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**LIMNOLOGICAL SURVEY OF
LAKES MICHIGAN, SUPERIOR, HURON AND ERIE**

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MASTER

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To David C. Chandler,
for his continued dedication to
studies of the Great Lakes

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INTRODUCTION

The St. Lawrence Great Lakes comprise the largest freshwater system on earth. The combined volume of the Great Lakes equals that of Lake Baikal, the world's largest lake in terms of volume; but the combined area of the Great Lakes is 246,000 km² or 8 times the area of Lake Baikal. Lake Superior is the world's largest freshwater lake in area, 82,000 km² (Table 1), more than twice that of Lake Baikal. The five Great Lakes cover an extensive geographic area, from approximately 41°30'N at the southern extremes of Chicago on Lake Michigan and Toledo on Lake Erie to 49°N at the northern boundary of Lake Superior and extending east/west from 76°W at the eastern end of Lake Ontario to 92°W at Duluth at the western end of Lake Superior (Fig. 1). The Great Lakes waterway, from Duluth, Minnesota at the western tip of Lake Superior to the mouth of the St. Lawrence River at the Atlantic Ocean, provides a shipping lane extending for more than 3,000 km.

Limnological research on this immense, and immensely important, natural resource was largely neglected until recently. Smith (1956) and Beeton and Chandler (1963) provided historical reviews of early Great Lakes research efforts. Since 1960, the lakes have been studied more intensively, and accelerated changes in them are now apparent. These changes have been reviewed by Beeton (1961, 1965, 1966, 1969, 1971), Davis (1964), Powers and Robertson (1966) and others. Indeed, today's popular awareness of environmental issues is due in no small part to Great Lakes studies. Words such as "ecology" and "eutrophication" now appear frequently in the popular press. This new ecological consciousness has led to a demand that we "do something" about the Great Lakes.

Any plans to manage the Great Lakes environment must be based on up-to-date and accurate information about existing conditions. Although there are many agencies engaged in Great Lakes research and management, the area to be covered is so large that information is often incomplete, limited either in geographical scope or in number of parameters investigated. Fragmentation of effort has hampered comparison between or among lakes due to a lack of data that are comparable seasonally and methodologically.

The literature contains some notable examples of coordinated and cooperative research efforts which are exceptions to the fragmented approach. Lake Erie studies conducted in 1928-1931 (Wright 1955; Fish et al. 1960) are the earliest examples. Synoptic studies of Lake Huron and Lake Michigan undertaken by the Great Lakes Research Institute, now the Great Lakes Research Division, at the University of Michigan in the late 1950's provided information on currents, water masses and other related limnological data on two lakes (Ayers et al. 1956, 1958). Since 1967, the Canada Centre for Inland Waters has been conducting coordinated research on all the Great Lakes except Lake Michigan, the only lake located entirely within the boundaries of the United States. Project Hypo is a recent example of an intensive coordinated research effort by Canadian and U. S. researchers on the problem of hypolimnetic oxygen depletion in the central basin of Lake Erie (Burns and Ross 1972). By far the most ambitious undertakings to date are investigations on Lake Ontario by scientists from government agencies and universities in Canada and the United States, as part of the International Field Year for the Great Lakes (IFYGL). These investigations, conceived as part of the International Hydrological Decade (1965-1975), were planned to extend from 1 April 1972 to 31 March 1973 and will include hydrological, meteorological, physical, chemical and biological studies (National Oceanic and Atmospheric Administration 1972).

TABLE 1. Morphometric and hydrologic data on the Laurentian Great Lakes^a.

	Lake Superior	Lake Michigan	Lake Huron	Lake St. Clair	Lake Erie	Lake Ontario
1. Length (right line in clear), km	560	490	330	42	385	309
2. Breadth (right line), km	256	188	292	38	91	85
3. Length of coastline in km (including islands) . . .	4,768	2,656	5,088	270	1,369	1,161
4. Areas in km ²						
Water surface, United States.	53,618	58,016	23,569	512	12,898	9,324
Water surface, Canada.	28,749	—	36,001	756	12,768	10,360
Drainage basin land, United States.	43,253	117,845	41,958	7,380	46,620	39,370
Drainage basin land, Canada.	81,585	—	86,500	10,570	12,224	31,080
Drainage basin land, total.	124,838	117,845	128,464	17,948	58,793	70,448
Drainage basin (land & water), total	207,200	175,860	188,034	19,217	87,434	90,132
5. Maximum depth, m	406	281	228	6	60	244
6. Average depth, m	148	84	53	3	17	86
7. Volume of water, km ³	12,221	4,871	3,535	4	458	1,636
8. Mean elevation above sea level, m	183	176	176	175	174	75
9. Average annual precipitation, mm	736	787	787	—	863	863
10. Mean outflow, m ³ /sec	2,067	1,556	—	5,041	5,551	6,627

^aFrom Chandler (1964).

FIG. 1. Map of St. Lawrence Great Lakes depicting areas studied in Lake Superior, Lake Michigan, Lake Huron and Lake Erie.

Our study is unique in that we gathered extensive physical, chemical and biological information with uniform methods from four of the lakes within a 4-week period. Most reports treating the subject of Great Lakes eutrophication have been based on data collected by numerous investigators over several years and lacking uniform methodology. Our data include temperature, transparency, dissolved gasses, pH, alkalinity, major ions, nutrients, chlorophyll, carbon fixation by phytoplankton, phytoplankton, zooplankton and benthos. Our investigations were conducted in the summer of 1970 at 87 stations in Lakes Michigan, Superior, Huron and Erie (Fig. 1) as follows:

Lake Michigan	6 stations	July 7
Lake Superior	35 stations	July 9-12
Lake Huron	26 stations	July 27-30
Lake Erie	20 stations	July 31-August 2

METHODS

Data were collected on two training cruises of the R/V INLAND SEAS (Fig. 2). Students practiced procedures at Douglas Lake, where the Biological Station is located, and performed most of the analyses on water from Douglas Lake and other lakes in the vicinity.

Methods described below have been used routinely by the Great Lakes Research Division (Figs. 3-4).

SAMPLING PROCEDURES

Upon arrival at each station, we measured the water depth with the ship's sounder, made a bathythermograph cast (Fig. 3), and measured the water transparency with a white Secchi disc. We made one or more Nansen bottle casts (Fig. 4), as needed to obtain water samples for analysis. In Lake Erie, water samples were collected with a 17.5-liter horizontal Van Dorn bottle (Fig. 3). Two vertical plankton tows (bottom to surface) were made with half-meter nets, #5 mesh (aperture size $282\ \mu$) for zooplankton, and #20 mesh (aperture size $76\ \mu$) for phytoplankton (Fig. 3). Benthos was collected with a Ponar grab (Powers and Robertson 1967), which sampled an area of $484\ \text{cm}^2$ (Fig. 4); usually three grabs were taken at each station and combined. Plankton and benthos samples were preserved with buffered formalin.

SHIPBOARD ANALYSES

As the ship steamed between stations, we analyzed samples from the previous station. Several tests were made on unfiltered water. These included pH, measured with an AC line-operated Corning Model 12 pH meter; specific conductance corrected to 25°C , measured with an Industrial Instruments Model RC 16B2 bridge; total alkalinity, by titration of 100 ml with $0.020\text{N}\ \text{H}_2\text{SO}_4$, using methyl orange indicator; and dissolved oxygen by titration of 100 ml samples with 0.0050N sodium thiosulfate (Pomeroy-Kirschmann-Alsterberg modification of the Winkler method). Water samples for the determination of dissolved minerals and nutrients were passed through an HA Millipore filter (aperture size $0.45\ \mu$). To prevent contamination of the filtered water we discarded the first 100 ml filtered. Part of the filtered water was placed in a 250-ml polyethylene bottle and frozen for later analysis in the laboratory. Filters were brought back to the laboratory for particulate phosphate determinations.

Analyses for calcium, sulfate, and soluble reactive phosphate were made on shipboard on filtered water. Calcium was measured by titration with Na_2EDTA , using hydroxy naphthol blue as the indicator (Shapiro and Brannock 1962). Sulfate determinations were made turbidimetrically, using Hach Chemical Co. SulfaVer® III pillows, and read on a battery-powered Beckman Spectronic 20 spectrophotometer; calibration curves were made for each lake or lake area. Soluble reactive phosphorus was measured by combining methods from Stephens (1963) and Murphy and Riley (1962).

The chlorophyll *a* extraction procedure followed Strickland and Parsons (1968); 500-2000 ml of lake water was filtered, depending upon the amount of phytoplankton present. The extraction vials were stored in a dark refrigerator

FIG. 2. R/V INLAND SEAS.

FIG. 3. Sampling procedures and equipment
A. Bathythermograph
B. Half-meter plankton net
C. Van Dorn bottle and Ponar grab

FIG. 4. Sampling procedures and equipment on the "hero board"
A. Setting Nansen bottle
B. Preparing to dump sediment sample from Ponar grab
C. Removing Nansen bottle

for processing ashore. Primary production was measured with C-14 according to the procedures given by Schelske and Callender (1970). Inoculated 260-ml bottles were maintained at reduced light intensities in a shipboard daylight incubator at surface water temperature for 4 to 6 hours, after which the water was filtered, and the filters were cemented to aluminum planchets for later counting ashore.

Grab samples of sediments were examined and briefly described; then the benthos was removed with an elutriation-screening device, the "critter catcher" (Powers and Robertson 1965); it was equipped with a 760 μ mesh nylon screen.

During the cruises, the seven students were rotated among three work areas. To insure continuity of procedures and methods at least one student remained at an area for two consecutive days. On the first day the new student learned the procedure from the person who had been there the day previously and on the second day was responsible for the area's activities and for training a new person.

LABORATORY ANALYSES

With the exception of the particulate phosphate analyses, which were made in the Great Lakes Research Division laboratory in Ann Arbor several months after the cruises according to the procedure given by Schelske and Stoermer (1972), all laboratory analyses were made a few days after the cruises at the University of Michigan Biological Station.

A Technicon AutoAnalyzer was used to measure silica, nitrate, and ammonia colorimetrically (Schelske and Callender 1970) and to measure chloride using mercuric thiocyanate and ferric ammonium sulfate (Technicon Industrial Method 11-68W). Filters for C-14 productivity were counted on a Nuclear Chicago planchet counting system Model 4338, and rates of carbon fixation were calculated as described by Saunders, Trama and Bachmann (1962). Absorbance of chlorophyll samples was measured in 2.5-cm diameter tubes on a Beckman Spectronic 20 spectrophotometer, and concentrations of chlorophyll were determined with the Strickland and Parsons (1968) formula. We calculated the photosynthetic assimilation ratio by dividing rates of carbon fixation by chlorophyll standing crops at all stations where both parameters were measured at the same depth.

Identification of phytoplankton was limited to the generic level due to the inexperienced personnel. With the limited time available for the compilation of results, it would not have been possible to train people to identify phytoplankton at the species level. Even generic identification would have been difficult without the assistance of a phycologist experienced with Great Lakes phytoplankton. Smaller forms (nannoplankton) were not adequately treated, since the net size used precluded their quantitative capture and the samples were examined at only ca. 500X magnification.

The abundance of phytoplankton genera was not determined quantitatively due to the large numbers of samples which were processed in a relatively short time. Relative estimates of abundance were made subjectively, however, for three categories. The most abundant group of genera was designated "abundant," the next most abundant category was designated "common," and if a genus was neither abundant nor common it was recorded as an occurrence.

Zooplankton samples were examined qualitatively at the generic level, to determine the dominant forms at each station. Genera were scored on an arbitrary scale from 5-1, the lower numbers indicating increasing rarity. Zooplankton volumes were measured after settling each sample overnight in a graduated centrifuge tube.

The relatively large mesh size of our net retained only the larger forms, so that most rotifers, virtually all copepod nauplii and some adults (e.g., *Tropocyclops*) were unsampled. We have expressed the quantitative results as milliliters of settled volume per volume of water column sampled (ml/m^3). To do this we have made two assumptions. First, we have assumed that the net did not clog, so that the volume sampled was equal to the area of the net opening times the length of the tow. Second, in basing the data on volume of water sampled, we assumed that the organisms were uniformly distributed with respect to depth. This second assumption is almost certainly not satisfied, and we have undoubtedly introduced a bias in favor of the shallower stations. Nevertheless, these data permit a basis for crude, but surprisingly distinct, comparisons between lakes and lake zones. Depths for each station are given, so the settled volumes of zooplankton can be calculated as ml/m^2 .

Benthos samples were placed in white enamel pans, and the organisms were separated from any remaining debris. The number of animals in each group was recorded; identifications were usually made to the family level, except for the Crustacea, which were identified to genus. Benthos counts were expressed as the number of animals/ m^2 .

PRESENTATION AND ORGANIZATION

Cruise results with a discussion section are presented in separate chapters for each of the four lakes. Lengths of the discussion sections for the different lakes vary depending primarily on availability of related studies in the literature. Discussion of the Great Lakes in general and comparisons among the lakes are deferred to the final chapter on "Comparison of Lakes." The final chapter also includes general conclusions and a section on the general interpretation and significance of our results.

Data gathered during the study have been summarized in tables and figures from data presented in Appendix Tables. References to the Appendix Tables are not cited in the presentation of data, but for the interested reader the primary data are presented as follows in eight tables: station locations and depths (Appendix Table A), physical and chemical data (Appendix Tables B, C), carbon fixation rates (Appendix Table D), phytoplankton (Appendix Table E), zooplankton (Appendix Table F), sediment descriptions (Appendix Table G), and benthos (Appendix Table H).

We used means and standard deviations to evaluate the need for further data reduction. For example, we determined the mean and standard deviation for chemical measurements of parameters in each lake. If this exercise resulted in a large standard deviation, we separated the data into other groups, either by depth or geographical location. In Lake Michigan the standard deviations could be minimized by separation into depth strata, but in Lake Huron and Lake Erie separation by depths and zones was necessary.

LAKE MICHIGAN

On July 7 we sampled six stations in northern Lake Michigan, located on a line passing east of the Manitou Islands from Frankfort, Mich., to Beaver Island (Fig. 5). Four of the six stations were less than 45 m deep; only Stations 4 and 5 were over 100 m deep. Usually about five depths were sampled, including surface and bottom at each station. Since depths of sampling were selected on the basis of temperature distribution, the same depths were not sampled at each station. It is thus expedient to consider the average values within each of the following depth ranges: surface, 2-15 m, 20-30 m, 40 m, and 110-125 m. All six stations are treated together since between-station trends were not apparent.

PHYSICAL-CHEMICAL ASPECTS

The Lake Michigan basin is composed of easily weathered bedrock and glacial deposits which give rise to well-buffered, calcareous waters. The water was fairly alkaline in reaction, mean pH 8.5 (Table 2). Total alkalinity averaged

TABLE 2. Lake Michigan environmental factors (all depths). Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Transparency, m	4.8 $\pm$ 0.6	(6)
Dissolved oxygen, ppm	10.4 $\pm$ 1.2	(10)
pH	8.50 $\pm$ 0.16	(19)
Alkalinity, ppm	109 $\pm$ 2.8	(19)
Calcium, ppm	37.4 $\pm$ 1.6	(17)
Chloride, ppm	7.22 $\pm$ 0.32	(16)
Sulfate, ppm	15.5 $\pm$ 3.0	(17)
Specific conductance, μ mhos @ 25°C ^a	261	(1)
Chlorophyll <i>a</i> , mg/m ³	1.34 $\pm$ 0.62	(7)
Carbon fixation, mg C/m ³ /hr	2.40 $\pm$ 0.82	(13)
Assimilation ratio @ 0m, mg C/hr/mg Chl <i>a</i> ^b	0.74	(1)

^aOne surface determination at the Mackinaw City dock, July 8.

^bOne surface determination at Station 3.

109 ppm; dissolved calcium averaged 37.4 ppm. Conductivity measurements were not made on the Lake Michigan stations, but a surface reading of 261 μ mhos (corrected to 25°C) was taken near the Mackinaw City dock.

Thermal stratification was well established in the area sampled. Surface temperatures ranged from 12.5-16.0°C, and the epilimnion extended to a depth of about 30 m (Fig. 6). The vertical distribution of dissolved oxygen was the familiar orthograde type associated with deep, unproductive lakes (Hutchinson 1957). Major ion chemistry, however, can be characterized by mean values summed over all depths (Table 2).

FIG. 5. Lake Michigan sampling area showing locations of six stations.

FIG. 6. Lake Michigan temperature, dissolved oxygen, silica, nitrate nitrogen, ammonia nitrogen, soluble reactive phosphate and particulate phosphate. Curves depict means with error bars representing $\pm$ one standard deviation.

In contrast to the major ions (Table 2) concentrations of some nutrients (Table 3) were reduced in the epilimnetic waters due to utilization by phytoplankton. The silica distribution (Fig. 6) shows a striking depletion in the epilimnion, most values being between 0.3 and 0.5 ppm, a threefold decrease from the deepwater values of ca. 1.3 ppm. Concentration of nitrate nitrogen in the epilimnetic layer averaged 130 ppb, about one-third smaller than bottom values. Concentrations of ammonia nitrogen were also less in the epilimnion than in the deeper waters, but the difference, if significant, may have been due to production in the deeper waters instead of increased utilization in the surface waters.

Phosphorus data were quite variable; however, soluble reactive phosphate concentrations were low, ranging from near the lower limit of detectability (ca. 0.5 ppb, as PO_4) to 12.0 ppb. Mean values were around 5 ppb (Fig. 6); the apparent metalimnetic minimum may not be significant, in view of the large variability between determinations. Particulate (sestonic) phosphate values were several times greater than the soluble reactive phosphate. The large average for 40 m is due to one unusually high value of 95.3 ppb; it is possible that this sample was contaminated. If this anomalous point is disregarded, the curve would follow the dotted line. In either case there appears to be a metalimnetic maximum in sestonic phosphorus.

Transparency measurements indicated moderate amounts of suspended materials and standing crops of phytoplankton for the Great Lakes. Secchi disc limits of visibility ranged from 4.0-5.5 m (Table 2).

BIOLOGICAL ASPECTS

Chlorophyll *a* concentrations (based on epilimnetic samples, usually from the surface) averaged 1.86 ppb at the shallow-water stations, and 0.95 at the two deep stations (4 and 5). The mean of all determinations was 1.34 ppb (Table 2).

Carbon fixation rates at Stations 1-4 averaged $2.40 \text{ mg C/m}^3/\text{hr}$ (Table 2). There were no important differences between carbon fixation rates in water from the depths sampled (usually surface and 3 m), so all depths are considered together. Most of the values were between 2.0 and $3.0 \text{ mg C/m}^3/\text{hr}$, except at Station 4, a deepwater station, where two trials averaged $0.86 \text{ mg C/m}^3/\text{hr}$. Also at Station 4, we measured carbon fixation rates on water brought up from 125 m; rates obtained in two bottles were 1.93 and $1.92 \text{ mg C/m}^3/\text{hr}$, over twice the rate at 10 m. We found a similar high potential productivity (and chloro-

TABLE 3. Lake Michigan silica, nitrate nitrogen, ammonia nitrogen, soluble reactive phosphate and particulate phosphate. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Depth m	SiO ₂ ppm	NO ₃ -N ppb	NH ₃ -N ppb	Sol. PO ₄ ppb	Part. PO ₄ ppb
All	0.51 $\pm$ 0.38 (17)	147 $\pm$ 24 (16)	18 $\pm$ 6.4 (16)	5.2 $\pm$ 3.5 (16)	18 $\pm$ 23 (14)
Surface	0.27 $\pm$ 0.05 (4)	129 $\pm$ 6.0 (4)	15 $\pm$ 10 (4)	5.0 $\pm$ 2.8 (4)	8.4 $\pm$ 10 (2)
2 - 15	0.29 $\pm$ 0.08 (5)	131 $\pm$ 12 (4)	17 $\pm$ 2.8 (4)	6.0 $\pm$ 1.2 (4)	9.5 $\pm$ 9.5 (4)
20 - 30	0.40 $\pm$ 0.12 (4)	147 $\pm$ 6.0 (4)	15 $\pm$ 5.5 (4)	4.8 $\pm$ 5.2 (4)	15 $\pm$ 4.5 (4)
40	0.99 $\pm$ 0.01 (2)	175 $\pm$ 1.4 (2)	23 $\pm$ 0.0 (2)	4.0 $\pm$ 4.2 (2)	55 $\pm$ 57 (2)
110-125	1.28 $\pm$ 0.08 (2)	190 $\pm$ 4.2 (2)	23 $\pm$ 3.5 (2)	6.0 $\pm$ 7.1 (2)	12 $\pm$ 0.49 (2)

phyll concentration) in samples collected below the euphotic zone in Lake Superior.

At Station 3 we sampled chlorophyll and carbon fixation in surface samples. The ratio of carbon fixation to chlorophyll standing crop was 0.74 mg C/hr/mg Chl *a*, reflecting a phosphate-poor, but nitrate-rich condition (see p. 70).

Twenty-four genera of phytoplankton were identified. Three genera, *Asterionella*, *Tabellaria*, and *Fragilaria* dominated the phytoplankton assemblage, and three other genera of diatoms, *Synedra*, *Melosira*, and *Rhizosolenia*, were common at most of the stations. At Station 3, the blue-green alga, *Anabaena*, was the most abundant genus. *Dinobryon*, a chrysophycean genus, was common at all stations except Station 3. Settled volumes of zooplankton averaged ca. 2 ml/m³, ranging from over 4 ml/m³ at shallow Station 2, to 0.37 ml/m³ at Station 5. Qualitatively, the zooplankton was dominated by three genera: the small cladoceran, *Bosmina*, and the copepods *Diaptomus* (Calanoida) and *Cyclops* (Cyclopoida). *Bosmina* was dominant or co-dominant at every station. Three other genera were of lesser importance. They were the large cladoceran, *Daphnia*, which occurred at most stations, and the rotifers *Asplanchna* and *Kellicottia* of which each occurred at one station. *Kellicottia* is very small, and certainly was not quantitatively collected with our #5 net; it may have been more common than our collections reveal.

Bottom sediments were sandy at the shallow stations and silty at the deeper ones. Total counts of bottom fauna were highest, 5000-6000 individuals/m² at mid-depth stations (Station 1, medium sand, 43 m; Station 3, sandy silt, 37 m), and only a third to half as high at the deeper stations. Only 800 organisms/m² were found in the shallow and sandy sediments of Station 6 (13 m deep).

The benthic fauna was numerically dominated by *Pontoporeia*, an amphipod crustacean characteristic of the Great Lakes, which accounted for 58-86% of the total fauna at all stations except Station 6. The balance was made up of oligochaete annelids (6-31%), sphaeriid clams (5-13%), and chironomid larvae (0-3%). A few nematodes and coleopterous larvae were found as well. At shallow Station 6, the fauna was quite different. Oligochaetes were nearly 60% of the total, and most of the remainder was made up of chironomid larvae (19%) and snails (18%). *Pontoporeia* was relatively rare (1.8%), as were sphaeriids (3%).

DISCUSSION

Ayers, Stoermer and McWilliam (1967) summarized Secchi disc transparencies observed by various investigators from 1954-1966. At their stations, mainly in the southern basin—where transparencies were less than in the northern basin—the annual mean values for all offshore stations and seasons ranged between 5.7 and 7.9 m. Maxima ranged from 8.8 to 18.3 m. Only 14-42% of the observations were less than 5.1 m. At our six northern basin stations, five were in the range 4-5 m, and only one was over 5.1 m (5.5 m at Station 5). This may indicate reduced transparency in the intervening years, but firm conclusions cannot be made on data so limited in time and area.

Although our stations were all located in a small section of the northern basin, our results are in reasonable agreement with recent summaries of Lake Michigan chemistry (e.g., Weiler and Chawla 1969; Beeton 1971). These authors concluded that recent increases in chloride and sulfate levels are due to human activities. Our sulfate data do not show any increase over levels found in 1960-1964, but our mean chloride concentration of 7.2 ppm (Table 2) is 10-16% higher than averages given by Beeton (6.5 ppm) and Weiler and Chawla (6.2 ppm). Unpublished chloride data for the northern basin obtained by the Great Lakes Re-

search Division in 1969 and 1970 range from 7-8 ppm, similar to 1966 values reported for the Milwaukee water intake (Beeton 1969). Chloride concentrations increased rapidly at Milwaukee from about 1950 to 1966. Our data indicate that the increase is not an anomaly associated with sampling nearshore waters, but is general over the lake basin.

Summertime values for surface pH (Table 2) are also much higher than the commonly cited average of 8.0 from Beeton and Chandler (1963). Data for the open lake, exclusive of inshore stations, averaged 8.5 in 1969, and at inshore stations in the southern basin pH ranged from 8.7-8.9 (Schelske and Callender 1970). Recent studies have led to the generalization:

Accelerated eutrophication stimulated by pollution inputs is causing silica depletion in the surface waters of Lake Michigan during summer stagnation. Limitation of the reproduction of the presently dominant phytoplankton organisms [diatoms], which require silica, may lead to drastic and, on the whole, undesirable changes in the ecosystem.

(Schelske and Stoermer 1971.)

These conclusions are corroborated by our silica data (Table 4).

TABLE 4. Comparison of data on silica, nitrate nitrogen, ammonia nitrogen, transparency and carbon fixation for stations in northern Lake Michigan. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Schelske and Callender (1970) 15-23 August 1969 ^a		This Study 7 July 1970	
SiO ₂				
Surface, ppm	0.22 $\pm$	0.03 (4)	0.27 $\pm$	0.05 (4)
Bottom, ppm	1.43 $\pm$	0.13 (3)	1.14 $\pm$	0.18 (4) ^b
NO ₃ -N				
Surface, ppb	115 $\pm$	4 (4)	129 $\pm$	6 (4)
Bottom, ppb	233 $\pm$	23 (3)	183 $\pm$	9 (4) ^b
NH ₃ -N				
Surface, ppb	22 $\pm$	8 (4)	15 $\pm$	10 (4)
Bottom, ppb	18 $\pm$	11 (3)	23 $\pm$	2.1 (4) ^b
Transparency, m	7.75 $\pm$	1.0 (4)	4.75 $\pm$	0.61 (6)
Carbon fixation mg C/m ³ /hr	3.35 $\pm$	2.17 (3)	2.29 $\pm$	0.77 (8)

^aStations 21, 23, 51, 53.

^bExcluding the two shallow stations.

Four of the stations sampled by Schelske and Callender were located in the same general area we studied, and can be compared directly to our data on dissolved nutrients, transparency, and carbon fixation rates (Table 4). Silica and nitrate are slightly more depleted in surface samples than in our 1970 samples, but in 1969 data were collected 5-6 weeks later. The mean carbon fixation rate reported by Schelske and Callender is higher than ours, but this is due to one observation of 5.85 mg C/m³/hr at Station 51; they found 1.89 and 2.31 mg C/m³/hr at Stations 21 and 23, in closer agreement with our measurements. Parkos, Olson and Odlaug (1969) made carbon fixation measure-

ments in 1967, and three of their stations (18-20) are spatially and temporally comparable to our stations. They found 2.91 ± 1.49 mg C/m³/hr, slightly higher and more variable than our values. Comparable photosynthetic results were obtained with a shipboard technique on a car ferry running between Milwaukee, Wisc. and Ludington, Mich. and were used to develop a model to estimate integral photosynthesis (Fee 1971).

Historically, the phytoplankton of Lake Michigan has been dominated by diatoms. As H. D. Thompson stated (in Ward 1896b): "The Diatomaceae greatly outnumbering all other plants both as to species and individuals, force themselves constantly upon the attention of the botanist." In examining collections from 1930 and 1931, Ahlstrom (1936) concluded that "the plankton of Lake Michigan is dominated by diatoms at all seasons." In 1962 and 1963 Stoermer (1967), resampling Ahlstrom's stations, and Stoermer and Kopczynska (1967) found that in terms of number of cells, diatoms were the most abundant phytoplankton. Until very recently, Griffith (1955) was the only author to report a predominance of anything but diatoms in the phytoplankton; but these samples collected from a pier at Evanston, Ill. would not represent conditions in the open lake. During the autumn of 1969 the offshore phytoplankton had a greater proportion of greens and blue-greens than earlier in the summer, and in terms of cell counts was not dominated by diatoms (Schelske, Stoermer and Feldt 1971).

Eutrophication of Lake Michigan has been documented from studies of both standing crop and changes in species composition of phytoplankton. Damann (1960) studied phytoplankton collected from 1926-1958 at the Chicago water intake and found an increase in standing crop of 13 ± 4.6 organisms/ml/yr. Stoermer and Yang (1970) found evidences for eutrophication in changes in species composition of diatoms. Diatoms indicative of eutrophic conditions occur more frequently near shore and in harbors than in offshore waters (Holland and Beeton 1972; Stoermer and Yang 1969). Holland (1968) has associated different species of *Melosira* with varying trophic conditions, ranging from eutrophic in Green Bay to the more oligotrophic conditions in the open lake.

Recent changes in the Lake Michigan zooplankton composition have been documented by Wells (1960, 1970) and Gannon (1972a, 1972b). Wells showed that between 1954-1955 and 1966 size-selective predation by planktivorous alewives (*Alosa pseudoharengus*) caused a decline in the numbers of large species (*Leptodora kindtii*, *Daphnia galeata mendotae*, *D. retrocurva*, *Limnocalanus macrurus*, *Epischura lacustris*, *Diaptomus sicilis*, and *Mesocyclops edax*) which was accompanied by an increase in several smaller species (*Daphnia longiremis*, *Holopedium gibberum*, *Polyphemus pediculus*, *Bosmina longirostris*, *B. coregoni*, *Ceriodaphnia* sp., *Cyclops bicuspidatus*, *C. vernalis*, and *Diaptomus ashlandi*). After a massive alewife dieoff in 1967, the 1968 zooplankton partly returned to the pre-alewife assemblage. Gannon's studies also showed that an increase in smaller species is associated with accelerated eutrophication and that the effects of alewife predation are not easily separated from those concomitant with advancing eutrophication. Our zooplankton collections were dominated by small and medium-sized forms (*Bosmina*, *Cyclops*, *Diaptomus*). We found no *Leptodora*, *Limnocalanus* or *Mesocyclops*, larger genera which Wells found near Frankfort, Michigan in 1955 (his 1966 and 1968 samples were taken in southern Lake Michigan near Grand Haven). However, our 1970 samples are few and mostly from shallow areas where *Limnocalanus* is scarce in summer (Gannon 1972b).

Changes in Lake Michigan bottom fauna between 1931-1932 (Eggleton 1936, 1937) and 1964 were documented by Robertson and Alley (1966). Although the fauna was dominated by the same groups (*Pontoporeia*, oligochaetes and sphae-

riids), all three increased in abundance between 1931-1932 and 1964. *Pontoporeia* was most abundant at ca. 40-m depth in both studies. Robertson and Alley sampled mainly in the southern basin; however, their Station E-1 was also comparable seasonally and by depth to two of our stations (Table 5). The close

TABLE 5. Comparison of data on abundance of *Pontoporeia*, oligochaetes, sphaeriids (number/m²) at stations in northern Lake Michigan.

	Station	Date	Depth	Number/m ²		
				Pont.	Olig.	Spha.
This study	LM70-1	9 July 1970	42.7 m	3818	1101	275
	LM70-3	9 July 1970	37.2 m	3474	1858	502
Robertson and Alley (1966)	E-1	14 July 1964	46.0 m	3700	905	335

agreement between the two sets of stations may be fortuitous; indeed, firm conclusions cannot be made on the basis of so little data. But these data are consistent with the hypothesis that the bottom fauna in this part of the lake has not changed qualitatively nor quantitatively between 1964 and 1970.

Our Lake Michigan findings may be summarized as follows:

1. In the past decade, chlorides may have increased from 10-16%, and pH is obviously greater than the commonly cited value of 8.0.
2. Silica is depleted to less than 0.3 ppm in near-surface waters in summer, and succession to a phytoplankton flora with smaller proportions of diatoms is likely if this trend continues.
3. Recently observed size frequency changes in southern basin zooplankton composition also occurred in the northern basin.
4. No changes in the bottom fauna were apparent in the last 6 years.

LAKE SUPERIOR

Thirty-five stations were sampled in Lake Superior during four days, July 9-12 (Fig. 7). Beginning in Goulais Bay, we sampled four stations in Whitefish Bay and six in the open lake on a line to Michipicoten Island, passing east of Caribou Island. On the second day, eight stations were visited between Michipicoten Island and Copper Harbor. On the third day we covered seven stations, from the Keweenaw Peninsula passing near Stannard Rock to the lake's deepest sounding of 400 m near Station 28, then southward to Munising. The fourth day, we sampled nine stations along the southern shore of the lake, from off Grand Portal Point to Whitefish Point. From three to five depths (usually four) were sampled at each station; these always included surface and bottom samples. Intermediate depths usually included one or two epilimnetic samples.

Most of the data are characterized by a monotonous uniformity of conditions, both between stations and vertically. For some parameters data from the open lake and data from Whitefish Bay and Munising Harbor were sufficiently distinct to establish two separate zones. When vertical distribution of variables is discussed, data have been grouped according to depth ranges: surface, 3-25 m; 30-60 m; 72-390 m.

PHYSICAL-CHEMICAL ASPECTS

Lake Superior was in limnological spring during our cruise, as evidenced by the presence of the thermal bar. The thermal bar is a phenomenon peculiar to large lakes, and although it has been observed in the Great Lakes (Rodgers 1965), few observations have been made in Lake Superior. The thermal bar, an area of downwelling water at maximum density (near 4°C), separates shallow inshore water which is warmer than 4°C from the deeper offshore water which is colder than 4°C. The inshore waters may be stratified, while the offshore waters remain homothermous. In the spring the thermal bar forms as the shallow, nearshore waters (perhaps including warm runoff water) heat to above 4°C before the deeper, central regions. As spring progresses, the cold zone enclosed by the thermal bar contracts lakeward.

When present, the thermal bar acts as a barrier to the exchange of water between the inshore and offshore water masses (Huang 1972). Mixing between the two water masses occurs in the area of downwelling where the inshore water is cooled and the offshore water warmed to 4°C. "The thermal bar, when it is close to shore in spring, appears to impound runoff and probably limits the dissipation of 'pollution' injected into the zone between the shore and the thermal bar" (Rodgers 1965). A thermal bar may also be present in the fall when the shallow inshore waters cool more rapidly than offshore waters.

Several of our stations had surface temperatures of less than 4°C, and therefore were lakeward of the thermal bar (Fig. 7). On the first day we passed near the thermal bar at Stations 7 and 10 (Fig. 8A); on the second, after leaving Michipicoten Island, the first five stations sampled were on the lakeward side of the thermal bar, which we crossed between Stations 19 and 20 (Fig. 8B). We again approached the bar at Station 28 on the third day (Fig. 8C); our course on the fourth day (Fig. 8D) was entirely on the shoreward side of the bar.

FIG. 7. Lake Superior sampling area showing locations of 35 stations. Approximate limits of the thermal bar on 9-12 July 1970 are indicated by the broken line.

FIG. 8. Vertical distribution of isotherms (°C) on cruise tracks for 4 days of sampling in Lake Superior. Distance between stations and station number are given at the bottom of plot for each day's course. Note: Not all cruise tracks were straight lines (See Fig. 7).

Chemical results obtained can be related to the relative insolubility of the Canadian Shield rock, which comprises a large part of the drainage basin. Insolubility of the granite rocks is reflected by the average total alkalinity (43.5 ppm) and calcium concentrations (14.5 ppm, Table 6), both less than half the

TABLE 6. Lake Superior alkalinity, pH, and calcium (all stations). Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Depths	Alkalinity ppm	pH	Calcium ppm
All	43.5 $\pm$ 2.0 (104)	8.03 $\pm$ 0.14 (106)	14.5 $\pm$ 1.5 (83)
Surface	43.5 $\pm$ 1.9 (30)	8.06 $\pm$ 0.10 (30)	14.2 $\pm$ 1.7 (29)
3 - 25 m	42.9 $\pm$ 2.2 (42)	8.05 $\pm$ 0.19 (43)	14.9 $\pm$ 1.2 (23)
30 - 60 m	44.5 $\pm$ 2.1 (8)	8.01 $\pm$ 0.09 (8)	13.9 $\pm$ 2.4 (6)
72 - 390 m	44.2 $\pm$ 1.5 (24)	7.96 $\pm$ 0.06 (25)	14.7 $\pm$ 1.1 (25)

Lake Michigan averages (Table 2). The water, as would be expected, is not as highly buffered as Lake Michigan waters with 106 pH measurements having a mean and standard deviation of 8.03 $\pm$ 0.14.

In Whitefish Bay and Munising Harbor, average concentrations of chloride and sulfate were significantly higher than in the open lake (Table 7). The

TABLE 7. Lake Superior chloride and sulfate. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Depths	Open lake stations	Whitefish Bay and Munising Harbor	t-value
Chloride, ppm			
All	1.06 $\pm$ 0.08 (70)	1.13 $\pm$ 0.10 (15)	2.77 ^a
Surface	1.06 $\pm$ 0.08 (25)	1.24 $\pm$ 0.09 (5)	4.40 ^a
3 - 25 m	1.07 $\pm$ 0.08 (16)	1.09 $\pm$ 0.04 (8)	-
30 - 60 m	1.10 $\pm$ 0.09 (6)		-
72 - 390 m	1.04 $\pm$ 0.07 (23)	1.05 $\pm$ 0.07 (2)	-
Sulfate, ppm			
All	1.46 $\pm$ 0.41 (57)	1.85 $\pm$ 0.49 (13)	3.00 ^a
Surface	1.46 $\pm$ 0.41 (23)	2.10 $\pm$ 0.65 (4)	2.91 ^a
3 - 25 m	1.48 $\pm$ 0.39 (12)	1.74 $\pm$ 0.46 (7)	1.20
30 - 60 m	1.54 $\pm$ 0.54 (5)		-
72 - 390 m	1.42 $\pm$ 0.41 (17)	1.75 $\pm$ 0.21 (2)	1.07

^aSignificant difference at the 95% level.

greatest differences occurred in surface waters. The larger concentrations are probably attributable to inputs of pollutants which are maintained in the relatively warmer surface waters of Whitefish Bay and Munising Harbor. For the open lake stations, the mean surface temperature was 8.4°C, but the mean surface temperature in Whitefish Bay and Munising Harbor was 14.1°C. Amounts of these pollutants were too small to affect specific conductance since there

was no significant difference between the two groups of stations (Table 8).

Secchi disc transparency at the bay stations was ca. 6.6 m, about half the open lake average of 12.6 m (Table 8).

TABLE 8. Lake Superior conductivity, transparency, carbon fixation, chlorophyll and photosynthetic assimilation ratio (all depths). Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Open lake stations	Whitefish Bay and Munising Harbor	t-value
Specific conductance, μmho at 25°C	95 $\pm$ 4.8 (30)	93 $\pm$ 3.0 (5)	.915
Transparency, m	12.6 $\pm$ 3.4 (30)	6.6 $\pm$ 1.1 (5)	3.93 ^d
Carbon fixation, mg C/m ³ /hr	0.37 $\pm$ 0.18 (67) ^a	0.59 $\pm$ 0.14 (15) ^b	4.45 ^d
Chlorophyll <i>a</i> , mg/m ³	0.66 $\pm$ 0.42 (27) ^c	1.46 $\pm$ 0.19 (5)	15.5 ^d
Assimilation ratio, mg C/hr/mg Chl <i>a</i>	0.82 $\pm$ 0.45 (15)		

^aDoes not include observations at Station 7 for 60, 120 and 180 m.

^bWhitefish Bay only.

^cIncludes measurements at Station 7 for 60, 120 and 180 m.

^dSignificant difference at the 95% level.

Vertical distribution of dissolved oxygen in the open lake and the bays was orthograde, with values near saturation or in some cases supersaturated at all depths (Table 9, Fig. 9). Lower oxygen values in the upper waters of the bays were caused by decreased solubility due to warmer water.

Silica in the open lake was uniformly distributed vertically, averaging 2.28 ppm (Table 9, Fig. 9). Silica in the deep water of the bays was comparable to lake values, but near-surface silica levels were about 0.15-0.20 ppm less, probably indicating utilization by diatoms in the epilimnion.

A similar situation is apparent with nitrate nitrogen. Open lake nitrate concentrations averaged 256 ppb, comparable to deep-water concentrations in the bays; but near-surface nitrate concentrations in the bays were 20-30 ppb less (Table 9, Fig. 9).

Ammonia concentrations in the open lake averaged 8.4 ppb; concentrations in the bays were higher, averaging 15 ppb (Table 9, Fig. 9). The high average surface value for the bays is due to an observation of 69 ppb in Munising Harbor, which probably resulted from cultural influents in the Munising area.

We did not obtain reliable particulate phosphorus data in Lake Superior. However, Schelske et al. (1972) measured Lake Superior phosphates in 1971. Concentrations of total phosphate averaged $9.9 \pm 5.4 \mu\text{g PO}_4/1$ for surface samples and $7.2 \pm 4.2 \mu\text{g PO}_4/1$ for bottom samples at 21 stations occupied in the eastern basin. Larger values were found at a station near Freda, north and west of Houghton, where the total phosphate averaged $23 \pm 5.4 \mu\text{g PO}_4/1$ for 10 samples taken on six different days. Dobson¹ also reported small concentrations of total phosphorus in open lake samples with a weighted mean average of $9.6 \mu\text{g PO}_4/1$ for 988 measurements taken during 1970 and 1971. The weighted mean for 219 surface samples was $10.2 \mu\text{g PO}_4/1$.

BIOLOGICAL ASPECTS

Chlorophyll *a* concentrations in near-surface samples for the open lake were generally low, around 0.5 ppb or less, with occasional values up to 1.4

¹Dobson, H. 1972. Nutrients in Lake Superior. Unpublished Report. Canada Centre for Inland Waters. 68 p.

TABLE 9. Lake Superior dissolved oxygen and nutrients. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Depths	Dissolved oxygen ppm	SiO ₂ ppm	NO ₃ -N ppb	NH ₃ -N ppb	Sol. PO ₄ ppb
OPEN LAKE STATIONS					
All	12.7 $\pm$ 0.70 (70)	2.28 $\pm$ 0.13 (70)	256 $\pm$ 13 (69)	8.4 $\pm$ 3.9 (67)	1.7 $\pm$ 1.4 (37)
Surface	12.5 $\pm$ 0.87 (20)	2.28 $\pm$ 0.07 (25)	254 $\pm$ 14 (25)	8.8 $\pm$ 3.2 (24)	1.2 $\pm$ 0.4 (14)
3 - 25 m	12.6 $\pm$ 0.62 (24)	2.28 $\pm$ 0.06 (16)	249 $\pm$ 12 (15)	6.7 $\pm$ 2.0 (15)	1.9 $\pm$ 1.4 (4)
30 - 60 m	12.8 $\pm$ 0.68 (6)	2.32 $\pm$ 0.04 (6)	256 $\pm$ 10 (6)	9.2 $\pm$ 6.4 (5)	1.3 $\pm$ 0.6 (3)
72 - 390 m	13.1 $\pm$ 0.46 (20)	2.28 $\pm$ 0.21 (23)	264 $\pm$ 7.7 (23)	8.9 $\pm$ 4.9 (23)	2.1 $\pm$ 1.8 (16)
WHITEFISH BAY AND MUNISING HARBOR					
All	11.7 $\pm$ 0.86 (10)	2.15 $\pm$ 0.12 (15)	239 $\pm$ 13 (15)	15 $\pm$ 15 (15)	2.8 $\pm$ 1.9 (12)
Surface	10.8 $\pm$ 0.21 (4)	2.10 $\pm$ 0.13 (5)	229 $\pm$ 11 (5)	22 $\pm$ 26 (5)	3.4 $\pm$ 1.5 (5)
3 - 25 m	12.1 $\pm$ 0.37 (5)	2.15 $\pm$ 0.10 (8)	239 $\pm$ 7.6 (8)	11 $\pm$ 2.6 (8)	1.8 $\pm$ 1.8 (5)
30 - 60 m					
72 - 390 m	13.2 (1)	2.31 $\pm$ 0.01 (2)	263 $\pm$ 2.1 (2)	13 $\pm$ 2.1 (2)	4.0 $\pm$ 2.8 (2)

FIG. 9. Lake Superior dissolved oxygen, silica, nitrate nitrogen and ammonia nitrogen. Curves depict means with error bars representing $\pm$ one standard deviation. Top: open-lake stations; bottom: Whitefish Bay and Munising Harbor.

suggesting light inhibition in the surface flora. But these differences were small, and in the following discussion all the observations at each station, except Station 7, were averaged. Open lake stations had very low photosynthetic activity with a mean carbon fixation rate of $0.37 \text{ mg C/m}^3/\text{hr}$ (Table 8). No observation exceeded $1.0 \text{ mg C/m}^3/\text{hr}$, and many values were less than $0.2 \text{ mg C/m}^3/\text{hr}$. Stations in Whitefish Bay had somewhat higher photosynthetic activity, averaging $0.59 \text{ mg C/m}^3/\text{hr}$, about 50 per cent greater than the open lake mean. Bay values ranged between 0.41 and $0.93 \text{ mg C/m}^3/\text{hr}$. Carbon fixation rates appeared to increase with depth (Fig. 10) which indicates that the increased chlorophyll noted at great depths represents not algal detritus, but, at least in part, viable algal cells.

It was possible to calculate the photosynthetic assimilation ratio for 15 open lake stations, 12 from 3-m samples, and the others from surface samples. The ratio averaged $0.82 \text{ mg C/hr/mg Chl } a$ (Table 8) over all stations. Ten stations ranged between 0.20 and 0.80 ; of the remaining five stations, ranging from 1.00 to 1.65 , four were Stations 26-29 along the southern shore. According to Beeton, Johnson and Smith (1959) there is an easterly flowing littoral current in this area which contains relatively high chemical and plankton concentrations. The assimilation ratio at Station 7 decreased from ca. 1.4 at 60 m to 0.64 at 180 m depth (Fig. 10). All values for assimilation ratio are in the nutrient-poor category (see p. 70).

In Lake Superior 28 genera of phytoplankton were identified and the assemblage was dominated by two genera of diatoms, *Asterionella* and *Tabellaria*. *Asterionella* was either abundant or common at all 31 stations for which we have estimates of relative abundance, and *Tabellaria* was in these categories at

ppb. In contrast, chlorophyll *a* in the bays ranged from 1.2 - 1.7 ppb and averaged twice as concentrated as in the open lake (Table 8). At Station 7, concentrations at 60 , 120 and 180 m were 0.8 , 1.2 and 1.6 ppb, respectively (Fig. 10), suggesting that bottom waters may have more chlorophyll than surface waters. Of the four near-surface chlorophyll values over 1.0 ppb, three were collected at Stations 15, 16 and 17, lakeward of the thermal bar. These stations were presumably in an area of upwelling (Rodgers 1965), and high chlorophyll concentrations at 3 m may represent algae which were brought to the surface with upwelled water.

Carbon fixation rates were measured at 22 stations, usually on water from the surface and 3 m , but occasionally from 6 or 8 m . At some stations the carbon fixation rates were slightly higher in water from the subsurface depth than at the surface,

FIG. 10. Vertical distribution of rates of carbon fixation, chlorophyll *a* and photosynthetic assimilation ratio at Station 7 in Lake Superior. Samples taken at 0, 60, 120 and 180 m.

29 of the 31 stations. *Synedra* was common at 22 of the 31 stations, but unlike *Asterionella* and *Tabellaria* it was never in the abundant category. *Dinobryon* was abundant or common at 21 stations. *Melosira* and *Rhizosolenia* were abundant or common in at least 25 percent of the samples. Other genera common in one or more samples were *Fragilaria*, *Lyngbya*, *Cyclotella*, *Navicula*, *Chroococcus*, and *Oscillatoria*. No great difference was noted for Stations 1-4 in Whitefish Bay, as compared to the open lake stations, except that *Oscillatoria* and *Chroococcus* were common at Station 4. *Chroococcus* was also common at Station 35 in the area of the littoral current.

Zooplankton was sparse; settled volumes of 31 samples ranged from 0.10 to 0.85 ml/m³ (mean = 0.36 ± 0.20). There was no apparent difference between quantities of zooplankton in the open lake and in Whitefish Bay. The qualitative composition of the Lake Superior zooplankton, like other environmental conditions, was remarkably uniform from station to station.

Copepods dominated the open-lake zooplankton to the virtual exclusion of all other forms. *Diaptomus* and *Limnocalanus* were the dominant genera; *Cyclops* and *Senecella* were often present in lesser numbers. The ordinarily planktobenthic opossum shrimp, *Mysis*, was collected at a few deepwater stations; *Mysis* also occurred in sediment samples, but probably was not quantitatively sampled by either net or grab.

Zooplankton samples collected in Whitefish Bay were also dominated by calanoid copepods, but several other genera occurred in small numbers, which included the Cladocera *Daphnia*, *Bosmina*, *Holopedium*, *Polyphemus*, and *Leptodora*, and the rotifer *Asplanchna*. Outside of the bay a few cladocerans were also found in small numbers at some shallow, inshore stations, namely 6, 23, 30, 31, 32, 33, and 40. Most of these are in the littoral current. The only cladoceran found at an open lake station deeper than 35 m was *Bosmina*, a few specimens of which occurred at Station 25.

Descriptions of bottom sediments in Lake Superior may be summarized as follows: silty sediments were found near shore in Whitefish Bay (Stations 1, 2), near Michipicoten Island (Station 10), and near the Keweenaw Peninsula (Stations 21, 22); sandy sediments occurred along the shore between Munising and Whitefish Point, in the region of the littoral current; and clayey sediments, often of the layered type observed by Powers and Robertson (1968), were present at most of the open-lake stations. We found rocky bottoms at Stations 6, 29, and 30.

Bottom fauna was very sparse. Of 32 stations for which we have data, only seven had over 700 individuals/m². Six of these stations (2, 22, 23, 26, 32, and 34) were located near shore and at medium depths (20-96 m), and most were in sandy bottoms. Stations 2 and 22 were silty clay. These six stations were located in Whitefish Bay, near the tip of the Keweenaw Peninsula and in the littoral current. Counts ranged between 750 and 1200 individuals/m², lower

by a factor of 5 than the Lake Michigan maxima. Fauna at Station 29, the seventh station with over 700 individuals/m², differed qualitatively from the other stations. At Station 29, the bottom was rocks and pebbles, and the dominant organism was *Hydra*.

Pontoporeia occurred at every Lake Superior station and was the dominant benthic animal at most stations. Typically, open-lake stations had a few oligochaetes, *Mysis*, and sphaeriids. At a few stations, mostly in Whitefish Bay and in the littoral current, *Pontoporeia* made up less than 50% of the total numbers of bottom fauna. Oligochaetes were relatively more numerous at most of these stations, making up 30-77% of the animals found at Stations 1, 3, 5, 7, 8, 28, 31, 32, 35, and 38. Chironomid larvae were usually scarce except at Stations 1 and 3 in Whitefish Bay and Stations 31, 33, 34, 36, 39, 40 in the littoral current, where they accounted for 16-50% of the animals found. Fingernail clams (*Sphaeriidae*) were often present, but usually in unimportant numbers. A few *Ephemerella* nymphs were found at Station 8, near Caribou Island.

DISCUSSION

Lake Superior continues to epitomize the oligotrophic lake: dilute, nitrate- and silica-rich, but phosphate-poor waters; very low primary productivity; a biota dominated by diatoms and calanoid copepods in the plankton, and *Pontoporeia* and *Mysis* in the benthos. During our cruise offshore stations had not emerged from limnological spring, which minimized metabolic activity, and partly accounted for the differences noted between the lake proper and Whitefish Bay, which was already well into limnological summer.

Weiler and Chawla (1969) reported on chemical conditions in 1968; they concluded that the concentration of major ions is controlled by the balance between chemicals added in runoff from the drainage basin and those lost through the St. Mary's River. Their mean values for the whole lake, collected in late August, agree quite well with ours with the exception of sulfate (Table 10). Our

TABLE 10. Comparison of major ion chemistry for calcium, sulfate, chloride, alkalinity and pH in Lake Superior. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Weiler & Chawla (1969) ^a 18-28 August 1968	This study ^b 9-12 July 1970
Calcium, ppm	13.2	14.5 $\pm$ 1.48 (83)
Sulfate, ppm	3.9	1.53 $\pm$ 0.45 (70)
Chloride, ppm	1.3	1.07 $\pm$ 0.09 (85)
Alkalinity, ppm	51.8	43.5 $\pm$ 2.0 (104)
pH	7.8	8.03 $\pm$ 0.14 (106)

^aData are averages of all samples.

^bData from Tables 6 and 7.

sulfate values are only about half as large as those reported by Weiler and Chawla (1969) and by Beeton (1965, 1969). Other than sulfate, differences in concentration could be explained partly by seasonal differences in sampling and location. The 1968 data were collected 5 weeks later than ours and at 21 stations distributed throughout the lake, over half of them close to shore. Differences in analytical methods may also have been a factor. In any case, our data provide no evidence for any recent increase in major ion concentrations, but do indicate a higher pH than reported previously.

TABLE 11. Comparison of data on silica, nitrate nitrogen, ammonia nitrogen, transparency, carbon fixation and chlorophyll *a* in Lake Superior.

	Schelske & Callender ^a (1970) 2-9 July 1969	Schelske et al. (1972) ^a 5-20 August 1971	Dobson ^b 30 June-7 July 1971	This study ^a 9-12 July 1970
SiO ₂				
Surface, ppm	1.86 ± 0.07 (15)	1.99 ± 0.08 (16)	2.17 (57)	2.25 ± 0.10 (30)
Bottom, ppm	1.99 ± 0.15 (17)	2.11 ± 0.18 (15)	2.19 (283)	2.28 ± 0.20 (25) ^c
NO ₃ -N				
Surface, ppb	270 ± 23 (14)	250 ± 71 (15)	248 (57)	250 ± 17 (30)
Bottom, ppb	279 ± 18 (16)	257 ± 20 (13)	255 (283)	264 ± 7.4 (25) ^c
NH ₃ -N				
Surface, ppb	4.6 ± 6.9 (17)		5 (57)	11 ± 12 (29)
Bottom, ppb	16.7 ± 8.2 (17)		4 (283)	9.2 ± 4.8 (25)
Transparency, m	10.0 ± 2.4 (17)	10.3 ± 2.8 (16)	8.3 (43)	11.8 ± 3.8 (35)
Carbon fixation mg C/m ³ /hr	0.35 ± 0.08 (11)	0.75 ± 0.29 (16)		0.44 ± 0.24 (46)
Chlorophyll <i>a</i> , mg/m ³		0.76 ± 0.26 (15)		0.78 ± 0.49 (32)

^aData for each parameter are given as the mean ± one standard deviation followed by the number of observations in parenthesis.

^bData are means with number of observations in parenthesis. Surface samples are from a depth of 1 meter when water temperature is greater than 5.0°C. Bottom samples are from the "cold-water mass" with temperatures less than 5.0°C. (Footnote 2.)

^cAll samples deeper than 72 m.

Schelske and Callender (1970) reported nutrient conditions and carbon fixation rates for early July 1969. Seventeen of their stations were located east of the Keweenaw Peninsula and can be compared with our 1970 findings. Most of the 1969 stations were located in the littoral current and in Whitefish Bay. Dobson² recently summarized lake averages for nutrient data collected by the Canada Centre for Inland Waters from 1968-1971.

Our 1970 silica and nitrate data are similar to other data available for Lake Superior (Table 11). None of the three sets of data shows much depletion of silica or nitrate in the near-surface layer. While our ammonia figures are somewhat higher than the other studies, the variability in the data is so great that these differences cannot be considered significant. The average transparency observed on our cruise was higher, probably not significantly, than the 1969 or 1971 studies.

Very low carbon fixation rates in 1970 are corroborated by Schelske and Callender's 1969 data and by Verduin's 1969 data (Verduin 1972). However, Parkos et al. (1969) made carbon fixation measurements in early July 1968, and their values, based on data from 11 stations located east of the Keweenaw Peninsula, averaged 1.07 ± 0.38 mg C/m³/hr, nearly twice as great as in the studies of 1969 and 1970. Differences in methodology may help explain this discrepancy; in particular, Parkos et al. used artificial illumination and temperature control (1000 ft candles at 15.6°C) and counted their samples by liquid scintillation. In August 1971 carbon fixation rates at 16 stations along the south shore between the Keweenaw Peninsula and Whitefish Bay averaged 0.75 ± 0.29 mg C/m³/hr (Schelske et al. 1972).

Holland (1965) found an oligotrophic diatom assemblage in 1964 dominated by small species of *Cyclotella*, as did Schelske et al. (1972). The mesh size of our nets and the relatively low power of our microscopes were inadequate to reveal these nanoplankters. We found phytoplankton assemblages dominated by three genera of diatoms, *Asterionella*, *Tabellaria*, and *Synedra*.

Few studies of Lake Superior zooplankton or benthos have been published. Swain, Olson and Odlaug (1970) used a continuous plankton recorder in the lake in 1966-1968. Differences in sampling apparatus prevent quantitative comparisons with our data, but these authors also found few cladocerans in the offshore areas. Adams and Kregear (1969) reported on the benthos of eastern Lake Superior based on collections made with a Shipek sampler in September and October 1968. Their results agree closely with ours: they found a relatively simple fauna, dominated by *Pontoporeia*. Amphipods averaged 153 individuals/m² in the pelagic (clay-bottom) zone, and were most numerous on sandy bottoms, where they averaged 500 individuals/m².

²See footnote 1, p. 23.

LAKE HURON

Twenty-six stations were sampled in Lake Huron from July 27-30, all located within 20 miles (32 km) of the Michigan shore (Fig. 11). We sampled seven stations on the first day between Cheboygan and North Point; on the second day we occupied eight stations beginning in Thunder Bay just inside North Point and ending near Tawas City; on the third day we visited six stations in Saginaw Bay and one station at the mouth of the bay about 10 km northwest of Pte. aux Barques; and on the fourth day we occupied four stations along the shore of Michigan's "thumb" between Harbor Beach and Port Huron. At every station samples were taken at the surface, 3 m, and bottom; at the deeper stations an additional subsurface depth was sampled.

Our data for Lake Huron are strikingly non-uniform, but it is possible to group stations into four distinct and fairly homogeneous zones. The zones (Fig. 11) are:

Zone I	Stations 1-7	Above Alpena
Zone II	Stations 8-15	Alpena to Tawas City
Zone III	Stations 16-21	Saginaw Bay
Zone IV	Stations 22-26	Pte. aux Barques to Port Huron

Within each zone samples are classified according to depths: surface, 3 m, 8-22 m, and 32-80 m.

PHYSICAL-CHEMICAL ASPECTS

The chemical composition of water in Lake Huron is determined to a large extent by two major influences. First, because Lake Huron is a mixing basin for the outflows from Lakes Michigan and Superior, concentrations of conservative ions over much of the lake are intermediate between those in Lake Michigan and those in the more dilute Lake Superior water. Second, large amounts of dissolved substances enter Saginaw Bay from the Saginaw River and its tributaries, increasing concentrations of dissolved substances in parts of Lake Huron. The Saginaw valley contains oil fields and chemical industries that empty brine into the bay. According to the investigations of Ayers et al. (1956), the water mass leaving Saginaw Bay usually moves south toward the lake's outlet at Port Huron. Under certain wind regimes, however, these authors found that bay water travels northward along the Michigan shore. It will be seen that the four lake zones we sampled show chemical characteristics largely determined by these two major factors. Dissolved chemical levels are lowest in Zone I (essentially uninfluenced by Saginaw River water), slightly higher in Zone II (perhaps occasionally influenced by that water), highest in Saginaw Bay itself, Zone III (where the Saginaw River has a major influence), and second-highest in Zone IV (where inputs from Saginaw Bay increase concentrations of dissolved substances relative to the more northerly zones).

Temperatures during our cruise were influenced by water depth and latitude. Thermal stratification was established in all four zones. At the deep northern stations (in Zones I and II) the thermocline was at ca. 20 m. Mean surface temperatures were 16.5 and 18.5°C in Zones I and II (Fig. 12). At the shallower and more southerly stations (in Zones III and IV) surface temperatures

FIG. 11. Lake Huron sampling area showing locations of 4 zones and 26 stations.

FIG. 12. Lake Huron temperature, dissolved oxygen, silica, nitrate nitrogen, ammonia nitrogen, soluble reactive phosphate and particulate phosphate. Curves depict means with error bars representing $\pm$ one standard deviation.

were higher, averaging 20.6°C in Zone IV and 22.7°C in Zone III, Saginaw Bay.

Vertical distributions of dissolved oxygen in Zones I, II, and IV were orthograde, the oxygen concentration increasing with increasing depth (Table 12, Fig. 12). Dissolved oxygen in Saginaw Bay decreased slightly with depth, so that near-bottom samples were slightly undersaturated (ca. 92% saturation at Station 21).

Concentrations of conservative ions in the four zones can be related to inputs from Saginaw Bay. Concentrations increased from north to south in the three open-lake zones and were highest in Zone III, Saginaw Bay (Table 13). Data from the four zones for conductivity, calcium and chloride clearly follow this pattern which is also suggested by data for pH, alkalinity and sulfate. In Zone I, concentrations of conservative elements are approximately that expected from a mixture of 40% Lake Michigan and 60% Lake Superior water, the relative proportions of the two largest inputs to the northeastern part of the lake.

Water transparency in Zones I and II averaged 9.1 and 8.0 m respectively; in Saginaw Bay it was fivefold less (Table 13). Transparency in Zone IV averaged 5.9 m.

Before discussing nutrient distributions, it should be noted that the inflection points at 3 m in Zone I (Fig. 12) which denote low concentrations of dissolved nutrients and high particulate phosphorus levels are in each case due to a single observation at Station 6. This station was located on a shallow (10.7 m) reef, and conditions there were atypical of Zone I. Similarly, 3-m samples from Zone II refer to a shallow station, Station 15, near Tawas City, which may not have been typical of Zone II.

Except in Saginaw Bay, concentrations of silica were reduced in the upper waters relative to the bottom waters (Fig. 12), the extent of depletion increasing southward. Silica in surface samples averaged 1.07 ppm in Zone I, 0.81 ppm in Zone II, and 0.65 ppm in Zone IV, with larger concentrations for each zone in the thermocline region (8-22 m), and largest concentrations in the hypolimnion (32-80 m) in Zones I and II (Table 12). It is evident that utilization by diatoms has reduced the concentration of silica in the epilimnion; these changes are paralleled by corresponding southward increases in open-lake chlorophyll concentrations and carbon fixation rates and decreases in transparency (Table 13).

The silica distribution in Saginaw Bay is very different from that at the open-lake stations. Silica concentrations in the bay were quite variable between stations, but silica was not depleted near the surface, nor were there important vertical differences (Table 12, Fig. 12). Lack of vertical stratification may indicate that the shallow bay waters are occasionally mixed by the wind to or near the bottom. Another explanation for the abundance of near-surface silica in the bay is that the phytoplankton flora there during our cruise consisted mostly of a dense blue-green algal bloom, while diatoms, which require silica for growth, were relatively unimportant.

Nitrate concentrations in the open water were slightly reduced in the surface waters compared to the lowest depths of each zone (Table 12, Fig. 12). A curious feature of the nitrate data was the larger concentration in the deep water of Zone II (ca. 190 ppb) compared with the same depth in Zone I (ca. 160 ppb). The large amount of variability among observations suggests that this difference is not significant. If the raw data (Table 14) are examined, it is seen that in each group an anomalous observation accounts for most of the variability. When the two discrepant observations are excluded, the difference between the means becomes even more pronounced, and the standard deviations are reduced by a factor of 4 or 5. The cause of the higher values in Zone II

TABLE 12. Lake Huron dissolved oxygen, silica, nitrate nitrogen, ammonia nitrogen, soluble reactive phosphate and particulate phosphate. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Depths	Dissolved oxygen, ppm	SiO ₂ , ppm	NO ₃ -N, ppb	NH ₃ -N, ppb	Sol. PO ₄ , ppb	Part. PO ₄ , ppb
<i>Zone I</i>						
All	10.7 $\pm$ 0.79 (23)	1.29 $\pm$ 0.33 (21)	145 $\pm$ 30 (21)	12.6 $\pm$ 3.9 (20)	2.7 $\pm$ 3.2 (8)	23 $\pm$ 12 (6)
Surface	10.1 $\pm$ 0.37 (6)	1.07 $\pm$ 0.15 (7)	139 $\pm$ 31 (7)	13.6 $\pm$ 5.7 (7)	2.5 $\pm$ 1.7 (3)	13 $\pm$ 0.78 (2)
3 m	10.2 $\pm$ 0.49 (4)	0.94 (1)	111 (1)	10.0 (1)	1.5 (1)	28 (1)
8-22 m	11.0 $\pm$ 0.67 (8)	1.20 $\pm$ 0.13 (8)	147 $\pm$ 26 (8)	11.0 $\pm$ 2.5 (7)	3.8 $\pm$ 5.4 (3)	21 $\pm$ 12 (2)
32-80 m	11.5 $\pm$ 0.67 (5)	1.80 $\pm$ 0.16 (5)	159 $\pm$ 33 (5)	13.8 $\pm$ 2.5 (5)	1.0 (1)	41 (1)
<i>Zone II</i>						
All	10.6 $\pm$ 1.0 (24)	1.15 $\pm$ 0.42 (23)	159 $\pm$ 35 (23)	25.7 $\pm$ 9.5 (20)	2.7 $\pm$ 1.4 (16)	22 $\pm$ 26 (22)
Surface	9.51 $\pm$ 0.27 (8)	0.81 $\pm$ 0.15 (8)	141 $\pm$ 24 (8)	20.0 $\pm$ 6.2 (6)	2.4 $\pm$ 0.78 (8)	19 $\pm$ 23 (7)
3 m	9.90 (1)	0.73 (1)	146 (1)	15.0 (1)	-----	17 (1)
8-22 m	10.8 $\pm$ 0.73 (10)	1.15 $\pm$ 0.23 (9)	159 $\pm$ 24 (9)	28 $\pm$ 11 (9)	2.7 $\pm$ 2.3 (3)	33 $\pm$ 22 (10)
32-80 m	11.8 $\pm$ 0.20 (5)	1.78 $\pm$ 0.19 (5)	190 $\pm$ 52 (5)	31.8 $\pm$ 5.3 (4)	3.2 $\pm$ 1.6 (5)	11 $\pm$ 14 (4)
<i>Zone III</i>						
All	9.53 $\pm$ 0.48 (18)	1.06 $\pm$ 0.22 (18)	42 $\pm$ 38 (18)	25.9 $\pm$ 9.2 (16)	5.3 $\pm$ 5.5 (12)	34 $\pm$ 14 (15)
Surface	9.58 $\pm$ 0.50 (6)	1.08 $\pm$ 0.26 (6)	21 $\pm$ 16 (6)	20.0 $\pm$ 3.7 (5)	6.6 $\pm$ 6.9 (6)	37 $\pm$ 19 (6)
3 m	9.67 $\pm$ 0.50 (6)	1.03 $\pm$ 0.22 (6)	32 $\pm$ 26 (6)	23.4 $\pm$ 4.7 (5)	-----	33 $\pm$ 11 (3)
8-22 m	9.35 $\pm$ 0.48 (6)	1.06 $\pm$ 0.23 (6)	72 $\pm$ 48 (6)	33 $\pm$ 11 (6)	4.0 $\pm$ 3.8 (6)	30 $\pm$ 11 (6)
32-80 m	-----	-----	-----	-----	-----	-----
<i>Zone IV</i>						
All	9.81 $\pm$ 0.38 (15)	0.86 $\pm$ 0.21 (16)	146 $\pm$ 27 (16)	21.4 $\pm$ 7.6 (12)	3.3 $\pm$ 1.3 (2)	12 $\pm$ 7.6 (13)
Surface	9.40 $\pm$ 0.20 (5)	0.65 $\pm$ 0.11 (5)	136 $\pm$ 35 (5)	21.3 $\pm$ 9.9 (4)	4.2 (1)	12 $\pm$ 5.4 (5)
3 m	-----	0.73 (1)	123 (1)	22.0 (1)	-----	-----
8-22 m	10.0 $\pm$ 0.26 (10)	0.98 $\pm$ 0.17 (10)	154 $\pm$ 23 (10)	21.4 $\pm$ 7.4 (7)	2.4 (1)	12 $\pm$ 9.0 (8)
32-80 m	-----	-----	-----	-----	-----	-----

TABLE 13. Lake Huron environmental factors (all depths). Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Zone I			Zone II			Zone III			Zone IV		
Specific conductance, μmho at 25°C	192	± 8.0	(7)	195	± 5.7	(8)	247	± 20	(6)	204	± 2.7	(5)
Transparency, m	9.1	± 2.4	(7)	8.0	± 2.4	(7)	1.80	± 0.40	(6)	5.9	± 0.62	(5)
pH	8.50	± 0.04	(7) ^a	8.38	± 0.16	(24)	8.65	± 0.17	(18)	8.40	± 0.06	(15)
Alkalinity, ppm	76.5	± 1.9	(25)	76.5	± 6.7	(24)	88.6	± 3.7	(18)	82.5	± 1.2	(15)
Calcium, ppm	21.2	± 1.7	(21)	26.5	± 0.58	(24)	30.3	± 1.7	(18)	28.0	± 0.76	(13)
Chloride, ppm	4.65	± 1.5	(21)	5.58	± 0.94	(23)	10.6	± 2.3	(18)	6.6	± 1.4	(16)
Sulfate, ppm	-----			10.0		(1) ^a	12.8	± 1.8	(5) ^a	10.9	± 0.72	(12)
Chlorophyll <i>a</i> , ppb at 3 m	0.81	± 0.72	(7)	0.86	± 0.46	(8)	7.26	± 3.1	(6)	0.85	± 0.04	(4)
Carbon fixation, mg C/m ³ /hr at 0 m	0.61	± 0.28	(4)	0.95	± 0.43	(5)	31	± 23	(5)	1.05	± 0.26	(4)
at 3 m	0.77	± 0.38	(4)	1.69	± 0.51	(5)	28	± 17	(5)	1.50	± 0.53	(4)
Assimilation ratio, mg C/hr/mg Chl <i>a</i>	1.26	± 1.0	(4)	2.67	± 1.4	(5)	4.16	± 2.5	(5)	1.76	± 0.63	(4)

^aSurface only.

TABLE 14. Lake Huron near-bottom nitrate nitrogen values at deep-water stations in Lake Huron Zones I and II.

ZONE I			ZONE II		
Station #	Depth	NO ₃ -N, ppb	Station #	Depth	NO ₃ -N, ppb
HU70-2	55 m	148	HU70-9	33 m	98
3	80 m	151	10	55 m	213
4	80 m	218	11	65 m	200
5	50 m	134	12	60 m	223
7	32 m	145	13	46 m	218
Mean (w/o Sta. 4)		145	Mean (w/o Sta. 9)		214
Std. Dev. "		7	Std. Dev. "		10

is problematic. High nitrate values are typical of water from Lake Superior or Georgian Bay, but the deep water in Zone II had larger than the expected ammonia concentrations for oligotrophic waters.

Concentrations of nitrate in Zones I, II, and IV differ conspicuously from the Saginaw Bay values (Table 12). Saginaw Bay nitrates were strikingly depleted (Fig. 12). Surface values averaged 20 ppb, perhaps approaching the limiting concentration of combined nitrogen for non-nitrogen fixing algae.

Concentrations of ammonia nitrogen appeared to be smaller at all depths in Zone I than in the other zones (Table 12, Fig. 12). As mentioned earlier, deep-water ammonia values in Zone II averaged 30 ppb, at least twice as large as in Zone I. Average concentrations of ammonia in Saginaw Bay ranged from 20 ppb at the surface to more than 30 ppb near the bottom. In Zone IV, means were about 20 ppb at all depths.

Mean concentrations of soluble reactive phosphate in open Lake Huron were low, usually less than 3 ppb, and fairly uniformly distributed with respect to depth (Table 12, Fig. 12). In Saginaw Bay concentrations were variable but somewhat higher, ranging from 0.5 ppb (at Station 20) to 20 ppb (at Station 21) and averaging about 5 ppb.

Particulate (sestonic) phosphate, a measure of detrital and phytoplanktonic phosphorus, varied greatly in Lake Huron. In Zone I, six determinations ranged between 13 and 41 ppb, averaging 23 ppb (Table 12). The highest value was found at 32-m depth, but this is the only deep-water observation available in that zone (Fig. 12). Sestonic phosphate in Zone II was even more variable. Surface samples ranged between 3.9 and 17 ppb, except for one value of 71 ppb at Station 8 near Alpena. In the 8-22 m stratum, values ranged from 3.5 to 91 ppb and averaged 30 ppb. Smaller values were found in deeper water. Saginaw Bay sestonic phosphate values were higher and less variable than in Zones I and II, ranging from 15-61 ppb. Low values were found in Zone IV.

BIOLOGICAL ASPECTS

The distribution of chlorophyll *a* at 3 m was similar to the pattern for chemical conditions in the four lake zones. Concentrations of chlorophyll were lowest in Zone I, averaging 0.81 ppb (all observations but one ranged from 0.4 and 0.8 ppb), and in Zone II, averaging 0.86 ppb and ranging between 0.44 and

1.72 ppb (Table 13). Concentrations in Saginaw Bay averaged 9 times greater, ranging from 2.6-10.9 ppb. In Zone IV, average concentrations were similar to the other zones in the open lake.

Data for carbon fixation show an even more striking difference between Saginaw Bay and the open-lake zones. Frequently there were differences between carbon fixation rates of samples collected from the surface and 3 m, so these are presented separately (Table 13). Average rates at the open-lake stations were somewhat higher in the 3-m samples than in surface samples, suggesting light inhibition at the surface. Three of five Saginaw Bay stations also showed lower surface uptake. Rates in the open-lake surface averaged 0.61, 0.95, and 1.05 mg C/m³/hr in Zones I, II, and IV. Average rates at 3 m were 0.77, 1.69, and 1.50 in the same zones. Mean rates in Saginaw Bay were much larger than those in the open lake, as much as 50 times greater than rates in surface samples from Zone I. The highest carbon fixation rates (29-66 mg C/m³/hr) were found in the three innermost bay stations (17-19).

Assimilation ratios in Saginaw Bay, as might be expected, also differed from ratios calculated for stations in the open lake (Table 13). For the three open-lake zones, assimilation ratios, while somewhat higher than those found in Lakes Michigan and Superior, are still within the range of values expected in a nitrate-rich, phosphate-limited system (see p. 70). In Saginaw Bay, on the other hand, the low-nitrate, high-phosphate conditions are reflected in higher ratios, especially in the inner bay (Stations 17-19; range: 3.45-8.15 mg C/hr/mg Chl *a*). In these stations nitrates ranged from 8 to 10 ppb, perhaps approaching the limiting concentration for phytoplankton uptake.

Phytoplankton assemblages could be separated into two groups, one from the open-lake station of Zones I, II, and IV, and another from Zone III, Saginaw Bay.

Diatoms dominated the phytoplankton at the open-lake stations. The dominant genus was *Tabellaria*. It occurred as the most abundant genus at 16 of the 19 stations. *Fragilaria* and *Asterionella* were the next most common genera and were common or abundant at all stations except Station 2. *Melosira* was common or abundant at 15 stations. Other common or abundant genera were *Synedra*, *Dinobryon*, and *Rhizosolenia*.

Phytoplankton assemblages in Zone III, Saginaw Bay, were easily discernible from those in the open lake by fewer diatoms as abundant or common genera. The dominant genera for all the stations was *Ceratium*, which was either common or abundant at five stations. *Microcystis* was either common or abundant at four of the six stations. *Aphanizomenon* and an unidentified organism, which was either a sulfur-reducing bacteria or a blue-green alga, were common at Stations 16, 17, and 20.

Zooplankton was intermediate between Lakes Michigan and Superior in abundance. Eutrophic conditions noted in Saginaw Bay were not reflected in greater standing crops of zooplankton per unit volume of water (Table 15), although the Saginaw Bay fauna was qualitatively quite different from the open-

TABLE 15. Lake Huron settled volumes (ml/m³) of zooplankton. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Zone I	0.92 $\pm$ 0.19 (7)
Zone II	1.11 $\pm$ 0.47 (5)
Zone III	0.67 $\pm$ 0.28 (6)
Zone IV	0.77 $\pm$ 0.52 (3)

lake stations. At a few stations (8, 13, 14, 24, and 26) where *Holopedium* was fairly common, the settled volumes were much higher, ranging between 2.6 and 9.4 ml/m³. *Holopedium* is a cladoceran which secretes a thick gelatinous sheath around its carapace; as Hutchinson (1967) noted, it resembles "tapioca in a towel-net." Since *Holopedium* does not settle compactly, the volume figures obtained at the *Holopedium* stations are not comparable with the other stations, and are not included in the zone averages shown in Table 15.

Qualitatively, Lake Huron zooplankton is more complex than that of Lake Superior, as the number of filled spaces in App. Table F shows. In Zones I and II the fauna was somewhat similar to that found at our Lake Michigan stations, except that of the three dominants, *Diaptomus* usually outnumbered *Bosmina* and *Cyclops*, whereas in Lake Michigan, *Bosmina* was most numerous. A variety of other genera occurred in lesser numbers, including *Limnocalanus*, *Epischura*, *Senecella*, *Daphnia*, *Holopedium*, *Leptodora*, *Polyphemus*, and *Asplanchna*. In the outer portion of Saginaw Bay (Stations 16, 17, 21) the fauna was similar to that in the open lake, except that *Bosmina* outnumbered *Diaptomus*, and *Asplanchna* was more common. In the inner bay (Stations 18-20), copepods were much less conspicuous; the dominant form was an unidentified rotifer, and many of the open-lake Cladocera were found as well, except that we found no *Polyphemus*. One cladoceran genus, *Ceriodaphnia*, often considered a pond form, was found in the bay, but was absent in the open lake. At the southern lake stations (Zone IV) the faunal composition was much like that in the outer part of Saginaw Bay. *Holopedium*, present at all Zone IV stations, was the dominant zooplankton at Station 24.

Sediments were sandy, the shallow stations grading to clayey sand or silty sand at depths 30 m or greater. In Saginaw Bay the sediments were usually silty sand, except at the innermost station (18) which was silt. We found a few cinders in the sediments at several stations, which were evidence that part of our course intersected former steamship lanes.

Abundance of bottom fauna in Lake Huron was comparable to that found in Lake Michigan. As was the case in Lakes Michigan and Superior, the maximum abundance of benthos was generally found at intermediate depths. Deep stations in Zones I and II (66-87 m) had between 2300 and 3500 organisms/m², while medium-depth stations in these zones (36-57 m) usually had 4000-5700 organisms/m². Shallow stations (8-25 m) had less than 2000 organisms/m². There were, however, three exceptions to the generalizations given above. One shallow station (Station 14, depth 20 m) had 14,500 individuals/m²; and two medium-depth stations (Station 5, depth 57 m; and Station 7, 38 m) had only 800-1700 individuals/m². These exceptional stations also differed from the others in the qualitative composition of the fauna. In Saginaw Bay all stations were shallow (8-11 m). Outer bay stations had benthos abundances comparable to shallow open-lake stations (400-1700 individuals/m² at Stations 20-21), but inner bay stations (Stations 16-19) had much higher counts, between 3200 and 6000 organisms/m². Zone IV stations ranged in depth from 16-26 m, and benthos abundance there was comparable to shallow stations in Zones I and II (125-1300 individuals/m²).

Benthos at medium-depth and deep stations in Zones I and II was dominated by *Pontoporeia*, which made up 60-92% of the animals counted. The remaining fauna consisted of oligochaetes (3-38%), sphaeriids (0-16%), a few *Mysis*, and a few chironomid larvae. *Pontoporeia* at the two exceptional medium-depth stations mentioned above comprised 41-46% of the count. The other animals were oligochaetes (31-46%), chironomids (1-14%), sphaeriids (7-8%), and snails (4% at Station 5, but absent at Station 7). At three shallow stations in Zones I and II (Stations 1, 6, and 8), fauna resembled qualitatively that at the deeper

stations, with amphipods less clearly dominant. *Pontoporeia* made up 22-68% of the total fauna, with oligochaetes (25-42%), chironomids (3-33%), and snails (0-11%) comprising the balance. A few sphaeriids and a few ostracods were found at Station 8.

Two other shallow stations in Zone II (Stations 14 and 15, off Au Sable Point and Tawas City respectively) had bottom faunas more like nearby Saginaw Bay stations. Oligochaetes made up 64% of the fauna at Station 14, nearly 10,000 worms/m², the largest number we found in the four lakes. *Pontoporeia* was also abundant, with over 4500 individuals/m². *Pontoporeia* represented only 30% of the fauna but the 4,500 individuals/m² was the greatest density we found in the four lakes. Chironomids and sphaeriids, while present in fairly high absolute numbers, amounted to only 4 and 2% of the total, respectively. *Asellus*, an isopod, occurred in small numbers, but was not found in the open lake. At Station 15, fewer animals were found (1200/m²), but again oligochaetes were most numerous (62%). *Pontoporeia*, sphaeriids, and chironomids were about equally abundant (ca. 7% each). *Asellus* occurred again at this station, but was rare. *Gammarus*, a genus of Amphipoda more eurytopic than *Pontoporeia*, was nearly twice as abundant as *Pontoporeia*.

At Saginaw Bay Stations 16, 20, and 21, *Gammarus* also outnumbered *Pontoporeia*. *Pontoporeia* was absent at Station 20. *Gammarus* was the dominant organism at Station 21; oligochaetes dominated at Stations 16 and 20, making up 80 and 66% of the total. *Asellus* was present but rare at Stations 16 and 20. A few sphaeriids, snails, chironomids, leeches, and caddisfly larvae were also found at these bay stations. Degraded environmental conditions in Saginaw Bay are reflected in the bottom fauna at the three innermost bay stations (Stations 17-19): crustaceans were totally absent, and the fauna consisted entirely of oligochaetes (80-94%) and chironomid larvae.

The bottom fauna in Zone IV was qualitatively similar to the outer Saginaw Bay stations, except that *Pontoporeia* was the only amphipod. *Pontoporeia* was rare at Station 26, absent at Station 23; and made up 30-47% of the fauna at the other stations. Oligochaetes were dominant or co-dominant at all Zone IV stations. Chironomids were present at every station. A few sphaeriids occurred at two stations, and snails, nematodes, ostracods, and chydorid Cladocera each occurred at one station.

DISCUSSION

Open Lake Huron will be considered separately from Saginaw Bay because the two regions are so distinct limnologically.

Open Lake

Recent data for major ions collected by the Canada Centre for Inland Waters (CCIW) in 1968 (Weiler and Chawla 1969) are similar to our values collected in 1970, except for sulfate and pH (Table 16). Canadian data include Saginaw Bay stations and ours do not, but if this were the reason for the sulfate discrepancy, it should also appear in the chloride data, which it does not. Weiler and Chawla reported "a basic trend of increasing concentrations in all ions (except bicarbonate) from north to south," a conclusion borne out by our 1970 data (Table 13).

Dobson³ recently summarized transparency, dissolved oxygen, and nutrient

³Dobson, H. H. 1971. Nutrients in Lake Huron. Unpublished report, Canada Centre for Inland Waters. 55 p.

TABLE 16. Comparison of data on calcium, sulfate, chloride, alkalinity and pH in open lake stations in Lake Huron

	Weiler & Chawla (1969) ^a 5-14 August 1968	This study ^b 27-30 July 1970
Calcium, ppm	28.1	26.2 $\pm$ 3.6 (76)
Sulfate, ppm	17.2	11.4 $\pm$ 1.4 (18)
Chloride, ppm	6.3	6.71 $\pm$ 2.7 (78)
Alkalinity, ppm	78.6	80.3 $\pm$ 6.5 (82)
pH	8.0	8.47 $\pm$ 0.18 (64)

^aData are mean values.

^bData for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

data collected by the CCIW in 1971. Data from the 19-27 July cruise of the MARTIN KARLSEN were tabulated excluding Saginaw Bay and can be compared with our results.

Transparencies were greater during our cruise than in the 1971 study (Table 17). Dobson presented a review of transparency data collected since 1954, and showed that the mean value has decreased from ca. 10 m to ca. 7 m in the past 16 years. Our dissolved oxygen values are lower than those col-

TABLE 17. Comparison of transparency, dissolved oxygen, silica, nitrate nitrogen, and ammonia nitrogen in Lake Huron.

	Dobson ^a 19-27 July 1971	This study ^b 27-30 July 1970
Transparency, m	6.5 (45)	7.9 $\pm$ 2.4 (18)
Dissolved oxygen, ppm near-bottom	13.3 (105) ^c	11.6 $\pm$ 0.5 (10) ^d
SiO ₂ , ppm surface	1.0 (59) ^e	0.9 $\pm$ 0.2 (19)
near-bottom	1.4 (91) ^c	1.8 $\pm$ 0.2 (10) ^d
NO ₃ -N, ppb surface	204 (58) ^e	139 $\pm$ 29 (19)
near-bottom	240 (91) ^c	175 $\pm$ 45 (10) ^d
NH ₃ -N, ppb surface	9 (59) ^e	18 $\pm$ 7.7 (16)
near-bottom	12 (91) ^c	22 $\pm$ 10 (9) ^d

^aData are means with number of observations in parenthesis, from unpublished data, footnote 3.

^bData for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

^c"Cold-water mass" with temperatures less than 5.0°C.

^dStations in Zones I and II with depths 32 m or greater and bottom temperatures less than 5.0°C.

^eDepth of 1 meter when temperature was greater than 5.0°C.

lected in 1971, but we had few deep-water stations, and none deeper than 80 m. Silica values are comparable in the two studies. Both studies show ca. 35 ppb nitrate nitrogen depletion in near-surface waters, but our 1970 absolute nitrogen concentrations are only about two-thirds as high as the 1971 data, presumably because our stations were not located to sample the areas of the lake which receive inputs of nitrate-rich water from Lake Superior and Georgian Bay. Our ammonia data are somewhat higher than the Canadian data, but are so variable that it is difficult to draw firm conclusions.

Our results for carbon fixation measurements are similar to those reported by Parkos, Olson and Odlaug (1969) who sampled roughly the same open lake areas we visited (Table 18).

TABLE 18. Comparison of data on carbon fixation for open-lake stations in Lake Huron. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Parkos et al. (1969) 25-28 July 1968	This study 27-30 July 1970
Carbon fixation		
mg C/m ³ /hr	1.62 $\pm$ 0.52 (13)	1.25 $\pm$ 0.91 (27)

Few studies of Lake Huron plankton have been published (Davis 1966a). Studies by Fenwick (1962, 1968) reported on a few phytoplankton species from the lake, but there is no comprehensive study. Swain, Olson and Odlaug (1970) reported on zooplankton collected with a continuous plankton recorder in June and August 1968. In June, copepods (*Diaptomus* and *Cyclops*) dominated the fauna. Cladocera increased in abundance, and the total quantity of plankton increased toward the southern end of the lake. In late August, Cladocera (*Daphnia*, *Bosmina*) outnumbered copepods throughout the lake, and standing stocks were higher than in June. In general, our collections from late July resembled those from June 1968 more closely than those from August 1968. Patalas (1972) found 23 crustacean species, with *Diaptomus* and *Cyclops* as dominants.

Teter (1960) studied Lake Huron bottom fauna samples collected by the U. S. Bureau of Commercial Fisheries in 1952 and 1956, and as in our study, found that *Pontoporeia* was the dominant benthic animal, with oligochaetes, sphaeriids, and chironomids occurring commonly. Shallow stations (5.5-25 m) averaged 625 individuals/m², while deep stations (25-119 m) averaged 2,000 individuals/m². These counts are lower than ours as much as 50%, but whether they represent a real increase in benthos during the intervening 15 years is impossible to say, because Teter did not use the Ponar grab, but the less efficient Peterson grab (Powers and Robertson 1967).

Schuytema and Powers (1966) reported on the bottom fauna of Lake Huron and Saginaw Bay collected by the Federal Water Pollution Control Administration in 1965. Again the Peterson grab was used, and again fewer animals were found, only about one-third as many as Teter (1960). The fauna at their offshore stations, many of which were located in Canadian waters, was similar qualitatively to that reported by us and Teter. Shirivastava (1972) collected samples from the open lake with a Ponar grab between April and June 1971. He also found fewer animals than we did: his mean count (individuals/m²) for shallow stations (9-25 m) was 690; for depths from 25-100 m, 1080; and for 100-200 m depths, 720.

Saginaw Bay

Much of the available data on Saginaw Bay emerged from a series of three synoptic surveys conducted in June, August, and October 1956 by the U. S. Bureau of Commercial Fisheries and the Michigan Department of Conservation. Physical and chemical results were presented by Beeton, Smith and Hooper (1967); currents were described by Johnson (1958); distribution and movements of fish were studied by I. A. Carr (1962); food habits of smelt and yellow perch were reported by Gordon (1961) and Tharratt (1959); sediments were described by Wood (1964); and benthos was analyzed by Brinkhurst (1967) and Schneider, Hooper and Beeton (1969).

Comparison of chemical data from Saginaw Bay is difficult for three reasons (Beeton, Smith and Hooper 1967): 1) the brine inputs to the bay vary according to "high but varying concentrations of salts in brine waste discharged to the river"⁴; 2) under different wind regimes the current patterns in the bay vary (clockwise circulation under northeast, east and southeast winds, counterclockwise under west and southwest winds), and these variations are reflected in concentrations of chemicals within the bay; and 3) the dilution of Saginaw River water by Lake Huron water as the former moves through the bay causes a decrease in chemical content lakeward. We did not sample areas near shore and near the mouth of the Saginaw River, where highest chemical concentrations are expected. Beeton, Smith and Hooper reported their results in terms of the inner, middle and outer bay; our 1970 stations were all in their middle and outer bay. It is clear from Table 19 that the inner bay has considerably higher chemical concentrations than the outer bay, and that our data are quite comparable to values found in the middle and outer bay in 1956. Our data indicate that the high chemical loading of Saginaw Bay has continued since the 1956 study.

TABLE 19. Comparison of data on calcium, chloride, sulfate and specific conductance in Saginaw Bay.

	Beeton, Smith and Hooper (1967) ^a June-August 1956				This study ^b 29 July 1970	
	Inner bay		Middle and outer bay		Middle and outer bay	
Calcium, ppm	46	(39 - 55)	29	(29 - 31)	30.2 [±]	1.7 (18)
Chloride, ppm	59.5	(57.5 - 61.4)	11.0	(8.4 - 13.6)	10.6 [±]	2.3 (18)
Sulfate, ppm	22	(16 - 29)	11	(10 - 12)	12.8 [±]	1.8 (5)
Specific conductance μmho	469 ^c	(391 - 553)	253 ^c	(237 - 270)	247 ^d ± 20	(6)

^aData are expressed as the overall mean followed in parentheses by the range in mean values for each sampling date.

^bData for each parameter are given as the mean [±] one standard deviation followed by the number of observations in parentheses.

^c@18°C.

^d@25°C.

⁴Beeton, Smith and Hooper cited Dow Chemical Company analyses of Saginaw River water during May, June and July 1956; chloride ranged from 64-614 ppm, total alkalinity from 123-187 ppm CaCO₃, and sulfate from 70-115 ppm.

No comparative information on the phytoplankton or zooplankton of Saginaw Bay is available. Two studies of benthos originated from the 1956 cooperative study (Schneider, Hooper and Beeton 1969; Brinkhurst 1967). Brinkhurst found eight species of Naididae, including *Paranais litoralis*, ordinarily a salt- or brackish-water species; and 18 species of Tubificidae, the dominant being the pollution-tolerant *Limnodrilus hoffmeisteri*. The 1956 survey was composed of 50 stations. Our study had only six stations near the center of the bay, corresponding to their "intermediate depths." Most of our stations were located in their "middle" and "outer" bay zones, where those authors reported fewer oligochaetes (mean = 695/m²) at intermediate depths than in the inner zone (mean = 1756/m²). We found between 1100 and 5500 oligochaetes/m² (mean = ca. 3500) at our Stations 16-20, about 5 times as many as in the 1956 study. In 1956 the middle bay fauna at intermediate depths was about half insects and crustaceans; in 1970 65-80% of the animals at comparable depths were oligochaetes, and crustaceans were absent at three of our five stations.

Benthos was also studied in 1965 by Schuytema and Powers (1966). They found oligochaetes most numerous near the Saginaw River mouth (ca. 25,000/m²); in areas near our stations they reported ca. 500-1000 oligochaetes/m², only one-third to one-sixth as many as we found. In 1965, as in our study, *Gammarus* replaced *Pontoporeia* at middle bay locations, and crustaceans were absent closer to the river mouth. In 1965 less than 100 amphipods/m² were found 15 miles from the river mouth; this density in 1970 occurred between our Stations 17 and 20, 12-15 miles lakeward of its 1965 location.

Mayflies (mostly *Hexagenia*), once prominent members of the Saginaw Bay fauna, decreased from 63/m² in 1955 to 9/m² in 1956, to 1/m² in 1965 (Schneider, Hooper and Beeton 1969). We found none.

Changes in the bottom fauna of Saginaw Bay over the past 15 years can be summarized as follows. In the middle bay numbers of oligochaetes have increased by perhaps as much as 6 times (even if it is assumed that the Ponar grab collects 3 times as many as the Peterson, the increase would be 2 times); this has been accompanied by a 12-15 mile lakeward extension of the zone devoid of benthic crustacea. Mayflies are no longer found in the offshore parts of the middle bay. The general features of these changes closely parallel those recently reported for western Lake Erie.

LAKE ERIE

Twenty stations were sampled in Lake Erie from July 31-August 2 (Fig. 13). On the first day we occupied three stations along the north shore of the western basin, and three more on a southerly course ending near the Bass Islands. The second day we occupied eight stations in the central basin, four on a line east of the Bass Islands and four more along the Ohio shore between Lorain and Sandusky. On the last day six more stations in the western basin were visited; all but the last were south of a line between Pelee Island and Monroe, Mich. At each station water samples were collected at the surface, 2 m, and bottom with a 17.5-liter Van Dorn sampler operated in a horizontal position (Fig. 3). The deepest sample was taken from 1-2 m above the bottom.

In the following presentation the Lake Erie stations are grouped into the following three lake zones (Fig. 13):

Zone I	Stations 1-4, 20	Western Basin, north of a line between Pelee Island and Monroe
Zone II	Stations 5-6, 15-19	Western Basin, south of the line between Pelee Island and Monroe
Zone III	Stations 7-14	Central Basin

PHYSICAL-CHEMICAL ASPECTS

Lake Erie's western basin, being very shallow (mean depth = 7.3 m), is occasionally wind-stirred to the bottom during the summer, so thermal stratification is temporary and limited to calm periods. The weather during the first two days of our cruise was calm and sunny, so that an average temperature difference of about 1.4°C existed between the surface and bottom in Zones I and II (Fig. 14). This difference may be conservative because the bottom temperatures plotted refer to the depth where water samples were collected for chemical analysis, and in some cases lower temperatures below the depth of sample collection were indicated on the bathythermograph slides.

The thermal regime in the central basin of Lake Erie is quite different from the western basin; the deeper water (mean depth = 18.3 m, maximum depth = 24.4 m) permits a stable thermal stratification to develop in summer. Although our stations in the central basin were confined to its southwest corner where the maximum depth is less than 19 m, bottom temperatures averaged nearly 10°C colder than the mean surface temperature of 25°C (Fig. 14).

The lake's chemical characteristics are influenced by its populated, industrialized watershed and its morphology. Lake Erie receives water from the upper lakes via the Detroit River. Industrial and municipal wastes increase the chemical content of the Detroit River 2-1/2 times that of Lake Huron (Beeton 1969). In addition, the southern shore is heavily populated and industrialized (11.5 million people lived in the watershed in 1970). Most of the tributary streams are polluted, some heavily (FWPCA 1968b).

Superimposed on the heavy chemical loading are the influences of the basin morphology. Since the lake is shallow the total volume is much smaller than the other Great Lakes (Table 1). The western basin is too shallow for stable summer thermal stratification, so nutrients regenerated in the bottom water are

FIG. 13. Lake Erie sampling area showing locations of 3 zones and 20 stations.

FIG. 14. Lake Erie temperature, dissolved oxygen, pH, silica, nitrate nitrogen, ammonia nitrogen, soluble reactive phosphate and particulate phosphate. Curves depict means with error bars representing $\pm$ one standard deviation.

mixed frequently with the surface waters. The islands situated between the central and western basins complicate the movements of water masses and deter water flow in the southern section of the western basin. Most of the Detroit River flow passes through the northern section of the western basin into the central basin via the Pelee Passage (Powers et al. 1960). Although the Detroit River is the largest source of chemical loading to the western basin, it also had the largest flow rate and tends to provide higher quality water than that in the southern part of the western basin. Chemical loads from the southern tributary streams are not diluted as much by the Detroit River, giving the southern part of the western basin a more eutrophic character than the northern part.

Our lake zones show characteristics consistent with the morphometric and hydrographic factors outlined above. The southern part of the western basin (Zone II) tends to be somewhat more eutrophic and to have higher chemical levels than the northern part (Zone I). And in the central basin (Zone III), although chemical levels are even higher than in Zones I or II, a more mesotrophic plankton biota occurs due to the deeper water and its concomitant thermal stratification. The degree of eutrophication is undoubtedly related to concentrations of either particulate (Fig. 14) or total phosphorus (Burns and Ross 1972).

Major Ion Chemistry

Concentrations of some of the major ions were lowest in Zone I and highest in Zone III. In Zone I, alkalinity averaged about 84 ppm (Table 20), comparable to southern Lake Huron values (Table 13). Alkalinity in Zone II was about 4 ppm higher (88 ppm) than Zone I and that in Zone III about 92 ppm. Average calcium concentrations show a similar pattern: lowest in Zone I (31.6 ppm, over 3 ppm higher than southern Lake Huron), higher in Zone II (32.7 ppm), and highest (37.8 ppm) in Zone III.

Concentrations of sulfate indicate inputs of "pollutants": in Zone I, sulfate averaged 11.8 ppm, which is comparable to values found in southern Lake Huron; Zone II averaged 16.7 ppm, and Zone III, 21.6 ppm, nearly twice the Zone I average (Table 20).

The relatively large chemical content in Lake Erie is reflected by specific conductance. In Zone II it averaged 246 μ mhos, about the same as values found in Saginaw Bay; and the other two zones were even higher: 257 μ mhos in Zone I, and 293 μ mhos in Zone III (Table 20). Chloride concentrations and surface pH did not vary as much among the zones as other parameters associated with major ion chemistry. Surface pH averaged 8.6-8.8 in the 3 lake zones with much smaller values for bottom samples (Fig. 14).

Transparency

Light penetration in the western basin was similar to that found in Saginaw Bay. Transparency averaged 2 m in Zones I and II (range: 1.3-2.8 m) and 4.4 m in Zone III (range: 2.8-6.0 m), higher, but still less than open Lake Huron transparency which ranged from 6 to 9 meters (Table 20).

Dissolved Oxygen and Nutrients

Vertical differences in dissolved oxygen in the western basin, despite the short-lived thermal stratification there, are an indication of the amount of meta-

TABLE 20. Lake Erie environmental factors (all depths). Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Zone I				Zone II				Zone III			
Specific conductance, μmho @ 25 C	257	$\pm$	11	(4)	246	$\pm$	7	(2)	293	$\pm$	9	(8)
Transparency, m	1.96	$\pm$	0.43	(5)	1.99	$\pm$	0.53	(7)	4.41	$\pm$	1.21	(8)
Alkalinity, ppm	83.7	$\pm$	2.1	(14)	88.1	$\pm$	2.9	(21)	92.5	$\pm$	2.5	(24)
Calcium, ppm	31.6	$\pm$	1.2	(10)	32.7	$\pm$	1.6	(14)	37.8	$\pm$	1.2	(16)
Chloride, ppm	14.3	$\pm$	1.3	(14)	13.2	$\pm$	0.5	(20)	14.6	$\pm$	1.6	(24)
Sulfate, ppm	11.8	$\pm$	0.84	(14)	16.7	$\pm$	2.4	(16)	21.6	$\pm$	3.3	(16)
Chlorophyll <i>a</i> , ppb @ 2 m	3.65	$\pm$	1.28	(5)	12.1	$\pm$	3.8	(7)	7.3	$\pm$	6.7	(8)
Carbon fixation, mg C/m ³ /hr @ 0 m	8.90	$\pm$	5.56	(3)	59.6	$\pm$	20	(5)	23.3	$\pm$	14	(5)
@ 2 m	11.0	$\pm$	5.1	(3)	57.9	$\pm$	18	(5)	23.9	$\pm$	15.8	(5)
Assimilation ratio, mg C/hr/mg Chl <i>a</i> @ 2 m	3.75	$\pm$	2.86	(3)	4.91	$\pm$	0.78	(5)	3.78	$\pm$	1.47	(5)

bolic activity in the basin. Bottom dissolved oxygen concentrations averaged about 1 ppm lower than surface values, which were near saturation (Table 21). The smallest oxygen saturation values found in Zones I and II were about 80% at Stations 3 and 15 (Fig. 14). However, as J. F. Carr (1962) observed, minimum values occur a few centimeters above the sediment surface, a zone unsampled in our study. In the central basin, the oxygen curve (Fig. 14) was the clinograde type associated with eutrophic waters. The minimum oxygen value was 1.1 ppm (16% saturation) at Station 13. All of the bottom oxygen values in Zone III were obviously under-saturated except shallow and thermally unstratified Station 12.

It is usual for the pH curve of productive lakes in summer to parallel the oxygen curve (Hutchinson 1957). In Zone I pH near the bottom averaged about 0.2 pH unit lower than at the surface (Table 21, Fig. 14). This difference increased to 0.5 pH unit in Zone II, and to 0.9 pH unit in the central basin where oxygen depletion was the greatest.

The distribution of silica in Zones I and II was similar, with surface values being slightly smaller than bottom values (Fig. 14). Concentrations at the surface averaged 0.94 ppm in Zone I and 0.66 in Zone II (Table 21). In the central basin, Zone III, silica in the surface waters was depleted more, relative to the bottom waters, than in the other two zones and averaged 0.25 ppm.

Nitrate nitrogen in western Lake Erie was usually depleted by about 30-40 ppb near the surface relative to bottom values (Fig. 14), but this tendency is somewhat obscured by large variations between stations. A few stations had much higher nitrates at all levels (Stations 1, 15, 17, 19, and 20, where surface nitrates ranged between 109 and 143 ppb) than the other stations (where the range was 43-85 ppb at the surface). In the central basin, surface nitrates were lower and somewhat less variable, averaging 34 ppb. Bottom concentrations ranged from 115-178 ppb at Stations 9, 10, 11, and 14, but a bottom nitrate maximum was not present at shallower Stations 7, 8, 12, and 13, where concentrations ranged from 25-68 ppb. Nitrate averages (Fig. 14) show a vertical difference of only about 70 ppb, but the differences between surface and bottom values at some stations was twice that large, as indicated by the relatively large standard deviation for the bottom samples (Table 21).

Ammonia nitrogen in Zones I and II was most abundant near the bottom (Table 21, Fig. 14), but there was no such accumulation of ammonia at lower depths in Zone II. Accumulation of ammonia in the deep water of the central basin was striking, the mean value being 87 ppb (maximum: 182 ppb at Station 13, a low-nitrate station) in contrast to averages of about 20 ppb at the surface and 2 m.

Soluble reactive phosphate in Zone I averaged 3.1 ppb (Table 21, Fig. 14), much lower than the average of 22 ppb in Zone II. Bottom concentrations in Zone II were also larger, about twice as large as those in Zone I. In Zone III, surface concentrations averaged 12 ppb (range: 3.5-18 ppb), and values near the bottom averaged about three times larger. Except for a value of 120 ppb at Station 13, off Vermilion, Ohio, a station already singled out for its low oxygen, low nitrate, and high ammonia, soluble reactive phosphates in bottom samples from Zone III ranged between 3.5-72 ppb.

Sestonic phosphate values were quite variable, but in general were lowest in Zone I, and highest in Zone II (Table 21). Maximum values occurred at 2 m in all zones. Zone II had the largest particulate phosphate; surface and bottom means were 53 ppb, and the 2-m average was 72 ppb (Fig. 14). Values at 2 m in Zone II ranged from 31 to 151 ppb (with the maximum occurring at Station 18, off the mouth of Maumee Bay). Mean sestonic phosphate values in the central basin were also variable. Highest values were found at Stations 13

TABLE 21. Lake Erie dissolved oxygen, pH, silica, nitrate nitrogen, ammonia nitrogen, soluble reactive phosphate and particulate phosphate. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

Depths	Dissolved oxygen, ppm	pH	SiO ₂ , ppm	NO ₃ -N, ppb	NH ₃ -N, ppb	Sol. PO ₄ , ppb	Part. PO ₄ , ppb
<i>Zone I</i>							
All	8.23 $\pm$ 0.69 (14)	8.60 $\pm$ 0.23 (13)	1.08 $\pm$ 0.25 (14)	95 $\pm$ 49 (14)	41 $\pm$ 15 (13)	8.6 $\pm$ 9.3 (12)	21 $\pm$ 13 (12)
Surface	8.62 $\pm$ 0.49 (4)	8.63 $\pm$ 0.25 (5)	0.97 $\pm$ 0.12 (4)	79 $\pm$ 46 (4)	33 $\pm$ 8.7 (4)	3.1 $\pm$ 2.6 (4)	12 $\pm$ 4.8 (4)
2 m	8.54 $\pm$ 0.49 (5)	8.69 $\pm$ 0.23 (4)	1.01 $\pm$ 0.12 (5)	97 $\pm$ 57 (5)	35 $\pm$ 7.2 (5)	6.4 $\pm$ 8.5 (3)	30 $\pm$ 16 (5)
Bottom	7.60 $\pm$ 0.60 (5)	8.48 $\pm$ 0.23 (4)	1.24 $\pm$ 0.35 (5)	106 $\pm$ 52 (5)	57 $\pm$ 14 (4)	14 $\pm$ 11 (5)	18 $\pm$ 7.8 (3)
<i>Zone II</i>							
All	7.85 $\pm$ 1.12 (21)	8.77 $\pm$ 0.22 (11)	0.73 $\pm$ 0.25 (20)	93 $\pm$ 45 (20)	41 $\pm$ 13 (18)	24 $\pm$ 11 (15)	59 $\pm$ 35 (19)
Surface	8.13 $\pm$ 0.76 (7)	8.82 $\pm$ 0.11 (7)	0.66 $\pm$ 0.26 (7)	86 $\pm$ 33 (7)	47 $\pm$ 13 (6)	22 $\pm$ 7.6 (7)	53 $\pm$ 24 (6)
2 m	8.21 $\pm$ 1.04 (7)	8.98 $\pm$ 0.09 (2)	0.67 $\pm$ 0.27 (6)	64 $\pm$ 26 (6)	34 $\pm$ 11 (6)	4.0 $\pm$ (1)	72 $\pm$ 48 (6)
Bottom	7.20 $\pm$ 1.35 (7)	8.42 $\pm$ 0.25 (2)	0.85 $\pm$ 0.20 (7)	125 $\pm$ 51 (7)	42 $\pm$ 13 (6)	29 $\pm$ 12 (7)	53 $\pm$ 31 (7)
<i>Zone III</i>							
All	8.16 $\pm$ 2.58 (24)	8.62 $\pm$ 0.52 (24)	0.64 $\pm$ 0.68 (24)	59 $\pm$ 49 (24)	43 $\pm$ 44 (21)	25 $\pm$ 30 (16)	32 $\pm$ 43 (13)
Surface	9.56 $\pm$ 0.58 (8)	8.93 $\pm$ 0.06 (8)	0.25 $\pm$ 0.10 (8)	34 $\pm$ 24 (8)	24 $\pm$ 18 (7)	12 $\pm$ 5.5 (8)	15 $\pm$ 15 (5)
2 m	9.77 $\pm$ 0.65 (8)	8.94 $\pm$ 0.07 (8)	0.29 $\pm$ 0.18 (8)	41 $\pm$ 27 (8)	17 $\pm$ 6.6 (7)	----	45 $\pm$ 58 (5)
Bottom	5.15 $\pm$ 2.33 (8)	7.99 $\pm$ 0.46 (8)	1.36 $\pm$ 0.76 (8)	103 $\pm$ 57 (8)	87 $\pm$ 51 (7)	38 $\pm$ 39 (8)	39 $\pm$ 54 (3)

(102 ppb near bottom) and 14 (148 ppb at 2 m), near Vermilion and Sandusky, respectively.

BIOLOGICAL ASPECTS

Chlorophyll *a* was measured on samples collected at 2 m (Table 20). Values were lowest in Zone I, with an average (3.65 ppb) four times greater than open Lake Huron (Table 13). In Zone II, chlorophyll *a* averaged 12.1 ppb, higher even than Saginaw Bay. Zone III chlorophyll *a* averaged 7.3 ppb, comparable to values found in Saginaw Bay. Values were variable and ranged from 1.6-1.9 ppb at Stations 9 and 11 to 22.7 ppb at Station 14, near Sandusky. The Sandusky value is twice as large as the maximum value for Saginaw Bay.

Carbon fixation rates were measured on water from the surface and 2 m. Surface rates exceeded 2-m rates at 8 stations, although the difference between depths at each station was far less than the difference between stations. Zone I rates ranged from 3.3 to 15.4 mg C/m³/hr, averaging 10 mg C/m³/hr (Table 20). Values obtained in the southern part of the western basin (Zone II) were much higher, ranging from 30.2 to 81.4, averaging 59 mg C/m³/hr, twice the Saginaw Bay average. The highest values occurred at Station 18 near Maumee Bay. In the central basin, carbon fixation rates ranged between 26.8 and 44.2 mg C/m³/hr, except for Stations 9 and 10, the two easternmost offshore stations, which had much lower rates, between 7.3 and 8.8 mg C/m³/hr.

The photosynthetic assimilation ratio was calculated for the 2-m depth at 13 Lake Erie stations. It averaged 3.8 mg C/hr/mg Chl *a* at three stations in the northern part of the western basin, and about the same in the central basin (Table 20). The assimilation ratio was greatest in the southern part of the western basin, averaging nearly 5 mg C/hr/mg Chl *a*, higher than the Saginaw Bay average. Except for two stations (3 and 12, where the ratio was 1.28 and 1.29), every Lake Erie station for which we have data had a ratio in excess of 3.0 mg C/hr/mg Chl *a*, indicating nutrient-rich waters (see p. 70).

Phytoplankton assemblages were dominated by *Ceratium*, *Aphanizomenon*, and *Microcystis*, genera which were abundant or common at more than half of the stations sampled. *Aphanizomenon* was abundant at 13 of the 15 stations in Zone II and III but was not found in Zone I. *Microcystis* occurred at the same stations as *Aphanizomenon*, except it was common instead of abundant. The absence of diatoms in the abundant or common categories in Zones II and III contrasts sharply with the qualitative composition of phytoplankton in the other lakes. Zone I, in the northern part of the western basin, was the only zone in which diatoms predominated. *Fragilaria* was either abundant or common at the four stations sampled. *Ceratium* and *Anabaena* were also encountered frequently.

In Zone III, five genera, *Aphanizomenon*, *Microcystis*, *Ceratium*, *Fragilaria* and *Pediastrum* were either abundant or common at six of the eight stations. *Staurastrum* was abundant or common at five of the eight stations. *Pediastrum* and *Staurastrum* are genera of desmids which are characteristic of eutrophic waters. As we proceeded east from the island region, the phytoplankton assemblage was dominated by the blue-green alga, *Aphanizomenon* at Stations 7, 8 and 9, by *Ceratium* at Station 10; and by *Anabaena* at Station 11, much more than is indicated by the data on relative abundance.

Zooplankton of Lake Erie was several times more abundant than that of the upper three lakes (Table 22).

In Zone I, two types of zooplankton assemblages were found. The first, which occurred at Stations 1 and 20 (the two westernmost stations), consisted of a fauna qualitatively and quantitatively similar to that found in open Lake

TABLE 22. Lake Erie settled volumes (ml/m³) of zooplankton. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Settled volume (ml/m ³)
Zone I	3.9 $\pm$ 3.5 (5)
Zone II	8.7 $\pm$ 2.6 (7)
Zone III	8.3 $\pm$ 4.3 (8)

Huron: a *Diaptomus-Cyclops-Bosmina* assemblage, with other Cladocera, *Daphnia*, *Leptodera*, *Holopedium*, and the rotifer *Asplanchna* occurring less frequently. One additional cladoceran, *Diaphanosoma*, occurred at every Lake Erie station except Stations 10, 14, and 18. The other Zone I stations, 2-4, were farther from the mouth of the Detroit River and had a much greater quantity of zooplankton. The cladocerans, *Daphnia*, *Bosmina*, *Diaphanosoma*, were dominant. The copepods, *Diaptomus* and *Cyclops*, were present in lesser numbers as were *Leptodora*, *Holopedium* and *Asplanchna*.

The Zone II zooplankton was also dominated by Cladocera. At the easternmost stations, near the Bass Islands (Stations 5, 6, and 15), *Daphnia* was dominant. *Bosmina* dominated at Stations 17-19. The rarer components of the assemblages in Zone II were similar to those in Zone I, with perhaps more *Leptodora*. A few *Mesocyclops*, a genus we did not find in Zone I, were found at Stations 16 and 19.

In the central basin (Zone III) zooplankton was most abundant at the shallowest stations, which may have been in part an artifact of expressing the volumetric abundance in terms of lake volume rather than lake area. The qualitative composition of the zooplankton varied along a west-to-east gradient. Near the islands (Stations 7, 8) *Daphnia* was the dominant zooplankter, with *Bosmina*, *Cyclops*, and *Diaptomus* of secondary importance. *Asplanchna*, *Diaphanosoma*, and *Leptodora* were rarer still. *Holopedium* was not found in Zone III. Copepods increased in relative abundance as we moved eastward, so that at Stations 9, 10, and 11, *Daphnia*, *Diaptomus*, and *Cyclops* were co-dominants. This association resembled the fauna of Lake Michigan and open Lake Huron, except that *Bosmina* was replaced in Lake Erie by *Daphnia*. *Bosmina* was present in central Lake Erie, but fairly uncommon. As we moved westward again, closer to the Ohio shore (Stations 12, 13, 14) *Daphnia* again increased relative to copepods and was the only dominant at Station 14.

Except for some coarse sand, cinders, and pebbles found at Station 1, and rocks at Station 12 near Lorain, Ohio, the sediments were similar at all stations. In each case we found dark gray, slightly silty mud. This mud often had an oily consistency, and at some stations (notably Stations 13 and 14 near Sandusky and Vermilion) the sediments smelled of oil, and an oil film appeared on the water in the sediment washer. Oily sediments were also noted at Station 1, off the Detroit River mouth, and at Stations 18 and 19, off the mouths of the Maumee River and the River Raisin. Sediments at Stations 8-11, offshore in the central basin, were covered with a layer of a yellow-green alga, *Tribonema* sp.

The abundance of bottom fauna, like other environmental factors, was quite variable. Except for rocky Station 12, which yielded only a few leeches, the benthic populations ranged from 500 to 10,000 individuals/m². Abundance of benthic organisms showed no discernible geographic pattern within the three zones (Table 23). Most of these abundance ranges contain widely scattered

TABLE 23. Lake Erie bottom fauna. Ranges of abundance (number/m²) for stations in different zones.

Abundance (#/m ²)	Number of stations	Station nos.	Zones
400-800	4	2,3,6,9	I, II, III
1200-1700	4	1,8,10,13	I, III
2300-3300	6	4,5,11,14,19	I, II, III
4500-5000	3	7,16,18	II, III
9500-10,000	2	17,20	I, II

stations in at least two of the three zones. There was no apparent relationship between benthic abundance and water depth; but depths ranged only from 7-19 m.

Qualitatively the Lake Erie bottom fauna was not diverse. Three groups dominated the fauna at all stations, namely oligochaetes, chironomid larvae, and sphaeriids. At most stations oligochaetes were the dominant group.

Oligochaetes outnumbered other animals in three of the five Zone I stations and comprised 26-37% of the fauna at the other stations. Chironomids were dominant at Station 2. Sphaeriids, present at every station, were numerically unimportant except for Station 1 with 850/m² and Station 20, where we found 2500/m², the highest absolute density of sphaeriids in the four lakes. Chironomids were rare or absent at the two stations with large numbers of sphaeriids, and made up 14-46% of the fauna at the others. Leeches and snails occurred at every Zone I station, always in small numbers. We found a few *Gammarus* at Stations 1, 2 and 20, and a few flatworms (*Turbellaria*) associated with pebbles at Station 1.

In Zone II, oligochaetes dominated at every station, accounting for 67-95% of the animals found. Chironomids and sphaeriids were present at all stations, but their relative importance varied along an east-west gradient. At the four easternmost stations (5, 6, 15, 16) chironomids made up 23-30% of the fauna, and sphaeriids were rare (1-6%); at the three westernmost stations (17-19) chironomids were rare (1-4%), and sphaeriids slightly more common (2-10%). As in Zone I, leeches and snails occurred in small numbers at several, but not all stations. *Gammarus* was present at Stations 16 and 17 in the western part of Zone II. At Station 17 a few flatworms and one water mite (*Hydracarina*) were found on a large cinder.

At our central basin stations (Zone III) the bottom fauna was even less diverse than in the western basin. Except for one *Gammarus* at Station 7 and 3 leeches at Station 14, only three groups made up the entire fauna: oligochaetes, chironomids, and sphaeriids. Oligochaetes were present at every station, and were the dominant or co-dominant at most of them. Worm densities were highest at the two westernmost stations: Station 7 near the islands, and Station 14 near Sandusky. Few worms were found at Station 13, near Vermilion. Sphaeriids were most numerous at the easternmost stations (9, 10, 11, 13), where they accounted for 34-72% of the animals, and chironomids were more common at the stations (7, 8) closer to the islands than at the eastern stations. More than 1200 midges/m² were present at Station 8, which was 73% of the animals counted, and the greatest density of chironomids that we found in

the four lakes. However, Station 17 in Saginaw Bay and Station 16 in the western basin of Lake Erie had nearly as many midges.

DISCUSSION

Widespread environmental changes were evident much sooner in Lake Erie than in the open waters of the other Great Lakes. Two major limnological studies were conducted to determine the cause of the collapse of the commercial cisco fishery in the mid-1920's. Both the western basin survey report (Wright 1955) and that of the eastern and central basin survey (Fish et al. 1960) concluded that Lake Erie was relatively unpolluted and that pollution was not the cause of the fishery decline. It is interesting to note that the two reports were published to document eutrophication of the lake 25-30 years after the surveys were completed. These studies provide historical data which are not available for the other Great Lakes.

Another reason that more early data on Lake Erie are available than exist for the other lakes is that the Ohio State University operated the Franz Theodore Stone Laboratory from 1928-1955 on a year-round basis. During this period basic limnological studies were conducted, most notably the series "Limnological Studies of Western Lake Erie" (Chandler 1940, 1942a, 1942b, 1944; Chandler and Weeks 1945), which became a paradigm for Great Lakes limnological studies. Langlois (1954) summarized many of the studies conducted at the Stone Laboratory.

In the 1950's and 1960's changes in Lake Erie were evident to many investigators (Britt 1955; Beeton 1961; J. F. Carr 1962; Davis 1964; Verduin 1964) and became the subject of newspaper and popular magazine articles which focused public awareness on environmental issues (Douglas 1968a,b; Young 1972; Dadisman 1972; Shrag 1969).

By the 1960's Lake Erie was clearly a "problem" area; major studies were undertaken by several agencies. Seven agencies cooperated in synoptic surveys in 1959-1960 (Beeton 1963); the U. S. Federal Water Pollution Control Administration conducted a survey in 1963-1964 (FWPCA 1968a, 1968b); the International Lake Erie Water Pollution Board (1969) reviewed earlier data and reported the results of studies by six agencies in 1965-1967; Weiler and Chawla (1968, 1969) reported some of the chemical results of the CCIW surveys of 1967 and 1968; and CCIW and EPA cooperated on "Project Hypo," an intensive study of the central basin hypolimnion in 1970 (Burns and Ross 1972; also results were published in 1971 as a symposium in the Proceedings of the 14th Conference on Great Lakes Research).

Good sources of references on environmental characteristics of Lake Erie are given in Table II of Beeton (1971); recent volumes of the annual Proceedings of the Conference on Great Lakes Research, published by the International Association for Great Lakes Research; and recent conferences on biological and chemical changes (Sweeney 1969, 1971).

Recent major ion data were reported by Weiler and Chawla (1968), based on eight CCIW cruises. Two of their stations (157, 159) were located in our Zone I; one (162) was in our Zone II; and one offshore station in the central basin (88), while located farther out than any of our stations, was used to compare our Zone III data.

Our conductivity and calcium data are in close agreement with the 1967 observations (Table 24). Weiler and Chawla estimated that there has been a gradual upward trend in Lake Erie conductivity, amounting to about 3-4 μ mhos per year. Both the 1967 and 1970 calcium values are somewhat lower than

TABLE 24. Comparison of Lake Erie major ion data collected in 1967 with the 1970 averages.

	Weiler & Chawla (1968) ^a (1 June-30 October 1967)	This study ^b (31 July-2 August 1970)
Specific conductance		
$\mu\text{mho @ } 25^{\circ}\text{C}$		
Zone I	261 $\pm$ 22	257 $\pm$ 11 (4)
Zone II	283 $\pm$ 22	246 $\pm$ 7 (2)
Zone III	316 $\pm$ 7	293 $\pm$ 9 (8)
Calcium, ppm		
Zone I	32.7 $\pm$ 4.9	32.2 $\pm$ 0.3 (4)
Zone II	34.5 $\pm$ 2.9	32.7 $\pm$ 1.5 (7)
Zone III	38.4 $\pm$ 1.3	38.1 $\pm$ 1.2 (8)
Sulfate, ppm		
Zone I	19.6 $\pm$ 3.4	11.8 $\pm$ 1.1 (4)
Zone II	23.1 $\pm$ 4.3	17.1 $\pm$ 2.7 (7)
Zone III	25.3 $\pm$ 0.6	22.9 $\pm$ 4.2 (8)
Chloride, ppm		
Zone I	19.9 $\pm$ 5.9	14.4 $\pm$ 0.8 (4)
Zone II	19.8 $\pm$ 1.9	13.1 $\pm$ 0.3 (7)
Zone III	25.7 $\pm$ 0.8	14.6 $\pm$ 1.7 (8)

^aData are mean values $\pm$ one standard deviation for 1-m samples.

^bData for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis for surface samples.

previously published figures. Chawla (1971), on the basis of the 1967 Canadian data, revised Beeton's (1965) estimates of the rate of increase of various ions in Lake Erie during the past 50-60 years. Whereas Beeton estimated that calcium was increasing about 1.6 ppm/decade, the later figures indicate that the increase has been less, only about 1.0 ppm/decade.

Our chloride and sulfate values are considerably lower than the 1967 values (Table 24). Canadian values for chloride average 20 ppm in the western basin and 25 ppm in the central basin. The range observed was 14-32 ppm. Our values ranged from 11-17 ppm. Mean chloride values reported for 1963-1964 (FWPCA 1968a) are comparable to the CCIW findings, although the earlier data ranged from 10-46 ppm. There is no obvious reason for a decrease in chlorides between 1967 and 1970. Indeed, one would predict a chloride increase, since the main chloride sources (industrial effluents, 57%; and the upper lakes, 27%; according to Ownbey and Kee 1967) are not known to have decreased in that interval. Rates of chloride increase have been estimated at 2.8 ppm/decade (Beeton 1965) and 2.6 ppm/decade (Chawla 1971).

It is therefore reasonable to question the accuracy of our 1970 chloride values (Table 24) as an artifact of noncomparable methodology or technical error. Our results seem to be valid, however, for three reasons. First, our chloride procedure was identical to that used by the CCIW. Second, technical errors are an unlikely explanation, since the Lake Erie samples were processed during the same runs as the Lake Huron samples (Table 16), and the latter were similar to CCIW values. Third, five analyses made on water collected in August and September near the mouth of the Detroit River at Trenton, Michigan

(where the water quality would likely be comparable to that in Zone I of Lake Erie) ranged from 12-18 ppm (U. S. Geological Survey 1972), close to our values. We can therefore consider that the values for chloride in 1970 may be valid. It is impossible to know whether the low values represent a decrease in chloride concentrations over the entire lake or whether some other explanation, such as the location of sampling stations, is needed. The latter explanation seems plausible, in view of the non-uniform distribution of western Lake Erie chloride shown for 1963 by Beeton, Moffett and Parker (1969).

Our sulfate data are also lower than the 1967 figures, particularly in Zone I where concentrations averaged 12 ppm vs. 20 ppm in 1967 (Table 24). But in Zones II and III the differences were smaller, amounting to only 10 per cent for Zone III. Sulfate determinations averaged from 16-21 ppm in 1963-1964 (FWPCA 1968a) and ranged from 17-18 ppm at the Trenton Station on the Detroit River in August and September 1970 (USGS 1972).

Chawla (1971) recently reviewed the available information on nutrient increases in Lake Erie. The major change came in the period 1948-1962 (Verduin 1964), during which phosphorus increased five-fold. Concentrations of nutrients now exceed the level necessary to trigger algal blooms (Harlow 1966).

Nutrient figures for various recent studies are highly diverse. This is so not only due to differences in analytical procedures, but also because the lake is a spatially and temporally heterogeneous system. An example of the short-term variability in nutrient conditions of western Lake Erie is provided by Brydges (1971b), who sampled eight stations daily for nine days in July 1968. He found that "the ranges observed at all stations for total and soluble phosphorus, nitrate and conductivity were as large within the nine day survey as they had been throughout the entire 1967 season." At Station 395 which was close to Maumee Bay and our Station 18, soluble phosphate ranged from 51-198 ppb (mean = 120), and nitrate nitrogen from 0.18 to 2.8 ppm (mean = 0.39).

Some other recent figures may be mentioned; rigorous comparison, however, does not seem warranted. In 1963-1964, western basin silica averaged (all depths) 1.2 ppm, nitrate 124 ppb, ammonia 160 ppb and soluble phosphate 96 ppb (FWPCA 1968a); by 1967-1968 western basin silica was reduced to around 1 ppm, and nitrate, ammonia and soluble phosphate averages had increased to 200, 170 and 120 ppb, respectively (FWPCA 1968c). Chawla (1971) presented surface and bottom averages for the whole lake in April 1970, which he considers representative of the nutrient content of Lake Erie prior to the growing season. Silica averaged ca. 1.6 ppm, nitrate ca. 225 ppb, ammonia ca. 46 ppb and soluble phosphate ca. 19 ppb.

Lake Erie phosphate supplies continue to be high, but generalizations based on comparisons of the data are difficult because of seasonal and methodological non-comparability as well as the lack of detailed knowledge of the biochemistry of phosphorus in its several forms.

In the western basin, dissolved oxygen in the bottom waters is depleted due to the large oxygen demand in the sediments (J. F. Carr 1962); oxygen depletion occurred in 1963 after only 5 calm days of temporary thermal stratification (Carr, Applegate and Keller 1965). These authors concluded that the conditions necessary for thermal stratification are: 1) a daily average wind speed of less than 6 knots, 2) a highest wind speed of less than 13 knots, and 3) an average daily temperature of more than 18°C. Weather records indicated that such conditions persisted for 5 days or more on 33 occasions between 1953 and 1963, or about 3 times per year.

During our cruise the weather was hot and calm on the days preceding the first sampling day (when we occupied Stations 1-6), but strong winds occurred before we visited Stations 15-20, two days later. Bottom oxygen con-

centrations averaged 7.0 ppm for Stations 1-6 (minimum 4.4 ppm) and 7.7 ppm for Stations 15-20 (minimum 6.7 ppm). This difference may be regarded as minimal because samples were not obtained close to the sediment-water interface where lowest oxygen values could be expected (J. F. Carr 1962).

Dissolved oxygen depletion in the central basin of Lake Erie, where stable thermal stratification is usual in the summer, is now a regular occurrence, the anoxic area covering some 6600 km² (Burns and Ross 1972). The critical oxygen depletion rate, 3 ppm/month, required to consume the hypolimnetic oxygen during the summer, first occurred about 1960 (Dobson and Gilbertson 1972). Dobson and Gilbertson estimate that in the past two decades the rate of depletion has increased 0.075 ppm/month/year. Environmental factors associated with oxygen depletion were investigated intensively in the summer of 1970 during "Project Hypo" (Burns and Ross 1972). Phosphorus regeneration from the sediments was 11 times greater under anaerobic than aerobic conditions, creating a significant "internal loading" of phosphorus during the period of summer anaerobiosis. Major fall algal blooms can therefore be expected by 1980 if nutrient inputs are not reduced.

Phosphorus input to Lake Erie must be reduced immediately; if this is done, a quick improvement in the conditions of the lake can be expected; if it is not done, the rate of deterioration of the lake will be much greater than it has been in recent years.

(Burns and Ross 1972:125)

Our minimum value for dissolved oxygen was 1.1 ppm at Station 13, but our central basin stations included only a small corner of the critical area and were occupied before the critical period. Presently anoxic conditions are not expected until August (Dobson and Gilbertson 1972).

The alga *Tribonema utriculosum* was first observed in 1969 growing on the sediments in the central basin (Kleveno, Braidech and Gehring 1971). These authors speculated that this alga (and *Oedogonium* sp.) exists on the bottom until light penetration is reduced by plankton blooms in the overlying water. Death and decomposition of the benthic algae cause an increased oxygen demand near the sediments, accelerating depletion of hypolimnetic oxygen in August. This theory was verified in 1970 by observations as part of "Project Hypo" (Braidech, Gehring and Kleveno 1972).

Turbidity in the western basin may be due largely to inorganic materials and is influenced greatly by meteorological conditions (Andrews 1948; Chandler 1942a). Secchi disc transparency in the western basin apparently has not changed greatly in the past 30 years. Our data and those collected by Chandler from 1938-1942 (Chandler 1940, 1942b, 1944; Chandler and Weeks 1945) do not seem to differ. In fact the older data indicate that transparencies were less for comparable time periods than our measurements taken 30 years later.

Our primary productivity observations can be compared with recent observations of Parkos, Olson and Odlaug (1969) who sampled one station in our Zone I and one station in our Zone II on 27 July 1968. They reported 32 mg C/m³/hr in Zone I, where our values averaged around 9 mg C/m³/hr. At their central basin station they found 14 mg C/m³/hr, less than our mean value of 23 mg C/m³/hr. Glooschenko and Moore (1972) reported primary production data based on 13 cruises in 1970. Their western basin values ranged from 3-228 mg C/m³/hr, and the central basin stations ranged from 1-46 mg C/m³/hr. The western basin had a midsummer maximum; the central basin had peaks in the late summer and early fall. They found highest assimilation ratios in the western basin (maximum 3.48 mg C/hr/mg Chl *a*); our assimilation ratios were slightly higher, averaging from 3.7 (Zone I) to 4.9 mg C/hr/mg Chl *a* (Zone III).

Variability among primary production data collected in western Lake Erie is additional evidence of a complex, heterogeneous system. Productivity values in the western basin during 1957-1958 were also large. Verduin (1960) reported CO_2 absorption rates in the open water ranging from 0.60 to 1.68 mg C/m³/day or equivalent to a range of 50 to 140 mg C/m³/hr based on a 12-hour day. In bottles the rates of CO_2 absorption were similar, also ranging from 50 to 140 mg C/m³/hr.

Changes in the phytoplankton of Lake Erie associated with eutrophication have been documented (Davis 1964; Hohn 1969). From collections made at the water intake for Cleveland, Ohio, Davis reported a marked increase in standing crop from 1919 to 1963. He observed larger spring and fall pulses and the loss of a winter minimum with time. Hohn has shown that the number of cells in the spring and fall diatom pulse increased from 1939 to 1965 and that the two pulses in 1939 changed to three pulses, spring, summer and fall by 1965. He also documented changes at the species level with time. Some species that were formerly abundant or common have disappeared, and others that were not present or observed occasionally have become major dominants. Other species have not changed in terms of numbers per ml, indicating that their population size is not controlled by pollution-induced factors.

Studies by Chandler from 1938-1942 were conducted at frequent intervals (approximately weekly). One of the important conclusions from Chandler's investigations was that year-to-year variations in the standing crop were so great that limited data from a variable environment like the western basin may be misleading in terms of adequately describing or understanding the system (Table 25). A threefold variation was noted in the annual crop of phytoplankton and a fivefold variation in spring and autumn crops. The variation is due primarily

TABLE 25. Phytoplankton standing crops as percent of 1941 crops in western Lake Erie (from Chandler and Weeks 1945).

Year	Annual crop	Spring crop	Autumn crop
1939	47	17	98
1940	29	25	23
1941	100	100	100
1942	45	19	86

to the exceptionally large values in 1941, but the annual crops in 1939 and 1942 were 50% larger than the crops in 1940. An even larger variation was found by Verduin (1951) who observed standing crops of organic matter 12 times as large in 1949 as in 1950. Most of the organic matter can be attributed directly to phytoplankton.

Chandler's studies during the four years showed a bimodal phytoplankton standing crop with a spring and fall pulse. Spring pulses started under ice cover and occurred between February and May; fall pulses occurred between July and November. *Asterionella* dominated the spring pulses with *Synedra* co-existing in 1940. Other dominants in the spring pulse were *Fragilaria*, *Tabel-laria*, and *Melosira*. In contrast to spring pulses dominated by diatoms, autumn pulses contained greater proportions of greens and blue-greens, with diatoms comprising only 25 to 70% of the phytoplankton. Initially, fall pulses were dominated by blue-greens followed by "ascendancy of the diatom population in September."

Our collections were probably made during the beginning of the autumn pulse and, as expected from Chandler's studies, blue-greens dominated the population. Dominant genera in our collections were *Aphanizomenon* and *Microcystis*; *Aphanizomenon* had been the most abundant blue-green in Chandler's studies. He also found *Microcystis*, but *Chroococcus*, *Coelosphaerium*, and in one year *Merismopedia*, were more abundant genera of blue-greens than *Microcystis*. Of these three genera only *Coelosphaerium* occurred in our collections from Lake Erie.

In addition to the blue-greens, *Aphanizomenon* and *Microcystis*, abundant genera in our collections were *Staurastrum* and *Ceratium*. Neither *Staurastrum* nor *Ceratium* appeared to be abundant from 1938-1942. Chandler found *Staurastrum* in July and August in quantities that did not exceed 1500 phytoplankton units/liter compared to blooms of *Aphanizomenon* which ranged from 36,000 to 336,000 phytoplankton units/liter in different years. Chandler grouped *Ceratium* with the Protozoa, and results are available only for 1938 and 1939 (Chandler 1940), but he reported this genus as being rare. Davis (1964) found that *Anabaena* and *Pediastrum* became more important at the Cleveland water intake in the fall pulse after 1948 and that *Microcystis* dominated the autumnal phytoplankton of 1956 in Cleveland Harbor.

Comparison of our data with Chandler's and Davis's indicates that the beginning of the fall pulse is still dominated by blue-greens, but that now *Microcystis* is relatively more abundant, and that *Ceratium* and *Staurastrum* make up a much larger proportion of the bloom than 30 years ago.

The zooplankton has also undergone changes in recent years (reviewed by Davis 1966a). Early zooplankton data are available from 1928-1930 (Wilson 1960; Wright and Tidd 1955) and from 1938-1939 (Chandler 1940). Zooplankton before 1940 was quantitatively richer than that of the upper lakes, and it contained a higher percentage of cladoceran species. Abundance of copepods and cladocera in 1959 was greater than in 1939 or 1949 (Bradshaw 1964). Cladoceran species found in the early studies were not perennial; later collections showed that these species were abundant for more of the year. Several species increased in relative abundance, including *Daphnia retrocurva*, *Chydorus sphaericus*, *Diaptomus siciloides*, and *Eurytomora affinis*. The last named species is a marine invader which was first observed in 1961 (Engel 1962). Gannon and Beeton (1971) recently documented the decline of *Limnocalanus macrurus*.

Detailed studies of zooplankton were published by Davis based on samples collected by the FWPCA in July 1967 (Davis 1968), October 1967 and January 1968 (Davis 1969). In the July samples, rotifers, daphnids and *Bosmina* were more abundant in the western basin than in the central basin, and copepods were more abundant in the central basin. Although our collections were not evaluated quantitatively nor identified to species, the major results agree with the 1967 data.

Prior to 1953 the benthos of western Lake Erie was unlike that of the other Great Lakes. Western Lake Erie not only supported a rich and diverse invertebrate bottom fauna, but also supported a large commercial fishery. The broad expanse of shallow water, well oxygenated by currents and seiches, with a short residence time, gave the area west of the islands a decidedly riverine character. On the basis of its rich naiade (mussel) fauna, it was called a "river lake" (van der Schalie 1961).

Burrowing mayflies, mussels (naiades), caddisflies and midges (the "*Hexagenia-Oecetis* community" of Shelford and Boesel 1942) formerly dominated the offshore, mud-bottomed areas of western Lake Erie. Thirty naiade species were reported from Lake Erie (Walker 1913; Goodrich and van der Schalie 1932). Before 1947, *Hexagenia* nymphs averaged over 350/m² (Chandler 1963), and their

winged stages ("Canadian soldiers") caused brief but truly massive swarms along the shore. As late as 1951-1952, when studied by Wood (1963), the bottom fauna was diverse and abundant; the dominant form numerically was *Hexagenia*, although the naiades (shells excluded) accounted for three-fourths of the wet weight. One naiade species, *Lampsilis siliquioidea* accounted for nearly half the total benthic biomass.

Following the low-oxygen catastrophe of 1953 which decimated the *Hexagenia* population (Britt 1955) the bottom fauna changed rapidly. The benthos stations sampled in 1930 (Wright 1955) were resampled in 1961 by Carr and Hiltunen (1965). They concluded that

the most important changes in fauna during the 31-year period were: ninefold increase in Oligochaeta; fourfold increase in Tenipodidae [=Chironomidae]; twofold increase in Sphaeriidae; sixfold increase in Gastropoda; and a reduction of *Hexagenia* to less than 1% of former abundance. The area of pollution (as judged from the abundance of Oligochaeta) increased from 263 km² in 1930 to 1,020 km² in 1961.

The "heavily polluted" zones in 1961 (those with over 5,000 oligochaetes/m²) were concentrated around the mouths of the Detroit, Raisin and Maumee Rivers. Most of the area within 14 km of the western shore was judged "moderately polluted" (1,000-5,000 oligochaetes/m²). Qualitatively, over 90% of the oligochaetes in the degraded areas were pollution-tolerant species of *Limnodrilus* (Hiltunen 1969). Most of the chironomids belonged to the genus *Procladius*, another tolerant group (Carr and Hiltunen 1965).

Some qualitative aspects of the oligochaetes, chironomids and sphaeriids were reported by Brinkhurst, Hamilton and Herrington (1968), and Brinkhurst (1969), based on collections made in 1963 by the Great Lakes Institute, University of Toronto. Most of the chironomids found in western Lake Erie by 1963 were *Chironomus plumosus* (or a closely related species), which caused them to classify the area as "extremely eutrophic."

By 1963, the Japanese snail, *Viviparus japonicus*, an introduced species, was found in Lake Erie and was particularly abundant in Sandusky Bay, where it was a nuisance to commercial fishermen, who sometimes caught two tons in one seine haul (Wolfert and Hiltunen 1968).

Studies in 1963-1964 revealed less faunal diversity than the 1961 study (FWPCA 1968a). Amphipods only occurred well offshore; inshore stations were dominated by oligochaetes, chironomids, sphaeriids, nematodes, leeches, snails and isopods. The last four named were scarce, and totally absent near the Michigan shore.

A study by the Ontario Water Resources Commission (OWRC) in 1967 of western Lake Erie benthos (Veal and Osmond 1968) found over 99% of the animals belonged to four groups: oligochaetes (86%), sphaeriids (7%), chironomids (6%), and snails (1%). Amphipods were found at only six of their 42 stations, isopods (*Asellus*) at two. Three naiade species were found in unimportant numbers in open water. A single caddisfly specimen (*Oecetis*) was found. *Hexagenia* was absent.

Information provided by our study indicates that conditions for bottom fauna in western Lake Erie continue to deteriorate. Although our stations were located farther offshore than the "heavily polluted" zones of 1961 (Carr and Hiltunen 1965), our Stations 17 and 20 with more than 5,000 oligochaetes/m² fit this category. All but four of our stations had over 1,000 oligochaetes/m² and would be considered "moderately polluted" by Wright's (1955) criterion. Stations 1, 2, and 3, near the Canadian shore and Station 6 near the islands had less than 1,000 oligochaetes/m². Amphipods were found at only 5 of the 12

western basin stations, and no other pollution-intolerant forms (e. g. *Asellus*) occurred. No living naiades were collected, although earlier workers (Wood 1963; Carr and Hiltunen 1965) found maximum numbers offshore, where all our stations were located. Although our sampling effort was only about 30% that expended by Carr and Hiltunen in offshore areas, the total absence of naiades in 1970 makes it reasonable to suppose that they may be extinct or very rare. No mayflies or caddflies were found.

Unlike the case of western Lake Erie, little information is available about the bottom fauna of the central basin (Davis 1966b). The survey of 1928-1929 (Fish et al. 1960) unfortunately did not include benthos sampling. At that time there was plentiful hypolimnetic oxygen, but because the central basin is shallow (maximum = 26 m) the bottom temperatures in summer were over 12°C. In the absence of any data from that early period it is reasonable to suppose that the bottom fauna was composed of a more mesotrophic association than was found in the upper lakes, perhaps including gammarids, *Asellus* and chironomids in the deep water and mayflies in the sublittoral. This is consistent with the occurrence of *Mysis* and *Pontoporeia* in summer plankton samples in 1928-1929 (Wilson 1960): they only occurred in the deep (over 50 m) hole in the eastern basin. The hypolimnion of most of the central basin has been anaerobic or nearly so in summer since 1960. Virtually the only comparative data available were collected in 1963 and 1964 (FWPCA 1968a), by which time what must have been the original benthic association was largely replaced by species tolerant of anaerobiosis, consisting of oligochaetes, chironomids, sphaeriids and nematodes. In a narrow zone south of Point Pelee, which includes our Station 7, a few other forms including Amphipods (not *Pontoporeia*) were found. Qualitatively, the species found in the central basin in 1963 by the Great Lakes Institute were classified as only slightly less eutrophic than those from the western basin (Brinkhurst 1969).

In the central basin, we found a single *Gammarus* at Station 7, a single snail at Station 11 and three leeches at Station 14; at all the other stations the fauna consisted only of oligochaetes, chironomids and sphaeriids. These widely spaced stations (7, 11 and 14) had over 1,000 oligochaetes/m², and so would be classified as "moderately polluted" by Wright's (1955) criterion.

COMPARISON OF LAKES

In the preceding chapters we have described and discussed various limnological characteristics of each of the four lakes, enabling us to divide the lakes into ten distinct geographical zones. In this chapter we will compare data on some of the parameters for the ten zones. Certain relationships as well as differences between different lakes and zones will become apparent from these comparisons. We will consider these relationships and differences as they relate to pollution, eutrophication, or both eutrophication and pollution of the Great Lakes.

To present our data for comparison of the four lakes, we have summarized the data in a number of tables for different physical, chemical, and biological parameters (Tables 26-32, 34, 35).

TEMPERATURE AND DISSOLVED OXYGEN

Temperature regimes varied greatly among the four lakes due to differences in latitudes and depths of the lakes as well as the time of sampling. Lake Superior, the deepest and northernmost lake, was sampled early in July during limnological spring when thermal stratification was poorly developed. Surface temperatures averaged 8.4°C (Table 26). In greatest contrast to the cold, deep lake are the western basin of Lake Erie and Saginaw Bay in Lake Huron, where mean surface temperatures ranged from 23 to 24°C . In these warm, shallow areas, thermal stratification was also poorly developed with mean bottom temperatures ranging from 17 to 23°C . Pronounced summer thermal stratification with a discernible epilimnion, thermocline and cold hypolimnion occurred only in the deep open-lake stations in Lake Huron and Lake Michigan.

Surface waters of the four lakes were generally saturated with oxygen, but were supersaturated in the central basin of Lake Erie and in the open waters of Lake Superior. Supersaturation was attributed to algal production in Lake Erie and to temperature changes in Lake Superior.

In the central basin of Lake Erie, comparison of the mean surface temperature with the mean concentration of dissolved oxygen indicates 120% saturation (Table 26). Supersaturation was undoubtedly due to the production of oxygen by phytoplankton, a conclusion supported by concentrations of dissolved oxygen at 2 m which were larger than surface values in some cases, and by the fact that during the day of sampling in the central basin, both water temperatures and dissolved oxygen concentrations increased as the day progressed.

In Lake Superior the mean dissolved oxygen concentration (13.1 ppm) for bottom samples was about 105% saturated at the mean temperature (3.8°C) (Table 26). At stations which were not stratified, temperatures ranged from 3.0 to 4.0° , and dissolved oxygen concentrations ranged from 13.0 to 13.6 ppm. Saturated values for dissolved oxygen at these temperatures are 12.7 and 12.4 ppm, respectively. The same techniques used a few days earlier on Lake Michigan revealed 12.5 ppm of oxygen at Station 4 where the water temperature was 4.0°C . If the cold water masses of Lake Superior are in fact saturated with oxygen prior to stratification, the degree of supersaturation during the spring turnover may be related to winter water temperatures. The main part of Lake

TABLE 26. Summary of temperature and dissolved oxygen in all zones of the four lakes. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis.

	Temperature, °C		Dissolved Oxygen, ppm	
	Surface	Bottom	Surface	Bottom
Lake Superior				
Open lake	8.4 $\pm$ 3.7 (30)	3.82 $\pm$ 0.36 (29)	12.5 $\pm$ 0.87 (20)	13.1 $\pm$ 0.46 (20)
Bays	14.1 $\pm$ 1.2 (5)	4.45 $\pm$ 0.64 (2)	10.8 $\pm$ 0.21 (4)	13.2 $\pm$ 0.46 (1)
Lake Huron				
Open lake (I)	16.5 $\pm$ 1.2 (7)	4.62 $\pm$ 0.84 (5)	10.1 $\pm$ 0.37 (6)	11.5 $\pm$ 0.67 (5)
Open lake (II)	18.5 $\pm$ 1.6 (8)	4.68 $\pm$ 0.82 (5)	9.51 $\pm$ 0.27 (8)	11.8 $\pm$ 0.20 (5)
Open lake (IV)	20.6 $\pm$ 0.9 (5)	13.9 $\pm$ 2.7 (10)	9.40 $\pm$ 0.20 (5)	10.0 $\pm$ 0.26 (10)
Saginaw Bay (III)	22.7 $\pm$ 1.1 (6)	16.5 $\pm$ 2.7 (6)	9.58 $\pm$ 0.50 (6)	9.35 $\pm$ 0.48 (6)
Lake Michigan				
Open lake	14.2 $\pm$ 1.2 (6)	4.10 $\pm$ 0.14 (2)	10.1 1.4 (2)	12.5 (1)
Lake Erie				
W. B. North (I)	24.0 $\pm$ 0.9 (5)	22.6 $\pm$ 0.8 (5)	8.62 0.49 (4)	7.60 $\pm$ 0.6 (5)
W. B. South (II)	24.4 $\pm$ 0.4 (7)	23.0 $\pm$ 1.1 (7)	8.13 0.76 (7)	7.20 $\pm$ 1.4 (7)
C. B. (III)	24.9 $\pm$ 0.5 (8)	16.3 $\pm$ 5.2 (8)	9.56 0.58 (8)	5.15 $\pm$ 2.3 (8)

Superior does not freeze, so one would expect that the lake would be well mixed and saturated with oxygen during the winter circulation. When the lake warms in the spring, the rate of oxygen loss is less than the rate of warming, and the water becomes supersaturated. Supersaturated values have been observed by Dobson⁵, who reported a lake-wide mean surface temperature of 0.9°C (Dobson 1972) in April 1970.

MAJOR ION CHEMISTRY

Understanding the hydrological relationships of the Great Lakes system (Table 1) provides an opportunity to evaluate the chemical significance of man's impact on the environment. Input of pollutants influences water quality as water flows from Lake Superior to Lake Huron and then to Lake Erie. This influence can be shown by comparing major ion chemistry among the lakes. Data for two parameters, alkalinity and calcium, show relatively little variation, whereas values for conductivity, sulfate and chloride were greater in Lake Erie than in open Lake Huron (Table 27), indicating an input of pollutants downstream from Lake Huron (Fig. 1).

Calcium and alkalinity values are largely controlled by the mineralogical characteristics of the drainage basin; in contrast, inputs of sulfate and chloride are largely the products of urbanization and industrialization. Calcium and alkalinity values in Lake Huron are intermediate between Lake Michigan and Lake Superior, and values for both in the central basin of Lake Erie are similar to, but not greater than, those found in Lake Michigan (Table 27). On the other hand, values for conductivity, sulfate and chloride are all larger in the central basin of Lake Erie than in Lake Michigan. Sources of these pollutants can be traced generally to Saginaw Bay, the Detroit River or the southern part of the western basin of Lake Erie by comparing the values among zones sampled (Table 27).

Saginaw Bay contributes relatively more chloride than sulfate to the open waters of Lake Huron (Table 27). Above Saginaw Bay in Lake Huron (Zone II), chloride concentrations averaged 5.0 ppm less than Saginaw Bay. The input from Saginaw Bay was great enough to increase the average concentration in the open lake below Saginaw Bay (Zone IV) by 1.0 ppm compared to stations above Saginaw Bay (Zone II). Sulfate, on the other hand, was only about 2.0 ppm more concentrated in Saginaw Bay than in the open lake. Sulfate data are not available to make comparisons among the open lake zones, but the relationships are reflected generally by averages for surface conductivity (Table 27).

Concentrations of chloride varied little among the zones sampled in Lake Erie (Table 27), indicating that the chief source is the Detroit River. Concentrations of chloride were about twice as large in Lake Erie as in Lake Huron. On the other hand, concentrations of sulfate in the northern part of the western basin only averaged 1.0 ppm more than in Lake Huron (Zone IV), indicating that sulfate contributions from the Detroit River are less than chloride. Sulfate input appeared to be from sources in the southern part of the western basin and possibly from sources in the central basin, because average concentrations were largest in the central basin and smallest in the northern part of the western basin.

MAJOR PHYTOPLANKTON NUTRIENTS

Two major plant nutrients, unlike the conservative ions discussed in the preceding section, are diluted as water moves from Lake Superior via Lake

⁵See footnote 1, p. 23.

TABLE 27. Summary of pH, alkalinity, conductivity, calcium, sulfate and chloride in all zones of the four lakes. Data for each parameter are given as the mean of all depths sampled $\pm$ one standard deviation followed by the number of observations in parenthesis.

	pH	Alkalinity ppm	Specific conductance μ mho @ 25°C	Calcium ppm	Sulfate ppm	Chloride ppm
Lake Superior						
Open lake	8.04 $\pm$ 0.10 (87)	43.9 $\pm$ 1.8 (85)	95 $\pm$ 4.8 (30)	14.5 $\pm$ 1.6 (68)	1.46 $\pm$ 0.41 (57)	1.06 $\pm$ 0.08 (70)
Bays	8.01 $\pm$ 0.26 (19)	41.9 $\pm$ 2.4 (19)	93 $\pm$ 3.0 (5)	14.7 $\pm$ 0.9 (15)	1.85 $\pm$ 0.49 (13)	1.13 $\pm$ 0.10 (15)
Lake Huron						
Open lake (I)	8.50 $\pm$ 0.04 (7)	76.5 $\pm$ 1.9 (25)	192 $\pm$ 8.0 (7)	21.2 $\pm$ 1.7 (21)		4.6 $\pm$ 1.5 (21)
Open lake (II)	8.38 $\pm$ 0.16 (24)	76.5 $\pm$ 6.7 (24)	195 $\pm$ 5.7 (8)	26.5 $\pm$ 0.6 (24)	10 (1)	5.6 $\pm$ 0.9 (23)
Open lake (IV)	8.40 $\pm$ 0.06 (15)	82.5 $\pm$ 1.2 (15)	204 $\pm$ 2.7 (5)	28.0 $\pm$ 0.8 (13)	10.9 $\pm$ 0.72 (12)	6.6 $\pm$ 1.4 (16)
Saginaw Bay (III)	8.65 $\pm$ 0.17 (18)	88.6 $\pm$ 3.7 (18)	247 $\pm$ 20 (6)	30.3 $\pm$ 1.7 (18)	12.8 $\pm$ 1.8 (5)	10.6 $\pm$ 2.3 (18)
Lake Michigan						
Open lake	8.50 $\pm$ 0.16 (19)	109 $\pm$ 2.8 (19)	261 (1)	37.4 $\pm$ 1.6 (17)	15.5 $\pm$ 3.0 (17)	7.22 $\pm$ 0.32 (16)
Lake Erie						
W.B. North (I)	8.63 $\pm$ 0.25 (5) ^a	83.7 $\pm$ 2.1 (14)	257 $\pm$ 11 (4)	31.6 $\pm$ 1.2 (10)	11.8 $\pm$ 0.84 (14)	14.3 $\pm$ 1.3 (14)
W.B. South (II)	8.82 $\pm$ 0.11 (7) ^a	88.1 $\pm$ 2.9 (21)	246 $\pm$ 7 (2)	32.7 $\pm$ 1.6 (14)	16.7 $\pm$ 2.4 (16)	13.2 $\pm$ 0.5 (20)
C.B. (III)	8.93 $\pm$ 0.06 (8) ^a	92.5 $\pm$ 2.5 (24)	293 $\pm$ 9 (8)	37.8 $\pm$ 1.2 (16)	21.6 $\pm$ 3.3 (16)	14.6 $\pm$ 1.6 (24)

^a Surface values only.

Huron to Lake Erie. Silica and nitrate nitrogen in the outflow from Lake Superior are diluted in Lake Huron by the outflow from Lake Michigan since the oligotrophic waters of Lake Superior contain greater concentrations of these two nutrients than the more eutrophic waters of Lake Michigan (Table 28). Silica concentrations in the outflow from Lake Michigan during the summer stratification are characteristic of surface waters, averaging about one-tenth those of Lake Superior. When Lake Michigan waters are thoroughly mixed, i.e. in the winter when there is no thermal stratification, silica concentrations would be greater than in the summer but about half those in Lake Superior because silica concentrations in bottom waters are less in Lake Michigan (Tables 4, 11) than for any depth interval in Lake Superior. Nitrate is not diluted as much by mixing waters from the two lakes because the maximum differences in concentration during the summer are smaller than for silica or only about 50% less in Lake Michigan than in Lake Superior (Table 28).

Absolute levels of silica and nitrate nitrogen in Lake Huron are controlled to a large extent by concentrations of the nutrients in inputs from Lake Michigan and Lake Superior. On the other hand, it is obvious from silica concentrations in surface waters (Table 28) that other factors affect concentrations in Lake Huron. Average concentrations of silica in surface waters decrease from north to south in the open-lake zones, indicating the cumulative effects of utilization by diatoms.

Depletion of silica and nitrate in the epilimnion increases with increasing degree of eutrophication, decreasing reserves of these nutrients.⁶ It is assumed that nitrate nitrogen is the principal nitrogen source for algal growth in the upper Great Lakes, where eutrophication has not reached a state in which supplies of nitrate are depleted during summer stratification. On the other hand, data for more eutrophic areas suggest that phytoplankton deplete nitrate supplies to limiting or near limiting concentrations in surface waters of Saginaw Bay and the central basin of Lake Erie (Table 28). One would have to conclude that nitrate would become limiting during the summer unless additional nitrate was supplied, ammonia or some other form of nitrogen was utilized, nitrogen was being regenerated rapidly, free nitrogen was being fixed by nitrogen fixers, or some combination of these alternatives was operative. Nitrogen is probably supplied by all these alternative mechanisms. Evidence for nitrogen fixation has been obtained for Lake Erie (Howard et al. 1970) and for Green Bay (Stewart et al. 1971; Vanderhoef et al. 1972), a eutrophic part of Lake Michigan. Green Bay has characteristics associated with eutrophic waters similar to Saginaw Bay and western Lake Erie (Schelske and Callender 1970).

Silica is supplied in smaller amounts than nitrate nitrogen relative to the amounts required for phytoplankton growth, and as a consequence is depleted more rapidly.⁷ Lake Michigan is the only lake we sampled in which supplies of silica (Table 28) are depleted in the open waters over the entire lake. Silica is depleted more rapidly in the southern part of Lake Michigan than in the northern part we sampled, but nitrate nitrogen is not depleted (Schelske and Callender 1970).

Direct evidence has been obtained that phosphorus limits algal growth in Lake Michigan (Schelske and Stoermer 1971, 1972) and in Lake Superior

⁶Schelske, C. L. 1971. Eutrophication of Lake Michigan in relation to nutrient inputs, particularly phosphorus and silica. Unpublished report, Great Lakes Research Division. Paper presented at Symposium on Interaction between Land and Water jointly sponsored by International Ecological Society and Societas Internationalis Limnologiae, Aug. 1971, Leningrad.
⁷*Ibid.*

TABLE 28. Summary of silica, nitrate nitrogen and particulate phosphorus in all zones of the four lakes. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations in parenthesis. Bottom is the depth interval from 72-390 m in Lake Superior, 32-80 m in Lake Huron, and 110-125 m in Lake Michigan.

	SiO ₂ , ppm		NO ₃ -N, ppb		Part. PO ₄ , ppb	
	Surface	Bottom	Surface	Bottom	Surface	Bottom
Lake Superior						
Open lake	2.28 $\pm$ 0.07 (25)	2.28 $\pm$ 0.21 (23)	254 $\pm$ 14 (25)	264 $\pm$ 7.7 (23)		
Bays	2.10 $\pm$ 0.13 (5)	2.31 $\pm$ 0.01 (2)	229 $\pm$ 11 (5)	263 $\pm$ 2.1 (2)		
Lake Huron						
Open lake (I)	1.07 $\pm$ 0.15 (7)	1.80 $\pm$ 0.16 (5)	139 $\pm$ 31 (7)	159 $\pm$ 33 (5)	13 $\pm$ 0.8 (2)	41 (1)
Open lake (II)	0.81 $\pm$ 0.15 (8)	1.78 $\pm$ 0.19 (5)	141 $\pm$ 24 (8)	190 $\pm$ 52 (5)	19 $\pm$ 23 (7)	11 $\pm$ 14 (4)
Open lake (IV)	0.65 $\pm$ 0.11 (5)		136 $\pm$ 35 (5)		12 $\pm$ 5.4 (5)	
Saginaw Bay	1.08 $\pm$ 0.26 (6)		21 $\pm$ 16 (6)		37 $\pm$ 19 (6)	
Lake Michigan						
Open lake	0.27 $\pm$ 0.05 (4)	1.28 $\pm$ 0.08 (2)	129 $\pm$ 6 (4)	190 $\pm$ 4 (2)	8 $\pm$ 10 (2)	12 $\pm$ 0.5 (2)
Lake Erie						
W.B. North	0.97 $\pm$ 0.12 (4)	1.24 $\pm$ 0.35 (5)	79 $\pm$ 46 (4)	106 $\pm$ 52 (5)	12 $\pm$ 4.8 (4)	18 $\pm$ 7.8 (3)
W.B. South	0.66 $\pm$ 0.26 (7)	0.85 $\pm$ 0.20 (7)	86 $\pm$ 33 (7)	125 $\pm$ 51 (7)	53 $\pm$ 24 (6)	53 $\pm$ 31 (7)
C.B.	0.25 $\pm$ 0.10 (8)	1.36 $\pm$ 0.76 (8)	34 $\pm$ 24 (8)	103 $\pm$ 57 (8)	15 $\pm$ 15 (5)	39 $\pm$ 54 (3)

(Schelske et al. 1972). As the supplies of phosphorus increase, larger standing crops of phytoplankton are produced which utilize nutrients and deplete concentrations in the epilimnion relative to the hypolimnion. When supplies of silica become limiting, the typical phytoplankton assemblage dominated by diatoms is replaced by assemblages with smaller and smaller proportions of diatoms.⁸ Under such conditions, diatoms may not be able to compete for nutrients as effectively as other phytoplankton, and silica may not be depleted, as indicated by data for Saginaw Bay and the western basin of Lake Erie (Table 28).

Other studies have shown an obvious relationship between phosphorus and environmental factors related to eutrophication. The rate of oxygen depletion in the central basin of Lake Erie has increased as a function of municipal phosphorus loadings (Gilbertson, Dobson and Lee 1972). Station averages of chlorophyll *a* (mg/m³) and total phosphorus (μg P/liter) for open lake stations in western Lake Erie were related by regression analysis. Lines fitted were:

$$\text{Chlor } a = -2.5 + 0.23 (\text{total P}) \text{ for 1967 data, and}$$

$$\text{Chlor } a = -2.1 + 0.25 (\text{total P}) \text{ for 1969 data}$$

(Brydges 1971a)

Data from the Detroit River and other areas near nutrient sources with high phosphorus values but relatively lower chlorophyll values were omitted. Dobson⁹ related Secchi disc transparency (SD) and surface concentrations of particulate phosphorus (PP) from data for all the Great Lakes except Michigan.

$$\text{SD} = \frac{30}{\text{PP}}$$

Dobson's empirical relationship was based largely on data for Lake Erie and seems to overestimate particulate phosphorus in Lake Superior where one would infer that the relationship might be closer to:

$$\text{SD} = \frac{20}{\text{PP}}$$

These data and others indicate that particulate or total phosphorus concentrations are good measures of trophic state in the Great Lakes because phosphorus is the nutrient that limits phytoplankton growth and controls standing crops.

CHLOROPHYLL AND CARBON FIXATION

The lakes studied ranked in order of most oligotrophic to most eutrophic are Lake Superior, Lake Huron, Lake Michigan and Lake Erie, with Saginaw Bay being as eutrophic as parts of Lake Erie. Concentrations of chlorophyll with the exception of "bays" in Lake Superior increase from the least oligotrophic to the more eutrophic, and rates of carbon fixation can be ranked in the same order (Table 29). Three trophic zones in Lake Erie can be differentiated with these parameters: the highly eutrophic southern part of the western basin, the less eutrophic central basin, which had chlorophyll concentrations and rates of carbon fixation that were similar to Saginaw Bay, and the northern part of the western basin. The northern part of the western basin is the least eutrophic part of Lake Erie, but it is obviously more eutrophic than open lake areas in the other lakes.

⁸See footnote 6.

⁹Dobson, H. 1972. Nutrients in the Great Lakes: a new comparison. Unpublished report Canada Centre for Inland Waters. Burlington, Ontario. 82 p.

TABLE 29. Summary of transparency, chlorophyll *a*, carbon fixation and assimilation ratio in all zones of the four lakes. Data for each parameter are given as the mean $\pm$ one standard deviation followed by the number of observations.

	Transparency, m	Chlorophyll <i>a</i> mg/m ³	Carbon fixation mg C/m ³ /hr	Assimilation ratio mg C/hr/mg Chl <i>a</i>
Lake Superior				
Open lake	12.6 $\pm$ 3.4 (30)	0.66 $\pm$ 0.42 (27)	0.37 $\pm$ 0.18 (67)	0.82 $\pm$ 0.45 (15)
Bays	6.6 $\pm$ 1.1 (5)	1.46 $\pm$ 0.19 (5)	0.59 $\pm$ 0.14 (15)	
Lake Huron				
Open lake (I)	9.1 $\pm$ 2.4 (7)	0.81 $\pm$ 0.72 (7)	0.77 $\pm$ 0.38 (4)	1.26 $\pm$ 1.0 (4)
Open lake (II)	8.0 $\pm$ 2.4 (7)	0.86 $\pm$ 0.46 (8)	1.69 $\pm$ 0.51 (5)	2.67 $\pm$ 1.4 (5)
Open lake (IV)	5.9 $\pm$ 0.62 (5)	0.85 $\pm$ 0.04 (4)	1.50 $\pm$ 0.53 (4)	1.76 $\pm$ 0.63 (4)
Saginaw Bay (III)	1.8 $\pm$ 0.40 (6)	7.26 $\pm$ 3.1 (6)	28 $\pm$ 17 (5)	4.16 $\pm$ 2.5 (5)
Lake Michigan				
Open lake	4.8 $\pm$ 0.6 (6)	1.34 $\pm$ 0.62 (7)	2.40 $\pm$ 0.82 (13)	0.74
Lake Erie				
W. B. North	1.96 $\pm$ 0.43 (5)	3.65 $\pm$ 1.3 (5)	11 $\pm$ 5.1 (3)	3.75 $\pm$ 2.9 (3)
W. B. South	1.99 $\pm$ 0.53 (7)	12.1 $\pm$ 3.8 (7)	58 $\pm$ 18 (5)	4.91 $\pm$ 0.78 (5)
C. B.	4.41 $\pm$ 1.21 (8)	7.3 $\pm$ 6.7 (8)	24 $\pm$ 16 (5)	3.78 $\pm$ 1.5 (5)

Transparency measurements generally reflect an inverse relationship with the trophic state as measured either by rates of carbon fixation or concentrations of chlorophyll (Table 29). There are obvious exceptions which qualify this simplistic approach. Secchi disc transparency in Lake Michigan was similar to that in the central basin of Lake Erie where concentrations of chlorophyll and rates of carbon fixation were larger than in Lake Michigan. Averages also show similar transparencies in both zones of the western basin of Lake Erie and in Saginaw Bay but different values for chlorophyll and rates of carbon fixation. Reduced transparencies in the northern part of the western basin obviously can not be attributed entirely to standing crops of phytoplankton because rates of carbon fixation and chlorophyll concentrations are smaller in this zone than in the other zones. Turbidity due to inorganic materials reduces transparency in the western basin of Lake Erie.

Photosynthetic assimilation ratios have been used to describe the nutrient conditions for phytoplankton populations. Curl and Small (1965) investigated the assimilation ratio in marine phytoplankton communities and concluded that ratios less than 3 indicated "nutrient depletion," those between 3 and 5 indicated "borderline nutrient deficiency," and ratios between 5 and 10 indicated "nutrient-rich" waters. But the photosynthesis/chlorophyll ratio in laboratory cultures increased with increasing *deficiency* of nitrogen in the presence of excess phosphorus and other nutrients (Fogg 1965, p. 87-89).

Assimilation ratios, rates of carbon fixation, and standing crops of phytoplankton chlorophyll *a* can be used to assess relative nutrient supplies for phytoplankton in the different Great Lakes (Table 29). Phytoplankton in Lake Superior with an assimilation ratio of less than 1.0 are obviously "nutrient deficient." Assimilation ratios for open-lake stations in Lake Huron, ranging from 1.3 to 2.7, are greater than those in Lake Superior, but would be in the "nutrient deficient" category of Curl and Small (1965). Only assimilation ratios greater than 3.0 for Saginaw Bay and Lake Erie are greater than those for "nutrient deficiency." The range in values for assimilation ratios in the Great Lakes (Table 29) is not as large as that found for marine communities (Curl and Small 1965), but the values in the Great Lakes do increase with increasing standing crops of chlorophyll and rates of carbon fixation as pointed out by Verduin (1972). Nutrient conditions (Table 28) associated with large assimilation ratios are larger supplies of phosphorus and smaller supplies of nitrate nitrogen than those associated with small assimilation ratios.

PHYTOPLANKTON

Little study has been made of phytoplankton in Lake Huron and Lake Superior compared to that on Lake Michigan and Lake Erie. Davis (1966a) determined that there were no long-range phytoplankton studies for Lake Huron. For the eastern part of Lake Superior where our studies were conducted, there have been only two recent studies of phytoplankton (Holland 1965; Schelske et al. 1972).

Recent compilations of historical information for Lake Michigan and Lake Erie dating back to the late 1800's have dealt only with the diatoms (Stoermer and Yang 1969; Hohn 1969). In the case of Lake Michigan, this approach is not too serious because Lake Michigan has been historically, like the other upper lakes, a diatom lake. For Lake Erie, much information is lost because a major part of phytoplankton assemblages in Lake Erie, particularly in the western and central basin, may no longer be diatoms. The western basin of Lake Erie has long been considered an exception to statements that the Great Lakes are diatom

lakes (Ward 1896a; Ahlstrom 1936; Chandler 1940, 1942b, 1944; Chandler and Weeks 1945). Both Ward and Ahlstrom imply that this was well known scientifically, but neither gives references or data to support the conclusion. Lake Erie, particularly the western basin, may then have always been more eutrophic than the upper Great Lakes. Evidence is available to show that phytoplankton changed in the last 30 years (Davis 1964; Hohn 1969).

Our qualitative analysis of phytoplankton provides additional insight into the trophic relations of the Great Lakes. Of the 57 different genera identified for the four lakes, 43 were found in Lake Huron (Table 30). Also, on the average, more genera were identified per station in Lake Huron than in the other three lakes, which may be due to the wide range of environmental conditions sampled in Lake Huron. The relatively homogeneous nature of Lake Superior is indicated as more stations were sampled than in the other lakes without a concomitant increase in number of genera.

Twenty-one of the 57 phytoplankton genera (Table 31) were reported more frequently on the basis of percent occurrence than the remaining 36 genera

TABLE 30. Summary of phytoplankton genera tabulated as occurrences in the four lakes.

	Superior	Michigan	Huron	Erie
Stations sampled	33	5	25	20
Total number of genera	28	24	43	34
Average number of genera/station	9.7	10.8	12.3	9.4

TABLE 31. Phytoplankton abundance as percent occurrence of 21 genera in collections from the four lakes.

Genus	L. Superior	L. Michigan	L. Huron	L. Erie	Average %
<i>Fragilaria</i>	73	100	100	90	90.8
<i>Tabellaria</i>	100	100	96	40	84.0
<i>Asterionella</i>	100	80	92	50	80.5
<i>Synedra</i>	100	100	76	30	76.5
<i>Dinobryon</i>	91	100	80	10	70.3
<i>Melosira</i>	82	80	84	20	66.5
<i>Anabaena</i>	24	60	76	75	58.8
<i>Rhizosolenia</i>	61	100	36	0	49.3
<i>Pediastrum</i>	6	20	48	90	41.0
<i>Cyclotella</i>	56	20	72	5	38.3
<i>Oscillatoria</i>	9	60	52	5	34.7
<i>Ceratium</i>	0	0	60	70	32.5
<i>Microcystis</i>	0	0	40	80	30.0
<i>Aphanizomenon</i>	0	0	24	85	27.3
<i>Lyngbya</i>	67	20	4	15	26.5
<i>Gloeocystis</i>	12	0	40	35	21.8
<i>Staurastrum</i>	0	0	32	55	21.8
<i>Cymbella</i>	40	20	20	0	20.0
<i>Stephanodiscus</i>	30	20	24	5	19.8
<i>Navicula</i>	30	20	20	0	17.5
<i>Oedogonium</i>	0	0	12	45	14.3

(Table 32). The unequal weighting of Lake Michigan collections, due to our sampling only 5 stations, was not a factor in determining which genera occurred in Table 31. These 21 genera occurred in at least 30 per cent of the collections from one of the lakes, whereas the remaining 36 genera were reported for the most part from only one or two stations in each lake (Table 32). Additionally, the two groups are different in that all of the 21 genera were recorded as common or abundant, whereas only 10 of the 36 less frequently recorded genera were recorded as common or abundant.

Trophic differences among the four lakes were reflected in the qualitative composition of the phytoplankton assemblages. Nearly half of the genera that occurred most frequently in the phytoplankton collections were diatoms. Five of the diatoms, *Fragilaria*, *Tabellaria*, *Asterionella*, *Synedra* and *Melosira*, were present in 75 per cent or more of the collections in Lake Superior, Lake Michigan and Lake Huron, but of the five, only *Fragilaria* was present in more than 50 per cent of the collections in Lake Erie (Table 31). Two other genera of diatoms, *Cyclotella* and *Rhizosolenia*, were found frequently in Lake Superior and Lake Huron but not in Lake Erie (Table 31). Nannoplanktonic species of

TABLE 32 Phytoplankton abundance as percent occurrence of 36 genera in collections from the four lakes.

Genus	L. Superior	L. Michigan	L. Huron	L. Erie	Average %
<i>Gomphosphaeria</i>	3	20	12	10	11.3
<i>Merismopedia</i>	12	0	0	0	3.0
<i>Chroococcus</i>	12	20	0	0	8.0
<i>Peridinium</i>	3	0	8	5	4.0
<i>Amphiprora</i>	3	0	4	0	1.8
<i>Dactylococcopsis</i>	3	0	0	0	0.8
<i>Planktonema</i>	3	20	4	0	6.8
<i>Spirogyra</i>	3	0	0	0	0.8
<i>Mougeotia</i>	3	0	0	0	0.8
<i>Stauroneis</i>	3	0	4	0	1.8
<i>Nephrocytium</i>	3	0	0	0	0.8
<i>Oocystis</i>	3	20	0	10	8.3
<i>Gyrosigma</i>	0	20	0	0	5.0
<i>Uroglenopsis</i>	0	20	0	0	5.0
<i>Botryococcus</i>	0	20	12	0	8.0
<i>Dictyosphaerium</i>	0	20	4	0	6.0
<i>Mallomonas</i>	0	20	0	0	5.0
<i>Amphipleura</i>	0	0	12	0	3.0
<i>Coscinodiscus</i>	0	0	12	10	5.5
<i>Cosmarium</i>	0	0	8	25	8.3
<i>Phormidium</i>	0	0	8	0	2.0
<i>Synura</i>	0	0	8	0	2.0
<i>Chodatella</i>	0	0	4	0	1.0
<i>Closterium</i>	0	0	4	10	3.5
<i>Coelastrum</i>	0	0	4	0	1.0
<i>Cosmocladium</i>	0	0	4	0	1.0
<i>Eudorina</i>	0	0	4	0	1.0
<i>Scenedesmus</i>	0	0	4	5	2.3
<i>Sphaerocystis</i>	0	0	4	10	3.5
<i>Sphaerosoma</i>	0	0	4	0	1.0
<i>Ulothrix</i>	0	0	4	5	2.3
<i>Actinastrum</i>	0	0	0	5	1.3
<i>Coelosphaerium</i>	0	0	0	5	1.3
<i>Colacium</i>	0	0	0	5	1.3
<i>Crucigenia</i>	0	0	0	5	1.3
<i>Tribonema</i>	0	0	0	5	1.3

Cyclotella were probably not sampled quantitatively in Lake Superior, but these may be dominant species in terms of numbers of cells (Schelske et al. 1972; Holland 1965).

Dinobryon has been associated with low supplies of phosphate (Hutchinson 1967). It was abundant or common at 21 of the 31 stations in Lake Superior and was present in most collections from the upper lakes, but was only present in 10% of the collections from Lake Erie (Table 31), where phosphate supplies were largest.

Presence of blue-green algae in our collections does not in itself indicate highly eutrophic conditions. *Lyngbya* and *Oscillatoria*, for example, occurred more commonly in Lake Superior and Lake Michigan than in Lake Erie (Table 31).

Blue-green genera characteristic of the most eutrophic zones sampled were *Aphanizomenon*, *Microcystis* and *Anabaena* (Table 33). *Anabaena* was abundant or common in Saginaw Bay and in the central basin, but not in the southern

TABLE 33. Occurrence of four genera as abundant or common at stations in Saginaw Bay and in Lake Erie.

	Saginaw Bay	Lake Erie	
		Central basin	Western basin, south
<i>Aphanizomenon</i>	2	6	7
<i>Microcystis</i>	4	6	7
<i>Ceratium</i>	5	6	4
<i>Staurastrum</i>	1	5	0
<i>Anabaena</i>	3	5	0
No. of stations	6	8	7

part of the western basin, of Lake Erie. In our samples *Anabaena* was most abundant where supplies of nitrate nitrogen were lowest, or where nitrate nitrogen concentrations were less than 30 ppb (Fig. 15). As suggested by our data,

FIG. 15. Occurrence of *Anabaena* plotted against surface concentrations of nitrate nitrogen. Occurrence was scored as abundant, common, or neither abundant nor common. Data are from stations in Zones II and III in Lake Erie and Zone III in Lake Huron.

its occurrence was associated with nitrogen fixation in southern Green Bay (Vanderhoef et al. 1972). In Lake Erie in 1969, *Microcystis*, *Aphanizomenon* and *Anabaena* were found during the period of nitrogen fixation (Howard et al. 1970).

Aphanizomenon and *Microcystis* were excellent indicators of the most eutrophic zones in Lake Erie (Table 33). Both were either common or abundant at every station in the southern part of the western basin, and neither was common or abundant at stations in the northern part. Also, both were common or abundant at six of the eight stations in the central basin.

Trophic conditions in the Laurentian Great Lakes range from extremely oligotrophic in Lake Superior to highly eutrophic in the western basin of Lake Erie, Saginaw Bay, and southern Green Bay in Lake Michigan. Standing crops and species composition of phytoplankton vary with trophic conditions. Standing crops associated with oligotrophy are small and increase with increased eutrophication. With extreme oligotrophy, there is some indication that only a small spring pulse occurs each year and that there is no discernible fall pulse (Davis 1964; Damann 1960). As standing crops increase, a definite pattern of spring and fall pulses is present (Chandler and Weeks 1945; Chandler 1940, 1942b, 1944). The fall pulse may be maintained throughout the winter, eliminating the winter minimum (Davis 1964), and in very advanced states of eutrophication one would anticipate a continual algal bloom. Whether such a condition occurs in the Great Lakes is conjecture due to the lack of recent seasonal data on the more enriched areas.

Species composition of the phytoplankton assemblages changes as standing crops increase during eutrophication. During oligotrophy, the lakes are diatom lakes (Hutchinson 1967) with several species of *Cyclotella*, and other diatoms including *Asterionella formosa*, *Tabellaria fenestrata*, *Rhizosolenia eriensis*, and *Melosira italica* as dominants in the phytoplankton assemblage. Several species of *Dinobryon*, which was classified as a protozoan by many of the earlier investigators, are also characteristic of oligotrophic conditions. Phytoplankton assemblages may be similar over a range of nutrient conditions (Stoermer et al. 1972); but with increasing standing crops, other species of diatoms become dominant including *Cyclotella meneghiniana*, *Stephanodiscus binderanus*, *S. hantzschii* and *Melosira granulata* (Stoermer and Yang 1969; Hohn 1969). When standing crops of diatoms become large enough to utilize available supplies of silica, the dominance of diatoms is changed to populations with increasing proportions of green and blue-green algae. From Chandler's studies of Lake Erie, the change is apparent first in the autumnal pulse which begins with a bloom of blue-green or green algae, including the blue-green algae: *Aphanizomenon*, *Coelosphaerium*, *Chroococcus*, *Merismopedia*, and *Microcystis*; and green algae: *Dictyosphaerium*, *Schroederia*, *Scenedesmus*, *Pediastrum*, *Oocystis*, and *Coelastrum*. Large standing crops of phytoplankton also reduce the available supplies of nitrate to limiting or near limiting levels, promoting conditions favorable for nitrogen fixing blue-greens. Our studies indicate that *Aphanizomenon* and *Microcystis* were the genera of blue-greens associated with *Staurastrum* and *Ceratium* in extremely eutrophic conditions (Table 33) and that *Anabaena* may have been associated with nitrogen fixation when supplies of nitrate were lowest (Fig. 15).

ZOOPLANKTON

Zooplankton assemblages we observed in 1970 (Table 34) ranged from low densities of a few genera of mainly calanoid copepods (offshore Lake Superior) through medium densities of a diverse assemblage dominated by copepods, but including several genera of Cladocera (Lake Huron) to high densities, mainly of cladocerans and rotifers (western Lake Erie). This spectrum can be attributed partly to differences in latitude and hence water temperature, partly to differences in water chemistry; but man's influence has not been uniform throughout the lakes, so superimposed on these fundamental differences are a range of effects due to eutrophication/pollution and the introduction of exotic predators.

Lake Superior, in addition to being the most northerly, is also the least modified by cultural factors. Calanoid copepods, epitomized by species of *Diaptomus* and by the large cold-stenotherm glacial relict, *Limnocalanus macrurus*,

TABLE 34. Summary of zooplankton data. For each genus and lake zone, the abundance is represented by the mean value of the relative abundance index (example: 5.0 = dominant at every station). Where no value appears, the genus was not found at any station in that zone. The average number of genera per station, the average settled volume, and the ratio of the sums of relative abundances of calanoids to cladocerans and rotifers are also given for each lake zone.

Genera	Lake Zones									
	Superior Open lake	Superior Bays	Huron Zone II	Michigan	Huron Zone I	Huron Zone IV	Erie Zone III	Saginaw Bay	Erie Zone I	Erie Zone II
Calanoid copepods										
<i>Limnocalanus</i>	3.2	3.0	1.5		1.7		0.1			
<i>Diaptomus</i>	5.0	5.0	5.0	4.4	4.7	4.6	4.2	2.8	2.6	2.1
<i>Senecella</i>	0.5		0.2		0.3					
<i>Epischura</i>			0.1							
<i>Mysis</i>	0.1									
Cyclopoid copepods										
<i>Cyclops</i>	2.1	3.6	3.9	4.2	3.8	4.0	4.0	2.8	3.6	3.1
<i>Mesocyclops</i>										0.4
Cladocerans										
<i>Polyphemus</i>	a	0.4	0.5		0.3	0.8				
<i>Bosmina</i> ^b	0.1	1.8	3.9	5.0	4.3	3.6	2.1	4.3	4.0	3.6
<i>Holopedium</i>		0.8	2.5		2.6	3.0		0.5	0.8	0.4
<i>Leptodora</i>	a	0.4	0.1		0.1	1.4	1.2	2.5	2.6	2.5
<i>Daphnia</i>	0.2	1.6	1.7	1.5	2.4	2.2	4.7	2.8	3.6	4.2
<i>Ceriodaphnia</i>								0.5		
<i>Diaphanosoma</i>							1.4		2.0	1.4
Rotifers										
<i>Kellicottia</i>				0.2						
<i>Asplanchna</i>	0.3	1.8	1.6	0.2	1.4	1.4	2.4	3.5	1.4	
Unident. Rotifer							0.5	2.5	1.0	
Average no. of genera/station	3.8	7.0	7.2	4.2	6.9	7.4	6.4	6.7	7.4	6.4
Settled volume, ml/m ³	0.35	0.38	1.11	1.92	0.92	0.77	8.32	0.67	3.93	8.75
Calanoids/ Cladocerans & rotifers	14.5	1.18	0.67	0.64	0.60	0.37	0.35	0.17	0.17	0.17

aLess than 0.1%. bIncluding *Eubosmina* (Deevey and Deevey 1971).

made up the fauna in the offshore areas; a few other forms, cyclopoid copepods, certain cladocerans and rotifers, were present but rare in Whitefish Bay where higher near-surface temperatures prevailed. Lakes Huron and Michigan, being farther south, have longer growing seasons and greater temperature ranges which permit denser populations and more diverse assemblages. Lake Erie and Saginaw Bay are shallower, warmer and eutrophic, which permits a denser phytoplankton growth and in turn an even larger community of zooplankton herbivores. As Patalas (1972) stated, "a general trend was seen from Lake Superior, the most oligotrophic, to Lake Erie, the most eutrophic: a diminishing proportion of calanoids accompanied by an increasing predominance of cyclopoids and cladocerans." Patalas also noted the increasing abundance of individuals. Our data show these trends (Table 34).

Cultural factors--eutrophication and exotic predators--also have influenced Great Lakes zooplankton communities. Wells (1970) has documented the diminution in average size of Lake Michigan zooplankters. Gannon (1972a, 1972b) showed that the direct effects of eutrophication may cause changes in abundance and species composition; these can be opposite in effect to those caused by a super-abundant predator. Gannon concluded that the relative proportions (numbers of calanoid copepods to numbers of cladocerans and rotifers) may be the most useful index to trophic change. This ratio (Table 34) ranks lake zones in much the same order as other factors studied, such as water chemistry and nutrient concentrations, because proportions of cladocerans and rotifers were highest in warm, inshore areas (western Lake Erie and Saginaw Bay), intermediate in Lake Michigan and upper Lake Huron, and lowest in Lake Superior. The ratio of 14.5 for open Lake Superior undoubtedly is influenced by the low temperatures during our cruises since cladocera are characteristically summer forms.

The average numbers of genera per station were similar in eight of the ten lake zones, ranging between 6.4 and 7.4 (Table 34). Two exceptions were open Lake Superior with 3.8, a reflection of cold water, and Lake Michigan with 4.2. Gannon (1972b) discussed reasons that the Great Lakes seem to have more zooplankton species than smaller lakes at comparable latitudes. He concluded that the long-term, large-scale homogeneity interacts with short-term, small-scale heterogeneity afforded by the separate water masses of a large lake to permit a more diverse zooplankton fauna.

BOTTOM FAUNA

A summary of our bottom fauna data (Table 35) also shows biological differences among lakes and lake zones. Small populations of cold stenothermal Crustacea (*Pontoporeia*, *Mysis*) and cold-water midges were found in Lake Superior, where deep, cold waters overlies sediments of relatively low organic content. In Lake Michigan, with a richer plankton biota, the sediments contain more organic matter and support a similar, but quantitatively richer bottom fauna than Lake Superior. The first response of the Lake Michigan benthic fauna to accelerated eutrophication was a numerical increase in individuals (Robertson and Alley, 1966). A similar increase probably occurred in offshore Lake Huron, but early data are lacking.

Ratios of Crustacea to Oligochaeta for our ten lake zones, with the exception of Lake Superior, serve as a "trophic index." Lower ratios in Lake Superior than expected may have been related to low total counts; seven open lake stations had no oligochaetes, a condition we never found in the other lakes, and the average number of Crustacea was smaller than in the other lakes. Ratios

TABLE 35. Summary of benthos data. For each taxon and lake zone, the mean percentage of the total fauna is given. The mean numerical total (number/m²) is given for each lake zone, as well as the ratio of total Crustacea numbers to total Oligochaeta numbers.

Taxa	Lake Zones									
	Superior Open lake	Superior Bays	Huron Zone I	Michigan	Huron Zone II	Huron Zone IV	Saginaw Bay	Erie Zone I	Erie Zone II	Erie Zone III
<i>Pontoporeia</i>	54.9	50.8	71.6	66.6	52.0	31.5	0.9			
<i>Mysis</i>	1.8	0.9	0.3		0.3					
Chironomidae	5.2	7.7	2.6	1.7	2.3	8.3	10.4	5.8	11.1	18.2
Gastropoda	0.1		0.3	0.9	0.2	0.8	0.1	7.1	0.7	0.1
Sphaeriidae	8.0	13.7	3.1	7.2	5.0	1.2	0.5	22.6	5.1	23.9
<i>Gammarus</i>					0.4		3.1	3.0	0.7	0.1
Hirudinea					0.1		0.1	2.4	0.9	0.2
Oligochaeta	20.9	26.8	22.0	23.2	39.7	52.7	83.7	57.4	81.4	57.5
Other	8.9		0.1	0.4	0.6	5.4	1.1	1.6	0.2	
Total no./m ²	376	482	1863	3222	4837	623	3499	2967	4204	2293
Crustacea/ Oligochaeta	2.71	1.92	3.27	2.87	1.33	0.60	0.05	0.05	0.01	0.001

in upper Lake Huron and Lake Michigan ranged from 0.05 in the western basin to 0.001 in the central basin.

In most regions in the upper Great Lakes, bottom oxygen supplies are plentiful, and typical stenoxymbiont Great Lakes organisms persist. Saginaw Bay and western Lake Erie are shallow regions which once supported rich, riverlike invertebrate bottom faunas and valuable commercial fisheries. These areas underwent drastic changes in response to increased inputs of pollutants. High sediment oxygen demands eliminated many species of invertebrates, and these were replaced by pollution-tolerant forms such as *Limnodrilus* and *Chironomus*. Our 1970 data show that the situation in Saginaw Bay has worsened since 1965. Similarly, our western Lake Erie observations revealed a more deteriorated benthic fauna. Central Lake Erie also has high sediment oxygen demand, and being deep enough to stratify thermally, regularly experiences hypolimnetic anaerobiosis. This presumably has decimated the original fauna, and in its place we found an assemblage characteristic of extreme eutrophy.

SIGNIFICANCE AND INTERPRETATION OF DATA

Several factors enter into the interpretation of data as pointed out in the text. The biological data, with the exception of benthos, obviously are seasonal data, i.e. we would not expect the species composition of phytoplankton and zooplankton to remain constant throughout the year, nor would we expect standing crops of chlorophyll *a* and settled volumes of zooplankton to remain constant. The species composition of the benthos would not change as much seasonally as the plankton, but the numbers would change depending on such factors as time of emergence for aquatic insect larvae, time of recruitment of young into the population and sizes of the organisms sampled by collection methods.

Concentrations of plant nutrients vary seasonally. In the three upper lakes the magnitude of these ranges for silica and nitrate can be estimated from data on surface and bottom concentrations. Bottom concentrations are comparable to concentrations during spring circulation. Although limited in seasonal aspects, our data on silica and nitrate for the upper lakes are much more representative than some cited in the past because they can be used to infer seasonal ranges. Seasonal and day-to-day changes are so large in Lake Erie and Saginaw Bay that collections from any point in time have little meaning.

Our phosphate data can be used to show general increases in levels of phosphate with other parameters, rates of carbon fixation by phytoplankton and standing crops of chlorophyll, that increase during eutrophication. However, data on particulate phosphate are most useful for this purpose, and our particulate phosphate data are not particularly reliable due to analyses made on filters and are also limited in number.

Major ion chemistry of the parameters we measured is least influenced by seasonal variations. Our data for pH, alkalinity and specific conductance measured on shipboard appear to be very reliable and to represent conditions at the time of measurement. Values for pH are higher than some reported in the past, but in all the lakes except Lake Superior, this difference at least partly represents changes in water chemistry. Accuracy of early pH measurements made by color comparison is also subject to question.

Our chloride data for Lake Erie are much lower than the commonly cited lake averages. Lower values are probably related to our sampling locations, which were primarily in the western part of the lake, rather than to an error in estimating concentrations. Our data suggest that either the input of chloride from the Detroit River and other western basin sources varies greatly with time

or that a large fraction of the input is from sources which contribute little chloride to the western basin.

Calcium and sulfate were determined with simple methods, and the resulting data, although limited in number, are similar to that reported previously.

Our data have been used primarily for conclusions regarding eutrophication of the Great Lakes. We have used eutrophication in the general sense of environmental change. Limnologists generally restrict the use to nutrient enrichment (Vollenweider 1968), but since many environmental changes in the Great Lakes have now been related to inputs and levels of phosphorus and to changes in levels of nitrate and silica, our use of eutrophication is at least partly justified.

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APPENDIX

TABLES A - H

APPENDIX

APPENDIX TABLE A. Location, depth (meters), date, and time (Eastern Standard Time, hours), for each station.

Sta. No.	Location		Depth	Date	Time
Lake Michigan					
LM70- 1	44° 42.9' N	86° 16.9' W	42.7	July 7	0650
LM70- 2	44 54.6	86 08.7	12.2	July 7	0838
LM70- 3	45 00.2	85 59.4	37.2	July 7	0947
LM70- 4	45 15.3	85 46.7	149	July 7	1154
LM70- 5	45 32.8	85 30.5	114	July 7	1440
LM70- 6	45 44.2	85 26.1	13.0	July 7	1634
Lake Superior					
SU70- 1	46 41.5	84 29.0	24.4	July 9	0617
SU70- 2	46 40.5	84 37.5	77.7	July 9	0722
SU70- 3	46 47.0	84 41.0	20.4	July 9	0829
SU70- 4	46 52.3	84 44.7	104	July 9	0925
SU70- 5	47 00.7	84 51.0	152	July 9	1048
SU70- 6	47 00.8	84 53.3	11.9	July 9	1130
SU70- 7	47 06.7	85 09.3	192	July 9	1252
SU70- 8	47 21.1	85 46.4	88.4	July 9	1622
SU70- 9	47 26.1	85 47.7	17.4	July 9	1721
SU70-10	47 39.8	85 47.9	169	July 9	1858
SU70-15	47 41.0	85 50.8	136	July 10	0628
SU70-16	47 39.2	86 08.4	181	July 10	0802
SU70-17	47 37.5	86 26.2	184	July 10	0946
SU70-18	47 36.0	86 44.5	274	July 10	1131
SU70-19	47 34.0	87 03.0	320	July 10	1327
SU70-20	47 32.5	87 21.0	216	July 10	1520
SU70-21	47 31.2	87 38.7	141	July 10	1702
SU70-22	47 29.1	87 49.2	94.8	July 10	1914
SU70-23	47 23.6	87 46.9	35.0	July 11	0717
SU70-25	47 14.4	87 20.8	166	July 11	0912
SU70-26	47 10.3	87 13.8	53.3	July 11	1022
SU70-27	47 02.7	86 55.3	178	July 11	1211
SU70-28	46 54.6	86 35.8	397	July 11	1412
SU70-29	46 44.8	86 39.2	204	July 11	1610
SU70-30	46 32.8	86 43.3	32.3	July 11	1747
SU70-31	46 25.5	86 38.3	25.0	July 11	1857
SU70-32	46 34.0	86 30.4	96.0	July 12	0603
SU70-33	46 33.6	86 26.3	18.3	July 12	0648
SU70-34	46 34.7	86 23.4	20.4	July 12	0714
SU70-35	46 40.6	86 21.0	123	July 12	0801
SU70-36	46 41.0	86 09.8	21.9	July 12	0907
SU70-37	46 44.4	86 00.0	25.9	July 12	1007
SU70-38	46 45.0	85 30.0	131	July 12	1147
SU70-39	46 46.5	85 14.5	17.4	July 12	1355
SU70-40	46 47.2	84 58.5	15.2	July 12	1518
Lake Huron					
HU70- 1	45 41.1	84 15.6	24.7	July 27	0705
HU70- 2	45 39.6	84 05.3	57.0	July 27	0803
HU70- 3	45 38.1	83 51.3	86.9	July 27	0920
HU70- 4	45 27.8	83 27.0	86.9	July 27	1139
HU70- 5	45 19.0	83 20.2	57.3	July 27	1255
HU70- 6	45 07.6	83 11.0	10.7	July 27	1425
HU70- 7	45 01.3	83 06.0	38.1	July 27	1524
HU70- 8	45 00.0	83 19.0	16.1	July 28	0640
HU70- 9	44 55.2	83 13.7	36.0	July 28	0731
HU70-10	44 49.5	83 06.6	57.3	July 28	0831
HU70-11	44 42.8	82 59.2	70.1	July 28	0944

Appendix Table A (continued)

Sta. No.	Location		Depth	Date	Time
HU70-12	44° 30.2' N	83° 00.7' W	66.1	July 28	1116
HU70-13	44 23.7	83 09.6	48.8	July 28	1218
HU70-14	44 18.0	83 17.0	20.4	July 28	1328
HU70-15	44 14.2	83 30.0	8.5	July 28	1444
HU70-16	44 07.5	83 31.8	10.7	July 29	0705
HU70-17	43 58.0	83 36.3	12.2	July 29	0820
HU70-18	43 49.6	83 43.5	8.5	July 29	0928
HU70-19	43 53.5	83 36.5	11.0	July 29	1020
HU70-20	43 58.8	83 32.2	10.7	July 29	1112
HU70-21	44 06.6	83 24.9	10.7	July 29	1234
HU70-22	44 06.5	83 04.0	25.9	July 29	1418
HU70-23	43 41.8	82 32.8	20.4	July 30	0701
HU70-24	43 31.1	82 30.4	23.2	July 30	0821
HU70-25	43 20.0	82 28.1	20.7	July 30	0940
HU70-26	43 09.8	82 25.7	16.1	July 30	1104
<i>Lake Erie</i>					
ER70- 1	41 57.2	83 05.5	9.1	July 31	1311
ER70- 2	41 57.0	82 58.7	9.7	July 31	1401
ER70- 3	41 57.3	82 52.2	9.7	July 31	1453
ER70- 4	41 50.7	82 52.7	10.7	July 31	1604
ER70- 5	41 45.3	82 52.5	10.0	July 31	1655
ER70- 6	41 39.8	82 52.1	9.7	July 31	1757
ER70- 7	41 39.0	82 36.8	14.6	August 1	0740
ER70- 8	41 38.6	82 27.5	12.5	August 1	0840
ER70- 9	41 38.2	82 15.0	15.2	August 1	0947
ER70-10	41 37.7	82 03.4	18.6	August 1	1058
ER70-11	41 35.0	82 04.9	16.1	August 1	1152
ER70-12	41 32.7	82 08.4	10.0	August 1	1240
ER70-13	41 28.8	82 23.4	14.6	August 1	1341
ER70-14	41 29.8	82 37.8	12.2	August 1	1500
ER70-15	41 44.7	82 53.8	10.7	August 2	0644
ER70-16	41 48.0	83 02.2	10.4	August 2	0743
ER70-17	41 49.0	83 10.6	7.3	August 2	0846
ER70-18	41 45.7	83 8.2	7.3	August 2	0947
ER70-19	41 48.8	83 14.9	7.9	August 2	1032
ER70-20	41 54.1	83 09.4	7.9	August 2	1128

APPENDIX TABLE B. Physical and chemical data collected during the study.

Abbreviations used in Appendix Table B

STA NO	- Station number	CA	- Calcium, ppm
DEPTH	- Depth, m	PO4	- Soluble reactive phosphate, ppb PO ₄
TEMP	- Temperature, °C	NO3	- Nitrate, ppb NO ₃ -N
DISC	- Secchi disc, m	NH3	- Ammonia, ppb NH ₃ -N
COND	- Specific conductance, $\mu\text{mho}@25^{\circ}\text{C}$	CL	- Chloride, ppm CL
D.O.	- Dissolved oxygen, ppm	SO4	- Sulfate, ppm SO ₄
PH	- pH	SIO2	- Silica, ppm SiO ₂
ALK	- Methyl orange alkalinity, ppm CaCO ₃	CHL	- Chlorophyll <i>a</i> , mg/m ³

STA NO	DEPTH	TEMP	DISC	COND	D.O.	PH	ALK	CA	PO4	NO3	NH3	CL	SO4	SIO2	CHL
LAKE MICHIGAN															
LM70-1	0	14.9	5.0			8.56	109.0	36.0	7.0	133	14	7.6	15.0	0.33	
LM70-1	10	14.8				8.55	110.0	38.5	7.0				16.5		
LM70-1	15	13.0				8.55	118.0	36.0	5.0	127	18	7.8	14.5	0.34	
LM70-1	25	10.5				8.54	110.0	36.0	1.0	156	21	7.3	14.0	0.53	
LM70-1	40	7.0				8.39	109.0	37.5	1.0	174	23	7.2	12.5	1.00	
LM70-2	0	14.0	4.0			8.63	110.0	35.0	7.0	127	30	7.2	13.0	0.22	1.80
LM70-2	6	13.9				8.63	110.0	36.0	7.0	147	14	7.8	15.0	0.27	
LM70-2	11	13.7													
LM70-3	0	13.5	4.0												2.1
LM70-3	2	13.5				8.61	110.0								
LM70-3	5	13.4						38.5	5.0	131	20	6.9	13.0	0.39	
LM70-3	10	13.4													1.7
LM70-3	15	13.0			10.1										
LM70-3	20	12.5			9.0			37.5	12.0	144	12	7.6	11.0	0.26	
LM70-3	30	9.0				8.44	110.0								
LM70-3	40	7.0				8.38	112.0	38.5	7.0	176	23	7.2	14.5	0.98	
LM70-4	0	12.5	5.0		11.1			37.5	5.0	134	5	7.0	17.5	0.28	
LM70-4	10	12.4			12.4	8.63	110.0	37.0							
LM70-4	25	8.0				8.54	108.0	37.0	1.0	143	9	7.0	15.0	0.47	1.7
LM70-4	40	5.5													
LM70-4	125	4.0				12.5	8.29	106.0	40.0	1.0	187	20	6.9	14.5	1.23
LM70-5	0	14.5	5.5			9.1	8.66	109.0	34.5	1.0	121	13	7.2	14.5	0.27
LM70-5	10	14.0				9.5	8.49	108.0							0.7
LM70-5	25	9.7			10.0	8.48	107.0	38.5	5.0	146	18	7.2	21.0	0.35	0.7
LM70-5	110	4.2				8.00	106.0	38.5	11.0	193	25	6.9	21.5	1.34	
LM70-6	0	16.0	5.0												0.7
LM70-6	2	15.7						39.5		117	15	6.8	20.0	0.29	
LM70-6	4	15.5			10.3	8.58	106.0								
LM70-6	8	15.0			10.4	8.46	106.0								
LM70-6	13	14.5													
LAKE SUPERIOR															
SU70-1	0	13.5	6.0	96	10.8	7.90	42.0	14.0	4.0	233	9	1.2	2.8	2.02	1.6
SU70-1	8	12.0				8.16	41.0	13.4	1.0	226	10	1.0	1.8	1.98	
SU70-1	12	9.5						14.0		232	7	1.1	2.6	2.05	
SU70-1	22	7.0			12.6	7.76	43.0	13.8	1.0	243	14	1.1	2.0	2.17	
SU70-2	0	15.1	5.5	88		7.82	40.0	14.2	3.0	215	11	1.3	2.4	2.30	
SU70-2	3	15.0				8.19	43.0								1.2
SU70-2	6	14.0				8.01	42.0								
SU70-2	22	9.0			12.0	7.85	42.0	15.0		234	13	1.1	1.7	2.08	
SU70-2	72	4.9						15.0	2.0	261	14	1.0	1.9	2.32	
SU70-3	0	13.0	8.0	94	10.8	8.08	44.0	16.2	4.0	241	15	1.3	1.9	1.98	
SU70-3	3	13.0				8.09	42.0								1.4
SU70-3	6	13.0				8.16	42.0								
SU70-3	12	10.0			11.6	7.69	34.0	15.0		246	8	1.1	1.3	2.25	
SU70-3	19	7.5				8.10	44.0	15.8	5.0	249	11	1.1	1.5	2.25	
SU70-4	0	13.2	7.5	94	10.6	8.13	41.0	15.4	5.0	235	7	1.1	1.3	2.03	
SU70-4	3	13.0				8.19	43.0								1.7
SU70-4	6	13.0				8.19	41.0								
SU70-4	12	11.0			12.2	8.17	40.0	15.8	1.0	239	13	1.1	1.3	2.18	
SU70-4	59	4.0			13.2	7.93	42.0	15.4	6.0	264	11	1.1	1.6	2.30	
SU70-5	0	11.2	9.0	96				16.7	1.0	244	14	1.1	1.0	2.24	
SU70-5	3	11.0			11.4	8.12	42.0								0.9
SU70-5	6	11.0													
SU70-5	15	8.5			12.8	8.11	41.0	15.2		245	8	1.0	1.3	2.22	
SU70-5	155	3.5			13.8	7.99		15.5	2.5	256	11	1.1	1.4	2.26	
SU70-6	0	10.2	10.0	93				15.8	1.0	253		1.0	1.4	2.26	1.2
SU70-6	3	10.0			11.8	8.12	41.0								
SU70-6	6	9.0				8.12	42.0								
SU70-6	9	7.2			12.6	8.19	41.0								
SU70-6	11	6.5													
SU70-7	0	3.5	15.0	94	13.2	8.02	38.0	16.2		262	10	1.1	1.2	2.32	

Appendix Table B (continued)

STA NO	DEPTH	TEMP	DISC	CCND	D.O.	PH	ALK	CA	PO4	NO3	NH3	CL	SO4	SI02	CHL
SU70-7	60	3.4				8.03	43.0								0.8
SU70-7	120	3.3				8.03	45.0								1.2
SU70-7	180	3.1			13.2	7.73	44.0	17.0	1.0	258	24	1.0	1.2	2.25	1.6
SU70-8	0	5.0	12.5	96		8.08	41.0	15.8	1.0	271	17	1.1	1.4	2.28	
SU70-8	5	4.8			13.2	8.05	41.0								0.5
SU70-8	20	4.5			13.2	8.08	46.0	15.4	1.0	265	6	1.0	1.3	2.28	
SU70-8	85	4.0			13.2	7.94	42.0	16.2	2.0	261	6	1.0	0.8	2.25	
SU70-9	0	4.6	11.0	95		13.2	8.05	44.0	1.0	263	5	1.0	1.1	2.32	
SU70-9	5	4.2			13.0	8.08	42.0								0.8
SU70-9	15	3.8			13.2	7.84	42.0		4.0	267	10	1.1	1.5	2.30	
SU70-10	0	5.1	9.0	93		13.0	8.07	44.0	2.5	255	7	1.0	1.0	2.24	
SU70-10	6	4.9			13.0	8.07	44.0								0.6
SU70-10	50	4.3			13.4	8.06	45.0								
SU70-10	160	4.1			13.2	8.04	45.0	15.7	2.5	273	18	1.1	0.8	2.25	
SU70-15	0	4.0	12.0	91		13.5	8.00	44.0	1.5	261	6	1.0	1.4	2.25	
SU70-15	3	4.0				8.00	46.0								1.4
SU70-15	56	4.4			13.6	7.83	42.0	15.0	2.0	267		1.1		2.30	
SU70-15	126	4.2			13.6	7.95	44.0	15.0	3.3	262	5	1.0	1.4	2.25	
SU70-16	0	3.5	13.3	92		13.3	8.06	41.0		257	7	1.0	1.2	2.24	
SU70-16	3	3.5				8.03	44.0								1.3
SU70-16	78	3.5			13.3	7.92	43.0	15.0		270	9	1.0	1.9	2.32	
SU70-16	178	3.5							7.5						
SU70-17	0	3.8	16.0	92		8.05	43.0	15.0	1.0	263	6	1.0	1.8	2.31	
SU70-17	3	3.8			13.1	7.75	41.0								1.2
SU70-17	90	3.5				7.97	43.0	15.0		263	5	1.0	1.8	2.36	
SU70-17	180	3.4			13.2	7.96	41.0	15.0	1.0	282	17	1.2		2.30	
SU70-18	0	4.3	19.0	91		13.0	7.92	42.0	1.1	268	10	1.0	1.8	2.38	
SU70-18	3	4.2													0.4
SU70-18	130	4.1				7.96	43.0	16.5		267	6	1.0		2.31	
SU70-18	260	4.5			13.0	7.96	44.0	15.0	2.3	261	5	1.0	1.4	2.32	
SU70-19	0	4.0	20.5	93		13.1	7.90	43.0							
SU70-19	3	4.0				7.97	44.0	15.0		263	5	1.0	1.9	2.31	0.3
SU70-19	150	3.8				7.98	44.0	14.2		274	5	1.0		2.36	
SU70-19	300	3.7			13.2	7.57	44.0	14.2	1.1	269	11	1.0	1.5	1.37	
SU70-20	0	5.3	19.0	95											
SU70-20	50	4.5													
SU70-20	150	4.1													
SU70-20	215	4.0													
SU70-21	0	8.0	12.5	91	13.2	8.07	45.0	15.0	1.0	250	6	1.0	1.9	2.29	
SU70-21	3	7.5				8.07	46.0								0.2
SU70-21	50	5.0			13.0	7.57	44.0	15.0		255	5	1.0	1.9	2.30	
SU70-21	140	3.8			12.9	7.57	45.0	15.0	1.0	268	6	1.0	1.5	2.37	
SU70-22	0	15.3	9.0	92											0.6
SU70-22	10	15.0													
SU70-22	20	11.0													
SU70-22	35	9.0													
SU70-22	90	4.0													
SU70-23	0	14.0	9.0	94	10.8	8.08	44.0								0.7
SU70-23	3	14.5						16.0	1.0	242	8	1.1	2.5	2.28	
SU70-23	15	11.6			11.9	8.09	46.5	15.5		251	9	1.0		2.24	
SU70-23	30	8.5			11.8	8.05	45.4	15.5	1.0	255	20	1.1	1.9	2.31	
SU70-25	0	7.5	14.0	101		8.07	45.7	13.5	1.0	257	6	1.0	1.9	2.31	
SU70-25	3	7.0			12.0	8.03	45.2								0.4
SU70-25	75	4.0				7.98	44.8	13.5	1.0	262	6	1.0		2.36	
SU70-25	150	3.7			11.9	7.95	47.2	13.5	1.0	268	11	1.0	1.9	2.29	
SU70-26	0	7.5	15.0	89		8.04	45.5	13.5	1.5	259	9	1.0	1.5	2.31	
SU70-26	3	6.3				8.04	44.5								0.3
SU70-26	25	5.0						17.5	1.5	266	6	1.0		2.28	
SU70-26	50	4.9				8.07	47.5	9.5	1.0	263	10	1.0	1.6	2.29	
SU70-27	0	6.4	16.5	92	13.1	8.06	46.2	10.5	1.0	268	6	1.0	2.2	2.36	
SU70-27	3	4.4													0.3
SU70-27	85	3.9			13.0	8.01	45.3	13.5	1.0	263	7	1.0		2.31	
SU70-27	165	3.5			13.1		13.7		1.0	264	6	1.0	1.3	2.36	
SU70-28	0	5.5	15.0	94		8.02	44.3	13.5	1.5	276	10	1.0	2.5	2.34	
SU70-28	3	4.3			13.1	8.07									
SU70-28	90	3.8			13.0	7.97	45.3								
SU70-28	390	3.7			13.0	7.96	44.8	13.7	5.0	265	9	1.0	1.9	2.29	
SU70-29	0	9.0	14.0	94	12.7	8.05	45.3	13.5	1.0	266	14	1.0	1.5	2.28	0.1
SU70-29	3	9.0													
SU70-29	90	3.8			12.9	8.01	46.2	13.7		268	7	1.0		2.29	
SU70-29	180	3.5			13.0	7.98	46.2	13.5	1.0	258	7	1.0	1.9	2.32	
SU70-30	0	12.2	8.5	99	11.5	8.23	46.7	13.7		224	10	1.2	1.2	2.18	
SU70-30	3	12.0				8.22	45.4								0.6
SU70-30	30	9.2			12.3	8.14	47.0	15.5		237	6	1.2	1.7	2.30	
SU70-31	0	15.5	6.0	94	11.1	8.23	45.3	13.7	1.0	222	69	1.3		2.17	1.4
SU70-31	3	15.5													
SU70-31	22	8.5			11.9	8.10	45.1	13.5	1.0	240	9	1.1		2.23	
SU70-32	0	12.5	10.0	91	11.5	8.10	44.6	9.0		229	10	1.2	0.9	2.21	
SU70-32	3	11.5													
SU70-32	10	10.5			12.4										
SU70-32	90	4.8			12.2	8.0	44.6	14.0		243	10	1.2	0.6	2.35	
SU70-33	0	12.0	9.0	94	12.2	8.15	43.6	14.0		233	5	1.2	1.3	2.23	0.5

Appendix Table B (continued)

STA NO	DEPTH	TEMP	DISC	COND	D.O.	PH	ALK	CA	PO4	NO3	NH3	CL	SO4	SiO2	CHL
SU70-33	3	11.0													
SU70-33	18	9.3			12.4	8.14	45.4	13.0		240	5	1.2	1.2	2.29	
SU70-34	0	13.5	9.0	96											
SU70-34	7	11.0													
SU70-34	14	10.0													
SU70-35	0	8.5	12.0	110	12.6	8.13	43.9			254	12	1.1		2.28	
SU70-35	3	8.0													0.6
SU70-35	25	6.2			13.0	8.04	44.5	14.8		248	6	1.1	1.3	2.41	
SU70-35	115	4.0			13.9	8.00	45.0	13.0		259	6	1.1	1.2	2.47	
SU70-36	0	12.5	13.5	95	11.4	7.57	45.1	13.0		252	10	1.1	1.8	2.17	
SU70-36	3	10.5													0.2
SU70-36	10	9.0			13.0	7.95	43.6							2.21	
SU70-36	19	7.5			12.8	8.17	43.8	11.6		246	5	1.0	1.2	2.26	
SU70-37	0	10.0	14.0	108	12.6	8.07	42.6	16.0		256	6	1.0	1.2	2.25	
SU70-37	3	7.6													0.3
SU70-37	10	7.1			13.0	8.06	41.6	15.0		252	5	1.0	1.2		
SU70-37	20	6.8			13.2	8.06	42.2	16.0		253	6	1.0	1.4	2.26	
SU70-38	0	7.5	14.0	93	13.2	8.00	42.6	13.0		261	10	1.2	1.2	2.45	
SU70-38	3	6.8													0.2
SU70-38	30	4.4			12.8	7.97	42.4	13.0		258	5	1.2	0.6	2.40	
SU70-38	120	4.0			13.4	7.95	42.2	15.0		257	7	1.2	1.7	2.47	
SU70-39	0	13.0	9.0	94	11.2	8.22	43.7	13.0		227	5	1.0	1.2	2.17	
SU70-39	3	12.0													0.5
SU70-39	10	11.5			12.0	8.22	44.6	15.0		235	5	1.2	1.3	2.28	
SU70-39	15	10.6			12.4	8.25	43.8	16.0		236	11	1.2	1.7	2.40	
SU70-40	0	12.4	9.0	102	11.2	8.21	43.7	13.0		232	9	1.2		2.28	
SU70-40	3	11.1			11.2	8.14	43.6	15.0		228	6	1.1		2.28	
SU70-40	12	10.0			11.8	8.13	42.2	15.0				1.1		2.23	
LAKE HURON															
HU70-1	0	18.0	6.0	196		8.54	80.0	19.7		134	12	5.6		1.16	
HU70-1	3	17.5													0.40
HU70-1	12	14.0			10.7		72.0	19.4		158		4.0		1.29	
HU70-1	20	12.0			12.0		75.0	18.0		143	15	9.6		1.29	
HU70-2	0	16.5	8.0	182	10.0	8.51	75.0	17.5		146	9	4.2		1.21	
HU70-2	3	15.0													2.40
HU70-2	20	11.0			10.7		74.5	20.1		161	12	4.4		1.24	
HU70-2	55	4.5			11.0		77.0	22.7		148	13	3.6		1.83	
HU70-3	0	15.0	9.0	180	10.2	8.53	74.5	20.1		163	21	4.7		1.20	
HU70-3	3	15.0					74.3								0.64
HU70-3	15	8.0			11.9		74.5	21.3		106	11	3.5		1.38	
HU70-3	80	4.0			12.2		77.0	22.0		151	12	3.9		1.88	
HU70-4	0	15.0	10.0	198	10.5	8.49	76.3	22.5		175	13	5.6		1.08	
HU70-4	3	15.0			10.8		76.2								0.40
HU70-4	15	10.0			11.0		75.6	21.6		158	7	4.9		1.00	
HU70-4	80	3.9			11.9		79.3	22.8		218	18	5.7		1.95	
HU70-5	0	16.5	13.0	191	10.2	8.47	78.0	19.3	0.5	88	10	2.6		1.08	
HU70-5	3	16.2			10.2		75.6								0.40
HU70-5	20	11.5			10.0		77.4	20.1	0.5	108	11	3.0		1.24	
HU70-5	50	4.7			10.6		78.1	22.0	1.0	134	14	3.6		1.78	
HU70-6	0	16.2	11.0	199	10.0	8.49	79.0	22.1	3.5	155	22	5.8		1.00	
HU70-6	3	16.0			10.1		78.0	22.8	1.5	111	10	3.6		0.94	0.64
HU70-6	8	12.0			10.8		76.7	22.5	1.0	163	12	5.5		1.08	
HU70-7	0	18.0	7.0	198	9.4	8.44	78.6	23.5	3.5	110	8	3.9		0.77	
HU70-7	3	17.9			9.6		78.1								0.80
HU70-7	15	12.4			10.6		75.0	22.2	10.0	178	9	5.7		1.07	
HU70-7	32	6.0			11.8		76.6	22.8	0.0	145	12	4.2		1.54	
HU70-8	0	19.5	6.0	199	9.4	8.46	82.0	26.4	3.3	136	11	5.5		0.62	
HU70-8	3	19.5													1.0
HU70-8	8	15.0			10.8	8.39	59.5	25.5		171	13	5.4		1.05	
HU70-8	14	11.5			10.7	8.28	60.0	25.5	2.0	183	15	5.7		1.21	
HU70-9	0	16.8	10.0	192	5.7	8.37	78.0	26.6	1.0	105	22	3.8		0.94	
HU70-9	3	16.8													0.44
HU70-9	20	11.0			11.2	8.33	78.5	26.4		128	42	3.8		1.22	
HU70-9	33	6.0			11.6	8.20	80.0	26.6	1.3	98		3.1		1.47	
HU70-10	0	17.1	9.0	193	9.8	8.46	81.0	26.4	1.8	163	18	5.2		0.97	
HU70-10	3	16.8													0.68
HU70-10	20	10.4			11.8	8.45	79.0	25.7		128	31	5.7		1.16	
HU70-10	55	4.8			12.1	8.16	80.0	25.5	4.8	213	25	5.9		1.74	
HU70-11	0	17.4	7.0	189	9.9	8.48	78.5	26.7	2.3	161	30	5.4		0.84	
HU70-11	3	16.8													1.2
HU70-11	20	10.7			11.2	8.48	78.0	26.4		181	19	5.8		1.12	
HU70-11	65	4.1			11.8	8.15	76.5	27.0	2.5	200	38	5.6		1.95	
HU70-12	0	16.9	12.0	188	9.5	8.47	77.5	26.8	2.0	173		5.5		0.98	
HU70-12	3	16.3													0.40
HU70-12	20	9.3			12.0	8.47	64.5	26.5		153	28	5.8		1.10	
HU70-12	60	3.9			11.8	8.12	70.5	27.0	5.0	223	32	5.9		1.85	
HU70-13	0	20.0	5.5	193	9.4	8.52	82.0	26.9	3.3	143		7.2		0.65	
HU70-13	3	18.5													1.0
HU70-13	20	13.0			10.4	8.43	72.5	25.6							
HU70-13	46	4.6			11.6	8.08	79.0	26.4	2.3	218	32	5.9		1.87	

APPENDIX

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Appendix Table B (continued)

STA NO	DEPTH	TEMP	DISC	CCND	D.O.	PH	ALK	CA	P04	NO3	NH3	CL	SO4	SI02	CHL
HU70-14	0	20.5		202	9.1	8.54	80.5	26.8	2.3	115	21	5.7		0.77	
HU70-14	3	17.5													0.44
HU70-14	10	15.0			9.8	8.47	79.5	26.4		153	26	6.2		0.80	
HU70-14	18	12.0			10.2	8.11	81.0	26.8	5.3	193	43	5.5		1.68	
HU70-15	0	19.8	6.5	203	9.3	8.60	83.5	27.4	2.8	128	18	6.9	10.0	0.69	
HU70-15	3	17.1			9.9	8.59	72.0	26.8		146	15	6.6		0.73	1.72
HU70-15	8	16.2			10.1	0.54	83.0	27.6	0.8	145	34	6.2		1.04	
HU70-16	0	21.0	2.5	223	10.1	8.59	84.8	29.7	4.4	48	22	10.3	12.0	0.84	
HU70-16	3	20.0			10.0	8.62	82.2	28.5		64	18	7.6		0.75	2.60
HU70-16	10	14.8			10.3	8.55	82.2	28.7	4.4	76	13	9.7		0.75	
HU70-17	0	22.0	1.5	266	8.9	8.68	93.1	32.8	6.5	10	19	11.2	14.0	1.37	
HU70-17	3	21.0			9.0	8.60	91.3	29.6		65	22	12.0		1.05	4.84
HU70-17	11	14.5			9.1	8.27	83.7	27.5	1.4	138	37	6.1		1.00	
HU70-18	0	23.9	1.5	263	9.1	8.88	89.0	32.0	5.1	8	14	12.8		1.35	
HU70-18	3	23.9			9.2	8.72	91.2	30.7		11	31	11.8		1.27	10.90
HU70-18	7	19.8			9.3	8.66	91.2	31.4	5.0	16	36	11.9		1.41	
HU70-19	0	23.5	1.5	266	9.5	8.78	93.5	31.8	2.8	10	23	13.8	15.2	1.13	
HU70-19	3	23.2			9.6	8.67	92.0	31.5		12	23	13.3		1.18	9.40
HU70-19	8	20.0			9.2	8.72	93.0	32.2	10.8	18	28	13.6		1.19	
HU70-20	0	22.8	1.8	238	9.9	8.83	88.5	30.9	0.5	18		10.9	11.8	1.08	
HU70-20	3	22.8			9.9	8.72	89.6	30.5		12		9.3		1.16	8.24
HU70-20	9	15.7			9.0	8.46	87.7	28.9	1.8	82	44	8.8		1.06	
HU70-21	0	23.1	2.0	227	10.0	8.76	87.8	31.6	20.0	33	22	10.2	10.8	0.73	
HU70-21	3	22.8			10.3	8.86	89.0	30.0		26	23	11.3		0.76	7.56
HU70-21	9	14.0			9.2	8.29	84.4	26.6	0.5	100	40	6.8		0.94	
HU70-22	0	21.5	7.0	199	9.4	8.41	81.8	29.3	4.2	153	34	6.0		0.82	
HU70-22	3	20.5					28.1			123	22	8.2		0.73	
HU70-22	15	13.9			10.2	8.39	80.8	29.0		123		3.7		0.95	
HU70-22	22	9.0			10.2	8.31	81.2	27.6	2.4	176	30	5.8		1.05	
HU70-23	0	20.0	5.5	206	9.6	8.45	82.5	27.5		144	19	7.3	10.5	0.57	
HU70-23	3	17.6													0.80
HU70-23	10	16.0			9.8	8.40	82.0	28.0		105	16	6.8	11.0	1.00	
HU70-23	15	12.2			9.8	8.33	82.8	27.5		161	22	7.1	11.1	1.14	
HU70-24	0	19.5	5.8	204	9.6	8.48	84.0	27.0		73	10	3.4	11.8	0.53	
HU70-24	3	18.5													0.88
HU70-24	10	16.0			9.6	8.36	82.8	27.5		161		7.3	11.5	0.83	
HU70-24	19	10.5			10.2	8.28	82.8			168	29	7.3	10.8	1.18	
HU70-25	0	20.5	5.5	205	9.2	8.46	83.6	28.5		153		7.4	11.8	0.63	
HU70-25	3	20.0													0.84
HU70-25	10	15.5			10.2	8.47	82.0			156	17	6.6	10.6	1.01	
HU70-25	18	13.0			10.4	8.45	82.0	29.0		175		6.0	9.5	1.15	
HU70-26	0	21.5	5.8	204	9.2	8.47	83.5	28.0		155	22	7.4	9.8	0.70	
HU70-26	3	21.0													0.88
HU70-26	10	17.2			9.8	8.44	81.0			158	10	8.5	11.3	0.70	
HU70-26	15	15.3			10.0	8.37	85.0	27.0		158	26	7.4	10.8	0.77	
LAKE ERIE															
ERT0-1	0	22.8	2.0	261	8.0	8.40	80.1	32.0	7.0	143	39	14.0	10.7	1.00	
ERT0-1	2	22.1			8.2	8.37	83.0			156	28	13.9	11.2	1.06	2.24
ERT0-1	9	21.5			7.8	8.21	83.4	32.3	4.0	160	62	16.2	11.0	1.13	
ERT0-2	0	24.0	2.5	268	8.6	8.66	86.7	32.7	2.5	78	20	15.2	11.4	1.14	
ERT0-2	2	24.0			9.0	8.66	83.8			81	32	15.7	11.5	1.09	3.96
ERT0-2	9	23.5			7.6	8.43	85.2	32.0	9.0	86	75	15.0	11.2	1.33	
ERT0-3	0	25.0	2.0	256	8.7	8.86	84.3	32.0	1.5	49	37	15.0	12.0	0.86	
ERT0-3	2	25.0			8.6	8.85	84.0		1.5	46	39	15.0	12.5	0.87	4.24
ERT0-3	9	23.0			6.6	8.54	86.0	32.7	32.0	88		14.4	11.2	1.78	
ERT0-4	0	24.8	2.0	242	9.2	8.89	85.6	32.0	1.5	44	35	13.6	13.2	0.90	
ERT0-4	2	24.6			9.0	8.87	84.4		1.5	43	29	13.6	11.9	0.88	5.32
ERT0-4	9	22.1			8.2	8.76	84.7	31.0	8.0	40	42	13.2	11.5	0.83	
ERT0-5	0	25.0	2.5	241	8.8	8.88	86.3	30.5	15.8	56	35	12.9	12.7	0.40	
ERT0-5	2	24.8			9.2	8.92	86.7		4.0	48	28	12.6	14.0	0.36	7.84
ERT0-5	9	22.5			7.4	8.60	88.0	30.7	35.5	95	45	13.1	13.1	0.76	
ERT0-6	0	23.9	2.8	251	9.2	8.98	84.5	32.0	11.0	43	36	13.2	15.1	0.26	
ERT0-6	2	23.8			10.0	9.05	87.5			37	26	13.4	14.0	0.33	17.9
ERT0-6	7	22.5			4.4	8.24	96.8	36.5	52.0	195	37	14.1	18.5	1.22	
ERT0-7	0	24.5	3.0	286	9.4	8.90	93.0	36.5	7.0	85	63	14.7	25.0	0.30	
ERT0-7	2	24.5			9.4	8.89	93.0			66		13.1		0.22	7.44
ERT0-7	14	17.5			6.3	8.11	89.0	37.0	32.0	63	70	13.5	19.5	1.56	
ERT0-8	0	24.9	2.8	283	9.5	8.98	91.0	37.0	6.5	40	24	14.8	21.5	0.25	
ERT0-8	2	24.8			10.4	9.02	91.5			83	30	15.2		0.52	8.68
ERT0-8	13	15.0			7.1	8.27	91.0	38.0	15.1	63	46	14.0	21.5	0.81	
ERT0-9	0	24.3	6.0	293	9.3	8.90	91.5	38.5	17.5	49	19	13.8	21.5	0.30	
ERT0-9	2	24.2			9.4	8.90	90.5			61	15	15.7		0.30	1.96
ERT0-9	14	18.0			4.1	7.69	95.0	38.0	18.0	176	75	15.7	20.5	1.06	
ERT0-10	0	24.5	5.5	300	9.0	8.86	91.0	39.5	18.0	13	19	16.0	21.0	0.14	
ERT0-10	2	24.2			9.9	8.87	91.0			18	13	16.3		0.16	6.84
ERT0-10	17	9.5			4.3	7.61	93.5	39.0	16.0	178	122	16.7	21.0	1.36	
ERT0-11	0	24.8	5.5	300	9.3	8.85	93.5	38.5	15.1	13		15.7	21.5	0.16	
ERT0-11	2	24.4			8.9	8.86	93.5			8	13	11.0		0.11	1.60
ERT0-11	15	10.9			5.5	7.86	95.0	38.5	28.8	115		16.1	20.5	1.23	
ERT0-12	0	25.5	3.5	286	10.0	9.01	88.5	37.0	3.5	18	13	15.5	21.0	0.17	

Appendix Table B (continued)

STA NO	DEPTH	TEMP	DISC	COND	D.O.	PH	ALK	CA	PO4	NO3	NH3	CL	SO4	SiO2	CHL
ER70-12	2	25.3			10.0	9.01	89.0			18	23	12.3		0.16	6.0
ER70-12	9	25.1			8.8	8.93	90.0	35.0	3.5	25	29	15.1	21.0	0.21	
ER70-13	0	25.4	4.5	287	9.2	8.97	94.0	38.0	14.3	26	14	15.5	19.5	0.25	
ER70-13	2	25.0			9.3	8.97	91.5			36	15	15.7		0.23	3.32
ER70-13	13	13.8			1.1	7.52	99.0	37.0	120.0	68	182	15.5	18.0	2.73	
ER70-14	0	25.4	4.5	310	10.8	8.99	94.0	40.0	13.8	31	13	10.7	32.5	0.46	
ER70-14	2	25.0			10.9	9.03	94.5			38	13	14.0		0.60	22.7
ER70-14	11	20.8			4.0	7.96	55.5	38.0	72.0	136	85	14.6	19.5	1.96	
ER70-15	0	24.1	1.5		6.8	8.64	88.1	32.5	20.5	109		13.4	16.5	0.93	
ER70-15	2	24.0			7.0		86.8			49	26	13.3		0.85	8.88
ER70-15	9	23.0			6.7		85.7	31.8	17.2	116	26	13.4	15.7	0.92	
ER70-16	0	23.8	2.0		7.8	8.80	88.8	31.8	19.0	85	34	13.0	17.7	0.88	
ER70-16	2	23.8			7.6		84.8			86	30	13.1		0.92	8.76
ER70-16	10	22.0			8.4		83.0	32.5	21.0	80	30	13.4	17.7	0.84	
ER70-17	0	24.2	1.8		8.0	8.79	88.1	34.0	27.3	113	53	13.5	20.8	0.64	
ER70-17	2	24.2			7.9		88.8			104	44	12.2		0.65	14.8
ER70-17	7	24.2			8.0		87.7	33.0	22.6	123	55	13.7	17.5	0.67	
ER70-18	0	24.3	1.3		8.1	8.88	89.3	35.0	31.8	65	64	13.3	17.5	0.91	
ER70-18	2	24.2			8.2		88.9			58	52	12.3		0.93	14.5
ER70-18	7	24.2			7.6		91.0	32.5	27.3	73		13.4	17.7	0.90	
ER70-19	0	24.3	2.0		8.2	8.74	91.0	33.0	29.0	133	58	12.7	19.5	0.58	
ER70-19	2	24.3			7.6		90.9								11.7
ER70-19	8	23.5			7.9		87.8	31.8	26.5	195	58	13.4	19.5	0.62	
ER70-20	0	23.5	1.3			8.36									
ER70-20	2	23.5			7.9		80.1	29.0	16.3	158	45	13.5	12.9	1.14	2.48
ER70-20	5	23.1			7.8		80.4	30.0	18.0	158	48	11.2	13.3	1.12	

APPENDIX TABLE C. Particulate (sestonic) phosphate (ppb PO₄).

Station	Depth, m	PO ₄	Station	Depth, m	PO ₄
<i>Lake Michigan</i>					
LM70- 1	0	15.8	HU70-21	0	11.6
LM70- 1	15	18.5	HU70-22	15	3.4
LM70- 1	25	18.6	HU70-22	22	13.7
LM70- 1	40	95.3	HU70-23	0	7.1
LM70- 2	6	1.1	HU70-23	10	13.5
LM70- 3	5	16.8	HU70-23	15	14.1
LM70- 3	20	19.4	HU70-24	0	20.2
LM70- 3	40	15.3	HU70-24	19	28.2
LM70- 4	0	1.0	HU70-24	0	7.1
LM70- 4	25	12.4	HU70-25	18	18.2
LM70- 4	125	11.7	HU70-26	0	12.1
LM70- 5	25	10.3	HU70-26	15	4.8
LM70- 5	110	12.4	<i>Lake Erie</i>		
LM70- 6	2	1.5	ER70- 1	0	7.4
<i>Lake Huron</i>			ER70- 1	2	32.6
HU70- 3	0	13.9	ER70- 1	9	12.8
HU70- 5	0	12.8	ER70- 2	0	18.8
HU70- 6	3	27.5	ER70- 2	2	19.4
HU70- 6	8	29.7	ER70- 2	9	26.5
HU70- 7	15	12.9	ER70- 3	0	10.4
HU70- 7	32	41.4	ER70- 3	2	19.7
HU70- 8	0	70.9	ER70- 3	9	13.2
HU70- 8	8	39.5	ER70- 4	0	13.1
HU70- 8	14	54.2	ER70- 4	2	22.9
HU70- 9	0	15.2	ER70- 5	0	40.4
HU70- 9	20	5.7	ER70- 5	2	34.0
HU70-10	55	5.3	ER70- 5	9	32.6
HU70-11	0	12.9	ER70- 6	0	34.8
HU70-11	20	3.5	ER70- 6	2	31.2
HU70-11	65	2.7	ER70- 6	7	31.5
HU70-12	0	9.0	ER70- 7	0	1.8
HU70-12	20	13.4	ER70- 7	2	16.3
HU70-12	60	3.0	ER70- 7	14	7.5
HU70-13	0	7.0	ER70- 8	0	7.2
HU70-13	20	16.4	ER70- 8	2	8.9
HU70-13	46	31.9	ER70- 8	13	9.8
HU70-14	0	17.3	ER70- 9	0	7.1
HU70-14	10	4.9	ER70- 9	14	0.7
HU70-14	18	91.0	ER70-11	0	40.0
HU70-15	0	3.9	ER70-11	2	25.4
HU70-15	3	17.1	ER70-13	0	16.4
HU70-15	8	69.5	ER70-13	2	26.4
HU70-16	0	23.0	ER70-13	13	102.0
HU70-16	3	21.3	ER70-14	2	147.7
HU70-16	10	30.1	ER70-15	0	81.4
HU70-17	0	60.3	ER70-15	2	84.4
HU70-17	11	21.7	ER70-15	9	62.2
HU70-18	0	60.8	ER70-16	0	31.4
HU70-18	7	44.6	ER70-16	2	35.9
HU70-19	0	25.8	ER70-16	10	78.6
HU70-19	8	28.6	ER70-17	2	96.3
HU70-20	0	38.5	ER70-17	7	5.0
HU70-20	3	41.9	ER70-18	0	46.1
HU70-20	9	40.6	ER70-18	2	150.7
HU70-21	0	16.2	ER70-18	7	92.9
HU70-21	3	37.2	ER70-19	0	84.3
HU70-21	9	14.6	ER70-19	8	71.1
			ER70-20	2	57.1

APPENDIX TABLE D. Carbon fixation rates (mg C/m³/hr). Each entry represents the mean of two light bottles, except those marked with an asterisk (*), which are single bottles.

Station	Depth, m	Fix.	Station	Depth, m	Fix.	Station	Depth, m	Fix.
LM70- 1	0	2.90	SU70-28	0	0.14	HU70-18	0	37.70
LM70- 1	10	2.44	SU70-28	3	0.33	HU70-19	0	38.42
LM70- 2	3	2.64	SU70-32	0	0.48	HU70-19	3	44.41
LM70- 2	11	3.09	SU70-32	3	0.66	HU70-20	0	17.15
LM70- 3	0	1.56*	SU70-33	0	0.40	HU70-20	3	13.08
LM70- 3	2	2.87	SU70-33	3	0.70*	HU70-23	0	1.27
LM70- 4	10	0.86	SU70-35	0	0.32	HU70-23	3	1.66
LM70- 4	125	1.93	SU70-35	3	0.45	HU70-24	0	1.21
			SU70-36	0	0.18	HU70-24	3	1.93
			SU70-36	3	0.33	HU70-25	0	1.01
			SU70-37	0	0.22	HU70-25	3	1.67
SU70- 1	0	0.56	SU70-37	3	0.38	HU70-26	0	0.70
SU70- 1	8	0.72	SU70-38	0	0.17	HU70-26	3	0.73
SU70- 2	0	0.62*	SU70-38	3	0.28			
SU70- 2	6	0.88	SU70-39	0	0.40			
SU70- 3	0	0.50	SU70-39	3	0.50	ER70- 1	0	3.35
SU70- 3	6	0.53				ER70- 1	2	15.44
SU70- 4	0	0.43				ER70- 2	0	14.47
SU70- 4	6	0.54	HU70- 1	0	0.75	ER70- 2	2	12.26
SU70- 6	3	0.35*	HU70- 1	3	1.02	ER70- 3	0	8.88
SU70- 6	6	0.41	HU70- 2	0	0.90	ER70- 3	2	5.43
SU70- 7	0	0.65*	HU70- 2	3	1.14	ER70- 7	0	33.98
SU70- 7	60	0.78*	HU70- 3	0	0.28	ER70- 7	2	32.27
SU70- 7	120	1.19*	HU70- 3	3	0.30	ER70- 8	0	38.12
SU70- 7	180	1.02*	HU70- 4	0	0.47	ER70- 8	2	44.20
SU70-15	0	0.65	HU70- 4	3	0.62	ER70- 9	0	8.59
SU70-15	3	0.62	HU70- 8	0	1.70	ER70- 9	2	7.35
SU70-16	0	0.48	HU70- 8	3	2.30	ER70-10	0	7.67
SU70-16	3	0.51	HU70- 9	0	0.89	ER70-10	2	8.85
SU70-18	0	0.35	HU70- 9	3	2.18	ER70-12	0	28.24
SU70-18	3	0.08*	HU70-10	0	0.82	ER70-12	2	26.77
SU70-19	0	0.42	HU70-10	3	1.42	ER70-15	0	30.19
SU70-19	3	0.45	HU70-11	0	0.74	ER70-15	2	33.36
SU70-23	0	0.44	HU70-11	3	1.43	ER70-16	0	49.58
SU70-23	3	0.46	HU70-12	0	0.61	ER70-16	2	49.13
SU70-25	0	0.12	HU70-12	3	1.14	ER70-17	0	69.20
SU70-25	3	0.18	HU70-16	0	4.93	ER70-17	2	66.56
SU70-26	0	0.17	HU70-16	3	7.60	ER70-18	0	81.18
SU70-26	3	0.24	HU70-17	0	66.44	ER70-18	2	81.43
SU70-27	0	0.09	HU70-17	3	39.48	ER70-19	0	67.96
SU70-27	3	0.12	HU70-18	0	29.34	ER70-19	2	59.24

APPENDIX TABLE E. Number and relative abundance of phytoplankton genera for each station. "Abundant genera" were present in relatively greater numbers than "common genera." Genera that were neither "abundant" nor "common" are not tabulated, but are included in the "total number of genera."

Station #	Total number of genera	Abundant genera	Common genera
LM70- 1	11	<i>Asterionella</i> <i>Tabellaria</i> <i>Fragilaria</i>	<i>Synedra</i> <i>Melosira</i> <i>Dinobryon</i>
LM70- 2	10	<i>Tabellaria</i> <i>Fragilaria</i>	<i>Asterionella</i> <i>Synedra</i> <i>Dinobryon</i> <i>Botryococcus</i>
LM70- 3	7	<i>Anabaena</i>	<i>Tabellaria</i> <i>Synedra</i>
LM70- 5	12	<i>Asterionella</i> <i>Fragilaria</i> <i>Dinobryon</i>	<i>Tabellaria</i> <i>Synedra</i> <i>Rhizosolenia</i> <i>Lyngbya</i>
LM70- 6	14	<i>Tabellaria</i> <i>Fragilaria</i>	<i>Asterionella</i> <i>Synedra</i> <i>Melosira</i> <i>Cyclotella</i> <i>Dinobryon</i>
SU70- 1	10	<i>Asterionella</i>	<i>Tabellaria</i> <i>Fragilaria</i> <i>Synedra</i>
SU70- 2	17	<i>Tabellaria</i> <i>Melosira</i>	<i>Asterionella</i> <i>Synedra</i> <i>Rhizosolenia</i>
SU70- 3	14	<i>Asterionella</i> <i>Tabellaria</i>	<i>Fragilaria</i> <i>Synedra</i> <i>Melosira</i> <i>Rhizosolenia</i> <i>Dinobryon</i>
SU70- 4	14	<i>Asterionella</i> <i>Tabellaria</i> <i>Melosira</i> <i>Dinobryon</i>	<i>Fragilaria</i> <i>Synedra</i> <i>Rhizosolenia</i> <i>Oscillatoria</i> <i>Chroococcus</i>
SU70- 6	6	<i>Asterionella</i> <i>Dinobryon</i>	<i>Tabellaria</i> <i>Synedra</i>
SU70- 7	5	<i>Asterionella</i>	<i>Tabellaria</i> <i>Lyngbya</i>
SU70- 8	11	<i>Asterionella</i>	<i>Tabellaria</i> <i>Melosira</i>
SU70- 9	11	<i>Asterionella</i>	<i>Tabellaria</i> <i>Lyngbya</i>
SU70-10	9	<i>Asterionella</i> <i>Tabellaria</i>	<i>Fragilaria</i> <i>Synedra</i> <i>Melosira</i> <i>Rhizosolenia</i> <i>Dinobryon</i>
SU70-16	5	<i>Asterionella</i> <i>Tabellaria</i>	<i>Lyngbya</i>

Appendix Table E. (continued)

Station #	Total number of genera	Abundant genera	Common genera
SU70-17	8	<i>Asterionella</i>	<i>Tabellaria</i> <i>Synedra</i> <i>Fragilaria</i> <i>Stephanodiscus</i> <i>Dinobryon</i> <i>Lyngbya</i>
SU70-18	10	<i>Asterionella</i> <i>Tabellaria</i> <i>Rhizosolenia</i>	<i>Synedra</i> <i>Melosira</i> <i>Lyngbya</i>
SU70-19	7	<i>Asterionella</i> <i>Rhizosolenia</i>	<i>Tabellaria</i> <i>Synedra</i> <i>Melosira</i>
SU70-20	10	<i>Asterionella</i>	<i>Fragilaria</i> <i>Rhizosolenia</i> <i>Cyclotella</i> <i>Dinobryon</i> <i>Lyngbya</i>
SU70-21	10	<i>Asterionella</i>	<i>Tabellaria</i> <i>Synedra</i> <i>Dinobryon</i> <i>Lyngbya</i>
SU70-22	8	<i>Asterionella</i> <i>Tabellaria</i> <i>Dinobryon</i>	<i>Fragilaria</i> <i>Rhizosolenia</i>
SU70-23	11	<i>Asterionella</i>	<i>Tabellaria</i>
SU70-25	10	<i>Asterionella</i> <i>Tabellaria</i>	<i>Synedra</i> <i>Dinobryon</i> <i>Lyngbya</i>
SU70-26	4	<i>Asterionella</i>	<i>Tabellaria</i>
SU70-27	6	<i>Asterionella</i> <i>Tabellaria</i>	<i>Synedra</i> <i>Dinobryon</i> <i>Lyngbya</i>
SU70-28	9	NO QUALITATIVE ESTIMATES	
SU70-29	8	<i>Asterionella</i> <i>Rhizosolenia</i> <i>Dinobryon</i> <i>Lyngbya</i>	<i>Tabellaria</i> <i>Synedra</i>
SU70-30	11	<i>Asterionella</i> <i>Tabellaria</i> <i>Dinobryon</i>	<i>Fragilaria</i> <i>Synedra</i> <i>Rhizosolenia</i>
SU70-32	10	<i>Asterionella</i> <i>Tabellaria</i> <i>Dinobryon</i>	<i>Fragilaria</i> <i>Navicula</i>
SU70-33	6	<i>Tabellaria</i> <i>Fragilaria</i>	<i>Asterionella</i> <i>Synedra</i> <i>Dinobryon</i>
SU70-34	8	<i>Asterionella</i> <i>Tabellaria</i>	<i>Synedra</i> <i>Dinobryon</i>
SU70-35	13	<i>Asterionella</i> <i>Tabellaria</i> <i>Rhizosolenia</i> <i>Dinobryon</i>	<i>Synedra</i> <i>Melosira</i> <i>Cyclotella</i> <i>Navicula</i> <i>Lyngbya</i> <i>Chroococcus</i>

Appendix Table E. (continued)

Station #	Total number of genera	Abundant genera	Common genera
SU70-36	9	<i>Tabellaria</i>	<i>Asterionella</i> <i>Synedra</i> <i>Dinobryon</i>
SU70-37	11	<i>Asterionella</i> <i>Tabellaria</i> <i>Dinobryon</i>	<i>Synedra</i> <i>Rhizosolenia</i>
SU70-38	5	<i>Asterionella</i>	<i>Synedra</i> <i>Dinobryon</i> <i>Lyngbya</i>
SU70-39	8	<i>Tabellaria</i>	<i>Asterionella</i> <i>Synedra</i> <i>Dinobryon</i>
SU70-40	11	<i>Tabellaria</i>	<i>Asterionella</i> <i>Synedra</i> <i>Dinobryon</i>
HU70- 1	10	<i>Tabellaria</i> <i>Asterionella</i> <i>Synedra</i>	<i>Fragilaria</i> <i>Anabaena</i> <i>Melosira</i>
HU70- 2	14	<i>Tabellaria</i>	<i>Fragilaria</i> <i>Melosira</i> <i>Synedra</i>
HU70- 3	10	<i>Tabellaria</i> <i>Melosira</i>	<i>Fragilaria</i> <i>Asterionella</i> <i>Dinobryon</i> <i>Synedra</i> <i>Rhizosolenia</i> <i>Oscillatoria</i>
HU70- 5	13	<i>Tabellaria</i>	<i>Fragilaria</i> <i>Asterionella</i> <i>Melosira</i> <i>Lyngbya</i>
HU70- 6	9	-----	<i>Tabellaria</i> <i>Asterionella</i> <i>Fragilaria</i> <i>Melosira</i> <i>Synedra</i>
HU70- 7	8	<i>Tabellaria</i>	<i>Fragilaria</i> <i>Asterionella</i> <i>Melosira</i> <i>Dinobryon</i>
HU70- 8	13	-----	<i>Tabellaria</i> <i>Fragilaria</i> <i>Asterionella</i> <i>Anabaena</i> <i>Cyclotella</i> <i>Dinobryon</i> <i>Synedra</i> <i>Synura</i> <i>Sphaerocystis</i>
HU70- 9	15	<i>Tabellaria</i> <i>Fragilaria</i> <i>Melosira</i> <i>Synedra</i>	<i>Asterionella</i> <i>Dinobryon</i> <i>Rhizosolenia</i>

Appendix Table E. (continued)

Station #	Total number of genera	Abundant genera	Common genera
HU70-10	13	<i>Tabellaria</i> <i>Asterionella</i> <i>Melosira</i>	<i>Fragilaria</i> <i>Dinobryon</i> <i>Synedra</i>
HU70-11	16	<i>Tabellaria</i> <i>Fragilaria</i> <i>Melosira</i>	<i>Asterionella</i> <i>Dinobryon</i> <i>Synedra</i> <i>Rhizosolenia</i>
HU70-12	15	<i>Tabellaria</i> <i>Melosira</i> <i>Rhizosolenia</i>	<i>Fragilaria</i> <i>Asterionella</i> <i>Dinobryon</i> <i>Synedra</i> <i>Oscillatoria</i>
HU70-13	15	<i>Tabellaria</i>	<i>Fragilaria</i> <i>Asterionella</i> <i>Melosira</i> <i>Dinobryon</i> <i>Synedra</i> <i>Rhizosolenia</i> <i>Coscinodiscus</i>
HU70-14	14	<i>Tabellaria</i>	<i>Fragilaria</i> <i>Asterionella</i> <i>Ceratium</i> <i>Cyclotella</i>
HU70-15	7	<i>Tabellaria</i>	<i>Fragilaria</i> <i>Asterionella</i> <i>Anabaena</i> <i>Dinobryon</i> <i>Synedra</i>
HU70-16	12	SULFUR-REDUCING BACTERIA OR BLUE-GREENS <i>Tabellaria</i> <i>Fragilaria</i>	<i>Ceratium</i> <i>Melosira</i> <i>Microcystis</i>
HU70-17	18	SULFUR-REDUCING BACTERIA OR BLUE-GREENS <i>Tabellaria</i> <i>Fragilaria</i>	<i>Asterionella</i> <i>Anabaena</i> <i>Melosira</i> <i>Microcystis</i> <i>Oscillatoria</i> <i>Pediastrum</i> <i>Phormidium</i>
HU70-18	9	<i>Aphanizomenon</i> <i>Ceratium</i>	<i>Anabaena</i> <i>Staurastrum</i>
HU70-19	10	<i>Tabellaria</i>	<i>Fragilaria</i> <i>Anabaena</i> <i>Ceratium</i> <i>Melosira</i> <i>Microcystis</i> <i>Peridinium</i>
HU70-20	15	SULFUR-REDUCING BACTERIA OR BLUE-GREENS	<i>Tabellaria</i> <i>Fragilaria</i> <i>Ceratium</i> <i>Melosira</i> <i>Microcystis</i> <i>Oscillatoria</i> <i>Phormidium</i>

Appendix Table E. (continued)

Station #	Total number of genera	Abundant genera	Common genera
HU70-21	13	<i>Aphanizomenon</i>	<i>Tabellaria</i> <i>Asterionella</i> <i>Ceratium</i> <i>Oedogonium</i> <i>Synedra</i> <i>Oscillatoria</i>
HU70-22	16	<i>Fragilaria</i> <i>Melosira</i> <i>Synedra</i>	<i>Asterionella</i> <i>Anabaena</i> <i>Ceratium</i> <i>Cyclotella</i> <i>Dinobryon</i> <i>Microcystis</i> <i>Gloeocystis</i>
HU70-23	9	<i>Tabellaria</i> <i>Fragilaria</i>	<i>Asterionella</i> <i>Ceratium</i> <i>Melosira</i>
HU70-24	14	<i>Tabellaria</i> <i>Fragilaria</i>	<i>Asterionella</i> <i>Ceratium</i> <i>Dinobryon</i>
HU70-25	10	<i>Tabellaria</i> <i>Asterionella</i>	<i>Fragilaria</i> <i>Cyclotella</i> <i>Melosira</i>
HU70-26	10	<i>Tabellaria</i> <i>Fragilaria</i>	<i>Asterionella</i> <i>Melosira</i>
ER70- 1	7	NO QUALITATIVE ESTIMATES	
ER70- 2	9	<i>Fragilaria</i> <i>Ceratium</i>	<i>Asterionella</i> <i>Anabaena</i>
ER70- 3	13	<i>Fragilaria</i>	<i>Asterionella</i> <i>Sphaerocystis</i> <i>Pediastrum</i>
ER70- 4	13	<i>Fragilaria</i>	<i>Ceratium</i> <i>Anabaena</i> <i>Synedra</i> <i>Pediastrum</i>
ER70- 5	6	<i>Aphanizomenon</i>	<i>Ceratium</i> <i>Microcystis</i>
ER70- 6	10	<i>Aphanizomenon</i>	<i>Fragilaria</i> <i>Ceratium</i> <i>Pediastrum</i> <i>Microcystis</i> <i>Pandorina</i>
ER70- 7	8	<i>Aphanizomenon</i>	<i>Fragilaria</i> <i>Pediastrum</i> <i>Microcystis</i>
ER70- 8	9	<i>Aphanizomenon</i> <i>Ceratium</i>	<i>Fragilaria</i> <i>Pediastrum</i> <i>Staurastrum</i> <i>Microcystis</i>
ER70- 9	11	<i>Aphanizomenon</i> <i>Ceratium</i> <i>Staurastrum</i>	<i>Fragilaria</i> <i>Anabaena</i> <i>Oedogonium</i> <i>Microcystis</i>

Appendix Table E. (concluded)

Station #	Total number of genera	Abundant genera	Common genera
ER70-10	11	<i>Ceratium</i> <i>Anabaena</i> <i>Oedogonium</i>	<i>Staurastrum</i> <i>Pediastrum</i> <i>Microcystis</i> <i>Oscillatoria</i>
ER70-11	12	<i>Anabaena</i> <i>Oedogonium</i>	<i>Ceratium</i> <i>Staurastrum</i> <i>Coelosphaerium</i> <i>Pediastrum</i>
ER70-12	14	<i>Fragilaria</i> <i>Ceratium</i> <i>Anabaena</i> <i>Aphanizomenon</i>	<i>Peridinium</i> <i>Microcystis</i>
ER70-13	13	<i>Fragilaria</i> <i>Staurastrum</i> <i>Aphanizomenon</i>	<i>Anabaena</i> <i>Lyngbya</i> <i>Pediastrum</i> <i>Microcystis</i>
ER70-14	10	<i>Ceratium</i> <i>Aphanizomenon</i>	<i>Fragilaria</i> <i>Pediastrum</i>
ER70-15	7	<i>Aphanizomenon</i>	<i>Microcystis</i>
ER70-16	10	<i>Aphanizomenon</i>	<i>Microcystis</i> <i>Pediastrum</i>
ER70-17	6	<i>Aphanizomenon</i> <i>Microcystis</i>	<i>Ceratium</i>
ER70-18	6	<i>Aphanizomenon</i>	<i>Microcystis</i>
ER70-19	6	<i>Aphanizomenon</i> <i>Ceratium</i> <i>Microcystis</i>	-----
ER70-20	7	-----	<i>Fragilaria</i> <i>Ceratium</i> <i>Anabaena</i> <i>Ulothrix</i>

APPENDIX TABLE F. Settled volume (ml/m³) and relative generic abundance of zooplankton. Relative abundance is greatest for category 5 and least for category 1.

KEY TO GENERIC ABBREVIATIONS

Asp = <i>Asplanchna</i>	Dia = <i>Diaptomus</i>	Lep = <i>Leptodora</i>	Sen = <i>Senecella</i>
Bos = <i>Bosmina</i>	Dap = <i>Daphnia</i>	Lim = <i>Limnocalanus</i>	Unk = Unident. Rotifer
Cer = <i>Ceriodaphnia</i>	Epi = <i>Epischura</i>	Mes = <i>Mesocyclops</i>	
Cyc = <i>Cyclops</i>	Hol = <i>Holopedium</i>	Mys = <i>Mysis</i>	
Dma = <i>Diaphanosoma</i>	Kel = <i>Kellicottia</i>	Pol = <i>Polyphemus</i>	

Station	Vol. ml/m ³	Relative Abundance				
		5	4	3	2	1
<i>Lake Michigan</i>						
LM70- 1	2.21	Bos	Dia,Cyc			Dap
LM70- 2	4.04	Bos,Dia,Cyc				
LM70- 3	1.75	Bos	Dia,Cyc			Dap
LM70- 5	0.37	Bos	Dia,Cyc		Dap	Kel
LM70- 6	1.25	Bos,Dia	Cyc		Dap	Asp
<i>Lake Superior</i>						
SU70- 1	0.38	Dia	Lim,Bos,Asp	Cyc		Dap,Hol,Lep
SU70- 2	0.29	Dia,Dap	Cyc,Lim			Bos,Hol,Asp
SU70- 3	0.55	Dia,Cyc			Pol,Bos,Hol,Dap,Asp	
SU70- 4	0.18	Dia	Cyc,Dap,Lim			Bos,Asp
SU70- 5	0.16	Dia			Cyc	
SU70- 6	0.44	Dia	Lim	Cyc		Dap
SU70- 7	0.24	Dia		Cyc,Lim		
SU70- 8	0.27	Dia,Lim		Cyc		Sen
SU70- 9	0.49	Dia		Cyc		Sen
SU70-10	0.29	Dia			Cyc	
SU70-15	0.25	Dia	Lim	Cyc		
SU70-16	0.18	Dia	Lim			Sen
SU70-17	0.17	Dia	Lim	Cyc		
SU70-18	--	Dia				Cyc,Sen
SU70-19	0.10	Dia,Lim			Cyc	
SU70-20	0.13	Dia		Lim	Cyc	
SU70-21	0.20	Dia		Lim		Sen
SU70-23	0.52	Dia	Lim	Cyc	Asp	Dap,Bos,Lep

Appendix Table F. (continued)

Station	Vol. ml/m ³	Relative Abundance				
		5	4	3	2	1
SU70-25	0.26	Dia	Lim	Sen		Cyc, Bos
SU70-26	0.40	Dia	Lim			Cyc, Sen
SU70-27	0.19	Dia, Lim				Cyc, Sen, Mys
SU70-28	0.16	Dia, Lim		Sen, Cyc		Mys
SU70-29	0.30	Dia, Lim	Cyc			Mys
SU70-30	0.85	Dia		Lim, Cyc		Dap, Asp
SU70-31	0.50	Dia		Lim	Cyc	Dap, Bos, Lep, Asp
SU70-32	0.48	Dia		Lim		Cyc, Asp
SU70-33	0.75	Dia				Lim, Cyc, Dap, Asp
SU70-35	0.24	Dia, Lim			Sen	Cyc
SU70-36	0.47	Dia		Lim, Cyc		Asp
SU70-38	0.30	Dia, Lim			Cyc	
SU70-39	0.81	Dia	Lim, Cyc			
SU70-40	0.59	Dia		Cyc		Lim, Dap, Pol, Asp

Lake Huron

HU70- 1	1.18	Bos	Cyc, Dia	Dap, Hol		Lim
HU70- 2	1.06	Dia	Bos, Cyc	Dap	Hol, Asp	Lim, Lep
HU70- 3	0.85	Dia	Bos, Lim		Cyc, Dap, Asp	Hol
HU70- 4	0.62	Dia	Bos, Cyc	Lim, Hol, Asp	Dap	
HU70- 5	1.06	Dia, Cyc	Bos	Hol	Dap	Lim
HU70- 6	0.82	Cyc, Bos	Dia, Hol		Dap	
HU70- 7	0.86	Dia	Bos	Dap, Cyc, Asp	Lim, Sen, Pol, Hol	
HU70- 8	6.46	Dia, Bos		Cyc, Dap	Hol	Lim, Asp
HU70- 9	1.67	Dia	Bos, Cyc		Hol	Dap, Lim, Asp
HU70-10	0.67	Dia	Bos	Cyc, Hol, Asp	Lim	Pol
HU70-11	0.97	Dia	Bos, Cyc	Lim	Sen, Hol, Asp, Dap	
HU70-12	0.68	Dia	Lim	Cyc, Bos	Pol, Hol, Asp	Lep
HU70-13	4.11	Dia, Cyc		Bos, Dap	Hol, Asp	Lim
HU70-14	9.36	Dia, Cyc		Bos, Hol	Dap	Pol, Asp
HU70-15	1.55	Dia, Bos	Cyc, Hol	Dap		Epi, Asp
HU70-16	0.41		Dia, Dap, Bos	Cyc, Asp	Hol	
HU70-17	0.82	Bos	Dia, Dap, Asp	Cyc, Lep		
HU70-18	1.11	Unk	Bos, Dap	Lep, Asp	Cyc	
HU70-19	0.67	Unk	Dia, Cyc, Bos	Dap, Asp, Lep		Cer

Appendix Table F. (concluded)

Station	Vol. ml/m ³	Relative Abundance				
		5	4	3	2	1
HU70-20	0.64	Unk	Bos	Asp,Lep	Dia,Cyc,Cer	Hol
HU70-21	0.35	Bos,Asp		Dia,Cyc,Lep	Dap	
HU70-22	1.37	Dia,Bos	Asp	Cyc,Dap	Hol,Lep	Pol
HU70-23	0.43	Cyc	Dia,Bos	Hol	Dap,Lep	Pol
HU70-24	9.60	Hol	Dia,Cyc	Bos,Dap	Lep	Pol,Asp
HU70-25	0.52	Dia	Cyc,Bos		Dap,Hol	Asp
HU70-26	2.64	Dia	Cyc	Hol	Bos	Dap,Pol,Lep,Asp
<i>Lake Erie</i>						
ER70- 1	0.80	Cyc,Dia	Bos	Lep	Dap,Hol	Dma,Asp
ER70- 2	4.20	Dap,Unk	Bos	Lep,Cyc,Asp		Dma
ER70- 3	2.80	Dap	Bos,Dma	Cyc	Dia,Lep	Asp
ER70- 4	9.85	Bos	Dap	Lep,Dma,Cyc	Dia,Asp	Hol
ER70- 5	11.30	Dap		Bos,Lep,Cyc	Dia	Hol,Dma
ER70- 6	4.87	Dap	Cyc,Lim	Lep		Bos,Dma
ER70- 7	14.6	Dap	Dia	Bos,Asp,Cyc	Dma,Lep	
ER70- 8	8.35	Dap	Bos,Dia,Cyc	Asp	Dma	Lep
ER70- 9	4.87	Dap,Dia	Cyc	Asp	Dma,Lep,Bos	Lim
ER70-10	4.59	Dia,Cyc	Dap,Unk		Asp	Bos
ER70-11	3.97	Dia,Cyc,Dap	Asp	Bos	Dma	
ER70-12	12.65	Dap	Cyc,Dia		Dma	
ER70-13	5.23	Dia,Dap	Cyc	Asp	Bos,Lep	Dma
ER70-14	12.30	Dap		Lep,Cyc	Bos,Dia	Asp
ER70-15	9.55	Dap	Bos,Lep	Dma	Cyc	Dia
ER70-16	7.09	Dap	Bos,Lep		Cyc,Mes	Dia,Dma
ER70-17	9.60	Bos	Dap,Cyc	Dia,Dma	Lep	
ER70-18	6.73	Bos	Dap		Cyc,Dia,Lep	Hol
ER70-19	12.10		Bos,Dap,Dia	Cyc		Mes,Dma
ER70-20	2.00		Dia,Cyc	Bos	Dap,Lep	Hol,Dma

APPENDIX TABLE G. Description of bottom sediments. Compiled by C. I. Dell.

Station	Description
<i>Lake Michigan.</i>	
LM70- 1	Medium sand.
LM70- 2	Coarse sand.
LM70- 3	Sandy silt.
LM70- 4	Grey silt.
LM70- 5	Limonitic layer over grey muck.
LM70- 6	Sand.
<i>Lake Superior</i>	
SU70- 1	Dark brownish-grey silty mud.
SU70- 2	Dark grey slightly silty mud.
SU70- 3	Clean medium quartz sand with some granite pebbles; overlying pale reddish-brown clay.
SU70- 4	Dark brownish-grey slightly silty mud overlying dark greyish-brown slightly silty mud.
SU70- 5	Clayey, reddish-brown medium sand; top cm. dark greyish-brown.
SU70- 6	Rock bottom, no sediment.
SU70- 7	Greyish-brown sandy clay (about 40% sand, 60% clay); top cm. dark greyish-brown sandy clay.
SU70- 8	Greyish-brown clayey sand.
SU70- 9	Clean light brown medium quartz sand.
SU70-10	Light brownish-grey mud overlain by ± 1 cm. of more reddish-brown mud. Top cm. dark grey silty mud.
SU70-15	Pale brownish-grey clay, overlain by 1 cm. of reddish-brown sandy clay. Top few mm. are dark grey sandy clay.
SU70-16	Grey clay; upper ± 1 cm. alternating bands of hard crust-like limonitic material and clay.
SU70-17	Reddish-brown clay; A compact more reddish-brown layer about 3 cm. below the surface. Top mm. dark grey clay.
SU70-18	Sequence from the top; about 5 cm. of brown mud, 1 cm. of hard limonitic crust (the very top of this crust is black), grey clay.
SU70-19	Sequence from the top: Greyish-brown mud, soft limonitic layer, grey clay.
SU70-20	No sediment description.
SU70-21	Dark brown mud.
SU70-22	Reddish-brown silty clay.
SU70-23	Slightly clayey medium sand.
SU70-25	Dark brown slightly silty mud, limonitic layer 1 cm. under surface.
SU70-26	Slightly clayey medium sand.
SU70-27	Greyish-brown slightly silty mud; distinct limonitic layer 2-3 cm. below surface.
SU70-28	Reddish-brown clayey sand.
SU70-29	Rocks and pebbles, no sediment.
SU70-30	No sediment.

Appendix Table G. (continued)

Station	Description
SU70-31	Dark brown sandy clay.
SU70-32	Reddish clayey sand.
SU70-33	Medium sand.
SU70-34	Pale brown clean medium sand.
SU70-35	Dark reddish-brown clayey sand.
SU70-36	Coarse sand and some fine gravel.
SU70-37	Clean coarse sand.
SU70-38	Dark reddish-brown clayey sand.
SU70-39	Clean medium sand.
SU70-40	Clean medium sand.
<i>Lake Huron</i>	
HU70- 1	Light brown quite clean medium sand with numerous cinders and pebbles.
HU70- 2	Dark greyish-brown slightly silty mud.
HU70- 3	Reddish-brown sandy clay; top mm. dark brownish-grey clay.
HU70- 4	Reddish-brown slightly sandy clay; top mm. dark brownish-grey clay.
HU70- 5	Reddish-brown slightly sandy clay; top half cm. dark greyish-brown clayey sand with abundant black grains. A few cinders.
HU70- 6	Light brown, clean medium sand. (First ponar had some very compact reddish-brown sandy clay.)
HU70- 7	Clayey, dark brown sand with many black grains.
HU70- 8	Medium brown silty sand.
HU70- 9	Clayey, greyish-brown medium sand.
HU70-10	Slightly sandy greyish-brown clay. Several soft limonitic-looking layers 1 to 5 cm. below the surface.
HU70-11	Dark brownish-grey mud. Large cinders and piece of coal on top. Faint H ₂ S odor.
HU70-12	Reddish-brown clayey sand, medium. Top mm. dark greyish-brown.
HU70-13	Brown slightly clayey medium sand.
HU70-14	Brownish-grey slightly clayey medium sand.
HU70-15	Slightly clayey brown medium sand.
HU70-16	Greyish-brown, slightly clayey, fine sand.
HU70-17	Brownish-grey sandy mud.
HU70-18	Dark brownish-grey slightly silty mud.
HU70-19	Dark brownish-grey clayey sand. Some fragments of dark semi-metallic (probably man-made) material.
HU70-20	Brown medium sand and some black sandy mud. (Could not determine the stratigraphic relationship of the two but the mud probably was overlying the sand.)
HU70-21	Brown, clean medium sand; a few rounded pebbles.
HU70-22	Clean medium to coarse sand; some black silty mud (probably on top).
HU70-23	Clean coarse sand; some granules of white limestone and orange-brown chert.

Appendix Table G. (Concluded)

Station	Description
HU70-24	Clean medium sand and a small amount of dark grey silt (probably on top). Some cinders and rock fragments.
HU70-25	Medium sand and some granules and pebbles, mostly of orange-brown chert. A small amount of dark grey silt.
HU70-26	Coarse sand with granules and small pebbles - mostly of limestone and orange-brown chert.
<i>Lake Erie</i>	
ER70- 1	Grey sticky clay overlain by about 1.5 cm. of grey coarse sand. Many cinders and pebbles on the surface.
ER70- 2	Grey silty mud.
ER70- 3	No description made of sediment.
ER70- 4	Dark grey slightly silty mud.
ER70- 5	Dark grey slightly silty mud.
ER70- 6	Dark grey slightly silty mud.
ER70- 7	Dark grey slightly silty mud.
ER70- 8	Dark grey slightly silty mud.
ER70- 9	Dark grey slightly silty mud.
ER70-10	Dark grey slightly silty mud.
ER70-11	Dark grey slightly silty mud.
ER70-12	No sediment; ponar brought up some rocks: one rounded granite, two siltstones; a few leeches on these rocks.
ER70-13	Dark grey slightly silty mud.
ER70-14	Dark grey slightly silty mud.
ER70-15	Dark grey mud.
ER70-16	Dark grey slightly silty mud.
ER70-17	Dark grey fine sand; one large cinder.
ER70-18	Dark grey slightly silty mud.
ER70-19	Dark grey slightly silty mud.
ER70-20	Dark grey slightly silty mud.

APPENDIX TABLE H. Benthos total counts (individuals/m²) and percent composition. Based on 3 grab samples per station in Lakes Michigan, Superior, and Lake Huron stations 1 and 3-16; two grabs per station at Lake Huron stations 2 and 17-26, and all Lake Erie stations.

KEY TO TAXONOMIC ABBREVIATIONS

Olig - *Oligochaeta**Gamm* - *Gammarus**Spha* - *Sphaeriidae**Hiru* - *Hirudinea**Mysi* - *Mysis**Gast* - *Gastropoda**Pont* - *Pontoporeia**Chir* - *Chironomidae**Othe* - Other (see key below)

Station	Total #/m ²	<i>Olig</i>	<i>Hiru</i>	<i>Pont</i>	<i>Gamm</i>	<i>Mysi</i>	<i>Chir</i>	<i>Spha</i>	<i>Gast</i>	<i>Othe</i>
<i>Lake Michigan</i>										
LM70- 1	5208	21.1	--	73.3	--	--	0.3	5.3	--	--
LM70- 3	5923	31.4	--	58.6	--	--	0.6	8.5	--	0.9 ¹
LM70- 4	1410	11.7	--	72.6	--	--	2.9	12.6	--	--
LM70- 5	2787	5.9	--	86.1	--	--	1.0	6.4	--	0.5 ²
LM70- 6	784	57.9	--	1.8	--	--	19.2	2.6	18.3	--
<i>Lake Superior</i>										
SU70- 1	179	38.5	--	19.0	--	3.9	30.7	7.8	--	--
SU70- 2	1184	20.9	--	54.6	--	0.6	2.8	20.9	--	--
SU70- 3	110	37.3	--	43.6	--	--	19.1	--	--	--
SU70- 4	481	32.8	--	55.7	--	1.4	--	10.0	--	--
SU70- 5	392	56.1	--	33.4	--	1.8	--	8.7	--	--
SU70- 7	97	63.9	--	21.6	--	7.2	7.2	--	--	--
SU70- 8	407	59.2	--	10.1	--	3.4	5.1	20.4	--	1.7 ³
SU70- 9	104	20.2	--	66.3	--	13.4	--	--	--	--
SU70-10	221	12.7	--	74.7	--	3.2	6.3	3.2	--	--
SU70-15	166	12.6	--	66.3	--	--	8.4	12.6	--	--
SU70-16	28	--	--	75.0	--	25.0	--	--	--	--
SU70-17	14	--	--	100.0	--	--	--	--	--	--
SU70-18	76	--	--	90.8	--	9.2	--	--	--	--
SU70-20	21	--	--	66.7	--	33.3	--	--	--	--
SU70-21	214	3.3	--	90.2	--	3.3	3.3	--	--	--
SU70-22	833	--	--	94.9	--	1.7	3.7	--	--	--
SU70-23	991	17.3	0.7	67.3	--	--	2.8	11.8	--	--
SU70-25	158	21.5	4.4	65.2	--	4.4	--	4.4	--	--
SU70-26	1053	6.5	--	77.8	--	3.2	--	12.4	--	--
SU70-27	159	--	--	78.0	--	17.6	4.4	--	--	--
SU70-28	134	76.7	--	23.3	--	-- *	--	--	--	--
SU70-29	1177	8.7	--	15.8	--	-- *	--	--	--	75.5 ⁴
SU70-31	455	28.8	--	49.9	--	--	16.7	4.6	--	--
SU70-32	1190	48.8	--	46.2	--	--	--	5.8	--	--
SU70-33	317	8.8	--	65.0	--	--	21.8	--	--	4.4 ¹
SU70-34	729	9.5	--	56.6	--	--	20.7	13.2	--	--
SU70-35	400	50.0	--	27.5	--	--	5.2	17.2	--	--
SU70-36	110	6.4	--	43.6	--	--	50.0	--	--	--
SU70-37	103	--	--	86.4	--	13.6	--	--	--	--
SU70-38	564	29.2	--	36.5	--	1.2 *	1.2	31.7	--	--
SU70-39	110	--	--	62.7	--	--	37.3	--	--	--
SU70-40	385	--	--	82.1	--	--	16.1	--	1.8	--
<i>Lake Huron</i>										
HU70- 1	545	41.8	--	50.6	--	--	7.5	--	--	--
HU70- 2	4423	5.9	--	87.3	--	0.2	1.4	5.1	--	--
HU70- 3	2325	5.6	--	92.3	--	0.6	1.5	--	--	--
HU70- 4	3250	37.6	--	60.1	--	0.4	1.9	--	--	--
HU70- 5	772	31.2	--	41.1	--	--	14.2	8.0	3.6	1.8 ¹
HU70- 6	63	33.3	--	22.2	--	--	33.3	--	11.1	--
HU70- 7	1663	46.1	--	46.5	--	0.4	0.4	6.6	--	--
HU70- 8	1938	25.3	--	67.6	--	--	2.5	2.1	1.7	0.7 ⁵

Appendix Table H. (concluded)

Station	Total #/m ²	Olig	Hiru	Pont	Gamm	Mysi	Chir	Spha	Gast	Othe
HU70- 9	3988	2.6	--	77.8	--	0.2	--	15.6	--	3.8 ¹
HU70-10	4113	33.9	--	60.0	--	0.7	0.2	5.2	--	--
HU70-11	3450	32.4	--	64.4	--	1.4	--	1.8	--	--
HU70-12	2857	15.9	--	75.1	--	1.0	--	8.0	--	--
HU70-13	5657	20.4	--	70.2	--	--	1.3	8.0	--	--
HU70-14	15,475	64.0	0.3	29.4	--	--	4.4	1.6	0.1	0.3 ⁶
HU70-15	1222	62.7	--	7.1	12.6	--	6.8	6.2	1.7	2.8 ^{5,6}
HU70-16	3796	80.3	0.5	3.4	3.6	--	4.4	2.4	--	5.3 ^{5,6}
HU70-17	5968	79.8	--	--	--	--	20.2	--	--	--
HU70-18	5868	94.3	--	--	--	--	5.6	--	--	--
HU70-19	3219	92.6	--	--	--	--	7.4	--	--	--
HU70-20	1738	66.1	--	--	17.8	--	14.3	--	--	1.8 ⁶
HU70-21	403	25.5	--	12.9	51.4	--	--	2.5	7.7	--
HU70-22	1282	51.6	--	29.9	--	--	8.0	--	--	10.4 ^{1,7,8}
HU70-23	124	75.0	--	--	--	--	25.0	--	--	--
HU70-25	839	44.4	--	46.8	--	--	3.7	2.5	2.5	--
HU70-26	247	75.3	--	4.0	--	--	16.6	4.0	--	--
<i>Lake Erie</i>										
ER70- 1	1718	26.5	0.6	--	6.6	--	--	49.4	3.0	13.8 ⁹
ER70- 2	475	37.0	2.1	--	8.6	--	45.7	2.1	4.4	--
ER70- 3	775	61.4	1.3	--	--	--	34.7	1.3	1.3	--
ER70- 4	2339	84.5	0.4	--	--	--	13.7	0.4	0.9	--
ER70- 5	2576	75.9	0.4	--	--	--	23.3	0.4	--	--
ER70- 6	537	67.4	1.9	--	--	--	28.9	1.9	--	--
ER70- 7	4937	74.2	--	--	0.2	--	19.7	5.9	--	--
ER70- 8	1688	20.3	--	--	--	--	73.0	6.7	--	--
ER70- 9	713	30.8	--	--	--	--	5.7	63.8	--	--
ER70-10	1407	36.0	--	--	--	--	--	64.0	--	--
ER70-11	2919	62.4	--	--	--	--	2.8	34.4	--	--
ER70-13	1242	1.7	--	--	--	--	25.8	72.5	--	--
ER70-14	3146	84.5	1.0	--	--	--	8.9	5.6	--	--
ER70-15	3313	69.4	--	--	--	--	30.0	0.6	--	--
ER70-16	4556	68.9	--	--	0.2	--	24.9	5.8	0.2	--
ER70-17	10,247	84.1	1.7	--	2.0	--	0.3	9.7	1.8	0.3 ^{9,10}
ER70-18	4993	91.4	1.4	--	--	--	4.3	2.5	--	0.3 ¹
ER70-19	3104	94.7	--	--	--	--	3.3	2.0	--	--
ER70-20	9526	57.0	3.2	--	3.0	--	0.6	26.0	10.0	--

*Indicates *Mysis* found in zooplankton sample at this station.¹Nematoda⁴*Hydra*⁷Ostracoda¹⁰Hydracarina²Coleoptera (larvae)⁵Trichoptera⁸Chydoridae³*Ephemera*⁶*Asellus*⁹Turbellaria