SPECIAL REPORT NO. 13

REPORT ON A CRUISE OF THE R/V NEESKAY IN CENTRAL LAKE MICHIGAN AND GREEN BAY, 8 - 14 July 1971

by

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Introduction

The cruise was conceived and conducted as part of a course titled, "Problems and Methods in Great Lakes Research". As such, its primary goal was educational, to familiarize the students enrolled with Great Lakes waters and to provide them experience with a variety of shipboard research methods. A secondary goal was the collection and interpretation of limnological data, both as an educational experience and as a matter of surveillance of conditions in the areas visited.

While each student became familiar with many techniques during the cruise, they did not share equally in all of the work. Topics of special interest are discussed, as part of this report, by the persons who played a major role in exploring the particular subject.

A great deal of interest has been focused recently on the question of changing environmental conditions in the Great Lakes. To give our work a historical perspective and examine this question for Lake Michigan the cruise plan included twelve stations sampled by the U. S. Bureau of Commercial Fisheries (USBCF) from the M/V CISCO in 1954 and 1955 (Beeton and Moffett 1964)(Fig. 1). These stations will be referred to hereafter as "Cisco stations". Five additional stations were visited in Lake Michigan (Fig. 1). These were included to make more complete the two transects of the lake and to provide a visit to the deepest location (X3) in the lake.

Limnological measurements were made at twenty-one stations on lower and middle Green Bay (Fig. 2). The benthic fauna at these locations was sampled by Surber and Cooley (1952) and later by Howmiller (1971) who also measured physical and chemical

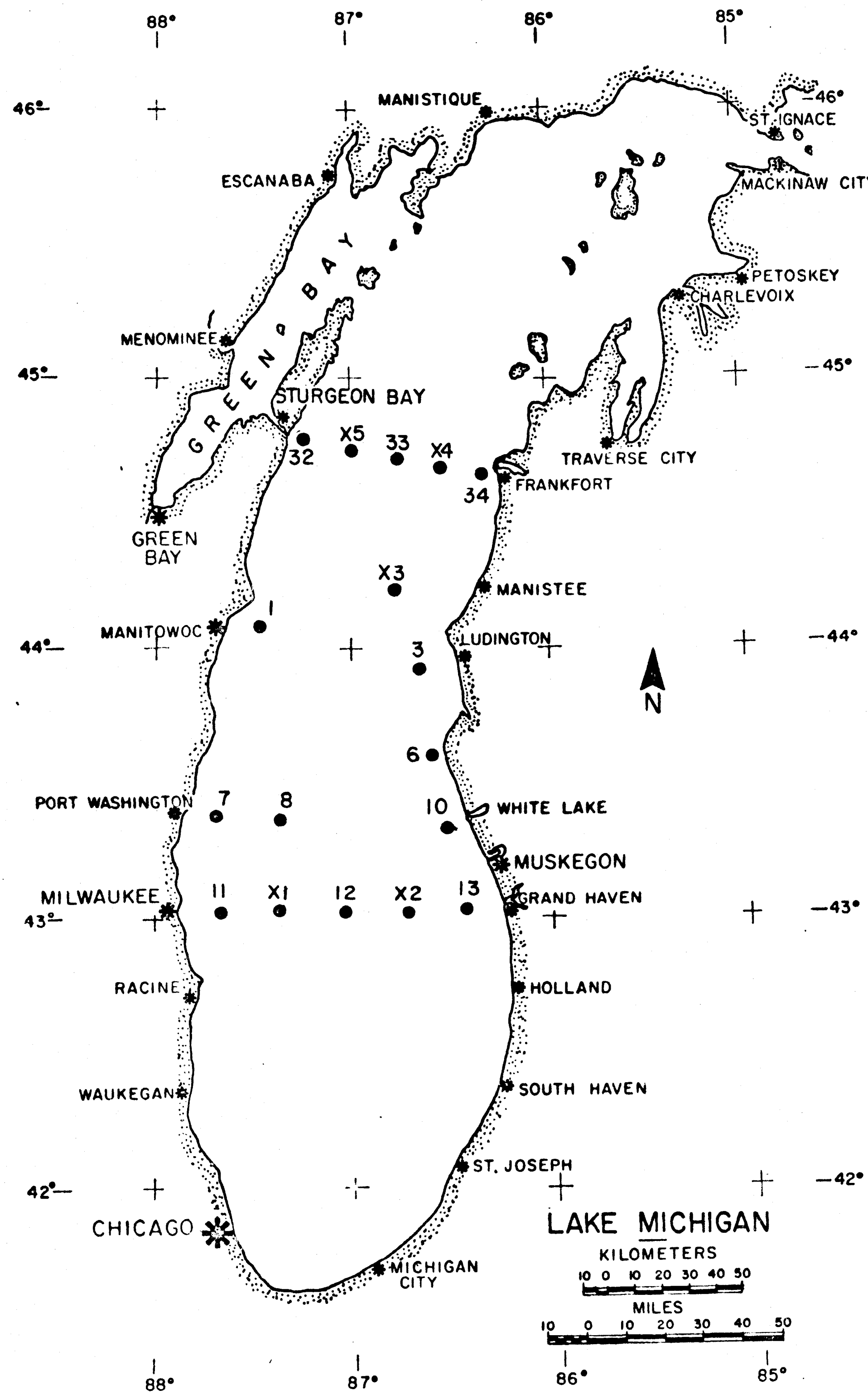

Figure 1. Lake Michigan, showing sampling stations. Stations labeled with a number only were previously sampled by the USBCF in 1954 or 1955. Locations labeled by a number preceded by an "X" are new stations.

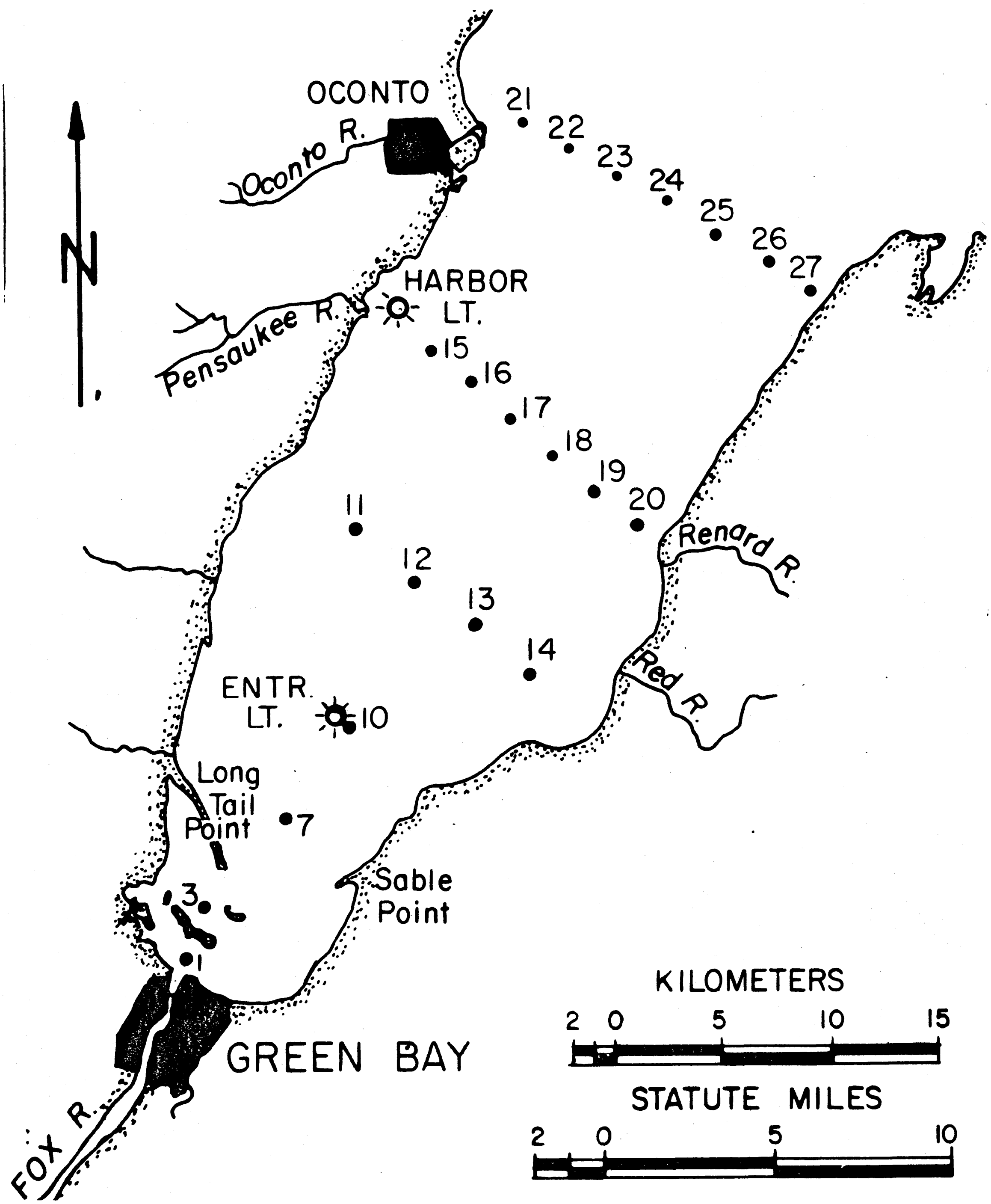

Figure 2. Green Bay, Lake Michigan, showing location of sampling stations.

parameters of the sediments. Coordinates for both Lake Michigan and Green Bay stations are listed in Table 1.

This research was supported in part by the University of Wisconsin Sea Grant Program, which is a part of the National Sea Grant Program, maintained by the National Oceanic and Atmospheric Administration of the U. S. Department of Commerce.

Table 1. Station coordinates.

Number	Latitude, N.	Longitude, W.
	Lake Michigan	
11	43 01 50	87 37 15
X1	43 02 00	87 20 00
12	43 02 25	86 58 00
X2	43 03 00	86 41 00
13	43 03 00	86 24 10
10	43 22 45	86 32 50
6	43 39 10	86 37 57
3	43 58 30	86 38 25
X3	44 28 30	86 43 00
34	44 38 10	86 18 40
X4		
33	44 41 15	86 42 20
X5	44 42 45	86 54 30
32	44 44 25	87 12 00
1	44 03 50	87 29 45
7	43 23 05	87 44 20
8	43 22 53	87 23 50
	Green Bay	
GB 1	44 32 50	88 00 00
GB 3	44 33 58	87 59 24
GB 7	44 36 24	87 56 29
GB 10	44 39 06	87 54 00
GB 11	44 43 18	87 54 20
GB 12	44 42 20	87 52 20
GB 13	44 41 36	87 50 22
GB 14	44 39 57	87 48 24
GB 15	44 48 57	87 51 30
GB 16	44 47 03	87 50 00
GB 17	44 46 10	87 48 33
GB 18	44 45 18	87 47 10
GB 19	44 44 27	87 45 44
GB 20	44 43 33	87 44 18
GB 21	44 53 59	87 48 42
GB 22	44 53 20	87 46 53
GB 23	44 52 40	87 45 00
GB 24	44 51 56	87 43 02
GB 25	44 51 14	87 41 08
GB 26	44 50 32	87 39 15
GB 27	44 49 55	87 37 36

General Hydrographic Methods

Navigation responsibilities were assumed by the Captain, Robert Popp. Stations were located by dead reckoning and the use of a radar system.

Activities at each station began with a bathythermograph (BT) cast, to provide a quick look at the thermal structure of the water column. More accurate temperature determinations were made on surface water, and at some stations on water from 2.0m depth, with a mercury thermometer in a bucket of sample water. Temperatures at greater depths were determined from reversing thermometers mounted on Nansen bottles. Reversing thermometer readings were corrected using calibration sheets provided by the manufacturer and the formulae given in the Instruction Manual for Oceanographic Observations (U.S.H.O. 1955).

Transparency was estimated using a 20cm white Secchi disc.

Water samples were obtained at 2.0m depth with a Van Dorn sampler and from greater depths with teflon-lined Nansen bottles. For the sake of comparing data, Nansen bottles were usually set at depths sampled by the USBCF at the same stations.

In addition to sub-samples for chemical determinations and seston measurement, which were taken from water samples at all depths, one liter of water from the 2.0m Van Dorn sample was preserved with Utermöhl's iodine preservative for analysis of phytoplankton composition. The phytoplankton samples have not yet been examined but will be made available to an interested and qualified investigator upon request.

A 0.5 m Nansen closing net of No. 10 mesh was used to sample zooplankton. One vertical tow was made from the bottom to the region of the thermocline and another from the thermocline to the surface at each Lake Michigan station. At several Green Bay stations, where thermal stratification was generally nonexistent, a single vertical tow was made from bottom to top.

A Ponar grab was used for benthic sampling. A single sample was taken at each station except that replicates were obtained when it was felt that the first sample was too small to be truly quantitative and three grabs were taken at Station X3 because of special interest in the benthos of this very deep area. Bottom samples were screened immediately with a U. S. Std. No. 30 sieve and the residue left on the sieve preserved in 10% formalin.

A neuston net, designed and built by Mary and Ed Mayhew, and a bottom sled fitted with a 1.0 m square No. 0 net, were towed at several stations. Mary Mayhew retained the neuston samples. Large benthic crustaceans (Mysis, Pontoporeia) obtained with the sled were frozen immediately preparatory to pesticide analysis by S. R. Peterson of the University of Wisconsin-Madison.

Details of methods used for chemical and pigment determinations and the measurement of light extinction are discussed in individual student papers.

Analysis of Surface Currents in Green Bay and Lake Michigan Using Drift Bottles

Introduction:

Scientific investigation of a body of water of the size of Lake Michigan, or even Green Bay, should involve some identification of the water being sampled beyond the usual limnological procedure of accurate station location. While little is known of the currents and water masses of the Great Lakes, the evidence at hand points to the existence of distinct water masses and patterns which may change from time to time.

Harrington (1895) used data from 672 drift bottle returns over a three-year period (1892-1894) to postulate surface current patterns for all the Great Lakes. Figure 3 is an approximate reproduction of Harrington's analysis of Lake Michigan currents. While Harrington's work has been severely criticized (Smith 1957), it is still widely cited.

Smith (1957) reported briefly on Lake Michigan current studies much more thorough than those of Harrington. During the operations of the R/V CISCO in 1954-55, 6300 drift bottles and other drift missiles were released in the lake. The bottles were released at 5-mile intervals (usually 20 released at each location) on several east-west transects at 3- to 6-week intervals between April and November.

The results of this work are discussed in greater detail by Johnson (1960). The general direction of surface currents was west to east and strong northbound currents existed along the eastern shore of the lake. No prevailing current was detected along the western shore. The results showed clearly that surface currents can change drastically within a period of 3 weeks and that currents often do not follow the patterns proposed by Harrington, sometimes flowing directly opposite to the directions shown in his figure (Smith 1957; Johnson 1960).

Ayers and co-workers (1958) deduced surface and bottom currents using the dynamic height method, chemical parameters and drift bottle data. Surface current patterns in the main body of the lake in June 1955, under wind conditions apparently normal for the summer, were in good agreement with the patterns reported by Harrington (1895) (Fig. 3). Current patterns deduced for a two-day

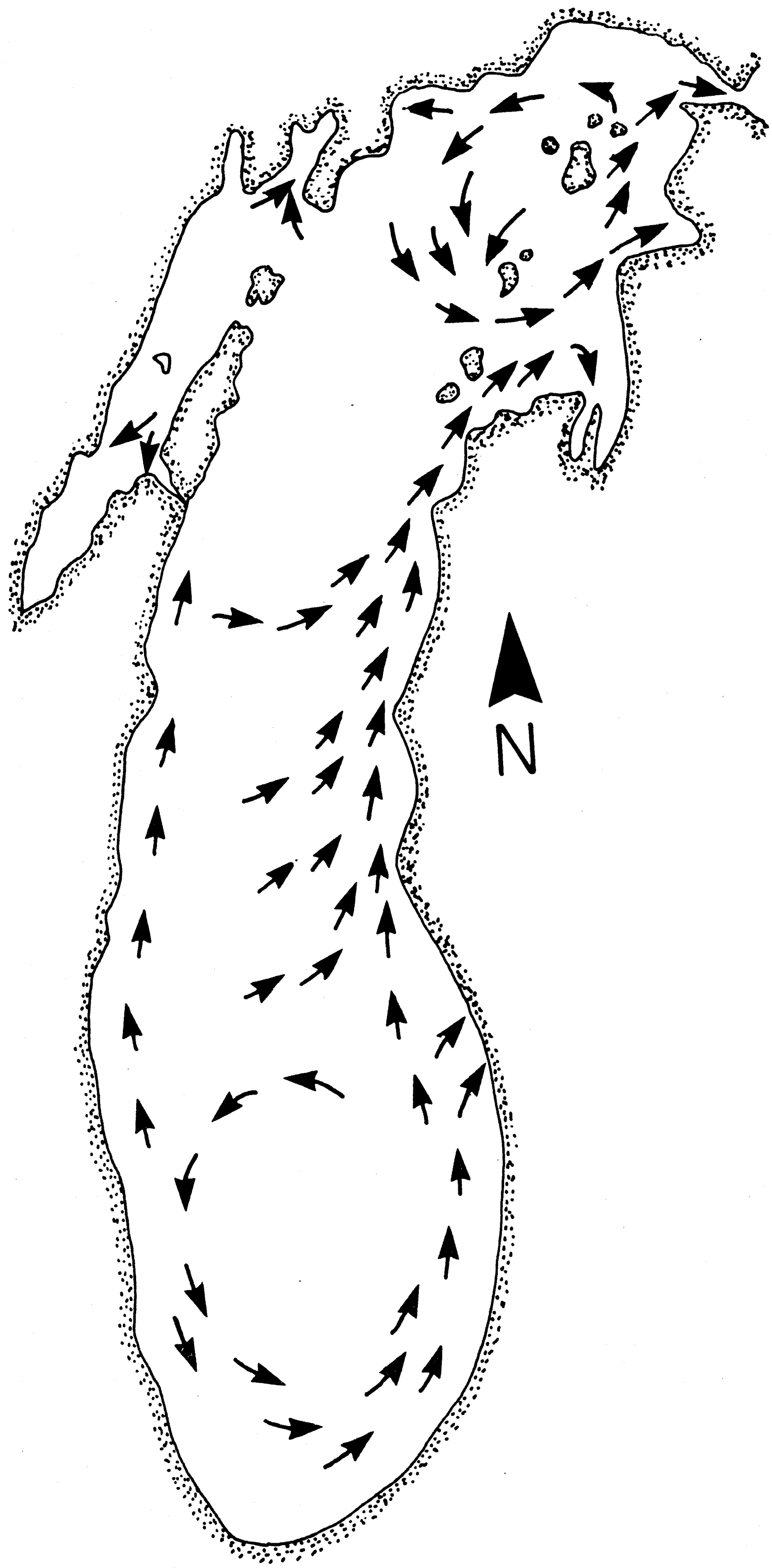

Figure 3. Lake Michigan showing generalized surface current patterns proposed by Harrington (1895).

period in August 1955 (Ayers et al 1958) were very different from those in June and from Harrington's findings. The situation prevailing in August differed primarily in that there was a strong southward current along the east shore of the lake. Ayers and co-workers attributed this to unusual wind conditions, and suggested that winds in the region of the Straits of Mackinac control the current regime of the entire lake.

An interesting detail in the pattern found in July 1955 was a large counterclockwise eddy in mid-lake near Frankfort. Water in this region had very high transparency and thermal and chemical characteristics suggesting upwelling (Ayers et al 1958). This upwelling and associated eddy are apparently recurring phenomena in this area. Ayers mentioned a personal communication with P. E. Church who recalled that steamer captains knew of this eddy and were in the habit of filling their tanks there because of the high quality of the water.

Circulation in the southern basin of the lake was dominated by a large clockwise eddy in both June and August 1955 (Ayers et al 1958). It is impossible to understand how Verber (1964) could have considered the southern basin currents proposed by Ayers and co-workers (1958) to be in "good agreement with the counterclockwise patterns shown by Harrington". Verber (1964) studied Lake Michigan currents by means of buoyed current meters. His observations in the southern basin suggested counterclockwise flow during the summer and a clockwise circulation during winter.

The current regime in Green Bay was not investigated in the studies of Ayers and co-workers (1958), Johnson (1960), or Verber (1964). It was barely touched upon by Harrington (1895). Schraufnagel (1966) reported that a counterclockwise current brings water down the western side of the bay and, after mixing with Fox River water entering at the head of the bay, returns northward along the eastern shore. Schraufnagel s conclusions seem to have been based on casual observations of water quality parameters rather than upon any rigorous analysis. The observations were confirmed, however, by studies of the distribution of conductivity values in July 1968 and August 1969 (Modlin and Beeton 1970). Ahrnsbrak and Ragotzkie (1970) indicated that the pattern may be changed by wind conditions. They found a tongue of water from the head of the bay (30-40% River water) extending 15 to 20 km up the east side of the bay corresponding to the picture of Schraufnagel (1966) and Modlin and Beeton (1970)-- under southerly winds. Under the influence of northerly winds this tongue was not observed.

Surface Current Patterns in Summer 1971:

Drift bottles were released during the cruise at 20 locations in central Lake Michigan and 15 stations in middle and lower Green Bay. Ten bottles were released at each Lake Michigan site and seven at each station in Green Bay. The bottles were 4 oz polyethylene bottles ballasted with dried sand so that only the neck and cap would ride above the water surface. The screw-type polyethylene caps were sealed with RTV silicone rubber. Each bottle contained a self-addressed card asking the finder to fill in the date and to indicate the location at which the bottle was found by direction and distance from the nearest town or landmark and with a mark on a small map.

Recovery of drift bottles was phenomenally successful. Forty-seven percent (49) of the bottles released in Green Bay were recovered within 10 days of the date of release. Drift times for Lake Michigan bottles were greater; twenty-eight percent of the Lake Michigan bottles were found within 20 days after the cruise. Perhaps the polyethylene bottles are more visible, and a more unusual item to see on a beach, than the glass drift bottles used by many investigators.

Furthermore, the great publicity currently being given to environmental problems may be responsible for an increased willingness of the general public to cooperate with research of this sort.

Figure 4 indicates the positions at which bottles were released in Lake Michigan and the paths which they are presumed to have taken. In addition to the large number of returns, one can see in the figure a remarkable consistency in the paths of the bottles from each station. This is in marked contrast with the figures in the paper of Johnson (1960) which frequently show returns from several very different directions from a single station.

The returns indicate a definite northeastward drift over the central portion of the lake and northward currents along the eastern shore (Fig. 4). In these respects, surface currents during July 1971 agree with the pattern proposed by Harrington (1895), and the general description for the lake in 1954-55 (Johnson 1960). The picture presented by Ayers and co-workers (1958) for "normal" wind conditions gives considerably more detail but we find agreement in eastward or northeastward surface currents over large areas of the central lake and a northward current along the eastern shore. Surface current patterns were apparently "normal" in July 1971.

Thermal and chemical data from our Station X3 indicate upwelling. This station is within the area of upwelling and the large eddy found in July 1955 (Ayers et al 1958). The eddy was probably also present in 1971. At the time of this writing (late August 1971) only two of the ten drift bottles have been recovered from Station X3, while recoveries from other stations average 53%. Possibly most of the bottles released at X3 are traveling within the eddy.

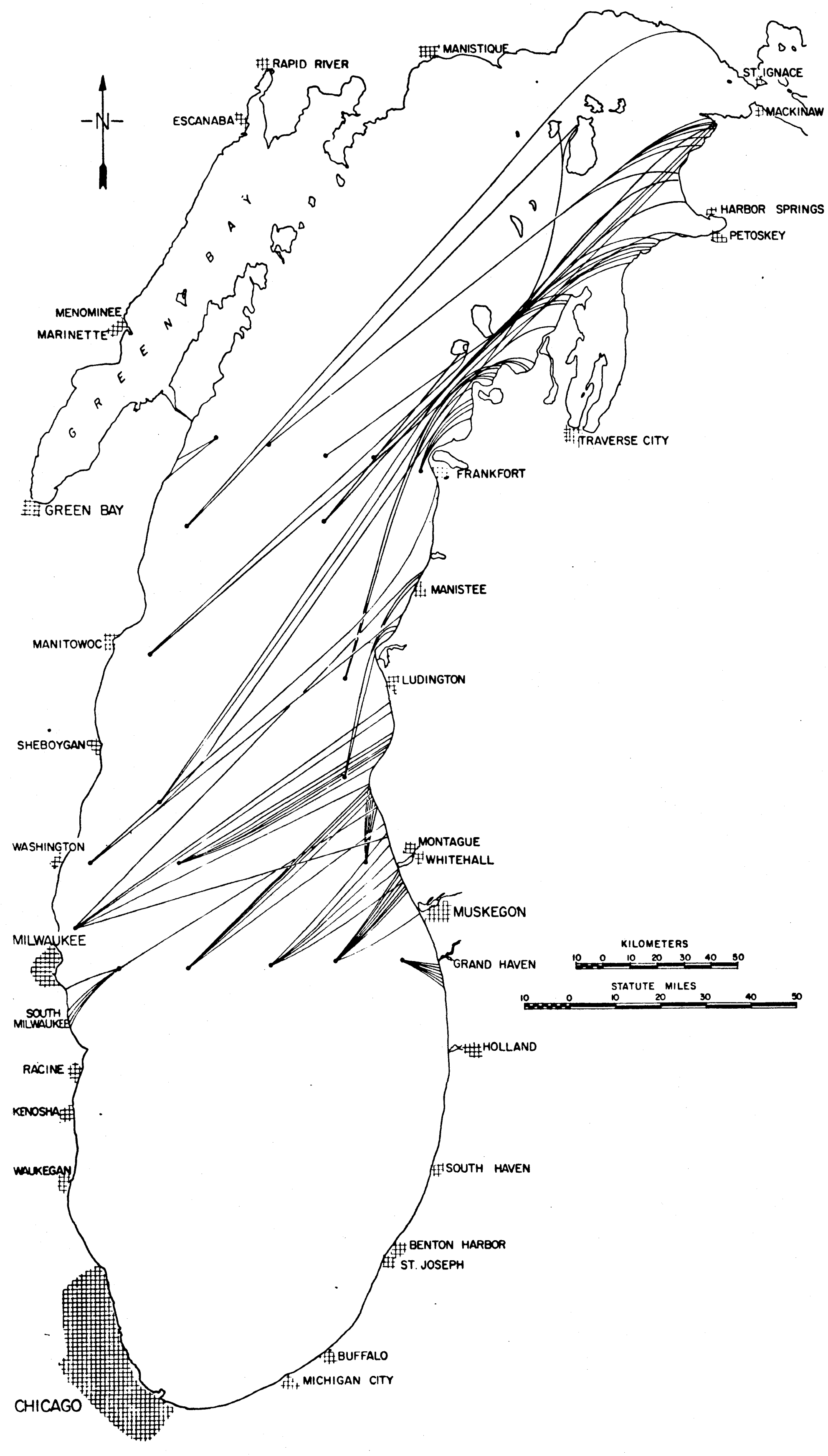

Figure 4. Lake Michigan, showing stations at which drift bottles were released and presumed paths of recovered bottles.

Bottles from the stations nearest shore (11, 13) on the Milwaukee-Grand Haven transect did not fit the general pattern but went shoreward and southward. With bottles from one station (13) heading clockwise and from the other (11) counterclockwise, no light is shed upon the question of southern basin circulation patterns.

Bottles from the westernmost station on the Sturgeon Bay-Frankfort transect (32), like those from the station nearest Milwaukee (11), headed southward. These may indicate the existence of small nearshore eddies. A southward current along the western shore cannot be postulated as bottles released near-shore between stations 11 and 32 followed the northeastward trend typical of central basin stations (Fig. 4).

Table 2 lists the direction, distance, duration and average velocity of drift for the bottle with the shortest drift time for each station. The calculated velocities are subject to errors introduced by assuming distance traveled to equal the shortest distance between the release and recovery point whereas many bottles probably followed a curved path. Further error is introduced by the interval a bottle lies undiscovered on the shore. The first error causes one to underestimate distance; the second results in underestimating velocity by overestimating the duration of drift. By calculating velocity on the basis of the bottle with the shortest drift time this second error is minimized.

Figure 5 shows the direction and velocity of drift for the bottles listed in Table 2. Drift velocities ranged from 1.2 to 6.2 miles per day with greater velocity of surface currents indicated in the northern and eastern portions of the central basin.

The stations at which drift bottles were released in Green Bay, and the presumed paths of recovered bottles, are shown in Figure 6. All drift bottle recoveries indicated northeastward

Table 2. Listing locations and dates of drift bottles released in central Lake Michigan and direction, distance, duration and average velocity for bottle with shortest drift time for each station.

Release Point	Release Date	Direction Travelled	Distance Miles	Duration Days	Velocity Miles/Day
Station					
11	8 July	225°	16	4	4.0
x1	"	46°	56	25	2.2
12	"	58°	34	21	1.6
x2	"	37°	22	15	1.5
13	"	61°	10	8	1.2
10	9 July	13°	14	7	2.0
6	"	13°	48	8	6.0
3	"	18°	80	17	4.7
x3	10 July	40°	47	17	2.8
34	11 July	25°	17	3	5.7
x4	"	50°	77	15	5.1
33	"	55°	106	29	4.1
x5	"	51°	121	26	4.6
32	"	232°	12	2	6.0
44° 27' 30" x 87° 20' 30"	13 July	44°	123	39	3.2
Station 1	"	49°	115	29	4.0
43° 34' 40" x 87° 27' 00"	14 July	36°	123	20	6.2
Station 8	"	59°	54	14	3.9
7	"	50°	88	29	3.0
43° 10' 00" x 87° 49' 00"	"	72°	71	27	2.6

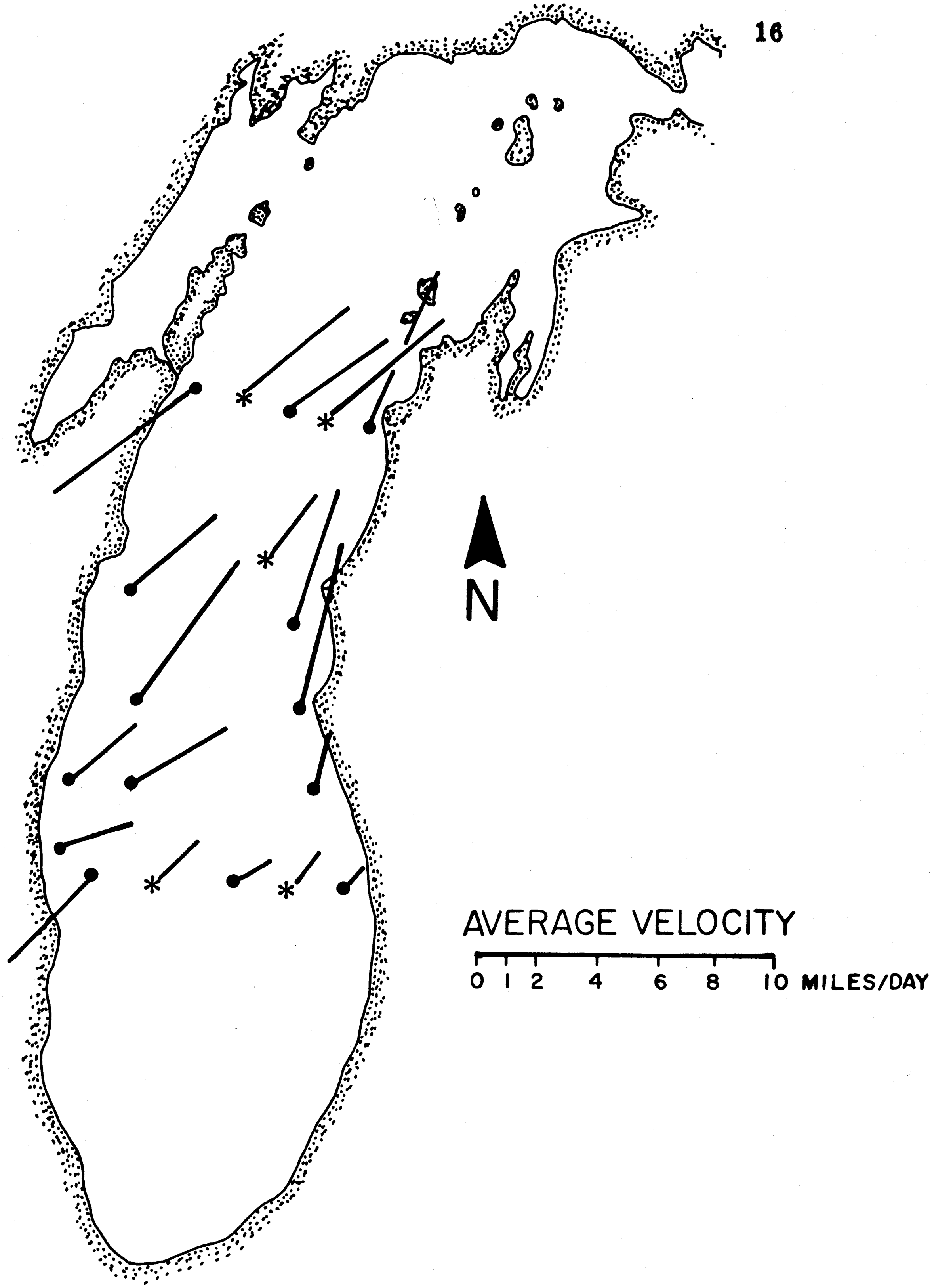

Figure 5. Showing direction and average velocity of drift for the bottle with the shortest drift time from each Lake Michigan station.

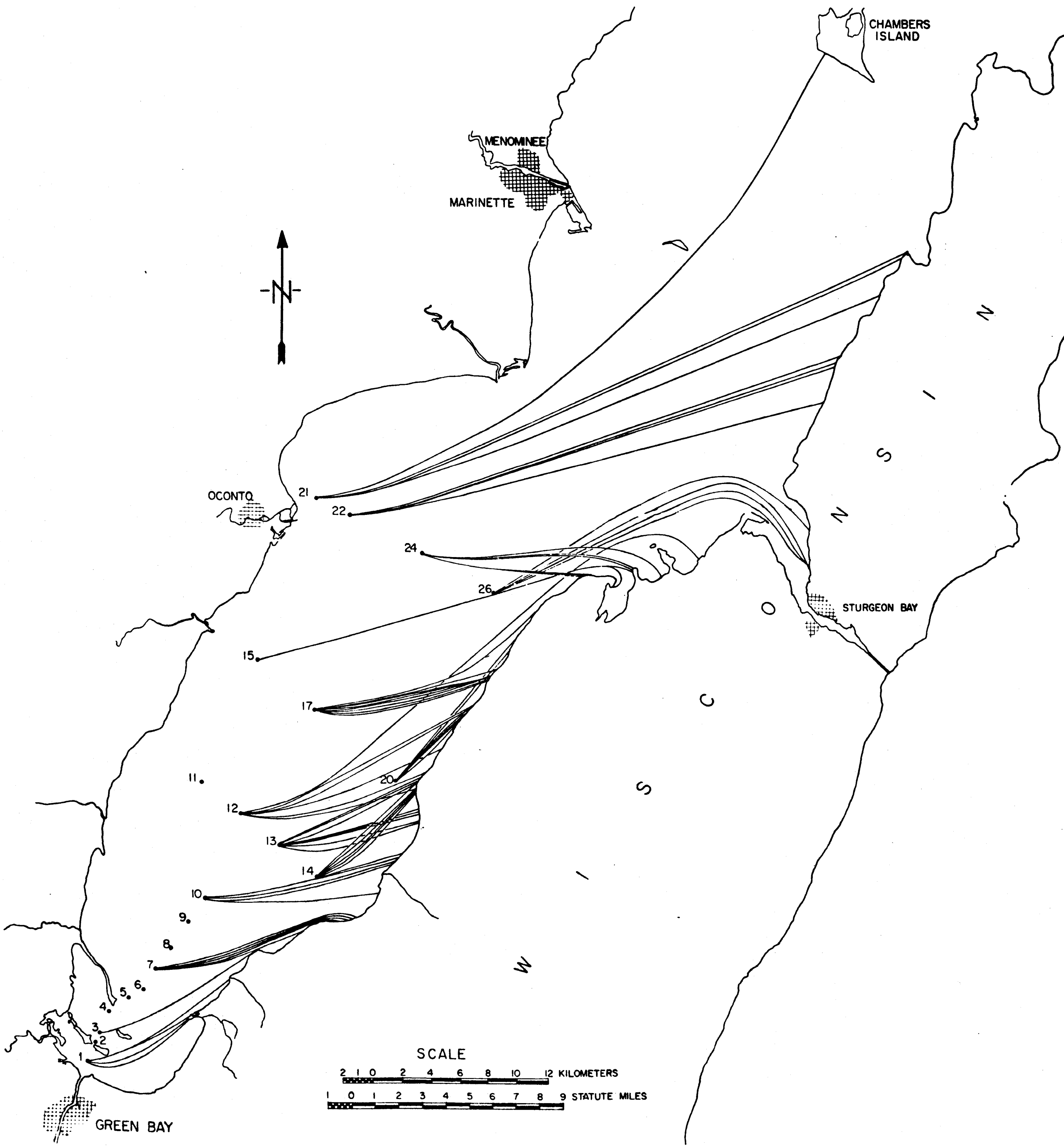

Figure 6. Green Bay, showing stations at which drift bottles were released and presumed paths of recovered bottles.

movement. According to Schraufnagel (1966) and Modlin and Beeton (1970) we would expect northeastward movement from stations in the eastern half of the bay. The expected southward currents in the western half of the bay were not shown by the drift bottles. This may be due to unusually strong winds out of the south during much of the day the drift bottles were released (Table 3). These winds could certainly have an important effect in producing a northward drift where a southward current was weak or only moderately strong. However, it seems probable that southward movement of drift bottles did occur where we would expect southward currents to be strongest. At the time of this writing (late August) there have been no drift bottle returns from the eastern most station on the southern transect (GB 11) and only one return from the easternmost station (GB 15) on the middle transect. Returns from the other stations now average 72%. If most of the bottles from these stations moved southward and washed up on the western shore, they may lay on shore a long time before being recovered. Unlike the eastern shore of the bay, the west side is shallow muddy marshland, little used for summer recreation.

The average velocity of drift for the bottles with the shortest duration of drift from each station ranged from 0.8 to 6.8 miles per day (Table 4). There was no pattern apparent in the distribution of the presumed surface current velocity (Fig. 7).

Summary:

The pattern of surface currents in Lake Michigan during July and August 1971 appears to have been very similar to that reported by other investigators. There was a general northeastward

Table 3. Wind direction and velocity determined at hydrographic stations on Green Bay, 12 July 1971.

Time	Station	Direction	Velocity
0636	GB27	E	not est.
0654	GB26	E	17
0725	GB25	E	23-24
0742	GB24	E	15-22
0803	GB23	E	20-22
0817	GB22	SE	18-20
0845	GB21	S	20-21
0940	GB15	SE	20-24
1013	GB16	SE	17-19
1030	GB17	SE	20
1055	GB18	SE	20
1105	GB19	SSE	20
1120	GB20	SSE	20
1206	GB14	SSE	12
1255	GB13	SW	4
1323	GB11	S	16-17
1415	GB10	SE	10
1445	GB7	ESE	"strong"*
1510	GB3	S	"strong"
1540	GB1	S	"strong"

* anemometer malfunction

Table 4. Listing stations at which drift bottles were released in Green Bay and direction, distance, time and average velocity for bottle with shortest drift time for each station.

Release Point	Direction Traveled	Distance, Miles	Time* Hours	Velocity, Miles/Day
GB 1	65°	4.75	17	6.8
GB 3	60°	7.5	92	2.0
GB 7	72°	8.5	44	4.7
GB 10	88°	7.25	47	3.7
GB 11	NO RETURNS -------------------------------			
GB 12	77°	7.75	46	4.0
GB 13	76°	6.1	46	3.2
GB 14	47°	5.75	46	3.0
GB 15	74°	16	169	2.3
GB 17	79°	7.5	73	2.5
GB 20	41°	7.0	216	0.8
GB 21	68°	28	98	6.9
GB 22	75°	20.75	411	1.2
GB 24	91°	10	51	4.7
GB 26	72°	16	51	7.5

* Time elapsed between time of release and time of recovery (using noon on day of recovery unless otherwise specified by finder).

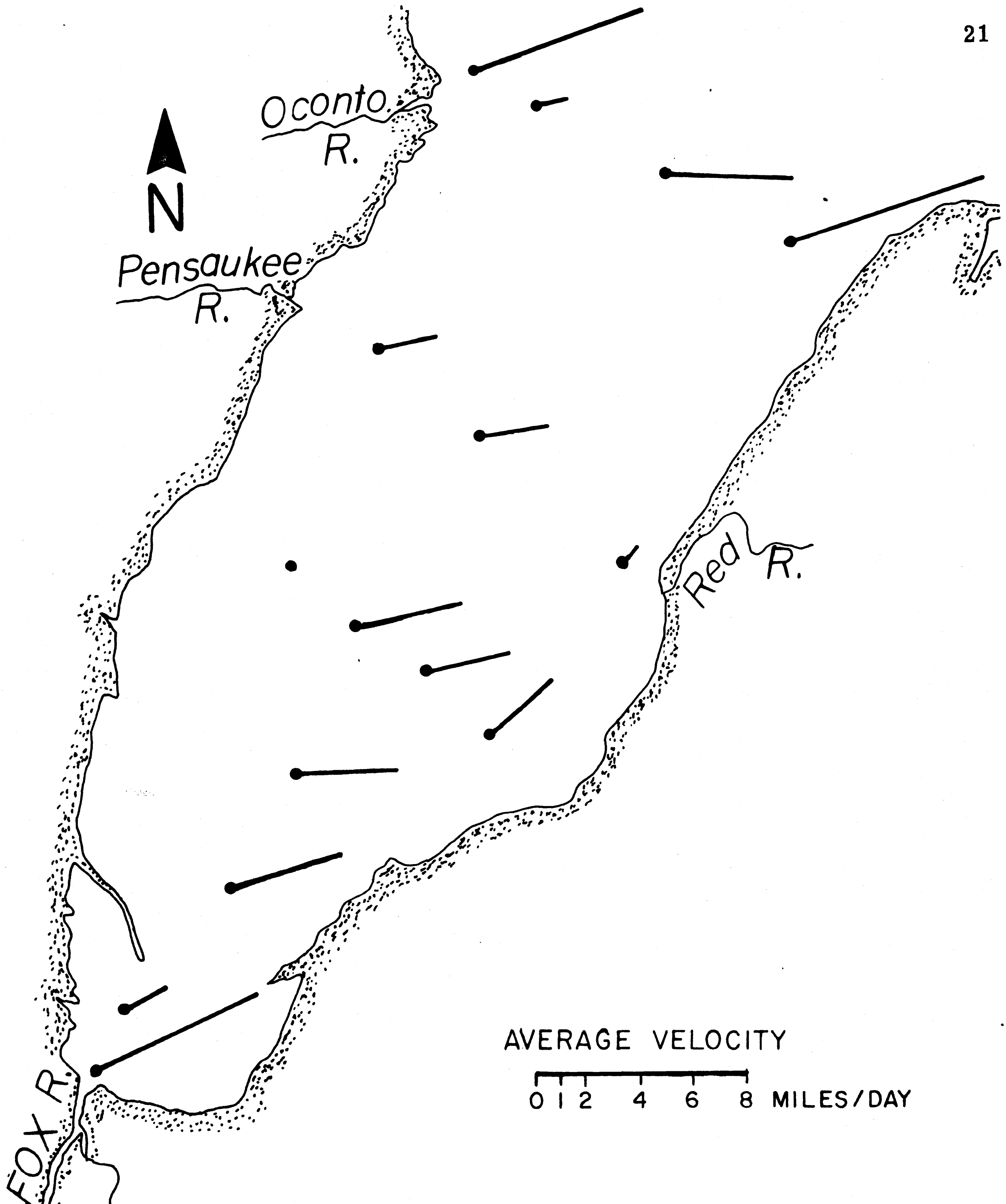

Figure 7. Showing direction and average velocity of drift for the bottle with the shortest drift time from each Green Bay station.

drift over most of the central basin and a strong northward current along the eastern shore.

Drift bottles recovered from Green Bay releases had all moved northeastward. A southward current along the western shore was not evident. These findings are at odds with the observations of other investigators. This may be a result of unusual wind conditions at the time of our study and the lesser likelihood of getting drift bottle returns from a marshy seldom-frequented shore.

Light Penetration in Central Lake Michigan and Green Bay

Introduction:

During the cruise measurements were made at various stations in Lake Michigan and Green Bay of light intensity as a function of depth. From these data a vertical extinction coefficient (K) was calculated to characterize the optical properties of the water of each station. The measurements were made directly as a percentage of surface light by an instrument built at the Center for Great Lakes Studies just prior to the cruise. This instrument functions in a manner similar to the Hydroproducts, Model 420, Underwater Photometer but is considered to be more sensitive to light differences between the deck and sea photocells, less likely to be affected by vessel movement and instrument shock, and easier to read and adjust than the Hydroproducts device.

It is standard procedure when doing light measurements such as these to make the observations on clear, bright days, at a time when the sun is unobstructed by clouds and near its zenith (Beeton 1962; Holmes 1968; Strickland 1958). In addition, the surface of the water should be calm. These requirements put serious limitations not only on the day but also on the hour when measurements can be made. These are difficult criteria to meet on a cruise of this sort which forced measurements to be made many times on a day and station that did not have these conditions. So it is that some data were taken when the waves were standing two to three feet high and the sky was overcast.

Methods:

The method of observation was simply to orient the stern of the vessel into the sun, balance the sea and deck photocells with surface light, and lower the sea cell into the water while reading percentage of surface light at various depths with the instrument. After a total light penetration measurement was made the sea cell was covered with a filter, balanced against the deck cell, and again lowered for measurement of the penetration of colored light. The filters used for estimates of blue, green, and red light penetration were respectively, the BG12 of bandwidth 340 mu to 480 mu, the VG9 of bandwidth 470 mu to 580 mu, and the RG2 for wavelengths above 570 mu. A filter was placed only on the sea cell.

Due to the fact that the instrument had been designed and built just before the cruise without benefit of testing and standardization, its accuracy is in some question. The results of the experiment are reported with this reservation and with the hope that more work will be done with the instrument to make its data more meaningful. Sources of error in the measurements arise from such things as the ship's shadow interfering with the light field of the sea photocell, the light quality change with depth (Hutchinson 1957), the refraction and reflection of light by surface waves, and low light intensities causing the normal transmittance of the filter's opaque wavelengths to become a larger percentage of the cell's total measurement (Tyler 1959).

Results and Discussion:

The extinction coefficients (K) listed in Table 5 for the different stations represent the best estimate of the slope of the data points plotted on semi-logarithmic graph paper. The graphs shown (Figs. 8 and 9) of the percentage surface light versus depth are not actual data curves but only serve to depict the extinction coefficients.

Assuming that the results of the experiment portray the actual situation in Lake Michigan and Green Bay, then all light penetrates deeper in Lake Michigan than in Green Bay. Values for all the extinction coefficients ranged from 0.03 m^{-1} to 0.90 m^{-1} for Lake Michigan and from 0.90 m^{-1} to 4.5 m^{-1} in Green Bay. The Secchi disc depths in Table 5 support this assumption.

From Figure 8 it is evident that blue and green light penetrate deeper in Lake Michigan than red light as is the case with pure water (Hutchinson 1957). The average value of K for blue light at all stations sampled in Lake Michigan is 0.17 m^{-1}. The values of K for green light averaged 0.14 m^{-1}, and for red light, 0.43 m^{-1}. On the other hand, Figure 9 shows that red light here being 1.2 m^{-1}, for blue light: 3.2 m^{-1} and for green light: 2.3 m^{-1}. Perhaps it is the color of the water and its turbidity that cause blue and green light to be attenuated faster than red light in Green Bay.

Table 5. Light extinction data for stations sampled in central Lake Michigan and Green Bay.

Station	Date	Time	Sky	Sea	Secchi Disc	Light	Extinction Coefficient (K)		
Lake Michigan		(CST)			(metered)	Total Light	Blue/340-480 mu	Green/470-580 mu	Red/570-mu
X1	7/8/71	1120-1230	partial clouds	2-3 ft waves	7.5	0.28	0.17	0.14	0.18
12	7/8/71	1500-1520	clear	3 ft swells lt. chop	10	0.21	0.18	0.14	0.90
10	7/9/71	1000-1030	lt. over-cast	1 ft swells lt. chop	10.5	0.15	0.03	0.05	0.20
6	7/9/71	1245-1315	over-cast	2 ft waves	8	0.23	0.22	0.23	0.49
X3	7/10/71	1025-1200	broken clouds	calm, sm. ripples	11.25	0.09	0.10	0.11	0.32
33	7/11/71	1205-1220	clear lt. haze	2-3 ft waves	7	0.12	0.22	0.15	0.40
7	7/14/71	1230-1300	partial clouds	calm, sm. ripples	5	0.35	0.30	0.22	0.45
8	7/14/71	0935-1000	partial clouds	sm. swell lt. chop	8.25	0.11	0.14	0.07	0.33

Table 5 (continued)

Station Green Bay	Date	Time (CST)	Sky	Sea	Secchi Disc (metered)	Light Total Light	Extinction Coefficient (K) Blue/340-480 mu	Green/470-580 mu	Red/570 mu
22	7/12/71	0820-0835	Clear	2-3 ft waves	2	0.98	-----	-----	-----
20	7/12/71	1120-1140	Over-cast	1-2 ft waves	1.3	1.8	3.4	1.7	1.4
15	7/12/71	0915-0930	Clear lt. haze on horizon	3-4 ft waves	1.6	1.1	2.9	-----	-----
14	7/12/71	1210-1230	Over-cast	1-ft waves	1.5	4.5	-----	3.7	0.90
11	7/12/71	1330-1350	Over-cast	1-ft waves	0.5	1.2	3.4	1.6	1.4

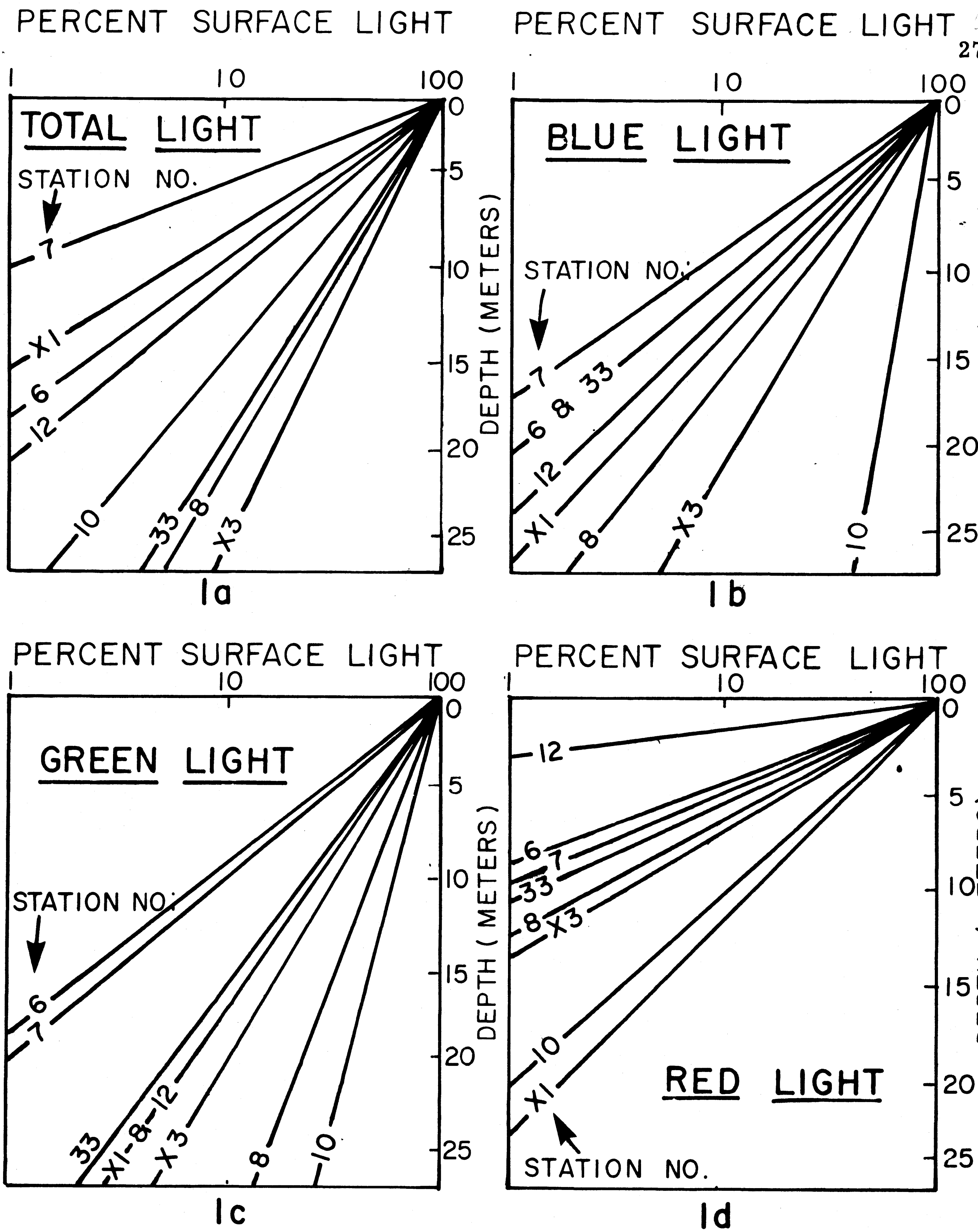

Figure 8. Light penetration in central Lake Michigan. The graphs do not show actual data points but depict the extinction coefficients (K) for total light (1a), blue (1b), green (1c), and red (1d) light.

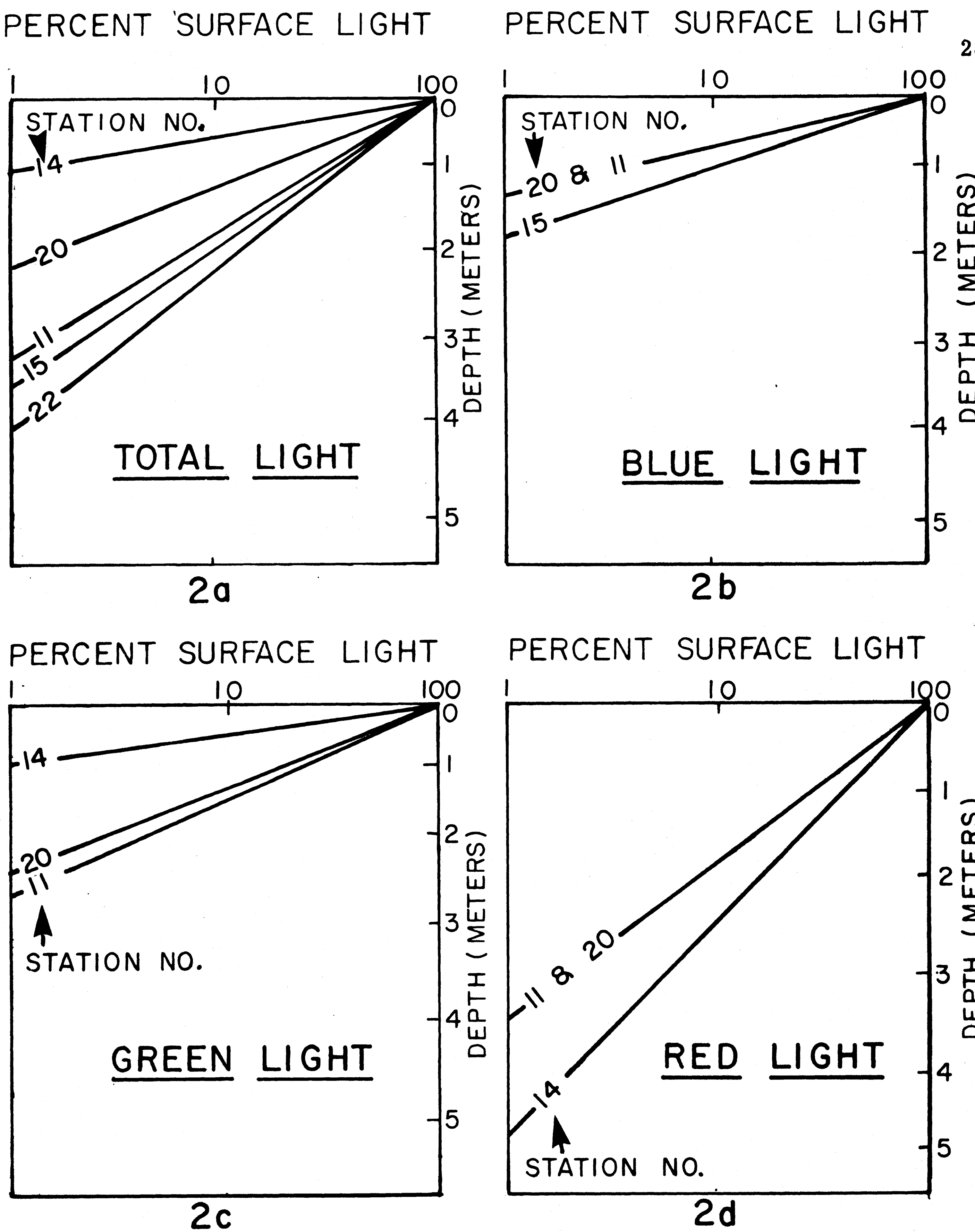

Figure 9. Light penetration in Green Bay. The graphs do not show actual data points but depict the extinction coefficients (K) for total light (2a), blue (2b), green (2c), and red (2d) light.

In agreement with the thesis that Green Bay contains two distinct water masses--one moving southward along the western shore, and one moving north on the eastern shore--(Modlin and Beeton 1970) Figure 9 shows the difference in the optical quality of stations in each water mass. The western water being clearer indicates that at least a portion of it is Lake Michigan water.

Dissolved Oxygen of Lake Michigan and Green Bay, Lake Michigan

Introduction:

Of all the chemical substances in lakes and streams, oxygen is one of the most important. Oxygen is significant both as a regulator of metabolic processes of lake organisms and as an indicator of lake conditions. Dissolved oxygen content along with morphometry, transparency, total dissolved solids, and conductivity have been used as a means of lake classification (Beeton 1965). Hutchinson (1957) has stated: "A skillful limnologist can probably learn more about the nature of a lake from a series of oxygen determinations than from any other kind of chemical data. If these oxygen determinations are accompanied by observations on Secchi disc transparency, lake color, and some morphometric data, a very great deal is known about the lake."

Recent reviews and studies of the changes occurring both in the biota and the physico-chemical conditions in Lake Erie (Beeton 1961) have raised interest in the eutrophication and pollution of the Great Lakes. Beeton (1965), in a review of the eutrophication of the Great Lakes, emphasized the possibility of detection and perhaps measurement of the rate of eutrophication of the Great Lakes.

Reviews of the indices of eutrophication have shown that increases in the nitrogen and phosphorus content and decreases in the dissolved oxygen content are accepted indices of eutrophication (Hasler 1947; Sawyer 1947; Thomas 1965).

This study has the objective of adding to the knowledge of the dissolved oxygen content of central Lake Michigan and Green Bay. Changes in the quality of Lake Michigan, hopefully may be measured by comparing these oxygen data with observations at some later date.

Methods:

Oxygen concentration was determined by the Alsterberg modification of the Winkler method, with the addition of the Carritt and Carpenter modifications (1966) for the prevention of loss of iodine through volatilization. Oxygen saturations were read from the nomogram of Mortimer as given by Hutchinson (1967, p. 582). The oxygen values obtained at all stations are given in the tabulations of hydrographic data.

Results and Discussion:

The dissolved oxygen content at the Lake Michigan stations was near saturation, or was super-saturated, at all depths. Comparison of data from this cruise with the 1954 data of Beeton and Moffett (1964) shows little, if any, change in dissolved oxygen content from the early 1950's (Table 6). Ayers, *et al.*, (1967) have reported a diminution in dissolved oxygen for some of these stations at near bottom depths during late September and early October. Our data show no decrease in hypolimnetic dissolved oxygen, but this may

Table 6. Comparison of oxygen content and percent saturation, July 1954 and July 1971 data. 1954 data listed first.

		Temp., C		O_2 ppm		O_2 % Saturation	
Station	Depth, m.	13 VII 54	13 VII 71	13 VII 54	13 VII 71	13 VII 54	13 VII 71
1	0	17.9	----	10.2	----	106	---
	2	----	12.3	----	11.7	---	110
	15	6.02	12.27	14.0	12.1	112	112
	30	4.95	4.57	12.5	12.8	99	100
	60	4.40	3.88	12.5	12.6	97	96
	70	3.99	----	11.5	----	89	---
		11 VII 54	9 VII 71	11 VII 54	9 VII 71	11 VII 54	9 VII 71
3	0	18.05	----	10.1	----	105	---
	2	----	16.2	----	11.8	---	119
	15	16.63	8.55	10.2	13.2	103	112
	30	5.25	4.47	12.7	13.2	101	103
	60	4.27	4.06	12.2	12.9	97	99
	70	4.13	3.88	12.2	13.2	97	99
		9 VII 54	8 VII 71	9 VII 54	8 VII 71	9 VII 54	8 VII 71
11	0	17.97	----	8.9	----	93	---
	2	----	19.0	----	9.9	---	105
	15	6.50	10.28	10.7	13.6	88	102
	30	5.62	4.55	12.3	12.2	100	96
	60	4.64	3.91	10.8	12.6	86	95
	70	4.09	3.83	10.4	12.1	81	91
		9 VII 54	8 VII 71	9 VII 54	8 VII 71	9 VII 54	8 VII 71
12	0	17.86	----	10.0	----	102	---
	2	----	17.4	----	11.1	---	114
	15	7.19	11.79	14.1	13.3	117	121
	30	5.27	4.57	13.1	12.1	103	93
	60	4.74	4.00	12.7	12.5	101	95
	70	4.8	3.96	11.4	11.0	91	85
		9 VII 54	8 VII 71	9 VII 54	8 VII 71	9 VII 54	8 VII 71
13	0	17.86	----	9.9	----	104	---
	2	----	19.0	----	10.9	---	114
	15	8.37	17.61	13.2	11.3	112	115
	30	5.48	5.81	11.6	12.7	94	101
	60	5.42	3.94	11.7	12.6	93	96
	70	4.28	3.91	12.2	12.5	95	95

be due to the fact that thermal stratification had only recently been established (usual onset of stratification is mid-June) and decreases in dissolved oxygen by oxidative processes in the hypolimnion are only just beginning at this time. Beeton (1966) has stated that "eutrophic" western Lake Erie required 28 days to show serious drops in dissolved oxygen this early after thermal stratification.

Oxygen concentrations and percent saturation values at stations in Green Bay are also given in the tables of hydrographic data. Figure 10 shows contoured oxygen concentration values at 2 m at Green Bay stations.

The extent of depletion of dissolved oxygen in the southern part of Green Bay, Lake Michigan, is quite evident. The lowest dissolved oxygen concentrations were between 2 and 3 ppm in late 1938-39 (Wisconsin State Committee on Water Pollution 1939), but between 0.0 and 1.0 ppm in 1955-56. The lowest values in our data were at Station GB 1 near the mouth of the Fox River, Wisconsin. Oxygen values increase northward from the mouth of the Fox River. Values also tend to be slightly higher on the west side of the bay. This would seem to be in order with the general circulation pattern of the bay, with the 'cleaner' Lake Michigan water flowing down the western side and after mixing with Fox River water, returning to the open lake along the eastern side (Modlin and Beeton 1970). Because of differences in the time, samples were taken (first at 7:00 AM, last at 5:00 PM, CDST) other than general trends cannot safely be discussed.

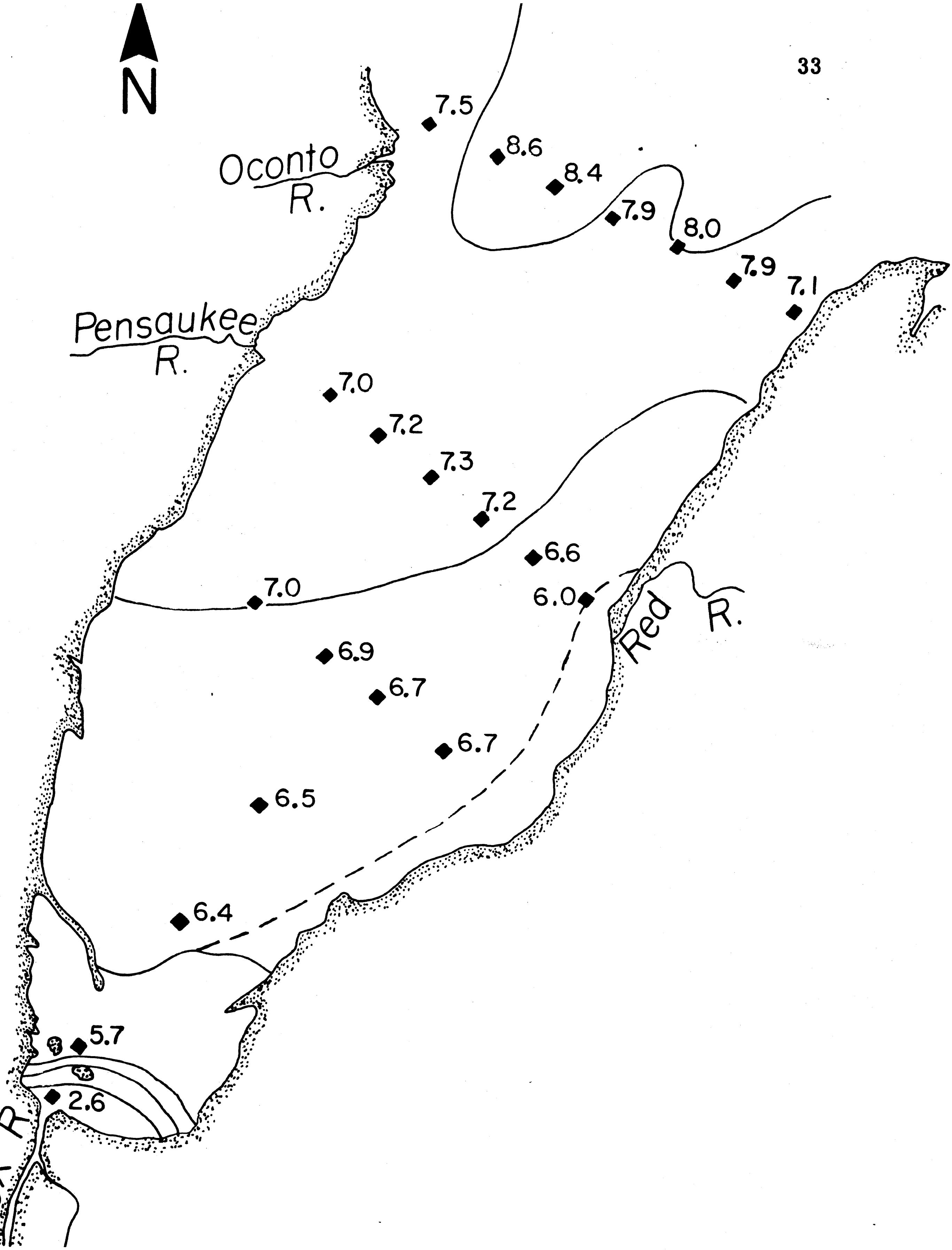

Figure 10. Green Bay, Lake Michigan, showing dissolved oxygen concentration (ppm) at 2 m depth on 13 July 1971.

Total Phosphorus, Soluble Reactive Silicate, Chlorophyll *a*, and Conductivity

Introduction:

The objective of this survey was to determine the spatial distribution of phosphorus, silica, chlorophyll *a*, and conductivity and to compare results with those from cruises taken by the U. S. Bureau of Commercial Fisheries in 1954-1955.

Material and Methods:

Water samples were collected with either a 9-liter Van Dorn sampler or by Teflon-lined 2-liter Nansen bottles. Temperatures were recorded by reversing thermometer or manually from a bucket. Unfiltered water was put into 250ml pyrex bottles which were brought back to Milwaukee for conductivity and total P analysis. Samples for pigment assay were prefiltered through a 250μm nylon mesh into polyethylene bottles and stored in the dark no longer than two hours before being refiltered. Water to be analyzed for silica was put in polyethylene bottles and filtered through 0.45μm HA Millipore filters of 47mm diameter within a day after collection. This filtered water was then stored in polyethylene bottles.

Total phosphorus was determined by the method of Gales *et al.*, (1966) but modified by using 0.3g potassium peroxydisulfate per sample and by autoclaving all blanks, standards, and samples at 15psi for 30 minutes. The standard deviation relative to the arithmetic mean (coefficient of variation) was 3.6% at 9μg P/liter concentration.

Soluble reactive silica was determined by the heteropoly blue method (A.P.H.A. 1965) with the following modification. The HCl solution was made by diluting 210ml concentrated HCl with 130ml distilled water. Other reagent solutions were not modified. To 50ml of sample, 2.5 ml of molybdate solution, 1.0ml diluted HCl, 1.0ml oxalic acid solution, and 2.0ml reducing agent were added sequentially at 5-minute intervals. A Fisher Electrophotometer II, with a red 650mm filter and 2.5cm diameter pyrex cells was used to measure absorbance of the reduced molybdosilicate complex no sooner than 30 minutes after addition of the reductant. The coefficient of variation was 1.3% at 1.3mg SiO_2/liter concentration.

Chlorophyll a and phaeo-pigments were measured fluorometrically by the methods of Strickland and Parsons (1968). This method was calibrated by measuring the pigments of a mixed laboratory culture spectrophotometrically. Aliquots (10-250ml) of prefiltered water were filtered through two 2.4cm diameter Reeve Angel glass filters (834 AH grade) at one-third atmospheric pressure onboard ship. The filters were then ground manually with 90% acetone, diluted to 10ml, and centrifuged. Five ml of supernatant were then transferred to pyrex tubes and measured fluorometrically. Dilutions with 90% acetone were made as required. Two drops of 5% HCl were next added, the solution mixed by inverting, and the fluorescence after acidification recorded. The coefficient of variation was 5.6% at 5.9μg chlorophyll a/liter.

A Leeds and Northrup electrolytic conductivity bridge (catalog no. 4959) was used to measure specific conductance of unfiltered water stored in glass stoppered pyrex bottles. Samples were brought to 25C before testing.

Results and Discussion:

LAKE MICHIGAN

Total Phosphorus

Total phosphorus ranged from 4.5 to 23.0μg P/liter, with an average of 10.4. By averaging values from 2m and 15m at each station, an epilimnetic average for all stations was 9.9μg P/liter.

Levels of total phosphorus found by Beeton and Moffett (1964) show greater variation but little difference from those reported here when data from the same stations at approximately similar dates are compared. Their average value for Lake Michigan exclusive of the extreme southern end was 13μg P/liter (Beeton 1970).

Soluble Reactive Silica

Soluble reactive silica from all depths ranged from 0.4 to 1.9mg SiO_2/liter and averaged 1.0mg SiO_2/liter. The epilimnetic average of all stations was 0.65mg SiO_2/liter with a range of 0.4-1.0mg SiO_2/liter.

The silica values given by Beeton and Moffett (1964) were consistently higher than ours, generally in the 2 to 4mg SiO_2/liter range. However, their determinations were made on unfiltered samples stored for longer periods of time, and some silica may have been released from particulate matter. Consequently no judgment can be reached on a long-term change in silica during thermal stratification.

Chlorophyll a and Phaeo-pigments

Total chlorophyll a for all Lake Michigan samples ranged from 0.4 to 6.9 and averaged 3.0μg chlorophyll a/liter, and phaeo-pigments were usually detectable. Epilimnetic total chlorophyll a averaged 2.2μg chlorophyll a/liter and ranged from 0.8 to 5.3.

Plant pigments were not measured in 1954-1955.

Conductivity

Values ranged from 215.9 to 273.3 μmhos/cm at 25C and averaged 256.1 for all Lake Michigan samples. Beeton and Chandler (1963) reported an average specific conductance of 225.8μmhos/cm at 18C (approximately 262 at 25C using a conversion factor of 1.16) for Lake Michigan.

GREEN BAY

Total Phosphorus

This parameter ranged from 30.5 to 430μg P/liter for all samples and averaged 87.8.

Soluble Reactive Silica

Silica ranged from 0.4 to 1.5mg SiO_2/liter and averaged 0.9.

Chlorophyll a and Phaeo-pigments

Total chlorophyll a ranged from 7.0 to 144 μg/liter for all stations; and, excluding stations 1, 3, and 7, averaged 19.6μg chlorophyll a/liter.

Conductivity

This measurement ranged from 205.7 to 376.0μmhos/cm and averaged 257.7 for all Green Bay samples.

Seston in Lake Michigan and Green Bay

Introduction:

Knowledge of the amount and distribution of seston, the suspended particulate matter in a lake, can give information about the condition of the water. Particularly in conjunction with other data, such as light penetration, dissolved oxygen content, and chemical data, the seston can give an indication of the trophic level and turbidity of the water.

Some work has been done on Lake Michigan using a technique similar to the one described in this paper. Robertson and Powers (1965) sampled 15 stations regularly in southern and northern Lake Michigan from April to November of 1964. Several water samples were obtained at depths between the surface and 25 m and filtered through a tared membrane filter; several were taken from below 25 m and filtered through another tared filter. The filters were dried and reweighed; the difference between the two weights representing the seston. The means of the seasonal weights of seston showed no north-south trends, but inshore mean weights of seston were higher than midlake mean weights. The two stations nearest the Chicago and Milwaukee metropolitan areas had the highest mean weights of seston. Further work, done in the summer of 1966 (Robertson and Powers 1967), showed little difference between inshore and offshore or between northern and southern stations. This may have been due to the small number of sampling stations (four), and the fact that they were sampled only once.

Methods:

Water samples were taken at stations in Lake Michigan (Fig. 11) and Green Bay (Fig. 12) and the particulate content determined by filtration through membrane filters. In Lake Michigan, the usual

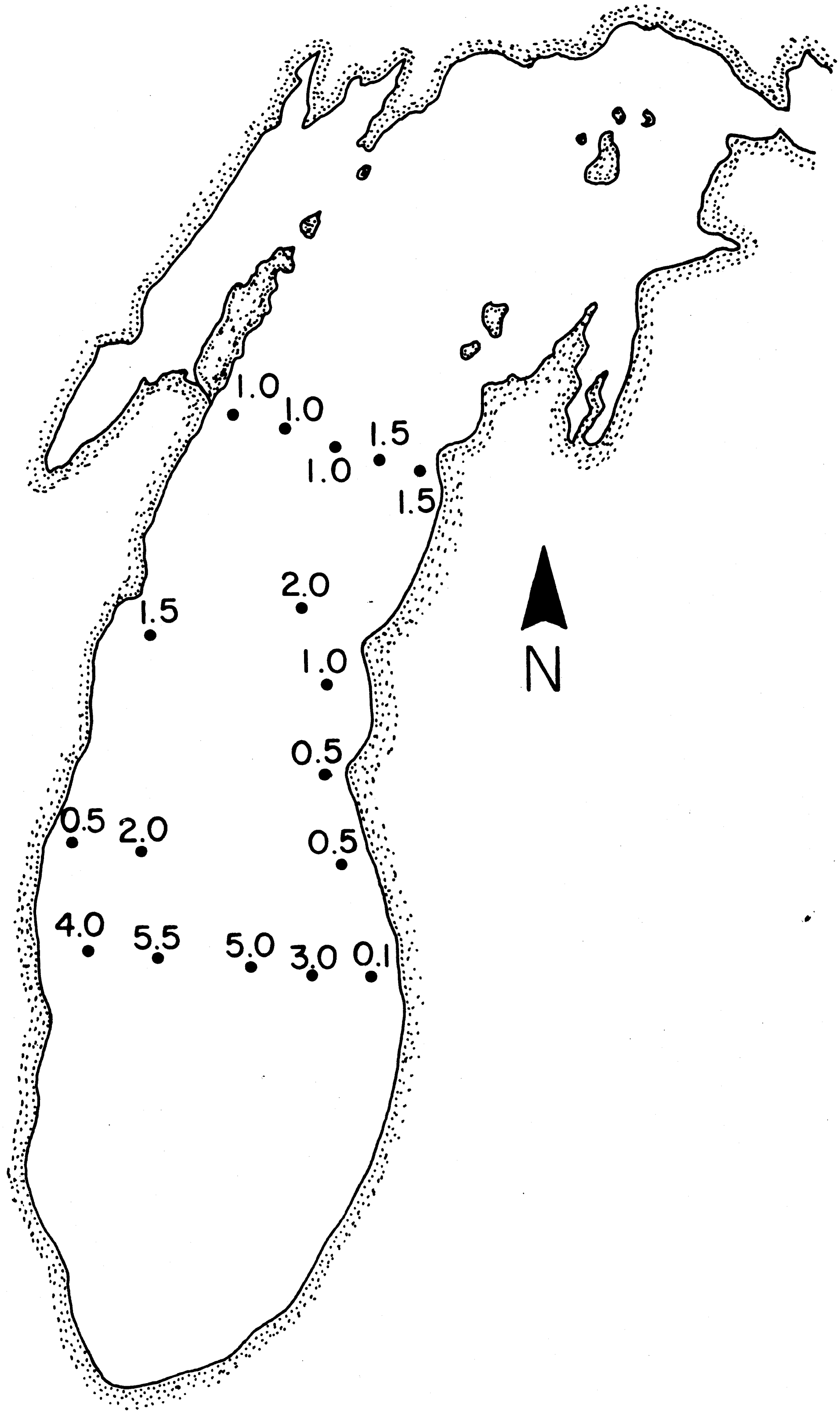

Figure 11. Lake Michigan seston concentrations (mg/liter), averaged values from 2 and 15 m depths.

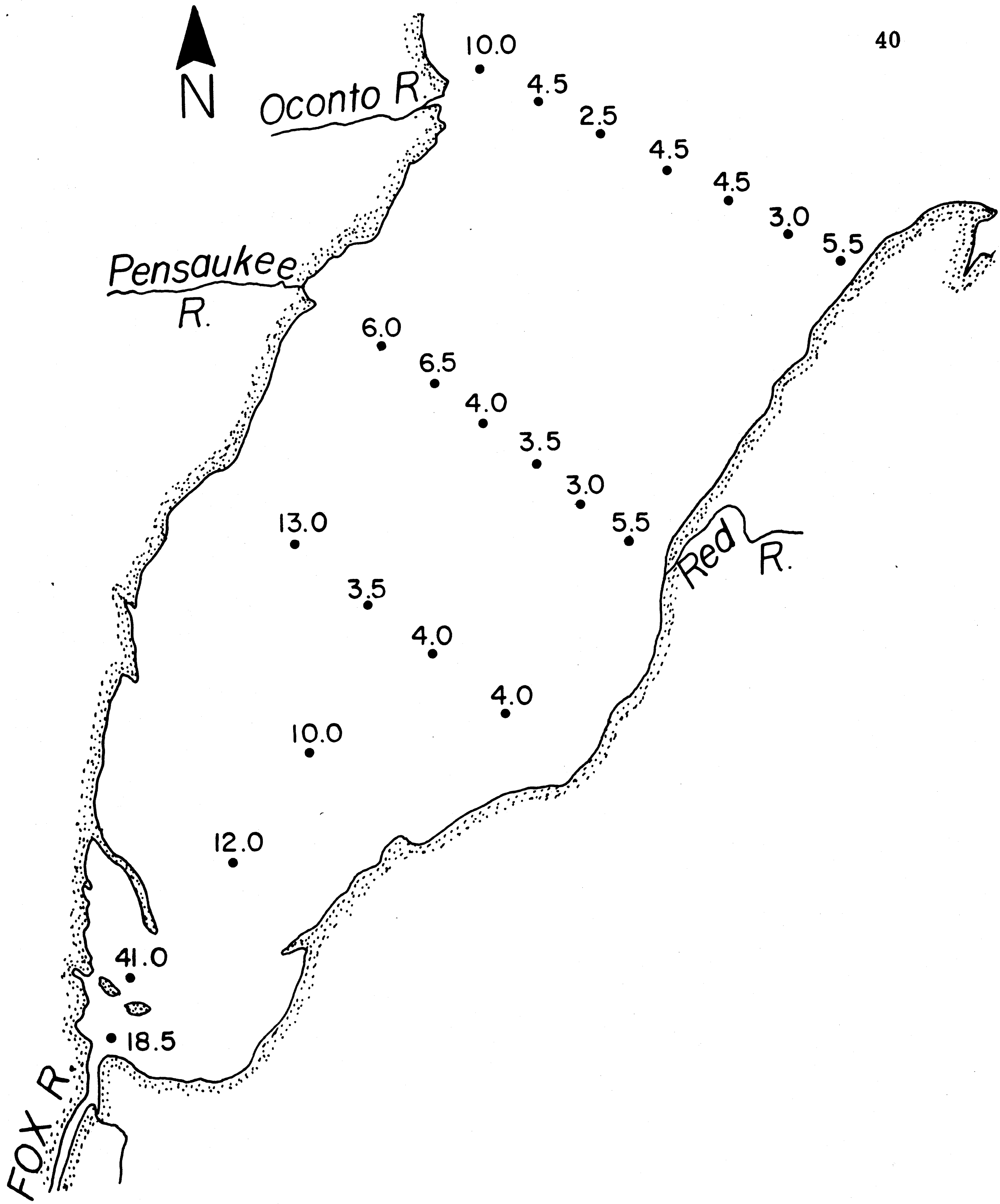

Figure 12. Green Bay seston concentrations (mg/liter), at 2 m depth.

sampling depths were 2 m, 15 m, 30 m, 60 m, and 70 m, though some stations varied from this. In Green Bay, stations at which samples were taken only from 2 m depth alternated with stations at which the 2 m depth and one or two other depths were sampled. The 2 m samples were taken with a Van Dorn water bottle; the rest of the samples were taken with a Nansen bottle.

Before the cruise, two hundred 0.45 μ membrane filters were numbered, soaked in distilled water a few minutes, placed on racks in aluminum planchets, and dried in an over at 70-80°C for one hour. The filters were stored on board the ship in a desiccator; during the course of the cruise, however, the lid was broken, and the desiccator was covered with aluminum foil for the remainder of the cruise. Filters were removed from the desiccator immediately before water samples were to be filtered. Water samples for seston were usually filtered within several hours after the hydrographic cast. The samples were filtered on board ship with a vacuum pump, under a pressure of 5 to 10 psi. Five hundred milliliters of water were filtered from Lake Michigan samples and 350 milliliters from Green Bay samples. After filtration, the filters were dried at 70-80°C, and stored in a desiccator until the end of the cruise.

Thirty of the unused filters were used as controls. The filters, including the controls, were redried at 70-80°C for one hour, and then placed in a desiccator to cool. The filters were then weighed. The controls were weighed before and after weighing the experimental filters, and the change in weight during the weighing period was applied as a correction factor for the effects of humidity on the filters. Since some of the experimental, and all of the control filters, were lighter than at the prefiltration weighing, the filters were dried at 70-80°C overnight to bring them to a constant low weight, and then reweighed. The difference between the prefiltration weight and this final dry weight of the control filters was used to get a correction factor for the experimental filter weights. A correction factor was determined for each batch of 25 filters which were packaged together. This was done by averaging the change in weight of the controls from each batch of 25 filters. The difference between the prefiltration weight and the final dry weight, after correction, was considered to represent the amount of seston in the filtered water.

The standard error of the mean for all 30 controls was 0.2 mg; the standard error of the means of the controls for each of the six separate groups of filters varied from 0.1 mg to 0.4 mg. Therefore the values shown in tables of hydrographic data have been rounded off to the nearest 0.5 mg.

The continued loss of weight after the first weighing is a problem that others using this method have either not encountered or have not found serious. Robertson and Powers (1965) avoided the problem by simply placing the filters in a dessicator until they reached a constant weight. Banse, Falls, and Hobson (1963), who first outlined the method described above, did not mention any problem of this sort. However, Huh (1969) mentioned that drying at temperatures above 90°C resulted in lower weights. Possibly prolonged storage in a desiccator would cause a similar loss of weight.

Results:

Seston determinations are reported with other data in the tables of hydrographic data. Figure 11 shows the estimated amounts of seston (mg/liter) in the top 15 m for all stations in Lake Michigan.

These estimates were obtained by averaging seston weights at 2 m and 15 m. Figure 12 shows seston weights of samples from 2 m depth at Green Bay stations.

Discussion:

LAKE MICHIGAN

In the southern transect, there was a decrease in the amount of seston from west to east. Low seston occurred along the eastern shore and the northern transect also showed lower values toward the east, although the values were lower than in the southern transect. Seston weights at stations on the transect along the western shore were much lower than those of the western part of the southern transect. Perhaps this was due to generally less particulate matter outside of the southern basin, or to a change in water masses between sampling dates.

GREEN BAY

In Green Bay, the amount of seston increased toward the mouth of the Fox River. This is probably due to the domestic and industrial wastes of the towns and factories along the Fox River. Seston concentrations along the western shore of the Bay were higher than along the eastern shore; this difference may be due to suspended particulate matter. Other data taken on the cruise, such as dissolved oxygen concentrations, indicate that higher quality water was on the western side of the Bay. The Secchi disc depths, however, show some correlation with seston concentrations (Fig. 13).

A plot of Lake Michigan seston concentrations against the Secchi depths did not show a significant correlation. Perhaps this is because there are more factors affecting the two parameters at lower seston concentrations and greater Secchi disc depths. It is

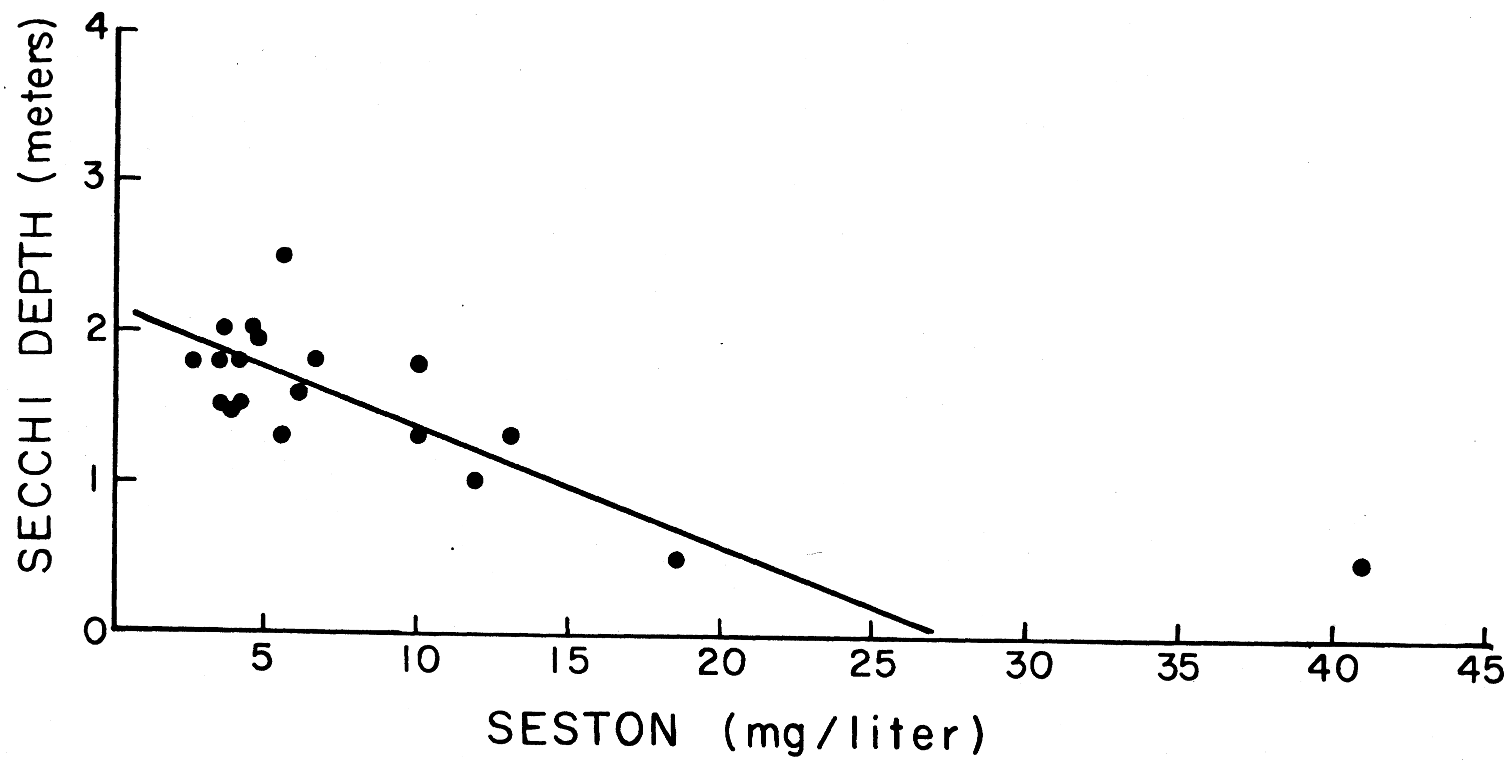

Figure 13. Secchi disc depth (m) plotted against seston concentration (mg/liter) at 2 m depth in Green Bay.

quite possibly an indication that larger amounts of lake water should have been filtered so that the seston concentrations could have been estimated more accurately.

The Distribution of Planktonic Crustacea in Southern Green Bay on 12 July 1971

Introduction:

During the July 1971 cruise of the R/V NEESKAY the author was afforded an opportunity to sample the zooplankton of southern Green Bay. Previous zooplankton investigations on Green Bay are limited to the work of Balch *et al.* (1956) and Gannon (1972a and b). In a brief study of extreme lower Green Bay in 1955, Balch identified organisms only as Copepoda or Cladocera. Gannon examined zooplankton Crustacea throughout Green Bay in 1969-70 and organisms were identified to species.

Methods:

Samples were taken at seven stations in southern Green Bay by single vertical tows from near the bottom to the surface, with a 1/2 m diameter standard plankton net. The net was constructed of No. 6 nylon mesh (aperture 0.239 mm) which allowed for the capture of all adult Crustacea, without serious phytoplankton clogging. The samples were narcotized with CO_2 charged water (club soda) for ten minutes and then preserved in 10% formalin and labeled. Each sample was subsampled with a 2 ml Stempel pipette 3 to 5 times depending upon the number of organisms within the sample. About 400 to 500 organisms were counted for each sample. All adult Crustacea and the large planktonic rotifer, *Asplanoina sp.* were identified and enumerated. Counts of all taxa except *Leptodora* were made in a circular revolving counting tray (Priegel 1970) under a binocular microscope. Leptodora was enumerated by taking ten 20 ml aliquots from each sample and counting these large organisms by eye in a petri dish. All Crustacea were identified to species except copepods of the genus Diaptomus. Twenty adult male and female Diaptomus were selected at random from each sample and identified to species. The percent occurrence of each of the diaptomid adults was used to calculate the percent occurrence of each species at each station. Copepodite stages were not identified. Results are expressed in both specimens/m^2 and specimens/m^3 for all species to allow comparison of these data with the results of other Great Lakes workers. The data should not be interpreted as true zooplankton densities, but rather as relative abundance values proportional to densities since the true sampling efficiency probably varies from 40 to 50% (Rawson 1956).

Results:

Seventeen species of crustaceans--9 cladocerans and 8 copepods--were identified. These are listed in Table 7 and their distributions are represented in Figures 14-18, which show numerical abundance at Green Bay Stations 7, 11, 14, 15, 20, 22, and 26. The most common species were Daphnia retrocurva and Eubosmina coregoni, both of which had greater densities at the southern stations than the northern stations. Daphnia galeata mendotae, Ceriodaphnia lacustris, Bosmina longirostris and Diaptomus siciloides were present in moderate numbers at all stations. Cyclops bicuspidatus thomasi was taken in small numbers at all stations, but was numerous only at Station 26. Daphnia longiremis and Diaptomus oregonensis were only taken at Station 26, where they were both common. Mesocyclops edax was also common only at Station 26. Cyclops vernalis was taken only at the southern stations. Diaptomus ashlandi was taken in small

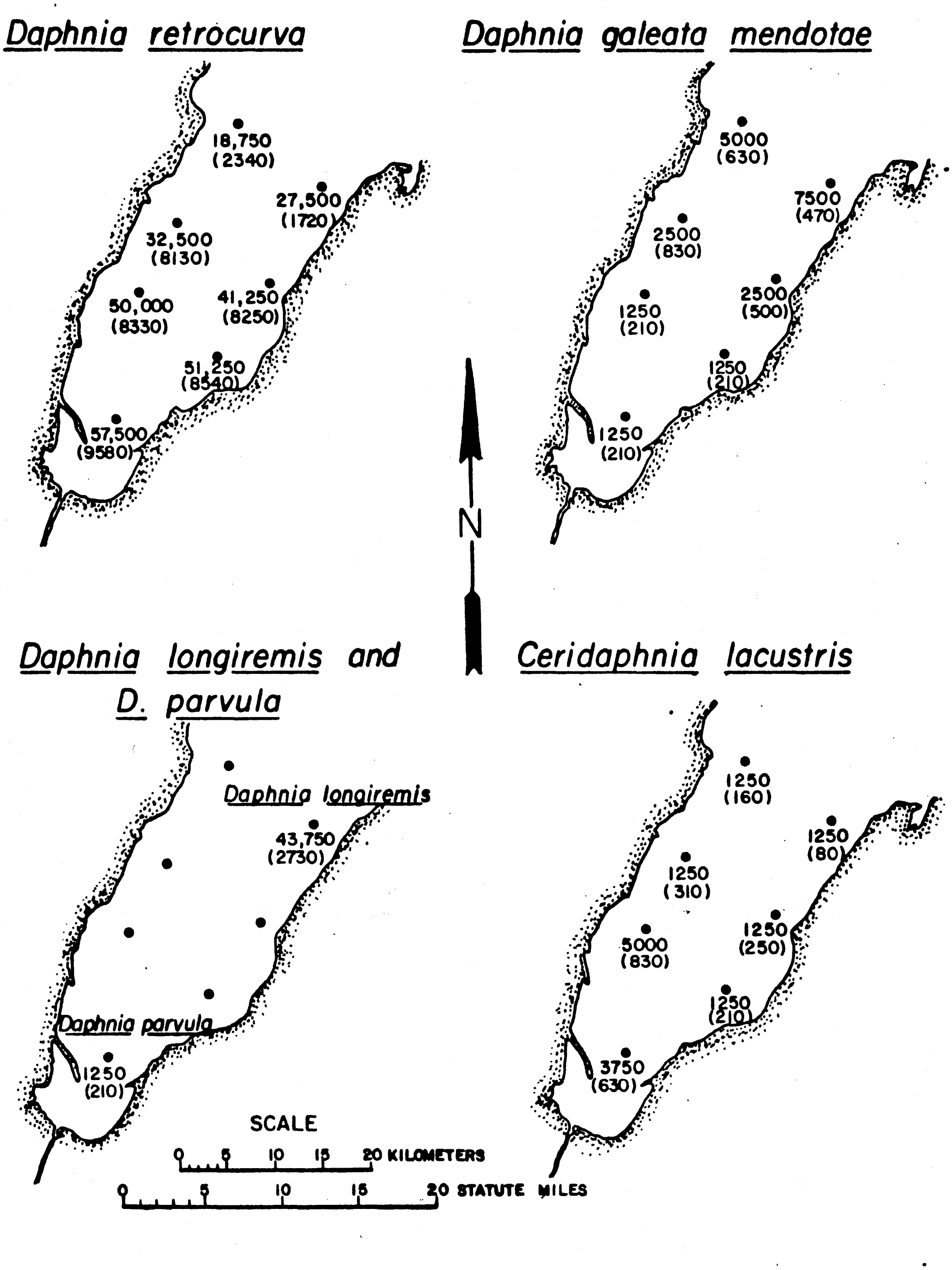

Figure 14. Distribution of five species of Cladocera on 12 July 1971; upper numbers are specimens/m^2, lower numbers in parentheses are specimens/m^3.

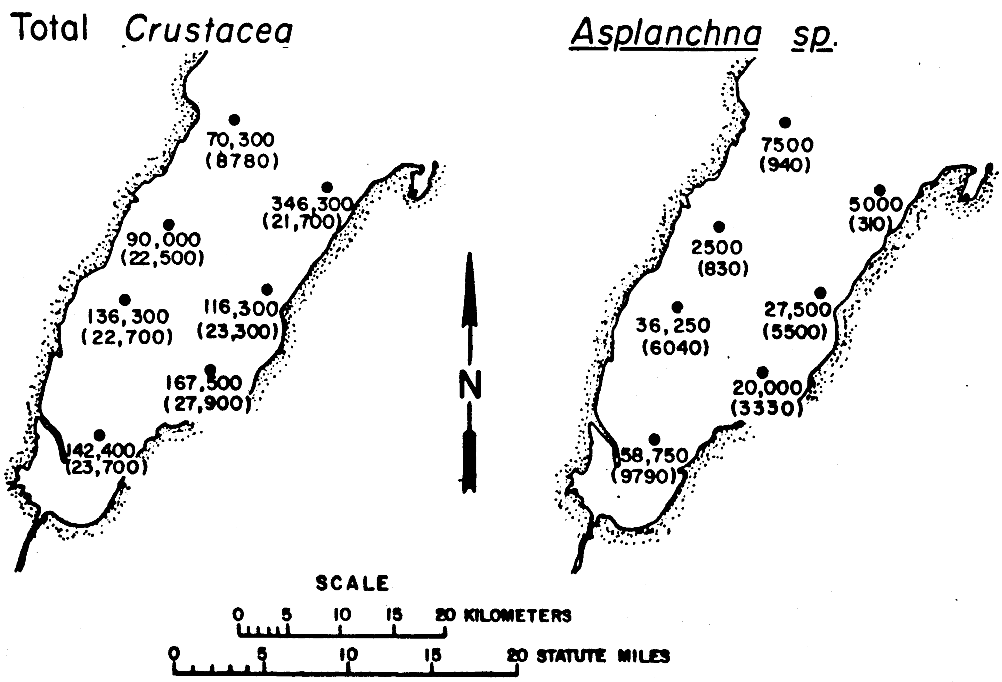

Figure 15. Distribution of four species of Cladocera on 12 July 1971; upper numbers are specimens/m^2, lower numbers are specimens/m^3.

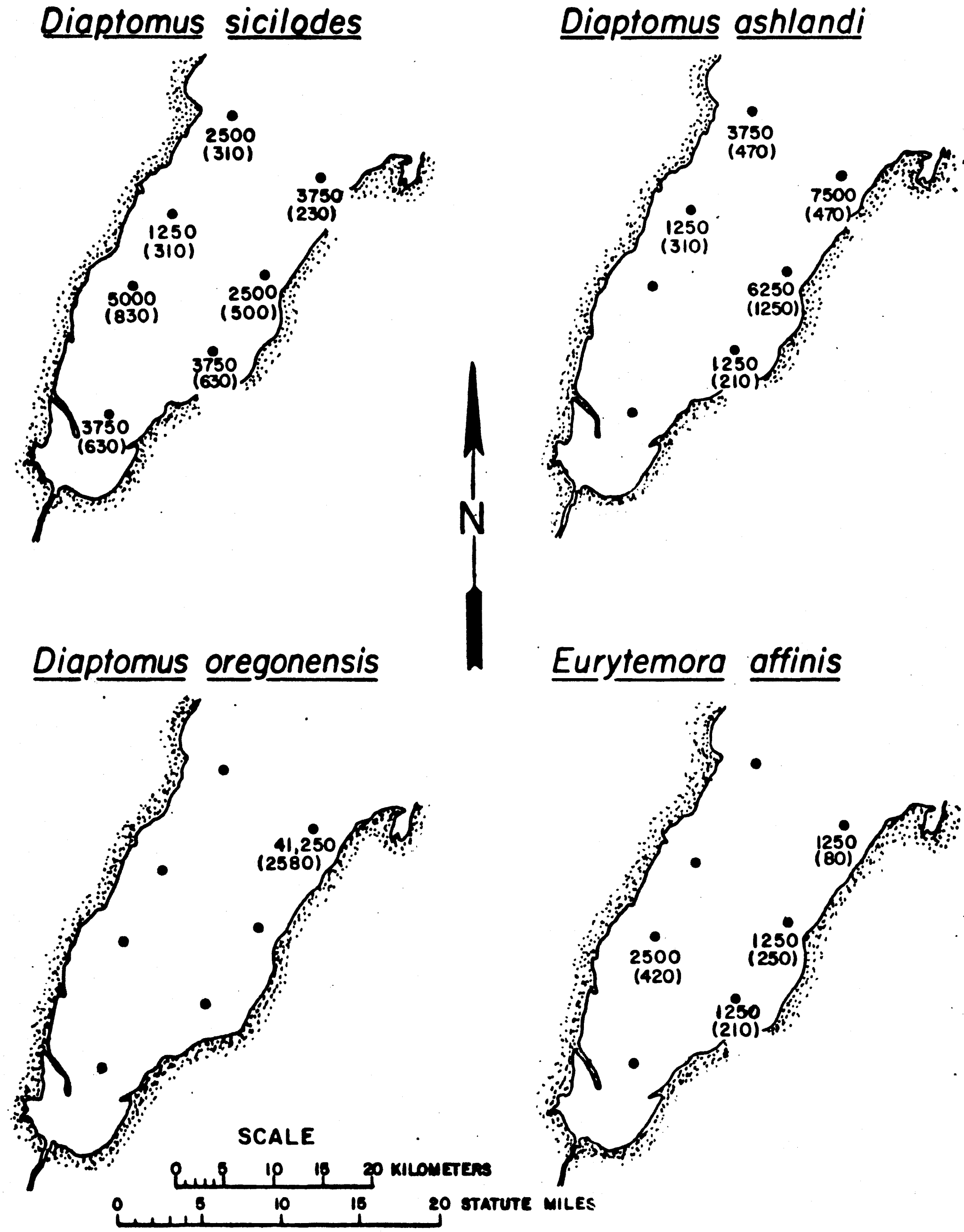

Figure 16. Distribution of four species of cyclopoid copepods.

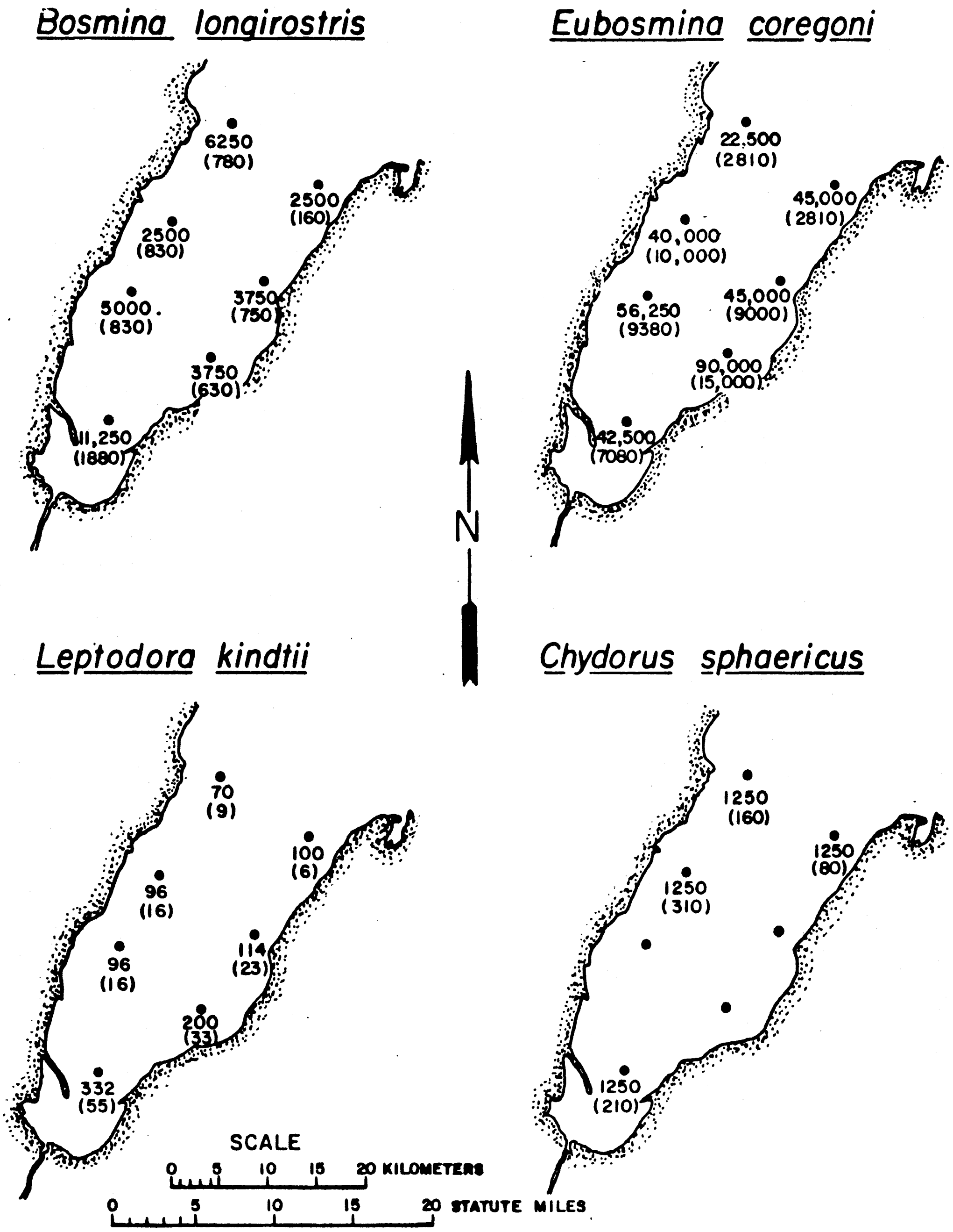

Figure 17. Distribution of four species of calanoid copepods.

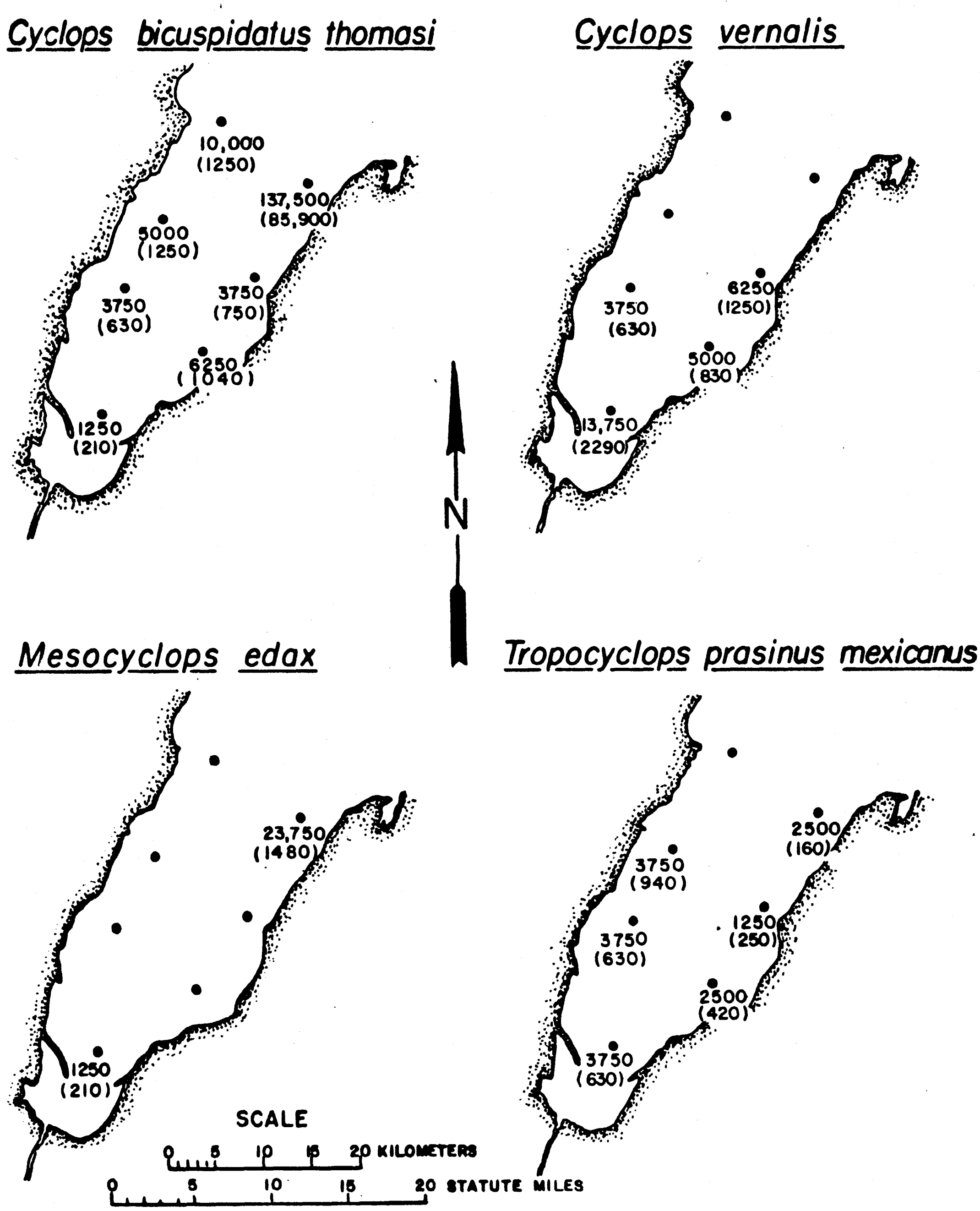

Figure 18. Distribution of total Crustacea and Asplanchna sp.

Table 7. Crustacean species collected in Green Bay on 12 July 1971, compared with July collections from Lakes Michigan and Erie (Lake Michigan data from Wells 1970; Lake Erie data from Davis 1968).

- \- = Virtually absent or absent
- X = Presence in small numbers
- C = Common (present in numbers often exceeding $100/m^3$)
- A = Abundant (present in numbers often exceeding $1000/m^3$)

CLADOCERA	Green Bay	Lake Michigan	W. Lake Erie	Central & E. Lake Erie
Ceriodaphnia lacustris Birge	C	X	-	-
Daphnia retrocurva Forbes	A	A	A	C
D. galeata mendotae Birge	C	C	A	A
D. longiremis Sars	X	X	-	-
D. parvula Fordyce	X	-	-	-
D. pulex leydig Fischer	-	-	X	-
Diaphanosoma leuchtenbergiana Fischer	-	X	X	-
Holopedium gibberum Zaddach	-	C	-	X
Bosmina longirostris (O. F. Muller)	C	C	-	-
Eubosmina coregoni (Baird)	A	C	A	C
Chydorus sphaericus (O. F. Muller)	X	X	X	X
Polyphemus pediculus (L.)	-	X	-	-
Leptodora kindtii (Focke)	C	C	C	C
COPEPODA				
Limnocalanus macrurus Sars	-	C	-	-
Senecella calanoides Juday	-	X	-	-
Epischura lacustris Forbes	-	C	-	-
Eurytemora affinis (Poppe)	X	X	X	-
Diaptomus minutus Lilljeborg	-	C	X	X
D. ashlandi Marsh	X	C	X	X
D. oregonensis Lilljeborg	X	C	X	C
D. sicilis Forbes	-	X	-	-
D. siciloides Lilljeborg	C	-	C	X
Cyclops bicuspidatus thomasi Forbes	C	A	A	A
C. vernalis Fischer	C	-	C	-
Tropocyclops prasinus mexicanus Kiefer	X	X	-	-
Mesocyclops edax (S. A. Forbes)	X	X	X	C

numbers at the northern stations. Chydorus sphaericus, Tropocyclops prasinus mexicanus, and Eurytemora affinis were taken at most stations in very small numbers. Their distribution can be considered as more or less uniform, but sparse. The predaceous Leptodora kindtii and Asplanchna sp. were common at all stations, being two to five times more numerous at the southern stations. Daphnia parvula was represented by one specimen from Station 7. The distribution of total Crustacea showed a slight decrease in total standing crop from the southern stations to the northern stations if one ignores Station 26, a station 2 to 3 times as deep as any of the other stations and the only station with pronounced thermal stratification.

Discussion:

As has been shown by Patalas (1970), standing crop measurements of zooplankton populations are of little use in predicting trophic conditions or turnover rates. Consequently, no attempts will be made to interpret trophic conditions on the basis of biomass estimates. It is interesting to note, however, that the populations of both the most abundant herbivores, Daphnia retrocurva and Eubosmina coregoni, and the zooplankton predators, Leptodora kindtii and Asplanchna sp., are several times greater at the southern stations compared to the northern stations.

Some information regarding trophic conditions can be inferred from observations of the species composition of the Green Bay zooplankton communities. Diaptomus siciloides and Cyclops vernalis, both common in the eutrophic western basin of Lake Erie, but uncommon or absent in central and eastern Lake Erie and Lake Michigan, were common in Green Bay (see Table 7). Gannon (1972a) proposes that D. siciloides may be a useful indicator of advancing eutrophication in the Great Lakes.

Ewers (1936) investigated the developmental rates of both Cyclops vernalis and C. bicuspidatus. She found that whereas development from egg to adult required 28 to 35 days for C. bicuspidatus at room temperature, only 8 days were required for the development of C. vernalis and whereas C. bicuspidatus produces egg packets of 10 to 40 eggs, C. vernalis egg packets contain from 40 to 80 eggs. It would appear then that C. vernalis is an animal adapted to rapid reproduction, able to take advantage of conditions where rapid turnover rates prevail, while C. bicuspidatus is adapted to living in ecosystems where the energy flow rates are considerably slower.

Station 26 stands out as the most unique collection of species among the seven stations. This was the only station with thermal stratification and a cold hypolimnion. Daphnia longiremis, a northern, holarctic, cold water species, was collected only here. D. longiremis is generally found below the thermocline in the more southerly parts of its range, and the Great Lakes appear to be the southernmost extension of its range in North America (Brooks 1957). Diaptomus oregonensis was also collected only here, and Mesocyclops edax and Cyclops bicuspidatus were far more common here than at the other stations. All three species are common components of the Lake Michigan zooplankton communities.

Daphnia retrocurva was far more numerous at all stations than the larger D. galeata mendotae. Wells (1970) and Brooks (1969) have both argued that size-selective predation by alewives (Alosa pseudoharengus) has been responsible for a shift in abundance of these two species. However, Davis (1968) reported D. g. mendotae as the more numerous of the two species in Lake Erie during July 1967. In the present survey Eubosmina coregoni was more abundant than the smaller B. longirostris. One would expect that B. longirostris would be the more common organism if size-selective predation was a major factor in Green Bay. However, as Brooks (1969) himself pointed out, other factors may influence the distributions of these two species. B. longirostris has long been considered to be an indicator of eutrophic conditions (Minder 1938). Once again, however, its distribution in the Great Lakes is not always predictable on the basis of this hypothesis. There also appears to be a difference between these two forms in regard to temperature preference. B. longirostris generally appears earlier in the spring in the Great Lakes than E. coregoni; as a rule their peak numbers do not occur simultaneously in the same area (Patalas 1969; Davis 1969; Torke 1971). It seems likely that a combination of factors operate in determining the success of these animals in any particular area.

Some zooplankton species, which have been found in Lake Michigan in July, were not seen in this study. Limnocalanus macrurus and Senecella calanoides, both inhabitants of cold deep water, were both absent in Green Bay. Epischura lacustris, Diaptomus minutus, D. sicilis, Holopedium gibberum, and Polyphemus pediculus were also absent. These species are present in southern Green Bay at other times of the year (Gannon, personal communication).

Benthic Invertebrates From Central Lake Michigan

Introduction:

The benthic fauna of Lake Michigan has been studied previously by several workers. Eggleton (1936, 1937) presented the first comprehensive report on the benthic fauna present in 1931 and 1932. Merna (1960) also analyzed a large number of benthos samples which were collected by the U. S. Bureau of Commercial Fisheries in 1951-1955. Robertson and Andrews (1966) conducted study of Lake Michigan benthos in 1964 to compare with the results of Eggleton's study. Powers and Robertson (1966) also reported on the 1964 study.

This report deals with bottom samples obtained from 17 stations in Lake Michigan from 8 July to 14 July 1971.

Methods:

A Ponar grab was used for benthic sampling. A single sample was taken at each station except that replicates were obtained when it was felt that the first sample was too small to be quantitative. Three grabs were taken at Station X3 because of special interest in the benthos of this deep region.

Samples were screened immediately with a U. S. Std. No. 30 mesh screen and the residue on the screen was washed into a 500 ml (16 oz) bottle and preserved in 10% formalin. Organisms were hand-picked from each sample in the laboratory.

Oligochaete worms were identified by Dr. R. P. Howmiller and the results are reported elsewhere in this report.

The triplicate determinations of Station X3 were averaged to give a single value.

Results and Discussion:

Adequate samples were obtained from all the stations except Station 32, which apparently had a bottom of coarse gravel and could not be sampled with the Ponar grab.

The Lake Michigan benthos was dominated by the same three categories of organisms as found in 1931, 1955 and 1964 (Table 8). Eggleton (1937) stated that the benthos is dominated, in order of decreasing abundance, by Pontoporeia, Tubificidae, and Sphaeriidae. Merna (1960) and Robertson and Alley (1966) also found these groups to be very abundant with Pontoporeia, the major organism. We found the benthos to be dominated by the same three groups with Pontoporeia predominant.

Comparisons between our results and those of previous workers are not definitive because of significant differences in methods, techniques, and sample sizes. Nevertheless, comparisons between matched

Table 8. Abundance of benthic invertebrates at Lake Michigan stations sampled 8 July-14 July 1971 arranged by increasing depth of station.

Depth (m)	Station	Abundance of Given Invertebrate (No./Sq.M.) Pontoporeia	Oligochaeta	Snails	Clams	Midges
26-38	32**	-	-	-	-	-
64-73	34	757	574	0	543	19
66	1	2,735	919	0	0	0
73	13	2,755	727	0	0	0
75	7	1,823	870	0	0	29
76	3	4,074	1,187	0	255	58
79	11	1,474	880	0	0	19
81	6*	-	-	-	-	-
82	12*	-	-	-	-	-
90	X1	1,494	1,976	0	2,365	0
101	X2	3,997	421	0	0	19
110	10	233	0	0	0	0
119	8	1,756	383	0	0	0
146	X4	1,125	421	0	2,658	0
264	33	*	-	-	-	-
266	X3	821	172	0	0	0

* sample not quantitative
** sample not obtained

stations of Eggleton (1937, 1939), Merna (1960), Robertson and Alley (1966), and the present work indicate that the two most abundant organisms, Pontoporeia and oligochaetes, are more abundant than they were in 1931 and seem to be as numerous as in 1964.

Eggleton's samples were collected with a Petersen grab as were those of Robertson et al. Beeton, Carr and Hiltunen (1965) have shown this grab to be inefficient in the quantitative measurement of the Great Lakes benthos. Most of Merna's samples were taken with an Orange-peel grab which Beeton, Carr, Hiltunen and Howmiller (unpublished manuscript) have shown to be more effective than the Petersen, especially for oligochaetes, and at depths greater than 36 meters. The Ponar grab was selected for this study because it seems to be efficient in a wider variety of sediments than the commonly used Petersen or Ekman grabs (Powers and Robertson 1967) and it was thought to be the best single sampler for the diversity of sediment types encountered in Lake Michigan.

The Oligochaete Fauna of Central Lake Michigan

Introduction:

The distribution of oligochaete species in Lake Michigan is known only from the work of Hiltunen (1967), whose very thorough study dealt mainly with samples from the southern basin, and the studies of Howmiller and Beeton (Howmiller 1971; Howmiller and Beeton 1970) on Green Bay.

Merna (1960) examined many bottom samples taken at the Cisco Stations in 1954 and 1955. He reported finding Limnodrilus udekemianus, Peloscolex sp., and Sparganophilus sp. A comparison of this meager list with the results of other Great Lakes investigations (summarized in Howmiller and Beeton 1970) leads to the conclusion that Merna's list is incomplete and probably partly incorrect. The true identity of the species found by Merna must remain unknown because his report included no descriptions or illustrations which could be used to confirm the determinations.

The bottom samples obtained during the present cruise provided an opportunity to increase the knowledge of the Great Lakes oligochaete fauna with an account of the species occurring in central Lake Michigan.

Methods:

All oligochaete worms were hand-picked from the sieve residue, mounted on microscope slides in a mixture of Turtox CMC and CMS, and examined at a magnification of at least 100X for species identification. The worms were identified using the keys of Brinkhurst and Cook (Brinkhurst 1965; Brinkhurst and Cook 1966). Samples of the Enchytraeidae found have been sent to J. K. Hiltunen for verification.

Results and Discussion:

Bottom samples were obtained from all Lake Michigan stations except Station 32, which apparently had a bottom of coarse gravel or rubble, and could not be sampled with the Ponar grab.

Worms found in the samples are listed in Table 9, which also gives estimates of abundance for each taxon. These estimates are, for the most part, based only on one sample at each station and may be very inaccurate.

The worms examined from 15 stations included very few species; two enchytraeids, one lumbriculid, and two tubificids (Table 9).

The most striking feature of the oligochaete fauna of central Lake Michigan is the great preponderance of the lumbriculid *Stylodrilus heringianus*. This species accounted for almost 90% of the worms examined. It was clearly dominant at 10 of the stations (Table 9).

Table 9. Estimated abundance of Oligochaete taxa at stations in central Lake Michigan. Also listed are the depth and sediment type at each station and the number of worms examined for species identification.

ORGANISM Stations:	1	3	6	7	8	10	11	12	13	33	34	X1	X2	X3	X4	X5
Enchytraeidae																
Lumbricillus		96		57												19
unknown		19														
Lumbriculidae																
Stylodrilus heringianus	919	1072		813	383		880	*	77	*	574	976	421	153	421	230
Tubificidae																
Tubifex tubifex									19							19
Limnodrilus hoffmeisteri									172							
Unidentified immature; with hair chaetae									19					19		
without hair chaetae									440				38			
Total Number $/m^2$	919	1187	**	870	383	0	880	**	727	**	574	976	459	172	421	268
Number Examined	76	62	1	91	40	0	46	1	38	1	30	51	24	27	22	44

*present
**sample not quantitative

While this finding is striking, it is not surprising. Brinkhurst (1969) noted that *Stylodrilus heringianus* is apparently an oligotrophic species, "typical of wide reaches of the Great Lakes where there is little evidence of eutrophication", Hiltunen (1967) found it common and abundant at his deeper stations in southern Lake Michigan.

The enchytraeid species were an unexpected find. Of nine major Great Lakes works listing oligochaete species, only two have reported enchytraeids. Hiltunen (1969a) reported finding Enchytraeidae at 10 of 16 stations sampled in the Apostle Islands region of Lake Superior, in water from 9 to 114 m in depth. Enchytraeids are apparently widespread, but nowhere abundant, in Lake Ontario (Hiltunen 1969b). Hiltunen has also found enchytraeids in samples from Lake Huron (personal communication). The most numerous of the enchytraeids found in Lake Michigan (at Stations 3, 7 and X5) seems to be the same taxon found by Hiltunen in Lakes Superior and Huron. It keys out to the genus *Lumbricillus*. The other enchytraeid, represented by only one specimen from Station 3, appears to be in the *Henlea-Enchytraeus* group.

Mature individuals of *Tubifex tubifex* occurred at two stations (13 and X5) and the unidentified immature worms with hair chaetae recorded at Stations 13 and X3 (Table 9) were probably also *T. tubifex*. *Tubifex tubifex* can be positively identified only from sexually mature specimens.

Limnodrilus hoffmeisteri was identified from Station 13 and, assuming that the immature worms without hair chaetae found in this sample were also *L. hoffmeisteri*, it appears to be the dominant oligochaete at this location. The composition of the fauna at Station 13 is thus greatly different from that at the other stations (Table 9). This may reflect the influence of organic enrichment of sediments from polluted rivers along the Michigan shore of the lake. Station 13 lies only 7 or 8 miles off Grand Haven and the mouth of the Grand River.

Limnodrilus hoffmeisteri is abundant in polluted areas in the Great Lakes (Hiltunen 1967; Brinkhurst 1969; Howmiller and Beeton 1970). Hiltunen (1967) described this species as saprophilous and Brinkhurst (1969) suggested that the percentage of L. hoffmeisteri in relation to other oligochaetes may be a useful index of organic pollution. Hiltunen (1967) found L. hoffmeisteri common, but never dominant, in samples taken in this same area in 1960. The difference may truly represent a change in the composition of the fauna or may be a function of our very limited sampling. The question is certainly worthy of further investigation.

Summary:

The oligochaete fauna of central Lake Michigan is poor in species and is dominated by the oligotrophic worm Stylodrilus heringianus. Enchytraeidae, found in few Great Lakes investigations, occurred at three stations. Two species appear to be present.

A station several miles off Grand Haven, Michigan, yielded a sample dominated by Limnodrilus hoffmeisteri. This may be a reflection of local enrichment of sediments by polluted tributary streams.

References

Ahrnsbrak, W. F. and R. A. Ragotzkie. 1970. Mixing processes in Green Bay. Proc. 13th Conf. Great Lakes Res., Int. Ass. Great Lakes Res., 880-890.

American Public Health Association. 1965. Standard Methods for the Analysis of Water and Wastewater. 12th ed., APHA, New York, 769 p.

Ayers, J. C., D. C. Chandler, G. H. Lauff, C. F. Powers and E. B. Henson. 1958. Currents and water masses of Lake Michigan. Great Lakes Res. Inst. Publ. No. 3, 196 p.

_______, E. F. Stoermer and P. McWilliam. 1967. Recently noted changes in the biology-chemistry of Lake Michigan. p. 95-111. In: J. C. Ayers and D. C. Chandler, Studies on the Environment and Eutrophication of Lake Michigan. Univ. Michigan, Great Lakes Res. Div., Spec. Rept. 30.

Balch, R. F., K. M. MacKenthum, W. M. Van Horn and T. F. Wisniewski. 1956. Biological studies of the Fox River and Green Bay, 1955-1956. Wis. State Comm. Water Poll. Bull. WP 102, 74 p. mimeo.

Banse, K., C. F. Falls and L. A. Hobson. 1963. A gravimetric method for determining suspended matter in seawater using Millipore Filters. Deep Sea Res. 10: 639-642.

Beeton, A. M. 1961. Environmental changes in Lake Erie. Trans. Am. Fish. Soc. 90: 153-159.

_______. 1962. Light penetration in the Great Lakes. Univ. Michigan, Great Lakes Res. Div., Publ. No. 9, p. 68-76.

_______. 1965. Eutrophication of the St. Lawrence Great Lakes. Limnol. Oceanogr. 10: 240-254.

_______. 1966. Indices of Great Lakes eutrophication. Univ. Michigan, Great Lakes Res. Div., Publ. No. 15, p. 1-8.

_______. 1970. Statement on pollution and eutrophication of the Great Lakes. Center for Great Lakes Studies, Univ. Wisconsin--Milwaukee, Spec. Rept. 11.

_______ and D. C. Chandler. 1963. The St. Lawrence Great Lakes. pp. 535-558. In: D. G. Frey [editor], Limnology in North America. Univ. Wisconsin Press, Madison.

_______ and J. W. Moffett. 1964. Lake Michigan chemical data, 1954-55, 1960-61. U. S. Fish Wildl. Serv., Data Rept. 6, 102 p.

_______, J. F. Carr and J. K. Hiltunen. 1965. Sampling efficiencies of three kinds of dredges in southern Lake Michigan. Univ. Michigan, Great Lakes Res. Div., Publ. No. 13, p. 209 (Abstract).

_______, J. F. Carr, J. K. Hiltunen and R. P. Howmiller. 1971. A comparative trial of Smith-McIntyre, Peterson, and orange-peel grabs in Lake Michigan. unpubl. ms.

Brinkhurst, R. O. 1965. Studies on the North American aquatic Oligochaeta. II. Tubificidae. Proc. Acad. Nat. Sci., Philadelphia 117: 117-142.

_______. 1969. Changes in the benthos of Lakes Erie and Ontario. Bull. Buffalo Soc. Nat. Sci. 25: 45-65.

_______ and D. G. Cook. 1966. Studies on the North American aquatic Oligochaeta. III. Lumbriculidae and additional notes and records of other families. Proc. Acad. Nat. Sci., Philadelphia 118: 1-33.

Brooks, J. L. 1957. Systematics of North American Daphnia. Mem. Conn. Acad. Arts, Sci., No. 13, 180 p.

_______. 1969. Eutrophication and changes in the composition of the zooplankton. p. 236-255. In: Eutrophication: causes, consequences, correctives. Nat. Acad. Sci., Publ. 1700.

Carritt, D. E. and J. H. Carpenter. 1966. Comparison and evaluation of currently employed modifications of the Winkler method for determining dissolved oxygen in seawater; a NASCO report. J. Mar. Res. 24: 286-318.

Davis, C. C. 1968. The July 1967 zooplankton of Lake Erie. Proc. 11th Conf. Great Lakes Res., Int. Ass. Great Lakes Res., 61-75.

_______. 1969. Seasonal distribution, constitution, and abundance of zooplankton in Lake Erie. J. Fish. Res. Bd. Canada 26: 2459-2476.

Eggleton, F. E. 1936. The deep-water bottom fauna of Lake Michigan. Papers Michigan Acad. Sci. 21: 599-612.

_______. 1937. Productivity of the profundal benthic zone in Lake Michigan. Papers Michigan Acad. Sci. 22: 593-611.

Ewers, L. A. 1936. Propagation and rate of reproduction of some freshwater Copepoda. Trans. Am. Microsc. Soc. 55: 230-238.

Gales, M. E., E. C. Julian and R. C. Kroner. 1966. Method for quantitative determination of total phosphorus in water. J. Am. Water Works Ass. 58: 1363-1368.

Gannon, J. E. 1972a. Effects of eutrophication and fish predation on recent changes in zooplankton Crustacea species composition in Lake Michigan. Trans. Am. Microsc. Soc. 91: 82-84.

_______. 1972b. Contributions to the ecology of zooplankton Crustacea of Lake Michigan and Green Bay. unpubl. Ph.D. dissertation, Univ. Wisconsin, 257 p.

Harrington, M. W. 1895. Surface currents of the Great Lakes, as deduced from the movements of bottle papers during the seasons of 1892, 1893, and 1894. U. S. Dept. Agric. Weather Bur., Bull. B (rev. edit.), 14 p.

Hasler, A. D. 1947. Eutrophication of lakes by domestic drainage. Ecology 28: 383-395.

Hiltunen, J. K. 1967. Some oligochaetes from Lake Michigan. Trans. Am. Microsc. Soc. 86: 433-454.

_______. 1969a. Invertebrate macrobenthos of western Lake Superior. Michigan Acad. 1: 123-133.

_______. 1969b. The benthic macrofauna of Lake Ontario. Great Lakes Fish. Comm. Tech. Rept. 14: 39-50.

Holmes, R. W. 1968. Description and evaluation of methods for determining incident solar radiation submarine daylight, Chlorophyll a, and primary production, used by Scripps Tuna Oceanography Research Program in the eastern tropical Pacific. U. S. Fish Wildl. Serv., Spec. Sci. Rept.--Fish. No. 564, 31 p.

Howmiller, R. P. 1971. The benthic macrofauna of Green Bay, Lake Michigan. unpubl. Ph.D. dissertation, Univ. Wisconsin, 225 p.

_______ and A. M. Beeton. 1970. The oligochaete fauna of Green Bay, Lake Michigan. Proc. 13th Conf. Great Lakes Res., p. 15-46.

Huh, H. T. 1969. Characteristics of inshore and offshore waters of Lake Michigan at Milwaukee, Wisconsin. unpubl. M.S. thesis, Univ. Wisconsin--Milwaukee, 92 p.

Hutchinson, G. E. 1957. A Treatise on Limnology, Vol. 1, Geography, Physics and Chemistry. John Wiley & Sons, New York, 1015 p.

Johnson, J. H. 1960. Surface currents in Lake Michigan, 1954 and 1955. U. S. Fish Wildl. Serv., Spec. Sci. Rept. --Fish. No. 338, 120 p.

Merna, J. W. 1960. A benthological investigation of Lake Michigan. unpubl. M.S. thesis, Michigan State Univ., 74 p.

Minder, L. 1938. Der Zurichsee als Eutrophierungs-phanom. Geol. Meere Binnengewasser 2: 284-299.

Modlin, R. and A. M. Beeton. 1970. Current studies in Green Bay. Proc. 13th Conf. Great Lakes Res., Int. Ass. Great Lakes Res., 468-476.

Patalas, K. 1969. Composition and horizontal distribution of crustacean plankton in Lake Ontario. J. Fish. Res. Bd. Canada 26: 2135-2164.

_______. 1970. Primary and secondary production in a lake heated by a thermal power plant. Proc. 1970 Am. Tech. Mtg. Inst. Environ. Sci., p. 267-271.

Powers, C. F. and A. Robertson. 1965. Some quantitative aspects of the macro-benthos of Lake Michigan. Great Lakes Res. Div., Univ. Michigan Publ. No. 13, p. 153-159.

_______ and _______. 1967. Design and evaluation of an all-purpose benthos sampler. Univ. Michigan, Great Lakes Res. Div., Spec. Rept. 30: 126-133.

Priegel, G. R. 1970. Food of the white bass, Roccus chrysops, in Lake Winnebago, Wisconsin. Trans. Am. Fish. Soc. 99: 440-443.

Rawson, D. C. 1956. The net plankton of Great Slave Lake. J. Fish. Res. Bd. Canada 13: 53-127.

Robertson, A. and W. P. Alley. 1966. A comparative study of Lake Michigan macrobenthos. Limnol. Oceanogr. 11: 576-583.

_______ and C. F. Powers. 1965. Particulate organic matter in Lake Michigan. Univ. Michigan, Great Lakes Res. Div., Publ. No. 13, p. 175-181.

_______ and _______. 1967. Comparison of the distribution of organic matter in the five Great Lakes. In: J. C. Ayers and D. C. Chandler, Studies on the Environment and Eutrophication of Lake Michigan. Univ. Michigan, Great Lakes Res. Div., Spec. Rept. 30.

Sawyer, C. N. 1947. Fertilization of lakes by agricultural and urban drainage. J. New England Water Works Ass. 61: 109-121.

Schraufnagel, F. H. 1966. Green Bay stream flows and currents. p. 178-182. In: L. P. Voight (Chairman) Lake Michigan Pollution, Governor's Conf. Proc., Nat. Resources Comm., State Agencies, Madison, Wisconsin.

Smith, S. H. 1957. Limnological surveys of the Great Lakes--early and recent. Trans. Am. Fish. Soc. 86: 409-418.

Strickland, J. D. H. 1958. Solar radiation penetrating the ocean: a review of requirements, data and methods of measurement, with particular reference to photosynthetic productivity. J. Fish. Res. Bd. Canada 15: 453-491.

_______ and T. R. Parsons. 1968. A practical handbook of seawater analysis. Fish. Res. Bd. Canada Bull. 167, 311 p.

Surber, E. W. and H. L. Cooley. 1952. Bottom fauna studies of Green Bay, Wisconsin, in relation to pollution. U. S. Publ. Health Serv. and Wisc. State Comm. Water Poll., 7 p. mimeo.

Thomas, E. A. 1965. The eutrophication of lakes and rivers, causes and prevention. Proc., Biol. Prob. in Water Poll., Cincinnati, p. 45.

Torke, B. G. 1971. Cladocera of Lake Michigan in the Milwaukee area. unpubl. M.S. thesis, Univ. Wisconsin--Milwaukee, 24 p.

Tyler, J. E. 1969. Natural water as a monochromator. Limnol. Oceanogr. 48: 102-105.

U. S. Hydrographic Office. 1955. Instruction manual for oceanographic observations. H. O. Publ. No. 607, 210 p.

Verber, J. L. 1964. Initial current studies in Lake Michigan. Limnol. Oceanogr. 9: 426-430.

Wells, L. 1970. Effects of alewife predation on zooplankton populations in Lake Michigan. Limnol. Oceanogr. 15: 556-565.