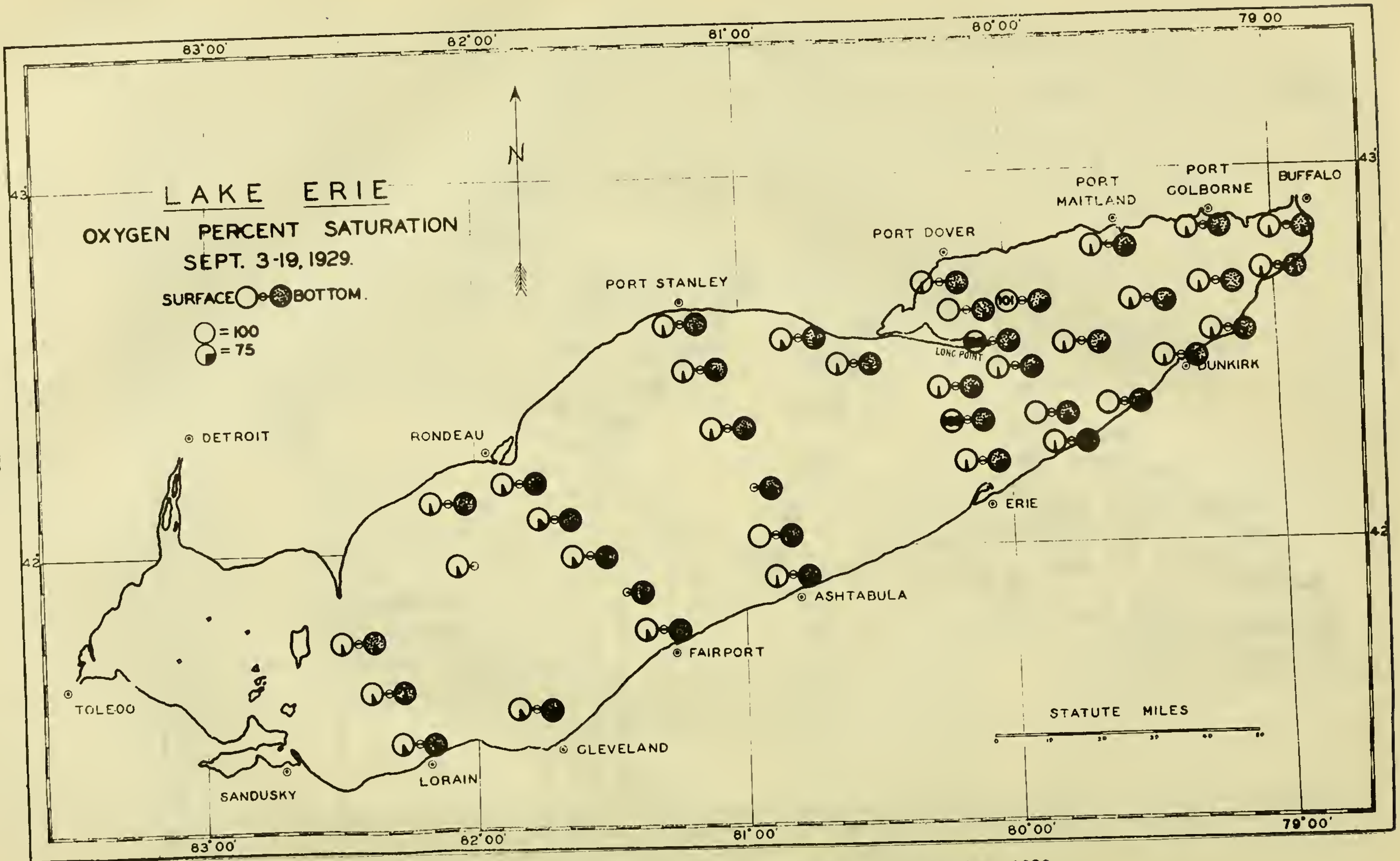

Figure 26.--Oxygen in terms of percent of saturation in September, 1929.

the normal carbonates to bicarbonates and thus make the water neutral to phenophthalein. It is twice the phenolphthalein alkalinity (in terms of calcium carbonate) expressed as parts per million of carbon dioxide.

In the summer of 1928 free carbon dioxide was encountered in the bottom water of those relatively deeper stations where there was a more or less pronounced thermocline. In August, free carbon dioxide was found in bottom water from 10 different stations. In September no free carbon dioxide was found in samples from relatively shallow stations. The 4 stations which showed free carbon dioxide at the bottom in August had lost this and in addition part of their half-bound carbon dioxide in September of the same year. The probable reasons are increased photosynthesis correlated with vertical mixing.

The free carbon dioxide progressively decreased in the bottom water during the summer of 1929. In June there were 27 stations which showed a free carbon dioxide content at the bottom, and only 3 with deficient or negative carbon dioxide. In July there were almost as many stations with negative carbon dioxide as with free carbon dioxide and in August the trend was still more pronounced when the number of stations with negative carbon dioxide exceeded by 4 the stations with positive carbon dioxide. In September, 36 stations yielded negative carbon dioxide and only 10 showed positive carbon dioxide in a total of 47 samples.

The carbon dioxide situation in the lake during July and September 1929 is shown in figures 27 and 28. Free carbon dioxide at the bottom, denoted by the black circles, occurred in the offshore stations throughout the lake in July, but in September positive carbon dioxide was almost without exception confined to the bottom in the vicinity of the Deep Hole off Long Point. The negative carbon dioxide values increased at both the surface and bottom in September; the bottom increase was particularly striking. As shown in table 12, the entire two sets of samples show an average increase of 1.26 p.p.m. of negative carbon dioxide at the bottom in September over that in July.

There was an inverse relationship between the dissolved oxygen and carbon dioxide content (figs. 31-34). Where oxygen was uncommonly high the free carbon dioxide was relatively low. This is true for the general trend of the curves as well as for the abrupt deviations from the average. The surface oxygen saturation curve runs higher than the bottom saturation curve, but the surface carbon dioxide curve runs lower than the bottom carbon dioxide curve.

Striking correlations of conspicuous variations of the carbon dioxide and oxygen curves for the bottom may be pointed out in figures 33 and 34. In August at stations 06.40, 06.41, and 06.42 there is a notable decrease in the bottom oxygen saturation and a correspondingly great increase in the free carbon dioxide content. The observations on these two sets of values for the month of September show a similar inverse ratio of carbon dioxide to oxygen in the Deep Hole area.

When the areas of low oxygen saturation and high carbon dioxide content are plotted, as in figures 29 and 30, some significant general tendencies are made obvious.

In figure 29 is shown the areas where the bottom oxygen saturation was found to be below 81 percent for the 4 summer months. If a lower figure had been plotted, the areas would have been much smaller, and if a higher figure had been chosen, the contours would have included a somewhat greater area. The system is an arbitrary one. In June there were several isolated regions where percentage saturation fell below 81 percent. Oxygen content had decreased in a considerable portion of the western lake area and also in the Deep Hole during July. August shows a similar situation in the west end and some increase in the oxygen content of the deep waters off Long Point. By September values for the entire lake had risen above 81 percent, except in this Deep Hole region where the oxygen saturation remained low.

In June free carbon dioxide was present in the bottom waters of practically the entire lake (fig. 30). A steady decrease was evident with advance of the summer until in September only the bottom water of the Deep Hole region off Long Point contained free carbon dioxide.

From these facts the trend in the lake seems very clear. After the spring overturn there was probably

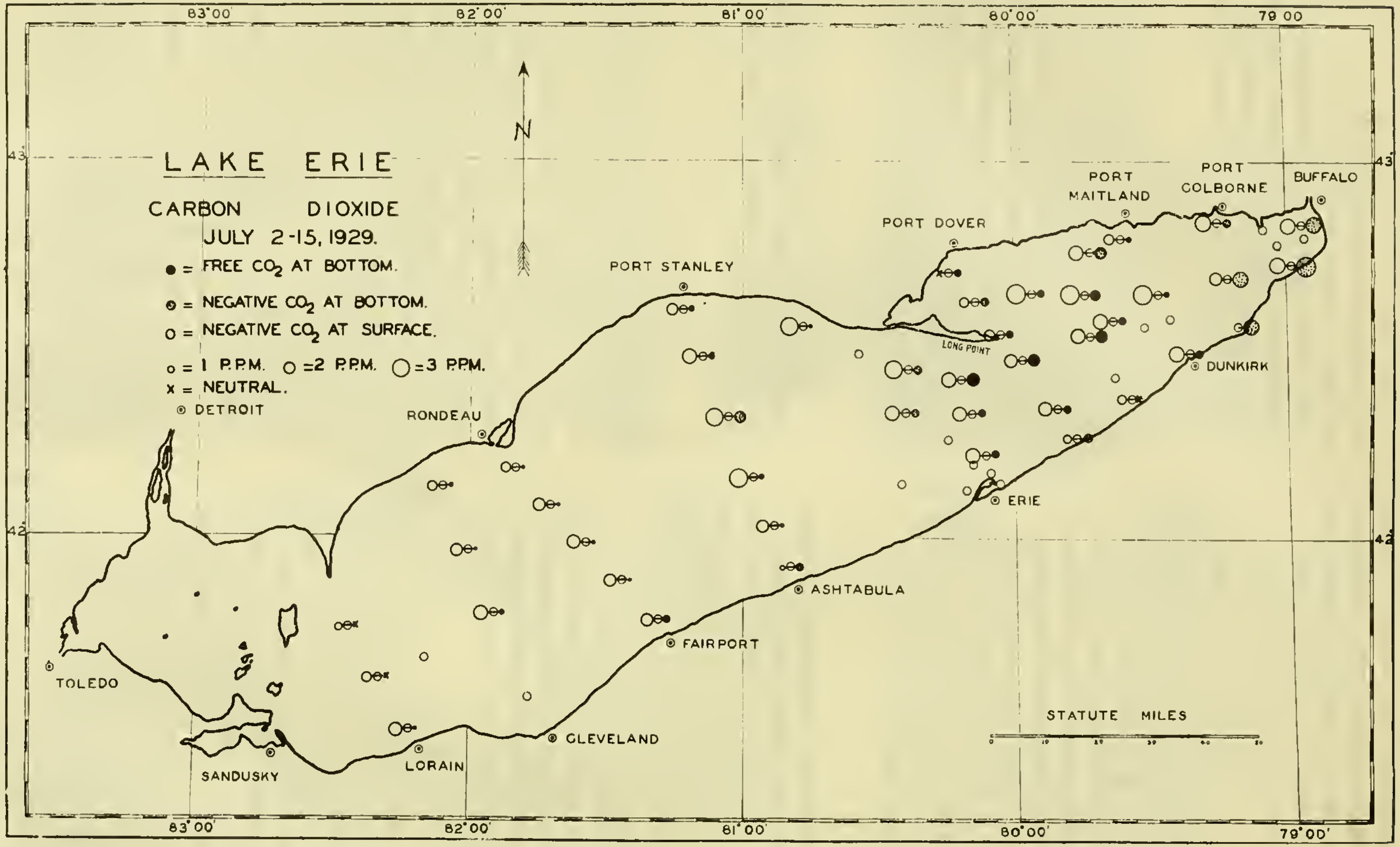

Figure 27. --Carbon dioxide as parts per million in July 1929. Free carbon dioxide present only at the bottom.

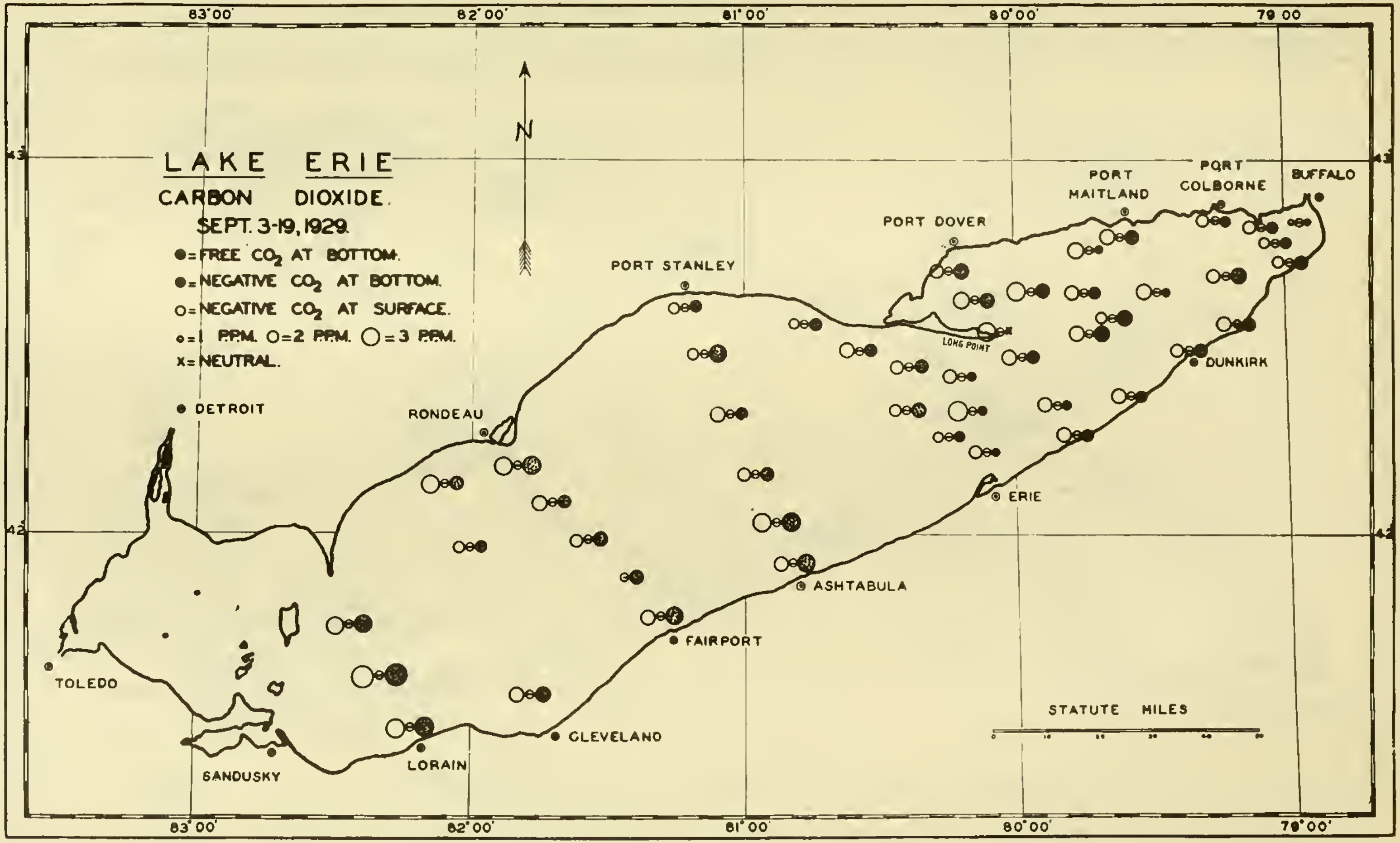

Figure 28. --Carbon dioxide as parts per million in September 1929. Free carbon dioxide limited to the bottom in the Deep Hole off Long Point.

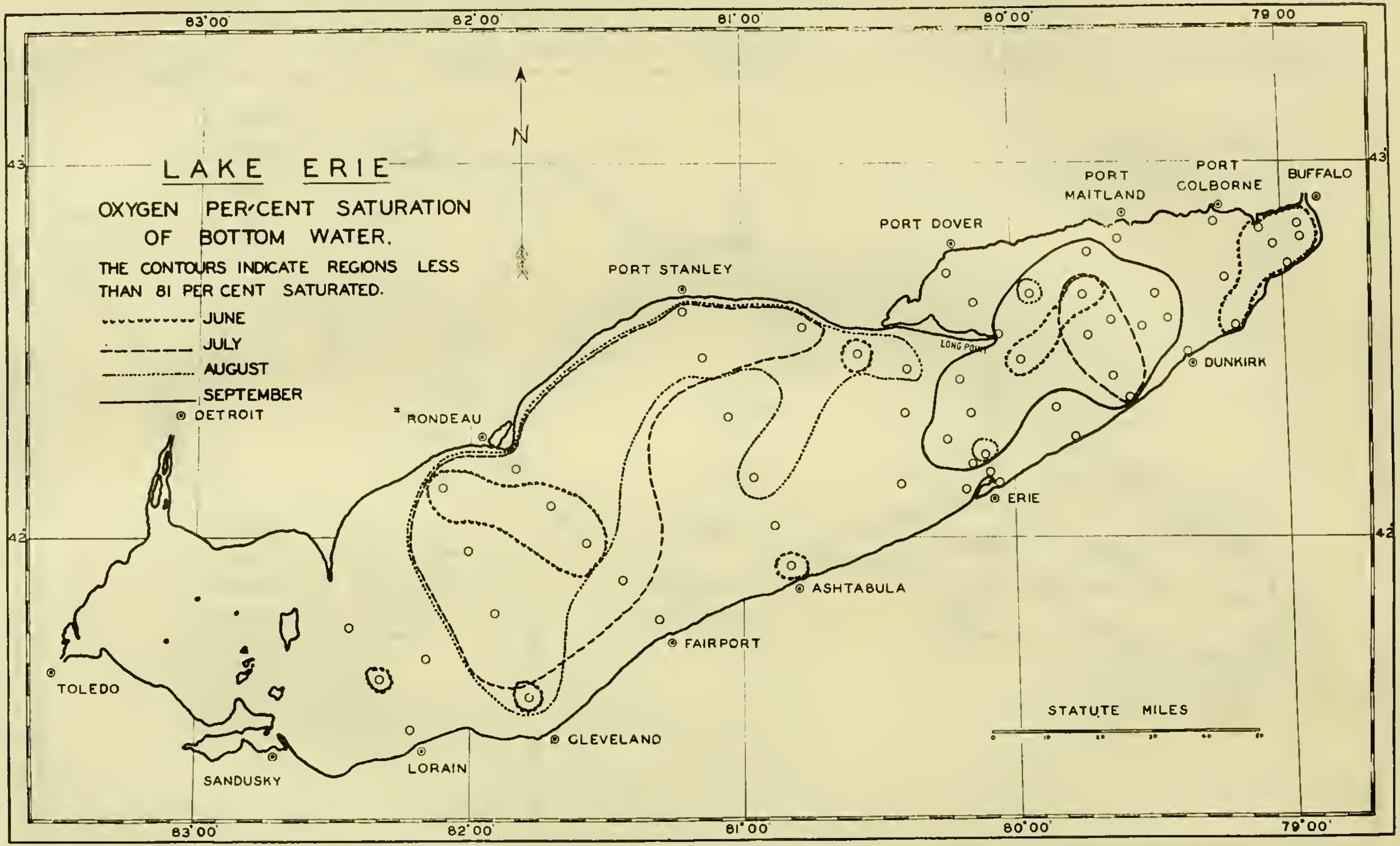

Figure 29. --Oxygen deficiency at the bottom in terms of percent of saturation, 1929. The bottom areas having less than 81 percent saturation are indicated within the contours.

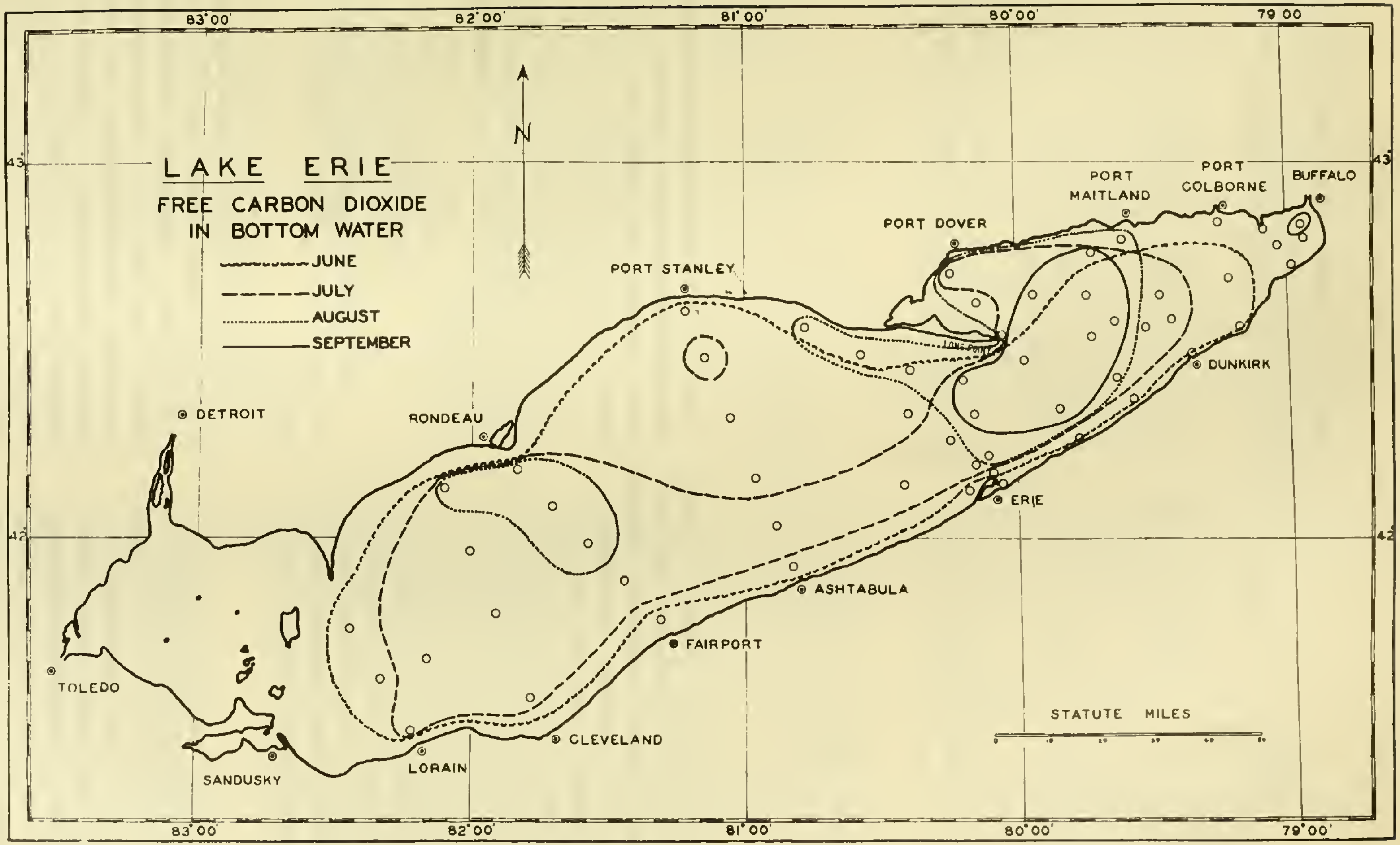

Figure 30. --Free carbon dioxide at the bottom, 1929, showing the gradual diminution with the advance of the season.

Table 12. --Average carbon dioxide values in the summer of 1929

Date and area	Total observations		Positive carbon dioxide (p. p. m.)		Negative carbon dioxide (p. p. m.)		Number of neutral observations
	Number	Average	Number	Average	Number	Average	
June							
Surface	37	-1.78	0	0	32	-2.7	5
Bottom	37	+0.78	27	+1.2	3	-1.3	7
July							
Surface	44	-2.28	0	0	43	-2.4	1
Bottom	45	-0.28	22	+1.0	20	-1.7	3
August							
Surface	45	-1.76	0	0	43	-1.8	2
Bottom	44	-0.20	19	+1.7	23	-1.8	2
September							
Surface	46	-2.53	0	0	46	-2.5	0
Bottom	47	-1.54	10	+1.7	36	-2.4	1

free carbon dioxide at all depths throughout the whole lake. By the time our first determinations were made in June, this carbon dioxide had already been removed by the phytoplankton. The analyses show no free carbon dioxide in the surface waters during the period from June to September and a marked decrease in free carbon dioxide at the bottom with advance of the season. The photosynthetic action of the phytoplankton must be tremendous to bring about such changes, especially since the processes which release carbon dioxide are also proceeding with perhaps more than usual speed at this same time of year. The Deep Hole is probably the only spot in the lake which is characterized by free carbon dioxide the year round, but even this may be neutralized by the autumnal overturn.

Entirely too little is known about the production and utilization of organic materials in aquatic environments. In a large lake like Erie it is the relatively shallow area which reacts to changing climatic conditions in larger measure than the deep zone. This is the region in which greater photosynthetic activity proceeds. During the warm and light summer period practically the whole lake yields to a pulse of photosynthesis whose pace is greater than opposing processes of carbohydrate fermentation and protein decomposition. The result must mean a seasonal increase in synthesized organic stuffs existing in the original manufacturing organisms, the plants; in the consumers, the animals; and in solution in the water. How nearly the distribution of organic matter in Lake Erie approaches that reported for the Wisconsin Lakes by Birge and Juday (1926) remains to be shown. How much exists in the plankton? How much in solution? How much is left over and above the annual turnover?

Methyl-Orange Alkalinity

The methyl-orange alkalinity of Lake Erie waters did not fluctuate appreciably during the period of observations.

The total alkalinity (expressed as p. p. m. of calcium carbonate) in the summer of 1929 ran consistently lower at the surface than at the bottom, as shown by the mean of all the determinations made each month. This difference was, however, only a fractional part per million. In June the mean surface alkalinity was 0.7 p. p. m. lower, and in September 0.2 p. p. m. lower than the mean bottom alkalinity.

There also was an apparent small seasonal variation in total alkalinity. In June the mean surface value was 97. 0 p. p. m., and in September 95. 2 p. p. m. There was a fairly consistent trend toward decreasing alkalinity at both the surface and the bottom with advance of the season from June to September. There was also some decrease through the summer of 1928.

This phenomenon appears logical when it is remembered that carbon dioxide is being removed from the lake to such an extent that some of the $CaCO_3 \cdot H_2CO_3$ is being turned to the relatively insoluble calcium carbonate. The normal carbonate probably precipitates out very slowly and sinks to the bottom, thus removing from the lake some considerable amount of alkaline matter. Probably a large amount of this is recovered when the carbon dioxide increases again in the winter and the lake overturns in the spring.

Hydrogen-ion Concentration

The water became slightly more alkaline as the season progressed and carbon dioxide was gradually removed from the lake. The mean surface pH in June was 8. 18 and in September 8. 22. At the bottom the pH was on the average somewhat lower than at the surface. In June the mean bottom pH stood at 7. 98 but by September it had risen slightly to 8. 06.

The general correlation between carbon dioxide conrent and pH is rather good (figs. 31-34). When the carbon dioxide curve dips the pH rises, and vice versa. Also there is a relation between fluctuations in oxygen and pH, as a corollary. The lowest pH value was 7. 6 and the highest was 8. 4. These extremes were practically always accompanied by correspondingly great inverse fluctuations in the amount of carbon dioxide.

Toward September when vertical temperature and carbon dioxide gradients were decreasing in the shallower regions of the lake, the pH curves for the surface and bottom also showed a gradual tendency to approach each other. The graph for September, in figure 34, shows very little difference in the pH of surface and bottom determinations except in the region of the Deep Hole. There, 2 p. p. m. of free carbon dioxide at the bottom caused a pH of 7. 6 in contrast to the surface with negative carbon dioxide and a pH of 8. 3.

The pH observations in the summer of 1928 agree with those of 1929 as to range, average, and general distribution.

Chloride

Chlorides are washed from the rocks of the drainage area into the lake waters and are hence a natural constituent among other solutes. The chloride content of Lake Erie ran somewhat higher than the figures given by Birge and Juday (1911) for the Wisconsin lakes. These workers report an average of about 5 p. p. m. and a maximum of 10 p. p. m. of chloride, while the analyses made on Lake Erie in the summer of 1929 show a range from 8 to 16 p. p. m. with a surface mean of 11. 93. Very little vertical difference in the chloride content was noted throughout the lake (figs. 31-34).

One of the conspicuous features of the horizontal distribution of chloride was that at certain points along the lake shore relatively high values occasionally occurred (fig. 35). The diameters of the circles signify the parts per million of chloride deviation from the arithmetic mean of all the determinations for the surface and for the bottom in September. At most of the stations only very small deviations occurred. Conspicuously high values were found near Port Colborne, off the mouth of Eighteen Mile Creek, near Erie, Fairport, and Cleveland. As pointed out in the report on "Pollution, " these high chloride figures are probably due to industrial wastes from manufacturing centers.

Only upon one occasion was a high chloride value found near the Buffalo water intake. In June the analyses showed low oxygen and high chloride at station 01 near Buffalo. It is possible that at times certain amounts of waste materials may find their way out into the lake opposite the Buffalo Harbor.

At the extreme western end of the lake, a puzzling low chloride area may be seen in figure 35 and figures 31 to 34. The values are consistently low in the line of stations running across from Lorain, Ohio, to Point Pelee. Just what is the significance of this condition is difficult to say without knowing the state of affairs further to the west.

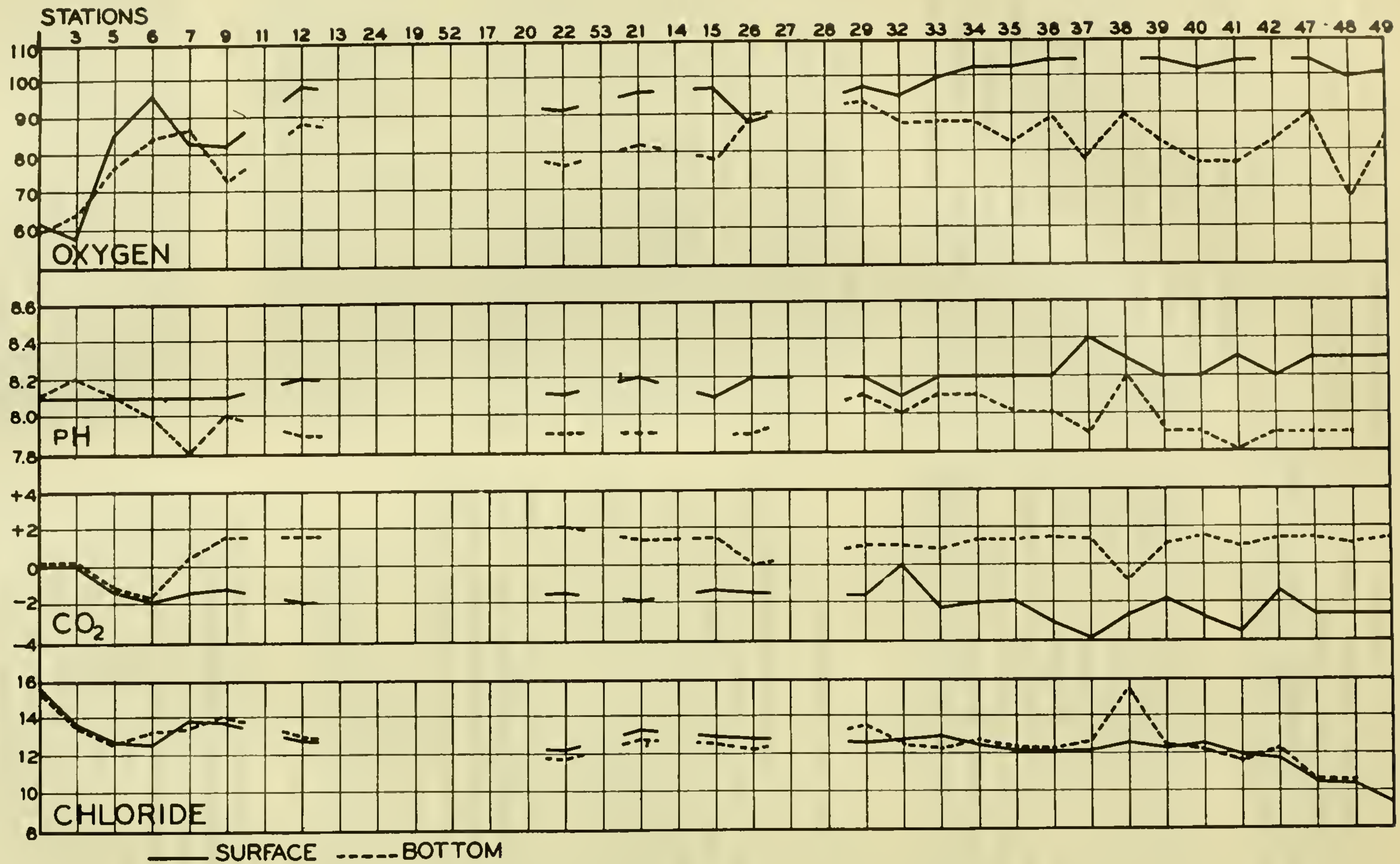

Figure 31. --Variation in the chemical values from station to station, June 7-19, 1929.

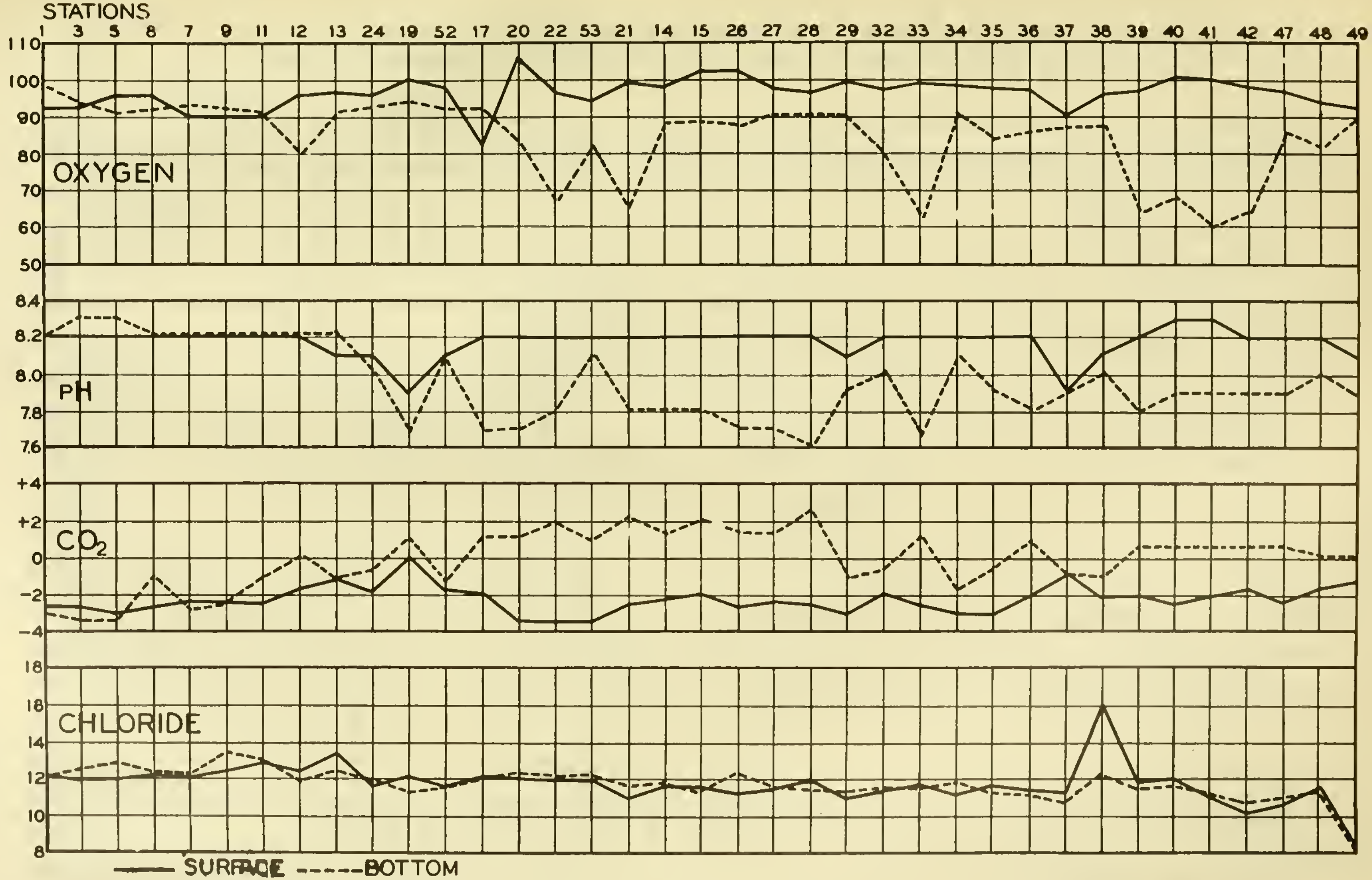

Figure 32. --Variation in the chemical values from station to station, July 2-15, 1929.

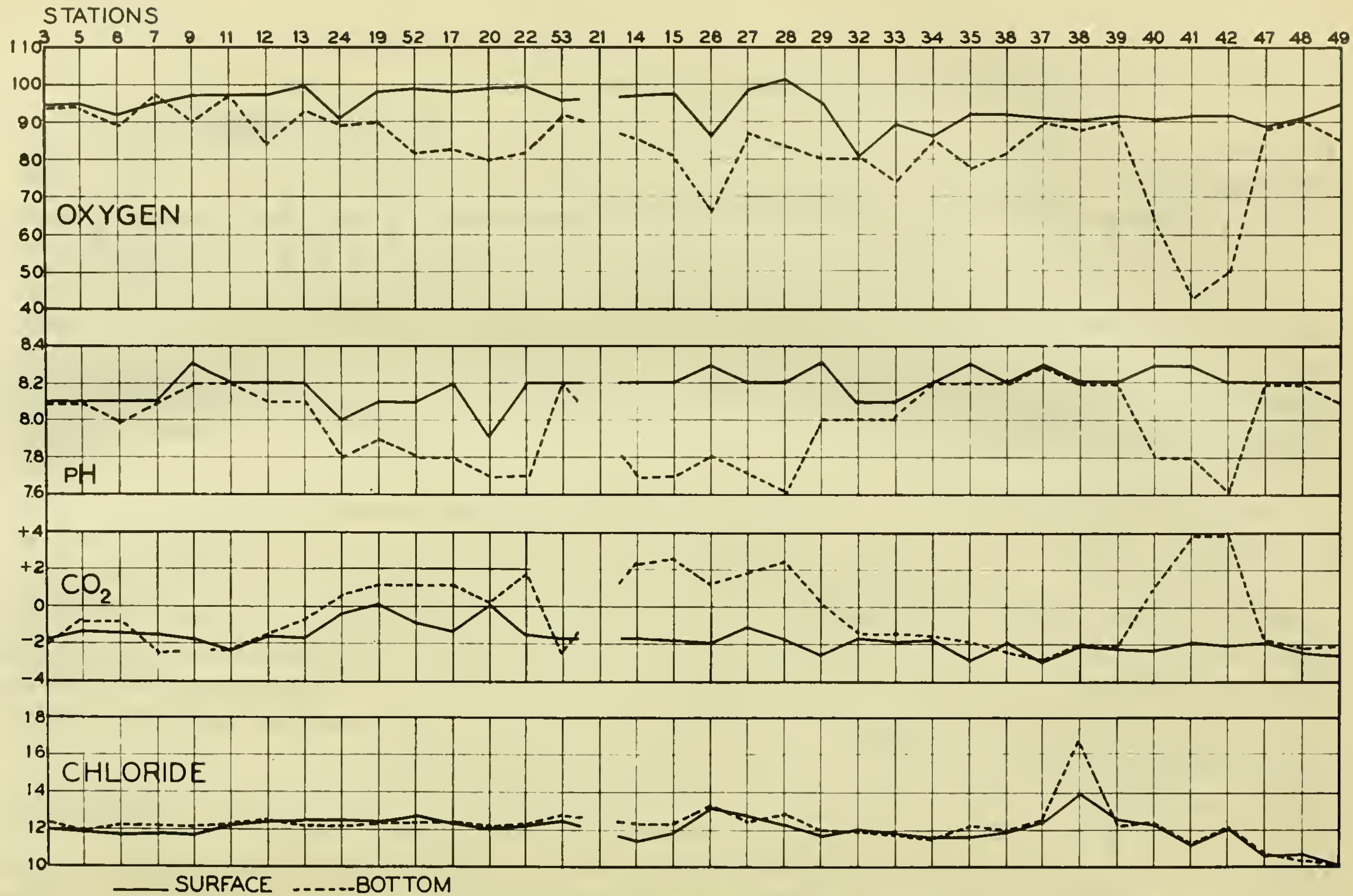

Figure 33. --Variation in the chemical values from station to station, August 6-20, 1929.

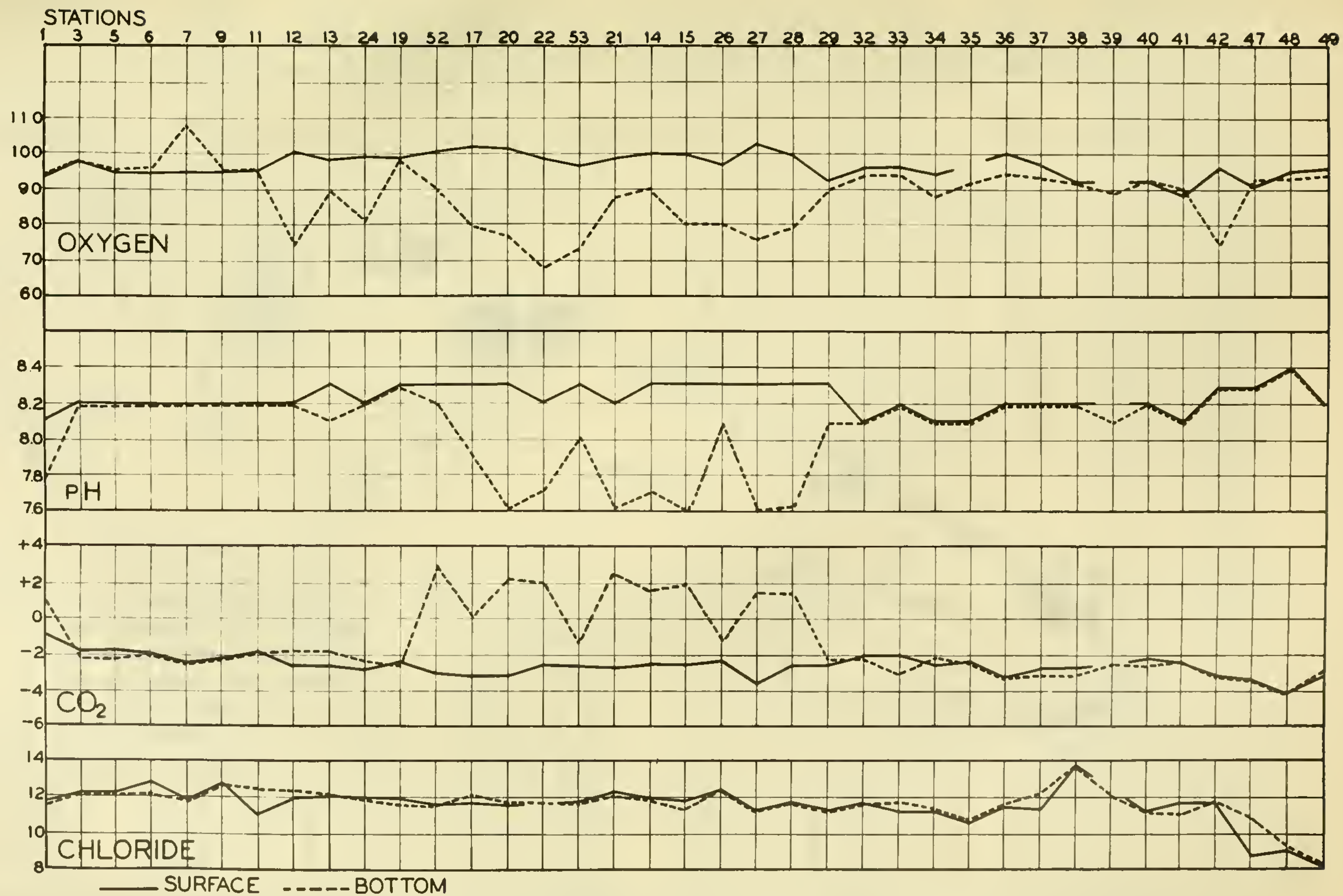

Figure 34. --Variation in the chemical values from station to station, September 3-19, 1929.

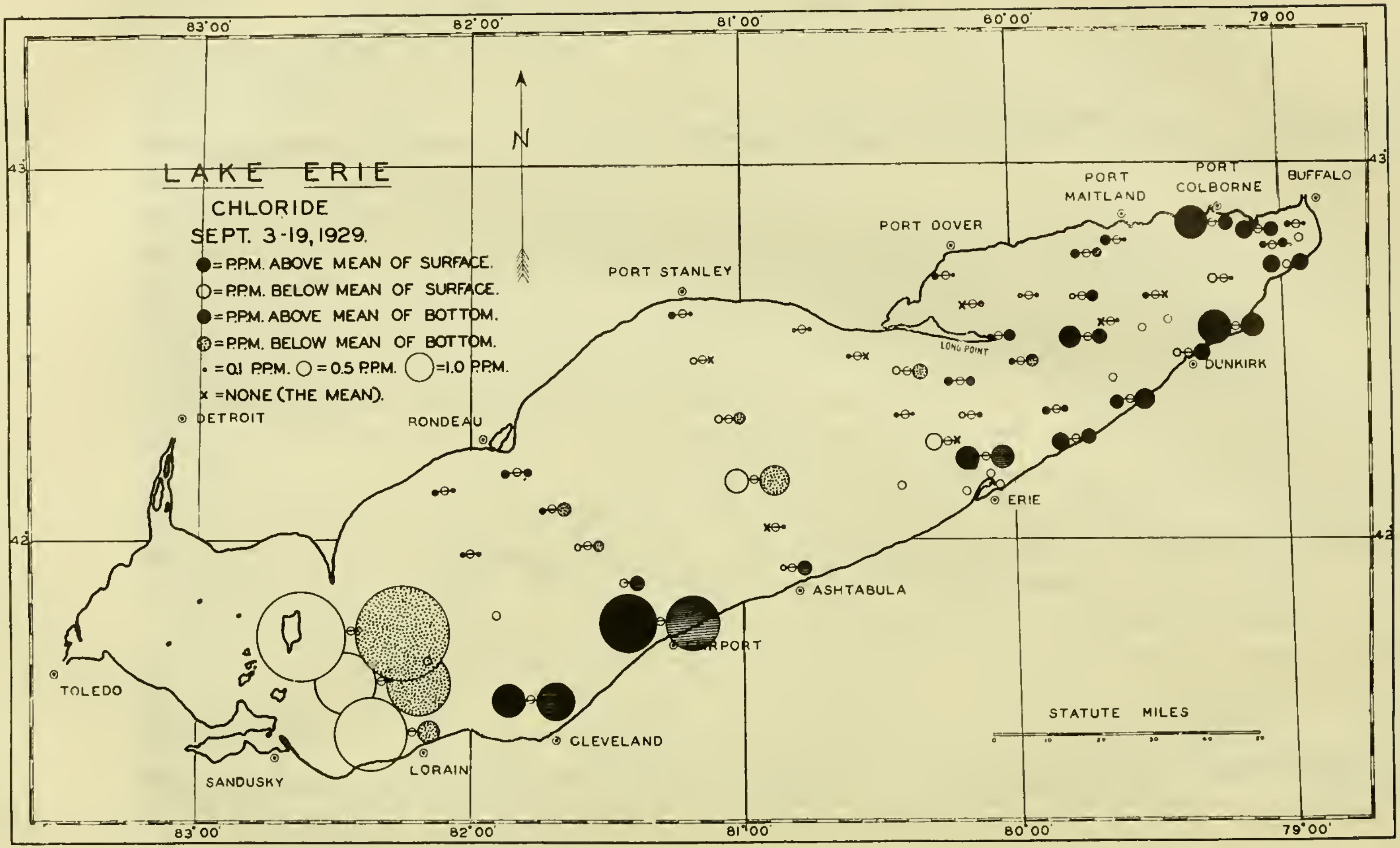

Figure 35. --The chloride content of the surface and bottom waters in September 1929. (Deviations above and below the mean are plotted for each station.)

Turbidity

The determinations of turbidity indicate relatively clear water at the surface of nearly all the stations throughout the lake. In the vicinity of the Deep Hole the bottom water was always clouded and showed the highest figures. The whole range of turbidity was from 0 to 100 p. p. m. of SiO_2 at the bottom and 0 to 25 p. p. m. at the surface.

In June the Buffalo station gave high turbidity figures at both the surface and bottom.

Figure 36 shows the distribution of turbidity for September. Nowhere else in the lake does the turbidity approximate the values shown for the bottom waters of the Deep Hole. In July the bottom waters were even more clouded than in September. The surface samples were quite clear; in fact, no turbidity was noted at a large number of the stations east from Long Point. It is suggested that bottom currents may have kept the dense waters of the Deep Hole in a constant state of agitation with the result that the fine bottom mud was dissipated into the overlying water mass.

GENERAL DISCUSSION

In the interpretation of a set of random samplings, such as that from the lake with which we are dealing, it is often very useful to apply certain standard statistical methods. In making the computations, aid was obtained from the standard treatices of Merriman (1901) and Chaddock (1925). The short formulae for the probable errors (r and r_0) were taken from the Smithsonian Physical Tables (Fowle 1927).

In figure 37 are shown the mean values and probable deviations of the mean for oxygen saturation, carbon dioxide, and pH. At a glance we can see the general trend of conditions.

As concerns oxygen saturation the surface more nearly approached complete saturation than did the bottom in the 4-month period from June to September. Also the probable deviations are relatively small. The values are closely grouped about the central tendency.

The mean negative carbon dioxide values at the surface throughour the season ran from -1.76 p. p. m. to -2.53 p. p. m. (table 12). At the bottom there was positive free carbon dioxide in June with a change to negative free carbon dioxide in July. Considerable increase in the negative value occurred in September. The probable errors of the mean carbon dioxide values are correspondingly greater than was the case for oxygen saturation. In other words, there was a greater dispersion from the average of the carbon dioxide determinations throughout the lake. This dispersion was relatively greater at the bottom in July and August, when there were almost as many negative as positive carbon dioxide quantities.

Relatively great changes in carbon dioxide produce small pH alterations, and hence only small fluctuations were observed in the mean surface and bottom pH values. Slight increases are nevertheless apparent with advance of the season. The surface means are slightly, but consistently more alkaline than the bottom. The largest probable deviations appear at the bottom toward autumn when there occurred a marked separation of the bottom waters into two areas, i. e., with and without free carbon dioxide which correspondingly affected the hydrogen-ion concentration.

There was a rather constant mean alkalinity content all through the summer, and probable errors are small (fig. 38). In general the bottom values were slightly higher than those for the surface. Toward autumn there was a slight reduction in the mean alkalinity along with the general decrease in free carbon dioxide.

Through the summer a decrease in the chloride content of the lake was witnessed at both the surface and the bottom. Though there was very little vertical difference of the averages, the bottom values for each month showed a slight margin above those at the surface. The probable errors are so small that it was not possible to show them on the particular scale used in plotting. The chloride values in the lake, hence, may be said to fluctuate relatively little from the mean.

The striking difference between the values at the surface and bottom is shown in the graph for turbidity. In all months the bottom water shows a far greater mean cloudiness. This vertical difference seems to have become most pronounced in July when the mean turbidity at the bottom was at a maximum of 13.2 p. p. m. SiO_2. At this time the mean surface turbidity was only 4.5 p.p.m. The probable error was greatest for the bottom also in July.

Another outstanding feature of the turbidity graph is that it indicates a decided clearing of the surface waters month by month, the mean decreasing steadily from 7.0 p.p.m. in June to 2.5 p.p.m. in September. When the surface cleared in late June there was an increase in the bottom turbidity. However, for the rest of the summer there was no evidence of such an inverse relationship, for after July there was a marked decrease in the mean turbidity at both the surface and bottom.

The chemical analyses of water samples collected in harbors and near potential sources of pollution have yielded positive evidences of contamination of the inshore waters. The effects of these various local domestic and industrial wastes are felt but little in the offshore waters. As a typical example we may mention for discussion the series of determinations made near Ashtabula, Ohio, in August 1929.

A series of samples was examined from the surface, beginning in the Ashtabula River above the bascule bridge and running out past the ore docks through the harbor entrance to the open lake. The results of these determinations are given in the appended table 14 and in figure 39.

The graph indicates pollution at station 01 in the river. All values plotted are abnormal when compared with the conditions in the open lake waters. The oxygen and pH were low and the carbon dioxide, chloride, and turbidity were high.

It is significant that conditions altered so quickly in a distance of 750 meters downstream to the next station, 02, at the ore docks. Here the oxygen, pH, carbon dioxide, and chloride content were rapidly approaching normal surface values. The recovery from pollution was quite rapid and stations 03 and 04, just inside and outside the harbor breakwall, were nearly normal.

Station 06.37 was offshore about 5,000 meters from Ashtabula. Here conditions were found to be practically normal on each of the 4 summer cruises. The curves going from the source of pollution in Ashtabula harbor out to this normal station show clearly the effect of dilution upon the abnormal local conditions. Recovery appears to be rapid at this time of the year, at least in the surface waters. If this may be taken as a typical example, it is easily seen how the inshore abnormallties are diluted, dissipated, and eventually lost in the lake. That the effects of certain centers of pollution can be detected far out into the lake is nevertheless true, as is brought out in the discussion of that subject in another paper.

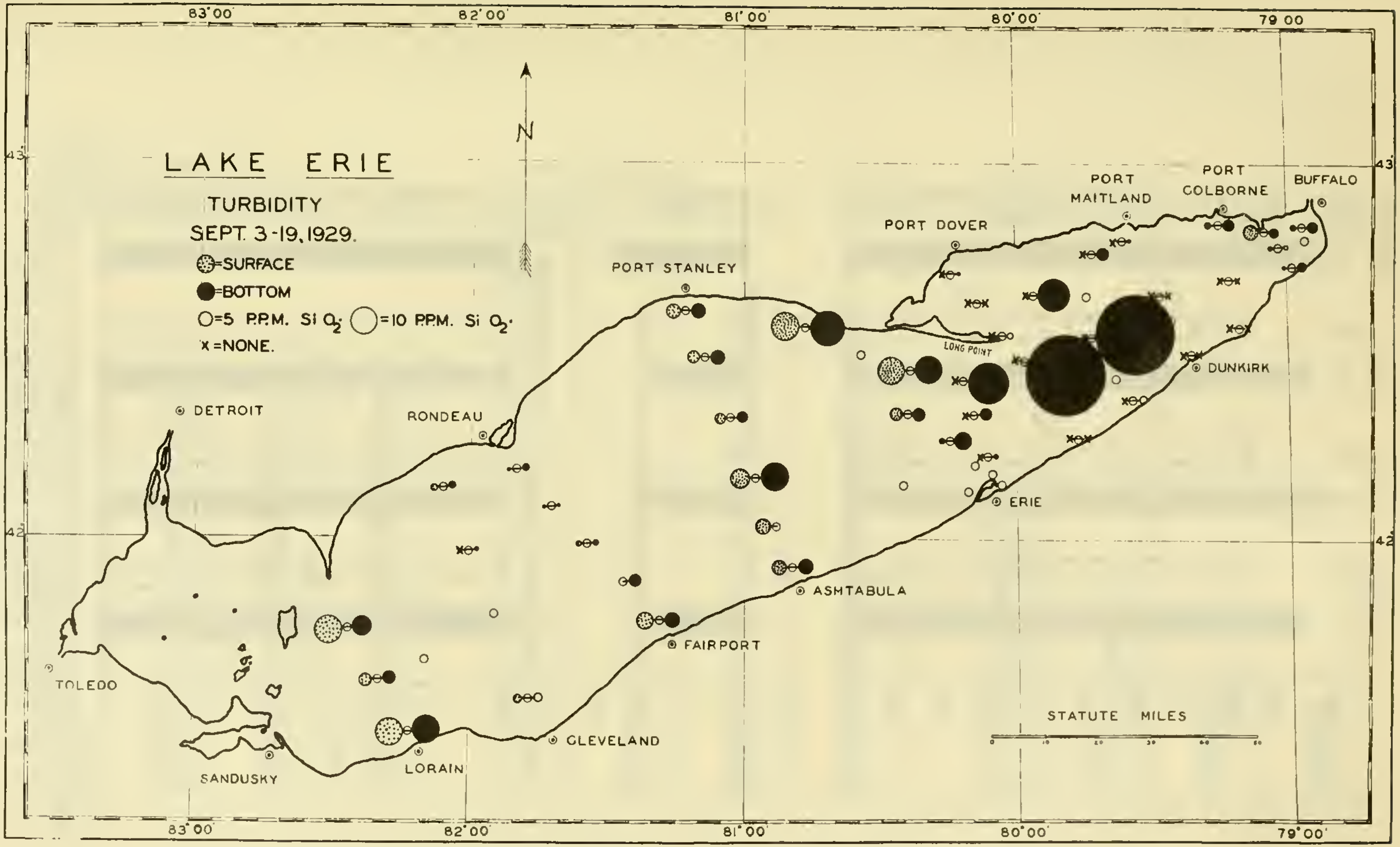

Figure 36. --Turbidity as parts per million in SiO_2 at the surface and bottom in September 1929.

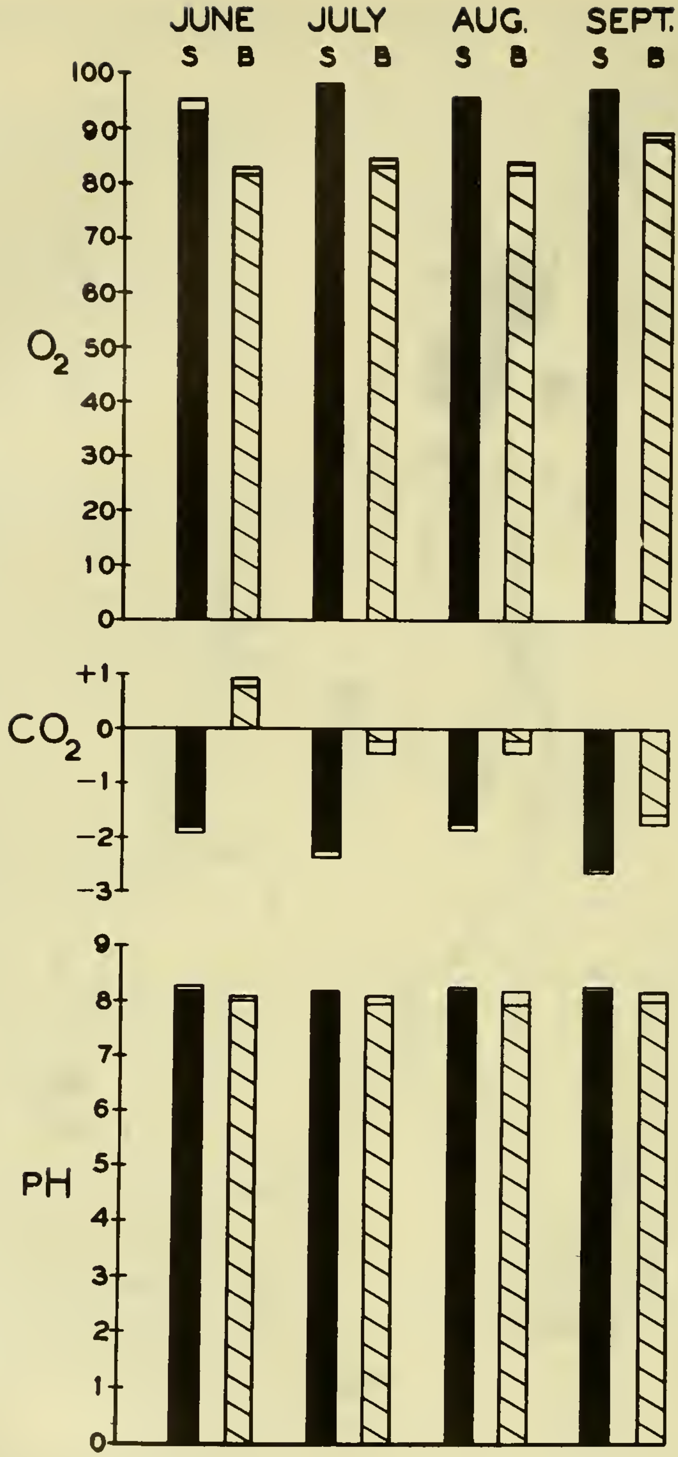

Figure 37. --The means and probable errors (r_0) of the oxygen saturation, carbon dioxide, and hydrogen-ion determinations on the surface and bottom waters of Lake Erie, 1929.

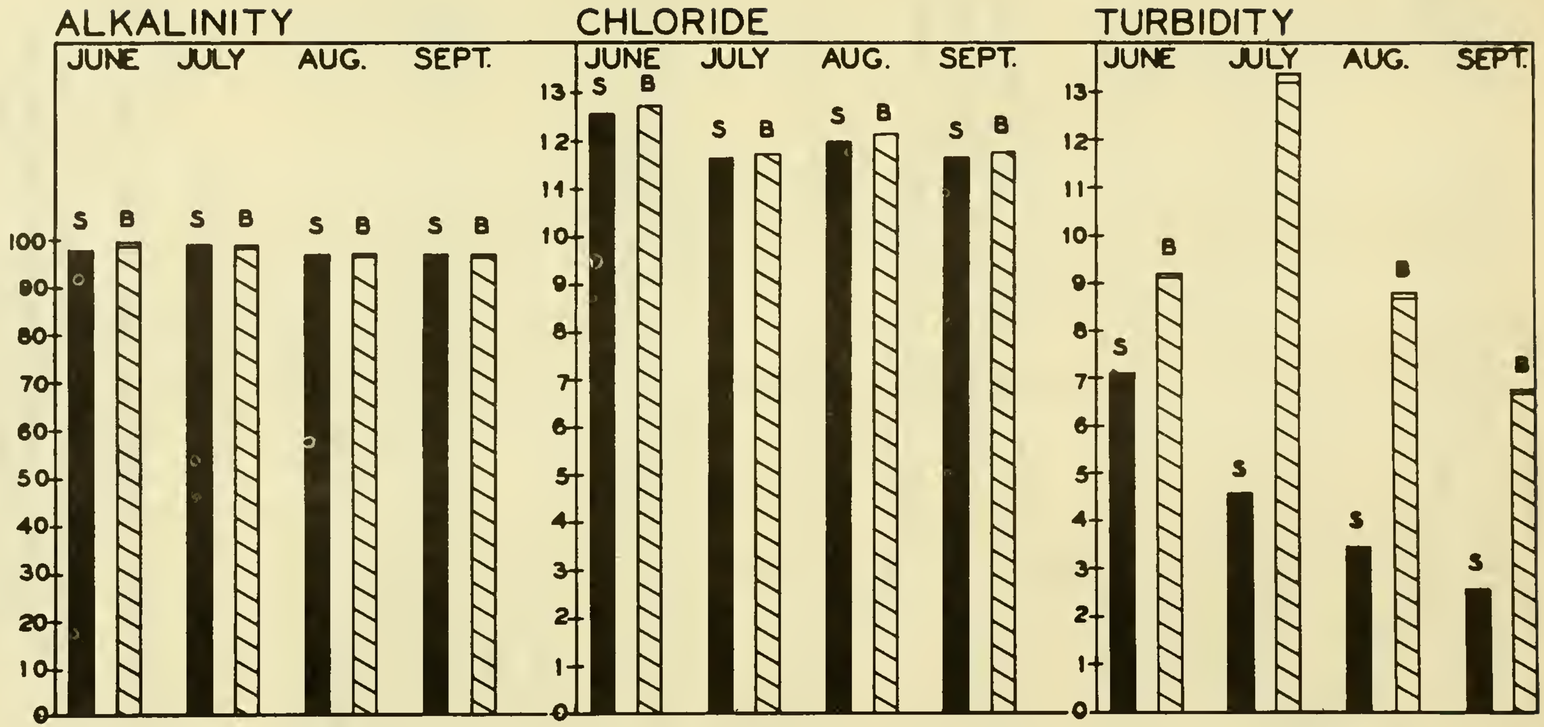

Figure 38. --The means and probable errors (r_0) of the methyl-orange alkalinity, chloride, and turbidity determinations on the surface and bottom waters of Lake Erie, 1929.

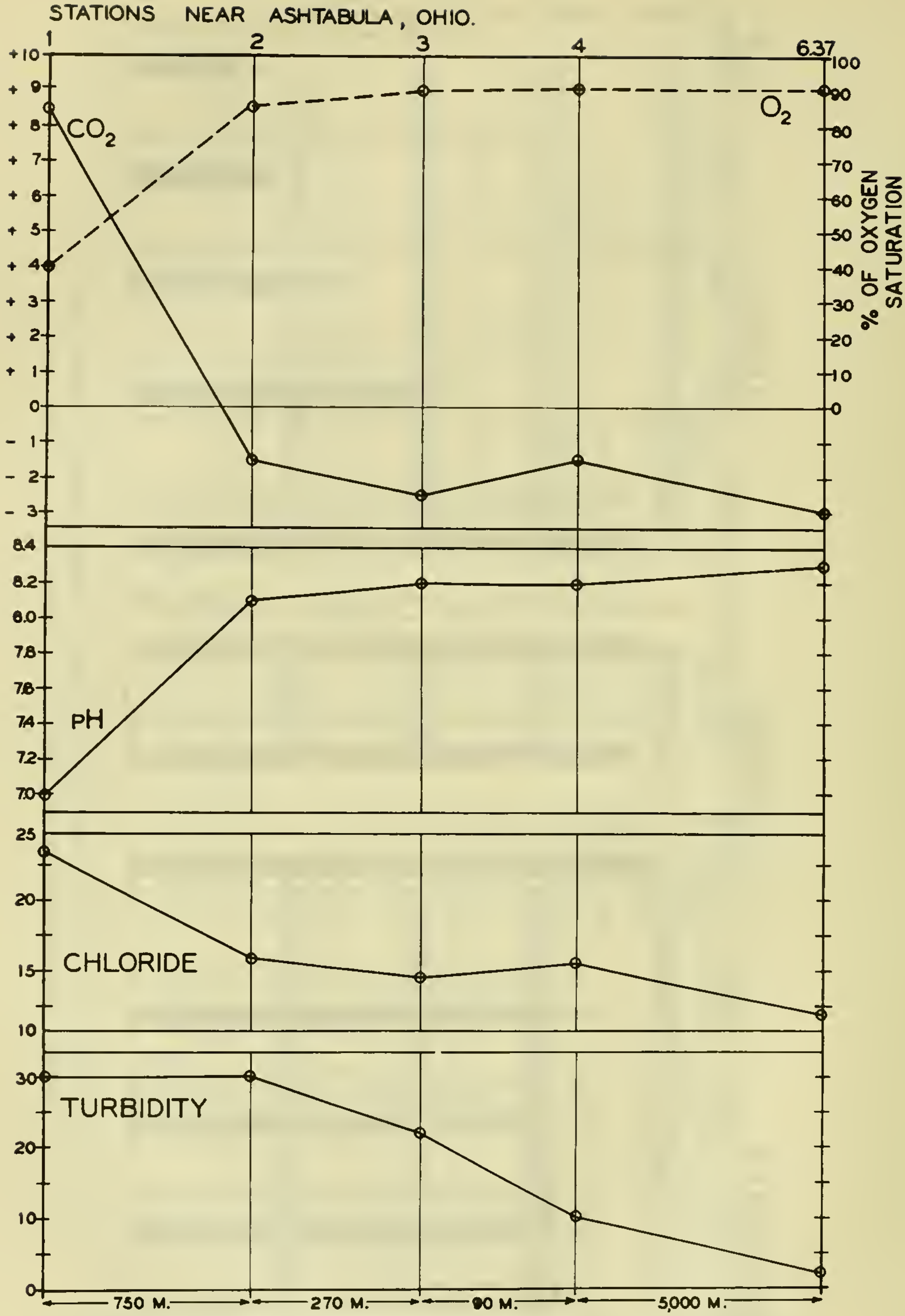

Figure 39. --Horizontal variation in chemical values of the surface waters near Ashtabula, Ohio. The scale from station No. 1 in Ashtabula River outward to station 06.37 is plotted as the logarithm of the distance in meters.

Table 13.--Chemical analyses of Lake Erie, June 7-September 19, 1929

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen		Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCo_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
				p. p. m.	Percent saturation						
02.01	June 7	5.5	0.5	6.4	62	0.0	0.0	91	8.1	15.7	25
			4.5	6.4	60	0.0	0.0	90	8.1	15.7	20
02.02	June 7	12.0	0.5	6.1	58	0.0	0.0	98	8.1	14.5	10
			10.0	7.3	66	0.0	0.0	98	8.1	14.5	10
02.03	June 7	9.5	0.5	5.9	57	0.0	0.0	100	8.1	13.7	10
			8.0	6.8	65	0.0	0.0	100	8.2	13.7	15
02.04	June 7	17.5	0.5	7.3	70	0.0	0.0	104	8.2	13.2	15
			16.0	8.3	75	0.0	0.0	104	8.1	13.2	15
02.05	June 7	13.0	0.5	9.1	84	-1.4	1.6	106	8.1	12.7	15
			12.0	8.8	77	-1.2	1.4	100	8.1	12.7	17
02.06	June 7	16.5	0.5	10.7	96	-1.8	2.0	106	8.1	13.2	7
			15.0	9.9	85	-1.8	2.0	100	8.0	12.6	10
02.07A	June 7	21.5	0.5	8.8	83	-1.4	1.6	100	8.1	13.5	9
			20.0	10.3	87	+0.4	0.0	99	7.8	13.8	16
02.09	June 8	12.0	0.5	8.7	82	-1.2	1.4	95	8.1	14.0	13
			10.0	8.1	73	+1.5	0.0	92	8.0	13.7	16
02.22	June 8	37.0	0.5	10.3	91	-1.4	1.6	92	8.1	11.6	14
			35.0	9.9	77	+2.0	0.0	93	7.9	12.2	25
02.21	June 8	58.0	0.5	10.6	96	-1.9	2.1	98	8.2	12.7	11
			56.0	10.5	82	+1.3	0.0	100	7.9	13.3	20
02.12	June 8	24.0	0.5	10.4	98	-2.0	2.3	95	8.2	12.7	10
			22.0	11.0	88	+1.5	0.0	99	7.9	12.7	15
02.15	June 12	61.0	0.5	10.8	97	-1.3	1.5	97	8.1	12.5	15
			55.0	10.0	78	+1.5	0.0	101	8.1	12.9	...
02.56	June 14	15.0	0.5	10.0	98	-0.9	1.0	94	8.1	13.2	5
			15.0	10.7	93	+1.5	0.0	97	8.1	13.5	5
02.26	June 14	20.0	0.5	9.0	88	-1.5	1.7	95	8.2	12.2	5
			18.0	10.7	90	0.0	0.0	100	7.9	12.7	5
02.51	June 14	22.0	0.5	10.0	98	-1.4	1.6	94	8.2	12.7	3
			21.0	10.5	90	+1.3	0.0	95	7.9	12.6	5
02.50	June 15	15.0	0.5	9.7	93	-1.8	2.0	93	8.1	12.0	3
			14.0	9.9	89	+1.0	...	...	...	...	...
02.29	June 15	17.0	0.5	9.9	97	-1.6	1.8	99	8.2	13.5	3
			15.0	10.1	93	+1.0	0.0	100	8.1	12.6	3

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen p. p. m.	Dissolved oxygen Percent saturation	Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
02.30	June 15	18.0	0.5	9.7	95	-1.1	1.2	100	8.2	13.2	4
			16.0	8.5	75	0.0	0.0	101	8.1	13.2	5
02.31	June 15	17.5	0.5	9.9	97	-1.8	2.0	98	8.2	13.2	2
			16.0	9.8	86	0.0	0.0	99	8.1	13.0	4
02.32	June 16	12.0	0.5	9.7	95	0.0	0.0	105	8.1	12.5	3
			10.0	9.9	87	+1.0	0.0	102	8.0	12.7	4
02.33	June 16	20.0	0.5	9.9	99	-2.3	2.6	97	8.2	12.2	3
			19.0	10.0	88	+0.8	0.0	97	8.1	12.9	4
02.34	June 16	21.0	0.5	10.2	102	-2.1	2.4	102	8.2	12.7	3
			20.0	10.1	88	+1.3	0.0	100	8.1	12.5	3
02.35	June 16	21.5	0.5	10.0	102	-1.9	2.2	104	8.2	12.3	5
			21.0	9.5	83	+1.5	0.0	101	8.0	12.2	5
02.36	June 16	22.0	0.5	10.2	104	-3.0	3.4	95	8.2	12.1	5
			21.0	10.1	89	+1.5	0.0	100	8.0	12.2	7
02.37	June 16	16.0	0.5	...	...	-4.4	5.0	90	8.4	12.2	6
			16.0	8.6	77	+1.4	0.0	94	7.9	12.5	6
02.38	June 17	15.0	0.5	...	...	-2.6	3.0	89	8.3	12.7	4
			14.0	8.8	90	-0.9	1.0	96	8.2	15.6	7
02.39	June 17	23.0	0.5	10.1	104	-1.8	2.0	95	8.2	12.7	3
			22.0	9.3	82	+0.9	0.0	95	7.9	12.4	4
02.40	June 17	24.5	0.5	9.7	102	-2.8	3.2	94	8.2	12.2	2
			23.0	8.9	77	+1.5	0.0	98	7.9	12.5	3
02.41	June 17	22.5	0.5	10.2	104	-3.5	4.0	97	8.3	11.6	3
			22.5	8.7	77	+1.0	0.0	100	7.8	11.8	4
02.42	June 17	19.0	0.5	...	...	-1.4	1.6	99	8.2	12.2	3
			18.0	9.5	83	+1.4	0.0	98	7.9	11.7	4
02.43	June 18	21.0	0.5	9.7	101	-1.8	2.0	101	8.0	11.5	2
			20.0	8.7	77	+1.0	0.0	97	7.9	12.0	6
02.44	June 18	23.0	0.5	9.6	102	-2.6	3.0	98	8.2	11.6	2
			21.0	9.2	83	+0.9	0.0	98	7.9	11.6	5
02.45	June 18	23.0	0.5	9.6	105	-2.6	3.0	97	8.2	11.7	3
			21.0	9.3	83	+1.0	0.0	95	7.9	11.6	4
02.46	June 18	18.0	0.5	...	...	-3.0	3.4	94	8.3	12.4	4
			17.0	8.1	73	+1.0	0.0	94	7.8	13.2	6

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen		Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
				p. p. m.	Percent saturation						
02.47	June 19	12.0	0.5	9.9	104	-2.6	3.0	95	8.3	10.4	18
			11.0	8.8	90	+1.5	0.0	92	7.9	10.5	18
02.48	June 19	14.0	0.5	8.9	99	-2.6	3.0	93	8.3	10.3	6
			13.0	7.1	68	+1.1	0.0	93	7.9	10.4	14
02.49	June 19	14.0	0.5	8.9	101	-2.6	2.9	90	8.3	9.4	4
			13.0	8.9	84	+1.5	0.0	...	...	...	...
04.01	July 2	6.0	0.5	8.5	92	-2.6	2.9	98	8.2	12.1	10
			5.0	9.0	98	-3.0	3.4	95	8.2	12.1	12
04.03	July 2	12.0	0.5	8.5	92	-2.7	3.1	94	8.2	11.9	7
			11.0	8.6	93	-3.5	4.0	92	8.3	12.5	8
04.04	July 2	18.5	0.5	8.3	91	-2.0	2.3	95	8.2	11.7	6
			17.0	8.8	94	-3.1	3.5	96	8.3	11.5	8
04.05	July 2	10.5	0.5	8.8	95	-3.1	3.5	93	8.2	11.9	8
			9.0	8.5	91	-3.5	4.0	94	8.3	12.8	10
04.06	July 2	16.0	0.5	9.1	95	-2.7	3.1	100	8.2	12.1	15
			15.0	9.0	92	-1.1	1.2	97	8.2	12.2	17
04.07	July 2	20.0	0.5	8.6	90	-2.4	2.7	94	8.2	11.9	4
			20.5	9.1	93	-2.9	3.3	100	8.2	12.1	5
04.09	July 2	15.0	0.5	...	...	...	...	...	...	...	...
			14.0	8.6	92	-2.6	3.0	96	8.2	13.3	6
04.11	July 5	17.0	0.5	8.5	91	-2.6	3.0	93	8.2	12.9	11
			15.0	8.4	90	-1.2	1.3	92	8.2	12.9	12
04.53	July 5	28.5	0.5	9.2	94	-3.5	4.0	92	8.2	11.9	1
			27.0	8.4	81	+0.8	0.0	93	8.1	12.2	30
04.54	July 5	53.0	0.5	9.7	95	-2.6	2.9	96	8.2	11.7	6
			52.0	11.7	91	+1.2	0.0	97	7.9	12.1	20
04.22	July 5	36.0	0.5	9.6	96	-3.6	4.1	102	8.2	11.8	4
			35.0	7.9	66	+1.8	0.0	103	7.8	11.9	100
04.21	July 5	57.5	0.5	9.9	99	-2.6	3.0	96	8.2	11.0	3
			55.0	8.4	65	+2.0	0.0	97	7.8	11.6	20
04.12	July 5	20.0	0.5	9.0	96	-1.7	1.9	101	8.2	12.3	7
			18.0	9.0	80	0.0	0.0	99	8.2	11.9	8
04.24	July 6	17.0	0.5	9.6	96	-1.9	2.2	96	8.1	11.6	4
			16.0	9.7	93	-0.8	0.9	99	8.0	11.8	9

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen p.p.m.	Dissolved oxygen Percent saturation	Carbon dioxide (p.p.m.)	Phenolphthalein alkalinity (p.p.m. $CaCO_3$)	Methyl-orange alkalinity (p.p.m. $CaCO_3$)	pH	Chloride (p.p.m.)	Turbidity (p.p.m. SiO_2)
04.23	July 6	21.0	0.5	9.5	98	-2.6	2.9	96	8.2	12.0	4
			20.0	9.5	93	-1.8	2.0	96	8.1	11.8	4
04.20	July 6	34.0	0.5	10.3	105	-3.5	4.0	98	8.2	12.0	4
			33.0	10.0	82	+1.0	0.0	101	7.7	12.2	50
04.19	July 6	8.5	0.5	10.3	100	0.0	0.0	100	7.9	12.0	8
			7.5	10.5	94	+1.0	0.0	98	7.7	11.3	9
04.52	July 8	12.5	0.5	10.4	98	-1.7	1.9	97	8.1	11.6	4
			11.5	10.2	92	-1.4	1.6	96	8.1	11.5	6
04.17	July 8	18.5	0.5	8.3	82	-2.0	2.3	95	8.2	12.1	2
			17.5	10.2	92	+1.0	0.0	98	7.7	12.0	9
04.15	July 8	61.0	0.5	10.2	102	-2.0	2.3	100	8.2	11.5	4
			60.0	11.4	89	+2.0	0.0	99	7.8	11.4	50
04.14	July 8	37.0	0.5	9.4	98	-2.3	2.6	96	8.2	11.6	3
			35.0	11.3	88	+1.3	0.0	96	7.8	11.7	30
04.13	July 8	17.0	0.5	8.7	97	-1.2	1.4	96	8.1	13.3	3
			16.0	8.7	91	-1.3	1.5	98	8.2	12.4	5
04.26	July 9	20.5	0.5	9.6	102	-2.8	3.2	98	8.2	11.2	5
			19.0	11.0	88	+1.3	0.0	98	7.7	12.3	30
04.27	July 9	28.5	0.5	9.3	97	-2.5	2.8	100	8.2	11.4	6
			27.0	11.4	91	+1.2	0.0	100	7.7	11.5	20
04.28	July 9	37.0	0.5	9.2	96	-2.6	3.0	102	8.2	11.9	2
			35.0	11.4	91	+2.2	0.0	99	7.6	11.4	20
04.50	July 10	16.0	0.5	9.9	105	-2.6	2.9	100	8.1	11.4	2
			15.0	9.3	87	-1.1	1.2	97	7.9	11.5	4
04.29	July 10	18.5	0.5	9.3	99	-3.1	3.5	104	8.1	11.0	5
			17.0	10.2	91	-1.3	1.5	100	7.9	11.3	6
04.31	July 10	18.0	0.5	9.2	98	-3.1	3.5	103	8.2	11.7	5
			16.0	5.5	50	-0.3	0.3	104	7.8	11.6	5
04.32	July 11	13.0	0.5	9.5	97	-2.0	2.3	103	8.2	11.3	3
			11.0	8.4	80	-0.9	1.0	99	8.0	11.5	4
04.33	July 11	20.0	0.5	9.7	99	-2.6	3.0	97	8.2	11.7	4
			18.0	7.1	63	+1.0	0.0	100	7.7	11.5	5
04.34	July 11	21.0	0.5	9.2	98	-3.1	3.5	98	8.2	11.2	2
			19.0	9.3	91	-1.9	2.2	101	8.1	11.8	3

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen		Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
				p. p. m.	Percent saturation						
04.35	July 11	22.0	0.5	9.1	97	-3.1	3.5	98	8.2	11.6	2
			20.0	9.3	84	-0.9	1.0	102	7.9	11.2	5
04.36	July 11	22.0	0.5	8.9	97	-2.2	2.5	99	8.2	11.3	2
			20.0	9.6	86	+0.6	0.0	98	7.8	11.1	7
04.37	July 11	17.0	0.5	7.9	90	-0.9	1.0	94	7.9	11.2	3
			15.0	8.0	87	-1.2	1.3	93	7.9	10.7	4
04.38	July 12	15.0	0.5	8.5	96	-2.2	2.5	92	8.1	16.2	8
			14.0	8.4	88	-1.1	1.2	94	8.0	12.2	4
04.39	July 12	23.0	0.5	8.9	97	-2.1	2.4	96	8.2	11.7	1
			22.0	7.2	64	+0.4	0.0	96	7.8	11.5	4
04.40	July 12	24.5	0.5	9.1	101	-2.5	2.8	98	8.3	11.9	1
			23.0	7.5	68	+0.4	0.0	98	7.9	11.7	5
04.41	July 12	23.5	0.5	9.0	100	-2.2	2.5	100	8.3	11.0	2
			22.0	6.8	61	+0.5	0.0	99	7.9	11.1	2
04.42	July 13	19.5	0.5	8.8	98	-1.8	2.1	100	8.2	10.2	3
			18.0	7.0	65	+0.4	0.0	99	7.9	10.7	5
04.43	July 13	21.0	0.5	8.8	100	-1.8	2.1	91	8.2	10.1	4
			20.0	7.0	65	+0.6	0.0	96	7.7	11.3	4
04.44	July 13	23.0	0.5	8.7	99	-2.0	2.3	99	8.2	11.2	1
			22.0	7.0	65	+0.4	0.0	96	7.8	11.5	1
04.45	July 13	22.5	0.5	9.1	101	-2.6	3.0	100	8.3	11.6	1
			21.0	8.0	72	+0.8	0.0	98	7.9	11.3	1
04.47	July 15	11.5	0.5	8.6	97	-2.4	2.7	94	8.2	10.5	7
			10.0	7.7	86	+0.4	0.0	94	7.9	11.0	10
04.48	July 15	13.5	0.5	8.5	94	-1.7	1.9	94	8.2	11.6	1
			12.0	7.8	82	0.0	0.0	94	8.0	11.5	6
04.49	July 15	12.5	0.5	8.4	93	-1.3	1.5	93	8.1	8.4	9
			11.0	8.1	90	0.0	0.0	97	7.9	8.1	9
06.01	Aug. 3	7.0	0.5	8.7	98	-1.9	2.2	94	8.1	12.1	1
			6.0	8.5	96	-2.3	2.6	94	8.1	12.3	2
06.03	Aug. 6	11.0	0.5	8.6	94	-1.8	2.0	94	8.1	12.0	15
			10.0	8.5	93	-2.1	2.4	93	8.1	12.5	15
06.04	Aug. 6	19.0	0.5	8.3	90	-1.1	1.2	95	8.1	12.2	10
			18.0	8.3	90	-0.88	1.0	96	8.2	12.5	7

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen		Carbon dioxide (p.p.m.)	Phenolphthalein alkalinity (p.p.m. $CaCO_3$)	Methyl-orange alkalinity (p.p.m. $CaCO_3$)	pH	Chloride (p.p.m.)	Turbidity (p.p.m. SiO_2)
				p.p.m.	Percent saturation						
06.05	Aug. 6	11.0	0.5	8.6	94	-1.4	1.6	94	8.1	11.8	9
			10.0	8.6	94	-0.88	1.0	95	8.1	11.8	9
06.06	Aug. 6	13.0	0.5	8.7	91	-1.4	1.6	97	8.1	11.7	4
			12.5	8.6	90	-0.88	1.0	99	8.0	12.2	8
06.07	Aug. 6	22.0	0.5	8.7	95	-1.6	1.8	94	8.1	11.8	4
			20.0	9.1	97	-2.5	2.2	96	8.1	12.1	5
06.09	Aug. 6	14.0	0.5	8.7	97	-1.8	2.0	98	8.3	11.7	7
			12.0	8.4	91	...	...	...	8.2	12.1	7
06.11	Aug. 7	16.5	0.5	8.7	97	-2.5	2.2	96	8.2	12.2	5
			15.5	8.8	98	-2.5	2.2	95	8.2	12.3	7
06.53	Aug. 7	27.5	0.5	8.6	96	-1.8	2.0	97	8.2	12.4	1
			26.5	8.6	92	-2.5	2.2	96	8.2	12.7	1
06.24	Aug. 7	17.0	0.5	8.9	91	-0.4	0.5	96	8.0	12.4	6
			16.0	9.2	89	+0.6	0.0	97	7.8	12.1	15
06.23	Aug. 7	21.0	0.5	9.1	99	-1.2	1.3	98	8.1	12.6	2
			20.0	8.6	82	+0.5	0.0	100	7.9	12.8	7
06.12	Aug. 8	22.0	0.5	8.9	97	-1.7	1.9	96	8.2	12.4	3
			20.0	9.4	84	-1.6	1.4	97	8.1	12.2	9
06.54	Aug. 8	52.0	0.5	8.8	96	-1.2	1.1	96	8.2	12.4	1
			5.0	10.7	85	+1.8	0.0	96	7.7	11.9	25
06.22	Aug. 8	37.0	0.5	8.9	99	-1.5	1.7	100	8.2	12.2	0
			35.0	10.0	82	+1.7	0.0	98	7.7	12.1	20
06.20	Aug. 8	34.0	0.5	9.7	99	0.0	0.0	96	7.9	11.9	5
			32.0	9.8	80	+2.0	0.0	95	7.7	11.9	24
06.19	Aug. 8	9.0	0.5	9.6	98	0.0	0.0	96	8.1	12.3	8
			8.0	10.0	90	+1.2	0.0	97	7.9	12.2	13
06.52	Aug. 9	13.0	0.5	9.5	99	-0.88	1.0	96	8.1	12.7	4
			11.5	9.8	82	+1.0	0.0	95	7.8	12.3	11
06.17	Aug. 9	22.0	0.5	9.2	98	-1.4	1.6	99	8.2	12.2	5
			21.0	9.2	83	+1.0	0.0	98	7.8	12.2	17
06.15	Aug. 9	61.5	0.5	8.7	97	-1.8	2.0	97	8.2	11.8	1
			59.0	10.4	81	+2.4	0.0	97	7.7	12.2	30
06.13	Aug. 10	16.0	0.5	8.9	99	-1.7	1.9	98	8.2	12.5	1
			15.0	9.0	92	-0.7	0.8	97	8.1	12.2	4

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen		Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
				p. p. m.	Percent saturation						
06.14	Aug. 10	37.0	0.5	8.7	97	-1.7	1.9	96	8.2	11.3	2
			36.0	10.7	86	+2.0	0.0	97	7.7	12.2	30
06.28	Aug. 10	39.0	0.5	9.1	101	-1.8	2.0	97	8.2	12.1	1
			38.0	10.8	84	+2.4	0.0	98	7.6	12.7	30
06.27	Aug. 10	29.5	0.5	8.8	99	-1.2	1.4	98	8.2	12.7	0
			28.0	10.3	86	+1.9	0.0	96	7.7	12.5	17
06.26	Aug. 13	21.0	0.5	7.6	86	-2.0	2.3	95	8.3	13.1	4
			19.0	7.5	66	+1.2	0.0	95	7.8	13.2	9
06.50	Aug. 13	17.0	0.5	8.7	98	-2.0	2.3	98	8.3	13.0	2
			16.0	8.3	89	-1.2	1.4	97	8.2	13.1	2
06.29	Aug. 13	18.5	0.5	8.7	95	-2.6	2.9	97	8.3	11.6	1
			17.5	8.3	80	0.0	0.0	96	8.0	11.7	2
06.30	Aug. 13	18.0	0.5	8.9	99	-2.6	3.0	97	8.3	11.3	1
			16.0	7.9	71	+1.0	0.0	99	7.8	11.5	5
06.31	Aug. 13	17.0	0.5	9.2	102	-2.1	2.4	97	8.3	11.7	1
			15.5	6.4	63	+1.4	0.0	98	7.7	11.7	5
06.32	Aug. 15	12.0	0.5	7.6	80	-1.8	2.0	98	8.1	11.9	10
			9.0	7.8	80	-1.9	2.2	96	8.0	11.7	8
06.33	Aug. 16	19.0	0.5	8.3	89	-2.0	2.3	97	8.1	11.7	3
			17.0	7.4	74	-1.5	1.7	97	8.0	11.7	2
06.34	Aug. 16	21.0	0.5	7.9	86	-1.8	2.1	94	8.2	11.5	1
			20.0	8.3	85	-1.6	1.8	95	8.2	11.5	1
06.35	Aug. 16	21.5	0.5	8.3	92	-2.9	3.3	96	8.3	11.8	1
			19.5	8.3	78	-2.0	2.3	94	8.2	12.0	1
06.36	Aug. 16	22.0	0.5	8.3	92	-1.8	2.1	96	8.2	11.8	0
			21.0	8.0	82	-2.6	2.9	96	8.2	11.7	1
06.37	Aug. 16	17.5	0.5	8.0	91	-3.0	3.4	98	8.3	12.4	2
			16.5	8.1	90	-2.9	3.3	96	8.3	12.6	3
06.38	Aug. 17	15.0	0.5	8.1	90	-2.1	2.4	94	8.2	13.9	5
			14.0	7.9	88	-2.0	2.3	92	8.2	16.9	4
06.39	Aug. 17	21.5	0.5	8.3	92	-2.3	2.6	95	8.2	12.4	1
			20.5	8.3	90	-2.5	2.8	94	8.2	12.2	1
06.40	Aug. 17	24.5	0.5	8.2	91	-2.4	2.7	95	8.3	12.1	0
			23.5	7.1	64	+1.2	0.0	95	7.8	12.3	2

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen		Carbon dioxide (p.p.m.)	Phenolphthalein alkalinity (p.p.m. $CaCO_3$)	Methyl-orange alkalinity (p.p.m. $CaCO_3$)	pH	Chloride (p.p.m.)	Turbidity (p.p.m. SiO_2)
				p.p.m.	Percent saturation						
06.41	Aug. 17	24.0	0.5	8.3	92	-1.9	2.2	93	8.3	11.2	1
			23.0	4.8	44	+4.0	0.0	99	7.6	11.2	2
06.42	Aug. 17	20.0	0.5	8.3	92	-2.2	2.5	91	8.2	12.1	1
			19.0	5.6	52	+3.8	0.0	97	7.6	12.1	5
06.43	Aug. 18	21.0	0.5	8.2	93	-1.7	1.9	92	8.2	11.5	1
			20.0	6.1	60	+1.9	0.0	93	7.8	12.5	1
06.44	Aug. 18	23.0	0.5	8.2	93	-1.7	1.9	94	8.2	12.0	0
			21.8	7.8	77	-1.1	1.2	94	8.0	11.9	0
06.45	Aug. 18	23.0	0.5	8.3	94	-1.5	1.7	95	8.2	11.7	1
			22.0	4.4	42	0.0	0.0	93	7.9	11.6	1
06.46	Aug. 18	19.0	0.5	8.4	95	-1.7	1.9	97	8.2	12.2	2
			18.0	7.1	79	-1.8	2.0	97	8.1	12.2	2
06.47	Aug. 20	12.0	0.5	8.0	89	-1.9	2.2	92	8.2	10.5	9
			11.0	8.1	90	-1.9	2.2	92	8.2	10.7	9
06.48	Aug. 20	14.0	0.5	8.0	91	-2.6	2.9	94	8.2	10.6	5
			12.5	8.1	90	-2.2	2.5	93	8.2	10.2	7
06.49	Aug. 20	13.0	0.5	8.4	95	-2.6	2.9	88	8.2	10.0	7
			11.5	7.8	85	-2.0	2.3	90	8.1	9.9	8
08.01	Sept. 3	6.0	0.5	8.4	93	-0.88	1.0	97	8.1	11.8	2
			4.5	8.5	93	+1.0	0.0	96	7.8	11.6	4
08.03	Sept. 3	11.0	0.5	8.7	97	-2.0	2.3	96	8.2	12.2	1
			10.0	8.8	98	-2.2	2.5	96	8.2	12.3	3
08.04	Sept. 3	18.0	0.5	8.9	97	-2.0	2.3	97	8.2	11.8	1
			16.5	8.6	94	-1.7	1.9	95	8.2	12.0	1
08.05	Sept. 3	12.0	0.5	8.6	94	-1.8	2.0	98	8.2	12.2	5
			10.5	8.7	95	-2.1	2.4	97	8.2	12.2	3
08.06	Sept. 3	16.0	0.5	8.6	94	-2.0	2.3	98	8.2	12.8	2
			13.0	8.8	96	-1.8	2.1	97	8.2	12.2	4
08.11	Sept. 4	16.0	0.5	8.7	95	-1.8	2.0	95	8.2	11.3	0
			14.5	8.7	95	-2.1	2.4	96	8.2	12.3	0
08.09	Sept. 4	14.0	0.5	8.7	95	-2.2	2.5	96	8.2	12.8	0
			13.0	8.8	96	-2.2	2.5	95	8.2	12.5	0
08.07A	Sept. 4	21.0	0.5	8.7	95	-2.4	2.7	95	8.2	11.9	0
			20.0	10.1	108	-2.3	2.6	94	8.2	11.8	0

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen p. p. m.	Dissolved oxygen Percent saturation	Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
08.24	Sept. 4	17.0	0.5	8.9	99	-2.8	3.2	97	8.2	11.9	0
			16.0	7.8	81	-2.4	2.7	94	8.2	11.8	1
08.23	Sept. 4	21.0	0.5	8.9	99	-2.8	3.2	94	8.3	11.9	0
			20.0	8.0	80	+1.2	0.0	99	7.7	11.5	4
08.53	Sept. 4	26.0	0.5	8.6	96	-2.7	3.1	96	8.3	11.8	0
			25.0	7.4	74	-1.5	1.7	97	8.0	11.7	0
08.12	Sept. 5	21.0	0.5	8.8	100	-2.6	3.0	96	8.2	12.1	0
			19.0	8.2	74	-1.9	2.2	94	8.2	12.4	13
08.21	Sept. 5	57.0	0.5	8.8	98	-2.8	3.2	97	8.2	12.4	0
			55.0	10.0	78	+2.6	0.0	98	7.6	12.2	50
08.54	Sept. 6	53.0	0.5	8.8	98	-2.0	2.3	95	8.2	11.6	0
			52.0	10.3	80	+2.4	0.0	97	7.6	11.6	30
08.22	Sept. 6	37.0	0.5	8.8	98	-2.6	3.0	95	8.2	11.4	0
			35.0	8.1	68	+1.9	0.0	94	7.7	12.1	12
08.20	Sept. 6	36.0	0.5	8.9	101	-3.2	3.6	96	8.3	11.5	0
			35.0	9.3	76	+2.2	0.0	96	7.6	11.6	12
08.17	Sept. 6	20.5	0.5	9.2	102	-3.2	3.6	96	8.3	11.7	0
			19.5	7.9	79	0.0	0.0	97	7.9	12.1	2
08.52	Sept. 6	14.0	0.5	9.0	100	-3.0	3.4	95	8.3	11.6	0
			13.0	8.7	90	-2.7	3.1	96	8.2	11.5	0
08.19	Sept. 7	9.0	0.5	8.8	98	-2.4	2.7	95	8.3	11.8	0
			8.0	8.7	97	-2.6	3.0	94	8.3	11.6	1
08.15	Sept. 7	60.0	0.5	8.9	99	-2.6	3.0	95	8.3	11.8	0
			58.0	10.0	80	+2.0	0.0	94	7.6	11.3	30
08.14	Sept. 7	38.0	0.5	9.0	100	-2.5	2.8	95	8.3	11.9	0
			37.0	9.8	90	+1.6	0.0	95	7.7	11.9	15
08.13	Sept. 7	16.5	0.5	8.8	98	-2.6	3.0	94	8.3	12.2	0
			15.5	8.3	90	-1.9	2.2	94	8.1	12.2	0
08.26	Sept. 9	20.0	0.5	8.6	96	-2.3	2.6	93	8.3	12.5	0
			19.0	8.2	80	-1.4	1.6	93	8.1	12.5	1
08.28	Sept. 9	39.0	0.5	8.9	99	-2.6	3.0	95	8.3	11.9	0
			37.0	9.6	78	+1.4	0.0	95	7.6	12.0	15
08.27	Sept. 9	29.0	0.5	9.2	102	-3.5	4.0	95	8.3	11.4	0
			28.0	8.6	76	+1.4	0.0	94	7.6	11.5	4
08.58	Sept. 12	22.0	0.5	8.6	92	-1.8	2.0	97	8.1	11.0	2
			20.0	8.1	73	-1.8	2.0	96	8.0	11.7	6

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen p. p. m.	Dissolved oxygen Percent saturation	Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.	Turbidity (p. p. m. SiO_2)
08.50	Sept. 12	14.5	0.5	8.9	95	-2.2	2.5	96	8.2	11.7	4
			12.5	8.6	90	-2.7	3.1	97	8.1	11.8	4
08.29	Sept. 12	15.0	0.5	8.5	92	-2.5	2.8	99	8.2	11.3	10
			13.0	8.4	90	-2.4	2.7	98	8.1	11.2	10
08.30	Sept. 12	16.0	0.5	8.6	94	-2.6	3.0	96	8.2	11.7	9
			14.5	8.5	93	-2.2	2.5	...	8.1	11.7	10
08.31	Sept. 12	16.0	0.5	8.4	91	-1.8	2.0	98	8.1	11.5	10
			15.0	7.8	83	-2.2	2.5	96	8.1	11.6	13
08.32	Sept. 15	12.5	0.5	9.0	96	-2.1	2.4	95	8.1	11.8	5
			11.5	8.8	94	-2.2	2.5	95	8.1	11.6	5
08.33	Sept. 15	19.5	0.5	8.8	96	-2.2	2.5	93	8.2	11.4	4
			18.5	8.7	94	-3.1	3.5	96	8.2	11.7	5
08.34	Sept. 15	21.0	0.5	8.8	94	-2.6	2.9	93	8.1	11.3	3
			20.0	8.3	88	-2.2	2.5	96	8.1	11.3	3
08.35	Sept. 15	21.5	0.5	...	...	-2.3	2.6	95	8.1	10.7	7
			20.0	8.6	92	-2.5	2.8	96	8.1	10.6	10
08.36	Sept. 15	22.0	0.5	9.2	100	-3.3	3.7	94	8.2	11.6	5
			21.0	8.8	94	-3.3	3.7	96	8.2	11.8	...
08.37	Sept. 15	17.0	0.5	8.9	97	-2.6	3.0	94	8.2	11.4	5
			16.0	8.6	93	-3.1	3.5	96	8.2	12.2	5
08.38	Sept. 16	15.5	0.5	8.5	92	-2.6	2.9	95	8.2	13.7	6
			14.5	8.5	92	-3.1	3.5	96	8.2	13.7	5
08.39	Sept. 16	22.0	...	...	...	...	...	...	...	...	...
			20.0	8.3	89	-2.4	2.7	97	8.1	12.2	4
08.40	Sept. 16	24.0	0.5	8.5	92	-2.2	2.5	96	8.2	11.4	2
			22.0	8.5	92	-2.6	3.0	96	8.2	11.3	2
08.41	Sept. 16	23.0	0.5	8.2	88	-2.4	2.7	97	8.1	11.8	1
			20.0	8.4	90	-2.2	2.5	97	8.1	11.2	1
08.42	Sept. 16	20.0	0.5	8.8	96	-3.2	3.6	95	8.3	11.9	1
			19.0	6.9	75	-3.3	3.7	95	8.3	12.0	2
08.43	Sept. 17	21.0	0.5	8.8	95	-2.6	3.0	94	8.2	11.8	2
			19.0	8.7	95	-2.3	2.6	94	8.2	11.8	2
08.44	Sept. 17	23.0	0.5	8.8	95	-2.8	2.1	94	8.2	11.7	0
			21.0	...	...	-1.9	2.2	96	8.2	11.8	1

(Continued)

Table 13. --Chemical analyses of Lake Erie, June 7-September 19, 1929 (Continued)

Cruise and station	Date	Water depth (meters)	Sample depth (meters)	Dissolved oxygen		Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
				p. p. m.	Percent saturation						
08.46	Sept. 19	17.0	0.5	8.6	92	-2.9	3.3	95	8.2	12.8	3
			15.5	8.8	94	-2.9	3.3	96	8.2	13.2	3
08.47	Sept. 19	12.0	0.5	8.5	91	-3.3	3.8	96	8.3	8.9	10
			11.0	8.6	92	-3.3	3.8	96	8.3	10.9	10
08.48	Sept. 19	14.0	0.5	8.9	95	-4.1	4.7	90	8.4	9.3	
			13.0	8.7	93	-4.0	4.6	92	8.4	9.3	
08.49	Sept. 19	13.0	0.5	9.2	96	-3.0	3.4	88	8.2	8.2	
			12.0	9.0	94	-3.0	3.4	86	8.2	8.0	

Table 14.--Analyses of harbor and river waters along the shores of Lake Erie, summer of 1929

Location	Date	Depth (meters)	Oxygen (p. p. m.)	Oxygen (percent saturation)	Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCo_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
Erie	June 6	0.5	6.3	62	+4.8	0.0	100	7.6	15.2	10
Buffalo Naval Res. Dock	July 7	0.5	7.5	82	+1.0	0.0	96	7.9	14.2	20
Dunkirk Harbor	July 5	0.5	7.3	79	+1.0	0.0	96	7.9	12.7	20
Port Stanley	July 11	0.5	8.3	80	...	0.0	109	7.7	11.3	50
Cleveland	July 15	0.5	0.29	3.3	+21.5	0.0	106	7.1	46.5	125
Buffalo Naval Res. Dock	Aug. 6	0.5	8.1	88	-1.4	1.6	95	8.1	13.5	22
		4.0	7.9	86	-1.4	1.6	97	8.1	13.9	24
Dunkirk Harbor at dock	Aug. 8	0.5	8.6	96	-1.8	2.0	99	8.2	12.8	18
		3.0	8.3	90	-0.7	0.8	99	8.1	12.9	25
Dunkirk inside break-	Aug. 8	0.5	8.8	96	-3.5	4.0	96	8.2	13.1	15
water		5.5	8.7	95	-3.3	3.8	95	8.2	13.4	14
Port Dover	Aug. 9	0.5	9.1	93	+0.8	0.0	104	7.9	12.3	21
		2.3	9.1		+1.2	0.0	103	7.9	12.5	24
Erie Sta. 1	Aug. 10	0.5	7.2	82	+1.9	0.0	90	7.7	15.3	3
		2.5	6.9	78	+1.9	0.0	93	7.7	15.6	4
Erie Sta. 2	Aug. 10	0.5	6.9	78	+2.0	0.0	92	7.7	15.5	2
		6.0	6.4		+2.5	0.0	93	7.6	15.5	3
Erie Sta. 3	Aug. 10	0.5	4.3	50	-5.6	0.0	96	7.5	15.6	
Erie Sta. 4	Aug. 10		5.1	58	+4.7	0.0	100	7.6	15.0	
Erie Sta. 5	Aug. 13	0.5	7.1	82	+1.0	0.0	99	7.9	13.7	8
		5.8	7.4	85	+1.2	0.0	97	7.8	14.2	10
Port Stanley	Aug. 16	0.5	6.3	67	+3.1	0.0	117	7.7	12.4	85
Ashtabula Sta. 1	Aug. 17	0.5	3.7	40	+8.5	0.0	77	7.1	23.0	30
		2.5	3.7	41	+8.6	0.0	77	7.2	23.0	35
Ashtabula Sta. 2	Aug. 17	0.5	7.9	86	-1.5	1.7	93	8.1	15.8	30
Ashtabula Sta. 3	Aug. 17	0.5	8.1	90	-2.5	2.7	96	8.2	14.4	22
Ashtabula Sta. 4	Aug. 17	0.5	8.2	91	-1.5	1.7	95	8.2	15.4	10
Rondeau Harbor	Aug. 18	0.5	7.9	86	-0.7	0.8	98	8.0	11.7	
Cleveland Sta. 1	Aug. 20	0.5	5.9	67	+3.1	0.0	98	7.6	24.5	40
Cleveland Sta. 2	Aug. 20	0.5	4.3	49	+8.2	0.0	105	7.3	49.5	50
Cleveland Sta. 3	Aug. 20	0.5	5.2	59	+4.9	0.0	101	7.4	32.7	43
Cleveland Sta. 4	Aug. 20	0.5	6.9	80	+1.3	0.0	94	7.7	19.5	17
Cleveland Sta. 5	Aug. 20	0.5	6.3	70	+3.0	0.0	96	7.6	24.5	19

(Continued)

Table 14. --Analyses of harbor and river waters along the shores of Lake Erie, summer of 1929 (Continued)

Location	Date	Depth (meters)	Oxygen (p. p. m.)	Oxygen (percent saturation)	Carbon dioxide (p. p. m.)	Phenolphthalein alkalinity (p. p. m. $CaCO_3$)	Methyl-orange alkalinity (p. p. m. $CaCO_3$)	pH	Chloride (p. p. m.)	Turbidity (p. p. m. SiO_2)
Cleveland Sta. 6	Aug. 20	0.5	7.1	79	-0.5	0.6	91	7.8	13.3	6
Buffalo Naval Res. Dock	Sept. 3	0.5	7.8	87	+2.5	0.0	99	7.6	15.1	11
Dunkirk Harbor	Sept. 5	0.5	7.5	84	-0.9	1.0	96	7.9	11.9	20
Sta. 1	Sept. 5	2.5	7.2	80	+0.8	0.0	100	7.8	12.2	20
Sta. 2	Sept. 6	0.5	8.2	91	-2.0	2.3	96	8.2	12.3	10
Port Dover	Sept. 7	0.5	7.2	80	+1.9	0.0	106	7.8	14.0	40
Erie Harbor	Sept. 12	0.5	6.8	76	+1.9	0.0	91	7.6	15.3	3
Port Stanley	Sept. 15	1.0	7.6	80	+2.0	0.0	...	7.8	14.7	110
Ashtabula	Sept. 16	1.0	5.2	55	+7.0	0.0	69	7.2	32.8	40
Rondeau	Sept. 17	1.0	8.0	84	-1.4	1.6	93	8.0	10.6	25
Cleveland	Sept. 19	0.5	6.9	72	+2.0	0.0	98	7.6	23.2	10
Buffalo Naval Res. Dock	Aug. 3	0.5	7.6	86	-0.5	0.6	97	7.9	14.8	7
Buffalo Sta. 2	Aug. 3	0.5	7.9	89	-1.2	1.4	94	8.1	12.7	3

CHEMICAL OBSERVATIONS ON POLLUTION

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CONTENTS

INTRODUCTION

An important aspect of the Lake Erie investigations was a determination of the extent and concentration of pollution from sewage and industrial wastes. During the second summer, i.e. 1929, the boats Veto and Investigator, belonging to the Ohio State Division of Fish and Game were used for chemical investigations on the western end of the lake in the interims between the regular monthly cruises of the Shearwater. The data and discussion of the results of analyses made in this western area appear in another report dealing with the general investigations in that region (Wright 1955). The present paper deals chiefly with the work performed on the Shearwater during the summer of 1929, with some consideration also of the preliminary results of the first season's work in 1928.

METHODS

During the first year when investigations were initiated in the eastern part of the lake, analyses were made on samples obtained at intermediate depths and at the surface and bottom. During the second season samples were collected at the surface and at the bottom of all stations visited, while at certain particular stations samples were also taken at various other depths. As far as it was possible to do so, all bottom samples were taken from a point 1 meter above the bottom. However, because of the rolling of the boat the distance of the sampler from the bottom was increased to 2 meters at certain times. For determinations the Standard Methods of Water Analysis of the American Public Health Association (1925) were used. The results are stated as parts per million in this report.

CENTERS OF POLLUTION

During the summer of 1928 a number of analyses were made by Roger Williams, Buffalo City Chemist, for the purpose of determining the extent of pollution, if any, in the open waters at the eastern end of Lake Erie. The results and conclusions from that work briefly were as follows: The amount of organic pollution was tested by several kinds of nitrogen analyses, all of which indicated no objectionable pollution in the open lake. The free ammonia content never reached more than 0. 038 p. p. m. of nitrogen and averaged 0. 016 p. p. m. Albuminoid ammonia showed a minimum figure of 0. 06 p. p. m. and a maximum of 0. 12 p. p. m. with an average of 0. 08 p. p. m. of nitrogen for the entire eastern end of the lake. The nitrate analyses indicated moderate amounts of nitrogen in its completely oxidized state. The largest quantity was determined in July at 0. 20 p. p. m.; the smallest occurred in August at 0. 08 p. p. m. Nitrates averaged about 0. 14 p. p. m.

As regards industrial wastes, the pH determinations and the phenolphthalein and methyl-orange titrations showed no indication of pollution. The range of all the observations was found to fall within the limits of variability which may be classed as natural phenomena.

The preliminary report (Fish et al. 1929) states that "as regards the open lake water the analyses warrant the conclusion that the lake proper is normal and free from objectionable pollution. In conclusion it ought to be pointed out that the analyses made and the conclusions drawn from the assembled data do not apply to the conditions that may exist in shallow water near shore."

Table 15.--The normal conditions of the surface of Lake Erie, summer of 1929

Determination	Units	Range
Dissolved oxygen	p.p.m.	8.0- 10.3
	percent saturation	88.0-106.0
	ml per L.	5.6- 7.2
Phenolphthalein alkalinity	p.p.m. of $CaCO_3$	1.00 4.0
Methyl-orange alkalinity	p.p.m. of $CaCO_3$	90.0-100.0
Free carbon dioxide	p.p.m.	0.0- 4.0
Hydrogen-ion concentration	pH	8.1- 8.3
Chloride	p.p.m.	11.3- 12.6
Turbidity	p.p.m. of SiO_2	0.0- 9.0

In the following summer of 1929, it was decided to extend investigations throughout practically the entire lake and also to test conditions in the more important harbors which were suspected as being sources of domestic and industrial pollution.

Normal lake conditions are represented by results from 55 stations on Lake Erie (table 15). The turbidity averaged consistently higher at both ends of the lake where the water is more shallow, and the chloride content was lower at the west end. Abnormalities can easily be detected in a given sample by comparing its analysis with the normal values.

Buffalo Harbor

At the beginning of the July cruise of the *Shearwater*, samples were taken from the Black Rock Canal at the Naval Reserve Dock and from the lake at the Buffalo water intake crib. The oxygen saturation was 82 percent at the surface of the canal, while the surface and bottom samples at the crib showed saturations of 92 percent and 98 percent respectively. The presence of free carbon dioxide together with 14.2 p.p.m. of chloride in the canal, as compared with a negative carbon dioxide content and a chloride content of 12.1 p.p.m. at the intake crib, indicated the existence of undesirable conditions in the canal.

On the third day of August the canal surface at the same dock showed an oxygen saturation of 86 percent and a chloride content of 14.8 p.p.m. At a point 50 yards within the north entrance to Buffalo Harbor the surface oxygen saturation was 89 percent and the chloride value had fallen to 12.7 p.p.m. At the intake crib the oxygen saturations were 98 percent for the surface and 96 percent for the bottom, with corresponding chloride values of 12.1 p.p.m. and 12.3 p.p.m. (fig. 40).

The percentage of saturation of oxygen in the canal surface on September 3 was 87 percent with 15.1 p.p.m. of chlorides, 2.5 p.p.m. of free carbon dioxide, and a pH value of 7.6. The canal surface was coated with an oil film, and gas bubbles rose through the water. On the same day at the intake crib the oxygen saturation of the surface was 93 percent; chlorides were 11.8 p.p.m.; the pH value was 8.1; and a negative carbon dioxide value was found.

The difference between the canal and intake samples in all cases, and the gradation from the canal to the lake shown by the August samples, indicate that polluting materials were present in the harbor water. If no wastes were emptied into the harbor at Buffalo, the canal and harbor water would show the same or very nearly the same analysis that the lake water does, for most of the canal and harbor water flows direct from the lake. Buffalo Creek makes the only other addition of importance.

The fact that wastes in the canal were no more concentrated than found was due to the continuous flow of water down the canal. This flow carried the putrefactive matter away from the harbor, thus eliminating the pronounced effects which would have been obtained if there were no outlet. The cleansing action of increased flow from the lake because of westerly winds, could be detected by the increase of oxygen saturation, lowering of the chloride content, and change in the hydrogen-ion concentration after strong winds.

The drainage afforded to Buffalo by the Black

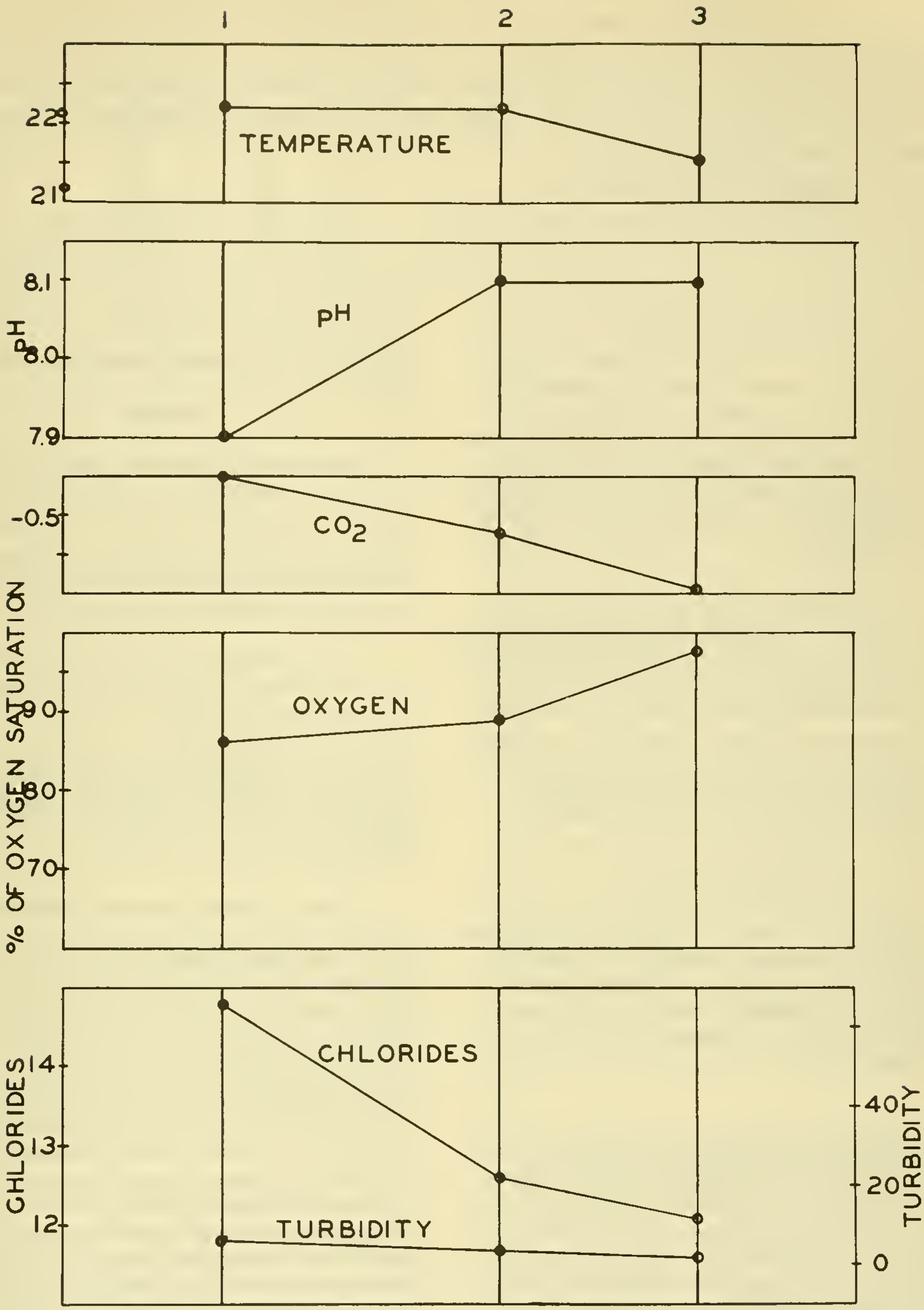

Figure 40. --Gradation of Buffalo Harbor waters from Black Rock Canal to Intake Canal.

Table 16. --Analyses of the water of Dunkirk Harbor, August 8, 1929

Point at which sample was taken	Central Avenue dock (west side)	Second red spar	Red can buoy No. 2	Station 11
Distance from preceding point in meters		600	500	1,600
Dissolved oxygen (percent saturation)	96	96	96	97
Free carbon dioxide (p. p. m.)	1.8	3.5	2.9	1.9
pH	8.2	8.2	8.2	8.2
Chloride (p. p. m.)	12.8	13.1	12.8	12.2
Turbidity (p. p. m. SiO_2)	18	18	7	5

Rock Canal and the Niagara River allows the wastes of the city to be disposed of most conveniently. The flow of the river is so large that the dilution of the canal water below the junction of the canal and river averts any harm to the aquatic life. The only danger that may follow the addition of untreated wastes to the river lies in the use of the river water without preliminary purification.

The direction of flow of the water of Buffalo Harbor is such that it is practically impossible for Buffalo's wastes to enter the lake. Wastes from Lackawanna may do this, but they do not seem to get far off shore because of the almost continuous breakwall. While the combined wastes of these two cities have little effect on the open lake, they certainly do harm fish life in the harbor and damage any possible spawning beds which may lie within it.

Stations 06, 24, and 09

Station 06 was about 1 1/2 miles off Port Colborne and station 24 was about 3 miles off Port Maitland. Analyses made on each of the 4 cruises showed no evidence of any substances that may have been discharged into the lake by either of the towns or the Grand River.

Station 09 lay about 1 1/2 miles off the mouth of Cattaraugus Creek and about 2 miles off the mouth of Silver Creek. The oxygen saturations at this station were low in June and July, while in August the bottom saturation only was low, although the surface and bottom temperatures were the same. High chloride values were obtained on 3 cruises: June, July, and September. These facts indicate that polluting substances were being dumped into the lake by these creeks and bear out reports of pollution on both streams. The added substances had been so diluted by the time they reached station 09 that no harm to fish could have resulted at the station. Inshore conditions were probably bad at the mouths of both streams.

Dunkirk

The dilution afforded by the harbor water is depended upon for the disposal of Dunkirk's sewage, which is emptied into the harbor. The shore to the east of the Central Avenue dock is made up of a deposit of granular sludge formed by the decomposition of sewage emptied into the harbor.

On July 5 the oxygen saturation found on the west side of the Central Avenue dock was 79 percent with a high free carbon dioxide content, and a pH of 7.9. On the same day at station 11, 1 mile off Dunkirk, the oxygen saturation was 91 percent, the pH value was 8.2, and negative carbon dioxide was found, while the chloride content agreed with that found in the harbor.

A series of samples was taken in Dunkirk Harbor on August 8. The first sample was taken on the west side of the Central Avenue dock; the second in the ship channel at the second red spar, coming into the harbor; and the third at the red can buoy, No. 2, which lies just outside of the harbor entrance. The analyses of these 3 samples, together with the analysis of a sample taken at station 11 on the previous evening, are given in table 16. This series showed that there was no variation of any significance from the harbor to the lake in oxygen saturation, pH value, or carbon dioxide content. The chloride content was slightly greater in the harbor than in the open lake. The turbidity alone showed a change, dropping off regularly as the dilution of the harbor water by the lake water increased. The high oxygen saturation in the presence of known pollution was due in all probability to the extensive weed beds which covered a large area in the west side of the harbor.

In September station 11 was normal with a turbidity of 0 p. p. m. On the next day the water on the west side of the Central Avenue dock gave an 84 percent oxygen saturation at the surface, 80 percent at the bottom, free carbon dioxide, and a turbidity of 20 p. p. m. On the following day the water on the east side of the dock was 91 percent oxygen saturated.

The results of the analyses of the water of Dunkirk Harbor show that critical conditions did not exist. The extent of the influence of the sewage was limited as it was dissipated in less than a mile of lake water. If critical conditions did exist at any point,they were restricted to the immediate vicinity of the sewer outfalls. The activity of the extensive weed beds seemed to counteract the effect of the sewage during the summer months. Critical conditions will develop, however, when the activity of the water weeds and algae decreases, since all factors tending to produce such conditions are operative.

The sludge deposits, in addition to rendering the shore unsightly, have probably ruined a good part of the spawning grounds lying in this naturally protected harbor.

Stations 11 and 12, and Port Dover

Station 11 lay directly in line with the flow from the mouth of Canadaway Creek, which empties the effluent of the Fredonia sewage disposal plant into the lake. Station 11 never varied from normal, however, although Canadaway Creek was reported to be polluted.

Station 12 was off the mouth of Chautauqua Creek, which flows by Westfield. Although surface samples taken at this station were normal at all times, the bottom samples yielded results indicative of pollution. These abnormal results were due, however, to a layer of cold water which extended into this region throughout the summer. This phenomenon will be further discussed later.

At Port Dover small fluctuations in oxygen and chloride results indicated the presence of slight pollution, but the effects are of no importance, for the substances which would cause trouble are soon disseminated in the lake.

Erie

The water of the enclosed harbor at Erie has a very deep color due to its organic content. This color is so deep that the water appears to be black when viewed through a considerable depth.

On the June cruise of the Shearwater conditions were normal at station 26, which was 5 miles directly off Erie. In Erie Harbor a sample was taken at the Anchor Coal Company's dock. This dock lies at the head of the first slip east of the Pennsylvania elevator. The water here was in bad condition, but the sample was not representative of general harbor conditions.

On the August cruise, 3 samples were obtained in the harbor at Erie, 2 outside the harbor, and 1 at station 26. The first sample was taken along the south shore of the harbor, about 200 feet east of the public steamboat landing. The water was very dark in color and contained much suspended matter; the Secchi disc reading was 2. 1 meters. Gas bubbles rose continuously through the water. The second sample was taken in the open harbor about 100 yards south of red buoy No. 8. The third was taken in the ship channel about 150 yards west of the harbor entrance.

The first sample taken just outside the harbor was collected at black buoy No. 1A. The second outside sample was taken 2 days later at the black gas buoy No. 1. The water at this buoy was dirty brown in color, because of the great amount of suspended matter. On the same day sludge floated on the surface of the harbor from the red buoy No. 8 to the harbor entrance. This material was brought to the surface by the heavy shipping activity of the previous day. When struck by waves the clumps of sludge broke up, forming an inky suspension in the water.

A sample taken at station 26 on the same day showed normal conditions for the open lake surface. The results of the analyses of the harbor samples are plotted in figure 41. In September, station 26 was normal on the ninth. On the twelfth the harbor water, after thorough mixing for 2 days by a strong westerly wind, showed an oxygen saturation of 76 percent, a chloride content of 15. 3 p. p. m. , a pH of 7. 6, and

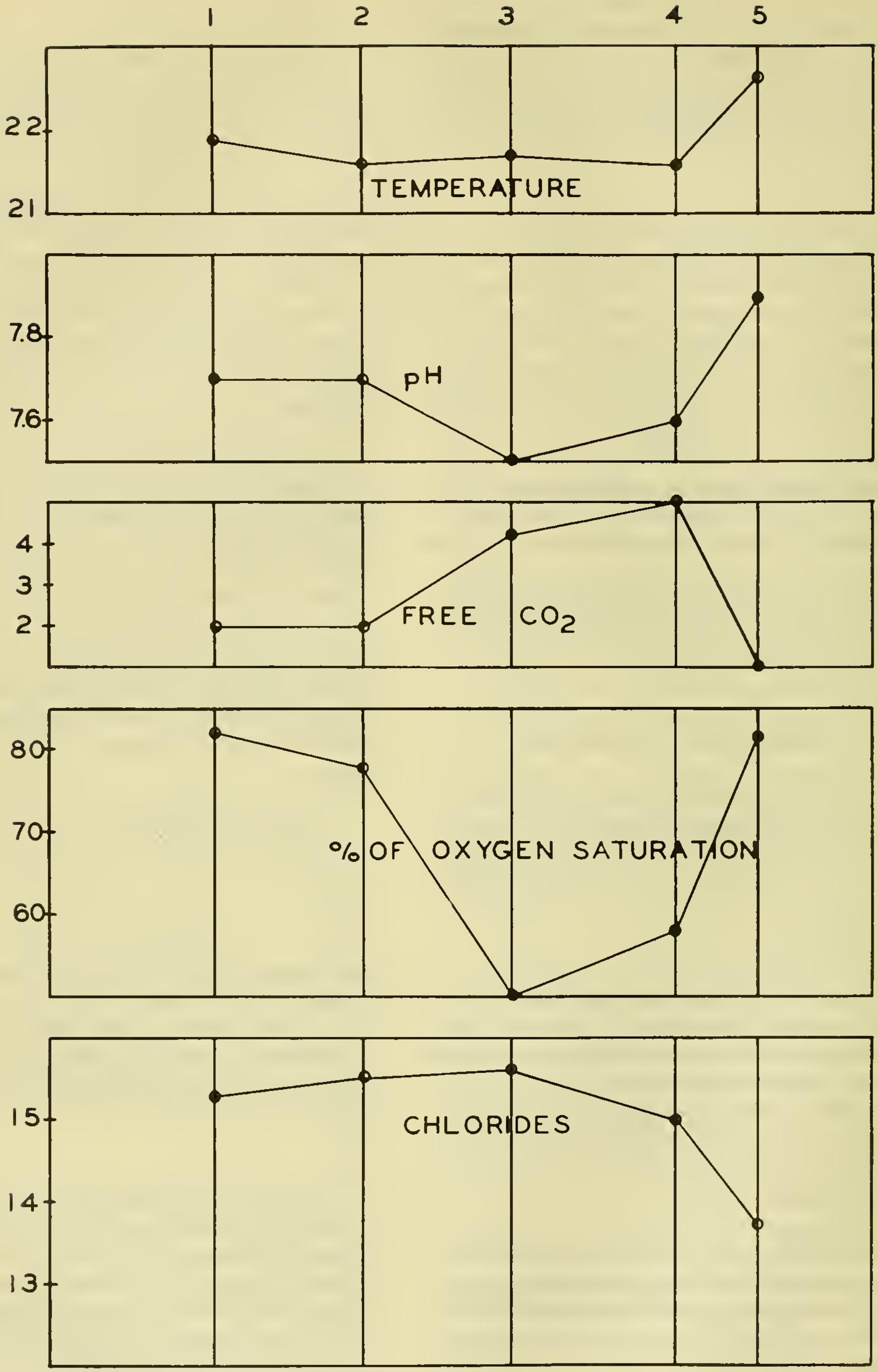

Figure 41. --Surface waters of Erie Harbor August 10 and 13, 1929.

1.9 p.p.m. of free carbon dioxide. Gas bubbles rose through the water from the decomposing deposits.

Detritus was found on the shores and in the harbor at all times. Sludge deposits seemed to cover a good portion of the eastern half of the harbor; the continual rising of gas bubbles indicated decomposition at the bottom. These bottom deposits make the harbor unsightly at times, since they are easily stirred up by freighters.

There can be no question of the existence of critical conditions in Erie Harbor. The existence of these conditions is due, undoubtedly, to the inclosed nature of the harbor, which makes it a natural sedimentation basin. Consequently, the effect of the wastes is more pronounced in the harbor, where the greater part of the decomposition takes place. The effect on the lake water is not as great as direct addition would be, since much of the waste is decomposed in the harbor. Water issuing from the harbor is almost in critical condition at buoy No. 1A, but has been greatly improved by the time it has been diluted and carried to buoy No. 1 (fig. 41).

The sulphite pulp mill of the Hammermill Paper Company empties a considerable volume of waste into the lake outside of the harbor along the south shore. This mill has a pulp capacity of 240,000 pounds per 24 hours. The waste from such a mill undoubtedly produces critical conditions near its point of entry. There is the possibility that the low oxygen saturation at black buoy No. 1 was partly due to this sulphite waste in addition to the harbor wastes.

Port Burwell and Port Stanley

Any additions to the lake at Port Burwell did not show in the analyses of samples taken at station 31 throughout the summer. Surface conditions were always normal, while bottom conditions varied considerably because of temperature changes.

The harbor water at Port Stanley showed low oxygen saturation in July and August. In August conditions were worse than in July, since free carbon dioxide with a correspondingly low pH value was found. The amounts of clayey matter suspended in the grayish-brown harbor water was so great that indicators added to the samples were rapidly absorbed. This absorption may account for the low oxygen saturations.

Station 32 off Port Stanley was normal at all times during the summer, so that even if the harbor water at Port Stanley was slightly polluted, it had little or no effect on the lake. The harbor water of Port Stanley was safe for fish, as small fish were taken in the plankton hauls made in the harbor at the times when the conditions were worst.

Ashtabula

At Ashtabula Harbor the Ashtabula River empties into the lake. The presence of polluting materials in this river was obvious and the condition of the harbor water was made to appear worse because of the additions of iron ore from the ore docks. This suspended iron imparted a characteristic red color to the water.

On the June, July, and August cruises the chemical conditions at station 37 were normal. This station lay about 2 miles directly off Ashtabula Harbor. The low oxygen saturation found at the bottom of this station in June was due to the penetration of a cold water layer to within 2 miles of the harbor. The chloride content of the water was steady at this station, with the exception of a slight lowering in July.

On August 17, samples were taken at four places in Ashtabula Harbor. The first was taken about 50 yards above the bascule bridge, the first bridge over the river. The second sample was taken at the end of the ore docks while the Shearwater lay in mid-channel, northwest of the end of the east dock. The third sample was obtained about 50 yards southeast of the west breakwall light. The last sample was taken in the channel about 50 yards off the harbor entrance.

The results of the analyses of these 4 samples are plotted in figure 42. From these data it will be seen that critical conditions existed in the river above the bridge. By the time the water had reached the ends of the docks it had recovered greatly, but still showed signs of pollution. However, the samples at the breakwall, both inside and out, show that the water was almost normal at these points.

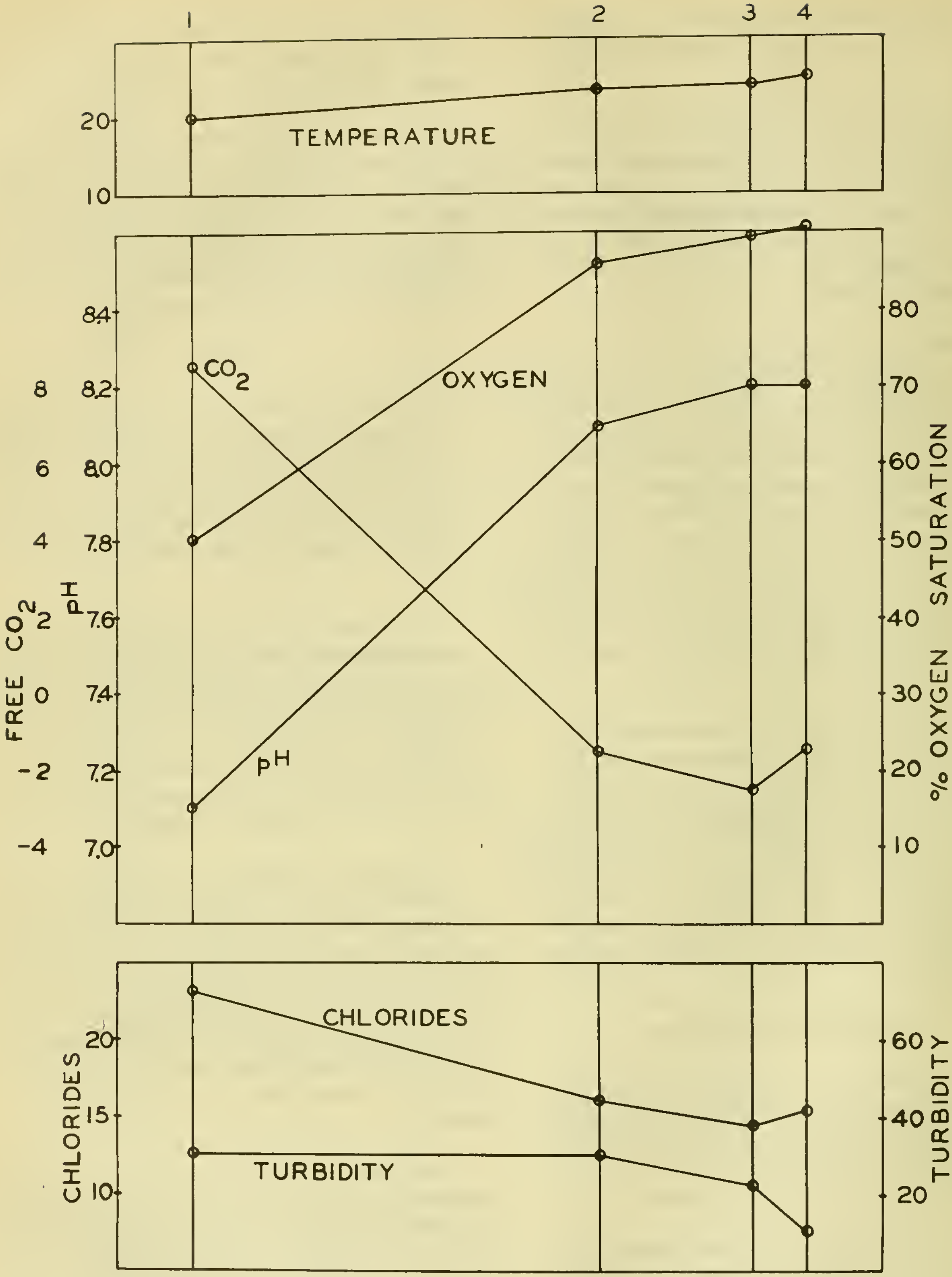

Figure 42. --Surface waters of Ashtabula Harbor.

In September, station 37 was normal as usual, but the river, 50 yards above the bascule bridge, showed almost critical conditions with an oxygen saturation of 55 percent, pH of 7.2, chloride content of 37.8 p.p.m., 7.0 p.p.m. of free carbon dioxide, and a turbidity of 40 p.p.m.

The gradation in figure 42 and the other analyses show that the polluted waters of the Ashtabula River are diluted to safe conditions for fish life outside the river mouth. There is no indication that the waters of Ashtabula River have any harmful influence on the lake beyond the local effect in the river and harbor.

Station 38

Conditions on the first 3 cruises were normal at station 38, off Fairport, with the exception of the chloride content. Great differences were found between the chloride values at the bottom and at the surface. In June and August the bottom chloride content was 3 p.p.m. greater than that of the surface, while in July the surface content exceeded that of the bottom by 4 p.p.m. In September both the top and bottom results agreed, but were higher than normal for the lake. This fluctuation was due to the dumping of industrial waste into the lake, probably at Fairport. This waste must be of considerable concentration when added to the lake water, as it could be detected at a distance of 3 1/2 miles out of Fairport. With the exception of a case at Toledo, this is the greatest distance that waste could be detected directly out in the lake from its point of entry. There is also the possibility of phenolic wastes entering the lake here.

Cleveland

If any of the wastes dumped into the lake at Cleveland did affect the water for a distance of 7 miles out into the lake, the effect would not be likely to show up at station 46, as this station lay too far to the west of Cleveland. The general drift of the lake water is to the northeast of Cleveland, and consequently, would carry wastes away from station 46. This station was normal at the surface throughout the summer.

In July a sample was taken in the Cuyahoga River about 25 yards below the New York Central Railroad bridge, which crosses the river near its mouth. The conditions found here were the worst encountered on the lake. The oxygen saturation was 3.3 percent; the chloride content was 46.5 p.p.m.; the free carbon dioxide amounted to 21.5 p.p.m.; turbidity reached 125 p.p.m.; and the color was very high. The high turbidity and color of the water were due to suspended matter, iron contributing most of the color. The odor of the river was musty and an oil film covered the surface. This mass of polluted water extended beyond the breakwall, where a distinct line showed the beginning of the clear lake water.

A sample was taken at the United States Engineer's dock on August 19, about 50 yards from the city pier at East Ninth Street. Here an oxygen saturation of 67 percent was found, with 24.2 p.p.m. of chloride; pH of 7.6; 3.1 p.p.m. of carbon dioxide; and a turbidity of 40 p.p.m. The color of the harbor water was dirty brown, clearing up a little in the open parts of the harbor.

On the same day 5 samples were obtained on a line running directly out of the river into the lake. The first sample was taken about 50 yards off the mouth of the river. The water's color was deep red, and the extent of the undiluted river water could be easily traced. The surface was covered with oil, and the musty odor was strong and disagreeable.

The second sample was taken within the protective breakwall of the main entrance to the harbor. This point was in mid-channel, about 50 yards from the main breakwall light. Two hundred yards off the main breakwall light the red color was still present. A third sample was taken there. The colored water extended about 400 yards off the main light, and a fourth sample was taken at that distance. A few yards beyond this point a very sharp break showed the limits of the polluted water. A fifth sample was taken just outside of the break.

It will be seen from figure 43 that critical conditions existed in the river and persisted, with little improvement, to the breakwall. However, 200 yards off the entrance the water, though far from normal, was out of the critical region. At 400 yards off, the analysis showed the presence of worse conditions than were found in the preceding sample. However, the water improved remarkably in the next 10 yards, and from there on out into the lake improvement was regular.

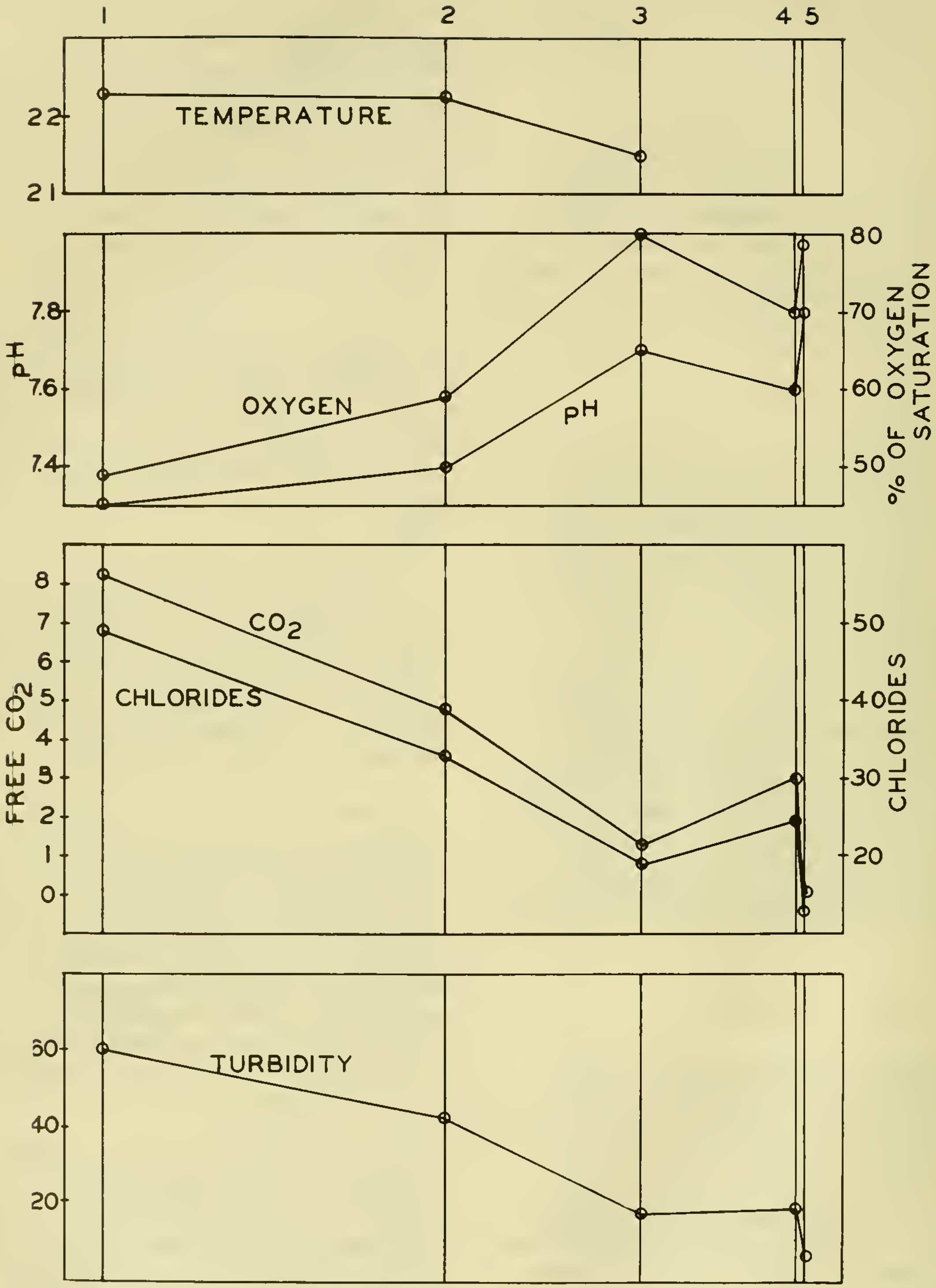

Figure 43. --Surface samples from Cleveland Harbor.

In September a sample taken at the outer end of the United States Engineer's dock showed an oxygen saturation of 72 percent, a chloride content of 23. 2 p. p. m., and a turbidity of 10 p. p. m. This was found after a 2-day "blow" had mixed the harbor water well.

The conditions found in the Cuyahoga River and Cleveland Harbor, together with those found in the Maumee River at Toledo, were the worst found on the lake. Critical conditions were found to extend from the river to the breakwall. In the river the carbon dioxide alone, 21 p. p. m. in July, would have caused the death of fish without the added help of the oxygen shortage. In the relatively short distance of 2, 000 yards, however, the polluted water was out of the critical stage and well on its way to normality. On the other hand, the flow of water is to the northeast at Cleveland; consequently, these wastes from the river are carried easterly through the harbor. In August and September conditions were bad at East Ninth Street, a distance of about 1 mile from the river mouth, but they were much improved over river conditions. The further addition of wastes all along the shore to the east of the Cuyahoga River makes the extent of Cleveland's pollution possibly the greatest on the lake. As a result of this, even though the harmful substances do not get far out into the lake, they do affect the water for probably 10 miles along the shore.

The wastes from Cleveland contain chemicals of various kinds because of the variety of industrial wastes. These chemicals increase the harm done by the wastes and affect water supplies by imparting disagreeable tastes. However, the effect of these chemicals on fishes is probably not extended over a greater area than is the detectable pollution.

Lorain

The water samples taken at station 47, 2 1/2 miles off Lorain, were normal throughout the summer.

Sandusky

In order to determine the conditions of the water of Sandusky Harbor, samples were taken in the harbor and in various parts of Sandusky Bay. On July 24, a sample was obtained at the dock of the Cleveland, Cincinnati, Chicago and St. Louis Railroad. This sample showed conditions to be normal for this part of the harbor, although an 11-percent difference in oxygen saturation was found between the top and bottom.

A group of samples was taken in the harbor and bay at Sandusky on August 28. A sample taken at the Chippewa dock showed an oxygen saturation of 62 percent, carbon dioxide content of 6. 0 p. p. m., a pH of 7. 7, chlorides to the extent of 13. 2 p. p. m., and a turbidity of 60 p. p. m. This sample showed that wastes were being emptied into the harbor by the city.

A second sample taken at the mouth of Mill Creek, seining station 34, indicated undesirable conditions as bad as those found in the harbor. A third sample was taken at the western end of the New York Central Railroad bridge across Sandusky Bay. This was seining station 29 and on the lower bay side of the bridge. The water was almost normal here, the oxygen saturation being 86 percent. The turbidity was high, but a high turbidity was found in the water of the bay at all times.

The water entering the bay from Sandusky River was sampled also. This water was normal, with the exception of high turbidity. While reports of pollution in this river had been made, no indications of such a state were found at the time of sampling. On the basis of the single sample, the only conclusion that can be drawn is that any wastes emptied into the river had been stabilized by the time they reached the bay. However, the potentiality of pollution by beet sugar wastes from Fremont exists in autumn, and from Bucyrus, Fremont, and Tiffin at all times.

The conditions in Sandusky Harbor are nearly critical, and would be worse in the northern part of the harbor. The wastes of a crayon factory, a paper mill, and other industrial plants are emptied into the bay, the colored wastes of the crayon plant being the most obvious. These colored bodies are inert chemically, but other products released with them may be harmful to aquatic life. Sandusky Bay offers a large volume of water for the dilution, and disposal of the wastes, but deposits from these wastes have probably covered a good portion of the harbor.

SUMMARY

The shore waters of Lake Erie have been shown to be polluted by wastes from several harbors and creeks or rivers east from Sandusky, Ohio. These sources are:

1. Buffalo Harbor by Buffalo and Lackawanna
2. Station 9 from Cattaraugus Creek and Silver Creek
3. Dunkirk Harbor by Dunkirk
4. Erie Harbor by Erie
5. Ashtabula River and Harbor by Ashtabula
6. Station 38 from Grand River by Fairport and Painesville
7. Cuyahoga River and Cleveland Harbor by Cleveland and Akron
8. Sandusky Harbor by Sandusky.

Out of this number, critical conditions were found only in Erie Harbor, Ashtabula River, Cuyahoga River, and Cleveland Harbor. The potentiality for critical conditions must be assumed for Buffalo Harbor, Dunkirk Harbor, and Sandusky Harbor.

At several other points, which were not closely investigated or not investigated at all, pollution may be found. These are: Port Colborne, Conneaut, and the Black, Huron, Vermilion, and Sandusky rivers.

In all cases except two, where undesirable conditions were found, these conditions were so modified by the diluting action of the lake water that no harm to aquatic life could have resulted at the distance of a mile directly out in the lake. The two exceptions were found at Fairport and Toledo. At Fairport the effect of wastes was detectable at a distance of 3 1/2 miles and at Toledo at a distance of 5 miles. However, in both of these cases conditions were nearly normal at the distances given.

The effect of polluting matter is more of a shore effect than an offshore one. Because of this the influence of pollution at Buffalo, Erie, and Cleveland is extended over a large area without getting far out into the lake in a harmful form.

Chemicals introduced with wastes can be safely considered as sufficiently dispersed, when normal conditions are restored in the water, and their influence is not spread over a much greater area than is the detectable pollution.

Rivers, in addition to the harm done to their waters by wastes, have been spoiled for fish life by the deposition of sludges which undergo slow decomposition. Harbors and shores have been spoiled in like manner.

Spawning beds more than 2 miles offshore would not be affected by pollution unless heavy charges of wastes were added to the lake by nearby cities. The number of such sources is so low that very few spawning grounds in the lake proper have probably been influenced by pollution.

CONCLUSION

The results of this study justify the conclusion that pollution is not a factor in the decline of the fishes of Lake Erie. The diluting action of the lake is so great that detectable evidence of waste was not found at a distance greater than a mile from shore, except in two cases. However, this does not mean that pollution has had no action on the fish population of the lake. Its effect has lain in the killing of the fish formerly found in rivers and harbors now polluted, and in the effect, slight at most, on the spawning beds in the lake itself.

A SURVEY OF THE MICROPLANKTON OF LAKE ERIE

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CONTENTS

INTRODUCTION

In a commercial fisheries investigation such as that under consideration in Lake Erie, the determination of the kinds and quantity of fish food and the conditions for its production are very important aspects of the general problem. When limnological investigations were initiated on the western end of Lake Erie more than thirty years ago (H. M. Smith 1898, J.E. Reighard 1893) considerable attention was devoted to studies of the micro-fauna and flora of the regional waters. A number of valuable scientific contributions (Jennings 1900, Pieters 1902, Snow 1903) to our knowledge of the plankton resulted from those early efforts. In view of the basic nature of microplankton in the economy of the lake, quantitative and qualitative analyses are of practical significance and were included in the general survey of the lake in the summers of 1928 and 1929.

Those methods of investigation employed in the survey of the eastern end of the lake during the summer of 1928 were resumed on a larger scale in the season of 1929 so as to include practically the entire lake with the exception of the extreme western end. On each of the four biological cruises, executed with the U. S. Fisheries Steamer *Shearwater*, during the months of June, July, August, and September 1929, the plankton samples were obtained from some 55 different stations established at selected points throughout the entire lake (fig. 1), for the purpose of determining the seasonal, vertical, and horizontal distribution of the constituent species. Townet gatherings were made also at a number of points along the shore, especially during the month of August, for the purpose of comparing the marginal areas with the limnetic.

METHODS

Qualitative samples were obtained at each station by towing a No. 20 silk bolting cloth net, 1 foot in diameter, for 5 minutes at the surface. These samples were preserved with formaldehyde and used in the laboratory for purposes of identification and as a supplement to the quantitative sampling.

For quantitative purposes, collections of microplankton were obtained by the following method: At each station samples of water were taken from the surface and bottom by means of a Gould hand pump and rubber hose. Fifty liters were measured into a galvanized iron can and then strained through a No. 20 silk net with attached bucket. The organisms retained in the bucket were washed into a 4-ounce bottle and sufficient formaldehyde added to preserve.

For the purpose of recovering any organisms which were so small as to go through the No. 20 silk strainer, 1-liter samples of water were also taken from the surface and bottom. These samples were preserved with formaldehyde in glass fruit jars until they could be centrifuged.

In the laboratory, samples which had been strained from the 50-liter water samples were all concentrated to a standard volume of 20 cc. and preserved in vials for counting. The 1-liter samples of water were run at uniform speed through a Foerst centrifuge and the recovered organisms made up to a standard suspension of 10 cc.

Enumeration of the phytoplankton was accomplished by the standard random count method. The rotifers were, however, counted by a slightly different procedure. Exactly 1 cc. from the 20 cc. suspension was measured into a counting cell and all the individuals recorded. From these data the number of individuals or colonies per liter was computed.

Comparison of the results obtained for those forms caught by both the "1-liter centrifuge" and the "50-liter net" methods showed that the latter gave the more reliable quantitative data. There were very few species recovered by the centrifuge which were not also taken in the net. Therefore the net plankton data will be emphasized in the discussion of quantitative distribution. Since the results of the first season's work have already been published (Fish et al. 1929) the present paper will be devoted chiefly to the presentation of the new data acquired in the season of 1929.

THE SPECIES OF MICROPLANKTON

Taxonomic investigations of the micro-organisms in Lake Erie began a little more than 50 years ago. Kellicott (1878) in Buffalo, and Vorce (1880-1881) in Cleveland were carrying on simultaneous investigations of the diatoms, algae, protozoa, and rotifers found in the water supplies of their respective cities. New species of diatoms were described from Lake Erie by H. M. Smith (1878), and Kellicott (1885) published a number of notes on new and rare species of protozoa and rotifers from the waters of the Buffalo region. At about this time appeared Day's "Plants of Buffalo and Vicinity" (1882), a catalog which included records of the observations on cryptogams made by D. S. Kellicott, J. W. Ward, Francis Wolle, and others.

Additional contributions were made to our knowledge of the protozoa and rotifers by Jennings (1894, 1900) and Kellicott (1896, 1897). In more recent years Landacre (1908) and Stehle (1923) have published on the protozoa found at the western end of Lake Erie, while Pieters (1902) and Snow (1903) have presented valuable papers on the algae. Not until the present effort in 1929 was an attempt made to survey the microplankton throughout practically the entire lake.

The following list of species includes those organisms collected from the regular stations (fig. 1) in the summers of 1928 and1929. Gatherings from the rivers and harbors along the lake shores have not been included. The majority of species listed are therefore true plankton organisms (euplanktonts), though there are also chance wanderers (tychoplanktonts), and those capable of adapting themselves to the planktonic existence (faculative planktonts). It is probable that the methods employed were inadequate for the catching and identification of the protozoa and rotifers, and for these groups the work of previous investigators is recommended as a guide. The general classification of West and Fritsch (1927) has been followed.

The following series of symbols has been used to indicate abundance: T, trace; R, rare; C, common; A, abundant; VA, very abundant.

Isokontae

Ankistrodesmus falcatus (Corda) Ralfs. (R). Western part of the lake.
Ankistrodesmus setigerus (Schröd.) G.S. West. (R).
Chlamydomonas sp. (T). Shallow water near Buffalo.
Cladophora glomerata (Linn.) Kützing. (T). Occurred only twice, at surface.
Closterium acerosum (Schrank) Ehrenberg. (T). Occurred once.
Closterium aciculare var. subpronum W. and G.S. West. (R). June.
Closterium Dianae Ehrenberg. (R). Western end of lake.
Closterium parvulum Naegeli (R).
Closterium Venus Kützing. (R).
Coelastrum microporum Naegeli. (C). Widely distributed; microcenobial colonies were commonly found in September.
Cosmarium crenatum Ralfs. (T). Shallow water.
Cosmarium cyclicum Lundell. (R). Western end of lake.
Cosmarium pygmaeum Arch. (R).
Cosmarium quadrum Lund. (R).
Cosmarium reniforme (Ralfs) Archer. (R)
Crucigenia irregularis Wille. (A). Surface during August.
Crucigenia rectangularis (Naegeli) Gay. (R).
Dictyosphaerium ehrenbergianum Naegeli. (R).
Dictyosphaerium pulchellum Woods. (A). Widespread, especially in spring and autumn.
Eudorina elegans Ehrenberg. (C). Shallow water, particularly in August and September. Maximum abundance was estimated at about 300 colonies per liter.
Elaktothrix gelatinosa Wille. (R)
Elaktothrix viridis (Snow) Printz. (R).
Geminella sp. (R). Shallow western area.
Gloeocystis gigas (Kützing) Lagerheim. (R).
Gonatozygon monotaenium DeBary. (T).

Kirchneriella lunaris (Kirchner) Mobius. (R).
Micractinium pusillum Fresenius. (R). Found only a few times in the plankton of the Buffalo region in 1928.
Mougeotia sp. (R). In shallow water.
Nephrocytium agardhianum Naegeli. (R).
Oocystis borgei Snow. (C). Autospores forming in September.
Oocystis crassa Wittrock. (C). Polar nodules often visible only on old cells.
Oocystis elliptica W. West. (C). Might be included with O. Borgei, though the latter does show the differences pointed out by Miss Snow.
Oocystis eremosphaeria G.M.Smith. (R). Plastids numerous. Cells 24-38 microns broad, 42-46 microns long.
Oocystis lacustris Chodat. (C).
Oocystis parva W. and G.S.West. (R).
Oocystis solitaria Wittrock. (R). Perhaps should be included under O. crassa. The range of variation in the forms encountered in Lake Erie make it very difficult to definitely place some of the members of this genus.
Oedogonium sp. (T).
Pandorina morum Bory. (C). In August reproduction by micro-colonies was common.
Pediastrum boryanum (Turpin) Meneghini. (C).
Pediastrum duplex Meyen. (C). Widespread.
Pediastrum simplex Meyen. (C). Widespread.
Quadrigula chodati (Tanner-Fullman) G.M.Smith (R).
Quadrigula lacustris (Chodat) G.M. Smith. (R). Smaller than above and with a single pyrenoid.
Quadrigula pfitzeri (Schroder) G.M.Smith. (R). Cells in characteristic tetrads.
Scenedesmus abundans (Kirchner) Chodat. (R). Western part of the lake.
Scenedesmus bijugatus var. flexuosus Lemmermann. (R). Colonies usually contained 32 cells, but 16 and 8 were sometimes found, as observed by Miss Snow (1903).
Scenedesmus quadricauda (Turpin) de Brebisson. (R). Shallow areas.
Sphaerocystis schroeteri Chodat. (A). Reproduction by formation of micro-colonies frequent. A maximum of about 300 per liter in midsummer.
Spirogyra tenuissima (Hassal) Kützing. (R). Occurred as solitary filaments.
Spirogyra sp. (R). Found only relatively near shore.
Staurastrum floriferum W. and G.S.West. (R).
Staurastrum gracile Ralfs. (A). Most common desmid in the plankton. Maximum apparently during July and August.
Staurastrum longiradiatum W. and G.S.West. (C). Accompanying above species.
Stigeoclonium tenue Kützing. (R). Wanderer from the marginal zone.
Tetraspora lacustris Lemmermann. (R). Late summer.
Volvox globator (Linnaeus) Ehrenberg. (R). Near Cleveland in August.
Westella botryoides (W. West) de Wildeman. (R).

Heterokontae

Botryococcus braunii Kützing. (C). Occasional swarms in the surface tow, but never abundant in the quantitative samples.
Stipitococcus sp. ?. (T). Found once on Zygnema. In appearance resembling figures for this genus in West and Fritsch (1927).

Chrysophyceae

Dinobryon bavaricum Imhof. (R).
Dinobryon divergens Imhof. (C).
Dinobryon stipitatum Stein. (C). The combined species of Dinobryon reached 400 per liter at a number of stations in August and increased in September to 3,000 per liter at stations 27 and 29.
Mallomonas alpina Pascher and Ruttner. (R).
Synura uvella Ehrenberg. (R).

Bacillariales

Amphiprora ornata Bailey. (R).
Amphora ovalis Kützing. (R).
Asterionella formosa Hassal. (A). 27,000 per liter at stations 37 and 38 in June. Decline in July and August followed by an increase to 60,000 per liter in September at some of the western stations. Present in every sample in September.
Cocconeis placentula Ehrenberg. (R).
Cyclotella comta (Ehrenberg) Kützing. (C). In centrifuged samples.
Cyclotella meneghiniana Kützing. (R). In centrifuged samples.
Cymatopleura elliptica (de Brebisson) W. Smith. (R).
Cymatopleura solea (de Brebisson) W. Smith. (R). In surface tows.
Cymbella cistula (Hempr.) Van Heurck. (R).

Cymbella ventricosa Kützing. (R).

Diatoma elongatum (Lyngbye) Agardh. (C). Common at certain stations. Reached 6,700 colonies per liter (10 cells to a colony) in June 1929 at station 19. Decreased in July and was never so abundant again.

Diatoma vulgare Bory. (T).

Fragilaria capucina Desmazieres. (C). Less abundant than F. crotonensis with which it occurs.

Fragilaria crotonensis Kitton. (VA). In September in the western area reaching 68,000 per liter. Present elsewhere in almost every sample.

Fragilaria virescens Ralfs. (R).

Gyrosigma attenuatum (Kützing) Cleve. (R).

Melosira arenaria Moore. (R).

Melosira crenulata (Ehrenberg) Kützing. (A). Occurring with M. granulata.

Melosira granulata (Ehrenberg) Ralfs. (A). In June the combined species M. crenulata and M. granulata, totalled 64,000 per liter at station 46. Summer decline followed by an increase to 60,000 per liter at a number of stations in September.

Navicula rhyncocephala Kützing. (R).

Navicula sp. (T). Not true planktonts.

Nitzschia linearis (Agardh.) W. Smith. (R).

Nitzschia vermicularis Kützing) Hantzsch. (R).

Rhizosolenia eriensis H. L. Smith. Abundant at certain stations in both the surface and bottom samples, especially in the eastern area. In June 1929 there were about 300 per liter in the waters of the Buffalo area. C. M. Vorce (1880) states that the species is most abundant in the winter months and appears to favor cold water.

Stephanodiscus niagarae Ehrenberg. (C). Reached 2,500 per liter in the western area in September. Vorce (1880) found Stephanodiscus most abundant in the winter and early spring. The present author has found it the most common diatom in the city water supply of Buffalo in the winter months.

Surirella biseriata de Brebisson. (C). About 100 per liter in surface samples in September.

Surirella ovalis Meneghini. (R).

Synedra longissima W. Smith. (R).

Synedra pulchella (Ralfs) Kützing. (R). Occurred with S. longissima.

Synedra ulna (Nitzsch.) Ehrenberg. (C). Widespread.

Tabellaria fenestrata (Lyngb.) Kützing. (A). Maximum of 2,500 per liter occurred in September in the western part of the lake where the other filamentous diatoms were also very numerous. The average for Tabellaria in September was estimated at about 500 per liter and its zig-zag chains occurred in every gathering made during this month.

Tabellaria flocculosa Kützing. (R). Western area in September.

Dinophyceae

Ceratium hirundinella Müller. (C). Rare in June, except in Long Point Bay, but increasing in late summer to 500-800 per liter in September.

Peridinium sp. (R).

Euglenineae

Euglena sp. (R).

Myxophyceae

Anabaena circinalis (Kützing) Rabenhorst. (R). Locally numerous at some western stations in August.

Anabaena flos-aquae (Lyngb.) de Brebisson (C). Following the decline in numbers of Aphanizomenon, Anabaena flos-aquae increased rapidly during August when 3,000 colonies per liter were found in the waters at both ends of the lake. Fewer were taken in the middle area. In September the species declined.

Anabaena lemmermanni P. Richter. (R).

Aphanizomenon flos-aquae Ralfs. (A). Reached 4,000 per liter in the west in June. Declined in July and was replaced by other blue-green algae, Anabaena, Coelosphaerium, etc.

Aphanocapsa elachista var. conferta W. and G.S. West. (R).

Aphanocapsa elachista var. planctonica G.M.Smith. (C). Rather widespread in small quantities throughout the lake in August and September.

Aphanothece clathrata var. brevis Nordstedt. (T).

Aphanothece nidulans P. Richter. (T). At surface; frequently found as traces in the surface tows.

Chroococcus dispersus (von Keissler) Lemmermann. (R).

Chroococcus limneticus Lemmermann. (C). Occurred in small quantities in August and to a greater degree in September.

Coelosphaerium kuetzingianum Naegeli. (C).

Coelosphaerium naegelianum Unger. (C). More abundant than the preceding species with which it was usually associated. Following the decline of Aphanizomenon in July, Coelosphaerium became conspicuous in late summer until in September the combined species reached 9, 000 per liter at station 48.

Gomphosphaeria aponina Kützing. (R).

Gomphosphaeria lacustris Chodat. (R). Small quantities at several western stations in September.

Lyngbya aerugineo-caerulea (Kützing) Gomont. (R). Probably a chance wanderer.

Lyngbya birgei G. M. Smith. (R). Throughout the summer.

Merismopedia elegans A. Braun. (R).

Merismopedia punctata Meyen. (C). This species and the following in western area totaled 2, 500 colonies per liter at station 48 in September.

Merismopedia tenuissima Lemmermann. (C). Western stations in September. A variety of this species with cells remote from each other was very abundant at station 48. The cells of this variety were 2 microns in diameter and occurred in pairs, the rows of cells being 10 microns apart.

Microcystis aeruginosa Kützing. (C). August and September, particularly in the western area.

Microcystis aeruginosa var. major (Wittrock) G. M. Smith. (T). Should perhaps be included under the species.

Microcystis flos-aquae (Wittrock) Kirchner. (R).

Microcystis incerta Lemmermann. (C). Widespread.

Microcystis sp. ?. (C). August. The description of M. holsatica var. minor Lemmermann seems to fit the organism, but it may be a bacterium rather than a blue-green alga.

Oscillatoria sp. (R).

Protozoa

Acanthocystis chaetophora Schrank. (R).

Amoeba sp. (R). Probably due to the method of preserving the samples these forms were often overlooked.

Cothurnia sp. ?. (R). Occurring on Melosira; figured by Vorce (1882).

Difflugia cratera Leidy. (C). Widespread.

Difflugia globulosa Duj. (C).

Difflugia sp. Cylindrical form occurring with the other species.

Epistylis plicatilis Ehrenberg? (T). Western area at surface. The colonies were floating free, apparently having broken away from their substrata.

Monosiga ovata S. Kent. (R). Found occasionally on diatoms.

Sphaerophrya sp. (R).

Vorticella rhabdostyloides Kellicott. (C). Commonly found attached to Anabaena flos-aquae, reaching 1, 000 per liter in August when its host was abundant in the eastern part of the lake.

Rotifera

Anapus ovalis Bergendal. Abundant only at several stations east from Long Point, reaching 200 per liter there. Not found in the western area.

Anuraea aculeata Ehrenberg. (R).

Anuraea cochlearis Gosse. Ubiquitous but not very numerous, except at several eastern stations where the maximum numbers were estimated at about 100 per liter.

Apsilus sp. (T).

Ascomorpha sp. (T).

Asplanchna priodonta Gosse. (T).

Asplanchnopus milticeps Schrank? (R). Shallow water only.

Conochilus unicornis Rousselet. Widespread but not abundant except in shallow water east from Long Point Bay. In July 1928 it occurred in swarms near shore at several stations.

Gastropus sp. (R).

Harringia eupoda Gosse. (R).

Lecane luna Muller? (R).

Monostyla cornuta Ehrenberg. (R).

Monostyla quadridentata Ehrenberg. (R).

Notholca longispina Kellicott. (R). Widespread.

Ploesoma truncatum Levander. (R).

Ploesoma hudsoni Imhof. (R).

Polyarthra platyptera Ehrenberg. (R). Occurring throughout the lake, 1-10 per liter at the surface and bottom.

Synchaeta stylata Wierzejski. (T). Eastern area.

Triarthra longiseta Ehrenberg. (R).

Trochosphaera sp. (R). Only in shallow water in 1928.

DISTRIBUTION AND SEASONAL VARIATION OF MAJOR MICROPLANKTON GROUPS

Analyses of the samples obtained on the various cruises show considerable variation in both the quality and quantity of microplankton in different parts of the lake and at different times. The data shown on the maps and graphs (figs. 44-52) are portrayed in terms of the aggregate number of individuals or colonies per liter of all species belonging to the several groups found at each station. The groups emphasized are the diatoms (Bacillariales), the green algae (Isokontae, Heterokontae, Chrysophyceae, Dinophyceae, and Euglenineae), the blue-green algae (Myxophyceae), and the rotifers (Rotifera).

The method of plotting the data is as follows: The number of organisms per liter is taken as the volume of a sphere whose size is represented as a circle. It should therefore be remembered that the size differences of these circles represent volumes of plankton which vary with the cube of the radius. In the supplementary graphs (figs. 46, 51, 52) the cube root of the number of organisms per liter have been plotted for comparison of the abundance of the more important groups.

Vertical Distribution

In general the data indicate uniform vertical distribution of the phytoplankton in the shallow areas. Only in the deep area off Long Point did the plankton decrease in the lower levels. In 1928 the diatoms were found to extend into somewhat greater depths than the other groups of phytoplankton (Burkholder 1929). Even the diatoms decreased markedly at 50 meters where temperature and light were less favorable for the vital processes. There was a decided decrease in the green algae below 10 meters in these deep waters, but in the shallow areas very little vertical difference was found in their quantitative distribution. The average number of diatoms for all stations observed in the summer of 1929 amounted to 4, 000 per liter at the surface and 4, 300 per liter at the bottom. Since the greater part of Lake Erie is relatively shallow, these averages, of course, obscure the local conditions in deep water where there is a paucity of green forms at the bottom.

During June when the blue-green algae were extremely abundant in the central western area (fig. 48), almost the entire volume was concentrated at the surface. This is due to the relatively low density of the elaborated cellular contents, which resulted in the "bloom" remaining suspended in the upper layer. Later in the season, e. g. in the August pulse of the eastern area, there was little average difference in the abundance of blue-green algae at the surface and bottom.

The rotifers were usually found in greater numbers at the surface, if there was any vertical gradient at all. The majority of stations, however, showed remarkable uniformity in the vertical distribution of this group. Notable exceptions may be pointed out in the case of the samples collected in Long Point Bay, Port Maitland, and south from Port Colborne. At these stations Anapus ovalis was very abundant and apparently thrived better at the surface.

Horizontal Distribution

Environmental conditions influencing the growth and reproduction of the plankton vary widely from place to place throughout Lake Erie. Since the time required in running each monthly cruise from Buffalo to Put-in-Bay, Ohio, was about 2 weeks, it should be remembered that the factors of seasonal periodicity, as well as simultaneous horizontal differences in the physical and chemical constituents, were probably active in causing the variations plotted on the maps.

Diatoms were relatively more abundant in the shallow waters near shore in June (fig. 44), decreasing at the deeper stations and also at certain shallow stations, e. g. off Rondeau, Ontario, and Lorain, Ohio. In July the greatest numbers occurred in the eastern part of the lake, mere traces being found at the western stations along the American shore.

The horizontal distribution of diatoms nearly approached uniformity in August (fig. 45). Only off Fairport, Ohio, were large numbers taken in the catches, the rest of the stations showing a remarkable diatom paucity at this time.

Relatively few diatoms were taken at the eastern stations in early September, but during the second week diatoms were very abundant in the western area. The single day's run from Port Stanley, Ontario, to Ashtabula, Ohio, shows a remarkable horizontal gradient, the diatoms becoming scarcer at the stations in Ohio waters.

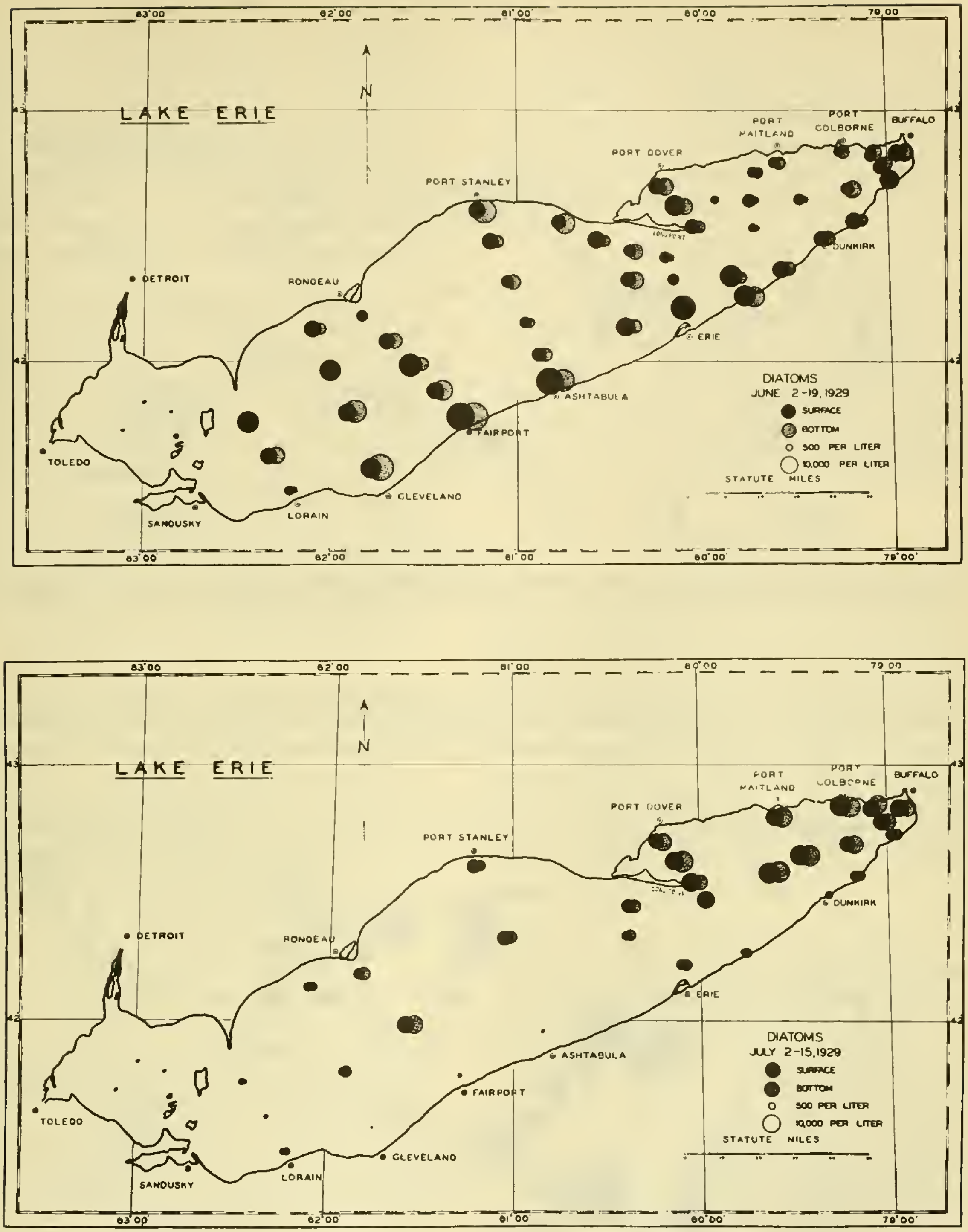


Figure 44. --Distribution of diatoms at the surface and bottom, June and July, 1929. The circles represent spheres whose volumes stand for the number of organisms per liter at the respective stations. The diameters in figures 44 and 45 should be doubled for a direct comparison of relative abundance with figures 47-49.

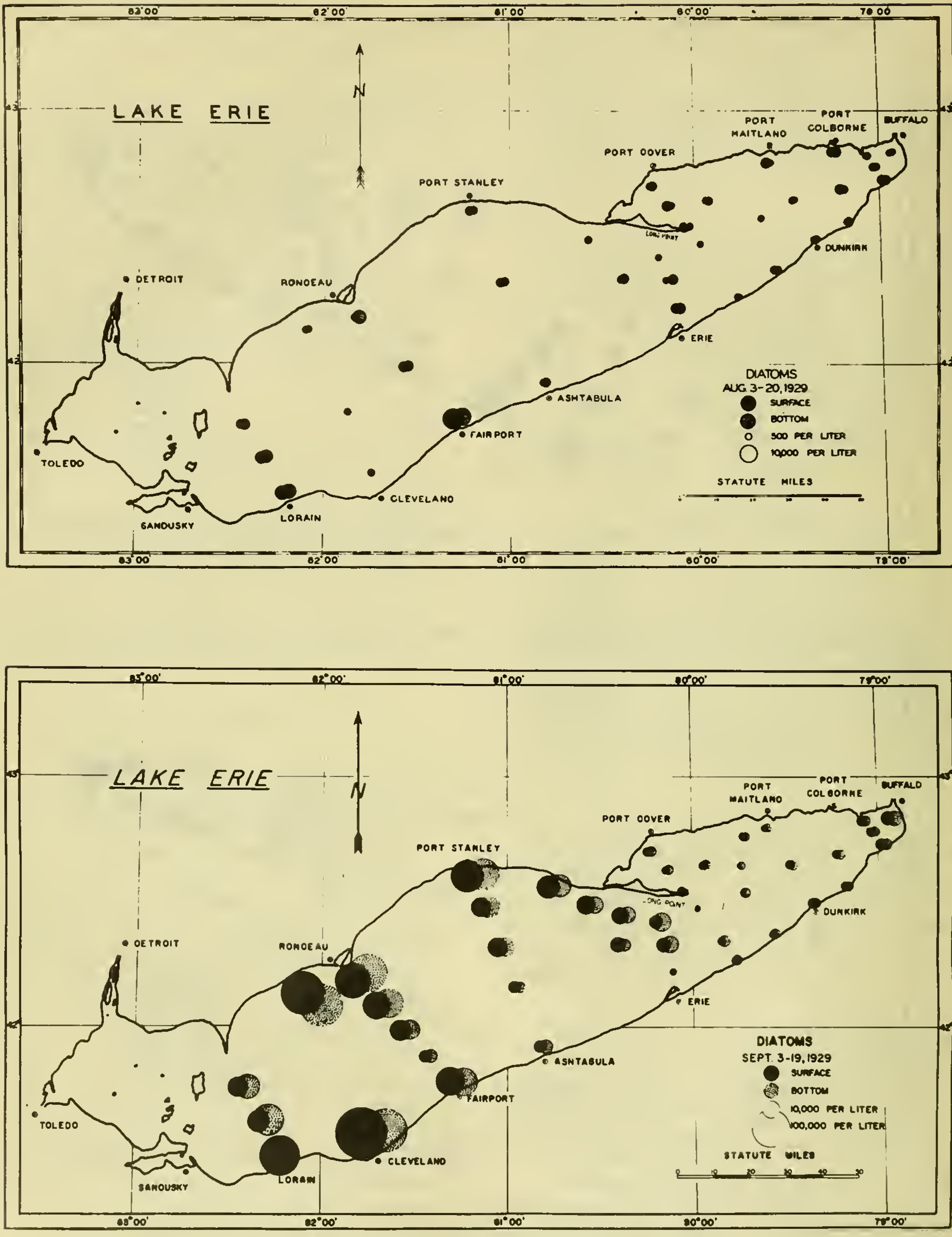


Figure 45. --Distribution of diatoms August and September, 1929. Note the increase in September. Asterionella, Fragilaria, Melosira, and Tabellaria are the common genera.

The distribution curves for diatoms (fig. 46) show graphically the fluctuations in the quantity from one station to another on each cruise during the 4 months. The "peaks" and "valleys" indicate remarkable variations in diatom production throughout the lake. August shows the least lateral variation and September the most. In general, production was greatest in the western area, least in the Long Point region, and moderate in the Buffalo end of the lake.

The horizontal variations in the abundance of green algae (fig. 47) were less striking than those of the diatoms, but differences were apparent. In June and July the Buffalo area, the Long Point region, and those stations between Rondeau and Fairport, all showed larger numbers than the numerous weaker stations marked with an "X" or small circle on the map. In August and September greater abundance occurred in the shallow areas. Decided infertility was apparent in the central western area in September. The map may, however, give an exaggerated impression of abundance in the eastern area because of the larger number of observations made in that region.

The blue-green algae (fig. 48) of the central western region outnumbered the entire eastern portion and most of the along-shore stations in June. These sharp differences were reduced in July, and a tendency toward uniform distribution was apparent. There was an abundance of blue-green algae in the eastern area in August while the western area was weak in this group. In September a slump occurred in the east, but the extreme western stations indicated strong increases in blue-green algae.

Rotifers (fig. 49) were abundant throughout the summer in the Long Point Bay region and also in the waters off Port Maitland and south of Port Colborne. Gatherings with the tow-net along shore (fig. 50) showed this same remarkable rotiferan fauna in Long Point Bay, Port Rowan, and Port Maitland. Long Point Bay was found to be very favorable for rotifers in 1928. Conditions in these parts must be peculiarly favorable for the development of a rotiferan fauna just as other regions in the west favor the growth of diatoms or blue-green algae.

These variations are not surprising when we consider that tributary creeks, cities, factories, etc., are continually emptying mineral matter and organic materials into the lake, thus altering the chemical environment. Some of these inflowing materials may be harmful (see chemical report in this bulletin), others beneficial to the natural fauna and flora as suggested for the English lakes by Pearsall (1923). The vernal and autumnal overturning, as well as the irregular upwelling of bottom materials due to wind and wave action, probably make available varying amounts of nutrients at different times and places.

It is an interesting fact that Reighard (1894) reported similar inequalities in the distribution of the total plankton in Lake St. Clair which empties its waters into Lake Erie at the extreme western end. Many other investigators (Apstein 1896, Bigelow 1924, Muenscher 1928) have likewise reported horizontal variations and swarms of plankton in different bodies of water, but very little definite correlation has been made with the causal factors.

Seasonal Variation

The earliest observations on the seasonal periodicity of plankton in Lake Erie are those made by C. M. Vorce (1880) who studied the species which he filtered from the city water supply in Cleveland, Ohio. He divided the annual cycle into three parts as follows: (1) the period from February to May, during which Stephanodiscus niagarae and Rhizosolenia eriensis are very abundant; (2) May to November, the period of greatest abundance of the prevalent forms Melosira, Tabellaria, etc.; (3) November to February, when the warm weather species decline and are replaced by the winter species.

This author also emphasizes the "marine relict" character of Amphiprora ornata, Rhizosolenia eriensis, and Stephanodiscus niagarae, whose relatives are marine species. The query raised by H. M. Smith (1878) as to whether the presence of the Rhizosolenia, just newly discovered, should be taken as an indication of saline bottom waters in the Great Lakes was discredited, but an interesting suggestion was at the same time offered to account for the observed facts. These "relicts" seemed to thrive best in cold winter waters, and this was taken as a further indication of their marine origin, for is not the sea cold?

The observations begun in June were perhaps a little too late to detect the maximum vernal pulse. In June diatoms occurred in large numbers at many shallow water stations near shore (fig. 44). Especially large catches were made off Cleveland, Fairport, Ashtabula, Erie, Port Stanley, etc. In July

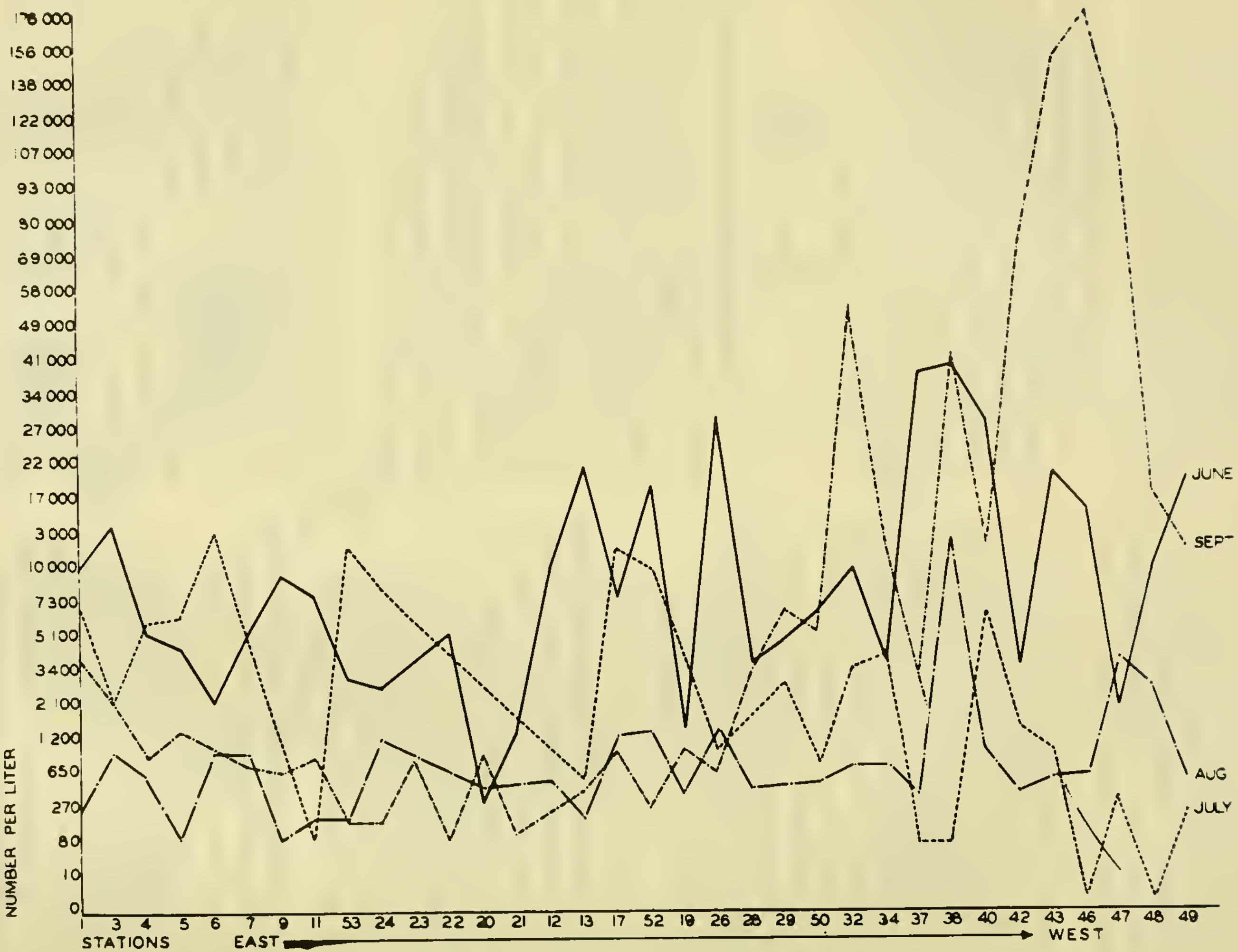


Figure 46. --Distribution of diatoms on each monthly cruise in 1929. The peaks and valleys indicate horizontal differences.

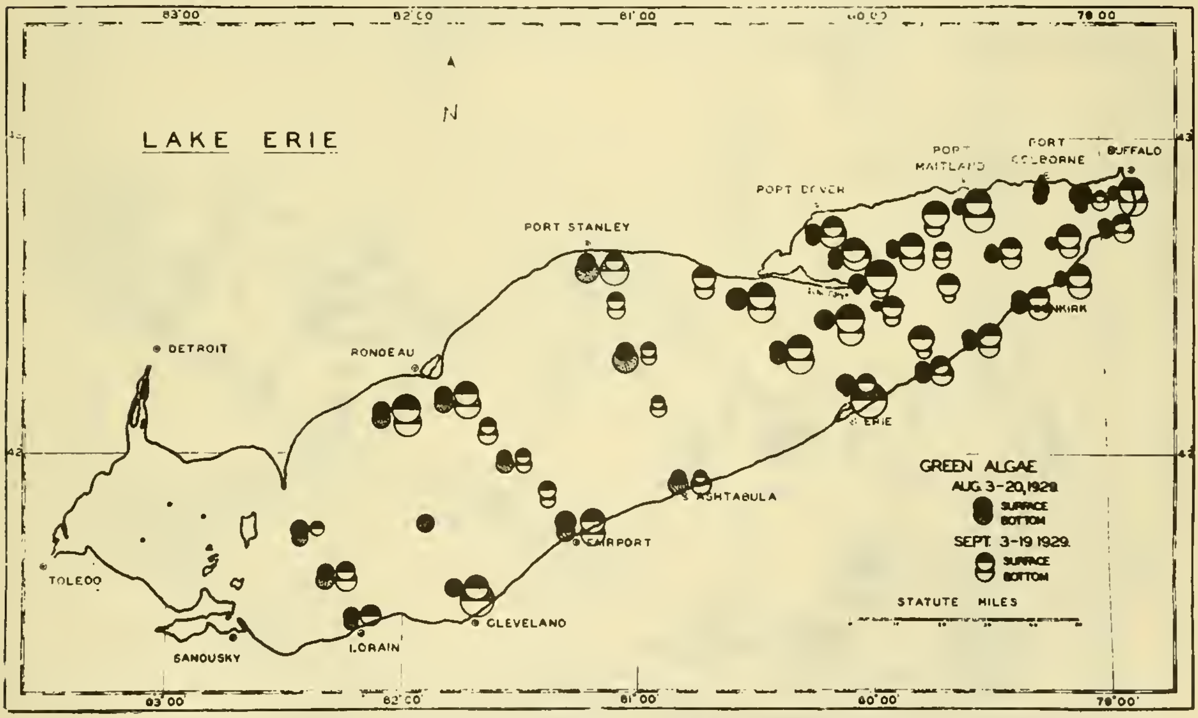


Figure 47. --Distribution of green algae during the summer of 1929. The autumnal increase of Sphaerocystis, Oocystis, Pediastrum, and Staurastrum is conspicuous.

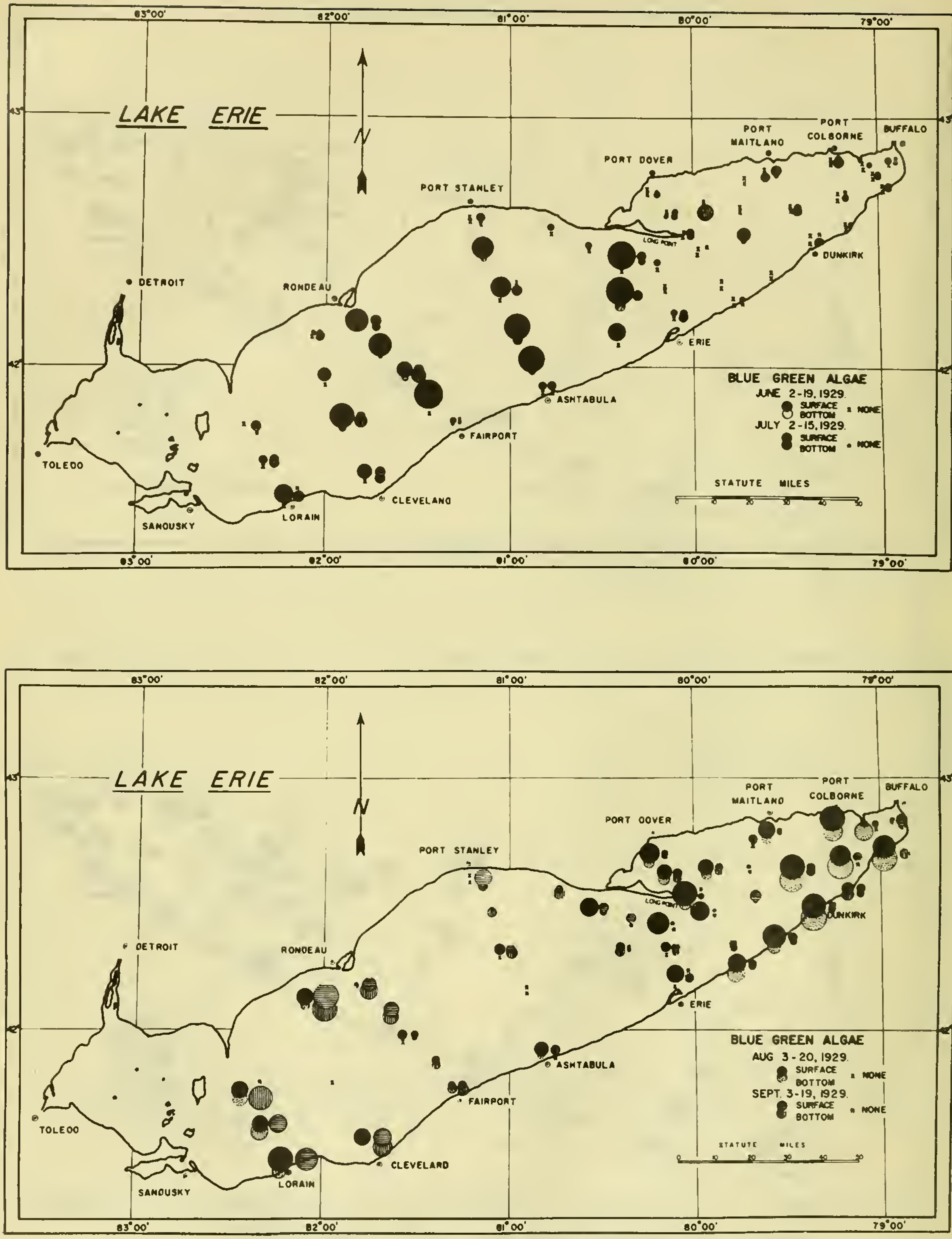


Figure 48. --Distribution of blue-green algae during the summer of 1929. Aphanizomenon was abundant during June in the west; in August Anabaena thrived in the east; and in September Coelosphaerium and Merismopedia were plentiful in the west.

Figure 49. --Distribution of rotifers in Lake Erie, 1929.

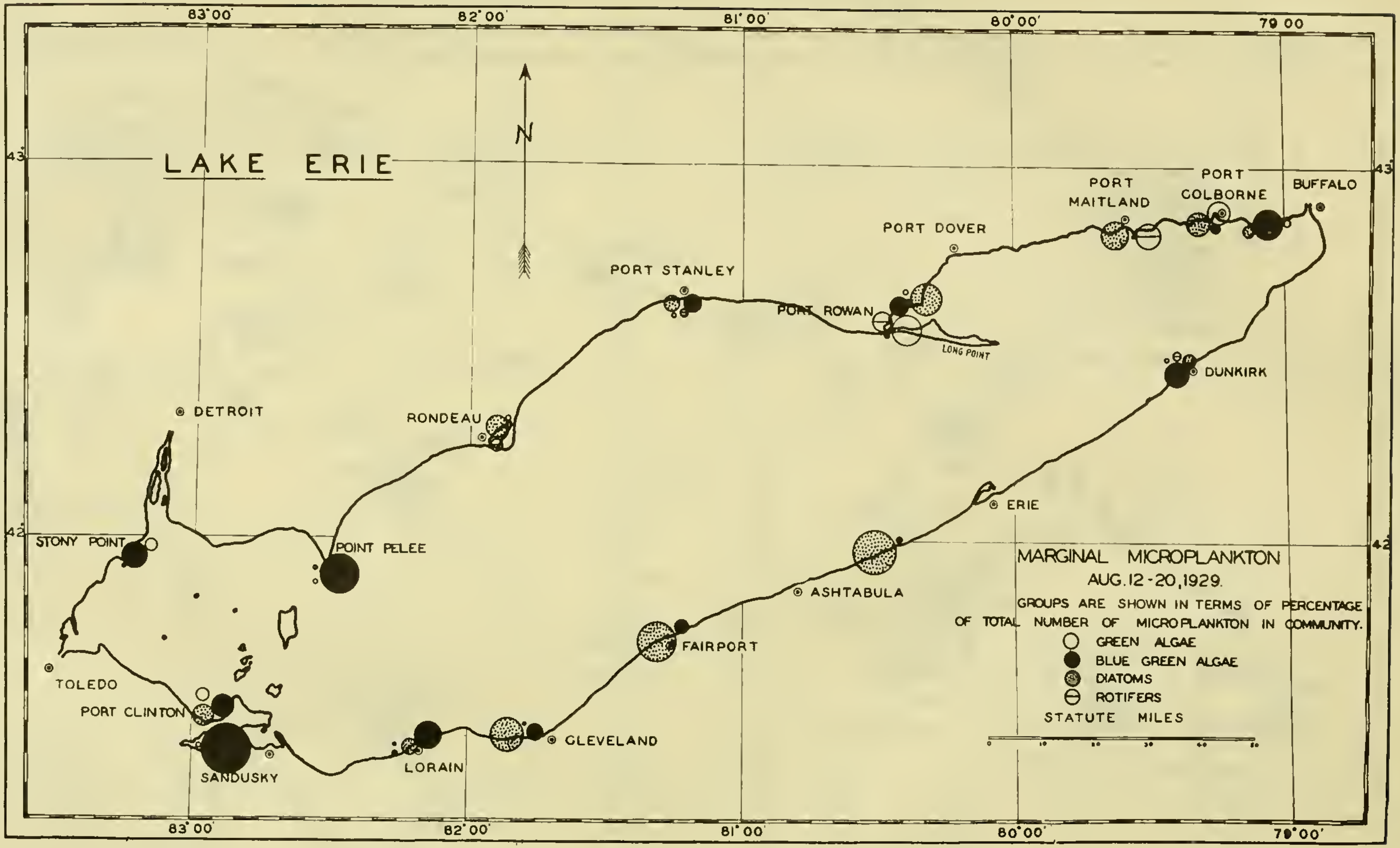


Figure 50. --Distribution of important groups of microplankton in the marginal communities found in harbors and along shore. (These gatherings and counts were made by Ralph Buchsbaum, University of Wisconsin, to whom the author is grateful for executing the tedious micro-enumerations throughout the season of 1929.) The circles signify the percentage of individuals belonging to each group in the community. Rotifers are plentiful in the northeast, blue-green algae abundant in the west, and diatoms relatively plentiful along the southern United States shore.

these same stations showed a marked decrease indicative of the summer decline. In fact mere traces were obtained at Cleveland, Fairport, and Ashtabula. At this time, however, the number of diatoms increased eastward from Long Point where the decline had not begun. Diatoms were relatively scarce throughout the lake in August (fig. 45), but a conspicuous rise occurred in the western area in mid-September. Of the 4 months, June and September showed the greatest diatom productivity (fig. 46). In order to determine accurately the cycle it would, of course, be desirable to extend investigations over a much longer period of time. Recent observations on the city water supply at Erie, Pennsylvania, have shown a diatom maximum in November with a decrease in January (Gottschall 1930).

During the period of observations, the prevalent species were Asterionella formosa, Fragilaria crotonensis, Melosira granulata, and to a lesser degree Tabellaria fenestrata. The other species, Stephanodiscus niagarae, Rhizosolenia eriensis, etc., were not common. The author has, however, found Stephanodiscus very plentiful in the Buffalo city water supply during the winter months. These observations appear to agree with those made by Vorce 50 years ago. Tabellaria did not, however, attain the the prominence in the summer community of diatoms in 1928 and 1929 that was claimed for it in 1880.

The green algae were scarce in June, but showed some increase in July and August at a few stations. A rapid rise occurred in this group throughout the lake in September. The common genera were Coelastrum, Dictyosphaerium, Pediastrum, Sphaerocystis, and Staurastrum. During the autumnal pulse, diatoms were more numerous than the green algae in the western area, but in the eastern part of the lake the green algae were more abundant than diatoms (fig. 52).

The blue-green algae were almost entirely absent from the eastern lake waters in early June. Westward from Long Point, however, the group was very abundant, Aphanizomenon being the common organism. In July this pulse of organisms declined but they became more abundant in the eastern waters. Anabaena continued to grow in this latter area until its abundance in August rivalled the conditions found for blue-green algae in the western section in June. There was a general decline in September except at some of the western stations where considerable numbers of Coelosphaerium and Merismopedia flourished.

Protozoa were found in comparatively small numbers throughout the lake. Probably the methods used in catching and preserving the plankton were not adequate for the apprehension of small and fragile members of this group. During August Vorticella was fairly common along with Anabaena to which the species was attached. This epiphytic protozoan reached 500 per liter at several stations. Difflugia was widespread in small numbers during June and July, declined in August, and reappeared in the September samples.

Rotifers were abundant in June and July at several eastern stations. Anapus ovalis reached 200 per liter at station 24. Anuraea cochlearis and Polyarthra platyptera were widely spread throughout the lake and were most numerous during July when their numbers varied from 10 to 40 per liter at the various stations.

MICROPLANKTON COMMUNITIES

The distribution of diatoms, green algae, and blue-green algae obtained in the surface samples has been plotted for the 4 months in figures 51 and 52. These graphs are intended to clarify the relationship of the more important groups in the phytoplankton communities.

Diatoms were the most abundant group in the communities of phytoplankton throughout the lake in June (fig. 51). Green algae occurred in relatively smaller numbers. The blue-green algae, however, did not parallel the fluctuations from station to station of the other two groups. In fact, where the blue-green algae were abundant, the diatoms were relatively few. This situation is particularly striking in the western part of the lake where there were great variations in the horizontal distribution of the diatoms, Asterionella and Melosira, and blue-green algae, chiefly Aphanizomenon. The data indicate considerable changes in the ratio of the component groups in the communities from one station to another at this time.

In July (fig. 51) there was again this parallelism in the fluctuating curves for diatoms and green algae. The blue-green algae had decreased in the western

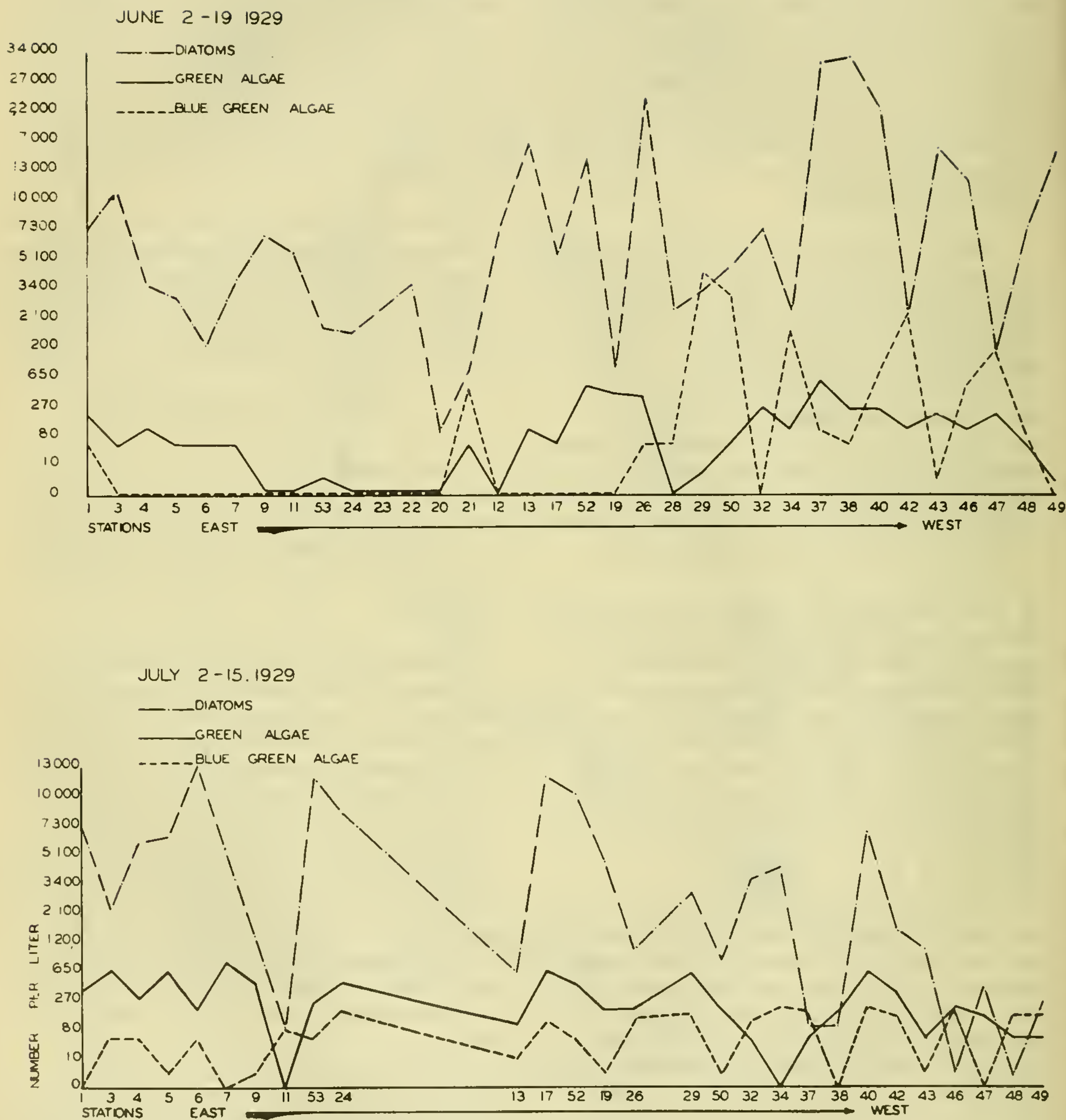


Figure 51. --Distribution of the major groups of phytoplankton June and July, 1929.

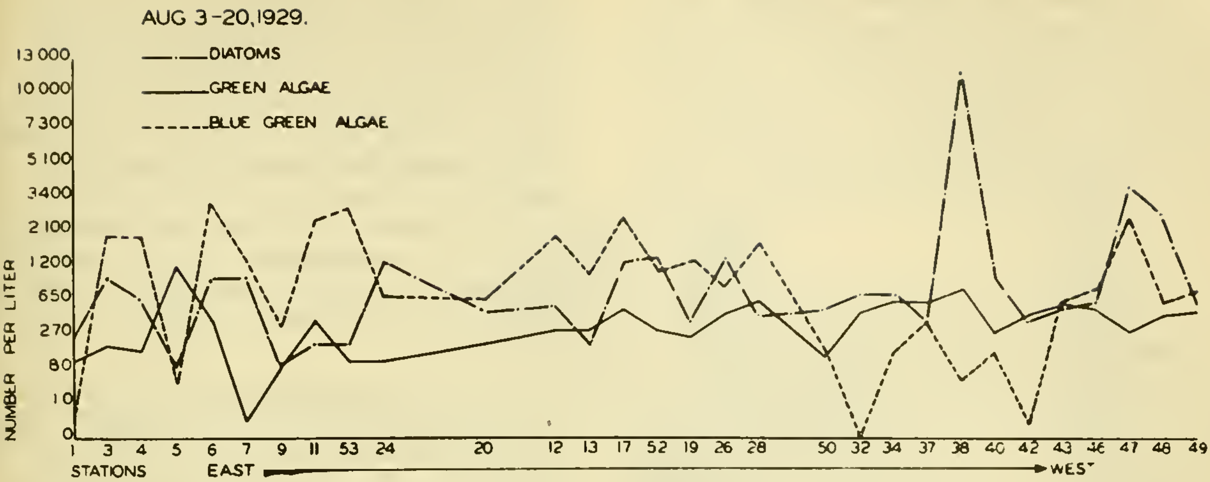


Figure 52. --Distribution of the major groups of phytoplankton August and September, 1929.

area, but had extended themselves into the Buffalo area, so that now their horizontal distribution was approaching uniformity with Anabaena growing in the west and Coelosphaerium in the east. The green algae were somewhat more numerous than the blue-green, and diatoms most plentiful of all. In general, the three curves show the same trend although at stations 6, 17, and 53 the diatoms were conspicuously prominent in the community.

Diatoms were at a minimum and the blue-green algae, especially Anabaena, had taken the lead at many stations in August (fig. 52). It is interesting to note that Anabaena fluctuated from none, or mere traces at several stations, up to 3,000 per liter at stations 6, 17, 47, and 53. In the west Melosira still persisted in large numbers at a few stations. In general, the trends of the groups were similar, but there were also notable exceptions where odd ratios of the constituents were observed in the communities.

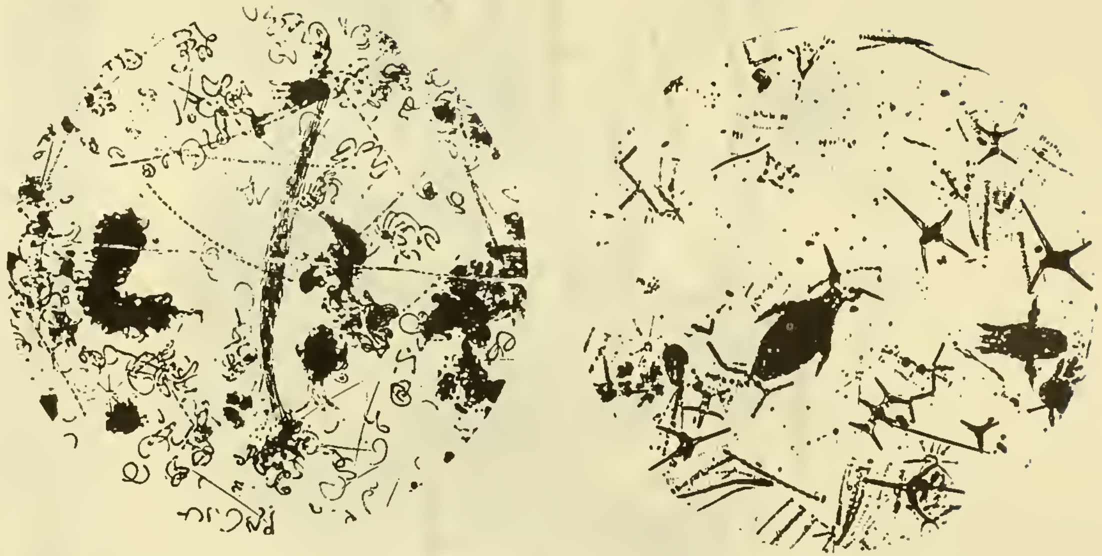
During the first week of September (fig. 52) samples obtained from the eastern waters showed considerable quantities of green algae. In fact, this group outnumbered the diatoms east from Long Point. The blue-green algae had decreased from a maximum abundance in August to minimum occurrence in the September communities. In the western area during the second week of September there occurred such a tremendous diatom maximum that the other components were rendered relatively insignificant. Even though Merismopedia and Coelosphaerium were numerous at several of the shallow western stations, the abundant diatoms, Asterionella, Fragilaria, and Melosira, almost obscured their presence.

The photomicrographs (figs. 53-56) show representative types of phytoplankton communities taken in the surface No. 20 net tows. The community found in the waters off Erie, Pennsylvania, on August 13, 1929 (fig. 53A) was composed chiefly of the blue-green algae, Aphanizomenon, Anabaena, and Microcystis together with a few colonies of the green alga, Sphaerocystis, and the diatom Melosira. Several days later the surface waters off Cleveland, Ohio (fig. 53B), supported a community dominated by the diatoms, Asterionella, Melosira, and Stephanodiscus. The green algae, Pediastrum and Staurastrum were also present in fair numbers, but blue-green algae were inconspicuous. These two communities illustrate a typical case of horizontal variation.

Seasonal variation in the communities is pictured for 2 stations in figures 54-56. The plankton gatherings from station 13, near the Pennsylvania-New York State line, show remarkable differences in the constituent species during June (fig. 54) and during August (fig. 55). The community in June consisted of Asterionella, Fragilaria, Melosira, and Tabellaria, an almost pure stand of diatoms. In August the diatoms had decreased and were largely replaced by the dinoflagellate, Ceratium, the blue-green alga, Anabaena, and green algae, Oocystis and Staurastrum, and the rotifer, Polyarthra.

Another interesting series (fig. 56) is shown by the 4 monthly tows from station 3 near Buffalo. Diatoms formed an almost pure standing crop in June. Fragilaria was still present in July but the other diatoms had declined and Ceratium, Dinobryon, Staurastrum, etc., were conspicuous in the community. By August the blue-green Anabaena had been introduced into the community and Fragilaria had decreased. In September diatoms regained their prominence again but a great many green and blue-green individuals are evident in the community.

From this discussion of communities it is obvious that diatoms are the prevalent group in the lake, but it is equally apparent that blue-green algae and green algae attain a very prominent position in the plankton at different times and places. In June and July diatoms were the dominant group. In August they decreased and the blue-green algae grew into prominence as the typical warm-water group. In the latter part of August the blue-green algae declined and the green algae came into prominence. In mid-September diatoms again developed so rapidly as to completely overshadow all other groups.



A. B.

Figure 53. --Typical communities of phytoplankton. A. Surface tow off Erie, Pennsylvania, August 1929, showing Anabaena, Aphanizomenon, and Microcystis. B. Surface tow off Cleveland, Ohio, August 1929, showing Asterionella, Melosira, Stephanodiscus, etc.

Figure 54. --Microplankton taken in foot-net No. 20 mesh, surface at station 13, June 1929. Compare with following plate for seasonal variation.

Figure 55. --Microplankton taken in foot-net No. 20 mesh, surface at station 13, August 1929. Compare with preceding plate for seasonal variation.

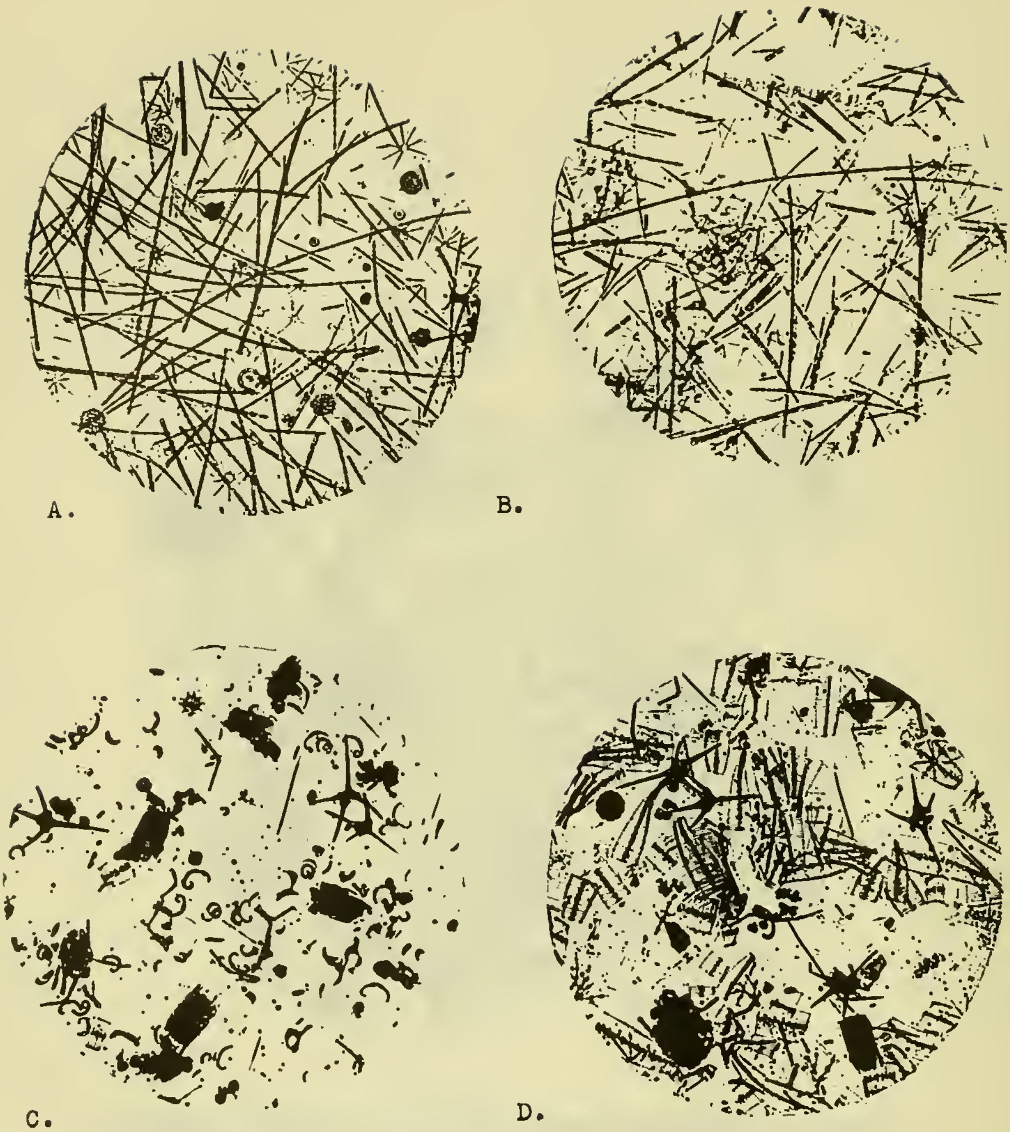


Figure 56. --Surface tows gathered at station 3 near Buffalo, New York, 1929. A. Community of diatoms obtained in June. B. Asterionella, Fragilaria, Melosira, mixed with Ceratium, Dinobryon, Staurastrum, etc., in July. C. Anabaena, Ceratium and a few diatoms in August. D. Diatoms, green and blue-green algae in September.

THE MACROPLANKTON OF LAKE ERIE

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CONTENTS

The following account of the macroplankton of Lake Erie is the final summary of the survey of the lake carried on during the summers of 1928 and 1929. A condensed preliminary report of the work of 1928, which included only a quarter of the lake at the extreme eastern end, has already been published (Fish *et al*. 1929).

APPARATUS AND METHODS

The macroplankton of the littoral and lacustric zones was collected by two 1-meter nets, one at the surface and the other just above the bottom, and by a Helgoland trawl towed on the bottom. The meter nets were drawn simultaneously at each station for 5 minutes and as nearly at a uniform rate as possible; no attention was given to the rate of towing. The macroplankton of the marginal zone was captured entirely in 1-foot nets, No. 12 mesh, or by washing out the sand and mud of the bottom and straining the wash water through the net. One-foot nets, No. 20 mesh, were used for the microplankton of all 3 zones and their contents were also examined for macroplankton to make sure that none of the smaller species escaped. During the entire survey, however, the only additions from these small-mesh nets were development stages of the copepods and cladocerans.

The meter nets and trawl were operated from the steamers *Navette* and *Shearwater*. An automobile trip was made around the entire margin of the lake in August 1929 in order that the marginal zone inside the steamer towings and the mouths of the numerous creeks and rivers that empty into the lake might also be included in the survey. During this trip frequent stops were made wherever the conditions looked favorable and both macroplankton and microplankton were collected, the former by the author, the latter by Ralph Buchsbaum. The marginal towing was done from a row boat, by casting the net from a wharf or jetty, or by wading among the water plants and scooping the net by hand.

During 1928 the steamer trips included only the eastern quarter of the lake, but during 1929 they covered the entire lake as far west as Point Pelee on the Canadian shore and Sandusky on the American shore. The extreme western end of the lake was under investigation during both years by the Ohio Division of Conservation and the summer laboratory of Ohio State University situated at Put-in-Bay. The marginal zone collections, however, included some from this western end as well as from the rest of the lake. Four of the steamer trips during each year were for the collection of plankton, one trip in June, July, August, and September, respectively. The 1929 auto trip was the only one that included the entire margin of the lake, but repeated short trips were made during both years to isolated localities within the marginal zone.

IMPORTANCE OF THE MACROPLANKTON

The number of fish that can be supported in a lake may at times be limited by the available food supply. The types and abundance of food organisms must suffice for the larval fishes at the proper seasons and later stages throughout the year. The Crustacea of the macroplankton fully meet these requirements by reproducing in great abundance through a large part of the year, and especially at times when the newly hatched fish fry require them. These fry, almost without exception, feed practically exclusively upon Crustacea, and such fish as ciscoes, minnows, and darters continue to feed largely upon them as adults. Other species change their diet as they become older, but directly or indirectly all are dependent on this vital link in the food chain. Hence the plankton Crustacea occupy a critical position in the life of all animals that inhabit the lake, and especially in the economy of fish propagation.

COMPONENTS AND AMOUNT OF PLANKTON

The bulk of the macroplankton is made up of 8 copepods, 7 cladocerans, 1 mysidacean, and a few insect larvae. The copepods include 3 species of Cyclops, 3 of Diaptomus, and 1 each of Epischura and Limnocalanus. The cladocerans include 2 species of Daphnia and 1 each of Bosmina, Diaphanosoma, Holopedium, Leptodora, and Sida. The other species are all included in the list beginning on page 163, but do not occur in sufficient numbers to form an appreciable percentage of the total bulk.

The cladocerans are probably of more value as fish food than the other Crustacea. Daphnia pulex is both larger and more numerous than any of the copepods, and forms on an average considerably more than half the entire macroplankton in the littoral and lacustric zones. It is not as abundant in the marginal zone but is supplemented there by large numbers of several other cladocerans that are absent in the other 2 zones. Limnocalanus and Epischura, the 2 largest copepods, each have as great food value as Daphnia, but their distribution is much more limited and erratic, and their percentages in the plankton are frequently very low. Mysis and Pontoporela are of course much larger than either the copepods or cladocerans, but as they are usually found adjacent to the bottom in the deeper portions of the lake their average food value is thereby considerably reduced.

Some investigators express the amount of the plankton in terms of weight, some in volume, and a third group in the number of individuals of each separate species. In the present survey a combination of the last two methods has been employed. The total bulk of each catch was measured in cubic centimeters, and the percentage of each species was computed by an actual count of the number of individuals present in a measured sample (2 cc.) of the catch. Other samples were then examined without counting to make certain that no species escaped detection.

This method of dealing with the plankton has established several things with reference to its amount and the relative value of its several components. One of the first facts came to light as a result of careful comparison of the macroplankton components in the tows made simultaneously with the foot and meter nets. The 2 nets were towed at the same rate and for the same length of time and were drawn through the water close together. Obviously the bulk of plankton in the meter net would be much greater than that in the foot net, but the percentages of the species in the 2 nets were expected to be the same. On the contrary, repeated comparisons showed striking differences, especially among the copepods. Limnocalanus and Epischura never appeared in the foot-net samples in anything like the relative percentages found in the meter-net samples. Indeed they were often entirely absent from the former but present in the latter in percentages that sometimes reached two figures. Obviously these larger and more active copepods were able to escape the smaller net. Such an admission, however, invalidates the foot-net samples as indicators of either the amount of the plankton or the percentage composition of its components. Hence, in the present survey all the data on macroplankton of the littoral and lacustric zones have been taken from the meter-net catches. And in the marginal zone where the foot net was necessarily used, the total amount of the macroplankton and the percentages of the species were not recorded since they would possess no quantitative accuracy. The species found in these marginal tows were recorded simply as abundant, common, few, or scarce. Necessary variations in the rate and length of the tows also made quantitative comparisons of marginal macroplankton impossible.

A second fact, very completely proven, is that no species of the macroplankton is uniformly distributed throughout either the lake as a whole or the particular zone in which the species is found. Indeed the exact opposite is true and every species exhibits the greatest inequalities in numbers and percentages at the various stations. Of 2 hauls made at adjacent stations under almost identical conditions and with only a comparatively short interval of time, the total bulk of the sample sometimes varied from 1 to several hundred cubic centimeters, and the percentages from 0 to 75 percent or more. If there is any single characteristic of the macroplankton that is more conspicuous than others, it is its consistent and exceptional disparity of distribution. In view of this fact it does not seem rational or even possible with current methods to make any reasonable computation of the amount of zooplankton per cubic liter of water, or per square meter of the lake surface. More can be accomplished, from both a biological and an economic viewpoint, by a discussion of the distribution of the separate species.

A third fact is that the bulk of the macroplankton varied greatly from month to month throughout the survey. By adding the total catches at all of the stations during each of the 4 months of the survey we obtain figures representing the relative amounts of the plankton in the lake during those months. These figures express in cubic centimeters the total plankton captured in the surface and bottom meter nets during the month, and are: for June, 5,464; for July, 16,494; for August, 18,921; and for September, 29,136. A comparison of these figures shows that the amount of plankton in the lake during July was three times the amount in June, that it increased slightly in August, and then increased 44 percent in September. These 4 months are probably typical of the entire year, and hence it is reasonable to suppose that the amount varies also during the other 8 months. Whether the differences are as great as those here recorded can only be determined by a continuous collection of plankton throughout an entire year.

The fourth fact is established by the figures just given, namely, that the amount of macroplankton in the lake is amply sufficient to feed a much larger number of fish than it now contains. When the survey first started each haul of the meter nets was scheduled to last for 15 minutes. Two or 3 trials were enough to show that the amount of macroplankton thus obtained was far greater than could be adequately handled, and the haul was reduced to 5 minutes. Even after such a reduction the amount of plankton in a single haul went beyond 1,000 cc. several times and on one occasion reached 2,000 cc. To those engaged in marine plankton investigations, so great an amount obtained in such a short time seems almost fabulous. It certainly proves that the amount of fish food in this lake is so great that the number of fish fry could be considerably increased without fear of depletion.

HORIZONTAL DISTRIBUTION

Attention is again called to the fact that the present survey covered only the months of June, July, August, and September, and hence the distribution here given is for those months only. In the horizontal distribution of the macroplankton, 3 zones can be distinguished with considerable precision; marginal, littoral, and lacustric. Of course along the margins between them there is always more or less overlapping of species, and migration back and forth from one zone to another. But in general the zone limits can be fairly well drawn, and each has its own characteristic species as well as those common to other zones. The marginal zone by virtue of its importance and the differences in the methods of collecting and recording its plankton will be treated separately. The littoral and lacustric zones may well be considered together since in the horizontal distribution of the plankton they have much in common.

The Marginal Zone

In the preliminary reports of the work done in 1928 it was stated that very little attention had been given to the marginal zone during that year, and it was determined to remedy this during 1929. The automobile trip around the margin of the lake was planned and carried out for this purpose. The stations where marginal plankton was collected during that trip are indicated upon the accompanying map by triangles, while the steamer stations covering the other 2 zones are represented by circles (fig. 57). As a further means of distinguishing the two, the marginal stations are lettered while the steamer stations are numbered. Inasmuch as the former were all reached from the shore, they can also be conveniently designated in the text by the name of the town, river, or creek where they were located.

Regarding the places to be included in the marginal zone, we are met at once by the same question that has confronted every investigator of lake plankton.

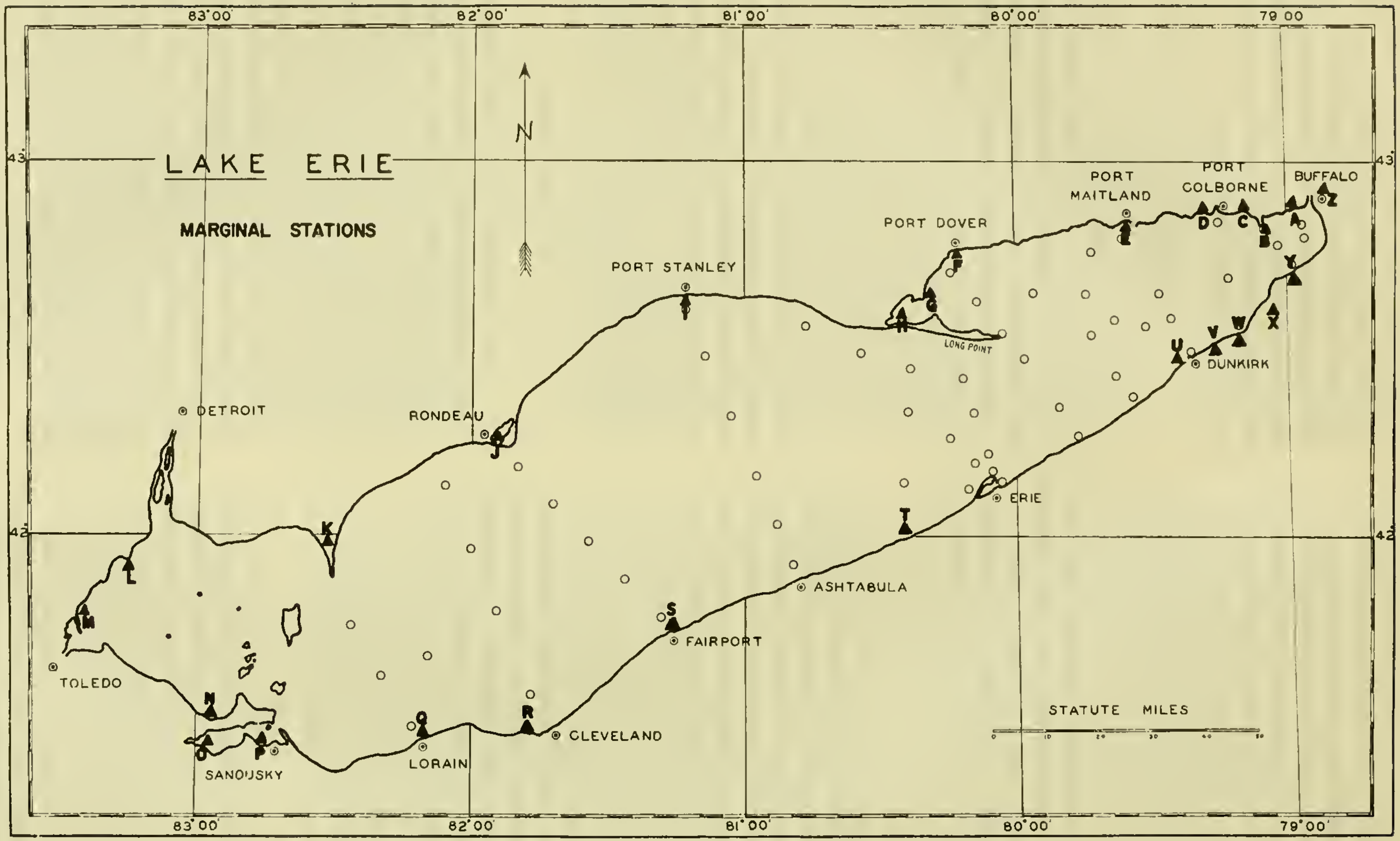

Figure 57. --Marginal stations, 1929; these stations are designated by black triangles and are placed in the water or on the land according as the collecting was done in the lake or in its drainage area.

Cunnington (1920) in his work upon the African lakes decided this question as follows: "There is finally the problem of deciding whether forms recorded from the neighborhood, but not actually from the waters of a particular lake, are to be reckoned as belonging to that lake's fauna or not. I have dealt with the difficulty in what seems the most common sense way, by definitely including all forms recorded from the drainage area of a lake as belonging to it." The same decision is adopted here and the localities outside of the lake itself may be designated first as the mouths of tributary creeks and rivers, directly connected with the lake, of which there are many along both the American and Canadian shores. Then there are small ponds, more or less removed from the lake, whose outlets run into these tributary creeks or rivers, and thus the ponds certainly belong to the drainage area of the lake. Neither the tributaries nor the ponds appear upon the map, but in the text the tributaries are designated by their names and the ponds by the name of the creek or river into which they empty.

Breeding Areas of the Marginal Zone

It has already been stated that the total bulk of the plankton is large enough to feed a stock of fish fry much larger than exists in the lake at the present time. That statement is correct, but it is equally true that a sufficient number of young fish by constant eating could consume the original supply although it might be exceptionally large. To obviate this there must be some method of rendering the supply inexhaustible through a continuous replacement of its elements as fast as they are used. This marginal zone supplies a sufficient number of natural breeding grounds where both copepods and cladocerans can and do multiply continuously under the most favorable conditions. These areas are indicated in figure 58 by hatched lines and it will be seen at once that they practically surround the entire lake. They separate naturally into 3 groups.

There are first a large number of small areas in the lake itself and close to the shore, whose shallow waters contain abundant aquatic vegetation varying with the depth of water and the kind of bottom. In general these are more numerous and relatively larger along the Canadian shore than on the American side. Nearly every point which protrudes into the lake from the Canadian shore is fringed on one or both sides with reeds and rushes or similar vegetation. And these furnish exceptionally good breeding grounds for the cladocerans and for many of the copepods, especially the Cyclops species. Examples of such breeding areas are the eastern side of Point Abino between Buffalo and Port Colborne and the eastern side of Turkey Point on the shore of Long Point Bay. At both places the lake is shallow for a long distance from the shore, the bottom is hard and solid so that the water seldom gets muddy, dense patches of rushes afford ample protection, and numerous open spaces furnish the requisite amount of free-swimming areas. Three copepods and 18 cladocerans, besides many ostracods, amphipods, and insect larvae were obtained from the Point Abino station. In the open water at Turkey Point 4 species of Cyclops and Diaptomus ashlandi were in considerable abundance. The reeds and rushes, which extend far out into the bay, sheltered 13 cladoceran species and numerous insect larvae.

These smaller areas, however, are not confined to the Canadian shore; one is located at Stony Point, Michigan. Epischura and Diaptomus oregonensis were exceptionally abundant there. Six species of Cyclops, 4 of Diaptomus, a few Epischura, 12 cladocerans, and a wealth of insect larvae, especially mayflies and caddisflies were collected in the rushes. When we reflect that there are literally hundreds of similar small areas scattered along the marginal zone around the entire lake, we realize that they must make an important contribution to the permanence of the plankton.

In addition to these smaller areas there are 3 very large natural breeding grounds, which are also a part of the lake itself, 2 on the Canadian and 1 on the American shore. Together they represent an area of more than 100 square miles. The first of these is the inner portion of Long Point Bay, which is designated as "Inner Bay" upon large maps. This area is 8 miles east and west and 5 miles north and south, with Port Rowan at about the center of the western shore. The deepest place in the area is charted as 6 feet, and most of it is 3 feet or less in depth and very large portions of it are covered with reeds and rushes. Nearer the shore the aquatic vegetation includes cattails, arrow-leaf, etc., and is so dense that it is very difficult to penetrate for the collection of plankton. Nine species of copepods and 23 cladocerans were obtained from this bay, all of them in active breeding; tows were taken at 3 different localities. To the

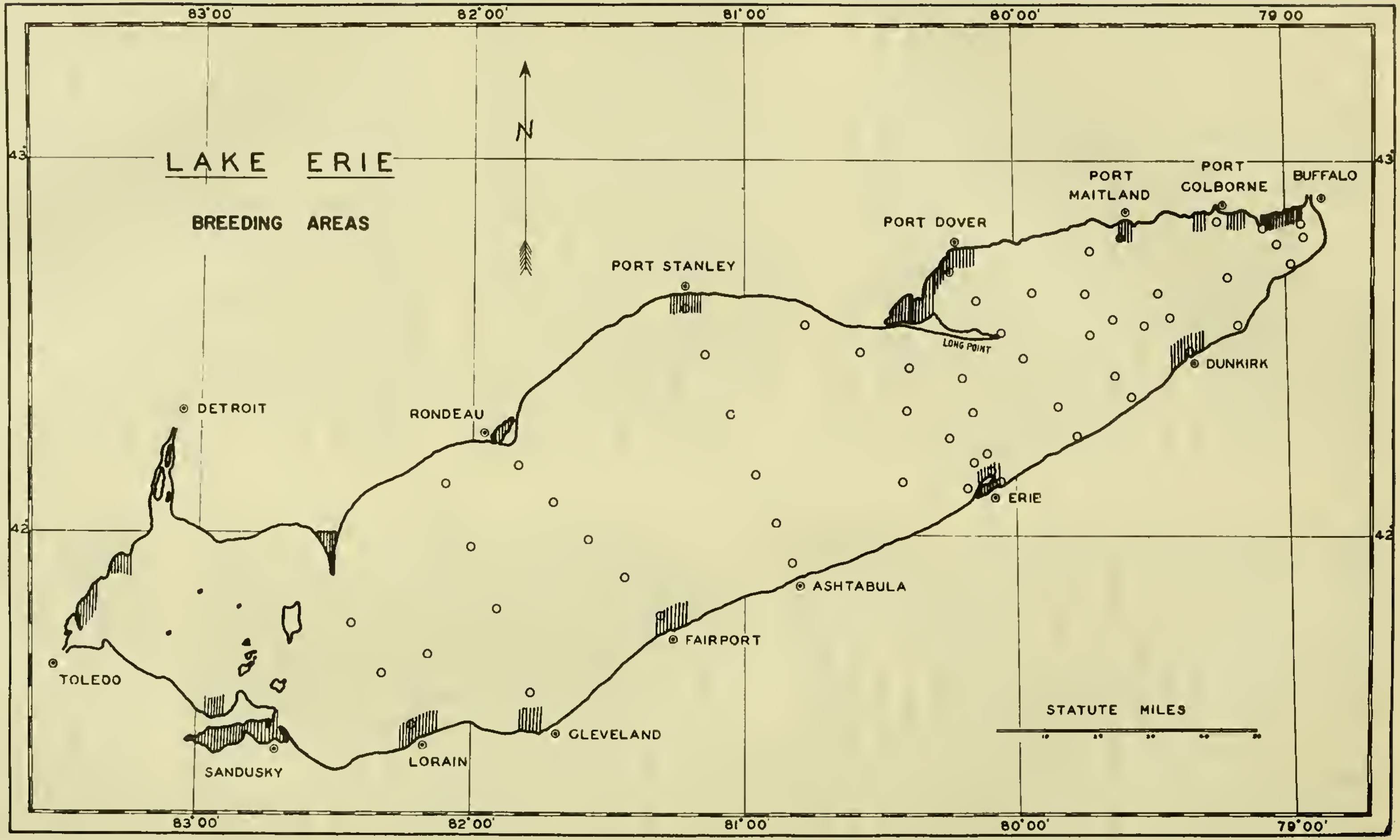

Figure 58. --Marginal breeding areas for Copepoda and Cladocera; these are the areas actually located but there are probably many others in the intervening spaces that were not examined.

north of Port Rowan the sample was largely made up of Diaptomus ashlandi, Sida, and at least 4 species of Cyclops. Off the wharf at Port Rowan amongst the denser vegetation the sample was the same except that no specimens of Sida were obtained. To the south of Port Rowan there were also these same species, but with them many Diaptomus oregonensis, Diaphanosoma leuchtenbergianum, and Acroperus harpae. As all the female copepods and most of the cladocerans carried eggs or young, this must be regarded as an important breeding ground for replenishing the supply of the species mentioned above.

The second large area is Rondeau Harbor, 6 miles long and 2 miles wide. The channel down the middle of the harbor is 13 feet deep but is quite narrow, and the broad area on either side of it is only 2 or 3 feet deep and is filled with all kinds of aquatic vegetation. Several deep artificial ditches open into the northern end of the harbor. These lead far inland and are so choked with water plants that it is difficult to push a boat through them. Both the ditches and harbor were swarming with plankton. Eight copepods and 23 cladocerans besides many insect larvae, especially mayfly and dragonfly nymphs were found in these habitats. A surface tow taken along the central channel was made up almost entirely of the developmental stages of the copepods and cladocerans found in the shallower water on either side. Sida, Diaptomus oregonensis and Bosmina were the most abundant, but there were also many Ceriodaphnia, Simocephalus, and Diaphanosoma, and at least 5 species of Cyclops and a few Epischura. As the latter do not carry their eggs in external cases but extrude them singly into the water,the indication of breeding was found in the presence of well developed eggs within the oviducts of the females.

The third large area is Sandusky Bay which is 15 miles long and 4 1/2 miles wide at its maximum, with an average depth of less than 4 feet. The shores are lined continuously with reeds, rushes and other water plants. The Sandusky River runs into the south side of the bay, about one-fourth the distance from the inner end to the mouth. Numerous creeks drain into the bay from either side. In a tow taken near the mouth of the river, 9 species of copepods and 10 of cladocerans were obtained; of the former, 6 species of Cyclops were especially abundant, with the males considerably outnumbering the females. Diaptomus sicilis was also present in very large numbers and this bay is evidently the breeding ground of that species just as Long Point Bay is for the species D. ashlandi. Among the cladocerans, Leptodora and Bosmina were most numerous, with Diaphanosoma a close third in abundance; the two former were evidently breeding while the latter was carrying young fully developed and ready to emerge.

To test the importance of the creeks which empty into the bay a tow was taken in one of them, Pickerel Creek, about a mile above its mouth and just below the highway bridge. This tow yielded 6 species of copepods and 8 of cladocerans; 5 of the copepods were Cyclops. Four of the cladocerans were the same as those obtained in the bay and four were different; only 2, Daphnia and Diaphanosoma, were abundant.

The larger areas just enumerated and the smaller ones previously mentioned are integral parts of the lake itself and would naturally be expected to contribute to the maintenance of its plankton. But there are also other localities outside the lake where the breeding of plankton occurs on a scale large enough and of sufficient duration to produce more than a local supply. These supplement the smaller and larger areas already discussed and constitute a third group, not as efficient as either of the others, but still contributing their quota towards the desired result. Each of the localities in this group is connected with the lake by a creek, stream, or river, through which the surplus of its entomostracan fauna is carried into the lake. Two such localities were visited and the plankton obtained from them verified the statements made above. The first of these was Portage River at Port Clinton, Ohio, where the river above its mouth widens out into a sort of bay with only a thin fringe of aquatic vegetation. A single vertical tow from a depth of 10 feet to the surface captured the following:

Species	Number captured
Cyclops albidus	9
Cyclops leuckarti	368
Cyclops serrulatus	15
Cyclops viridis	4
Diaptomus ashlandi	157
Diaptomus minutus	63
Diaptomus oregonensis	797
Diaptomus sicilis	7
Epischura lacustris	45

Species (cont'd)	Number captured
Bosmina longirostris	3
Ceriodaphnia laticaudata	8
Diaphanosoma leuchtenbergianum	435
Daphnia longispina	72
Daphnia pulex	5
Leptodora kindtii	4
Sida crystallina	6
	1,998

This amounts to 2,000 Entomostraca in less than 10 cubic feet of water, consequently this area must contribute materially to the maintenance of the plankton in the lake. The abundance of Cyclops leuckarti, Diaptomus oregonensis, and Diaphanosoma show that they were breeding prolifically in this river; all three are important components of the lake plankton. The number of specimens of Diaptomus minutus, which is rarely found in the lake itself, suggests that it may be more common in some of the lake tributaries. Evidently the copepods found conditions much better suited to their reproduction than did the cladocerans; this is especially true of Diaptomus. Indeed with the exception of Diaphanosoma the presence of cladocerans in Portage River plankton seems little more than accidental.

The second outside locality was the ponds within the National Park on Point Pelee, on the Canadian shore near the western end of the lake. The combined area of these ponds reaches nearly across the point, and the connecting passages as well as the ponds themselves are fairly choked with vegetation over most of their surface. These ponds were examined in considerable detail for Cladocera by Bigelow (1922). He found them especially adapted to the breeding of cladocerans and it was the large number of species reported by him that induced the present visit. The results supported his statements, for the plankton from these ponds yielded the largest number of species of any single locality examined during the survey, namely 8 copepods and 37 cladocerans. Among the copepods Diaptomus oregonensis and Cyclops albidus Jurine were the most abundant and nearly all the females carried egg strings. This means that the ponds are as well adapted to the breeding of some copepods as they are to that of the cladocerans. Among the latter Sida and Acroperus were most in evidence, with Camptocercus, Ceriodaphnia, Eurycercus, and Simocephalus also abundant, and a long list of species represented by very few specimens, many of these latter confined to this single locality and not found elsewhere.

From the account here given it is evident that somewhere in these three groups of breeding areas will be found ample provision for the maintenance of every species of cladocera found in the lake plankton, and for all the copepod species except Limnocalanus. That copepod, together with Mysis and Pontoporeia have practically no connection with the marginal zone, but find their breeding areas in the deeper portions of the lake.

Marginal Organisms

Copepods

Only a single genus of harpactid, Canthocamptus, is represented in the marginal plankton, but 5 species were found within the lake drainage. One of these, C. trispinosus, was taken in the mouth of a small creek at Cedar Bay on the Canadian shore and at Lackawanna Pond in the northern outskirts of Buffalo. It has never before been reported from any locality in America but is common in many European countries.

Of the genus Cyclops, using the old nomenclature, 9 species were obtained, and it is evident from their abundance that they are among the most important copepods of the marginal zone. The species C. serrulatus Fischer was the most widely distributed, being found in every locality examined and listed as abundant in half of them. Next come C. bicuspidatus Claus, C. leuckarti Claus, and C. albidus Jurine, which were found in about two-thirds of the localities and often in large numbers. The 368 specimens of C. leuckarti in the single vertical haul in the Portage River at Port Clinton, Ohio, was the largest number of any Cyclops species obtained at one locality within the marginal zone. Although the species C. viridis Jurine was captured at 13 of the stations its numbers were very small except in Sandusky Bay, and hence that locality is probably one of its breeding places. The remaining species are not widely distributed and are not found anywhere in sufficient numbers to give them more than petty economic value.

In the genus Diaptomus the species D. oregonensis is by far the most abundant, and the Portage River record given above shows that it breeds at some localities in this zone in very large numbers. This fact assumes greater significance when contrasted with its entire absence from the littoral and lacustric zones. On the other hand the species D. ashlandi and D. sicilis, which were so abundant in those two zones, are also well distributed in the marginal zone. Perhaps the former species is less capable of accommodating itself to different environments than the latter two; in proof of this, witness its absence from all marginal stations at the eastern end of the lake. The remaining species, D. minutus, was found at only 3 stations, Stony Point, Portage River, and Conneaut, all on the American shore at the middle and western end of the lake. It had been reported previously from the lake but was not found at the eastern end during 1928.

Epischura occurred in 23 of the marginal stations and in half of them it was abundant or common. This large copepod is usually considered as an open water or deep water form, and its presence in considerable numbers among the aquatic plants and in the ponds of the lake drainage was somewhat of a surprise. Only a single specimen of Limnocalanus was found in the marginal zone and that was after a heavy wind had been blowing on shore for 2 days so that its presence was probably casual.

Cladocera

Daphnia and Sida were present in considerable abundance at about two-thirds of the localities examined, and were evidently breeding at some of them. The varieties of the species D. longispina were far more numerous and more widely distributed in this zone than those of D. pulex. Diaphanosoma and Leptodora were next in abundance, the former in the middle and western end of the lake, the latter especially in Sandusky Bay and in the mouths of Cattaraugus and Eighteen Mile Creeks. Acroperus, Camptocercus, Chydorus, Scapholeberis, and Simocephalus are the only other cladocerans that are worthy of mention, the remaining species being well distributed but in small numbers. Attention is called, however, to Leydigia acanthocercoides which is listed by Ward and Whipple (1918) as "Rare; Louisiana." It was found at 5 localities in the lake, and at Turkey Point on the Canadian shore it was quite abundant together with Sida.

Other Crustacea

In addition to the Entomostraca species of Gammarus, Hyallella, and Palaemonetes were found at most of the stations. One or more of these usually occurred in sufficient numbers to make them of considerable value as fish food, supplementing the copepods and cladocerans. This was especially true amont the water plants along the Canadian shore and at the 3 larger breeding areas previously described. Ostracods were found at nearly all the stations, but in very small numbers except at Crescent Beach and Point Abino where they were abundant.

Other organisms

Damselfly and dragonfly nymphs and various fly larvae were found at nearly every locality in the marginal zone, often in considerable abundance. Caddisfly and mosquito larvae were also present nearly everywhere, but in much smaller numbers; beetle larvae and mayfly nymphs were rarely found. Besides the insects, 2 species of Hydra were fairly common, H. fusca being well distributed along both sides of the lake throughout its entire length, but H. viridis being confined to the American shore at the eastern end and to the ponds of the lake drainage.

Resumé of Marginal Zone Plankton

One general feature of the marginal plankton is worthy of special emphasis, namely that both its copepods and cladocerans showed a greater disparity of distribution than those of the other two zones. Nearly every station yielded 1 or 2 species in abundance, while all the others were more or less incidental, and only rarely were the abundant species the same at adjacent stations.

This zone was characterized positively by 5 species of Cyclops, C. albidus, C. fuscus, C. phaleratus, C. prasinus, and C. viridis; by 1 species of Diaptomus, D. minutus; and by 42 cladoceran species. Limnocalanus, Holopedium, Mysis, and Pontoporeia were absent.

LITTORAL AND LACUSTRIC ZONES

Littoral Zone

This zone includes the shallow water from 1 to 10 meters in depth and overlaps the marginal zone toward the shore and the lacustric zone toward the middle of the lake. In June and July, 1928, this zone was covered by the steamer Navette, which was small enough to enter quite shallow water. In the meter net hauls of this zone, 2 copepod and 2 cladoceran species constituted practically the entire macroplankton, with 3 other copepod and 3 cladoceran species appearing in small numbers. The copepods were in excess of the cladocerans along the Canadian shore except in the Niagara River where the latter jumped to 100 percent of the catch. The cladocerans were in excess of the copepods on the American shore, Daphnia being present at every station and averaging 61 percent of the total plankton. Another cladoceran, Leptodora, also was much more abundant on the American side; it is usually regarded as a surface form or at least as remaining considerably above the bottom. In this littoral zone, however, it proved to be much more abundant at the bottom, and in two of the hauls made with the Helgoland trawl near Dunkirk, New York, it constituted practically 100 percent of the plankton. The predominance of the copepods on the Canadian shore was due as much to a diminution in numbers and frequent total absence of cladocerans as to any increase in the copepods themselves.

The littoral zone was characterized by the abundance of Cyclops bicuspidatus, C. robustus, and Diaptomus oregonensis among the copepods, and of Bosmina longirostris, Leptodora kindtii, and Diaphanosoma leuchtenbergianum among the cladocerans. Five copepod and 42 cladoceran species characteristic of the marginal zone, as well as Mysis and Pontoporeia, characteristic of the lacustric zone, were absent. The percentages of Limnocalanus in this zone were always much smaller than in the lacustric zone, and it was frequently entirely absent from the plankton.

Lacustric Zone

This zone includes those waters of the lake which are more than 10 meters in depth, and which as shown elsewhere in this report exhibit a well defined thermocline over a large part of the area. Consequently, there is a much greater difference between the surface and bottom plankton than in the other zones. The difference is manifest not only in the total bulk of the plankton but also in its species composition. The water temperature drops suddenly and rapidly in the thermocline and induces an active vertical migration on the part of many of the Crustacea. Water below the 50-meter line maintains a constant temperature of between 4 to 6° C. throughout the entire summer. Mysis and Pontoporeia are never found outside of this cool area after the middle of June, and Limnocalanus shows a more and more decided preference for it as the summer advances.

Again since this zone is located in what may be termed the middle of the lake there is much less contrast between the American and Canadian sides. Limnocalanus still shows larger percentages near the Canadian shore while Daphnia is somewhat more abundant near the American shore. On comparing these percentages one is impressed by the abundance of the plankton in the lacustric zone. During July, August, and September, 1929, 31 of the 5-minute hauls with the meter nets at the surface and the bottom totalled more than 500 cc., 4 of these hauls reached the thousands and one exceeded 2,000 cc. In addition, 17 others totalled between 400 and 500 cc. and there were but two totals under 100 cc. The few small catches were at the surface and were offset in every instance by a large catch made simultaneously near the bottom.

The lacustric zone is characterized by Mysis and Pontoporeia, not found in the other two zones except possibly during the cold months, and by the greater abundance of Limnocalanus, Diaptomus sicilis, and Sida. The larger single percentages of Limnocalanus and Diaptomus in each of the 3 months mentioned above are all in this zone. In July and August there were 26 tows in which the percentage of Sida reached two figures, and 21 of these were in the lacustric zone, including all the larger ones.

This zone is distinguished from the littoral zone by the absence during the entire survey of D. minutus and D. oregonensis, and during August and September of C. bicuspidatus and C. robustus. It is also obvious that none of the characteristic copepods and cladocerans of the marginal zone appear at any time in the lacustric zone.

SEASONAL DISTRIBUTION OF THE MACROPLANKTON

In discussing the distribution of the macroplankton it will be more convenient to combine the two zones just characterized rather than to consider them separately. In these two zones are found 7 copepod species, 6 cladocerans, 2 amphipods, and 1 mysidacean, in all 16 Crustacea with an occasional Hydra, but with no ostracods, insect larvae or nymphs. The distribution of this plankton will be greatly simplified if we eliminate species and discuss genera, mentioning species only when necessary.

June Distribution

The total bulk of the samples obtained in June was much less than in the months following, making this the minimum of the plankton supply during the survey. The amounts from the surface net were also considerably smaller than those from the bottom net, and a third of them did not exceed 2 cc. At the surface the copepods were considerably more abundant than the cladocerans in the eastern half of the lake, but usually fell much below the latter in the western half (fig. 59). At the bottom there was the same preponderance of copepods in the eastern half of the lake, while in the western half the two were divided almost equally.

The Cyclops species were distributed quite evenly throughout the entire lake, but they were a little more abundant in the shallow water along the shores than in the deeper portions of the lake. The percentages of those taken in the bottom net were also larger than of those taken at the surface. It is worthy of note that the species C. bicuspidatus was more abundant than C. leuckarti in the eastern half of the lake, but that this proportion was more or less reversed in the western half. The largest percentages of both species were in the bottom net in the littoral zone between Dunkirk, New York and Erie, Pennsylvania.

During this month the genus Diaptomus outnumbered the other copepods everywhere except at the bottom in the deeper portions of the lake where it was surpassed by Limnocalanus, and at the surface in the littoral zone where it was surpassed a few times by Epischura. It also was more numerous in the eastern portion of the lake than in the western, and on the American shore than on the Canadian side. Only 2 species of the genus were found during June, and the larger 1 surpasses the smaller in abundance as well as in size. One or the other of these 2 species was present in every tow taken during this month, and with very few exceptions both species were represented by at least 1 or 2 specimens. The percentages often ran over 70 percent and reached as high as 95 percent, the latter in the bottom net on the American side in the littoral zone at station 51. Such an abundance of individuals goes far toward offsetting the relatively inferior size of these 2 species and gives the genus considerable economic importance.

Epischura was more abundant at the surface than at the bottom during June. It was most abundant at the surface through the central portion of the lake, while at the bottom its numbers were larger at either end of the lake. The percentages in the littoral zone were considerably larger than in the lacustric zone, but there was no appreciable difference between the Canadian and American sides. It was so well distributed that there was but a single station at which it did not appear either in the surface or the bottom net, and probably further research would reveal at least a few individuals.

The genus Limnocalanus was found at the surface in much larger numbers at the eastern end of the lake than through the central and western portions. Its percentages were greatest in samples taken at the bottom in the center of the lake and considerably smaller at either end. There was a decided preponderance of this genus on the Canadian rather than on the American side, and it was often found there in water that was comparatively shallow. Being a so-called "relict" form, it would naturally be expected to frequent the cooler water of the deeper portions of the lake.

The Daphnia species made up very small percentages of the plankton in the eastern half of the lake, but were present in large numbers in the western half. The contrast between the two portions is so great that it would suggest that the spring breeding ground for this genus is in the western end of the lake and probably in Sandusky Bay. Daphnia was found in larger numbers at the surface than at the bottom, especially in the deeper portions of the lake; the 2 species were about equally divided in abundance.

Holopedium and Sida were virtually absent from the eastern portion of the lake during June, but were present both at the surface and at the bottom in the central and western portions. The latter genus appeared at every station, its surface percentages being definitely larger than those at the bottom. The former genus only once obtained a percentage larger than 1 and was frequently absent.

Leptodora also was more abundant in the western than in the eastern half of the lake, but was seldom present in the meter net tows in sufficient numbers to constitute more than a trace. In the Helgoland trawl samples of 1928, however, it was clearly

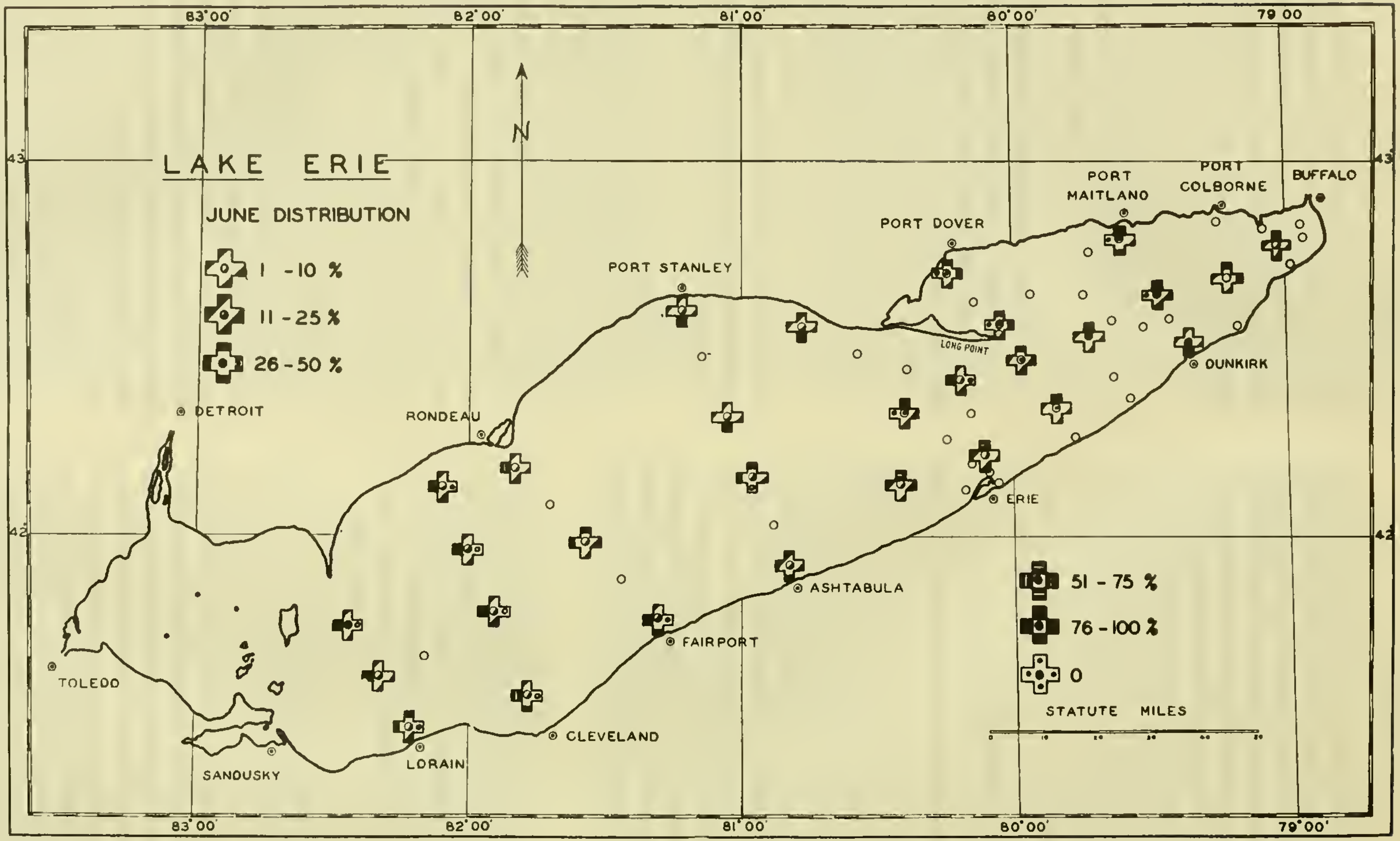

Figure 59. --June distribution of copepods and cladocerans at the surface, 1929.

shown that this cladoceran was present in large abundance in the bottom mud of the eastern end of the lake during the latter part of June. This would suggest that during the breeding season Leptodora frequents the bottom and either stays in the mud or so close to it that the bottom meter net, which was elevated a little above the mud, caught only a few stragglers.

Mysis was taken at 14 stations, always in the bottom net but not always in the deepest water, although that is its usual haunt. It was found along both the Canadian and American shores in the eastern portion of the lake, and near Lorain on the American shore in the western portion. The 3 highest percentages were east of Long Point in water from 40 to 60 meters in depth and a little nearer the Canadian shore. The genus Pontoporeia was collected in the bottom net at 3 of the deepest stations in the eastern end of the lake.

July Distribution

The total bulk of the samples increased to 3 1/2 times that of June, and this increase was largely due to cladocerans. As a result, although the actual numbers of the copepods also increased, their percentages showed a considerable decrease, especially in the shallower portions of the lake (fig. 60). The only stations at which the copepods still surpassed the cladocerans were in the deepest portion of the lake at the eastern end near the Canadian shore.

Cyclops were again distributed over the entire lake but their percentages were even smaller than in June. Cyclops leuckarti was taken either in the surface or in the bottom net at every station, but in 26 of the tows it constituted a mere trace, and only once did its percentage rise above 3. It was slightly more abundant in the western portion of the lake, while C. bicuspidatus predominated in the eastern portion.

Diaptomus retained its numerical superiority over the other copepods only in the western part of the lake; in the eastern part it was outnumbered by Epischura and in the central part by Limnocalanus. There were 2 species of the genus, as during June, but now their relative abundance was reversed, and D. ashlandi had become more numerous than D. sicilis in the western end of the lake and in the deep water at the eastern end. This reversal, however, was due as much to a marked decrease in the numbers of the latter species as to any increase in the numbers of the former species.

Epischura decreased in abundance but its distribution increased so that during this month it was found at every station and with but 3 exceptions in both surface and bottom samples. Although the highest percentages were still at the surface, it was much more equally divided. It was more numerous along the American shore for the entire length of the lake. The eastern half of the lake maintained its superiority over the western half both in actual numbers and in percentages.

Limnocalanus, which was found at nearly every station in June, was practically confined to the deeper portions of the lake during July. It was absent from 13 stations in the shallower waters and constituted but a trace at 5 others. At the deepest station in the lake it still had a percentage of 74 in the bottom net and 23 at the surface, and these figures combined with those of the other copepods at this station left the cladocerans in a very small minority. This suggests that while Limnocalanus is widely distributed during the colder portion of the year, when summer temperatures are reached there is an active migration from the surface toward the bottom, and from the shallower to the deeper portions of the lake.

Daphnia was found at the surface and at the bottom in every tow taken during July, and its percentages had so increased that at 27 stations it constituted more than half of the catch. It had also become fully as abundant in the eastern as in the western part of the lake, but showed a rather marked diminution in the central portion. The combined varieties of D. longispina were more numerous at the eastern end of the lake while D. pulex was more numerous at the western end. This is another bit of evidence which suggests that the latter species breeds in Sandusky Bay.

Holopedium was scattered sparingly throughout the entire lake, but its numbers were so small as to constitute a mere trace in all but 2 of the tows. Moreover, it was absent from more than half the bottom catches and from all the surface samples except 2 in the middle of the lake. On the other hand, Sida had spread over the entire lake and appeared in every tow, and usually in both surface and bottom samples. The percentages also greatly increased and in the

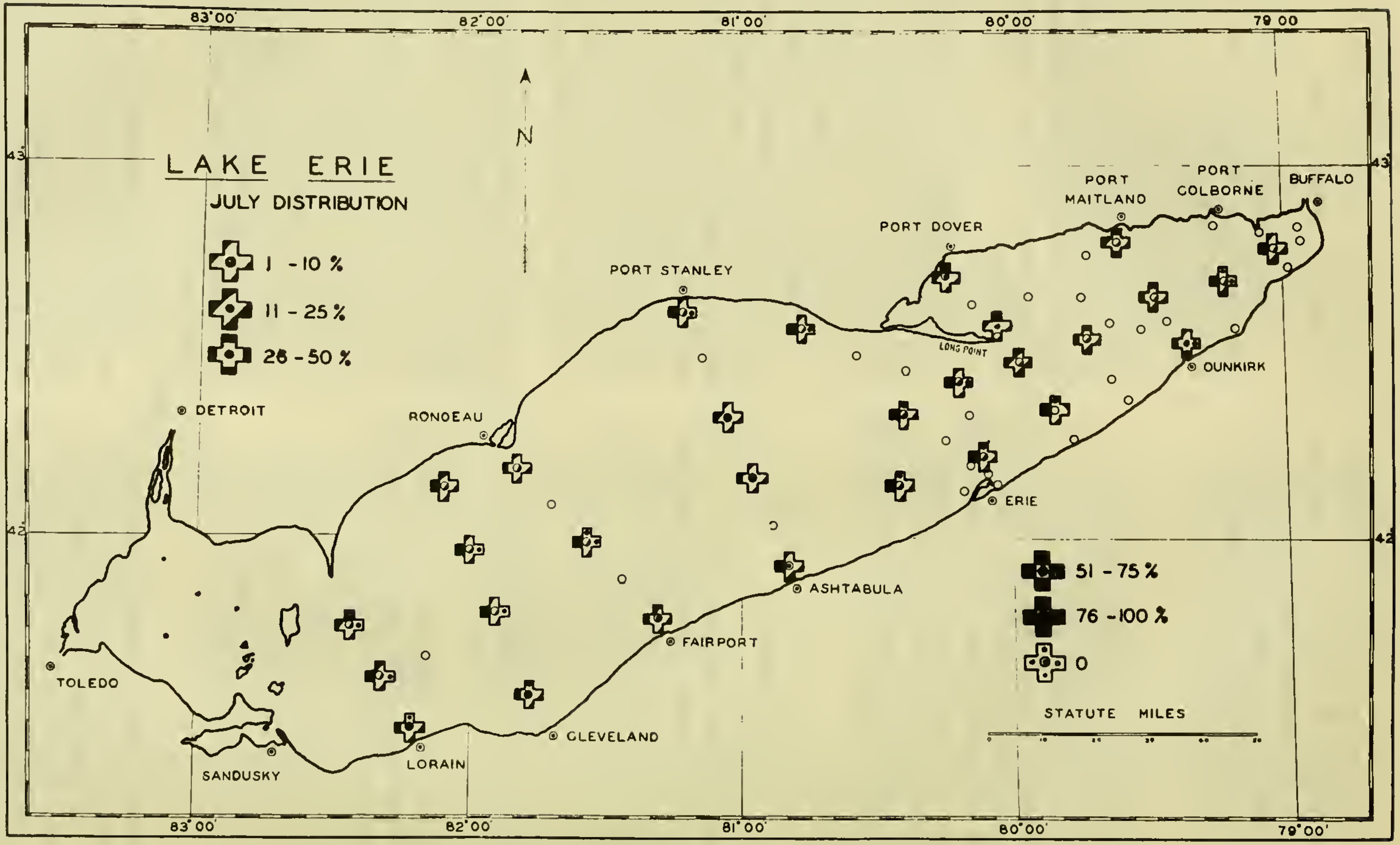

Figure 60. --July distribution of copepods and cladocerans at the surface, 1929.

surface samples they often comprised more than half the entire catch. At station 40 in the western-central portion of the lake they made up 94 percent of the plankton.

Leptodora also extended its distribution and appeared at every station except 4 in the Deep Hole off Long Point. It showed larger percentages at the bottom than at the surface, and was more abundant at the western end of the lake than at the eastern end. These records, however, were from meter net hauls; the Helgoland trawl was not used during 1929; if it had been, perhaps it would have shown as great a preponderance at the eastern end of the lake as during 1928.

Mysis and Pontoporeia were more restricted in distribution during this month, and were strictly confined to the bottom in the deepest part of the lake. The former genus appeared at 3 stations, but the latter at only the deepest station, No. 15.

August Distribution

The total bulk of the samples diminished slightly , but still remained at least 3 times as great as in June. As in July the large totals were due to increases among the cladocerans rather than among the copepods, and the former outnumbered the latter everywhere except at 4 stations (fig. 61).

Cyclops bicuspidatus and C. robustus practically disappeared, the former being found at only 4 stations and the latter at a single station in very small numbers. Cyclops leuckarti became more widely distributed than in June and July, and its percentages became slightly larger. It was more common at the surface and was present at nearly every station, but was absent from more than half the bottom tows.

Two Diaptomus species were taken at practically every station, the percentages being slightly larger in the western portion of the lake as well as at the surface. During August a third species, D. minutus, appeared in very small numbers at 4 of the littoral stations in the bottom net. This was its only appearance outside of the marginal zone during the entire survey; only 1 or 2 specimens were found at each of the 4 stations. It seems inconsistent that this, the smallest of the Diaptomus species, should come out of the marginal zone into deeper water, and that the much larger species, D. oregonensis, was not captured outside the marginal zone once during the entire survey.

Epischura had about the same distribution as in July and was quite evenly divided between the surface and bottom samples, but its percentages diminished considerably. Although it was present at every station throughout the entire lake, it was still somewhat more abundant on the American than on the Canadian side. Its highest percentage during the month was at the extreme western end of the lake.

Limnocalanus was again confined to the stations in the deeper portions of the lake with the exception of 4 in the littoral zone rather close to the shore. Two of these were on the Canadian side, off Rondeau Harbor and near Point Pelee; the other two were on the American side, off Cleveland and Lorain, Ohio. In the bottom samples at the deepest stations, the percentage of this copepod still remained above 50, and thus furnished another evidence of migration from the shallower waters into the cool layer below the thermocline.

The Daphnia species showed further increases and during August surpassed all the other macroplankton except at 1 or 2 stations. The numbers of D. pulex were greater than those of the combined varieties of D. longispina, especially in the bottom samples. And yet the highest percentage (100) of D. pulex was found in a surface net haul at one of the stations in the littoral zone near the Canadian shore at the western end of the lake. The general distribution of the 2 species was fairly equal throughout the entire lake and no section showed appreciable preponderance.

Holopedium disappeared entirely during this month and its place was taken by another cladoceran, Diaphanosoma leuchtenbergianum. This species was confined to the central and western portions of the lake and did not appear at all east of Long Point. This fact will account for its absence from the tows taken during 1928 since they were made in the eastern end of the lake. Sida remained as widely distributed as in July and its numbers were nearly as large, but it showed for the first time a decided difference in vertical distribution; the surface samples contained practically all the larger percentages.

Leptodora increased its distribution so that during August it was present at every station in the lake and usually occurred in both the surface and bottom nets. Its percentages increased even more than its distribution and at 2 stations at the western end of the lake on the American side it formed one-third of the

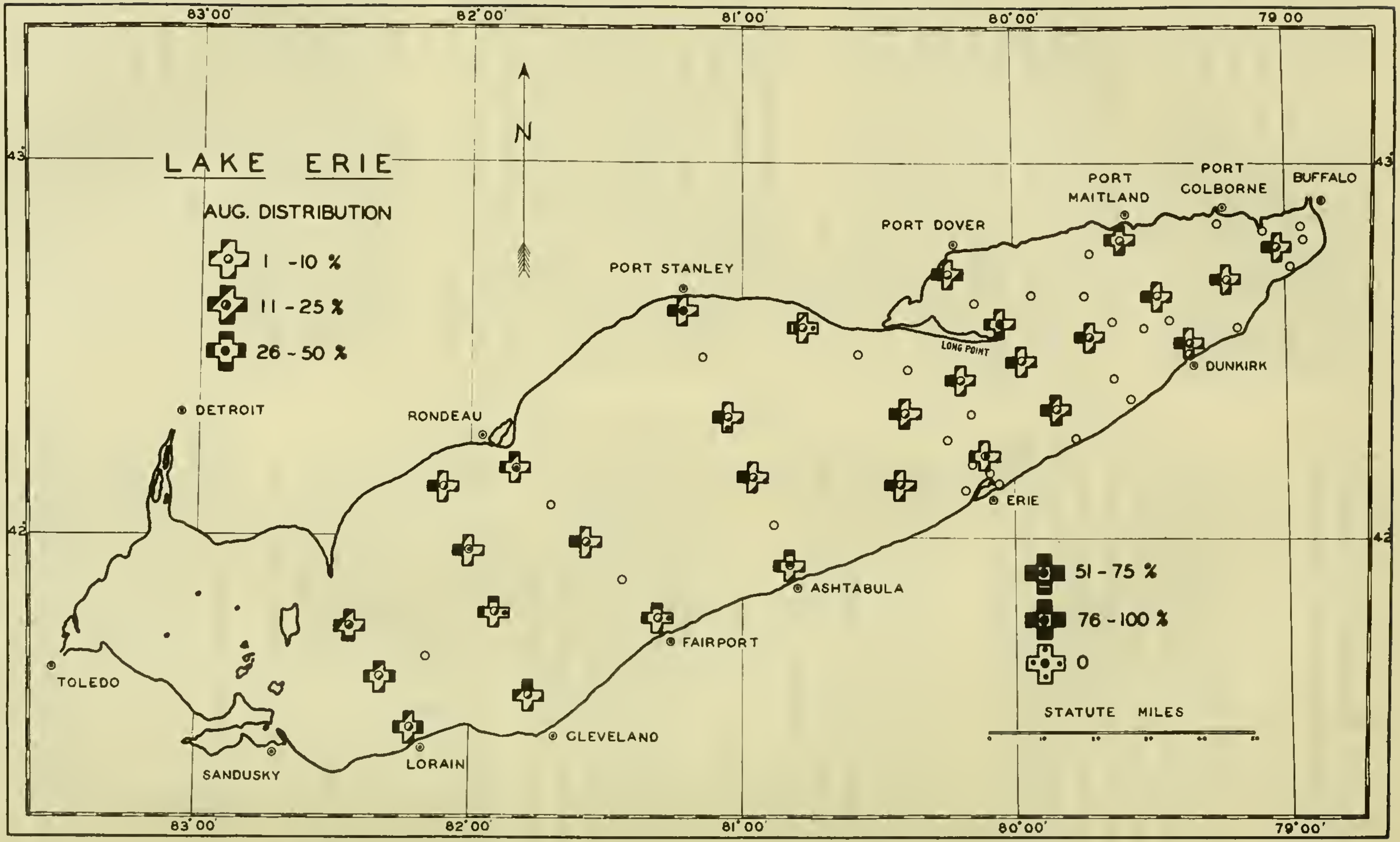

Figure 61. --August distribution of copepods and cladocerans at the surface, 1929.

entire surface samples. The individual specimens of this species were considerably larger than those obtained during June and July, so that from every point of view this cladoceran reached its maximum in August.

Mysis was again confined to the deepest part of the lake below the thermocline and was present in reduced numbers at stations where it was obtained in July. Pontoporeia did not appear in any of the tows made during August, probably due to a restricted distribution rather than to its entire absence.

September Distribution

The total bulk of the samples increased 75 percent over that of August and was the largest for the 4-month period (fig. 62). Only one of the bottom tows fell below 150 cc., 17 reached 500 cc. or more, and 4 totaled 1,000, 1,250, 1,500, and 2,000 cc., respectively. These 4 were in the lacustric zone, 2 at the eastern end and 2 in the center of the lake. The large numbers were entirely due to Daphnia, and it comprised two-thirds of the macroplankton at all but a single station.

Only 2 specimens of Cyclops bicuspidatus appeared in the surface tow at station 31, and 2 other specimens in the bottom tow at station 32, both in the littoral zone near the Canadian shore. Cyclops leuckarti was present at every station either in the surface or in the bottom samples, and often in both, but in such small numbers as to constitute merely a trace. The 2 Diaptomus species appeared at every station and in both the surface and bottom nets, reaching their highest percentages of the plankton in the central and western portions of the lake at the surface. The ratio between surface and bottom samples was about even, the percentages at half of the stations being greater at the surface and in the other half at the bottom. Cyclops minutus did not appear in any of the tows made during this month in the littoral and lacustric zones; it was confined to the marginal zone.

Epischura showed considerable reduction in its percentages of the total plankton although it was present at every station and usually in both surface and bottom samples. In 26 of the tows the percentage of this copepod was only 1 and in 13 others it was expressed as a trace. It was more abundant in the eastern half of the lake, but there were no differences between the American and Canadian shores.

Limnocalanus was no longer confined to the deepest stations in the eastern portion of the lake, although it was more abundant there than elsewhere. It had spread over practically the entire bottom of the lake except along the shores of the extreme eastern end off Buffalo and the mouth of the Niagara River. It was almost entirely confined to the bottom, being found in the surface tows of only 3 stations, 2 of which were in the deepest part of the lake. Its percentages of the plankton, however, were in general very small and only 3 times did they reach 2 figures.

Daphnia constituted the bulk of the macroplankton, the percentages of D. pulex in the plankton almost without exception being larger than those of D. longispina. Indeed in counting the September samples it became evident that the best method was to remove the comparatively few specimens of other Crustacea, keeping tally as they were taken out, and then count the Daphnia specimens without removing them. The distribution was practically uniform, D. pulex showing a little larger percentages in the bottom net and D. longispina in the surface tows.

Sida was as widely distributed as in August but its numbers were greatly diminished and its percentages of the macroplankton only twice exceeded 5. It was present, however, more often and in larger numbers at the surface than in the bottom samples. Holopedium and Diaphanosoma were not taken in the littoral or lacustric zones during September; the former entirely disappeared, the latter was still present in the marginal zone. Leptodora was almost as widely distributed as in August, but its numbers were reduced. Its percentages nowhere reached above 5 and in 22 of the tows the specimens were so few as to constitute a mere trace.

Mysis and Pontoporeia were both present in the deeper portions of the lake, so that the absence of the latter genus from the August samples must be due to very restricted distribution. The bottom nets at the deepest stations in the lake happened to hit the Pontoporeia habitat in June, July, and September, but missed it in August.

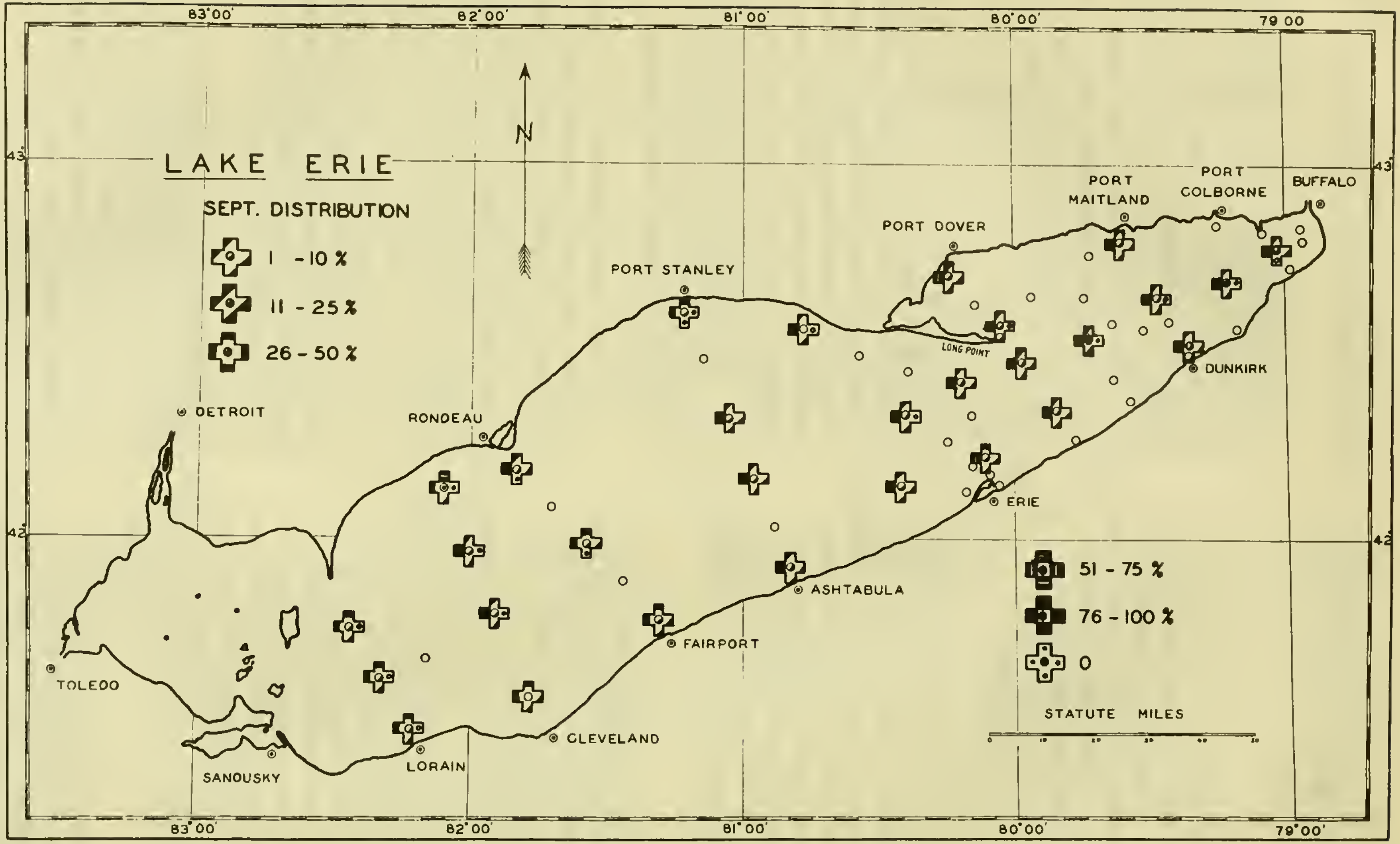

Figure 62. --September distribution of copepods and cladocerans at the surface in 1929. North arm of cross Diaptomus, east arm Leptodora, south arm Epischura, west arm Daphnia, center circle Sida.

SPECIES OCCURRING IN LAKE ERIE AND ITS DRAINAGE AREA

Non-parasitic Copepods

1. Canthocamptus illinoiensis Pearse. Present in the plankton of two small ponds of the Cattaraugus Creek drainage. Found in the stomach of small carp suckers seined on the lake shore nearing Irving, New York.

2. Canthocamptus northumbricus Brady. Present in the plankton of Lackawanna Pond in the Hertel suburb of Buffalo. It has not yet been found in the lake nor in any of the lake fish.

3. Canthocamptus staphylinoides Pearse. Present with the preceding species in Lackawanna Pond and also in the small pond of the Cayuga Creek drainage. Found in the stomach of small carp seined on the lake shore near Irving, New York.

4. Canthocamptus staphylinus (Jurine). Present in a small pond of the Canadaway Creek drainage, and in the mouth of Cedar Creek on the Canadian shore of the lake. Found in the stomach of small carp seined in Canadaway Creek a short distance above its mouth.

5. Canthocamptus trispinosus Brady. Present in the creek at Cedar Bay with the preceding species and in Lackawanna Pond, Buffalo, Hertel suburb. This copepod has never before been reported from America, but is a common European species; it has not yet been identified in the food of any lake fish.

6. Cyclops albidus (Jurine): Macrocyclops annulicornis (Koch). Present in the plankton of 20 of the marginal stations and abundant at Port Maitland, Point Pelee, Sandusky Bay, and a pond of the Cattaraugus Creek drainage. Found in the stomach of young bullheads caught along the shore of the eastern end of the lake.

7. Cyclops bicuspidatus Claus. Found in all three lake zones, especially the marginal and littoral zones, appearing at 24 of the marginal stations, and most of the littoral stations. It reached its maximum percentage early in June along the American shore, and diminished in abundance during the 3 following months. It also showed a decided preference for the bottom rather than the surface, and 3 times in June its percentage reached two figures. Found in the stomach of the cisco, carp sucker, Cayuga shiner, and a small unidentified fish. The fact that it is eaten freely by these small fish combined with its presence in large numbers at the principal fish-breeding areas compensates for its small size and gives it economic value.

8. Cyclops (Paracyclops) fimbriatus (Fischer). Found at 4 marginal stations and in a small pond of the Cattaraugus Creek drainage, but always in small numbers. It is common in the larger European lakes where it is a bottom species and keeps close to the bottom; it has been reported from Lake Michigan. Eaten by the yellow perch and an unidentified shiner.

9. Cyclops fuscus Jurine: Macrocyclops signatus (Koch). Found only once in a small pond of the Catturaugus Creek drainage, but quite abundant there. Taken from the stomach of small yellow perch seined along the American shore of the lake.

10. Cyclops leuckarti Claus: Mesocyclops obsoletus (Koch). Found in all three of the lake zones, especially the lacustric zone, and forming with the species C. bicuspidatus the bulk of the Cyclops plankton in the lake. Its breeding season is later than that of C. bicuspidatus so that although its largest percentages of the macroplankton came in June, it decreased but very little afterward. It was still present in small numbers at every station in September when the other species had practically disappeared. The bottom net and the Helgoland trawl contained the largest percentages except in August, so that it seems to show vertical migration during most of the summer.

In Lake Mendota Birge (1897) found a steady and rapid decline in the abundance of this species during the summer, which he attributed to lack of food, increase of water temperature, and competition. The lack of any such decline in Lake Erie substantiates Birge's judgment for there is here no lack of food and any increase of temperature is easily escaped by vertical migration. It is eaten by the cisco, mud minnow, and other small fishes, and it is present in large numbers at the chief fish-breeding areas, so that it thus acquires considerable economic value.

11. Cyclops (Paracyclops) phaleratus (Koch).

Present in small numbers in the plankton of 5 of the marginal stations, 4 of which were on the American shore and outside of the lake itself. It is eaten by small carp.

12. Cyclops (Eucyclops) prasinus (Fischer). Found at 4 of the marginal stations including Rondeau Harbor, Point Pelee and Sandusky Bay. It has not been found in the stomach contents of any of the small fish of the lake, but doubtless serves as food for some of them. It is stated by Marsh (1895) to be a limnetic form and common in the Great Lakes and hence is of some value as fish food.

13. Cyclops robustus G. O. Sars. Present in the plankton of 12 marginal stations and in 22 stations of the littoral and lacustric zones, most abundant in the littoral zone and along the American shore. This is a true bottom form and all the specimens with few exceptions were taken in the bottom net or in the Helgoland trawl. It is eaten by the carp and carp sucker, and on account of its large size and abundance it makes an important contribution to the fish food of the lake.

14. Cyclops serrulatus Fischer: Eucyclops agilis (Koch). Found at every station in the marginal zone, and rated as abundant at 12 of them; thus far it has not appeared in either of the other two zones. It has been obtained in the stomach contents of the bullhead, straw-colored minnow, Cayuga shiner, redhorse sucker, carp, and stoneroller. As it is more restless than most of the other species and is constantly darting about, it probably contributes more often to the food of hungry fish.

15. Cyclops viridis (Jurine): Cyclops vulgaris Koch. Present at 13 of the marginal stations but not found in either of the other two zones. The fact that it was washed out of the mud at 1 or 2 stations indicates that it frequents the bottom, and in European lakes it has been known to descend to rather considerable depths. It has been identified in the stomach contents of the redhorse sucker, whitenosed sucker, carp sucker, white sucker, carp, bullhead, straw-colored minnow, trout-perch, white bass, and yellow perch. Its large size and its habit of burrowing in the mud doubtless contribute to its being eaten by so many small fish, especially the suckers.

16. Diaptomus ashlandi Marsh. Present in all 3 lake zones but most abundant in the lacustric zone near the 20-meter line. It is one of the smaller species of the genus, but its great abundance more than makes up for its inferior size. Its breeding season must come in April or the first of May for its numbers were at their maximum early in June during the first trip for collecting plankton. Its percentages of the macroplankton diminished a little in July and August and increased again in September, but the diminution was largely due to a rapid increase in the cladocerans rather than to a decrease in the copepods. Another breeding toward the end of July and the beginning of August carried the percentages up again, and because the cladocerans were increasing at the same time the rise in the copepods was really greater than it appeared to be. A comparison of the surface and bottom tows shows that this species is an active migrant; when its percentage was large in the surface net it was at the same time small in the bottom net and vice versa. At the eastern end of the lake in 1928 this copepod was most abundant in the surface samples along the American shore and in the bottom samples along the Canadian shore. In 1929 during June and July it was more abundant at the surface in the eastern half of the lake and at the bottom in the western half of the lake, and there was a marked contrast between the two. During August and September this relationship was reversed in both halves, but at the same time the contrast between the two became so much less that it almost disappeared. The species was then universally distributed over the entire lake and in all 3 zones, and the percentages at the surface and bottom were often exactly the same. This would suggest that the vertical migration, which is very much in evidence during June and July, diminishes later in the season and practically disappears in many places. This copepod has been identified in the stomach contents of the silverside and Cayuga shiners, and is probably an important food in the deeper parts of the lake for the small fish there, very few of which have thus far been examined for food contents.

17. Diaptomus minutus Lilljeborg. Found at a few stations in the marginal and littoral zones, but not appearing at all in the lacustric zone. It is the smallest species of the genus and this combined with its scarcity gives it practically no economic value as fish food. It has not yet been identified in the stomach contents of any of the lake fish, but is probably eaten by some of the smaller ones.

18. Diaptomus oregonensis Lilljeborg. Present in the plankton of 14 of the marginal stations and rarely

extending into the littoral zone, but not yet found anywhere in the lacustric zone. At 10 of the marginal stations, including the principal fish-breeding areas of the lake, it was very abundant and so becomes an important fish food. This species has more of a tendency to gather in dense swarms than any of the others in the lake, and if the tow-net happens to pass through one of these swarms an exceptionally heavy catch results. It is found in nearly all the small ponds of the lake drainage, and is reported by Marsh (1907) as the most common species in the lakes of Wisconsin and Michigan. It has been found in the stomach contents of the carp sucker and yellow perch, and is probably eaten by many other small fish. According to Birge and Juday this copepod possesses a high percentage of nutritive material and hence should make food of the best quality.

19. Diaptomus sicilis Forbes. Present in the plankton of all 3 zones, but most abundant in the littoral zone and during June and July. It is the largest of the species found in the lake and usually lacks the red oil globules which are so prevalent in D. ashlandi, and this fact aids in separating the two. Its breeding season must have come sometime before the survey began for it was evidently at its maximum by the first of June and afterward its percentages steadily diminished. At the eastern end of the lake in 1928 its numbers were less than those of D. ashlandi, especially during July and August. On the contrary during June 1929, its numbers were much larger than those of D. ashlandi, then dropped so that the two were about equal in July and August, and finally became a little smaller in September. On contrasting the surface and bottom tows, the 1928 records showed very little differences throughout the season at the eastern end of the lake. In June 1929 the bottom percentages were larger than those at the surface at about two-thirds of the stations, quite evenly distributed over the entire lake. In July the bottom percentages were somewhat larger at the eastern end, and the surface percentages in the center and at the western end. In August and September there was not sufficient difference between the two to warrant any general statement. Here again, as in the case of D. ashlandi, the vertical migration was much more in evidence during June, diminished through July and August and almost disappeared in September. This species has been found in the stomach contents of the green-backed shiner, the spottailed shiner, the silversides, the troutperch, the yellow perch, the common sucker, and the redhorse sucker. This shows that it is freely eaten by different kinds of fish and suggests that future examination will add considerably to the above list.

20. Epischura lacustris Forbes. Present in the plankton of all 3 zones but most abundant in the littoral zone during June. Although its percentages of the macroplankton obtained in June were the largest for the 4 months covered by the present survey, Birge (1897) found that this copepod reached its maximum in Lake Mendota late in the autumn. The same might be true of Lake Erie, but the numbers steadily declined through July, August, and September and gave no indication of a later rise. In June the percentages at the surface were considerably larger than at the bottom, and there were 11 stations at which it did not appear at all in the bottom tow. A similar superiority in numbers at the surface was maintained through July and August, but they grew steadily less until in September the numbers at surface and bottom became practically equal. During this time the species had become more widely distributed and in August was present at every station throughout the entire lake and in both nets.

In Green Lake, Marsh (1903) found that 81 percent of the Epischura collected in August and 72 percent of those collected in September were in the upper 10 meters of water. He also found that during the warm summer nights large numbers came to the surface. He interpreted this to mean that Epischura prefers the warmer water and is controlled in its vertical distribution by conditions of temperature and food supply. It is a large species and a powerful swimmer and moves to the surface when the water there is warm and filled with rich food material.

This species has been identified in the stomachs of the green-backed shiner, the spottailed shiner, and the yellow perch. Its abundance and its wide distribution over the entire lake make it an important fish food.

21. Limnocalanus macrurus G. O. Sars. Present in the plankton of the littoral and lacustric zones, in Lake Erie but practically absent from the marginal zone. During the first 3 months of the survey it appeared in large numbers in the surface tows, but during September it was virtually confined to the bottom tows. Sars (1918) noted that all the

specimens of this copepod taken in the large Norwegian lakes in summer were fully grown, but that the ovarian tubes of the females were empty, which is exactly the condition in Lake Erie. From this he inferred that the breeding season was at a different time of the year from that of the other copepods, perhaps in winter.

Ekman (1920) has shown that in the Baltic lakes Limnocalanus has but a single breeding season late in the autumn. The copepodid stages are reached in March and the adults are fully grown by May; then there is a resting stage of 5 months, during which the sex organs remain undeveloped. Sexual maturity comes in the autumn and breeding begins in November at a temperature of 7° C. The adults of the previous year die off in the spring and have all disappeared by May, their places being taken by the young of the year. Marsh (1889) found in Green Lake that this copepod had 2 maxima during the year, May and November, the spring maximum showing the larger numbers. During February, March, and April most of the specimens obtained were immature, and judging from the specimens obtained the first of June this is probably the case in Lake Erie.

Limnocalanus is repelled by bright light and high temperature, and hence retreats more and more completely to the bottom through the summer. The maximum temperature of the water in which it can thrive is 14° C., but the water must be considerably colder than this before it will come freely to the surface. Its diurnal migrations are more pronounced in cold weather and throughout the summer it stays below the thermocline.

Limnocalanus was much more abundant at the eastern end of the lake in the littoral zone on the Canadian side during 1928, and was entirely absent from more than half of the stations on the American side. It still showed a decided preponderance along the Canadian shore during June and July 1929, was more uniformly distributed in August, and found only in the deepest part of the lake in September. In reality, the species is lacustric, not littoral.

It is known to be eaten by cisco, white bass, and yellow perch, and doubtless serves as food for many fishes of the lacustric zone, whose stomach contents have not thus far been examined.

Ekman (1913, p. 371) has pointed out that Limnocalanus macrurus is a descendent of L. grimaldii, the two species differing chiefly in the shape of the head. The dorsal contour of the forehead of L. grimaldii is much less than that of L. macrurus; the former lives in salt or brackish water, the latter is strictly a freshwater form. In general the greater the salinity the flatter the forehead, but as the salinity decreases the form of the head approaches the semi-circular contour of L. macrurus. The transformation thus becomes greater the longer the life in fresh water has lasted, and may serve as a sort of criterion of the length of time that has elapsed since the habitat changed from salt to fresh water. The form found in Lake Erie diverges from the extreme form of L. grimaldii much less than some of the European races, and would be, according to Ekman, of more recent origin.

The Lake Erie race of Limnocalanus is one of the largest known, greatly exceeding any other freshwater race and surpassed only by salt-water races of North Siberia and Finland. The length of the caudal rami in proportion to the length of the body varies greatly also in the different freshwater races. Gurney (1923) in his discussion of this copepod in the English Lake District said "The published information is too scanty to admit of a definite conclusion as to whether there is any connection between the shortness of the furca and the length of sojourn in fresh water." He gave the length of the caudal rami in American specimens sent to him by Dr. Juday as 13.3 percent of the body length in both sexes from Lake Erie, 13.8 to 14 percent from Green Lake, and 15 percent from Lake Canandaigua. These measurements were all notably shorter than those of the L. grimaldii form from the Caspian, but they do not agree with measurements made during the present survey. The average for 25 specimens, including both sexes and varying from 2.10 to 2.87 mm. in length was 15.6 percent, varying from 13.8 to 16.9 percent. This brings the average of the Lake Erie race much closer to that of the Caspian and Swedish forms and again indicates that the former are of recent origin, as is explained farther on under Pontoporeia.

Parasitic Copepods

22. Achtheres ambloplitis Kellicott. Parasitic in the mouth and on the gills of the smallmouthed black bass; only one infested fish found during the present survey.

23. Achtheres coregoni (S. I. Smith). Parasitic on the fins and gill arches of the cisco in the Niagara River near Lake Erie, and on whitefish in the other

Great Lakes; found but once during the present survey.

24. Achtheres corpulentus Kellicott. Parasitic on the gills and in the gill cavity of the lake herring in Buffalo Harbor, the Niagara River, and at Dunkirk, New York; not found during the present survey.

25. Achtheres pimelodi Kroyer. Parasitic on the gill arches of the bullhead at Put-in-Bay, Ohio; not found during the present survey.

26. Argulus stizostethii Kellicott. Parasitic on the outside surface of the walleye pike in the Niagara River near Buffalo; not found during the present survey but said by fishermen to infest this fish during midsummer in considerable numbers.

27. Ergasilus centrarchidarum Wright. Parasitic on the gill filaments of the pike-perch and the smallmouth black bass; very few infested fish found during the survey.

28. Ergasilus caeruleus Wilson. Parasitic on the gill filaments of the walleye pike in the western end of the lake; not obtained during the present survey.

29. Lernaea cruciata (Le Sueur). Parasitic in the flesh of the redeye in Lake Erie at Erie, Pennsylvania, and in the Sandusky River, and in the flesh of the sunfish in Cattaraugus Creek; only a few fish infested.

Cladocera

30. Acroperus angustatus Sars. Found in very small numbers at Point Abino, in the inner bay at Long Point, and in the ponds at Point Pelee, all on the Canadian Shore. Eaten by the yellow perch; confined to the marginal zone.

31. Acroperus harpae Baird. Abundant along the Canadian shore, but present only at Stony Point, Michigan, and Dunkirk, New York, on the American side. Eaten by a small unidentified fish caught in the Helgoland trawl near the mouth of Cattaraugus Creek; marginal zone only.

32. Alona affinis (Leydig). Well distributed along the Canadian shore but rare on the American side, and nowhere rated as abundant. Eaten by yellow perch, carp, and goldfish; marginal zone only.

33. Alona costata Sars. Found at only two of the marginal stations in very small numbers, Stony Point, Michigan, and Port Stanley. Eaten by yellow perch and an unidentified shiner.

34. Alona guttata Sars. A few specimens were found in the ponds on Point Pelee during the present survey; reported as very abundant there by Bigelow (1922).

35. Alona quadrangularis (O. F. Müller). Found only in very small numbers at Turkey Point and at Stony Point. Eaten by carp and redhorse suckers; confined to the marginal zone.

36. Alona rectangula Sars. Found at 3 marginal stations on the Canadian shore, at Dunkirk, New York, and in a mud washing at Eighteen Mile Creek, everywhere in very small numbers.

37. Alonella excisa (Fischer). Rare at Point Abino, Port Stanley, in the ponds on Point Pelee, and in Lackawanna Pond in the suburbs of Buffalo. Eaten by carp sucker; confined to the marginal zone.

38. Alonella nana (Baird). Found only at Point Abino and in ponds on Point Pelee. Eaten by carp and bullhead; confined to the marginal zone.

39. Bosmina longirostris (O. F. Müller). Found at 12 of the marginal stations evenly divided between the Canadian and American shores, and in the plankton of both the littoral and lacustric zones during June and July. Its numbers were less in July than in June and it did not appear at all during August or September; it breeds in Rondeau Harbor. In the open lake it was more in evidence at the two ends, and less so through the middle. Its highest percentage of the macroplankton was in the surface tow off Ashtabula, Ohio, in the littoral zone. Eaten by goldfish, the green-backed shiner, and the Cayuga minnow.

40. Bosmina longispina Leydig. Found in the marginal zone at 3 stations on the Canadian shore and at Sandusky Bay; 1 or 2 specimens were taken in the littoral zone along with the preceding species. Breeds in Rondeau Harbor, where it was very abundant and where the tow was filled with young in various

stages of development. It is eaten by goldfish and the yellow perch.

41. Camptocercus macrurus (O. F. Müller). A few specimens were found in the ponds on Point Pelee. It has not thus far been identified in the stomach contents of any fish.

42. Camptocercus rectirostris Schoedler. Found at 10 stations of the marginal zone, 6 on the Canadian and 4 on the American side. At one station on either side it was listed as abundant and these are evidently its breeding areas. This species was reported and figured by Vorce from the vicinity of Cleveland, but was referred by him to the wrong species. Eaten by redhorse sucker and the picconou.

43. Ceriodaphnia laticaudata P. E. Müller. Found at 9 stations of the marginal zone, all but one in the center or at the western end of the lake; abundant only in the ponds on Point Pelee; not found in the other zones. Eaten by carp and yellow perch.

44. Ceriodaphnia pulchella Sars. Found in very small numbers at 5 marginal stations on the Canadian and 3 on the American shore. Eaten by yellow perch and carp.

45. Ceriodaphnia quadrangula (O. F. Müller). Found at Cedar Bay, Long Point, Inner Bay, ponds on Point Pelee, and Sandusky Bay. Eaten by shiners.

46. Ceriodaphnia reticulata (Jurine). Found at 4 marginal stations on the Canadian and 3 on the American shore. Breeds in the Inner Bay at Long Point and in a small pond of the Cattaraugus Creek drainage. Eaten by carp.

47. Chydorus faviformis Birge. Reported by Bigelow (1922) from the ponds on Point Pelee; not obtained during the present survey. Not found in the stomach of any fish.

48. Chydorus gibbus Lilljeborg. Found at Point Abino and Rondeau Harbor on the Canadian shore and at 3 stations on the American side; confined to the marginal zone. Eaten by the bullhead.

49. Chydorus globosus Baird. Found only in the marginal zone at Point Abino, Rondeau Harbor, and Point Pelee, and breeding at the two latter places. Eaten by yellow perch.

50. Chydorus latus Sars. Found only at 4 marginal zone stations on the Canadian shore; breeding in the ponds on Point Pelee. Not identified in the food of any fish.

51. Chydorus sphaericus (O. F. Müller). Found at 6 Canadian and 5 American marginal zone stations, and washed out of the sand on Crystal Beach. Breeding in small ponds of the Cayuga Creek and the Cattaraugus Creek drainages. Eaten by the redhorse sucker, carp sucker, and bullhead.

52. Daphnia longispina (O. F. Müller). Under this specific name are included all the varieties which possess a crest of any sort, and which for the purposes of this survey do not demand varietal separation. Found at nearly every marginal station on both sides of the lake as well as in the littoral and lacustric zones. In the two latter zones the combined varieties of this species were more numerous than pulex during June and July, but less numerous during August and September. In June they were more abundant at the surface, in July and August at the bottom, and in September at the surface again, thus giving evidence of vertical migration. All the varieties appeared during the summer but mendotae was the prevailing one in June and July, while galeata was more common in August and September. The varieties typica and galeata seemed most abundant along the Canadian shore, and mendotae along the American shore. They are eaten by the cisco, the yellow perch, and an unidentified shiner.

53. Daphnia pulex (de Geer). Found at practically every station in all 3 zones and its percentages of the macroplankton were often from 75 to 100 percent of the total. Next to Leptodora it is the largest cladoceran in the lake and this combined with its exceptional abundance makes it the most important species in the macroplankton. In the marginal and littoral zones it was much more abundant along the American shore than on the Canadian side. Indeed the only stations at which it was entirely absent from the tow were in the marginal zone on the Canadian shore.

Stingelin and Weismann have found that this species has two reproductive periods each year, a larger one from the middle of July to the middle of August, and a smaller one in November. They also found that the spring generation which hatched from the winter eggs (ephippia) was different from the fall generation which hatched from the summer eggs. The observations of other investigators combined with those made during the present survey seem to support both these statements. The monthly distribution of this species has been already discussed.

Bigelow (1922) found that D. pulex was not present in any of the cisco stomachs from the eastern end of Lake Erie, but that it formed the bulk of the food of the ciscoes in the western portion of the lake during summer and autumn. It has been identified also in the stomach contents of the mooneye, carp, carp sucker, silverside, green-backed shiner, Cayuga shiner, sand-roller, white bass, yellow perch, log perch, and lake sheepshead. The fact that it is eaten by so many and such different fish is another convincing testimony of its value as a fish food.

54. Diaphanosoma brachyurum (Liéven). Found at 4 marginal stations on the Canadian shore and 5 on the American shore. Eaten by the cisco.

55. Diaphanosoma leuchtenbergianum Fischer. Found at 16 of the marginal stations including all those at the western half of the lake on both sides; frequently very abundant. It was found in small numbers at various stations scattered through the littoral and lacustric zones, the highest percentage off Lorain, Ohio. Its great abundance in the marginal zone indicates that it breeds there during the spring or early summer, and when it becomes sufficiently numerous migrates out into the lake in small numbers. Such migration is mostly confined to the littoral zone and lasts only a short time, so that in September the species is again confined to the marginal zone. It is eaten by the cisco and yellow perch.

56. Eurycercus lamellatus (O. F. Müller). Found in the marginal zone at 6 Canadian and 1 American stations; abundant only in the ponds on Point Pelee where it was breeding. Eaten by carp sucker and yellow perch.

57. Graptoleberis testudinaria (Fischer). Reported by Bigelow (1922) in small numbers in the ponds on Point Pelee; not obtained during the present survey. Not found in the stomach of any of the lake fish.

58. Holopedium gibberum Zaddach. Found in very small numbers in the littoral and lacustric zones during June and July, but disappearing entirely in August and September. Since this cladoceran was not found anywhere in the marginal zone we have to conclude either that it is pelagic and breeds in the open water or that its breeding areas in the marginal zone were so exceptionally restricted as to escape notice. Its presence in the tows of June and July and disappearance later suggest that its breeding period occurs earlier in the year. In June it was confined to the middle of the lake but during July it appeared also at the eastern end. It is eaten by the cisco.

59. Ilyocryptus sordidus (Lieven). Found at 9 marginal zone stations at the eastern end of the lake but divided subequally between the Canadian and American shores. reported by Bigelow (1922) from the ponds on Point Pelee but not obtained there during the present survey. Often found in mud washings; eaten by the carp.

60. Ilyocryptus spinifer Herrick. Found at 6 of the marginal stations in the middle and at the western end of the lake and on both shores. It is eaten by carp and the carp sucker.

61. Kurzia latissima (Kurz). Found only in the ponds on Point Pelee and Lackawanna Pond in the Hertel suburb of Buffalo. It is eaten by the yellow perch and an unidentified minnow.

62. Latona setifera (O. F. Müller). Found in the ponds on Point Pelee, in Grand River at Fairport, Ohio, and in Lackawanna Pond, Buffalo. Eleven specimens were also taken in the Helgoland trawl in the center of the eastern end of the lake, but none appeared in any of the meter net hauls. This would indicate that when it gets away from the marginal zone into deeper water it sticks closely to the bottom. Eaten by the carp sucker.

63. Latonopsis occidentalis Birge. Reported by Bigelow (1922) from the ponds of Point Pelee, but obtained during the present survey only in the stomach contents of small fish. Eaten by yellow perch.

64. Leptodora kindtii (Focke). Found at 14 of the marginal stations and in the other zones. A large number were also washed out of flocculent debris from Eighteen Mile Creek above its mouth and at the mouth of Cattaraugus Creek. These were all very small, only 2 or 3 mm. long, and were probably hatched in the immediate vicinity since at their stage

of development they would hardly swim into such a place from the open lake. This is a bottom form as was shown by the fact that it was far more abundant in the Helgoland trawl than in either of the meter nets. In the latter, also, it was more abundant near the bottom than at the surface except at 1 or 2 stations near the western end of the lake. At the eastern end of the lake during 1928 it showed a decided preponderance on the American shore. At 2 of the littoral stations off the New York shore the Helgoland trawl brought up a large plankton catch that was practically 100 percent Leptodora. This indicates that Leptodora has the habit of swarming or gathering in large numbers in a single limited area like the marine copepod Calanus finmarchicus. Since this swarming takes place in the shallow water of the marginal and littoral zones of the lake it brings Leptodora into the very region frequented by young fish, where they can be of most service as food. Eaten by cisco and lake herring.

65. Leydigia acanthocercoides (Fischer). Found at 5 marginal stations, 4 of which were on the Canadian shore; abundant only at Turkey Point.

66. Leydigia quadrangularis (Leydig). Found at 6 of the marginal stations, 4 on the American shore; very limited in numbers everywhere. Eaten by bullhead and carp.

67. Macrothrix laticornis (Jurine). Found at only 2 marginal stations on the Canadian shore at the eastern end of the lake. Eaten by carp sucker and redhorse sucker.

68. Macrothrix rosea (Jurine) Found only at Crescent Beach and in the ponds on Point Pelee. Eaten by the carp and carp sucker.

69. Moina affinis Birge. Found in very small numbers in the ponds on Point Pelee; also reported by Bigelow (1922). Eaten by carp.

70. Moina rectirostris (Leydig). Found only in a mud washing at Tonawanda on the American shore of the Niagara River and in the old Erie Canal. It is eaten by carp and the carp sucker.

71. Monospilus dispar Sars. Found at 3 marginal stations on the Canadian shore, but nowhere abundant. Eaten by yellow perch.

72. Oxyurella tenuicaudis (Sars). Found only in a pond of the Cayuga Creek drainage in very small numbers. Eaten by the yellow perch.

73. Pleuroxus aduncus (Jurine). A few specimens were found at Cedar Bay on the Canadian shore and in a small pond of the Cattaraugus Creek drainage on the American shore. Eaten by the carp and the carp sucker.

74. Pleuroxus denticulatus Birge. Found at 3 marginal stations on the Canadian shore and 6 on the American shore, abundant at 1 station on either side. Eaten by an unidentified minnow.

75. Pleuroxus procurvatus Birge. A few specimens were found in the ponds on Point Pelee; previously reported by Bigelow (1922). Eaten by yellow perch.

76. Pleuroxus striatus Schoedler. Found at 2 marginal stations on the Canadian shore and 2 on the American shore; not abundant. Eaten by the carp sucker.

77. Pleuroxus trigonellus (O. F. Müller). A few specimens were found in the ponds on Point Pelee; previously reported by Bigelow (1922). Not found in the food of any lake fish.

78. Polyphemus pediculus (Linnaeus). Reported by Bigelow (1922) from the ponds on Point Pelee but not collected during the present survey. Not in the food of any lake fish.

79. Scapholeberis aurita (Fischer). Found at 2 marginal stations on the Canadian shore and 2 on the American shore; not abundant. Eaten by carp.

80. Scapholeberis mucronata (O. F. Müller). Found at 14 marginal stations evenly divided between the two shores and abundant at 2 stations on either side. Eaten by the carp and carp sucker.

81. Sida crystallina (O. F. Müller). Found at nearly every marginal station and in the littoral and lacustric zones, frequently very abundant. The surface net captured far greater numbers than the bottom net through June, July, and August, but in September the numbers were about equally divided between the two nets. It attained its highest percentages

of the macroplankton in the middle and at the western end of the lake and nearer the American shore during July, after which the percentages steadily decreased. In general it may be classed as a shallow water cladoceran, preferring the aquatic vegetation along shore, where it breeds in great numbers. Eaten by the cisco and yellow perch. Bigelow (1922) ranked it third in the list of organisms found in cisco food, Daphnia being first and Leptodora second.

82. Simocephalus serrulatus (Koch). Found at 6 marginal stations on the Canadian shore and 5 on the American shore; abundant at 3 stations on either side. Eaten by the bullhead and the carp.

83. Simocephalus vetulus (O. F. Müller). Found at 4 marginal stations on the Canadian shore and 5 on the American shore; abundant at 2 of the latter. Eaten by the bullhead and carp.

Other Crustacea

84. Mysis relicta Lovén. Found only at the bottom in the lacustric zone but present there in great abundance throughout the entire year. Mysis was obtained in goodly numbers at several stations during June on both sides of the lake where the water was only 20 meters deep, but during the 3 remaining months it was found only in the Deep Hole. Here, however, its percentages of the macroplankton were very large and often above 50 percent and once or twice reached 100 percent. During the summer it is confined to the eastern end of the lake, but in the winter it probably spreads into the middle and may even reach the western end.

In the larger lakes of Germany Mysis is reported to come into the shallower water during the colder months of the year and doubtless does the same in Lake Erie. Kindle has reported it in Lake Ontario down to depths of 258 feet, and that its abundance in the deep water of that lake is one of the interesting features of the bottom plankton. Reproduction is said to take place at low temperatures and to be most vigorous in winter when the temperature falls to 3 or 4° C. It is reported to constitute quite a large percentage of the food of cisco in other lakes and is probably eaten by them here, but practically none of the deep-water fish in Lake Erie have been examined for their food contents.

85. Pontoporeia affinis Lindstrom. Dr. Chancey Juday sent specimens of the amphipod species, which had been named Pontoporeia hoyi by S. I. Smith, to G. O. Sars, who after careful examination declared them to be identical with Pontoporeia affinis Lindstrom of the European lakes. This is another species of the macroplankton that is found only in the deepest portion of the lake and on the bottom. Juday and Birge (1927) have reported that in Green Lake it is rarely found above a depth of 10 meters during the summer. Green Lake has approximately the same maximum depth (68 meters) as Lake Erie (62 meters), but the thermocline here is lower than in Green Lake, and probably these cold water forms do not come as near the surface as 10 meters.

Pearse (1921) found that Pontoporeia was an important source of food for the cisco in Green Lake during the summer and it is probably eaten by them in Lake Erie. The sturgeon also is a bottom feeder and in Lake Nipigon it has been found that a considerable portion of its food consisted of Pontoporeia and Hyalella. At all events this amphipod helps to form in the deepest portion of the lake a food supply of considerable economic importance.

Pontoporeia, Limnocalanus, and Mysis are "marine relicts," that is, they are species which were originally marine but have become acclimated to fresh water. Their presence in Lake Erie in considerable abundance gives rise to the same question that has presented itself in connection with their appearance in European lakes, namely how did they get there?

Two theories have been advanced, one of which supposes the lakes to have been filled originally with salt water, forming an inlet or bay of the ocean. Separated from the ocean by subsequent land movements, and receiving sufficient freshwater drainage, they have gradually changed into freshwater lakes.

The other theory is that these crustaceans migrated gradually from the ocean into the lakes after the close of the glacial period. The first of these theories is automatically eliminated in connection with Lake Erie, for although Lake Ontario is believed to have been filled with salt water at the close of the glacial period, Lake Erie was not, and there was between them the insurmountable barrier of Niagara Falls.

We must assume then that the introduction of these forms into Lake Erie was accomplished by migration after the close of the glacial period. Such a migration is not only possible but may well have happened during the changes in level known to have taken place subsequent to the melting of the great ice sheet. Before the ice melted it filled the basins of all the Great Lakes and entirely removed their previous fauna. In the course of the melting a succession of temporary lakes was formed, of varying sizes and with changing outlets. At first these lakes discharged to the west into the Mississippi River; they next found an outlet to the east through the Mohawk Valley into the Hudson River. Either of these 2 routes is apparently much too long for a successful migration from the ocean into Lake Erie. But at the close of the glacial period during the Champlain substage an arm of the ocean extended up the St. Lawrence valley and covered Lakes Ontario and Champlain, and was called the "Champlain Sea."

At the time Lakes Superior, Michigan, and Huron, the "Nipissing Great Lakes," were filled with fresh water, there was an outlet through the Ottawa River into this Champlain Sea. A migration up this outlet into what is now Lake Huron would cover only a comparatively short distance, and was the probable route. At the same time there was a shorter migration southward into the Finger Lakes, in which all three of these crustacean genera are found at the present time.

When found in Lake Ontario, therefore, these Crustacea are "relicts" in the strict sense of the word since they are found in a lake originally salt which has subsequently become fresh. But in Lake Erie they are not real relicts since this has never been a salt-water lake during or after the glacial period. They must therefore be regarded as migrants, for which they are all admirably fitted by the possession of peculiar locomotor ability. Once in Lake Huron their passage into the other Great Lakes could be easily accomplished.

COMPARISON OF LAKE ERIE AND VICTORIA NYANZA MACROPLANKTON

As the present survey of Lake Erie is the first comprehensive one of any of our American Great Lakes, it becomes of interest to compare its results with those obtained from similar large lakes elsewhere in the world. The African lakes have been examined with most detail, and of them Victoria Nyanza most resembles Lake Erie. This is the shallowest as well as the largest of African lakes, 200 miles long, 130 miles wide, 73 meters deep. Although it lies on the equator, it is elevated enough above sea level to greatly modify its macroplankton and make it temperate rather than tropical. The water, however, is much warmer than that of Lake Erie, the lowest temperature recorded being 73.3° F., the highest 81° F. The water is not normally fresh but contains various salts in solution, especially those of magnesium.

In Victoria Nyanza there have been recorded 2 calanids, 2 harpactids, 8 cyclopids, 1 ergasilid, and 31 cladocerans, 44 species in all, of which 8 were not obtained from the lake itself, but within its drainage area. In the present survey of Lake Erie, there have been recorded 6 calanids, 5 harpactids, 9 cyclopids, 2 ergasilids, and 54 cladocerans, 76 species in all, of which 8 were not obtained from the lake itself, but within its drainage area. In Victoria Nyanza 1 calanid, 1 harpactid, and 1 cyclopid were endemic while the remaining 41 species were more or less cosmopolitan. In Lake Erie none of the 76 species was endemic but all were more or less cosmopolitan. Among the copepods only 4 cyclopids are common to both lakes, while among the Cladocera 11 species belonging to 6 genera are found in both lakes.

MACROPLANKTON AS INTERMEDIATE HOSTS

Many species of macroplankton are intermediate hosts to the developmental stages of various fish parasites. Five of the Cyclops species recorded have been experimentally proved to be possible intermediate hosts for a tapeworm of the walleye pike by H. E. Essex (1928). Four of the Cyclops species, 3 of which were different from the 5 above, have been shown to be possible intermediate hosts for a tapeworm infesting the bass, by G. W. Hunter and W. S. Hunter (1928). Bigelow (1922) reported Leptodora as containing the immature stages of some trematode, probably a parasite of the "Jumbo Cisco," since the Leptodora was eaten by that fish.

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CONTENTS

In compiling the results of the investigations of 1928 and 1929, the outline adopted for the preliminary report published on the first season's work has been followed. This makes possible more readily a comparison of the two years' work. In the present paper greater attention has been given to the second year's findings except where significant differences occurred. For a detailed account of the investigations in 1928 the reader is referred to the Preliminary Report (Fish et al. 1929), particularly for data on the topographical and bacteriological studies which were not repeated in 1929.

Since it was not possible to retain the scientific staff after the termination of field work, the individual reports have necessarily been prepared simultaneously as independent units. In the present review an attempt is made to correlate the data when possible, and to include certain analyses omitted in previous discussion. The two seasons' results will be considered jointly.

TOPOGRAPHY

Lake Erie is located in a shallow glaciated basin 240 miles long, with an average width of 40 miles and an area of approximately 9, 633 square miles. It is the shallowest of the Great Lakes, only about 40 percent of its total area exceeding 20 meters and less than 9 percent exceeding 30 meters. The present survey included 2 of the 3 natural sections of the lake, the eastern or Deep Hole area having a maximum depth of 64 meters and the Central or Great Plain area having a maximum depth of 25. 5 meters. The western section including the islands in Ohio waters is not considered in the present report.

The Lake Erie basin has been formed for the most part in Devonian shales with a small amount of limestone and sandstone, and most of the entering streams drain through glacial deposits of sand and gravel. In cross section the eastern part of the lake is bounded on either side by sandy beaches or limestone cliffs merging into coarse sand, and beyond the influence of land outwash, into basic shale or faulted rock bottom free from sedimentary deposits except near the mouths of the larger creeks. The shale outcrop on the American side is smooth and forms a narrow alongshore band whose outer margin parallels the 10-meter contour. The Canadian outcrop is much broader, extending to the 15-meter contour, and is composed of honeycombed shale. The Central Basin contains a thick deposit of clay mud covering a great portion of the lake and whose outer margin for the most part parallels the 20-meter contour (fig. 63).

The clay mud area extends to the shore only in such places as Long Point Bay and Erie Harbor where outwash from the land settles in the lee of protecting cuspate bars. Two such bars penetrate into the lake from the north and south shores and constrict the lake west of the Deep Hole. The constriction is further accentuated by a sandy shoal area extending north and south across the lake and dividing it into two basins. Except for this sandy shoal the entire bottom within the 20-meter contour is of clay mud. Two interesting black mud areas of considerable size are located east and west of Rondeau on the Canadian side. The larger of these is approximately 45 miles long and has a maximum width of 15 miles.

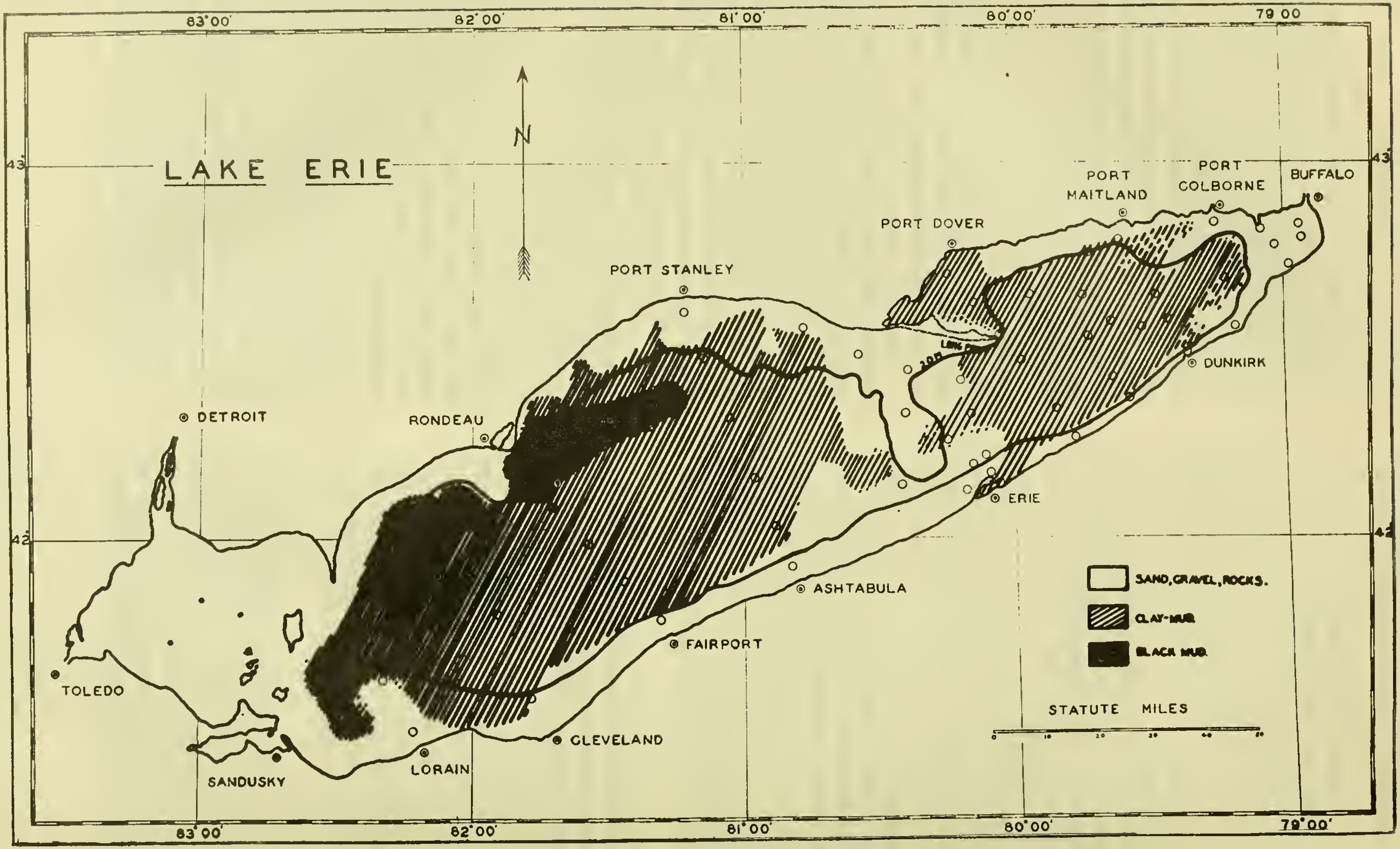

Figure 63. --Clay and mud areas in Lake Erie.

Compared with average meteorological conditions of weather and mean temperature over a period of years, 1929 may be considered an average year with conditions in the lake close to normal. Until the ice leaves, the lake remains cold and homothermous. In 1929 the last ice passed down the Niagara River on May 2; in 1928 a considerable quantity remained in the vicinity of Buffalo on May 15. As the temperature continued to rise in June the response was quite different in the eastern and middle sections of the lake, the former warming more slowly. This condition was reflected in both the plant and animal plankton in which augmentation occurred progressively later to the eastward. The maximum surface temperature was reached in August, although due to mixing by wind action the bottom temperature increased through September.

There was a slight and fairly even vertical temperature gradient in May, and during the early summer a thermocline formed in both basins. An area of cold bottom water of less than 12° C. extended over about 45 percent of the total lake in July 1929 and covered a large portion of the Central Basin. By August the area in the latter section had been reduced to a relatively small area of about 235 square miles. The depth of the thermocline was found to be influenced by the bottom, tending to follow the contour in some localities.

The thermocline in the Central Basin is short-lived and probably remains for 2 or at most 3 months. In 1929 heavy winds in early September thoroughly mixed the water from surface to bottom. In years of severe and frequent storms it is possible that no thermocline may be found there. The biological importance of this cold bottom water is uncertain. Observations on the summer population indicate that both the benthic and the pelagic communities are periodically subjected to such wide ranges of temperature that it seems doubtful if this delayed warming of variable duration exerts any very significant influence on summer non-migratory species. Such cold water forms as *Limnocalanus* probably remain longer in the Central Basin during years when the thermocline persists far into the summer.

A thermocline in the eastern area persisted throughout the summers of 1928 and 1929. A cold water mass, with a temperature from 4° to 6° C., remained in the basin of the Deep Hole. In 1929 6° C. water covered an area of 1,290 square miles in May, but during the summer contracted to 410 square miles in September. A considerable portion of the Deep Hole is thus covered by cold water throughout the year and serves as a favorable habitat for such "arctic relict" species as *Triglopsis thompsoni*, *Mysis relicta*, and *Pontoporeia affinis*.

The movements of the cold bottom water in the Deep Hole were first observed in 1928 when the eastern margin was found to have advanced 26 miles in 20 days and 2 weeks later had retreated again to the west. Although sufficient facilities for establishing the cause for this movement were not available during the first season, when compared with meteorological data "...it would appear that the oscillation of the cold bottom layer to the east in each case occurred as the water, piled up at the eastern end of the lake by westerly winds, was readjusting itself to the normal lake level. The rise in the level in the eastern part of the lake was accompanied by a retreat of the bottom layer, possibly due to the depression of the eastern end of the pycnocline and the consequent pressing back of the cold water mass. Thus a close correlation occurred between the wind and the movement of the water mass, the advance of the cold mass taking place in the readjustment process after the termination of the wind." (Fish *et al.* 1929, p. 196.)

Further investigation in 1929 indicated that when the level at the eastern end of the lake rises over a period of several days, even though the range does not exceed 6 inches, an oscillation of the cold bottom water to the west results. When the lake level becomes normal again the bottom water returns by gravity to its normal position, which in 1929 approximated the 40-meter contour (6° C. water). All evidence in 1929 points to wind and not barometric pressure as the principal factor controlling the oscillations. Wind may also cause a north-south oscillation of the bottom water but this was not observed as frequently as the east-west movement which may be more or less continuous in some years. The importance of this cold bottom water on the fishery in eastern Lake Erie has previously been discussed (Fish *et al.* 1929). It is well known that schools of those species favoring low temperatures move with the cold water mass, and the fishermen set their nets accordingly, using the wind as an indicator.

During the oscillatory movement of the water mass in the Deep Hole, cold bottom water is sometimes forced into Long Point Bay. At such times the level of the thermocline in the vicinity of the point (station 17) varies greatly and remarkable temperature gradients result. On one occasion the thermocline rose 3 meters in 9 hours. At another time a difference of 6. 6° C. was observed in one-half meter. The temperature of the bottom water in Long Point Bay may thus fluctuate widely during the summer and under the influence of strong winds contributions from the lower levels in the Deep Hole become mixed, lowering the surface temperature throughout the bay. The low surface temperatures often recorded from this area may be largely due to this. The rapid change in surface temperature is shown at one station when a rise of 3° C. occurred in 22 hours.

In view of frequent reports of strong currents in the open lake, it was surprising to find that during the interval of the investigations the maximum velocity recorded was 0. 6 m. p. h. in 1929 and 0. 63 m. p. h. in 1928. Nine observations taken during the former season in the most unsettled portion of the lake (station 17) showed a mean velocity of 0. 26 m. p. h. Here the water is forced past Long Point following any alteration of the lake level. It is probable that the natural eastward flow in the lake rarely exceeds 0. 1 m. p. h., except near the river mouths. This movement is mainly confined to the central axis of the lake, affecting mostly the middle third of the water mass. The movement is not continuous and may be halted or even reversed by wind action.

Current velocity was not always proportional to wind velocity and the direction of the wind and current did not always coincide. Sometimes winds of short duration were directly opposite to the current.

Two primary seiches, previously reported, were observed in 1929. The period for the east-west oscillation appears to be 14. 1 hours and for the north-south oscillation 2. 7 hours.

CHEMISTRY

The chemical results for the years 1928 and 1929 agree so well that there can be little doubt that the records for these years indicate normal conditions in the lake. The seasonal progression appears clear.

After the spring overturn, chemical conditions were no doubt uniform from top to bottom and free carbon dioxide accumulated during the winter was thoroughly distributed through the water mass. Active phytoplankton production during the vernal flowering season rapidly depleted the carbon dioxide in the surface waters where it was exhausted by June. The intensity of plant production was shown by this rapid change in spite of the fact that processes of decomposition would be accelerated by the rising temperature. The shallow area of the lake evidently responds more quickly to changing climatic conditions than the deeper zone and is also a region of greater photosynthetic activity.

Free carbon dioxide diminishes rapidly in the bottom waters during the summer, being limited to the two basins in August. The destruction of the thermocline in the western basin resulted in increased bottom oxygen and the elimination of carbon dioxide. Free carbon dioxide was absent in the Great Plain Basin by September. In seasons when winds might prevent the formation of a thermocline in this area it is probable that the free carbon dioxide would be found limited to the Deep Hole after June. Water with free carbon dioxide in the eastern basin had been restricted to a zone within the 30-meter contour by September 1929. Free carbon dioxide is present in the Deep Hole throughout the year.

The oxygen content in Lake Erie is relatively high and the extremes reported from other lakes never occur. The surface plant production, although extremely rich, does not greatly supersaturate the surface layers. Similarly bottom decomposition of organic materials does not seriously influence the oxygen content, which normally averages between 60 and 70 percent.

An interesting exception was found at stations 41 and 42 in the vicinity of Rondeau. Unusually low oxygen, low pH, and high carbon dioxide were recorded here in 1929. The cause of these conditions has not been established, but their occurrence in the only large, offshore, black mud area in the lake appears significant. Two large patches of black mud, rich in organic material, occur east and west of Rondeau, and the chemical values indicate active processes of decomposition. Elsewhere the chemical values were remarkably uniform, with gradual gradations into the deeper waters. It may be added that the macroplankton in the black mud area affords evidence that the low oxygen and high carbon dioxide occurring in the open lake during the summer of 1929 were not limiting factors to pelagic animal production or distribution. The community at stations 41 and 44 in the Rondeau region was found concentrated at the bottom and exceeded in volume the average for the Central Basin.

Methyl-orange alkalinity was uniform throughout the lake, the surface values being consistently lower. There was a very slight decrease during the summers of both years, probably due to the precipitation of calcium carbonate caused by the removal of carbon dioxide. Some of the precipitate is probably recovered when the carbon dioxide is again introduced in the lower levels by vertical mixing. This removal of the carbon dioxide resulted also in a gradual increase in pH, the bottom averaging somewhat lower than the surface.

Turbidity tests indicate relatively clear water for the lake as a whole. The highest figures were from the vicinity of the Deep Hole, as expected, for here the bottom is covered with fine clay silt and is subjected to great animal activity and active movement of the bottom water. The surface waters cleared rapidly over the whole lake and the bottom waters gradually during the summer.

The seasonal trend of the lake from June to September shows an increase in oxygen saturation, albuminoid nitrogen, free ammonia, and nitrates, and a decrease in dissolved carbon dioxide, pH, methyl orange alkalinity, and turbidity.

The bottom levels in the Deep Hole contrasted with the lake as a whole are characterized by relatively low oxygen, free carbon dioxide at all times, low pH, and high turbidity.

MICROPLANKTON

Horizontal Distribution and Seasonal Variation

An outstanding characteristic of the summer plankton of Lake Erie is the horizontal variation in both plants and animals. Four major groups of microplankton, diatoms, green algae, blue-green algae, and rotifers, occur in abundance at certain seasons of the year, but never do they appear to be uniformly distributed over the entire lake and in most instances their maxima do not occur at the same time.

Horizontal distribution at any time in Lake Erie must be related to seasonal variation, for the latter does not occur uniformly throughout the lake. There appears to be a correlation between the seasonal changes in temperature and microplankton response. As the shallower areas of the lake respond first to rising or falling temperatures, the plant pulses become noticeable first in the western area and gradually extend eastward.

When the investigation began in 1929, the vernal diatom maximum was drawing to a close in the western portion of the Great Plains Basin although diatoms were still fairly abundant over a considerable portion of the lake. The eastward trend became evident by July, with the diatom production concentrated in the region east of Long Point. The autumnal maximum made its first appearance in the western area early in September of 1929 and by the 19th had spread as far east as Fairport, being most pronounced in the very shallow alongshore zone. Unfortunately, the termination of the observations at this time did not permit a determination of the date of the response at the eastern end.

As reported by previous observers (Birge and Juday 1922) the diatoms were found to respond most vigorously to favorable environmental conditions and are the dominant forms in the vernal and autumnal maxima. The green algae paralleled in a general way the fluctuations of the diatoms but the blue-green algae appeared to vary inversely with them. In June in the Central Basin blue-green algae were fairly abundant but entirely absent in the eastern area. In August they appeared as the dominant midsummer group at the time that the diatom production was at its minimum. Whether this indicates a biological correlation between the two groups or a differential response is not known, although the latter appears more probable.

Vertical Distribution

Uniform vertical distribution was found in the shallow areas which comprise the greater part of the lake. Only in the vicinity of the Deep Hole did the diatoms, whose range exceeds that of the other groups, decrease in numbers. A marked decline was observed below 50 meters. The average number of diatoms per liter in 1929 was 4, 000 at the surface and 4, 300 at the bottom. (The vertical gradient in the limited deep area is in this instance obscured.)

It was not possible to determine the depth at which production can take place in Lake Erie. The presence of large numbers of diatoms in the deeper levels at the end of a productive period is not necessarily an indication that production is taking place there. The sinking to the bottom after active production has ceased may be slow and the vertical gradient at such times would not yield a true picture of the normal vertical range. Again, the vertical range at the beginning of the productive period may not be indicative of conditions at the peak. It is evident, however, that except for a very small sector, diatom production takes place from the surface to the bottom in Lake Erie.

Green algae were found most abundant in the upper 10 meters, but in shallow areas the vertical gradient was hardly perceptible. A seasonal change in the vertical range was observed in the blue-green algae. They were concentrated in the upper levels in June. Little difference was found between the surface and bottom in the eastern area in August. The rotifers showed little vertical variation except a tendency to concentrate in the upper levels.

Factors of Production

The time of appearance of major plant pulses in any area in the lake is largely a function of light and temperature; the degree of response is largely a function of available food stuffs. Thus the extreme fluctuations found on occasion, usually in limited alongshore areas, may be considered indicative of a variable food supply, but the general distribution over the lake as a whole can most closely be correlated with physical environment.

Since the present survey was designed to determine the pelagic flora of the lake and its quantitative and qualitative distribution during the period from June to September, no attempt has been made to determine the maximum plant population which Lake Erie is capable of supporting. In the limited time available and with so large an area under consideration, such a program could not be included in the scope of the present investigations. However, the rapidity with which the waters of the lake are depleted of carbon dioxide and the quantitative figures on the plants themselves, considering the rich fauna of predatory forms, indicate no artificial limiting factors introduced by man.

MACROPLANKTON

Special consideration was accorded the macroplankton in the Lake Erie investigations, first because of its importance as food for fishes, and secondly because the presence of artificial environmental conditions unfavorable to animal life can be more readily detected in plankton than in fishes.

The macroplankton of the Great Lakes plays a much more important role as a direct source of food for adult fishes than that of the sea. This is clearly indicated by the relatively large number of lake species which depend almost solely upon this source of supply. Such a condition is necessitated by very fundamental differences between the invertebrate communities of the two environments. Owing to the absence of an intertidal zone there is not the rich benthic community of larger invertebrates along the margin of the shore of Lake Erie that one finds in the ocean. In the neritic zone, also, although small forms such as insect larvae are particularly abundant at times, the vast numbers of larger benthic species which support practically all adult nonmigratory ocean fishes are conspicuously scarce at least in Lake Erie. The scanty fauna of crayfish, shrimp, and molluscs, appearing in the bottom trawls, may be partly accounted for by the concentration of predatory fishes, but the fact remains that to maintain themselves the vertebrates must depend on another source of supply, and this is provided in the macroplankton.

Macroplankton Production

In considering the production of pelagic Crustacea in Lake Erie, the seasonal fluctuation in the adult population serves as the basis for our calculations. Data were not obtained on the time of appearance of the larval stages, but development is rapid and actual production can be considered to have taken place several weeks earlier than the present records indicate.

The summer repopulation of the lake begins in the southwestern portion with the first rise in temperature. Here the response to meteorological conditions is most rapid. An eastward trend follows, the areas along shore being influenced first. Gradually the deeper central portions of the lake are affected. The last portion to be affected is the northeastern region comprising the Deep Hole and the Canadian littoral. This apparent easterly migration of certain species as the season progresses is probably due more to a differential response in the eastern and western regions of the lake than to any movement on the part of individual organisms. The response in the Eastern Basin may be from 4 to 6 weeks later than in the southwestern area, so that the community observed first in the Cleveland-Lorain area in July may be expected west of Long Point in August. This condition is shown both in the quantitative and qualitative distribution records.

During the period of rising temperature, differences in the relative proportion of members in the plankton community occur not only from east to west but also on the two sides of the lake. The latter condition results from the fact that in the eastern area the seasonal response is much more rapid on the American side, and persists until the dominant cladoceran species become generally distributed throughout the lake in late August. In July and early August (1929) copepods still formed the bulk of the catch in Canadian waters, while Cladocera dominated on the American side. A few weeks later the expansion of the cladoceran pulse was evidenced by a uniform distribution over the whole area.

The lake was restocked by some species such as Diaptomus ashlandi twice during the season. Other species, although widely distributed, never appeared in numbers sufficient to be of economic significance. Other species such as Sida and Diaphanosoma, with short breeding seasons, never appeared to flourish in the eastern part of the lake although in the Central Basin the former species comprised 94 percent of the macroplankton community in restricted localities in July. Probably the breeding periods of such species pass before the temperature in the Deep Hole region reaches their minimum reproductive requirements.

Volume of Plankton

To those accustomed to quantitative values in the sea, the volume of animal plankton in this lake is amazing. It is more remarkable because the total amount consists of organisms having high fish-food value. Except for insect larvae which, particularly in the marginal zone, often appear in significant quantities, the macroplankton is made up entirely of Crustacea. In the ocean the plankton is usually made up of several groups of animals. Often the greater portion may consist of coelenterates, Sagittae, and other forms which must contain relatively little nourishment.

The mean volume of macroplankton in Lake Erie for the summer of 1929 was 495 cc. (combined surface and bottom 5-minute hauls with a meter net), that of the area east of Long Point being 508 cc. and to the west 474 cc. When the investigations began in June the influence of vernal production was just becoming evident by an increase in the adult crustacean population. At this time, however, only 2 stations yielded over 300 cc. and only 11 out of 49 stations reached 200 cc. Except for occasional local responses in some alongshore outwash areas, widespread vernal production centered first in the southwestern portion of the Great Plains Basin, with a gradual trend toward the northeastern part of the basin and the Deep Hole as the summer progressed (figs. 64-65).

By July the mean volume for the lake had risen to 412 cc., an increase of 270 percent over the previous month. The western area had increased 227 percent, and the eastern 330 percent, the production in the latter area being concentrated for the most part along the American side except at the extreme eastern end (Pt. Abino).

There was a further increase of approximately 7 percent for the lake as a whole in August, but this was due to a steady rise of 35 percent at the eastern end where conditions now more closely resembled those of the previous month in the west. In the Great Plains Basin there was actually a decline of 17 percent, the mean volume dropping from 440 cc. in July to 364 cc. in August. During this period a rise from 399 cc. to 540 cc. took place in the eastern area.

The mean volume in September rose 44 percent over the lake as a whole. In the western area production again rose 69 percent to reach the season's peak of 633 cc., exceeding July production in the same area by 40 percent. In the eastern area a gradual increase of 8.5 percent took place yielding a mean volume of 586 cc. Although tables 19 and 20 indicate that the western area in September was still more productive than the eastern (fig. 65), this production was centered in the northeastern portion of the Central Basin although relatively high values extended over the whole lake at this time.

Unfortunately, figures for the whole lake are not available for 1928 but a comparison of the eastern area for the two years indicates that in 1928 the mean volume averaged 584 cc. or 15 percent higher than

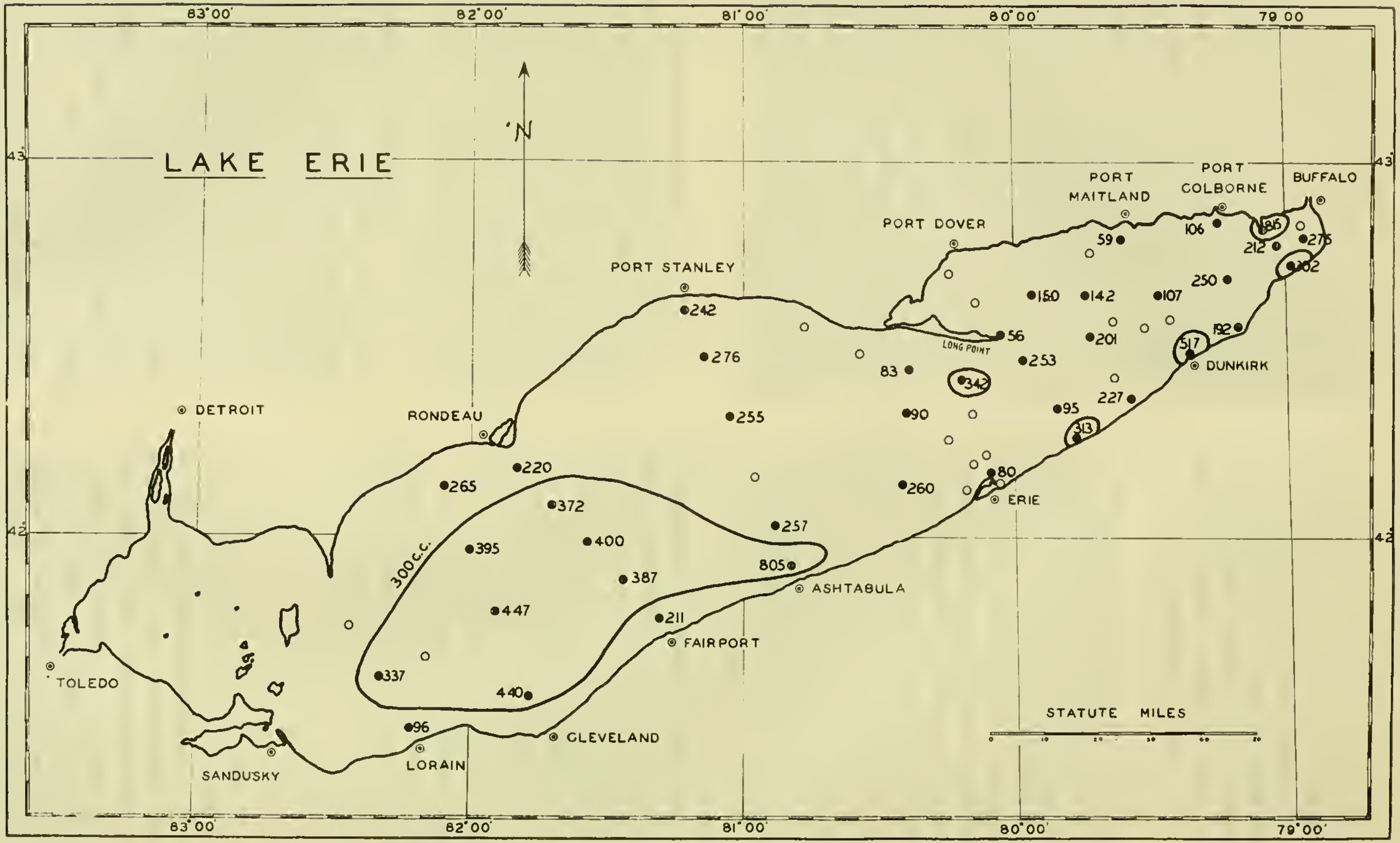

Figure 64A. --Mean volume of macroplankton in Lake Erie, June-July 1929.

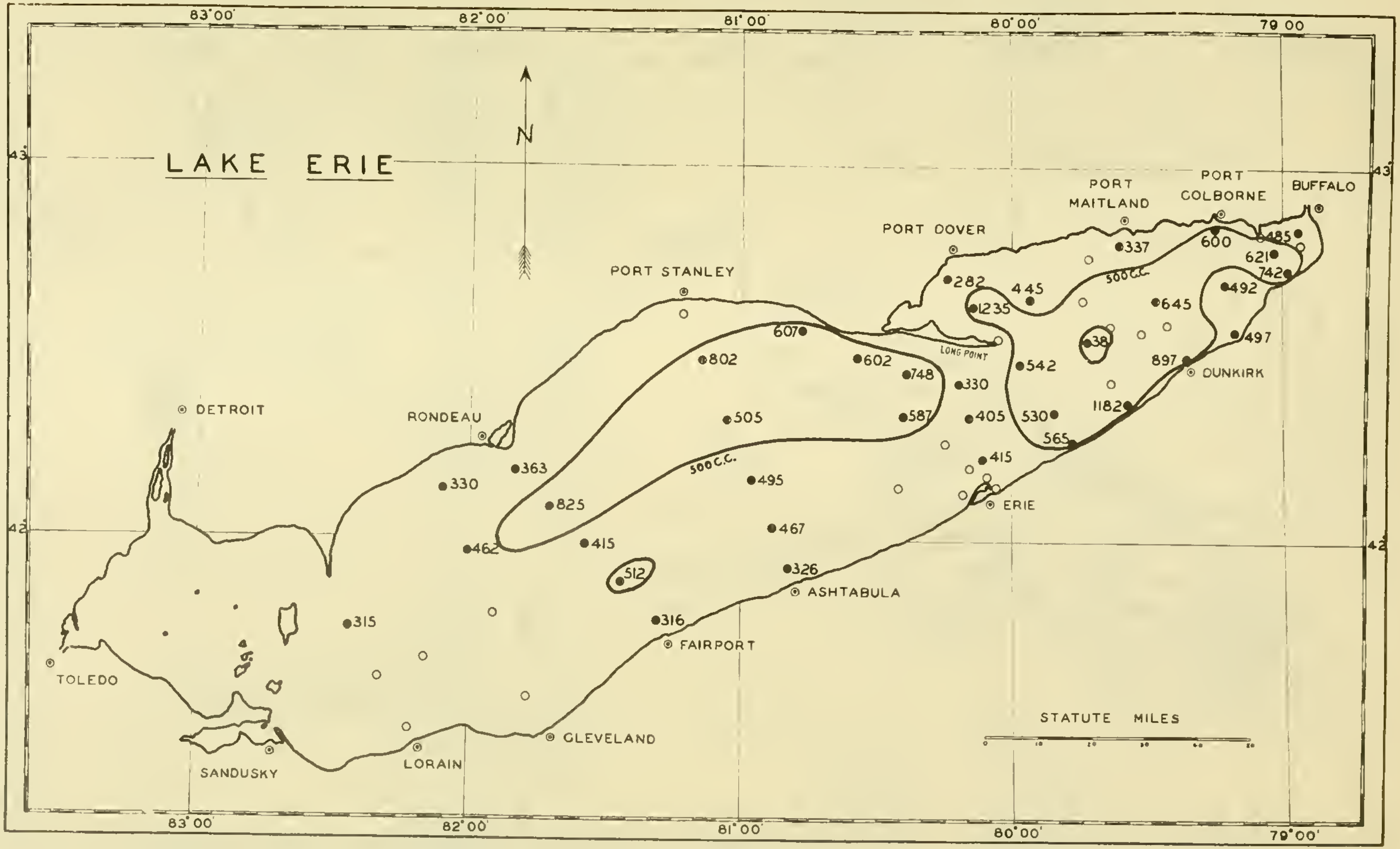

Figure 64B. Mean volume of macroplankton in Lake Erie, August-September 1929.

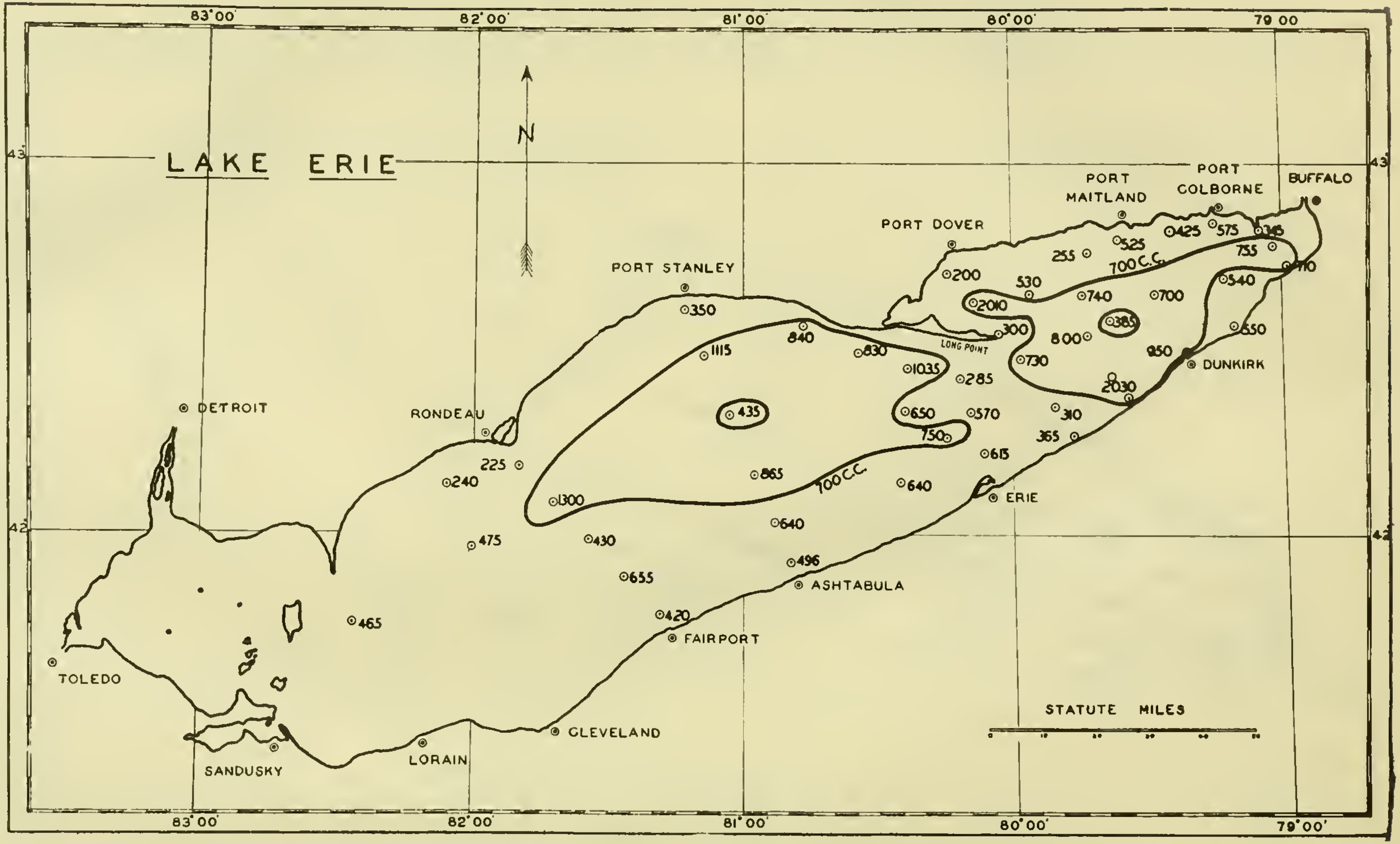

Figure 65. --Mean volume of macroplankton in Lake Erie in September, 1929.

Table 17. --Stations yielding the greatest volume of macroplankton on each cruise in 1928 and 1929
[Combined surface and bottom hauls of 5-minute duration]

Date	Cruise	Station	Volume (cc)	Mean surface temperature east area (° C.)	Location
1928					
July 27	01	11	1,800	21.8	South shore
August 16	03	18	3,500	22.9	Long Point Bay
September 1	05	18	1,986	21.6	Long Point Bay
September 12	06	10	1,028	20.9	South shore
1929					
June 12	02	28	540	12.3	Central Basin
July 11	04	37	1,425	18.8	West area
August 7	06	11	845	19.7	East area
September 4	08	11	2,830	20.7	East area

Table 18. --Macroplankton production in Lake Erie from June to September, 1929
[The factor is used for comparison with the minimum value of the season]

Date	Cruise	Number of stations	Total volume (cc)	Mean volume per station (cc)	Factor	Mean surface temperature at 37 stations (° C.)	Mean bottom temperature at 37 stations (° C.)
June 7-19	02	49	5,464	111.5	1.00	15.47	9.39
July 2-15	04	40	16,494	412.3	3.69	18.86	12.77
Aug. 3-20	06	43	18,921	440.0	3.94	20.58	14.73
Sept. 3-19	08	46	29,136	633.4	5.68	19.99	16.80

Table 19. --Macroplankton production in the eastern part of Lake Erie, stations 1 to 25, from June to September, 1929
[The factor is used for comparison with the minimum value of the season]

Date	Cruise	Number of stations	Total volume (cc)	Mean volume per station (cc)	Factor	Mean surface temperature (° C.)	Mean temperature at 10 meters (° C.)
June 7-12	02	20	1,854	92.7	1.0	12.3	10.4
July 2-8	04	17	6,778	398.7	4.31	18.8	16.6
Aug. 3-10	06	16	8,634	539.6	5.82	19.7	18.2
Sept. 3-7	08	20	11,715	585.7	6.32	20.7	20.1

Table 20. --Macroplankton production in Lake Erie west of Long Point, stations 26-51, from June to September, 1929
[The factor is used for comparison with the minimum value of the season]

Date	Cruise	Number of stations	Total volume (cc)	Mean volume per station (cc)	Factor	Mean surface temperature (° C.)	Mean temperature at 10 meters (° C.)
June 12-19	02	26	3,493	134.7	1.0	17.3	12.8
July 9-15	04	21	9,246	440.3	3.27	20.1	18.0
Aug. 10-20	06	24	8,747	364.5	2.71	21.0	19.8
Sept. 9-19	08	22	13,576	617.1	4.58	19.5	19.5

Table 21. --Comparative figures on macroplankton production in Lake Erie in 1928 and 1929 from July to September

[The factor is used for comparison with the minimum value of the season, the percentage change for comparison with the previous month]

Month	Mean volume 1928 East (cc)	Mean volume 1929 East (cc)	Mean volume 1929 West (cc)	Mean volume 1929 Lake (cc)	Factor 1928 East	Factor 1929 East	Factor 1929 West	Factor 1929 Lake	Percentage change 1928 East	Percentage change 1929 East	Percentage change 1929 West	Percentage change 1929 Lake
July	588.0	398.7	440.3	412.3	1.5	1.0	1.2	1.0	...	330.1	226.9	269.8
Aug.	815.0	539.6	364.5	440.0	2.0	1.35	1.0	1.1	38.6	35.3	-17.2	6.7
Sept.	385.0	585.7	617.1	1/633.4	1.0	1.5	1.7	1.6	-52.8	8.5	69.3	43.9

1/ Mean volume for lake includes 11 stations not considered in east or west area calculations.

Table 22. --Macroplankton production in the eastern part of Lake Erie, stations 1 to 25, in 1928

[The factor is used for comparison with the minimum value of the season, the percentage change for comparison with the previous month]

Date	Cruise	Number of stations	Total volume (cc)	Mean volume per station (cc)	Factor	Mean surface temperature (° C.)	Mean temperature at 10 meters (° C.)	Percentage change
July 26-Aug. 1	01	21	12, 352	588	1. 5	21. 8	20. 9	...
Aug. 15-17	03	21	17, 111	815	2. 0	22. 9	21. 3	38. 6
Aug. 28-Sept. 3	05	18	10, 814	601	1. 6	21. 6	21. 2	26. 3
Sept. 11-14	06	11	4, 239	385	1. 0	20. 9	20. 6	35. 9

in the following year (tables 21 and 22). In July and August 1928 the production averaged about 33 percent higher than in 1929, but in September of the former year the volume dropped 53 percent while in the second year it rose 8.5 percent. As the temperatures during 1928 averaged consistently higher until September than in 1929, it may be that the breeding season terminated earlier and the numbers declined with the slight drop in mean temperature that month. The mean temperature rose steadily in 1929 both at the surface and bottom throughout the season, reaching its peak in the region of the Deep Hole in September. Slightly lower temperatures were recorded in the western area on the last cruise together with indications that production was declining in the western part of the Great Plains Basin.

Evidently the summer macroplankton volume increases with the temperature and begins to decrease as soon as the temperature peak has been passed. During this interval the relative proportion of the various members of the plankton community fluctuates as the breeding season of none of the dominant species extends over the entire summer.

Faunal Zones

The lake may be divided into 3 faunal zones: a marginal zone confined to the alongshore waters to a depth of 1 meter, and including tributary streams; a littoral zone comprising the shoal areas from 1 to 10 meters; and a lacustric zone from 10 to 62 meters. The following conditions found in the eastern area in 1928 applied equally well to the lake as a whole in 1929, ... "More or less overlapping occurred in the two latter zones, but although the dominant species were found in both, they were present in such different proportions that it was possible, particularly during the early part of the season, to determine without difficulty which were endemic and which exotic in any particular zone. Later in the season when the dominant species of the lacustric zone expanded laterally into the littoral waters they outnumbered the species of the latter to such an extent that the proportions of lacustric species were often as great in shallow water as in the deeper parts of the lake." (Fish *et al*. 1929.)

Marginal zone.--This zone is of particular significance for two reasons: first, because it contains some of the most important macroplankton production centers in the lake; and second, because it has a rich and distinct fauna more closely related to that of the tributary waters than to the open lake. Breeding grounds almost surround the lake being more numerous and relatively larger on the Canadian shore.

There are 3 major centers covered with reeds and rushes, with a total area of more than 100 square miles, 2 on the Canadian shore and 1 on the American. Each forms an important breeding ground for a different species of the genus *Diaptomus*, as well as for many other forms; in fact all the cladocerans and copepods in the lake, with the exception of the cold-water genus *Limnocalanus*, were found breeding in at least 1 of these 3 localities.

Vast numbers of certain species carried into the lake never reappear beyond the immediate vicinity of the outwash. Such marked distribution limits are due to the rapidity with which freshwater Cladocera and Copepoda die or pass into resting stages when unfavorable environmental conditions are encountered. Contributions of organic matter of this sort from streams and ponds must supplement considerably local production in the marginal area and perhaps may explain the presence of large schools of small fishes in these localities at certain seasons. Although many species of Entomostraca never are able to establish themselves in the lake, some of the bodies of water in the drainage area were found to contain very rich faunas of important Lake Erie species. As might be expected, the marginal zone is characterized by much greater inequalities in distribution than the littoral or lacustric zones. Qualitatively the variation was not very great but the abundance of 1 or 2 species and the small numbers of all others at each station was particularly striking. Rarely did the same species dominate at even adjacent stations.

Littoral zone.--Except for the "arctic relict" species which when present always occur here in smaller numbers, the fauna of the littoral zone is very similar to that of the lacustric zone. The major distinction is that both cladocerans and copepods which later extend over the entire lake appear first in the littoral zone. The zone is best defined by the absence or presence of marginal and lacustric species rather than by any truly characteristic species of its own, although several species are found at all times in greatest abundance here. During the period of rising temperatures great differences were observed on the American and Canadian sides, particularly in the area east of Long Point.

Lacustric zone.--This zone is characterized by the "arctic relict" forms Mysis and Pontoporeia which are found only in the deep cold water after June, and by Limnocalanus which becomes more and more restricted to deeper areas as the summer advances. Differences in vertical distribution due to the thermocline are much more pronounced in the lacustric zone. These differences are both qualitative and quantitative.

Macroplankton Community

The macroplankton community of the open lake consists of 8 copepods, 7 cladocerans, 1 mysidacean, and a few insect larvae. Only 11 species can be considered of major significance in the economy of the lake in summer. These in order of their abundance over the lake as a whole are: Daphnia pulex, D. longispina, Diaptomus ashlandi, D. sicilis, Limnocalanus macrurus, Epischura lacustris, Cyclops bicuspidatus, C. leuckarti, Leptodora kindtii, Mysis relicta, and Sida crystallina.

Daphnia pulex was the most important macroplankton organism because of its size and abundance during the summer months, when together with D. longispina it formed considerably more than half of the plankton of the littoral and lacustric zones. The normal trend of plankton production in the lake was well illustrated in the seasonal distribution of these 2 species in 1929. D. longispina became abundant first in the southwestern portion of the Great Plains Basin with the rise in temperature in June. (At this time the copepods Diaptomus sicilis and D. ashlandi had passed their peak in the western area but were still increasing in the eastern part of the lake.) Gradually it spread out over the Central Basin and along the American shore into the eastern area. In June small numbers were found all along the south shore in the Deep Hole region but were entirely absent in the middle of the lake and on the Canadian side. By July it had extended its range to cover the whole lake, although in the northeastern sector (Canadian side) it was still outnumbered by Diaptomus ashlandi.

Daphnia pulex increased rapidly in the Central Basin during July and quickly expanded eastward. Since D. longispina had by now passed its peak, D. pulex soon became the dominant member of the lake community everywhere except below the thermocline in the Deep Hole where it was outnumbered by Limnocalanus. By September it had begun to decline in the southwestern portion of the Central Basin but in the east the numbers were still increasing at the termination of the investigations. In 1928, due probably to higher temperatures throughout the summer, D. pulex terminated its maximum earlier and in September was exceeded by Diaptomus ashlandi.

Of the copepods, Diaptomus ashlandi and D. sicilis form important and sometimes dominant members of the community for a limited period following their breeding seasons. D. sicilis became the dominant species for a short time in June and then declined slowly during the summer. D. ashlandi increased during the summer and in September 1928 dominated the catch. In 1929 it had not exceeded Daphnia at the termination of the investigations.

Although their distribution is greatly restricted during the warm season, Limnocalanus macrurus and Mysis relicta are important because of their size and abundance. Limnocalanus is generally distributed at all levels in June, but first seeks the bottom and then gradually becomes restricted to the eastern area as the bottom temperature in the Central Basin rises above 14° C. Mysis responds more readily to rising temperature than Limnocalanus and by June 1929 had retreated to the Deep Hole where it remained during the rest of the summer. Together these 2 species form the bulk of the macroplankton below the thermocline.

Epischura lacustris reached its maximum in the littoral zone during the period of rising temperatures in June and declined during July, August, and September. Although a warm water species (Marsh 1903) it did not favor the highest summer temperatures in Lake Erie and as the season advanced, it penetrated deeper and became more and more restricted to the cool eastern area.

Cyclops bicuspidatus and C. leuckarti were never the dominant species in the littoral or lacustric zones although each formed at times a significant part of the community. C. Bicuspidatus reached its maximum early and in 1929 was decreasing in the southwestern area by June 19. It had almost entirely disappeared by August. C. leuckarti increased over a wide area during the summer, reaching its maximum in August and declining to a mere trace in September.

Leptodora kindtii and Sida crystallina reached their maxima in midsummer and both had their center of production west of Long Point. Leptodora was present in small numbers throughout the lake until August when it increased rapidly and formed up to 33 percent of the hauls in the Great Plains area. The maximum was short lived and in September it nowhere exceeded 5 percent of the catch. Most of the collections yielded only occasional individuals. Sida reached its peak in July when it comprised up to 94 percent of the community in some parts of the Central Basin. Here it remained abundant throughout August and declined during September. Like Leptodora it occurred at all times in small numbers in the eastern area.

Vertical Distribution

The extent of the area investigated prevented special observations on vertical distribution and diurnal migration as all biological collections were made during daylight. These results, however, indicate that light forms but one of several factors governing vertical distribution in Lake Erie. Although the largest volumes were generally obtained at the bottom, uniform vertical diffusion and concentration at the surface were not uncommon even on the brightest days in midsummer. To a large extent the latter condition appears to be closely correlated with temperature. Warm-water species such as Epischura show a tendency to remain near the surface in offshore waters until the lower levels become heated. They then gradually increase their vertical range as the season progresses.

In contrast with Epischura, Limnocalanus, which during the early summer was often found at the surface during the day, later became restricted to the hypolimnion and although verification will be necessary, it is possible that a large part of the population does not rise to the surface at night. This suggestion is based on observations on ocean forms made in coastal waters south of Cape Cod where the dominant members of the spring plankton community of the neritic zone are found in the lower levels offshore in midsummer. A limited diurnal migration may take place during this season within their temperate range but repeated night hauls failed to reveal any at the surface. Since certain freshwater residents favoring low temperatures, such as Mysis relicta, are known to rise to the surface at night even in midsummer in some lakes (Birge and Juday 1927), it is questionable if very general application can be made from the findings in any single body of water. Results of previous observers indicate great variation in the diurnal range of the same species in different lakes.

It appears probable that the factor of feeding will also have to be considered in interpreting the vertical distribution of macroplankton in Lake Erie. This factor has recently been commented on by Worthington (1931) who observed food relationships in the vertical distribution of pelagic Crustacea in Lake Victoria Nyanza and Lake Lucerne. In August 1929 when the lowest oxygen values in Lake Erie were recorded from the bottom in the black mud area off Rondeau, the 4 stations (41 to 44) in contrast with the rest of Lake Erie yielded almost nothing at the surface. At each of these stations 1 cc. of plankton was taken in 5-minute surface hauls with a meter net. The fact that the entire community at this point was concentrated at or near the bottom while elsewhere, for the most part, it was more evenly diffused vertically, would suggest that the cladocerans and the copepods were feeding on organic matter in or on the black mud.

Vertical variation frequently occurred in the same community under conditions difficult to explain in terms of physical environment. Such conditions are indicated in table 23, showing the vertical distribution of Diaptomus ashlandi on 2 consecutive days in August 1928. The weather on both days was bright and clear with a moderate wind, but on August 28 D. ashlandi was found concentrated at the surface while on August 29, at 5 of the 6 stations, it was concentrated near the bottom. On August 29 bottom temperatures were lower at stations 05 to 07A than at stations 01 to 04 but were directly comparable at stations 09 to 11.

"Marine relict" Community

The "marine relict" species of the cold-water community in Lake Erie include Rhizosolenia eriensis, Stephanodiscus niagarae, Limnocalanus macrurus, Pontoporeia affinis, Mysis relicta, and Triglopsis thompsoni. As in the case of European "marine relicts" it is evident that the transfer from the ocean to their present habitat in Lake Erie did not necessarily take place in the same manner or at the same period of time. The community consists of two major

Table 23.--Vertical distribution of Diaptomus ashlandi on August 28 and 29, 1928

[Clear weather on both days]

Time	Station	Temperature (° C.)		Wind (direction and velocity)	Total volume (cc)	Percentage of volume at surface	Percentage of volume at bottom
		Surface	Bottom				
August 28							
9:30-10:00 a.m.	1	21.6	21.7	SW-4	368	70	4
10:30-11:00 a.m.	2	22.0	21.5	SW-5	562	26	3
11:25-12:00 noon	3	22.0	21.8	SW-5	366	54	2
12:25-1:00 p.m.	4	22.0	18.0	SW-5	1,082	43	1
August 29							
9:45-10:20 a.m.	5	21.8	16.8	SW-3	486	10	61
11:00-11:35 a.m.	6	22.0	14.3	SW-2	242	21	20
12:30-1:10 p.m.	7A	22.0	10.2	W-3	398	trace	49
2:20-2:35 p.m.	9	22.6	21.3	NW-3	376	7	50
3:05-3:30 p.m.	10	22.5	21.3	NW-3	964	2	45
4:25-5:00 p.m.	11	22.8	21.3	NW-2	242	4	71

groups, one of relatively local geographical distribution and limited to the American continent and the other of species occurring both in North America and Europe. A third group consisting of the eurythermic species Palaemonetes exilipes, Cottus ricei, and C. cognatus does not belong to the glacial relict fauna as defined by Ekman (1927) but is nevertheless of marine origin.

The first group, with very limited geographical range and consisting in Lake Erie of Rhizosolenia, Stephanodiscus, and Triglopsis, may very well be true glacial "marine relicts" which could have entered Lake Erie from the ocean under conditions described by Wilson (1929). Rhizosolenia and Stephanodiscus are common marine genera of American coastal waters and T. thompsoni is closely related to the circumpolar oceanic genus Oncocottus.

To explain the presence of the more widely distributed European-American species of the second group in American lakes by direct introduction from the sea seems unwarranted. Obviously they are of marine origin and together with other cold-water stenothermic forms may have extended their distribution as active or passive migrants through the agency of the glacial lakes. They may have been either real or secondary glacial relicts, (the latter presupposing them to be distributed from a freshwater point of introduction into North America). In either case, if we are to accept the evolutionary hypothesis that the same species has never originated in two different places, the presence of Mysis relicta, Pontoporeia affinis, etc., on the American and European continents implies a common source of origin.

In attempting to explain the direct introduction of European-American species into Lake Erie from the sea, several fundamental objections are encountered. The common point of origin must in this case have been the ocean and as no significant morphological changes have taken place within the species since their separation from the common source, it is obvious that the ancestral marine form must have had exactly the same specific characters. None of the American relict species occur in the sea at the present time, however, and to account for the complete extermination of several circumpolar marine species in so short a period of time and their retention in isolated lakes calls for considerable stretching of the imagination.

It appears more probable that the transition from the sea to freshwater and subsequent development of the present species took place in one locality, possibly under the conditions described by previous investigators (Ekman 1916, 1927; Högboms 1917). The dispersal over both continents took place later by way of freshwater. It is no more difficult to account for the freshwater dispersal of "marine relicts" than of other widely distributed freshwater forms. If the present species evolved before the termination of the last ice period, the temporary cold glacial lakes may have played an important part in extending their distribution. The present cold-water fauna of Lake Erie would then be the living remnant of the community which populated the fertile lakes in glacial times.

There is evidence of subsequent morphological changes in some of the "marine relict" species now located in isolated areas. This is particularly true in Limnocalanus in which several varieties are now found, the race in Lake Erie being the largest.

It is probable that the quantitative data on Mysis and Pontoporeia greatly underestimate their true abundance. As in the sea, pelagic net collections do not yield accurate data on such semi-benthic forms as the mysids and grammarids which for the most part spend the greater portion of the year on or adjacent to the bottom. When bottom studies were made in 1928 the largest numbers were always taken in the Helgoland trawls. Six species of larval fishes obtained with the Helgoland trawl were never taken with the meter nets or Petersen trawl in the upper levels. One of these species, Boleosoma nigrum nigrum was found from June 11 to August 8 throughout the eastern area in 1928 but did not appear in any of the 1929 collections when the Helgoland trawl was not used. The young of the smallmouth bass Micropterus dolomieu and the sculpins Cottus cognatus, C. ricei, and Triglopsis thompsoni were also taken only at the bottom. A similar condition exists at times in the case of Leptodora. Bottom trawls often yielded large numbers in 1928; few or none were taken in net collections made a few feet above bottom. Mud washing disclosed an abundance of individuals living in the mud in shallow water. As stated in the preliminary report (Fish et al. 1929) ... "to obtain a true picture of the macroplankton fauna of a large lake, it is necessary to tow at various levels with large silk nets, trawl along the bottom with Helgoland or similar apparatus, and to make mud and sand washings along the shore, and perhaps it will be found advisable to examine bottom samples from deeper water as well."

FISH

The plankton nets and trawls yielded appreciable numbers of young fishes which were found in greatest abundance in the littoral zone and over the shallower offshore parts of the lake. The larvae of only the "relict" species favored the cold water of the Deep Hole. The nets yielded 1,049 specimens representing 18 species in 1928, and 2,235 specimens representing 14 species in 1929. An additional collection of over 20,000 specimens taken in the western part of the lake was kindly loaned for study by the Ohio Division of Conservation. Of 92 species reported from Lake Erie 62 were identified and described by M. P. Fish (1932). The larval stages of most of these species were previously undescribed. Those not obtained are all of extremely rare occurrence, in many cases being represented by single records of capture.

Young stages and adults of some of the small species of fish are available in large numbers as food for larger predatory forms. Larval and postlarval Notropis atherinoides were taken at every station in the lake often in surprising abundance. Production appears to take place everywhere throughout the summer, but the vast schools of adults were found concentrated at the surface about the margin near shore. This species was the most common of all fishes found in the stomachs of larger species in the eastern area (Sibley 1929). Young of Perca flavescens were also taken in large numbers in the nets and may form an important food item in the littoral zone although only 3 specimens were found in the stomach analyses from the watershed and alongshore areas.

Not one specimen of whitefish (Coregonus clupeaformis) or herring (Leucichthys artedi) appeared among the thousands of larvae and postlarvae in the hauls. Since the time of hatching in these species varies considerably in the spring according to temperature, and with observations both in 1928 and 1929 starting soon after the disappearance of the ice in the eastern sector, it was expected that an evaluation might be made of the importance of the spawning grounds on the Canadian side of Long Point as a production center. Yet in a total of 107 hauls made in this sector no larvae were taken in either year. Either the young fish had already passed beyond the stages when they can be captured in meter-net day hauls or the principal nursery for these species in Lake Erie may prove to be in the western part of the lake.

POLLUTION

Chemical Observations

The second season's chemical observations were extended to include the alongshore areas and harbors, since detectable pollution was not found in the open waters of the lake in 1928. Eight major sources of pollution were found, the products of trade waste and sewage entering the lake from rivers and harbors. Most critical conditions were found in enclosed harbors protected from wave and current action. Conditions could be considered critical to animal and plant life in only 4 of these areas. Dilution renders the water harmless within a very short distance from shore, usually within a mile. Detectable traces of waste were observed at greater distances at Fairport, 3 1/2 miles, and Toledo, 5 miles. It may therefore be safely stated that pollution at the present time in Lake Erie is a problem only in the immediate vicinity of the shore. Spawning grounds located more than 2 miles from shore are probably in no way influenced by outwash during the production seasons, except possibly in the vicinity of larger cities, and even here the danger is questionable.

Chloride forms an important indicator of some types of industrial pollution. There was very little vertical difference in chloride values throughout the lake but great fluctuations occurred in horizontal distribution. The bulk of the chloride in the lake originates from the rocks in the drainage area, and the average values for most of the stations serve as an index of this supply. The high values in the vicinity of cities, however, indicate industrial waste. Extreme values were encountered along the western margin of the area investigated. Unfortunately, the program could not be extended sufficiently to determine the significance of these high values extending from Lorain toward Point Pelee.

Bacteriological Observations

Bacteriological collections were made at each station in the area east of Long Point in 1928. To continue this work in 1929, when the cruises were extended to approximately 2 weeks' duration, would have necessitated the establishment of a bacteriological laboratory on the vessel. For this reason and also because the conclusive results of the first season were substantiated by previous findings in Ohio waters, the work was not repeated in 1929. The present report is therefore based solely on the observations made in 1928 (Fish *et al.* 1929) but in view of the absence of chemical pollution over the Central Basin as well as the eastern sector, the bacteriological results are believed to be applicable to the whole area.

The objects of the bacteriological investigations were to determine the sanitary condition of the water and the extent to which sewage pollution might be a factor in the decline of the fisheries. Reports by fishermen of heavy pollution in different parts of the lake were common.

Collections were taken at approximately 6 inches below the surface and 12 inches above the bottom. The samples were immediately placed on ice and transferred for testing to the laboratories of the Buffalo City Health Department, except in the case of the more distant stations where inoculation and plating was carried on in an improvised laboratory on the vessel. The analyses were made by Andrew M. Zillig, Buffalo City Bacteriologist, as specified in *Standard Methods of Water Analysis* (Amer. Pub. Health Assoc. 1925).

Of 94 samples the average bacterial count was 34, the lowest 1, and the highest 210 per cubic centimeter of water (fig. 66). *B. coli* and *B. aerogenes* were absent in all one-tenth and 1 cc. counts and of 470 10 cc. counts only 20 gave positive results. These positive tests were always found in low total bacterial counts and (fig. 66) indicate outflow into the lake from nearby sources of pollution. The highest values were found in bottom samples during calm weather. The churning action of the water quickly eliminates pollution, and the small numbers prevailing during the calm warm weather may be considered maximum for the area in summer.

These results can not be interpreted as indicative of conditions throughout the year. The records of the Buffalo City Health Department covering a period of 35 years show a marked increase in bacterial counts following heavy rain storms in spring. These observations, however, were made close to the shore at the entrance of the Niagara River and do not indicate conditions prevailing at the time in the open lake. Since bacterial growth is greatly accelerated by high summer temperatures, and as the only effect of summer storms in the open lake seems to be a more even vertical distribution of bacteria, and not any significant increase in numbers, it is believed that winter conditions will not be more severe.

Therefore, in view of the repeated absence of

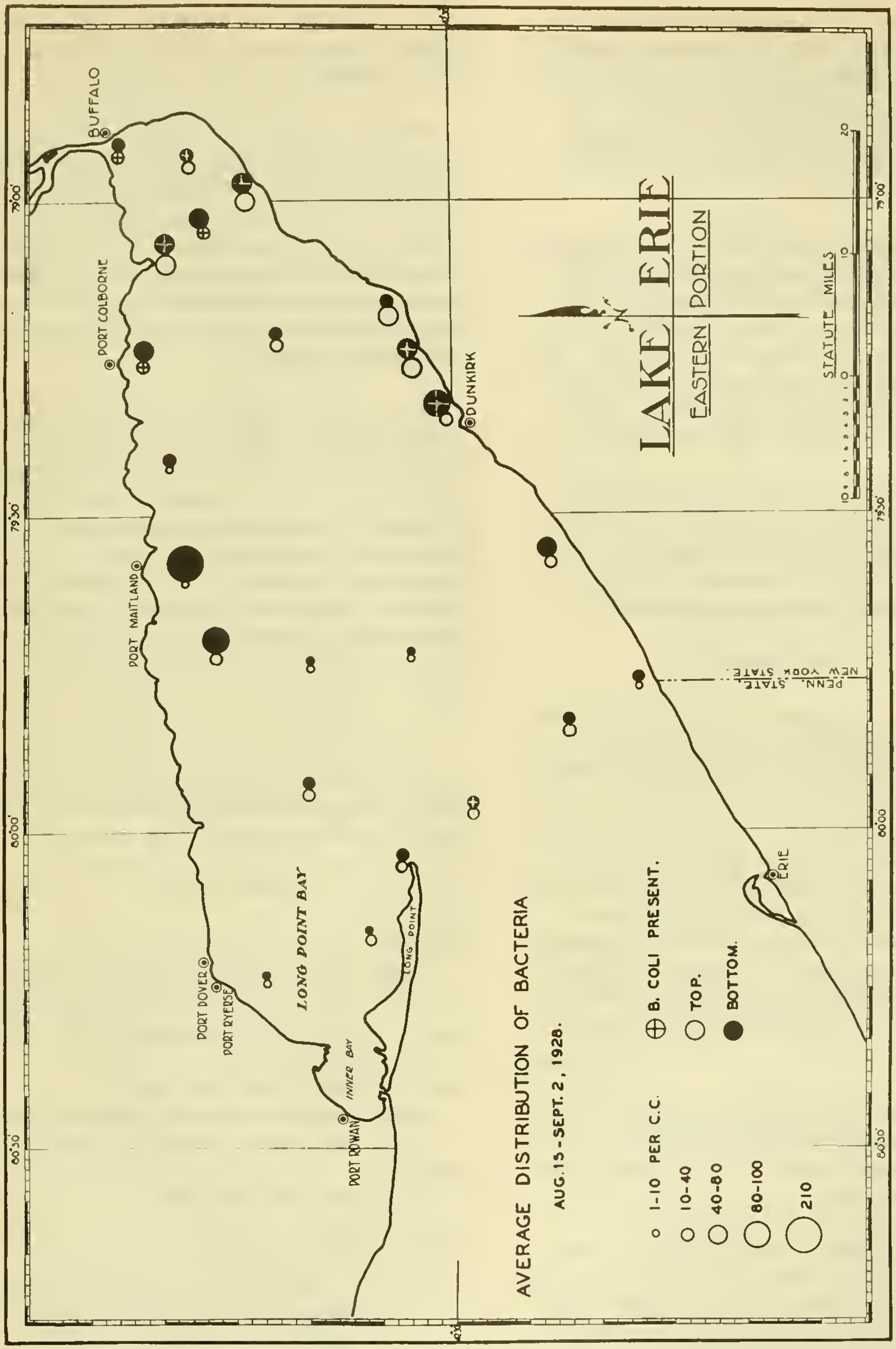

Figure 66. --Distribution of bacteria in Lake Erie, August 15 to September 2, 1928.

B. coli and other gas-forming organisms over the greater part of the eastern area and their presence in such small numbers in the few positive samples together with the remarkably low bacterial counts at all stations, it may safely be said that sewage pollution is not a limiting factor to animal life in the open lake.

There was little evidence of stagnation, even in the deepest parts of the lake. Its oligotrophic character is evidenced by the low bacterial counts and high bottom oxygen values (73 percent saturation in August and 72.4 percent in September). These results are even more significant when the lack of vertical mixing and the abundant oxygen-depleting fauna in the Deep Hole are considered.

As Entomostraca are known to feed freely on some forms of bacteria, it is probable that the low bacterial counts for Lake Erie, contrasted with those reported from some other lakes, may be partly due to the rich fauna of predatory macroplankton.

CONCLUSIONS

Since the object of the present survey has been to determine, if possible, the cause or causes for the decline in the fishery, this aspect will be briefly reviewed in light of the findings of the two seasons.

It is a far simpler task to determine limiting factors in an area known to be capable of supporting a rich fish fauna in its normal condition, than to attempt to determine the possibilities of an untried body of water. In Lake Erie, known to have once abounded with fish, it is necessary to ascertain to what extent the natural requirements have been altered by man.

The tentative conclusions advanced at the termination of the first season's investigations in the eastern area have been found to apply equally well to the lake as a whole.

Nothing was found to substantiate the claim that the physical effects of storms and violent current action form a vital factor to life of any sort in the region. As a matter of fact, the direct effect of meteorological and physical conditions can be disregarded because they are no more severe today than when the fishery was at its peak. The physical observations were made primarily to determine to what extent physical agencies might be of indirect importance in the transportation and distribution of silt and pollution.

There is no evidence that silt from industrial and sewage outwash is invading the offshore spawning grounds or in fact affecting any part of the area investigated at distances of more than one mile from the shore, except in two instances. The lake is remarkably free from chemical and sewage pollution and only those species spawning in or about the mouths of certain streams are likely to encounter seriously unfavorable conditions.

Food apparently is present in quantities sufficient to support a larger fish population than now exists in Lake Erie. Plant and animal plankton production appear to be normal and show no indication of depletion. The fish have diminished but their food probably has remained the same. The fact that the presence of unfavorable environmental conditions can often be more readily detected in these delicate organisms than in the relatively more resistant vertebrates offers further evidence that no environmental changes of significance have taken place to date.

The physical, chemical, and biological conditions thus afford no explanation for the decline in the fishery. It would be advisable, therefore, to examine the effects of fishing upon the fish stocks.

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