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# NUTRIENT ENRICHMENT AND EUTROPHICATION OF LAKE MICHIGAN

Progress Report

Claire L. Schelske

Great Lakes Research Division
The University of Michigan
Ann Arbor, Michigan



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## DISCLAIMER

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NEARSHORE PROCESSES

In 1976 the major cruise effort was focused on mixing processes in the nearshore zone of Lake Michigan near Holland, Michigan. During the September 1975 cruise to study the Grand River plume, we observed a mixing pattern whereby Grand River water mixed with upwelled water approximately one mile offshore, and the resulting water of intermediate temperature and density spread out into the open lake at mid-thermocline depth (Fig. 1). Mixing processes between this nearshore zone and the mid-lake water mass are difficult to study by conventional physical oceanographic techniques, as for example, current meter studies, and are not well understood at present (Csanady 1975). We felt that our approach, using a combination of chemical and biological tracers, was particularly suited for studying these processes. We chose the study area near Holland, Michigan, as an intensive study of water mass circulation was conducted in that area during 1976 by Dr. James Saylor of the NOAA Great Lakes Environmental Research Laboratory (GLERL) and Dr. Ted Green of the University of Wisconsin-Milwaukee (Fig. 2). We hope to be able to make some interesting comparisons with their data when it becomes available.

The objective of the 1976 nearshore cruise was to describe the typical summer mixing patterns between the nearshore zone and the mid-lake water mass. As the pattern varies with time, the most efficient use of the limited ship time available was to intersperse cruise days with another project being conducted by the Great Lakes Research Division. We were thus able to spread our 8 cruise days from 20 August to 13 September 1976, allowing us a three times longer time window than would have been possible without the coordinated effort. The primary emphasis of the cruise was

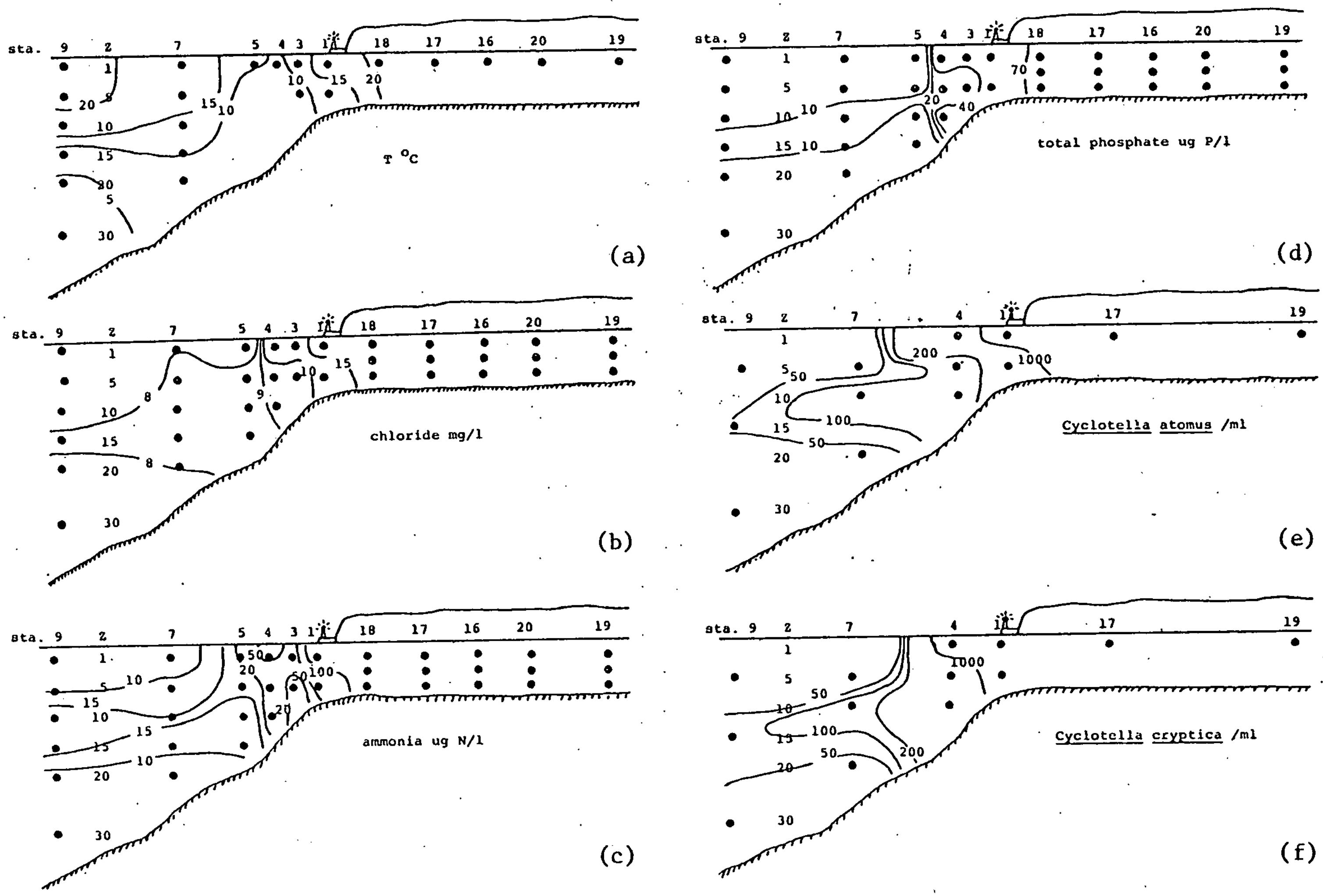



FIGURE 1. Temperature, nutrient and phytoplankton distribution in the Grand River and adjacent waters of Lake Michigan, 3 September 1975. (a) Temperature; (b) chloride mg/l; (3) ammonia μg N/l; (d) total phosphate μg P/l; (e) *Cyclotella atomus*/ml; (f) *Cyclotella cryptica*/ml.

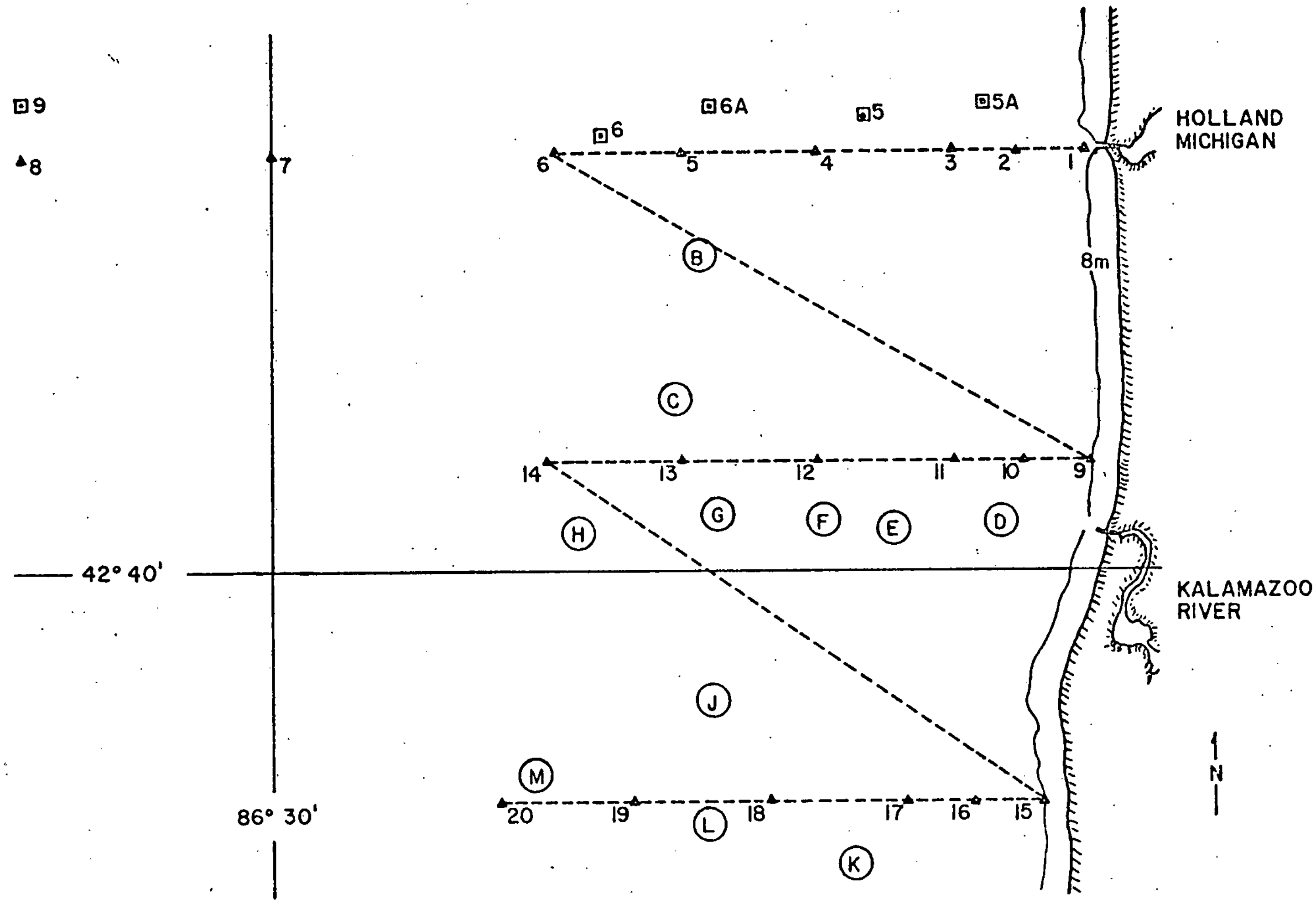



FIGURE 2. Transects for 1976 nearshore cruises. Numbers 1-20 denote sampling stations. Capital letters show stations where current meters were moored in 1976.

on three transects of stations extending 10 miles offshore (Fig. 2). The northernmost transect was repeated 12 times over the 24-day period to give an indication of time variations. Underway maps were made to look at the surface extent of plumes--particularly the Kalamazoo River plume. With the exception of the underway maps and phytoplankton species counts, which are being processed, all the data collected have been analyzed. A preliminary report of the salient findings was presented in May 1977 at the 20th Conference of the International Association for Great Lakes Research in Ann Arbor, Michigan. What follows is a summary of that presentation.

The overall pattern observed for the 24-day period, 20 August-13 September 1976, was as follows. Initially, river-borne material from the Kalamazoo River entered the lake as a surface plume. The river water was always warmer than the surface waters during the study. The river water was then transported along the shore in the long-shore current and slowly sank to eventually spread out into the open lake at thermocline depth. Of the parameters measured, chloride ion was the best tracer of river water and the chloride ion distributions were obtained from seven sections. In each section the position of the thermocline is delineated by the dashed lines indicating the 18, 14 and 10°C isotherms. Figures 3-5 show the conditions along the three transects on 21 August 1976. Figure 3 is typical of the pattern observed at the northernmost or Holland transect. The tongue of high chloride water is probably Kalamazoo River water as it is the major river in the area. Lake Makatawa at Holland is very high in chloride, nutrients and Chl *a* but the flow into Lake Michigan is very low. At the middle transect just north of the Kalamazoo River, the river water

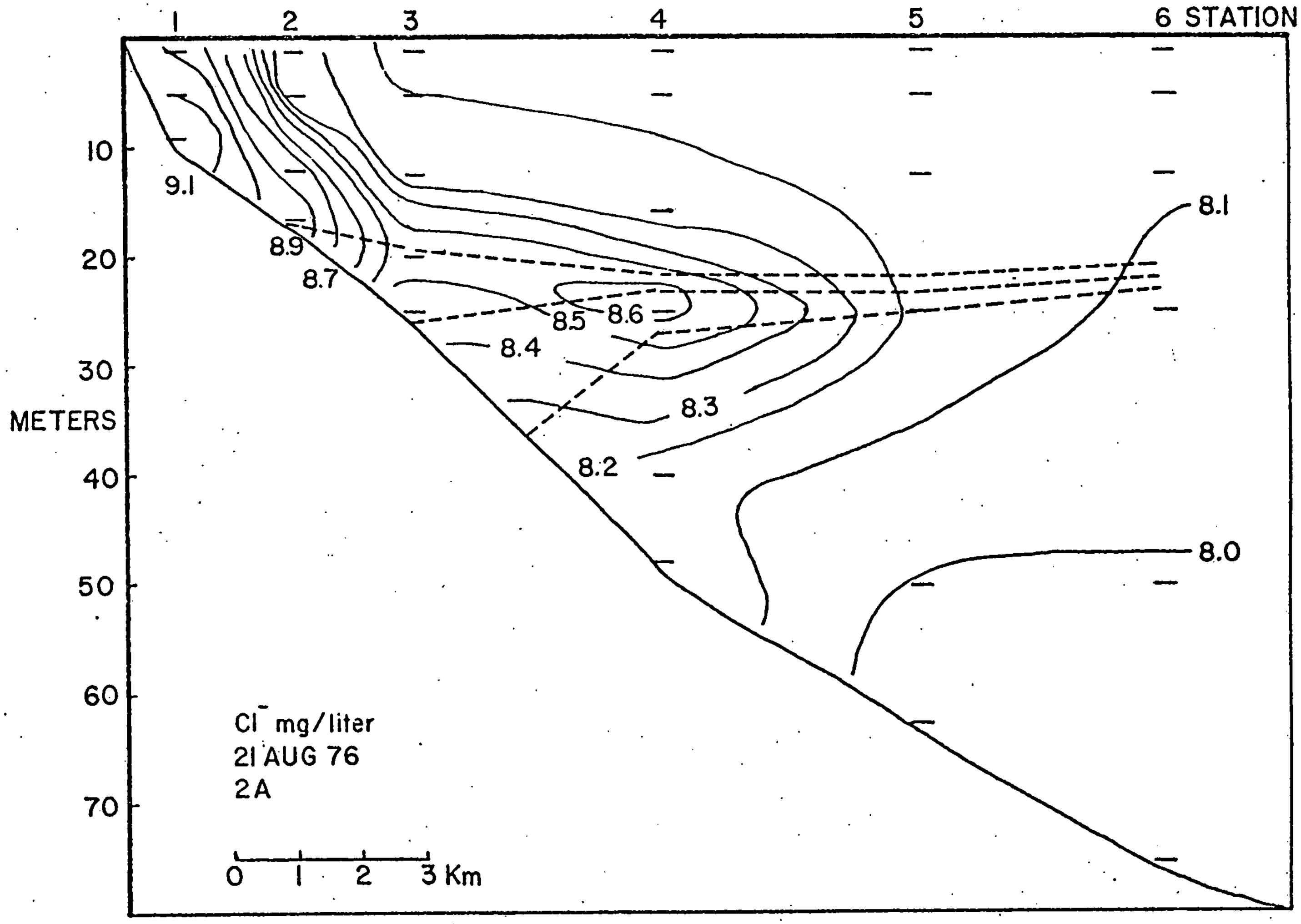



FIGURE 3. Distribution of chloride on the Holland transect. Dashed lines show 18, 14 and 10°C isotherms.

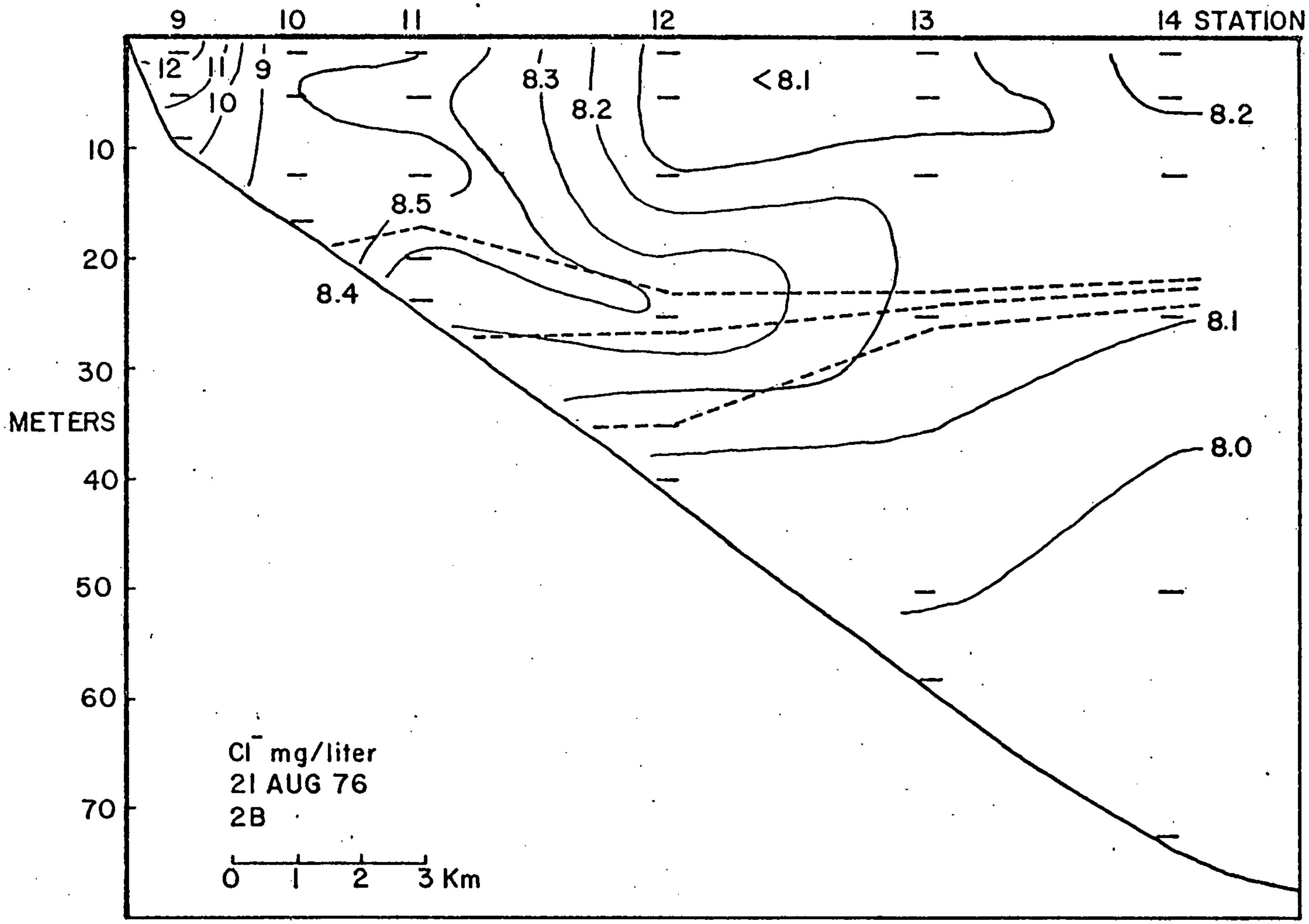



FIGURE 4. Distribution of chloride on Kalamazoo River transect. Dashed lines show 18, 14 and 10°C isotherms.

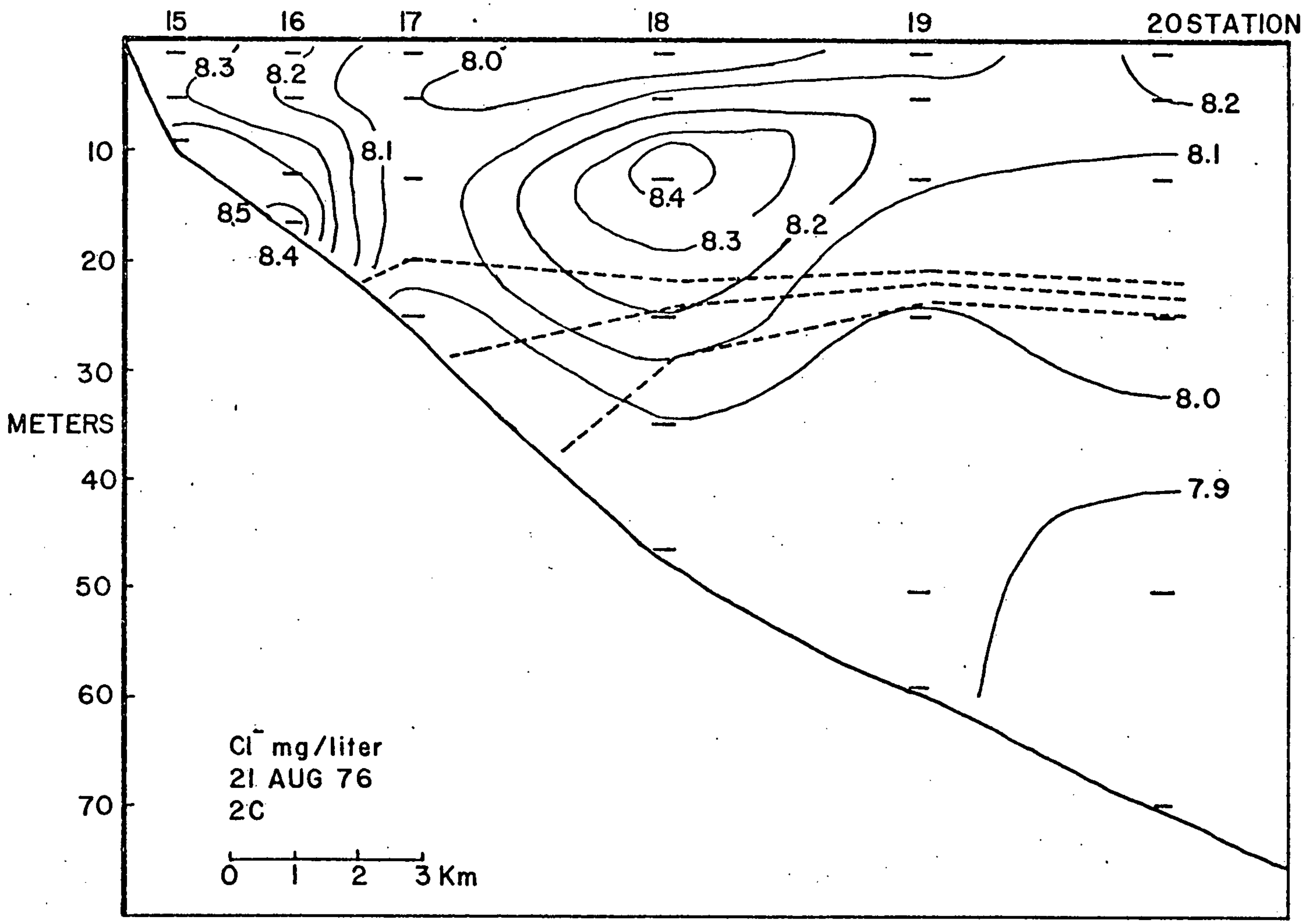



FIGURE 5. Distribution of chloride, stations 15-20. Dashed lines show 18, 14 and 10°C isotherms.

is seen near the surface at station 9 (Fig. 4); however, there is also a tongue of high chloride water at thermocline depth further offshore. At the southernmost transect (Fig. 5) we see high chloride water at depth at station 16 nearshore, and further offshore at station 18 we appear to have cut across what may be a river plume just above the thermocline.

Figures 6 and 7 are included to show the persistence of the high chloride water moving offshore at thermocline depth. Besides the five sections presented here, seven additional sections on the northernmost line indicated similar patterns persisted throughout the study. Figures 7-9 indicate the conditions before (Fig. 7) and one and two days after a storm event (Figs. 8 and 9, respectively). Clearly the storm has disturbed the thermal structure with considerable mixing at the nearshore-offshore boundary (around station 4) and large internal waves offshore. Similarly, the chloride ion distribution pattern has been disturbed, but by the second day after the storm (Fig. 9) the chloride layer was already being reestablished on the thermocline. Clearly this pattern of chloride distribution is a persistent feature along this shore of Lake Michigan.

During the entire 24-day study period the winds were onshore. The effects of a longshore current were observed and downwelling was apparently taking place along the boundary between the nearshore and offshore zones. One possible explanation for the observed chloride distributions is that river water is being entrained in the downwelling which transports it down and out into the open lake at thermocline depth. There are numerous other possible mechanisms, and we hope to be able to sort them out with the help of the results of the physical studies conducted in the area when those results become available.

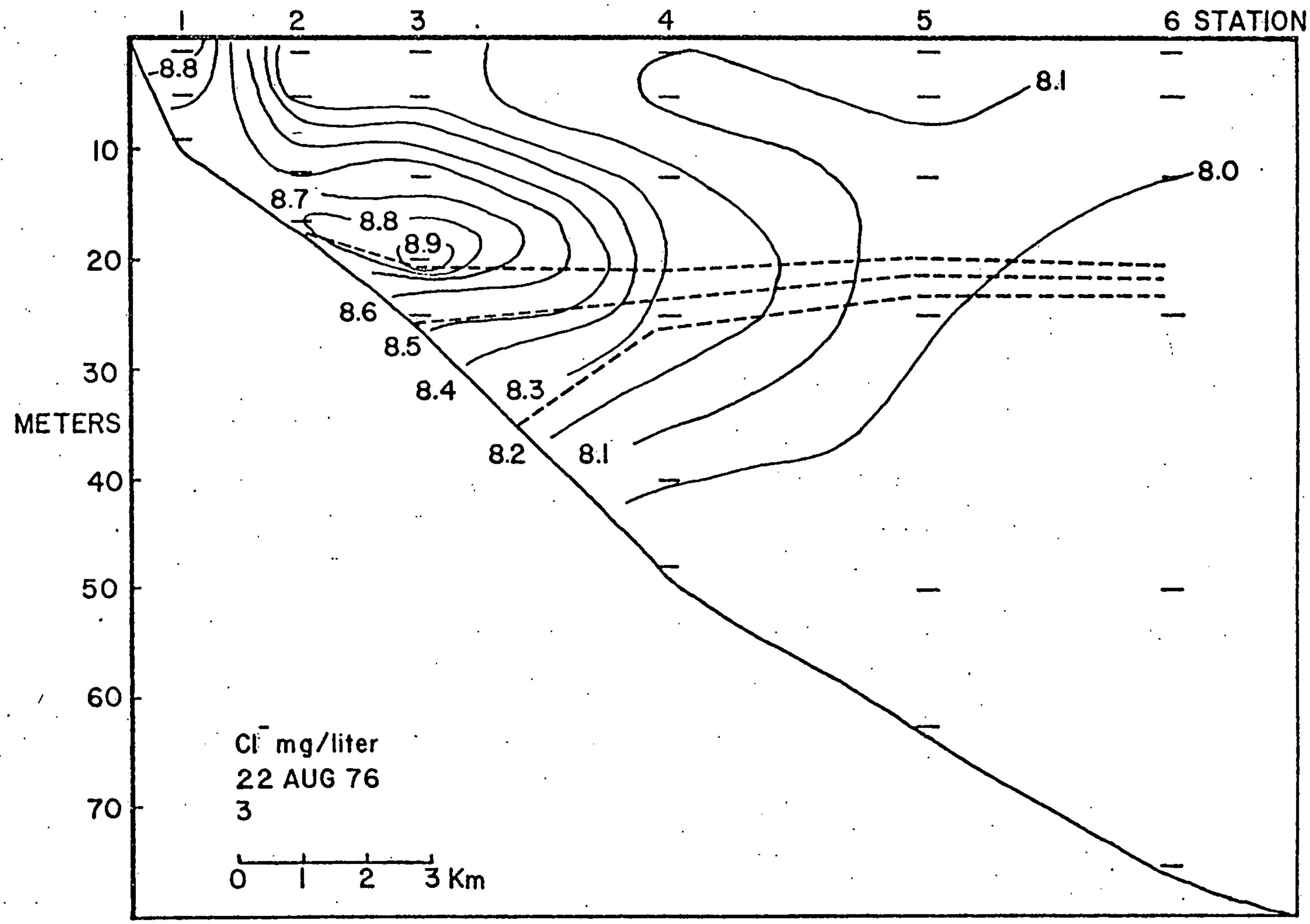



FIGURE 6. Distribution of chloride on the Holland transect. Dashed lines show 18, 14 and 10°C isotherms.

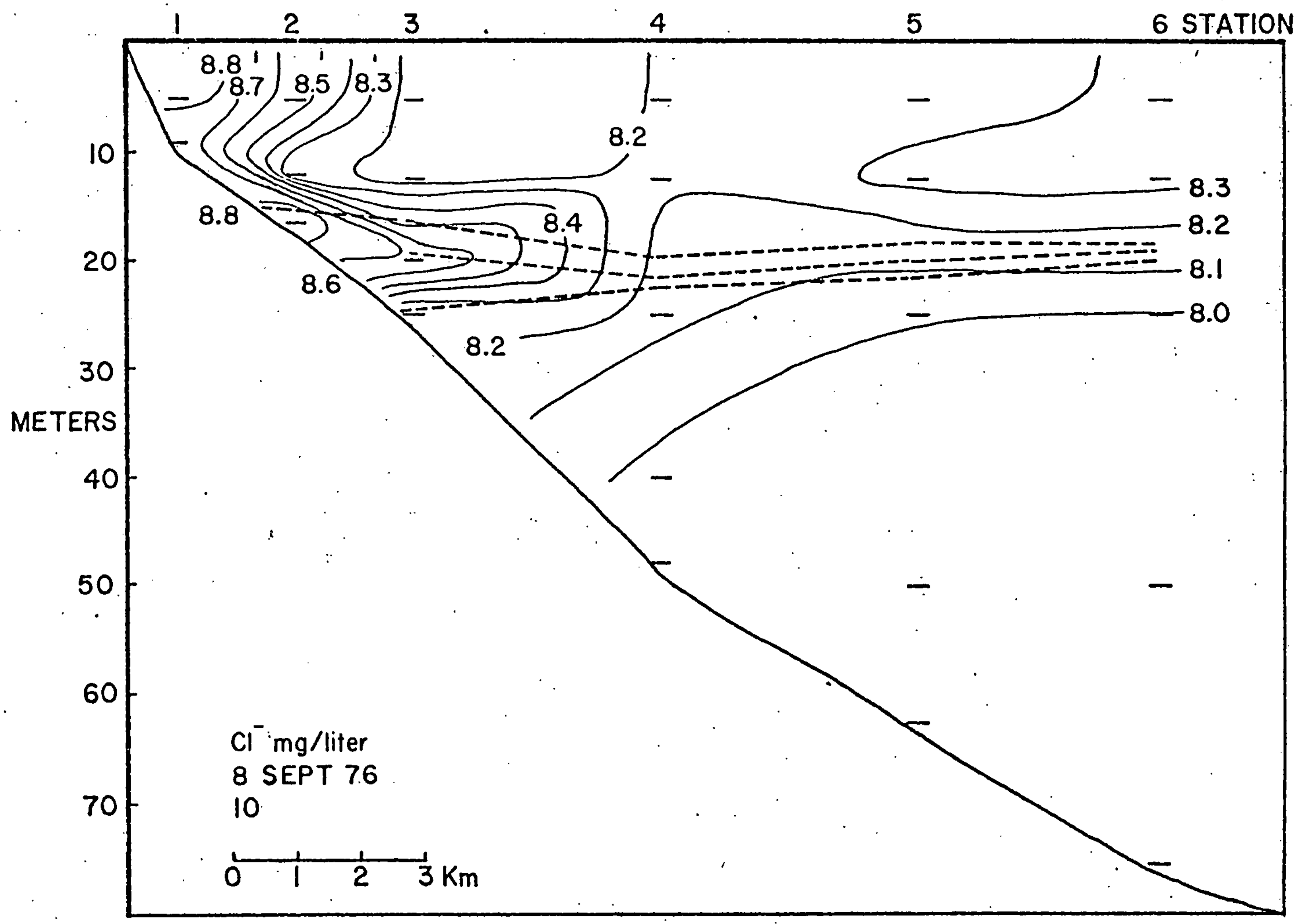



FIGURE 7. Distribution of chloride on the Holland transect. Dashed lines show 18, 14 and 10°C isotherms.

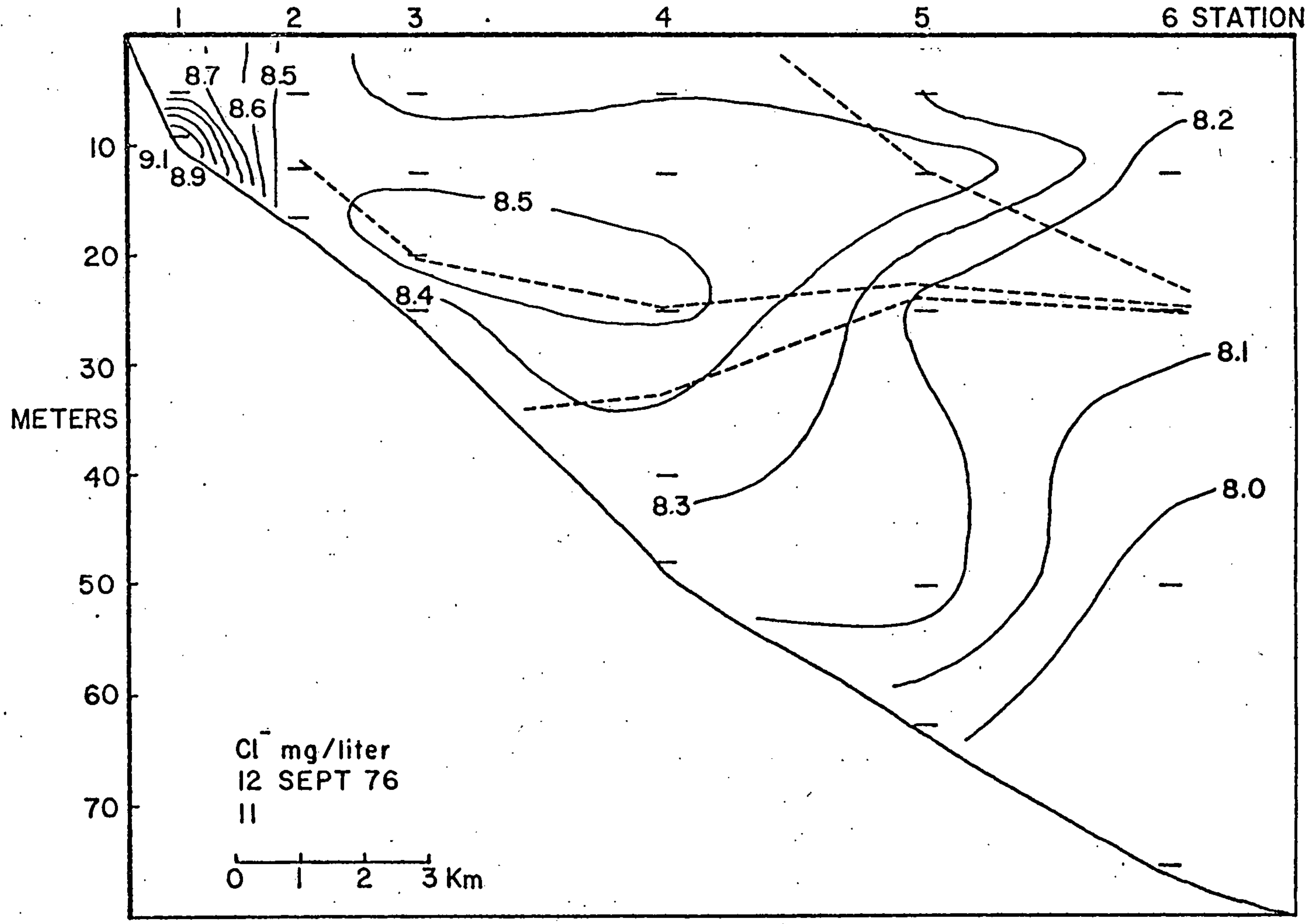



FIGURE 8. Distribution of chloride on the Holland transect. Dashed lines show 18, 14 and 10°C isotherms.

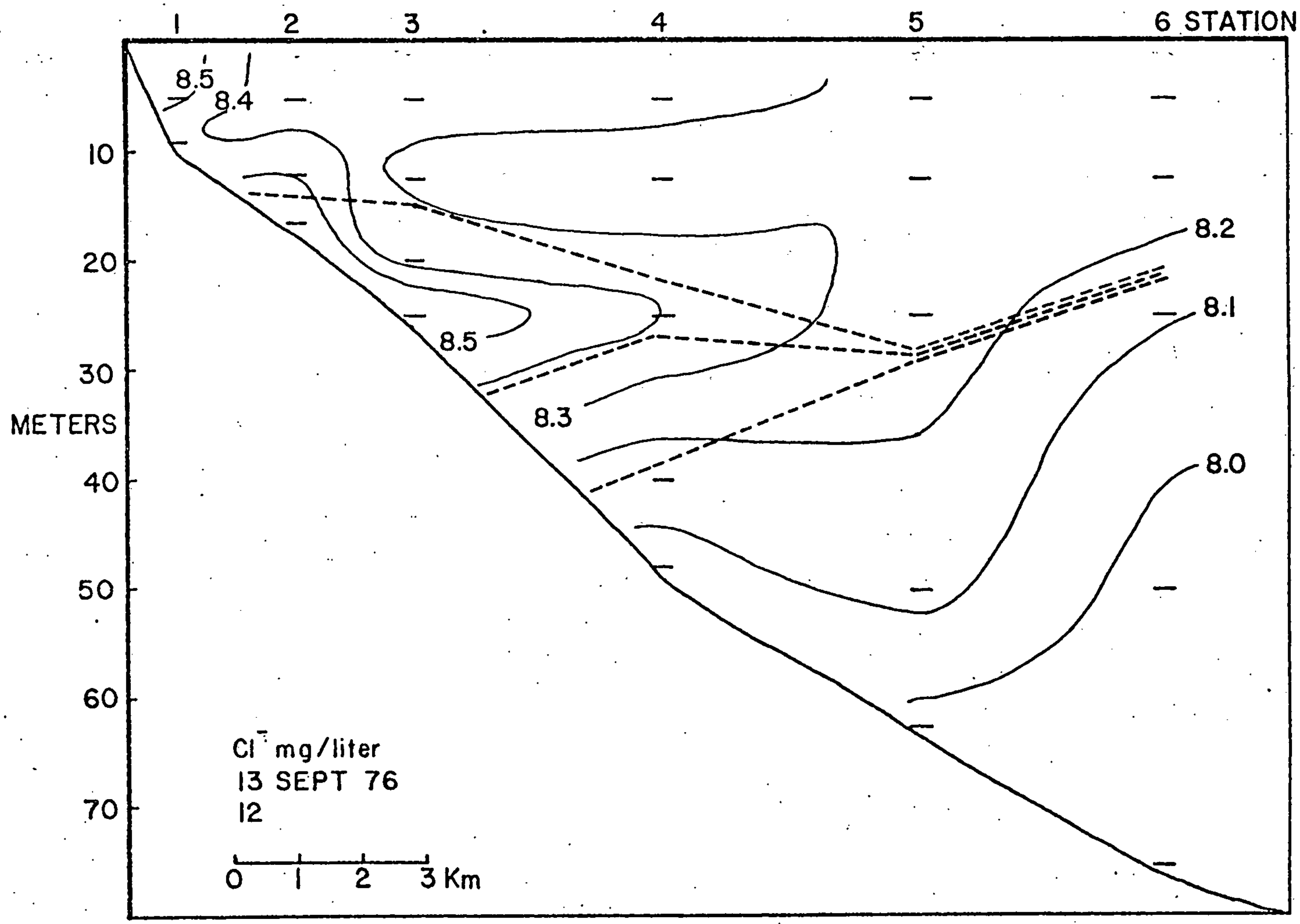



FIGURE 9. Distribution of chloride on the Holland transect. Dashed lines show 18, 14 and 10°C isotherms.

Regardless of the mechanism, this study indicates that during the stratified period at least part of the material entering Lake Michigan finds its way into the open lake at thermocline depth. This pattern has been observed with both offshore (September 1975) and onshore winds (August-September 1976) and clearly must be considered a major route for materials entering Lake Michigan from rivers, power plant effluents and other sources.

## NEARSHORE ENVIRONMENTAL CONDITIONS, 1972

In April, July and September samples were collected for eleven rivers flowing into Lake Michigan by occupying a series of stations on a transect perpendicular to the shoreline. With the exception of the Manistique transect, these stations were located on east-west lines. Stations were taken at the river mouth and at 1/8, 1/4, 1/2, 1, 2, 4 and 8 miles offshore from the river mouth. Phytoplankton samples were collected only at 2 meters, but data for water chemistry were obtained from a series of depths at each station. Only the 2-meter data are presented in this report.

Transects were sampled at all eleven rivers only in April. Three transects were located on the western shore at Milwaukee, Manitowoc and Sturgeon Bay (Fig. 10). The outlet into the lake at Sturgeon Bay is really not a river but a canal connecting Lake Michigan with Green Bay. The Manistique River on the north shore was sampled. Along the eastern shore, seven rivers were sampled including the Betsie, Pere Marquette, Manistee, Muskegon, Grand, Kalamazoo and St. Joseph.

These rivers have a broad range of flow rates and concentrations of nutrients (Table 1) so the loading from river to river varies greatly.

### Physical-Chemical Conditions, April 1972

Temperature. In the open waters of the lake, temperatures were cold, generally ranging from 1-2°C at stations 2 miles or more from shore (Table 2). As might be expected, the coldest temperatures were at the north end of the lake, which off Manistique were less than 1.0°C, and the warmest offshore temperatures were 2.0°C at the south end of the lake on the St. Joseph transect.

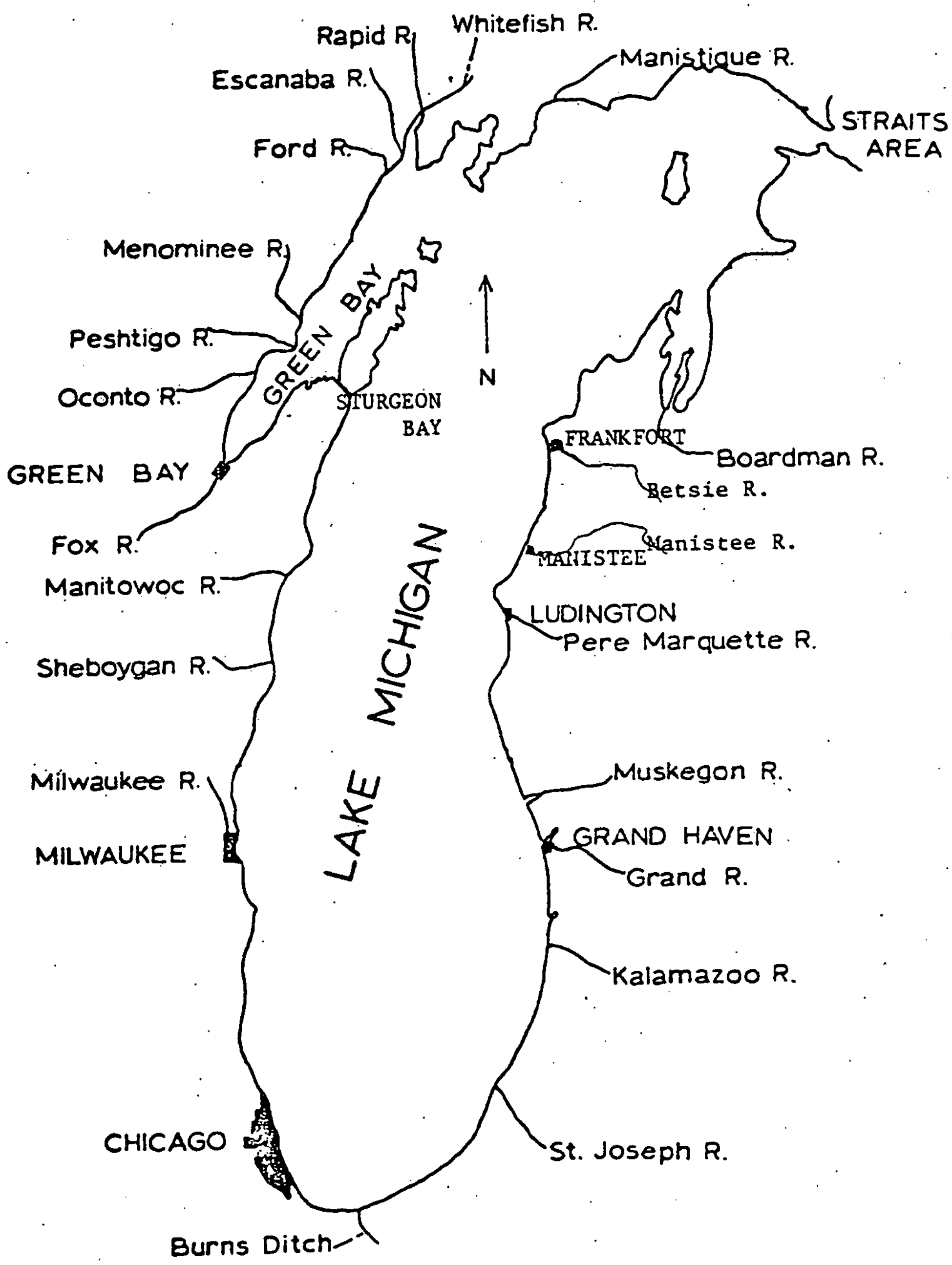



FIGURE 10. Map of Lake Michigan showing tributaries sampled.

TABLE 1. Contributions of total soluble $PO_4$[a] and silica to Lake Michigan by 19 tributaries (1963-1964).[b]

| River | Mean Flow ($m^3$/sec) | Mean Concentrations (mg/liter) Total Soluble $PO_4$ | $SiO_2$ | Ratios $SiO_2$/P | Loading (metric tons/day) Total soluble $PO_4$ | $SiO_2$ |
|---|---|---|---|---|---|---|
| Boardman | 5.26 | 0.20 | 7.5 | 114:1 | 0.125 | 4.69 |
| Manistique | 23.9 | 0.04 | 5.8 | 574:1 | 0.082 | 12.0 |
| Manitowoc | 2.35 | 0.62 | 5.7 | 28:1 | 0.125 | 1.16 |
| Sheboygan | 3.73 | 0.40 | 3.9 | 30:1 | 0.129 | 1.26 |
| Milwaukee | 5.41 | 0.61 | 2.8 | 14:1 | 0.285 | 1.31 |
| Burns Ditch | 4.24 | 1.8 | 10 | 17:1 | 0.661 | 3.68 |
| St. Joseph | 58.4 | 0.24 | 6.4 | 82:1 | 1.21 | 32.3 |
| Kalamazoo | 32.3 | 0.21 | 5.9 | 86:1 | 0.586 | 16.5 |
| Grand | 53.8 | 0.52 | 5.3 | 31:1 | 2.42 | 24.7 |
| Muskegon | 49.0 | 0.06 | 5.6 | 285:1 | 0.254 | 23.8 |
| Pere Marquette | 16.1 | 0.03 | 7.8 | 796:1 | 0.041 | 10.9 |
| Fox | 125.0 | 0.28 | 9.4 | 103:1 | 3.03 | 101.8 |
| Oconto | 22.4 | 0.17 | 9.2 | 166:1 | 0.329 | 17.8 |
| Peshtigo | 25.2 | 0.08 | 9.8 | 375:1 | 0.174 | 21.4 |
| Menominee | 92.1 | 0.11 | 4.4 | 122:1 | 0.877 | 35.0 |
| Ford | 9.54 | 0.04 | 7.0 | 536:1 | 0.033 | 5.77 |
| Escanaba | 28.8 | 0.06 | 7.0 | 357:1 | 0.149 | 17.5 |
| Rapid | 2.27 | 1.59 | 3.1 | 58:1 | 0.311 | 0.61 |
| Whitefish | 6.43 | 0.18 | 5.7 | 97:1 | 0.100 | 3.17 |
| | | | | | 10.9 | 335 |

[a]$PO_4$ values were divided by 3.06 to convert concentrations to phosphate as phosphorus for $SiO_2$/P ratios.

[b]From Schelske 1975.

These low temperatures are not unusual for early spring. Minimum temperatures reach 0°C during winter so increases in temperature of 1-2°C for the entire water mass represent a sizable spring input of heat to the system. The samples were taken prior to the formation of the spring thermal bar--temperatures greater than 4°C (Betsie, Manistee, Pere Marquette, Grand and Muskegon transects) appear to be due to plumes of warm river water in the lake rather than water heated in the lake (Table 2). That the maximum temperature on the Kalamazoo transect was 3.5°C provides additional evidence that the thermal bar had not formed. The Kalamazoo River has a low flow (Table 1), and is located along the eastern shore between the Grand River and the St. Joseph River, two rivers with large flows of warm water. Warm water probably was also flowing out of the Kalamazoo River, but the volume was too small to form a warm water plume in the lake.

TABLE 2. Water temperature at 2 meters at stations on transects off Lake Michigan rivers, April 1972.

| Rivers | Miles | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
| Manistique | 1.9 | 1.3 | 1.3 | 1.0 | 0.9 | 0.9 | 0.9 | 0.8 | | |
| Betsie | 4.5 | 1.0 | 0.8 | 0.8 | 0.9 | 1.2 | 1.2 | 1.5 | 1.7 | |
| Manistee | 5.4 | 4.2 | 3.4 | 2.0 | 1.5 | 1.0 | 1.0 | 1.0 | 1.3 | |
| Pere Marquette | 6.0 | 4.2 | 3.0 | 2.2 | 2.0 | 1.9 | 1.9 | 1.1 | | |
| Muskegon | 6.2 | 3.1 | 3.3 | 4.1 | 2.0 | 2.4 | 1.8 | 1.9 | | |
| Grand | — | 7.8 | 7.0 | 6.0 | 6.0 | 1.2 | 1.0 | 1.0 | 1.0 | |
| Kalamazoo | 3.5 | 3.1 | 2.9 | 2.2 | 1.6 | 1.1 | 1.6 | 1.2 | | |
| St. Joseph | 16.0 | 10.0 | 6.0 | 4.8 | 4.1 | 3.8 | 2.0 | 2.0 | | |
| Milwaukee | 3.0 | 3.0 | 3.0 | 2.6 | 2.2 | 2.0 | 1.3 | 1.0 | 1.0 | 1.5 |
| Manitowoc | -- | 2.3 | 2.1 | 2.0 | 1.4 | 1.1 | 1.0 | 0.9 | 1.0 | 1.0 |
| Sturgeon Bay | 1.9 | 1.8 | 1.3 | 1.0 | 1.0 | 0.9 | 0.9 | 0.7 | 0.8 | 0.9 |

Hydrogen ion concentration. Measurements of pH showed distinct differences among the rivers (Table 3). As will be noted for other parameters, the Manistique River was most different with the lowest pH. The low pH presumably resulted from the large organic loads in the Manistique.

Values of pH for offshore waters were in the range of 8.4 to 8.5 with most of the values being between 8.40 and 8.45. Nearshore waters on the Muskegon and Kalamazoo transects ranged from 8.5-8.6 and on the St. Joseph transect were even higher, ranging from 8.7-8.9. The higher values for pH in the nearshore waters are due to greater photosynthetic activity than in the offshore waters of the lake--data on cell counts and chlorophyll concentrations support this conclusion.

TABLE 3. Hydrogen ion concentration at 2 meters at stations on transects off Lake Michigan rivers, April 1972.

| Rivers | Miles | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
| Manistique | 7.40 | 8.47 | 8.46 | 8.46 | 8.52 | 8.53 | 8.55 | 8.53 | | |
| Betsie | 8.26 | 8.43 | 8.45 | 8.48 | 8.44 | 8.41 | 8.46 | 8.46 | 8.42 | |
| Manistee | 8.16 | 8.42 | 8.40 | 8.47 | 8.45 | 8.47 | 8.41 | 8.39 | 8.45 | |
| Pere Marquette | 8.23 | 8.45 | 8.49 | 8.49 | 8.47 | 8.46 | 8.48 | 8.43 | | |
| Muskegon | 8.49 | 8.63 | 8.60 | 8.56 | 8.54 | 8.59 | 8.40 | 8.45 | | |
| Grand | 8.11 | 8.10 | 8.24 | 8.28 | 8.28 | 8.50 | 8.44 | 8.45 | 8.46 | |
| Kalamazoo | 8.66 | 8.63 | 8.59 | 8.58 | 8.51 | 8.55 | 8.48 | 8.47 | | |
| St. Joseph | 8.33 | 8.68 | 8.93 | 8.80 | 8.75 | 8.73 | 8.60 | 8.56 | | |
| Milwaukee | 8.38 | 8.37 | 8.37 | 8.45 | 8.44 | 8.48 | 8.48 | 8.44 | 8.44 | 8.57 |
| Manitowoc | — | 8.56 | 8.51 | 8.50 | 8.53 | 8.46 | 8.48 | 8.45 | 8.40 | 8.43 |
| Sturgeon Bay | 8.53 | 8.54 | 8.53 | 8.52 | 8.52 | 8.51 | 8.45 | 8.48 | 8.42 | 8.43 |

Chloride. Data on chloride for some rivers can be used to trace river plumes, both due to relatively low and relatively high concentrations. Chloride concentrations representative of the open lake ranged from 7 to 8 mg/liter (Table 4). Both the Manistique and Betsie rivers had chloride concentrations less than the open lake. Whether the Manistique plume could be traced for several miles on the basis of low chloride concentrations is questionable because waters in the area of northern Lake Michigan frequently are mixed with Lake Huron which also would dilute the chloride concentration.

Water from the Grand and St. Joseph rivers was apparently present one mile offshore as chloride concentrations were obviously elevated at the one-mile stations and the intervening stations between the shore. High chloride values were also found on the Manistee transect.

TABLE 4. Chloride concentration (mg/l) at 2 meters on transects off Lake Michigan rivers, April 1972.

| Rivers | Miles | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
| Manistique | 2.3 | 5.3 | 5.5 | 5.3 | 6.7 | 4.7 | 5.6 | 7.4 | | |
| Betsie | 4.5 | 7.8 | 7.9 | 7.4 | 8.0 | 8.0 | 5.8 | 7.3 | 7.1 | |
| Manistee | — | 18.8 | 19.0 | 14.2 | 10.1 | 8.1 | 8.1 | 7.6 | 7.2 | |
| Pere Marquette | 15.3 | 10.5 | 8.5 | 7.7 | 8.2 | 8.3 | 8.3 | 5.7 | | |
| Muskegon | -- | -- | -- | 13.9 | 8.9 | 9.7 | 7.1 | 7.6 | | |
| Grand | 22.0 | 21.0 | 17.6 | 14.8 | 17.7 | 8.1 | 7.7 | 5.0 | 7.3 | |
| Kalamazoo | 10.6 | 9.0 | 9.4 | 9.0 | 6.8 | 8.5 | 8.4 | 7.9 | | |
| St. Joseph | 16.2 | 12.5 | 9.1 | 8.8 | 9.5 | 6.3 | 7.7 | -- | | |
| Milwaukee | 12.0 | 11.0 | 9.9 | 6.1 | 7.4 | 7.8 | 7.7 | 7.1 | 7.0 | 7.5 |
| Manitowoc | — | 7.7 | 7.7 | 6.7 | — | 7.7 | 7.7 | 7.9 | 7.7 | 7.7 |
| Sturgeon Bay | 5.9 | 7.2 | 7.3 | 7.3 | 7.7 | 7.3 | 7.4 | 7.5 | 7.5 | 7.3 |

On the basis of water temperature data, the relatively large chlorides off the Kalamazoo transect may not have originated in the Kalamazoo River but may have been due to inputs of chloride from other rivers, most likely the Grand or St. Joseph.

Specific Conductance. Data show the same patterns as those on chloride--with the lowest values in the Manistique and Betsie rivers and the highest values for the Grand, St. Joseph and Manistee transects.

Due to problems with temperature compensation on our conductivity bridge, the data can be used only for relative comparisons. Open lake specific conductance should have been in the range between 2.6 and 2.7 x $10^{-4}$ mho $cm^{-1}$, corrected to 25°C (Table 5).

TABLE 5. Specific conductance ($10^{-4}$ mho $cm^{-1}$) at 2 meters at stations on transects off Lake Michigan rivers, April 1972.

| | Miles | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Rivers | 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
| Manistique | 0.84 | 3.13 | 3.07 | 3.04 | 3.11 | 3.17 | 3.17 | 3.12 | | |
| Betsie | 3.02 | 3.07 | 3.22 | 3.17 | 3.13 | 3.20 | 3.07 | 3.22 | 3.22 | |
| Manistee | 5.78 | 3.53 | 3.57 | 3.28 | 3.12 | 2.94 | 3.01 | 3.00 | 3.02 | |
| Pere Marquette | 3.58 | 3.36 | 3.30 | 3.33 | 3.31 | 3.30 | 3.25 | 3.22 | | |
| Muskegon | 4.23 | 3.24 | 3.43 | 3.57 | 3.16 | 3.26 | 3.12 | 2.98 | | |
| Grand | 5.30 | 5.23 | 5.24 | 4.81 | 4.52 | 2.84 | 3.00 | 3.07 | 3.07 | |
| Kalamazoo | 3.42 | 3.27 | 3.37 | 3.26 | 3.21 | 3.17 | 3.22 | 3.21 | | |
| St. Joseph | 5.19 | 4.12 | 3.47 | 3.47 | 3.36 | 3.44 | 3.06 | 3.08 | | |
| Milwaukee | 3.67 | 3.61 | 3.47 | 3.27 | 3.14 | 3.12 | 3.15 | 3.12 | 3.08 | 3.05 |
| Manitowoc | — | 3.11 | 3.10 | 3.17 | 3.14 | 3.26 | 3.14 | 3.22 | 3.23 | 3.17 |
| Sturgeon Bay | 3.22 | 3.23 | 3.17 | 3.22 | 3.27 | 3.24 | 3.27 | 3.12 | 3.22 | 3.18 |

## Nutrients and Chlorophyll, April 1972

Inputs from tributaries not only affected the distribution of conservative chemical parameters, but also the distribution of nutrients.

Total Phosphorus. Open lake values for total phosphorus appeared to be less than 7 to 8 μg P/liter (Table 6). The largest concentrations of total phosphorus were in the Grand and St. Joseph rivers--phosphorus concentrations were elevated for at least one mile on the Grand transect and for four miles offshore on the St. Joseph transect.

Total phosphorus concentrations at the river mouth for all transects were greater than the open lake excepting the Sturgeon Bay transect. Because Sturgeon Bay represents a canal between Green Bay and Lake Michigan one possibly should not expect higher concentrations.

TABLE 6. Total phosphorus (μg P/1) at 2 meters at stations on transects off Lake Michigan rivers, April 1972.

| Rivers | Miles 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|
| Manistique | 18.3 | 6.1 | 4.7 | 11.0 | 9.6 | 10.4 | 5.1 | 6.1 | | |
| Betsie | 26.7 | 3.8 | 3.7 | 4.5 | 3.4 | 3.6 | 3.3 | 4.1 | 5.2 | |
| Manistee | 22.9 | 8.0 | 10.1 | 6.9 | 5.7 | 6.5 | 5.5 | 6.0 | 5.0 | |
| Pere Marquette | 35.6 | 15.9 | -- | 6.6 | 6.1 | 7.6 | 6.7 | 5.3 | | |
| Muskegon | 51.1 | 13.6 | 19.5 | 10.7 | 10.2 | 10.7 | 5.1 | 8.5 | | |
| Grand | 141.2 | 176.1 | 111.6 | -- | 92.5 | 6.8 | 7.9 | 5.8 | 5.1 | |
| Kalamazoo | 24.6 | 16.6 | 15.9 | 8.7 | 8.3 | 9.5 | 7.7 | 9.0 | | |
| St. Joseph | 136.8 | 77.1 | 22.1 | 20.4 | 16.1 | 16.0 | 13.6 | 6.1 | | |
| Milwaukee | 30.8 | 29.8 | 24.8 | 15.0 | 14.0 | 9.9 | 8.3 | 4.4 | 2.3 | 2.6 |
| Manitowoc | -- | 8.6 | 5.2 | 4.8 | 2.6 | 4.1 | 2.3 | 3.8 | 2.5 | 4.5 |
| Sturgeon Bay | 3.6 | -- | 3.7 | 4.0 | 4.7 | 3.2 | 3.9 | 5.7 | 4.1 | 3.8 |

Chlorophyll *a*. Concentrations of chlorophyll *a* in the open lake appeared to fall in the range between 1 and 2 mg/$m^3$ (Table 7). The largest values were found off the Grand and St. Joseph transects where total phosphorus concentrations were also largest--in addition highest total phosphorus concentrations were found out to one mile on the Grand transect as were the highest chlorophyll concentration; likewise the highest chlorophyll and total phosphorus concentrations were found on the St. Joseph transects, but at stations from 0 to 4 miles offshore.

In general the highest chlorophyll concentrations on each transect were associated with the highest total phosphorus concentrations.

Nitrate Nitrogen. Open lake values for nitrate nitrogen generally ranged from 260 to 290 μg N/liter (Table 8). The St. Joseph and Kalamazoo

TABLE 7. Chlorophyll *a* (μg/l) at 2 meters at stations on transects of Lake Michigan rivers, April 1972.

| Rivers | Miles | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
| Manistique | 0.42 | 2.00 | 1.92 | 2.13 | 2.08 | 2.81 | 2.20 | 3.15 | | |
| Betsie | 1.56 | 1.78 | 2.33 | 2.16 | 1.88 | 1.61 | 2.42 | 1.25 | 1.10 | |
| Manistee | 0.96 | 3.09 | 3.53 | 3.21 | 2.84 | 2.55 | 2.20 | 1.51 | 1.00 | |
| Pere Marquette | 2.23 | 4.13 | 3.21 | 3.69 | 2.92 | 2.64 | 1.72 | 1.99 | | |
| Muskegon | 14.25 | 11.41 | 12.25 | 11.86 | 5.47 | 6.69 | 1.38 | 1.90 | | |
| Grand | 18.09 | 21.45 | 15.80 | 20.13 | 23.46 | 3.26 | 2.26 | 1.96 | -- | |
| Kalamazoo | 5.55 | 9.28 | 8.06 | 6.59 | 4.70 | 3.12 | 3.41 | 3.06 | | |
| St. Joseph | 24.45 | 18.55 | 16.83 | 11.90 | 10.16 | 9.80 | 3.65 | 2.11 | | |
| Milwaukee | 6.76 | 5.96 | 6.83 | 7.26 | 6.39 | 5.96 | 4.96 | 3.72 | 1.66 | 1.76 |
| Manitowoc | — | 8.34 | 4.17 | 3.80 | 2.87 | 2.79 | 1.99 | 1.81 | 1.56 | 1.53 |
| Sturgeon Bay | 2.73 | 2.78 | 2.75 | 2.27 | 3.15 | 3.00 | 2.16 | 2.31 | 1.54 | 1.11 |

rivers were obviously contributing nitrate to the lake with concentrations being about six times greater than the open lake. The remaining tributaries were relatively smaller sources of nitrate and some like the Pere Marquette and Betsie had smaller concentration than those in the open lake.

Dissolved Reactive Silica. The open lake values for silica were in the range of 1.2 to 1.4 mg/liter (Table 9). Most of the tributaries had silica concentrations greater than the open lake. Off the Kalamazoo, Milwaukee, Manitowoc and Sturgeon Bay transects, however, silica concentrations were less than open lake values. These low silica values appeared to be related more to the presence of nearshore waters than to direct influence by the tributaries as all four of these sources have small stream flows.

TABLE 8. Nitrate nitrogen (μg N/l) at 2 meters at stations on transects off Lake Michigan rivers, April 1972.

| Rivers | Miles 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|
| Manistique | 201 | 135 | 141 | 143 | 161 | 110 | 201 | 216 | | |
| Betsie | 217 | 279 | 285 | 272 | 289 | 292 | 236 | 259 | 268 | |
| Manistee | 258 | 246 | 262 | 236 | 258 | 262 | 262 | 252 | 244 | |
| Pere Marquette | 171 | 266 | 232 | 222 | 242 | 262 | 272 | 203 | | |
| Muskegon | 436 | 308 | 302 | 344 | 281 | 304 | 247 | 276 | | |
| Grand | 1502 | 1501 | 1148 | 1921 | 1198 | 298 | 302 | 175 | 273 | |
| Kalamazoo | 379 | 342 | 377 | 344 | 293 | 330 | 330 | 309 | | |
| St. Joseph | 1714 | 951 | 404 | 403 | 420 | 311 | 293 | 126 | | |
| Milwaukee | 360 | 344 | 286 | 205 | 270 | 291 | 297 | 294 | 299 | 268 |
| Manitowoc | — | 271 | 271 | 211 | 234 | 251 | 256 | 263 | 270 | 287 |
| Sturgeon Bay | 200 | 231 | 224 | 227 | 222 | 226 | 237 | 263 | 252 | 270 |

The nearshore effect is particularly obvious off the St. Joseph transect where silica concentrations ranged from 0.1 to 0.4 mg/liter at the stations from 0.25 to 2 miles offshore. These low silica values undoubtedly reflect large amounts of silica utilized in diatom growth.

Phytoplankton Standing Crop and Species Composition, April 1972

In April the standing crop of phytoplankton in the open lake as measured by cell counts was similar over all the lake transects. Cell counts ranged from 800 to 1800 cells/ml with most of the counts ranging between 800 and 1100 cells/ml (Table 10). The only counts higher than 1100 were found off the Manistique transect and the Kalamazoo transect. The Manistique area was not typical of the rest of the lake so this deviation is probably not important. The Kalamazoo offshore sample dif-

TABLE 9. Dissolved reactive silica (mg $SiO_2$/1) at 2 meters at stations on transects off Lake Michigan rivers, April 1972.

| Rivers | Miles 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|
| Manistique | 2.92 | 0.86 | 0.89 | 0.90 | 0.81 | 0.77 | 0.80 | 0.89 | | |
| Betsie | 3.69 | 1.18 | 1.11 | 1.11 | 1.33 | 1.20 | 1.28 | 1.39 | 1.42 | |
| Manistee | 5.23 | 1.73 | 1.16 | 1.37 | 1.19 | 1.12 | 1.14 | 1.25 | 1.21 | |
| Pere Marquette | 3.87 | 1.61 | 1.26 | 1.15 | 1.17 | 1.19 | 1.15 | 1.10 | | |
| Muskegon | 4.84 | 1.23 | 2.00 | 2.65 | 1.22 | 1.41 | 1.35 | 1.26 | | |
| Grand | 2.34 | 2.20 | 2.06 | 1.85 | 1.94 | 1.23 | 1.22 | 1.35 | 1.24 | |
| Kalamazoo | 0.85 | 0.93 | 1.01 | 0.98 | 1.05 | 1.00 | 0.99 | 1.08 | | |
| St. Joseph | 3.11 | 1.14 | 0.07 | 0.22 | 0.44 | 0.36 | 1.00 | 1.19 | | |
| Milwaukee | 1.04 | 0.97 | 1.12 | 0.96 | 0.86 | 0.97 | 1.02 | 1.16 | 1.48 | 1.38 |
| Manitowoc | -- | 0.89 | 1.01 | 0.89 | 0.90 | 0.88 | 1.01 | 1.02 | 1.04 | 1.32 |
| Sturgeon Bay | 0.96 | 1.00 | 1.06 | 1.03 | 1.07 | 1.06 | 1.07 | 1.03 | 1.17 | 1.02 |

fered from the other offshore stations in that 25 per cent of the cell counts were *Stephanodiscus minutus*.

The number of species at the open lake stations ranged from 28 to 37, excepting the Manistique which had 44 species (Table 10). Many more species were found at the river station with numbers of species ranging from 48 to 76, excepting the Sturgeon Bay station, which has no river flow and the atypical Manistique station which had only 34 species.

In the April collections a total of 282 taxa were identified, 238 of which were diatoms. The assemblages at stations were dominated by diatoms with most of the samples containing 90 per cent or more diatoms.

Betsie, Pere Marquette, and Manistee Rivers. The species composition of phytoplankton at the offshore stations for these three rivers is

TABLE 10. Data on phytoplankton sampled on transects off Lake Michigan rivers, April 1972.

| River | Species | Cells/ml | Diversity | % diatoms |
|---|---|---|---|---|
| Manistique | 34 | 122 | 3.29 | 86.2 |
| Open lake | 44 | 1378 | 2.70 | 90.4 |
| Betsie | 76 | 966 | 3.62 | 97.2 |
| Open lake | 28 | 894 | 2.25 | 80.8 |
| Manistee | 67 | 513 | 3.57 | 100.0 |
| Open lake | 37 | 842 | 2.72 | 89.8 |
| Pere Marquette | 68 | 1047 | 3.46 | 99.2 |
| Open lake | 35 | 1007 | 2.56 | 84.6 |
| Muskegon | 61 | 11748 | 1.07 | 99.0 |
| Open lake | 33 | 890 | 2.56 | 91.3 |
| Grand | 76 | 3556 | 2.87 | 99.6 |
| Open lake | 36 | 1110 | 2.63 | 91.7 |
| Kalamazoo | 64 | 8409 | 1.70 | 98.9 |
| Open lake | 36 | 1845 | 2.53 | 94.5 |
| St. Joseph | 74 | 14506 | 1.65 | 99.9 |
| Open lake | 32 | 1141 | 2.68 | 82.9 |
| Milwaukee | 48 | 2897 | 2.75 | 99.1 |
| Open lake | 33 | 1068 | 2.56 | 98.2 |
| Manitowoc | 54 | 3171 | 2.65 | 95.6 |
| Open lake | 29 | 1089 | 2.39 | 87.3 |
| Sturgeon Bay | 42 | 1290 | 2.97 | 93.5 |
| Open lake | 34 | 1093 | 2.46 | 93.1 |

very similar with five species of diatoms being dominant in the assemblage. These five species are *Cyclotella stelligera, Rhizosolenia gracilis, Melosira italica, Synedra filiformis* and *Stephanodiscus minutus* (Figs. 11-13). *C. stelligera* and *R. gracilis* are abundant at all stations with *S. minutus* being most abundant on the Pere Marquette transect (Fig. 12). These three rivers on the Michigan shoreline are located in the northern half of the lake in areas that would be less polluted than the rivers farther south.

Rivers flowing into the southern half of the lake were also sampled. These rivers are more polluted than the northern rivers. Four transects were sampled along the Michigan coastline, two of these originated off rivers, Grand and St. Joseph, with large flows, and two off rivers, Muskegon and St. Joseph, with smaller flows (Table 1). Influences of the Grand and St. Joseph rivers were evident from chemical measurements at offshore stations, particularly total phosphorus (Table 6) and chloride (Table 4).

Grand and St. Joseph Rivers. Differences in flow between these two rivers and the Muskegon and Kalamazoo also produced different distributions of phytoplankton on the transects. Phytoplankton dominant in the rivers with higher flows were present at stations offshore which was not true of the Muskegon and Kalamazoo transects.

In the Grand River, stations close to the river mouth were dominated by *Stephanodiscus subtilis, S. tenuis, Cyclotella meneghiniana* v. *plana*, and *Melosira granulata* v. *angustissima* (Fig. 14). In the St. Joseph river, *Melosira granulata* dominated the stations closest to the river and *Stephanodiscus tenuis* was also common (Fig. 15).

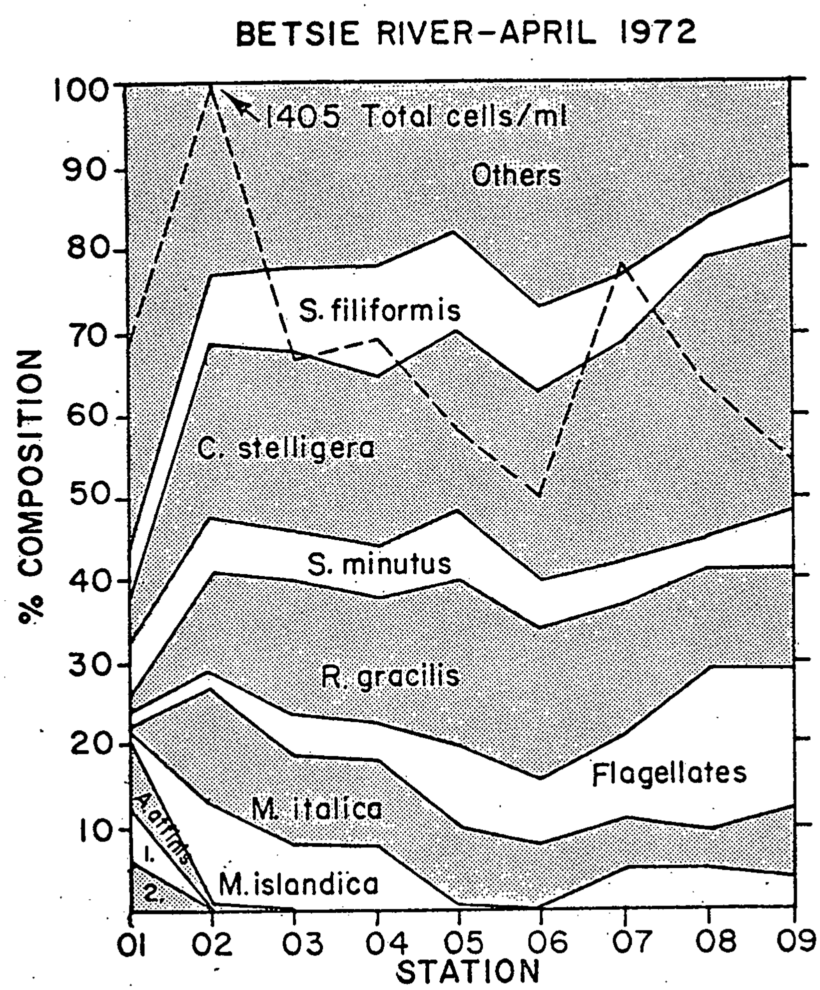



FIGURE 11. Dominant phytoplankton (per cent abundance) at stations on the Betsie River transect. The total standing crop (cells/ml) for each station is plotted as the percentage of the maximum standing crop on the transect (1405 cells/ml at station 2). Distances offshore for each station are listed in Table 2.

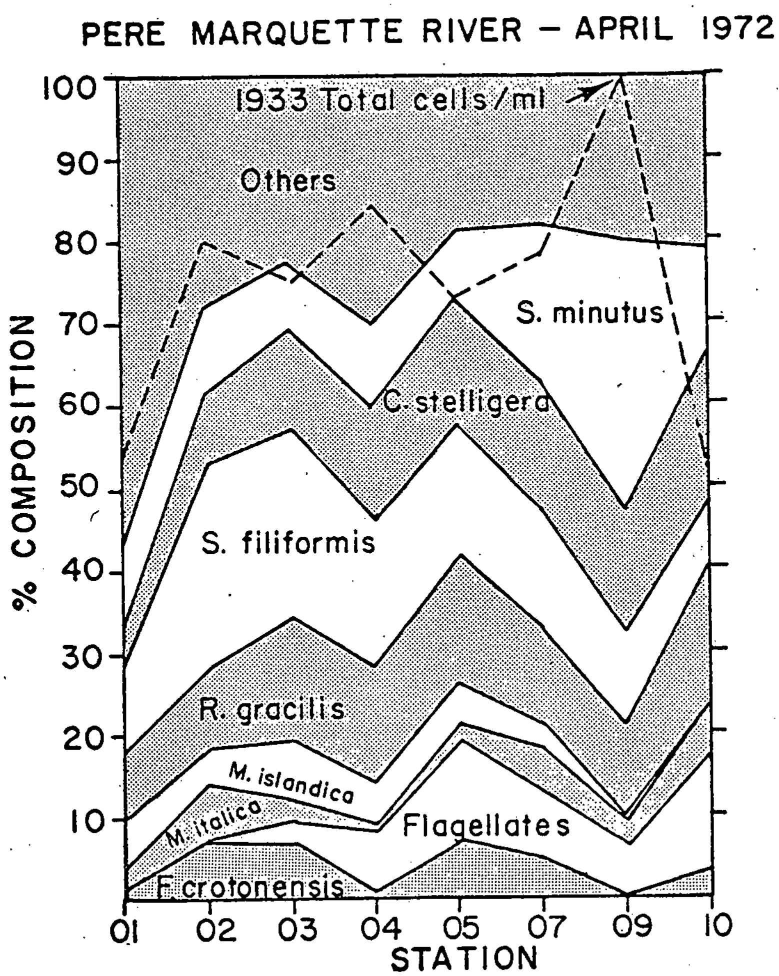



FIGURE 12. Dominant phytoplankton (per cent abundance) at stations on the Pere Marquette River transect. See Fig. 11 for additional explanation.

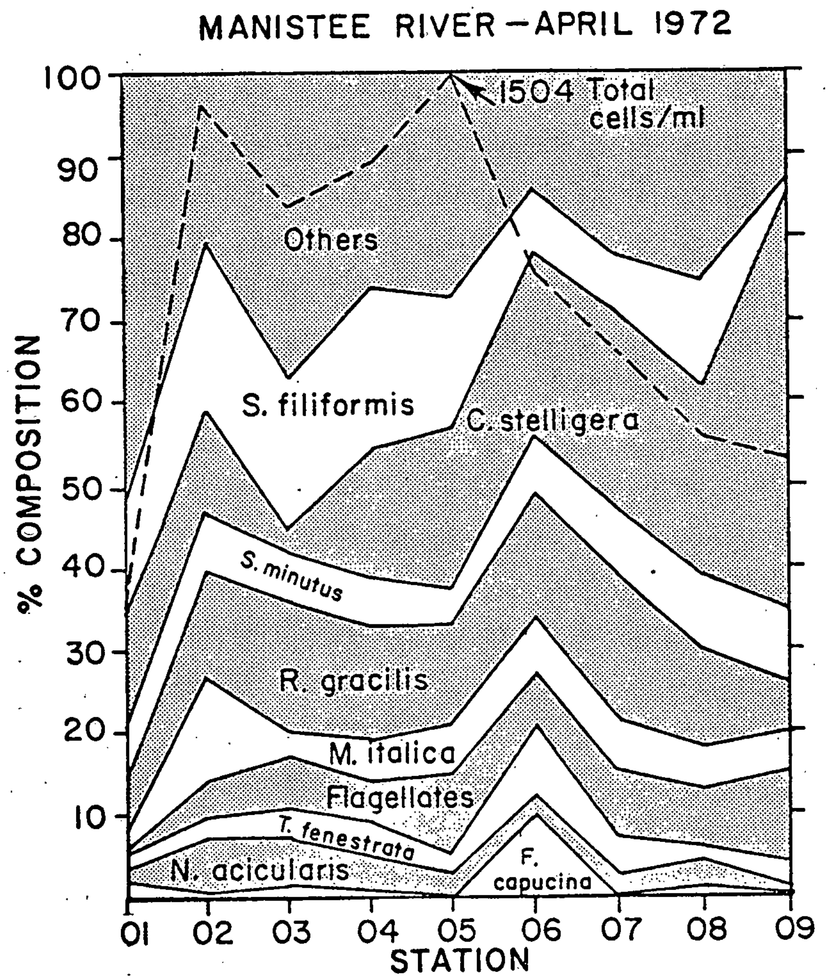



FIGURE 13. Dominant phytoplankton (per cent abundance) at stations on the Manistee River transect. See Fig. 11 for additional explanation.

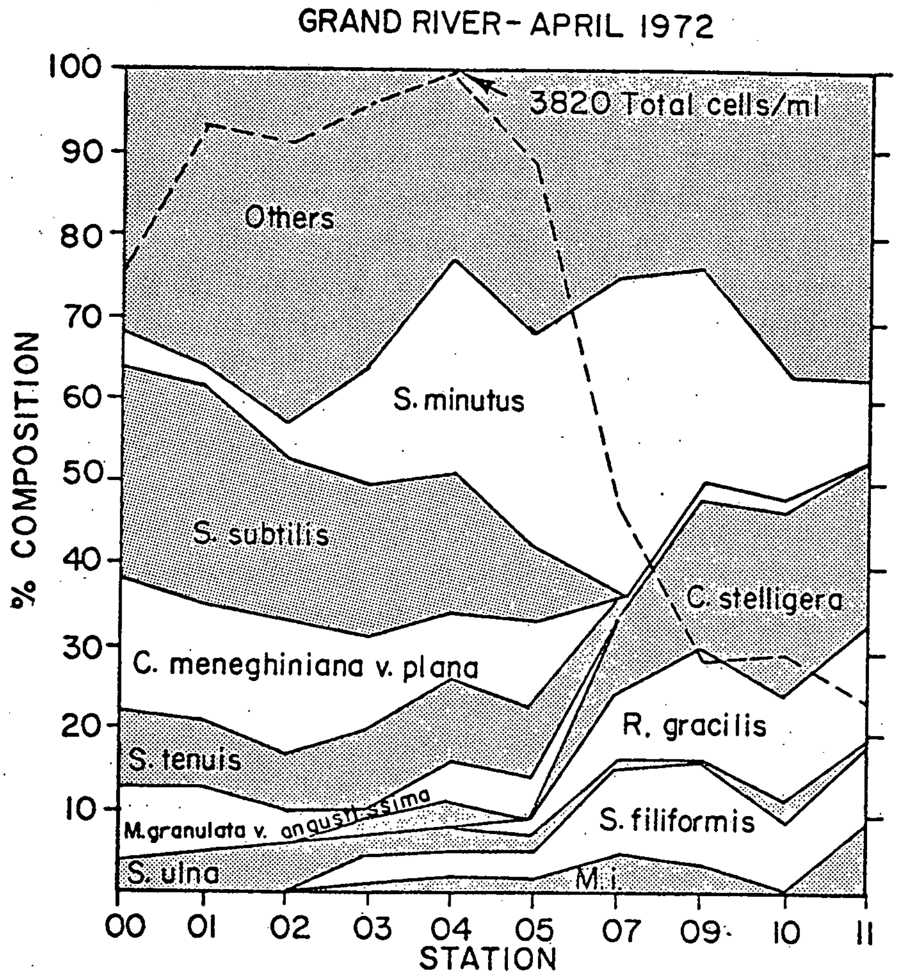



FIGURE 14. Dominant phytoplankton (per cent abundance) at stations on the Grand River transect. See Fig. 11 for additional explanation.

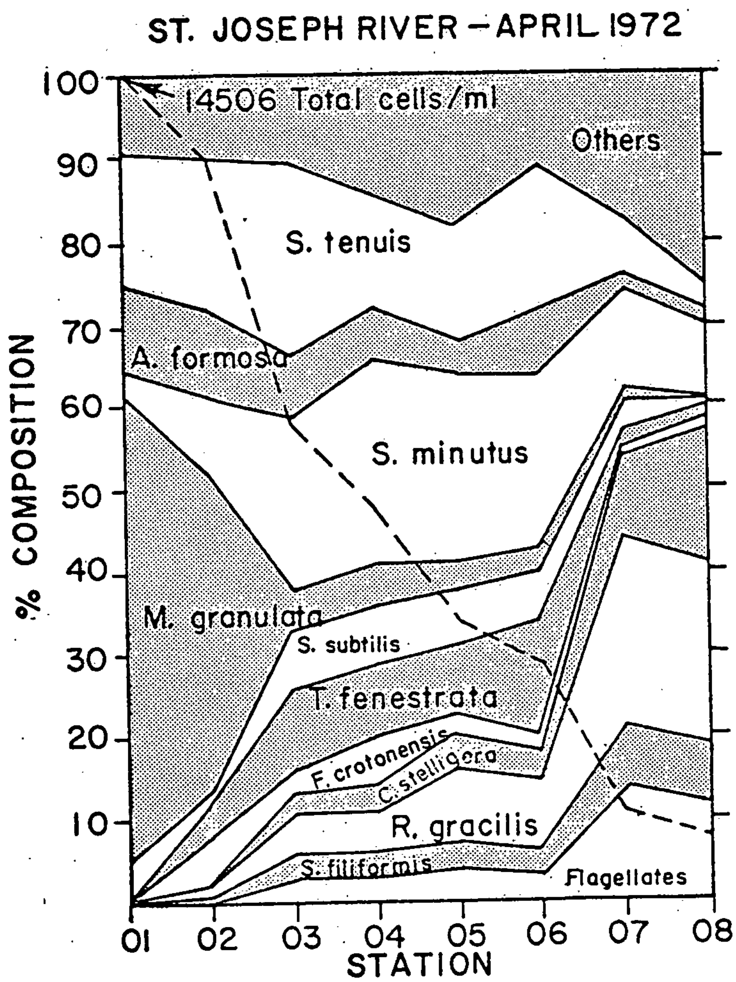



FIGURE 15. Dominant phytoplankton (per cent abundance) at stations on the St. Joseph River transect. See Fig. 11 for additional explanation.

Four of the five offshore dominant species found in the three northern rivers were present with *Melosira italica* not being a dominant. *Tabellaria fenestrata* and *Asterionella formosa* were new dominants on the St. Joseph transect and *Melosira islandica* was a dominant on the Grand River transect.

Kalamazoo and Muskegon Rivers. The outstanding feature in the phytoplankton distribution on these two transects is the dominance of *Stephanodiscus minutus* over the entire transect, particularly close to shore (Figs. 16-17). The offshore dominants were similar to the other rivers on the Michigan shoreline. The offshore dominants also contained *Stephanodiscus tenuis* and *Fragilaria crotonensis* at the Kalamazoo transect but in low abundance.

Milwaukee, Manitowoc and Sturgeon Bay Transects. Phytoplankton in these three rivers on the Wisconsin side of the lake differed from rivers on the Michigan side in that *S. minutus* comprised a smaller proportion of the assemblage (Figs. 18-20), particularly if the Milwaukee transect is excluded. The dominant offshore species was *C. stelligera*. No new species were found as dominants in the offshore plankton, but most of the dominant diatoms, other than *C. stelligera*, comprised a relatively small proportion of the assemblage.

*Fragilaria pinnata*, a benthic species, was abundant in the nearshore waters of the Manitowoc transect. It was the only transect where this species was found in that abundance.

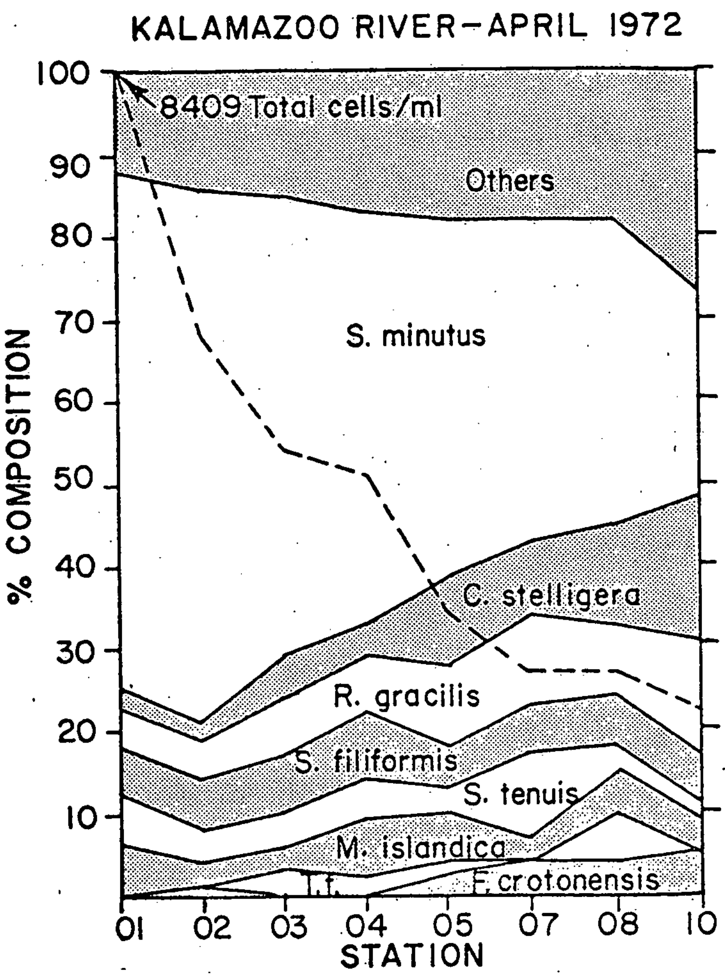



FIGURE 16. Dominant phytoplankton (per cent abundance) at stations on the Kalamazoo River transect. See Fig. 11 for additional explanation.

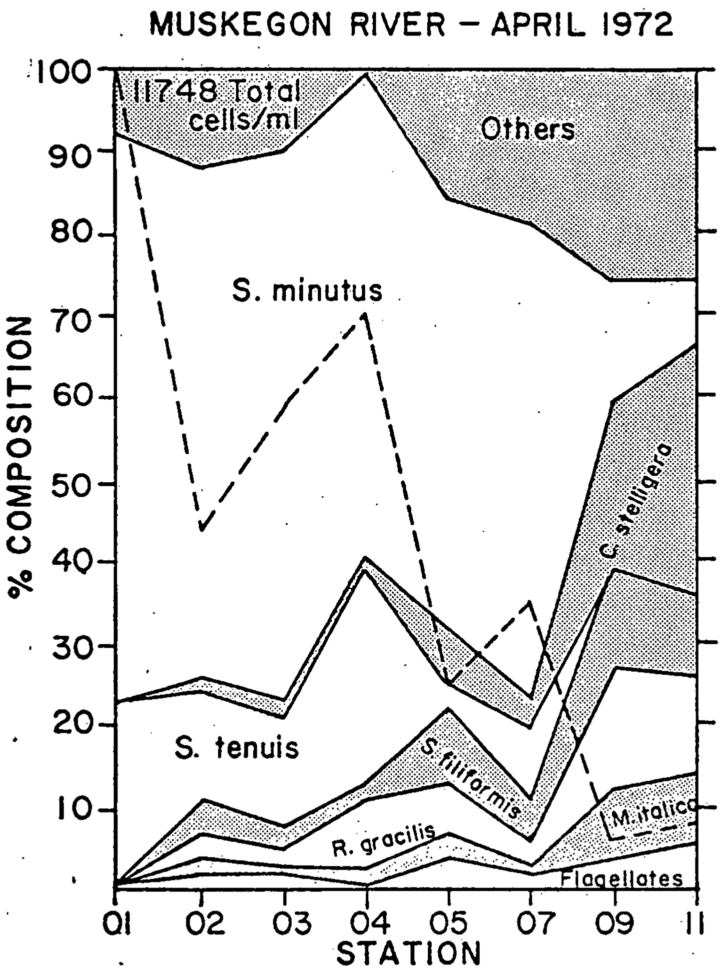



FIGURE 17. Dominant phytoplankton (per cent abundance) at stations on the Muskegon River transect. See Fig. 11 for additional explanation.

## MILWAUKEE RIVER – APRIL 1972

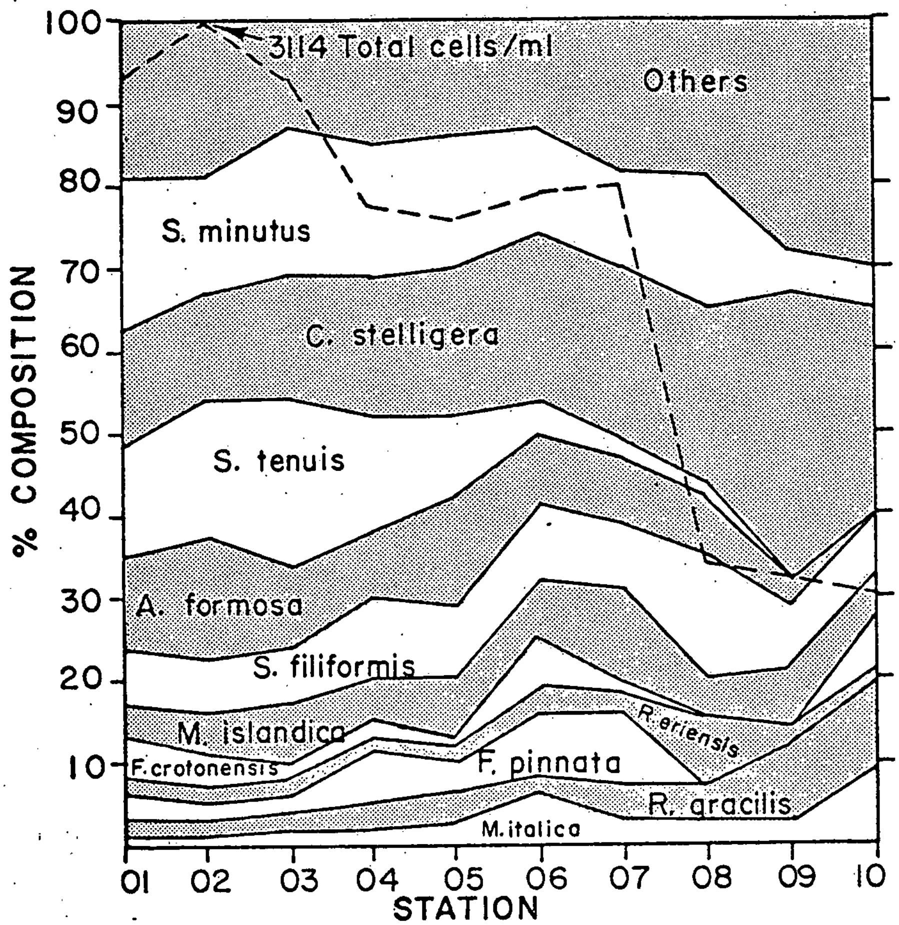



FIGURE 18. Dominant phytoplankton (per cent abundance) at stations on the Milwaukee River transect. See Fig. 11 for additional explanation.

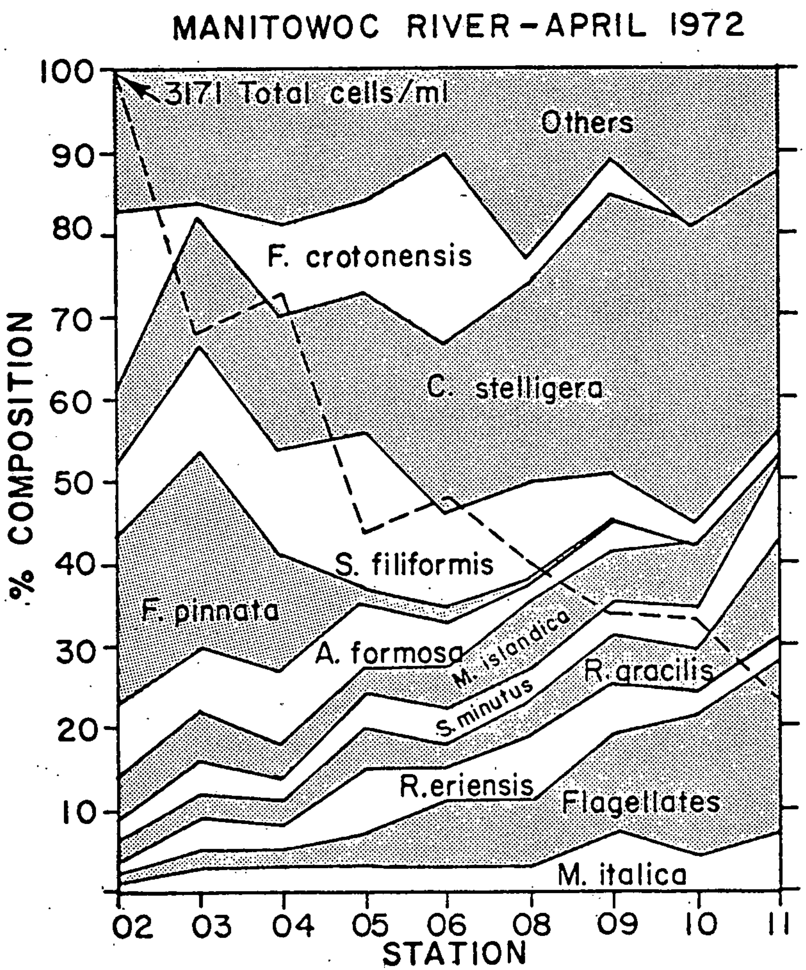



FIGURE 19. Dominant phytoplankton (per cent abundance) at stations on the Manitowoc River transect. See Fig. 11 for additional explanation.

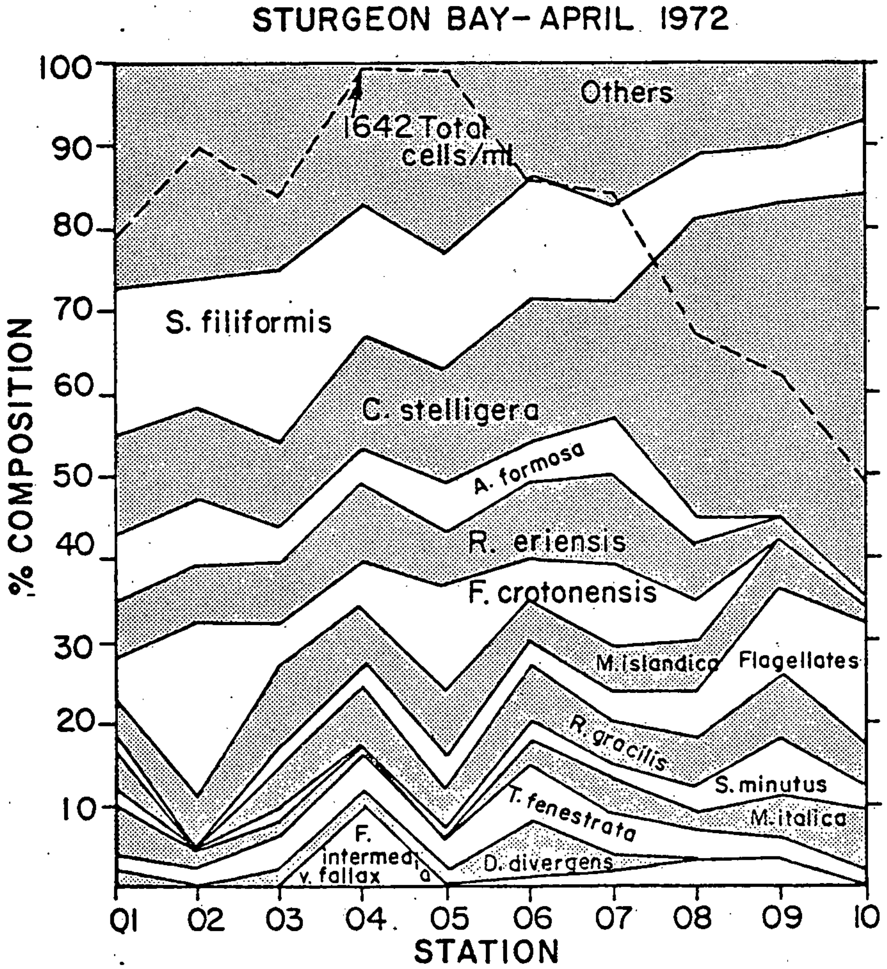



FIGURE 20. Dominant phytoplankton (per cent abundance) at stations on the Sturgeon Bay transect. See Fig. 11 for additional explanation.

Manistique River. This river is atypical for many of the parameters studied and the phytoplankton were not an exception. Many species identified from samples taken at the river mouth were unique and the majority of them were benthic. The large difference in species composition is evident from Fig. 21 as only about 16 per cent of the assemblage at the river mouth is due to dominants found at stations offshore.

Some of the offshore dominants are also different. *Rhizosolenia eriensis*, *Fragilaria crotonensis* and *Tabellaria fenestrata* are present in greater relative abundances than at other stations. Not present as dominants were *M. italica* and *S. minutus*.

Phytoplankton Standing Crop and Species Composition, July 1972

In July 1972, three rivers were sampled intensively over a 10-day period. This sampling was done in conjunction with a nutrient perturbation experiment being conducted in the same area (Schelske et al. 1975). The rivers sampled were the Grand, Kalamazoo and St. Joseph. For the rivers there were 309 taxa, of which 209 were diatoms.

The Grand River yielded 194 algal species, with 143 being diatoms. *Cyclotella atomus* was dominant. Three species not before reported as abundant for the Grand River also were identified. These were *Cyclotella cryptica*, *Melosira distans* v. *alpigena* and *Stephanodiscus subsalsus*. The total cells/ml increased over the 10-day period from 11,600 to 31,000 cells/ml on day 10. At the open lake station the total cells/ml were larger than for April. *Fragilaria crotonensis*, *Rhizosolenia gracilis*, *Diatoma tenue*, *Tabellaria fenestrata* and *Rhizosolenia eriensis* were the most dominant (Table 11).

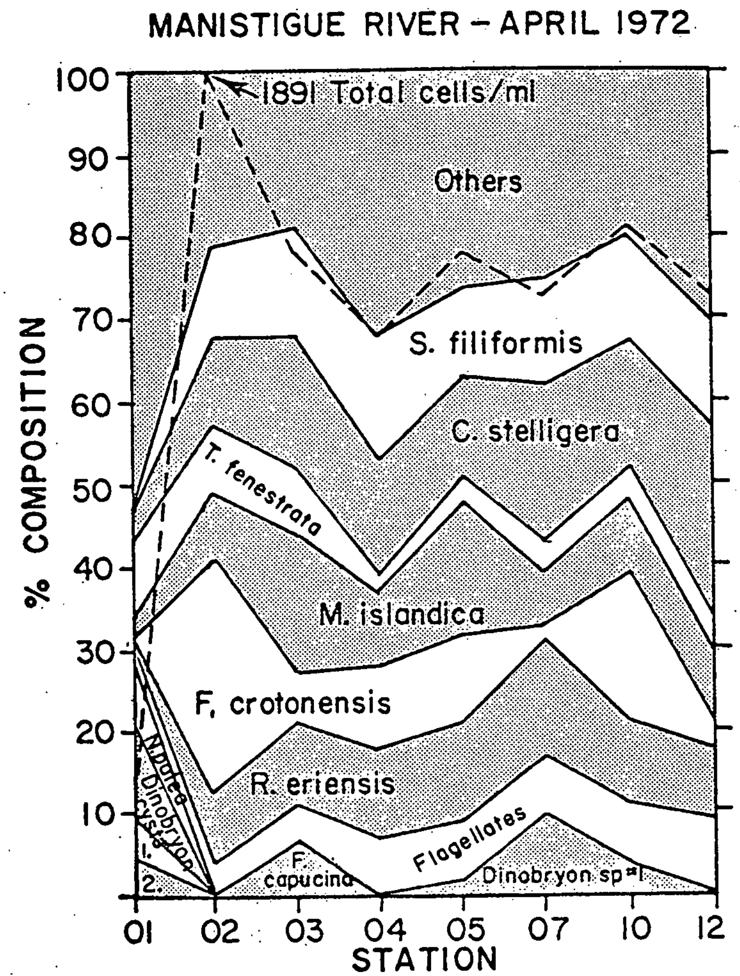



FIGURE 21. Dominant phytoplankton (per cent abundance) at stations on the Manistique River transect. See Fig. 11 for additional explanation.

TABLE 11. Phytoplankton standing crop and species composition off the Grand River, July 1972.

| Species | Stations 01 | 02 | 03 | 04 | 05 | 07 | 09 |
|---|---|---|---|---|---|---|---|
| *Melosira granulata* | 291 | 116 | 93 | 12 | | 12 | |
| *Cyclotella atomus* | 8575 | 3258 | | 12 | 70 | 12 | |
| *Melosira distans* v. *alpigena* | 128 | 23 | | | | | |
| *Fragilaria crotonensis* | | 291 | | | | | 337 |
| *Stephanodiscus subtilis* | 733 | 326 | 58 | | 23 | 12 | 70 |
| *Cyclotella meneghiniana* v. *plana* | 849 | 489 | 128 | 256 | 58 | 58 | 93 |
| *C. cryptica* | 151 | 23 | | | | | |
| *Asterionella formosa* | 35 | 12 | 23 | | 70 | 93 | 151 |
| *Melosira granulata* v. *angustissima* | | | | | | | |
| *Stephanodiscus tenuis* | 81 | 140 | 116 | 244 | 221 | 81 | 47 |
| *S. subsalsus* | | 23 | | | | | |
| *Synedra ulna* | 23 | 12 | 12 | 12 | 23 | | |
| *Fragilaria pinnata* | | | | | | | |
| *Cyclotella stelligera* | | 93 | 116 | 128 | 140 | 58 | 58 |
| Unidentified flagellates | 47 | 12 | 12 | 47 | 35 | 279 | 70 |
| *Anacystis thermalis* | | | | | | | |
| *Stephanodiscus binderanus* | | | | | | | |
| *Gomphonema olivaceum* | 12 | | | | | | |
| *Melosira varians* | | | | | | | |
| *Stephanodiscus minutus* | 70 | 116 | 23 | | 12 | 12 | 35 |
| *Rhizosolenia gracilis* | 23 | 209 | 198 | 81 | 105 | 198 | 372 |
| *Melosira islandica* | | 35 | | | | | |
| *Diatoma tenue* | | 116 | 47 | 58 | 12 | | 512 |
| *Tabellaria fenestrata* | 151 | 47 | 105 | 35 | 23 | | 710 |
| *Fragilaria intermedia* v. *fallax* | | | | | | | |
| *Rhizosolenia eriensis* | 23 | | 70 | 93 | 58 | 23 | 105 |
| *Cyclotella meneghiniana* | | | | | | | |
| *Rhoicosphenia curvata* | | | | | | | |
| No. of species | 31 | 32 | 22 | 21 | 20 | 17 | 17 |
| Cells/ml | 11566 | 5888 | 1257 | 1164 | 1024 | 1315 | 2851 |

Over the 10-day period, cells/ml at the Kalamazoo river ranged from 6,912-43,726. *Cyclotella atomus* was the dominant on July 11 (Table 12). However, it decreased considerably in abundance, and *Cyclotella meneghiniana* v. *plana* and *C. cryptica* increased considerably. On the final sampling day there were 37,432 cells/ml of *C. cryptica*. There were 175 taxa identified at the Kalamazoo River, with 135 of these being diatoms.

At the open lake stations there were very few diatoms with the standing crop being much lower than in April (Table 13). In July at the St. Joseph River the species were the same as those in April. *Stephanodiscus tenuis* and *Melosira granulata* were the dominants. *Cyclotella stelligera* was the dominant diatom at the offshore station. Cells/ml also increased at the river mouth over the 10-day period, from 3,700 to 18,000 cells/ml, but numbers were very low at the open lake station. There were 232 taxa including 149 diatoms that were identified from samples collected during the 10-day period.

Physical-Chemical Conditions, September 1972

Three rivers on the Michigan shoreline were sampled in September 1972--two of these, Betsie and Pere Marquette, as pointed out above, are relatively unpolluted rivers draining into the northern basin and the Grand River is a river which carries a large nutrient load (Table 1).

Temperature. Water temperatures were uniform with the open lake being about 15°C (Table 14). Water flowing out of the rivers was slightly warmer, about 16°C. The nearshore zone, based on water temperature, appeared to extend out to at least one to four miles offshore on the different transects.

TABLE 12. Phytoplankton standing crop and species composition off the Kalamazoo River, July 1972.

| Species | Stations 01 | 02 | 03 | 04 | 05 | 07 | 08 |
|---|---|---|---|---|---|---|---|
| *Melosira granulata* | 465 | 35 | 12 | | 12 | 23 | 12 |
| *Cyclotella atomus* | 4084 | | | 12 | 23 | | |
| *Melosira distans* v. *alpigena* | | | | | | | |
| *Fragilaria crotonensis* | | | | | | | |
| *Stephanodiscus subtilis* | 768 | 35 | 23 | 12 | 12 | | |
| *Cyclotella meneghiniana* v. *plana* | 640 | | | | | | |
| *C. cryptica* | 896 | | | | 58 | | |
| *Asterionella formosa* | 175 | 12 | 105 | 93 | | 81 | |
| *Melosira granulata* v. *angustissima* | 733 | | | 233 | | | |
| *Stephanodiscus tenuis* | 198 | 209 | 186 | 70 | 35 | | |
| *S. subsalsus* | 70 | | | | | | |
| *Synedra ulna* | 12 | 12 | 12 | | | | |
| *Fragilaria pinnata* | | | | | | | |
| *Cyclotella stelligera* | 23 | 151 | 198 | 93 | 93 | 23 | |
| Unidentified flagellates | 105 | | | 23 | 35 | 12 | 12 |
| *Anacystis thermalis* | | | | | | | |
| *Stephanodiscus binderanus* | | | | | | | |
| *Gomphonema olivaceum* | 35 | | | | | | |
| *Melosira varians* | | | | | | | |
| *Stephanodiscus minutus* | 128 | 12 | 12 | | | | |
| *Rhizosolenia gracilis* | 12 | 35 | 12 | | 47 | | 12 |
| *Melosira islandica* | | 47 | | 58 | | | |
| *Diatoma tenue* | 12 | 12 | | | 12 | | |
| *Tabellaria fenestrata* | 128 | 151 | 23 | | | 151 | |
| *Fragilaria intermedia* v. *fallax* | | | | | | | |
| *Rhizosolenia eriensis* | 35 | | | | | 12 | 23 |
| *Cyclotella meneghiniana* | 23 | | | | | | |
| *Rhiocosphenia curvata* | | | | | | | |
| *Dinobryon divergens* | | | | 116 | | | |
| No. of species | 35 | 21 | 19 | 17 | 15 | 9 | 6 |
| Cells/ml | 8878 | 873 | 745 | 838 | 454 | 337 | 93 |

TABLE 13. Phytoplankton standing crop and species composition off the St. Joseph River, July 1972.

| Species | Stations 01 | 02 | 03 | 04 | 05 | 06 | 07 |
|---|---|---|---|---|---|---|---|
| *Melosira granulata* | 826 | 477 | | | 70 | | 12 |
| *Cyclotella atomus* | 58 | 93 | | | | | |
| *Melosira distans* v. *alpigena* | | | | | | | |
| *Fragilaria crotonensis* | 12 | | 663 | | | | |
| *Stephanodiscus subtilis* | 116 | 105 | | | 35 | | |
| *Cyclotella meneghiniana* v. *plana* | | 47 | | | | | |
| *C. cryptica* | | 47 | | | | | |
| *Asterionella formosa* | 81 | 12 | | 175 | 58 | 12 | |
| *Melosira granulata* v. *angustissima* | | 12 | | | | | |
| *Stephanodiscus tenuis* | 1676 | 1210 | | 35 | 23 | 23 | |
| *S. subsalsus* | | | | | | | |
| *Synedra ulna* | 47 | 12 | | | | | |
| *Fragilaria pinnata* | | | | | | | |
| *Cyclotella stelligera* | 12 | 70 | 47 | 70 | 81 | 58 | 70 |
| Unidentified flagellates | 12 | 93 | 12 | 35 | 70 | 151 | 23 |
| *Anacystis thermalis* | | | | | | | |
| *Stephanodiscus binderanus* | | | | | | | |
| *Gomphonema olivaceum* | | 12 | | | | | |
| *Melosira varians* | | | | | | | |
| *Stephanodiscus minutus* | 23 | | | | 23 | | |
| *Rhizosolenia gracilis* | | | 12 | | | | |
| *Melosira islandica* | | | | | | | |
| *Diatoma tenue* | 198 | | | | | 58 | |
| *Tabellaria fenestrata* | 47 | | 12 | | 12 | | 12 |
| *Fragilaria intermedia* v. *fallax* | | | | | | | |
| *Rhizosolenia eriensis* | | | | 12 | | | |
| *Cyclotella meneghiniana* | 93 | | | | | | |
| *Rhoicosphenia curvata* | | | | | | | |
| *Fragilaria capucina* | 209 | | | | | | |
| *Stephanodiscus* #16 | 93 | 81 | | | | | |
| No. of species | 28 | 30 | 9 | 10 | 13 | 6 | 7 |
| Cells/ml | 3700 | 2618 | 791 | 396 | 431 | 314 | 163 |

TABLE 14. Physical-chemical conditions in the Betsie, Pere Marquette and Grand rivers, September 1972.

| Miles | Rivers: Betsie | Pere Marquette | Grand |
|---|---|---|---|
| | | Temp. °C - 2 m | |
| 0 | -- | 16.1 | 16.3 |
| 1/8 | 15.8 | 16.1 | -- |
| 1/4 | -- | 16.0 | 16.4 |
| 1/2 | 15.0 | 16.0 | 16.5 |
| 1 | -- | 16.0 | 16.2 |
| 2 | 15.5 | 15.5 | 16.0 |
| 4 | 15.1 | 15.6 | 16.0 |
| 8 | 15.0 | | 15.5 |
| 16 | -- | | 14.9 |
| | | pH | |
| 0 | -- | 8.31 | 8.49 |
| 1/8 | 8.52 | 8.56 | -- |
| 1/4 | -- | 8.55 | 8.59 |
| 1/2 | 8.53 | 8.56 | 8.59 |
| 1 | -- | 8.57 | 8.56 |
| 2 | 8.54 | 8.57 | 8.52 |
| 4 | 8.55 | 8.56 | 8.53 |
| 8 | 8.54 | -- | 8.55 |
| 16 | | | 8,54 |

| Miles | Rivers: Betsie | Pere Marquette | Grand |
|---|---|---|---|
| | | $Cl^-$ ppm | |
| 0 | | 22.7 | 16.0 |
| 1/8 | 8.6 | 8.7 | |
| 1/4 | | 8.9 | 10.1 |
| 1/2 | 9.3 | 8.3 | 8.7 |
| 1 | | 8.1 | 9.2 |
| 2 | 7.1 | 7.8 | 8.0 |
| 4 | 8.0 | 7.4 | 7.5 |
| 8 | 7.8 | | 7.6 |
| 16 | | | 8.0 |
| | | Conductivity | |
| 0 | | 4.01 | 4.16 |
| 1/8 | 2.92 | 2.88 | |
| 1/4 | | 2.87 | 3.21 |
| 1/2 | 2.91 | 2.85 | 3.21 |
| 1 | | 2.85 | 2.90 |
| 2 | 2.85 | 2.86 | 2.84 |
| 4 | 2.82 | 2.83 | 2.84 |
| 8 | 2.75 | | 2.83 |
| 16 | | | 2.83 |

Hydrogen Ion Concentration. Except at the river mouth stations of the Grand and Pere Marquette, pH generally was 8.55 with values ranging from 8.52 to 8.59 (Table 14).

Specific Conductance. Water at the mouth of the Grand and Pere Marquette rivers with low pH values had elevated specific conductance (Table 14) with only slightly higher values near the mouth of the Betsie River. On the Grand River transect, high specific conductance was evident at least out to the one-mile station.

Chloride. Chloride concentrations reflected the patterns of specific conductance discussed above. The Pere Marquette had a greater chloride concentration than the Grand (Table 14), but a lower specific conductance, indicating chemicals in addition to chloride contributed relatively more to the specific conductance of the Grand.

## Nutrients and Chlorophyll, September 1972

Total Phosphorus. The total phosphorus concentration in the Grand River was much greater than in the other two rivers (Table 15). Total phosphorus concentrations out to one mile off the Grand River mouth indicated the influence of tributary input as the concentration was greater than that in the open lake.

The total phosphorus concentration in the Pere Marquette was also greater than in the open lake, but the high value was restricted to the river mouth.

Chlorophyll *a*. Chlorophyll concentrations at stations removed from the influence of tributary inputs ranged from 1.0 to 1.4 μg/liter

(Table 15). Concentrations greater than 2.0 μg/liter were associated with total phosphorus concentrations greater than 9.0 μg P/liter at nearshore stations. On the Grand River transect, higher chlorophyll concentrations could be detected at least one mile offshore.

Even though the Grand River total phosphorus concentrations were four times greater than that in the Pere Marquette (Table 15), chlorophyll concentrations were similar.

Nitrate Nitrogen. Nitrage nitrogen in the Grand River was greater than at offshore stations (Table 15) but much less than during April 1972 (Table 8). The other rivers had concentrations similar to those found offshore.

Silica. Offshore silica values were less than 0.3 mg $SiO_2$/liter (Table 15). These concentrations are greater than the summer minimum which is 0.1 mg/liter, probably indicating some replenishment during the fall of silica in the surface waters. The concentration in the Grand was 2.5 mg/liter with concentrations higher than open lake levels being present out to 4 miles offshore.

Phytoplankton Standing Crop and Species Composition, September 1972

Standing crops of phytoplankton were small at the offshore station, being less than 400 cells/ml. Counts were highest at the river mouths for all three transects (Figs. 22-24). Samples from September yielded 184 taxa with 133 of these being diatoms.

Betsie and Pere Marquette Rivers. These two rivers had similar phytoplankton assemblages in that the dominant species was *Fragilaria*

TABLE 15. Nutrients and chlorophyll in the Betsie, Pere Marquette and Grand rivers, September 1972.

| Miles | Betsie | Pere Marquette | Grand |
|---|---|---|---|
| | Chlorophyll $mg/m^3$ | | |
| 0 | -- | 13.40 | 12.77 |
| 1/8 | 2.08 | 2.22 | -- |
| 1/4 | -- | 1.70 | 8.93 |
| 1/2 | 1.16 | 1.88 | 7.44 |
| 1 | -- | 1.91 | 3.32 |
| 2 | 1.00 | 0.51 | 1.85 |
| 4 | 1.31 | 1.35 | 1.31 |
| 8 | 1.44 | | 1.31 |
| 16 | | | 0.95 |
| | $SiO_2$ ppm | | |
| 0 | -- | 1.99 | 2.56 |
| 1/8 | 0.48 | 0.44 | -- |
| 1/4 | -- | 0.42 | 1.01 |
| 1/2 | 0.30 | 0.42 | 1.04 |
| 1 | -- | 0.40 | 0.58 |
| 2 | 0.27 | 0.33 | 0.52 |
| 4 | 0.26 | 0.29 | 0.47 |
| 8 | 0.28 | | 0.31 |
| 16 | | | 0.30 |

| Miles | Betsie | Pere Marquette | Grand |
|---|---|---|---|
| | $NO_3$ ppb-N | | |
| 0 | --- | 175 | 488 |
| 1/8 | 184 | 167 | --- |
| 1/4 | --- | 157 | 285 |
| 1/2 | 117 | 303 | 234 |
| 1 | --- | 159 | 185 |
| 2 | 148 | 160 | 171 |
| 4 | 192 | 401 | 170 |
| 8 | 130 | | 194 |
| 16 | | | 186 |
| | $PO_4$ ppb-Total @ 2m | | |
| 0 | | 28.9 | 110.7 |
| 1/8 | 5.7 | 8.9 | |
| 1/4 | | 7.3 | 25.0 |
| 1/2 | 5.4 | 6.0 | 27.8 |
| 1 | | 7.2 | 12.0 |
| 2 | 2.9 | 8.3 | 6.9 |
| 4 | 4.5 | 8.7 | 5.2 |
| 8 | 5.6 | | 4.0 |
| 16 | | | 4.4 |

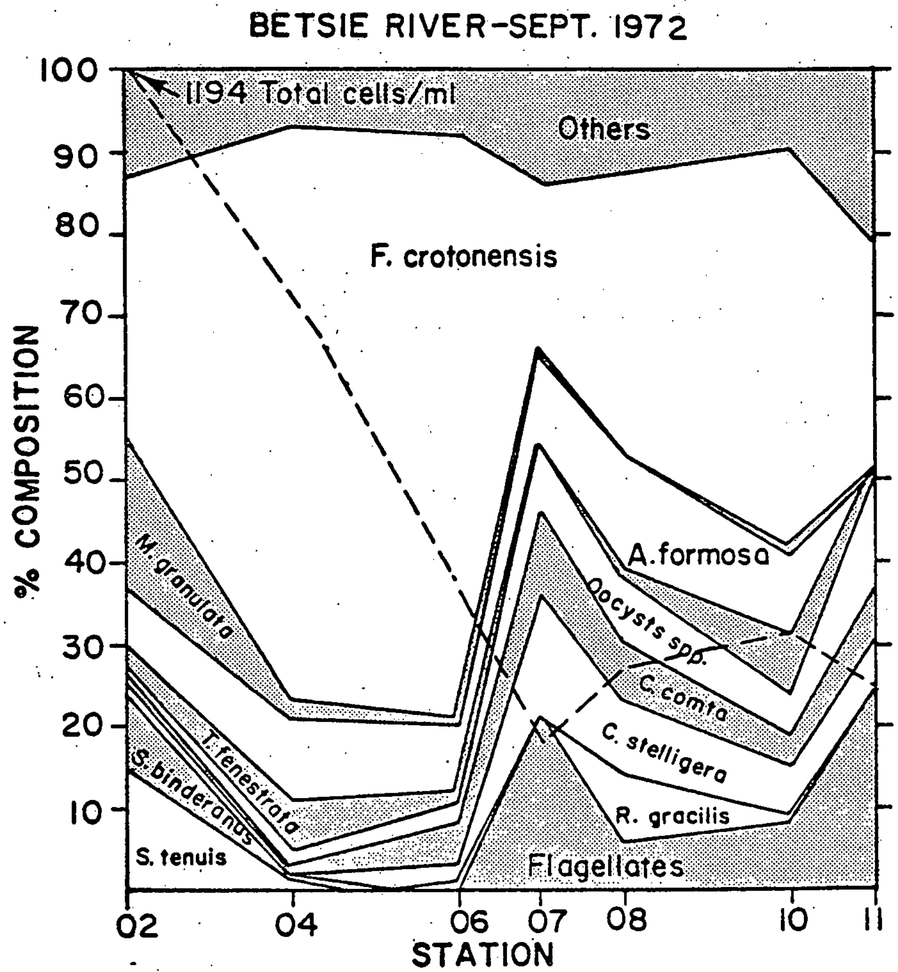



FIGURE 22. Dominant phytoplankton (per cent abundance) at stations on the Betsie River transect. See Fig. 11 for additional explanation.

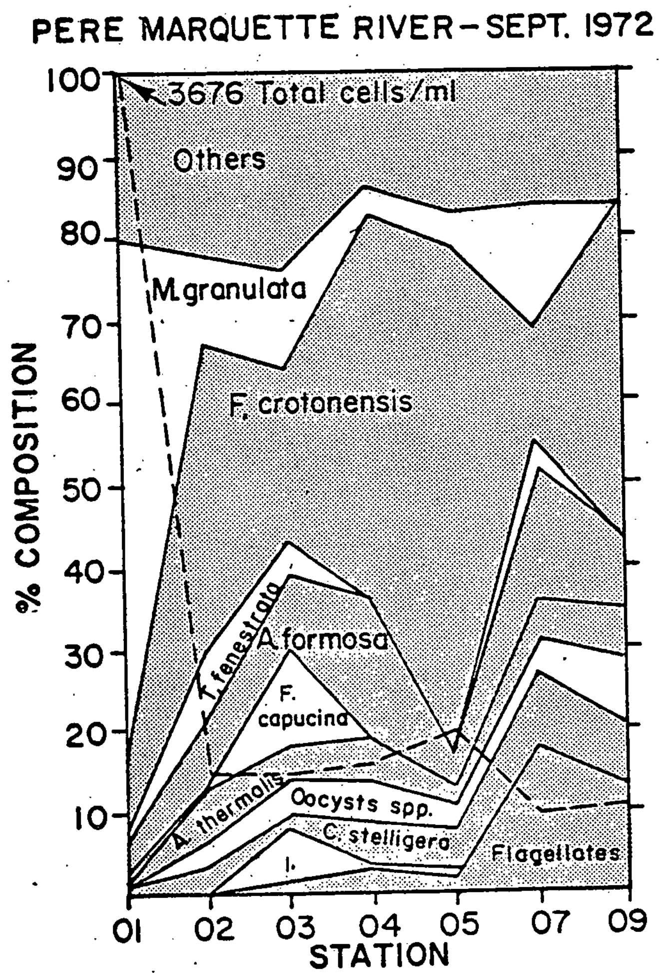



FIGURE 23. Dominant phytoplankton (per cent abundance) at stations on the Pere Marquette River transect. See Fig. 11 for additional explanation.

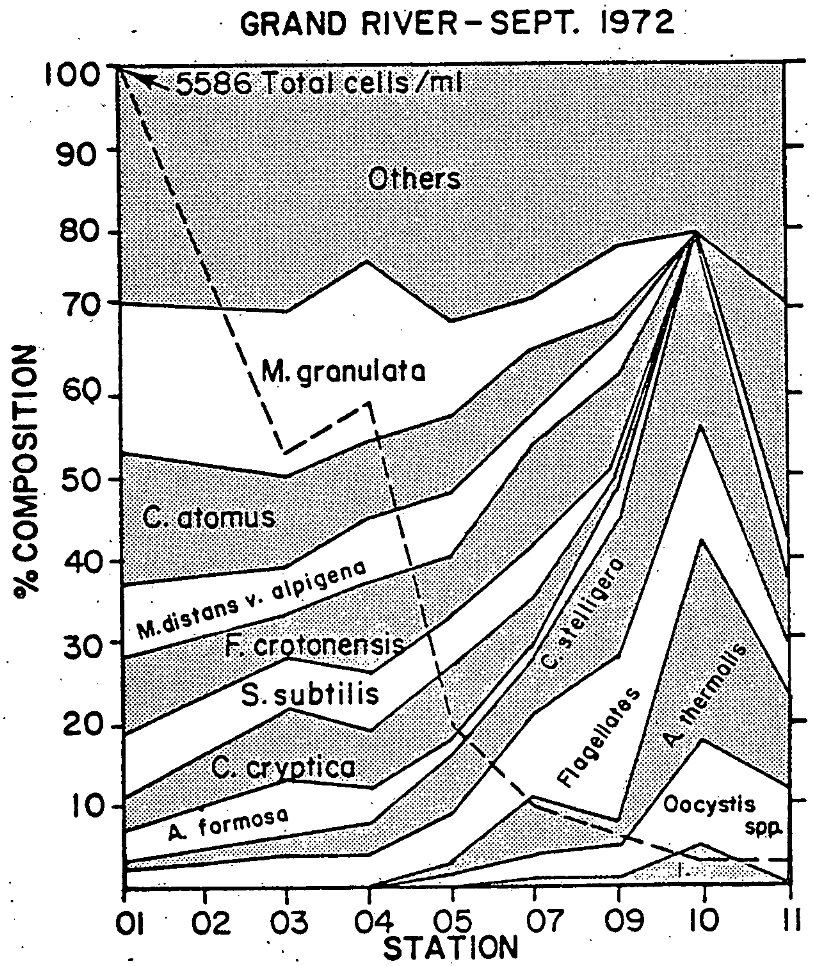



FIGURE 24. Dominant phytoplankton (per cent abundance) at stations on the Grand River transect. See Fig. 11 for additional explanation.

*crotonensis* with *Melosira granulata* forming an important component near shore. At the offshore stations where silica was reduced, flagellates and blue-greens, *Oocystis* sp. and *Anacystis thermalis*, comprised more than 25 per cent of the assemblage.

Grand River. In contrast to the two northern rivers, the influence of the large flow of the Grand River can be seen in the phytoplankton composition on the Grand transect. The river-borne species, *Melosira granulata, Cyclotella atomus, C. cryptica* and *Melosira distans* v. *alpigena* persist at the stations two and four miles offshore (Fig. 24). *Asterionella formosa, Fragilaria crotonensis* and *Cyclotella stelligera* are also common in the nearshore samples.

At the offshore stations blue-greens and flagellates comprise nearly half of the cell counts in the phytoplankton assemblage. *Anacystis thermalis* and *Oocystis* sp. are the dominant blue-greens and *Fragilaria crotonensis* was the dominant diatom.

A similar trend in the phytoplankton data was observed for the three transects in that larger numbers of species were found at the river-mouth stations and at the stations in the river plume than were found at the offshore stations. At the offshore stations, about 20 species were identified per sample while the river-mouth sample for the Grand River contained 97 species (Table 16). Phytoplankton assemblages at the river stations which had adequate quantities of silica were more than 90 per cent diatoms and as noted above, the offshore species included several dominants that were not diatoms. The per cent diatoms at the offshore stations ranged from 29 to 64 with decreasing percentages being related

TABLE 16. Phytoplankton assemblage composition and standing crop, September 1972.

| Transect | Distance offshore (miles) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1/8 | 1/4 | 1/2 | 1 | 2 | 4 | 8 | 16 |
| **Betsie** | | | | | | | | | |
| Per Cent Diatoms | | 95.8 | - | 95.1 | - | 89.2 | 58.4 | 76.0 | 45.1 |
| Per Cent Blue-greens | | 0.5 | - | 1.0 | - | 3.3 | 5.9 | 4.5 | 8.5 |
| Number of species | | 55 | | 20 | | 17 | 17 | 22 | 22 |
| Total cells/ml | | 1194 | | 865 | | 448 | 211 | 322 | 297 |
| **Pere Marquette** | | | | | | | | | |
| Per Cent Diatoms | 98.9 | 84.3 | 81.2 | 78.8 | 80.6 | 68 | 64 | | |
| Per Cent Blue-greens | 0.5 | 7.1 | 6.0 | 6.6 | 3.8 | 6.6 | 7.9 | | |
| Number of species | 68 | 40 | 42 | 27 | 24 | 23 | 22 | | |
| Total cells/ml | 3776 | 561 | 557 | 574 | 725 | 383 | 395 | | |
| **Grand** | | | | | | | | | |
| Per Cent Diatoms | 95 | | 91 | 92 | 86.3 | 70.0 | 63.8 | 29.1 | 58 |
| Per Cent Blue-greens | 1 | | 1.3 | 1.1 | 3.1 | 10.0 | 5.4 | 31.4 | 15 |
| Number of species | 97 | | 78 | 63 | 69 | 47 | 30 | 16 | 21 |
| Total cells/ml | 5586 | | 2957 | 3313 | 1131 | 566 | 312 | 180 | 191 |

to low silica values (Table 17). It should be noted that the standing crops at the offshore stations were small so that in absolute terms the populations of blue-greens and flagellates are not in the category that could be called nuisance blooms.

Summary, Environmental Conditions, 1972

A very large data set was obtained on the nearshore environment during 1972. The data set is probably unique in that samples were collected and analyzed for a number of physical-chemical parameters and for phytoplankton standing crop and species composition. Phytoplankton identified during the study totaled 431 taxa of which 306 were diatoms which is one illustration of the magnitude of the available data. Only a summary of the information has been presented in this report.

Data collected in the spring of 1972 show a wide variation among the rivers sampled and the nearshore areas influenced by the rivers.

The most obviously difference river was the Manistique. It differed chemically with a pH of 7.4 (Table 3) and low specific conductance (Table 5) and low chloride (Table 4). Although not measured directly, it was obvious that the river carried a greater organic load than any of the other rivers sampled. The water was foamy and contained wood chips and fibers from pulp and paper production. These chemical conditions contributed to a low standing crop of phytoplankton with a small number of species (Table 10). Even though nutrients were as abundant in the Manistique as in the other rivers, cell counts and chlorophyll were low comparatively.

The nutrient load of the rivers had an obvious effect on the nearshore zone. Only two rivers, the Grand and St. Joseph, produced loadings

TABLE 17. Comparison of phytoplankton composition and chemical conditions for river and open lake stations, September 1972.

| River | % composition | | | | | | |
|---|---|---|---|---|---|---|---|
| | Diatoms | Greens | Blue-greens | Chl *a* | Total P | Cl | $SiO_2$ |
| Grand | 95.3 | 2.03 | 0.94 | 12.8 | 110.7 | 16.04 | 2.56 |
| Lake | 29.1 | 23.3 | 31.4 | 1.31 | 4.0 | 7.55 | 0.31 |
| Pere Marquette | 98.9 | 0.40 | 0.46 | 13.4 | 28.8 | 22.71 | 1.99 |
| Lake | 64.0 | 13.8 | 7.9 | 1.35 | 8.7 | 7.39 | 0.29 |
| Betsie | 95.8 | 3.5 | 0.5 | 2.08 | 5.7 | 8.55 | 0.48 |
| Lake | 76.0 | 13.0 | 4.5 | 1.24 | 4.2 | 7.92 | 0.29 |

to the lake that with the methods employed in our sampling could be detected as river water for distances greater than one mile. Our sampling design utilized stations on transects perpendicular to shore. This strategy is not suited ideally to delineate the extent of river plumes as water transport is usually long shore. Under some conditions plumes of river water are distinct for many miles along shore. Intuitively one would expect the effect of tributary loading on phytoplankton to be manifested in the nearshore zone as the tributaries empty into this zone where nutrients can be processed by phytoplankton prior to being diluted or being transported offshore. The area of the nearshore influenced by tributary inputs will be first related to the volume of flow and the nutrient load and then be affected by physical and chemical processes.

One important chemical factor is nutrient availability, particulary phosphorus. Our data are for total phosphorus, which gives no information on availability. Large standing crops of chlorophyll, 15 to 20 μg/liter (Table 7) were associated with high phosphorus concentrations ranging from 20 to 175 μg P/liter (Table 6). This broad range indicates some of the phosphorus is not available. On the other hand, large supplies of phosphorus may be present in the environment and may not be immediately reflected in large standing crops of phytoplankton. Many experiments have been conducted in our laboratories which conclusively demonstrate that additions of phosphorus from 10 to 20 μg P/liter can produce chlorophyll standing stocks of the magnitude seen in our field experiments.

Data collected in this study support the conclusion that phosphorus supplies to the lake control the growth of phytoplankton (Schelske and Stoermer 1971, Schelske 1975). In addition the data also confirm the hypothesis that silica depletion resulting from increased diatom growth in the lake would affect the species composition by reducing the proportion of diatoms and increasing the proportion of green and blue-green algae in the assemblage. On the transect off St. Joseph, silica concentrations that are limiting to phytoplankton are present in the nearshore (Table 9). This condition is due to extreme phosphorus loadings and shallow nearshore water even though the water temperature is less than 5°C (Table 2).

Recently, Tarapchak and Stoermer (1976) have summarized data on diatoms which reflect the trophic status of waters. No oligotrophic species were identified as dominants in this study. *Cyclotella stelligera*, a dominant during the spring, was classified as species which reaches maximum abundance under mesotrophic conditions but is intolerant of nutrient enrichment. Also in this category are *Melosira islandica* and *Rhizosolenia eriensis*. Other mesotrophic species were abundant, but these including *Asterionella formosa*, *Tabellaria formosa* and *Fragilaria crotonensis* are species tolerant of moderate nutrient enrichment.

Four species which have maximum abundances under eutrophic conditions were dominant components of the phytoplankton. *Melosira granulata* was common at the river mouths, particularly the Grand. *Stephanodiscus minutus* and *S. subtilis* were abundant at many of the nearshore locations in the spring. *S. subtilis* and *S. tenuis*, another species which was dominant in the St. Joseph River are according to Tarapchak and Stoermer recently introduced eutrophic species.

Data on phytoplankton species composition then indicate the trophic state of Lake Michigan is mesotrophic for the offshore areas, but in the nearshore areas many of the species, like *S. minutus* are indicative of eutrophic conditions.

## CHEMOSTAT STUDIES

The chemostat studies of Si-limited diatoms were continued on a limited basis this year. Because of time constraints, the chemostats were not started until mid-January instead of immediately after the cruise season as planned. Freshwater diatoms taken from batch culture continue to be extremely difficult to adapt to chemostat conditions, requiring about 1-2 months adaptation time. A similar but less severe problem was observed previously with marine species requiring 2 weeks-1 month adaptation time. The difference is probably a reflection of the relative growth rates, as marine species grow on the average about twice as fast as freshwater species. One can then hypothesize that so much adaptation takes place at each cell division. Regardless, this phenomenon makes part-time chemostat operation very inefficient and once again the results are quite limited.

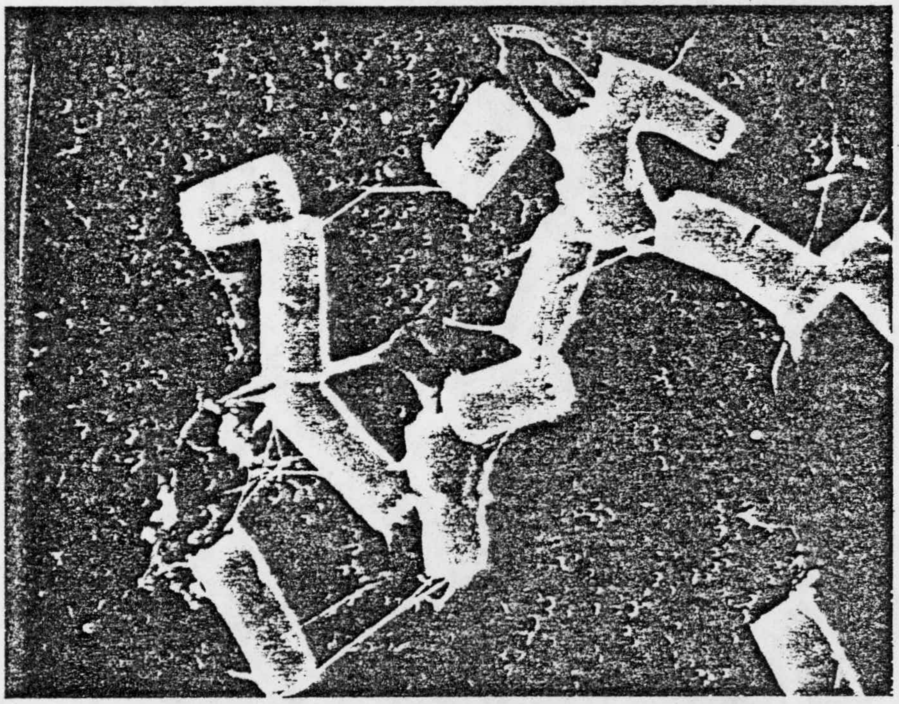
Two perturbation experiments were conducted this year using *Cyclotella meneghiniana*. The full results have not yet been calculated but first estimates agree with the first two experiments from last year, giving a $K_s$ for silicate uptake of about 0.1 mg $SiO_2$/1, which is in the low range of the late summer average silicate concentration in the upper 30 m in open Lake Michigan and provides further evidence that silicon depletion is limiting diatom growth in Lake Michigan. Considerably more information will be available when the kinetic analysis is complete.

Two other aspects of the chemostat studies have proved especially interesting. The morphology of the cells changes with silicon limitation. Cells become very fragile and are often deformed under silicon limitation as shown in Fig. 25a. Also they exude filiments through a pore at the base of the spines. These filaments are sticky and under silicon limitation large clumps of 50-200 cells are formed. The cells formed after silicon was added back to the reactor (Fig. 25b) had straight frustules; the slime strands were virtually gone and no clumps were observed.

What is perhaps most interesting about the clumping phenomenon is its effect on sinking rates. The normal rate for healthy *C. meneghiniana* is about 0.8 m/day. Silicon-limited populations in large clumps ($\sim$ 100 cells) sink at an approximately 50 times higher rate, 35-40 m/day. Is this clump-forming process then a mechanism to escape nutrient depleted water by sinking? A similar phenomenon has also been observed for the marine diatom *Skeletonema costatum*.

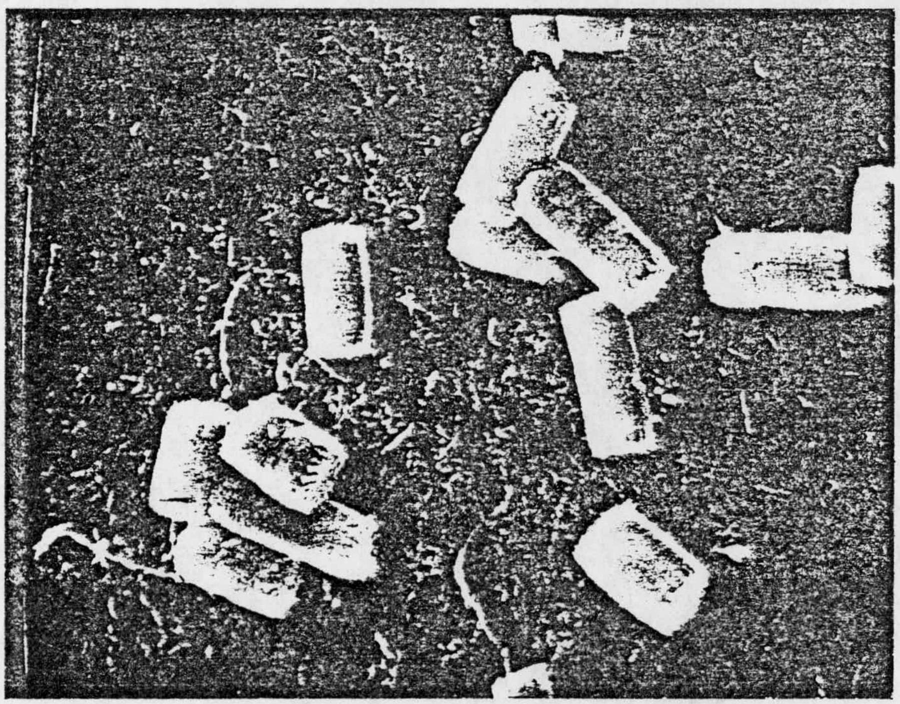
Because of the difficulty in doing chemostat work on a part-time basis, as mentioned in the first paragraph of this section, it is proposed to work up the results of the experiments conducted thus far, and thus discontinue this component of the project. This change will be reflected in the reduced portion of Curtiss Davis's time supported by this project. Dr. Davis, in turn, hopes to become involved in other projects as discussed under Other Financial Support in the proposal.

501 x 2000 3/16 12:56 sample



(a)

507 x 2000 3/17/77 9:40 Sample



(b)

FIGURE 25. Chemostat populations of *Cyclotella meneghiniana*. (a) Silicon limited population. (b) Same population 20 hrs after silicon was added to the reactive.

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