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BIOLOGICAL, CHEMICAL AND PHYSICAL RELATIONSHIPS IN THE STRAITS OF MACKINAC

by

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FOREWORD

Our nation's freshwaters are vital for all animals and plants, yet our diverse uses of water---for recreation, food, energy, transportation, and industry---physically and chemically alter lakes, rivers, and streams. Such alterations threaten terrestrial organisms, as well as those living in water. The Environmental Research Laboratory in Duluth, Minnesota develops methods, conducts laboratory and field studies, and extrapolates research findings

--to determine how physical and chemical pollution affects aquatic life

--to assess the effects of ecosystems on pollutants

--to predict effects of pollutants on large lakes through use of models

--to measure bioaccumulation of pollutants in aquatic organisms that are consumed by other animals, including man

This report, part of our program on large lakes, details our findings in the Straits of Mackinac, that waterway connecting Lake Michigan and Lake Huron.

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SECTION I

INTRODUCTION

The Straits of Mackinac, from the standpoint of physical dynamics, is a unique area in the Laurentian Great Lakes. It is unique in that the Straits connect two lakes with the same water level, and although there is a net water transport from Lake Michigan to Lake Huron the flow oscillates between the two lakes. Outflows at other points in the Great Lakes system are due to differences in water levels.

The oscillatory flow resulting from the connection of two lakes with the same water level would be expected to produce complicated physical dynamics and possibly a unique biological environment. The physical processes have been studied infrequently (Powers and Ayers 1960; Murty and Rao 1970; FWPCA 1967). Saylor and Sloss (In press) measured currents and water movements in the Straits during the time our study was conducted.

The biology and ecology of the Straits of Mackinac, northern Lake Michigan and northern Lake Huron are poorly known. The benthos has been studied by Henson (1962, 1970). To our knowledge there have been no investigations on the plankton--the limited data available are reviewed in Sections VI and VII, which present our results on phytoplankton and zooplankton. Likewise, little is known about the phytoplankton productivity and major nutrients in the Straits of Mackinac. Indications of accelerated eutrophication have been reported for Lake Michigan in recent years (Beeton 1969; Schelske and Stoermer 1971), but the impact of inputs of Lake Michigan water on eutrophication and primary productivity in the receiving waters of the Straits of Mackinac and Lake Huron has not been assessed. A review of the biological and chemical conditions in relation to the eutrophication and trophic status of Lake Michigan has been completed recently (Schelske, In press).

Our study was initiated in late August 1973 with data being collected on three cruises: 30 August-1 September, 16-18 September and 6-8 October. The purpose of this investigation was to gather baseline data on environmental quality in the Straits of Mackinac and to use these data as outlined in the objectives.

1.1 OBJECTIVES

1) To evaluate the effect of input of water from Lake Michigan on water

quality in the Straits of Mackinac and in the northern part of Lake Huron.

2) To identify water masses in the Straits of Mackinac, northern Lake Huron and the St. Marys River, by

- a) measuring chemical characteristics,
- b) measuring primary productivity of phytoplankton,
- c) determining the standing crop, species composition, and diversity estimates of phytoplankton assemblages,
- d) determining the standing crop and species composition of zooplankton, and
- e) measuring concentrations of phosphorus.

3) To evaluate our results in relation to other studies and available data and to assess whether more detailed studies of input from Lake Michigan, including estimates of water transport, will be needed to determine the significance of inputs of water from Lake Michigan on water quality in Lake Huron.

4) To use our data to assess water quality.

1.2 CURRENT PATTERNS IN THE STRAITS REGION

Although currents in the survey region (Fig. 1.1) are complicated and highly variable, several generalizations can be made about water movements. Detour Passage, in the northeastern corner of the survey area, serves as one mouth of the St. Marys River, which empties Lake Superior into northern Lake Huron. Total net flow at Detour Passage was measured as 2000 m^3/sec (Powers and Ayers 1960). It was shown from drift bottles and dynamic height calculations that the St. Marys River water is carried east or west with little tendency to move south in the survey area and that generally there is counterclockwise surface circulation in the east-central part of the survey area (Ayers et al. 1956).

Currents at Detour Passage may be considered reasonably constant in comparison to the highly variable currents at the Straits. The average net current in the Straits of Mackinac was eastward and ranged from 1500-1900 m^3/sec (Powers and Ayers 1960; FWPCA 1967; Saylor and Sloss, In press). Extreme variations are due mainly to the 50-60 hr seiche between Lake Michigan and Lake Huron. The net flow typically changes from 10,000 m^3/sec in one direction to a flow of equal magnitude in the opposite direction in a period of only 24 hr. During only a small fraction of a month is the instantaneous net flow in the Straits near the average 1500-1900 m^3/sec. Saylor and Sloss (In press) and FWPCA (1967) found net transport commonly exceeding 20,000 m^3/sec in either easterly or westerly directions. Such a large pulse of water traveling .18 m/sec for 12 hr moves about 8 km, which may be taken to be an estimate of a mixing radius near the Straits. Ayers et al. (1956) showed that surface water, after passing through the Straits from Lake Michigan, generally

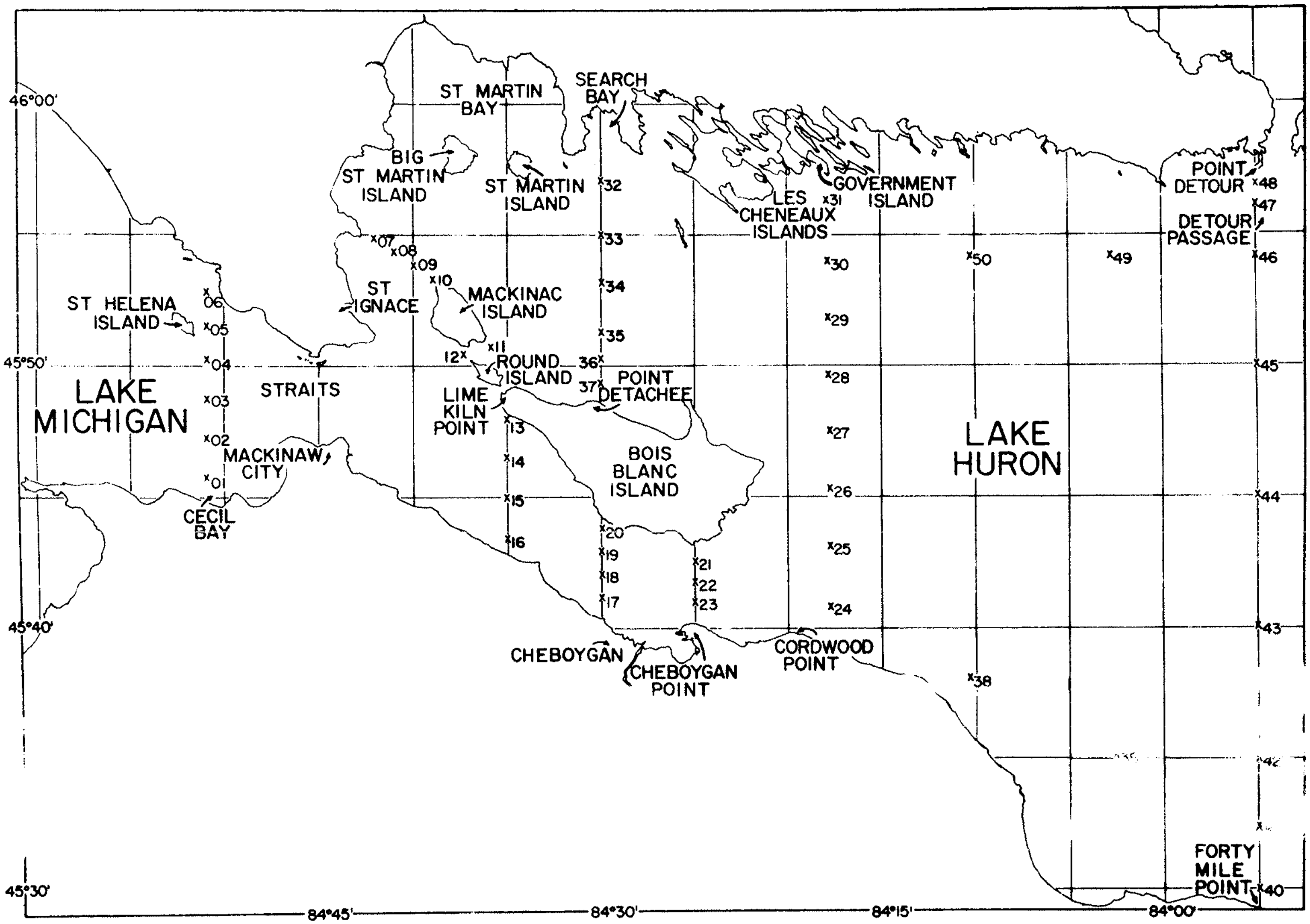

Figure 1.1. MAP OF STATIONS IN THE STRAITS SURVEY AREA.

flows southeastward along the southern shore, and that surface current speeds near Bois Blanc Island were about 4 km/day. From Figure 1.1 it is clear that stations are, in general, spaced within this mixing radius and that this mixing radius is fairly large compared with the size of the survey area.

Despite the extensive mixing, relatively little exchange occurs in the Straits between the epilimnion and hypolimnion. Powers and Ayers (1960) on 6 August 1957 found the flow below the thermocline was westerly at 1640 m^3/sec while the surface flow was easterly at 3200 m^3/sec. Saylor and Sloss (In press) found 100-day average flows (9 August 1973 to 13 November 1973) of 3320 m^3/sec easterly above 20 m and 1400 m^3/sec westerly below 20 m. They also found the greatest difference when the thermocline was most strongly developed. Before the breakdown of the thermocline on about 13 September 1973, current velocities above 20 m (taken to be the location of the thermocline) averaged about 7 cm/sec easterly but below 20 m were about 7 cm/sec westerly. After 13 September, the average flow of the current was easterly at 3.0 cm/sec above 20 m and 1.5 cm/sec below 20 m. Consequently the average currents above and below the thermocline are not only independent, they are opposite in direction during well developed summer stratification. After the breakdown of the thermocline, average currents at all depths would appear to be easterly in the Straits of Mackinac.

Knowledge of subsurface currents outside the immediate vicinity of the Straits is limited. Ayers et al. (1956) conducted cruises in the survey area on 28 June, 27 July and 25 August 1954. On the basis of the dynamic height technique (Ayers 1956), bottom currents in the deep regions to the north and east of Bois Blanc Island were westerly. Ayers et al. (1956) predicted, on the basis of these currents, that upwellings would occur west of Detour Passage along the northern shore. Upwelling was found in this area in two out of our three 1973 cruises. It is reasonable to expect that the westward bottom currents continue along the deep channel north of Mackinac Island and then south to the Straits of Mackinac, where they appear as the westward hypolimnetic currents in the Straits. The absence of upwellings in October 1973 coincided with the absence of thermal stratification and disappearance of the westward hypolimnetic flow in the Straits, suggesting that upwelling may be a regular feature along the northern shore while the Straits are thermally stratified.

Currents of northern Lake Michigan have been studied (e.g. Ayers et al. 1958; FWPCA 1967) but very little information is available for regions near the Straits because they are, for the most part, relatively shallow. Consequently it is not possible to determine from previous studies how far the deep westward currents extend into Lake Michigan.

1.3 DESCRIPTION OF STUDY AREA

The study was restricted to an area that could be sampled from a research vessel in 3 or 4 days. Factors that entered into consideration were logistic, i.e., the distance that could be traversed by the vessel, and scientific personnel which were not adequate for several days of continuous operation. Based on these considerations the study area extended 90 km from west to east and was 50 km north-south from Station 48 to Station 40. It was bounded on the west by stations running north-south between St. Helena Island and Waugoshance Point in Lake Michigan and on the east by stations between Point Detour and Forty Mile Point in Lake Huron (Fig. 1.1).

Locations of stations were based on three premises: 1) that there was a net transport of water from east to west, i.e., that water flows out of Lake Michigan through the Straits of Mackinac into Lake Huron; 2) that water from Lake Superior flows through the St. Marys River into Lake Huron, with part of the water flowing into Lake Huron through Detour Passage near Station 48; 3) that water characteristics at various points in the study area would result from mixtures of varying proportions of waters from Lake Michigan, Lake Superior, and Lake Huron.

Fifty stations were laid out, mostly on north-south transects so water characteristics could be determined for different parts of the study area. Stations 01-06, for example, were placed to evaluate and to assess quality and characteristics of water flowing out of Lake Michigan. In actuality our results showed evidence of mixing of Lake Michigan and Lake Huron surface waters on this transect and the presence of a subsurface flow from Lake Huron waters to Lake Michigan.

Stations 07-10 were located between Mackinac Island and Rabbit Back Peak to sample water flowing through the Straits on the north side of Mackinac Island; Stations 13-23 were located between Bois Blanc Island and the lower peninsula of Michigan to sample water flowing through the Straits on the south side of Bois Blanc Island; and Stations 11 and 12 were located to sample the water flowing through the narrow channel between Mackinac and Bois Blanc Island. Stations were located between Forty Mile Point and the Detour Passage to assess water quality in upper Lake Huron and to measure the influence of water flowing out of Lake Superior through the St. Marys River.

Chemically the waters in the three lakes are quite distinct, and a number of parameters are indicative of water masses from the three lakes (Table 1.1). Lake Huron waters in the study area are largely a mixture of waters from Lake Michigan and Lake Superior with chemical characteristics determined by the proportion of water from the two lakes.

Water temperature and specific conductance were useful in identifying water masses. During the summer, water temperatures in Lake Superior are somewhat colder than those in the surface waters of Lake Michigan. At other times of the year, differences in water temperature may not be as great. Specific conductance on the other hand is always much less in Lake Superior than in Lake Michigan, with expected values for Lake Superior being 100 μmho @ 25°C and for Lake Michigan about 265 μmho @ 25°C (Table 1.1). Values for Lake Huron are intermediate, about 200 μmho @ 25°C in the northern part of the lake.

Table 1.1. CHARACTERISTICS OF EPILIMNETIC WATERS, SUMMER 1970. Averages from Schelske and Roth (1973, p. 65-67).

Lake	pH	Specific conductance µmho @ 25°C	Sulfate (mg/l)	Chloride (mg/l)	Nitrate (mg N/l)	Silica (mg SiO_2/l)
N. Michigan	8.50	261	15.5	7.22	0.129	0.27
N. Huron	8.50	192	10	4.6	0.139	1.07
Superior	8.04	95	1.5	1.1	0.254	2.28

As pointed out recently (Schelske 1975), silica and nitrate nitrogen can be used to characterize water masses in the upper Great Lakes. Contrasted with the conservative ions which are more dilute in Lake Superior, these nutrients are more concentrated in Lake Superior and are diluted when mixed with waters from Lake Michigan (Table 1.1). Concentrations of silica in Lake Superior waters, in addition to being relatively large (> 2.0 mg/l), also vary less seasonally than those in Lake Michigan, which range from less than 0.1 mg/l during late summer to more than 1.0 mg/l during the period when the lake is homothermous (Schelske, In press). Values for nitrate do not differ as much between the two lakes, but in the summer, waters from Lake Superior contain at least twice as much nitrate as those in the outflow from Lake Michigan.

Other chemical parameters, including calcium, sodium, magnesium, potassium and alkalinity, vary greatly among the three lakes. Concentrations of phosphorus also vary with the smallest concentrations in Lake Superior and the largest concentrations in Lake Michigan.

More than 800 samples (Table 1.2) were collected at discrete depths as part of this study; physical-chemical data tabulated in Appendix A were

Table 1.2. SAMPLES COLLECTED ON THREE CRUISES IN 1973. Each sample represents data collected at one depth. C-14 samples include dark samples.

	Cruises		
	1	2	3
Stations not sampled	38 - 50	13, 20, 21, 32-37	None
C-14 samples at 5 m	69	130	156
Total samples	217	272	317

obtained from these samples. Samples for phytoplankton were also taken at the discrete depths, but samples for zooplankton were obtained with vertical net hauls. Specific sampling depths for the discrete samples are listed with the data in Appendix A.

The latitude, longitude and approximate depths for the 50 stations sampled are listed in Table 1.3.

Table 1.3. APPROXIMATE DEPTHS AND LOCATIONS OF STATIONS IN AND NEAR THE STRAITS OF MACKINAC.

Station number	Depth (meters)	Location	
		Latitude	Longitude
ST-01	14	45°45.8	84°51.0
ST-02	20	45°47.3	84°51.0
ST-03	33	45°48.7	84°51.0
ST-04	18	45°50.3	84°51.0
ST-05	14	45°51.5	84°51.0
ST-06	11	45°52.8	84°51.0
ST-07	12	45°54.8	84°42.1
ST-08	31	45°54.3	84°41.0
ST-09	41	45°53.0	84°40.0
ST-10	24	45°53.2	84°38.9
ST-11	24	45°50.8	84°35.8
ST-12	12	45°50.4	84°37.3
ST-13	14	45°47.9	84°35.0
ST-14	24	45°46.5	84°35.0
ST-15	24	45°45.0	84°35.0
ST-16	10.5	45°43.4	84°35.0
ST-17	10	45°41.2	84°30.0
ST-18	13	45°42.1	84°30.0
ST-19	22	45°42.9	84°30.0
ST-20	13	45°43.8	84°30.0
ST-21	15	45°42.6	84°25.0
ST-22	18	45°41.8	84°25.0
ST-23	15	45°41.0	84°25.0

Table 1.3 continued.

Station number	Depth (meters)	Location	
		Latitude	Longitude
ST-24	16.5	45°40.9	84°17.9
ST-25	24	45°43.2	84°17.8
ST-26	33	45°45.4	84°17.8
ST-27	51	45°47.6	84°17.8
ST-28	61	45°49.8	84°17.8
ST-29	69	45°52.0	84°17.8
ST-30	44	45°54.1	84°17.8
ST-31	23	45°56.4	84°17.8
ST-32	19	45°57.1	84°30.0
ST-33	19	45°55.0	84°30.0
ST-34	36	45°53.2	84°30.0
ST-35	45	45°51.3	84°30.0
ST-36	50	45°50.3	84°30.0
ST-37	49	45°49.3	84°30.0
ST-38	19	45°38.0	84°10.3
ST-39	38	45°35.2	84°02.4
ST-40	6	45°30.0	83°55.0
ST-41	46	45°32.2	83°55.0
ST-42	73	45°35.0	83°55.0
ST-43	73	45°40.0	83°55.0
ST-44	110	45°45.0	83°55.0
ST-45	76	45°50.0	83°55.0
ST-46	30	45°54.2	83°55.0
ST-47	22	45°56.2	83°55.0
ST-48	17	45°56.9	83°55.0
ST-49	57	45°54.2	84°02.3
ST-50	39	45°54.2	84°10.3

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SECTION II

CONCLUSIONS

The Straits of Mackinac and adjacent areas studied in this report comprise a complex environmental system. The complexity is attributable in part to three physical factors and their interaction: 1) the oscillatory flow of water between Lake Michigan and Lake Huron resulting from seiches between the two lake basins with equal mean elevations; 2) the net transport of water from Lake Michigan into Lake Huron, since the outflow for Lake Michigan is through the Straits of Mackinac into Lake Huron; 3) the westerly subsurface flow of water from Lake Huron into Lake Michigan, a phenomenon that is probably restricted to the period of summer thermal stratification.

Oscillatory and subsurface water movements confuse the simple straightforward identification of water masses, as they contribute to mixing over a broad geographical area extending from northern Lake Michigan into northern Lake Huron. Our study was too limited in the geographic sense to define the boundaries of the area affected by mixing of water masses.

Water masses characteristic of epilimnetic waters were delineated with four separate techniques:

1) Multivariate statistical techniques showed that water masses could be identified with cluster analysis. Stations with similar values for nine different environmental variables were grouped and identified on maps of the study area (Sec. V).

2) Ordination analyses of plankton assemblages also were used to group different stations. In this case the data were counts of zooplankton and phytoplankton for individual stations. The analyses groups closely related stations and provided data on the plankton community associated with each group of stations (Sec. VI, VII).

3) Temperature-conductivity plots were useful in identifying surface water masses on one of the three cruises. Data from the October cruise could be used in this analysis since three sources of water, one from Lake Michigan, one from Lake Huron and one from Lake Superior, were clearly identifiable on the basis of temperature and conductivity. The fraction of water from each of the three sources was determined and plotted (Sec. IV).

4) Various analyses for single parameters were used for identification of water masses. Average values for silica, specific conductance, pH and to a lesser extent for nitrate nitrogen and water temperature in different areas were related to water masses. These averages plus isopleths of the same parameters plotted on depth profiles for the transects sampled could be used to infer relationships among water masses. Comparison of isopleths on the depth profiles was the only approach that was applied extensively to characterization of subsurface water masses (Sec. III).

From the standpoint of identifying water masses in this type of survey, several physical-chemical parameters could have been applied successfully. Our results showed that specific conductance was very valuable and that silica, pH, alkalinity and nitrate nitrogen, although not conservative parameters in the usual sense, had conservative properties in this study (Sec. III, VI).

Although biological communities (phytoplankton and zooplankton) were readily associated with water masses from the ordination analysis (Sec. VI, VII), rates of carbon fixation and chlorophyll *a* varied little among water masses (Sec. III). The apparent cause for this lack of relationship was that phytoplankton standing crops were so small that differences among groups of stations could not be detected analytically. These small differences in values were also found for rates of carbon fixation and total phosphorus (Sec. III).

Although physicochemical characteristics were only subtly different, the community structure of crustacean zooplankton reflected water quality conditions within the Straits region. Species composition was nearly identical at every station, but principal component analysis based on percent composition data revealed patterns of community structure remarkably similar to water masses identified by cluster analysis (Sec. V). In general, cladocerans were proportionately most prevalent in waters towards Lake Michigan and south of Bois Blanc Island while calanoid copepods were relatively most abundant in waters towards Lake Huron and north of Bois Blanc Island. Cladocerans have been observed as most characteristic of eutrophic waters and calanoid copepods most prevalent in oligotrophic waters elsewhere in the Great Lakes. It is significant that the relative proportion of these two crustacean zooplankton groups to one another was a sensitive indicator of water quality in the Straits region where physicochemical conditions differed so subtly (Sec. VII).

The phytoplankton in the Straits of Mackinac region is floristically dissimilar from the open waters of both Lake Michigan and Lake Huron (Sec. VI). Besides mixing of populations developed in the primary water sources, it appears that conditions in the Straits region are favorable for the development of certain phytoplankton populations not usually found in offshore plankton assemblages in the upper lakes. Examples of this are the relatively large populations of *Chrysosphaerella longispina* and *Chrysococcus dokidophorus* noted in our study. The region is also affected by the injection of normally benthic species into the plankton. These populations are apparently derived from islands and shoal areas and from the St. Marys River. In most instances they constitute a quantitatively minor part of the assemblage.

It is clear that populations of blue-green algae developed in Lake Michigan are being transported to Lake Huron via surface flow through the Straits of Mackinac. On the basis of our results it appears that the populations involved are senescent and there is minimal reproduction in the Straits region and Lake Huron. These populations are characteristic of moderately eutrophied regions in the Great Lakes, especially regions with sufficient phosphorus loading to cause silica limitation during the summer. One of the primary populations involved, *Anacystis incerta*, is capable of forming nuisance blooms but does not constitute a nuisance in quantities noted in the present study. During this study the area most affected by input from Lake Michigan was the region south of Bois Blanc Island and the adjacent waters of open Lake Huron (Sec. VIII).

The net transport of water from Lake Michigan to Lake Huron has the following effects on the nutrient enrichment of northern Lake Huron (Sec. VIII):

1) A relatively rich but diffuse source of phosphorus is supplied. The degree of enrichment in northern Lake Huron is obviously small, although the total input is large due to the large flow of water. The flux of total phosphorus is approximately 10 g P sec^{-1} (1920 m^3 sec^{-1} x 5.0 mg P m^{-3}). Estimates could vary greatly due to several uncertainties, including errors in measurements of total phosphorus and net transport and seasonal variations in either or both of these parameters. A change of 0.1 mg P m^{-3} changes the flux by 4.0%. An error as large as 20% therefore might be associated with the estimate of annual phosphorus transport if the error in mean phosphorus concentrations were 0.5 mg P m^{-3}. Most of the phosphorus is transported in the particulate form, presumably combined in biological materials.

2) Silica-depleted waters are supplied, resulting in reduction of silica concentrations in northern Lake Huron. This relationship is most severe during late summer and fall, and the reduced supply of silica eventually will affect diatom standing crops in northern Lake Huron.

3) Nitrate-depleted waters are transported from Lake Michigan, resulting in decreased concentrations in northern Lake Huron. The effect is greatest in late summer and early fall when the greatest depletion of nitrate occurs in Lake Michigan. This relationship is not considered as important as that for silica and phosphorus since nitrate concentrations are not diluted to levels that would limit phytoplankton growth. It must also be recognized that the levels of organic nitrogen are probably greater in Lake Michigan than in Lake Huron, partly compensating for the nitrate reduction associated with mixing waters from the two lakes.

During the period of thermal stratification there is a subsurface flow of water from Lake Huron to Lake Michigan. This water flows west below the epilimnetic waters of Lake Michigan and is apparently entrained and mixed with the epilimnetic waters of Lake Michigan in an undetermined area west of the Straits of Mackinac.

Mixing of waters from Lake Michigan and Lake Huron increases the silica concentration in the silica-depleted waters of Lake Michigan. Removal or reducing the effect of silica limitation apparently allows some diatom populations to develop in the Straits area at higher population densities than occur either in northern Lake Michigan or northern Lake Huron (Sec. VIII). This relationship also suggests that some other nutrient limitation, possibly for phosphorus, may be removed by the mixing process. The transport of relatively high concentrations of phosphorus from Lake Michigan and the enrichment of mixed waters with silica from Lake Huron produced relatively large diatom crops in the study area even at times when Lake Michigan waters were silica depleted and contained significant populations of blue-green algae. In effect this increased growth of diatoms and demand for silica extends the potential for silica limitation from Lake Michigan into Lake Huron. It will also accelerate the rate of silica depletion in Lake Huron.

Generally it is concluded that there is a subtle effect of water transport from Lake Michigan on the water quality in northern Lake Huron. Some effects are seasonal; for example, silica-depleted and blue-green algae-bearing waters are transported from Lake Michigan in the severest form only during the late summer and fall.

This investigation provides an important and unique data set on the characterization of the area in and near the Straits of Mackinac. Its results are the only combined baseline data on plankton and chemistry for this part of the upper Great Lakes. The study is limited, since the period of observation was restricted to 40 days, from 30 August to 8 October 1973. Additional data obviously are needed to provide a comprehensive analysis of seasonal dynamics.

Future studies should be designed so the effect of short-term changes in physical dynamics could be included in the study. Part of the influence of these effects on the data could be minimized by synoptic coverage of the study area with several ships--the sampling period for each cruise of our study was about 60 hr or about the same period as that for the seiche between Lake Michigan and Lake Huron.

Data collection could be refined with a network of buoys that continuously record data for temperature, specific conductance and currents and with one or more ships to take additional samples. Data collected at different stations in the study area could then be related to the physical dynamics.

A larger study area would be needed than we sampled, as there are three separate questions that could be addressed in future studies:

1) What are the dynamics of transport and mixing between the two lakes?

2) What are the influences of Lake Michigan on northern Lake Huron and the areal extent of these influences?

3) Is the opposite effect, the influence of Lake Huron on northern Lake Michigan, restricted primarily to the period of thermal stratification?

SECTION III

DESCRIPTION OF PHYSICAL-CHEMICAL CONDITIONS AND PHYTOPLANKTON COMMUNITY PARAMETERS

by

Claire L. Schelske, Mila S. Simmons, and Laurie E. Feldt

The purpose of this section is to provide background data and to describe conditions in the Straits of Mackinac on the three cruises in 1973.

3.1 METHODS AND MATERIALS

Prior to each cruise, several types of bottles were prepared for use in sample collection. Labels containing sample numbers and other identification codes were placed on all bottles in which samples would be collected in the field. One or two days prior to the cruise, 5-dram glass amber vials were prepared for chlorophyll samples. The vials were spiked with 8-9 ml of 90% acetone (buffered with 0.1 g/liter of magnesium carbonate), tightly capped and stored upright in the freezer until needed for sample introduction on shipboard.

Bottles for alkalinity samples (2-oz polyethylene) were spiked with 5 ml of 0.01N HCl, tightly capped and stored upright in boxes.

Shipboard Analyses

Water samples were taken with clean 5-liter Nisken bottles, except surface samples which were taken with a clean plastic bucket; sample depths were generally at 5-m intervals from the surface to 20 m, and at 10-m intervals below that. As many as 11 depths were sampled at the deepest stations. Temperature was measured with a bathythermograph and with a mercury thermometer on shipboard.

Water samples were processed as illustrated in the flow chart (Fig. 3.1). Samples for chemical analyses were filtered through HA Millipore filter papers, which were previously rinsed several times and soaked in distilled deionized water. The bottles for chemical analyses were first rinsed once with the filtered water before sample introduction.

Specific conductance and pH were measured on board ship immediately after the water samples were collected. Specific conductance was measured with

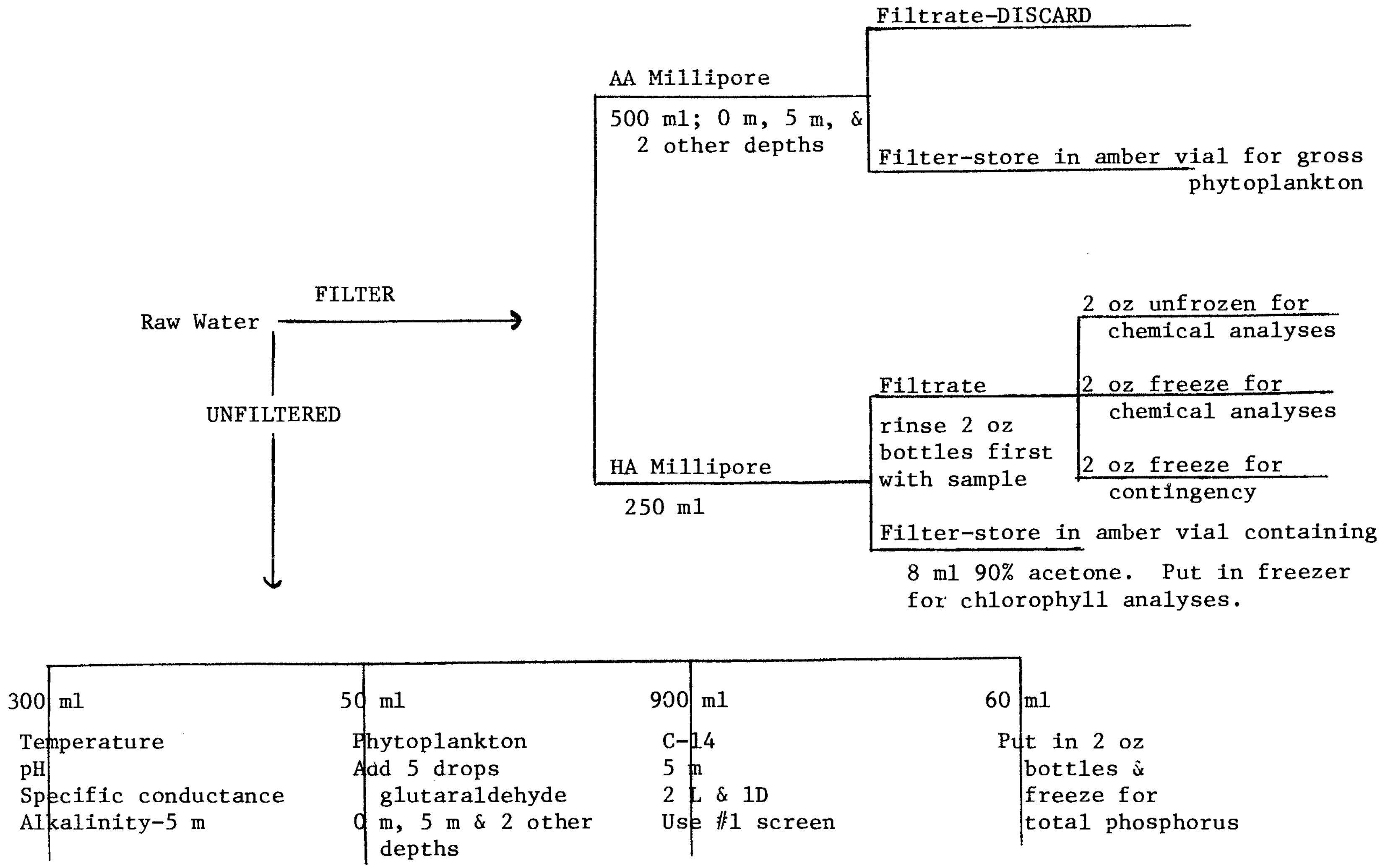

Figure 3.1. FLOW CHART ILLUSTRATING SAMPLE PROCESSING OF DISCRETE DEPTH SAMPLES, STRAITS OF MACKINAC 1973.

a Leeds and Northrop Model 4866-60 conductivity bridge equipped with a temperature compensator. A Corning pH meter Model 111 equipped with a digital readout and an automatic temperature compensator was used to measure pH. The two-buffer calibration technique, usually with pH 7.0 and 10.0 buffer solutions, was employed. The sample temperature was read to 0.1°C with a laboratory mercury thermometer.

The rate of carbon fixation by phytoplankton was measured by a previously described method (Schelske and Callender 1970). Water samples (250 ml) were collected in glass-stoppered Pyrex bottles, injected with 2.0 μCi C-14, incubated for 3-4 hr aboard ship and filtered through 47-mm HA Millipore filters. The filters were mounted with rubber cement on 52-mm diameter aluminum planchets and stored for counting. A Low Beta Beckmann Planchet Counter was used for counting. Efficiency of this counter and the absolute activity of the C-14 was determined with a Nuclear Chicago Liquid Scintillation Counter (Wolfe and Schelske 1967). Alkalinity was determined from pH measurements on 20-ml samples to which 5 ml of 0.010N HCl was added. Alkalinity measurements were performed only on samples from 5 m where C-14 productivity was measured.

Soluble reactive silica and nitrate nitrogen were measured on board ship with a Technicon® AutoAnalyzer. Silica was determined by the Technicon AutoAnalyzer Heteropoly-Blue Method. In the method, silica is complexed with acidified molybdate to form a silicomolybdate complex which is reduced to an intense heteropolyblue. Oxalic acid was added prior to the reduction with ascorbic acid to destroy any phosphomolybdate. The color produced was measured at 630 mμ.

Nitrate was reduced by copper-hydrazine solutions to nitrate at 54°C. The nitrite produced and the nitrite initially present in the sample were then determined by a diazotization-coupling reaction using sulfanilamide and N-1-naphthyl-ethylene diamine. This red-violet colored complex was measured at 520 mμ (Kamphake et al. 1967). Nitrite was not analyzed separately, as quantitatively insignificant values would be expected in non-polluted oxygenated waters.

Samples for chlorophyll (250 ml) were filtered through a 47-mm HA Millipore filter. The filters were extracted overnight at -10°C with 90% acetone buffered with magnesium carbonate. The samples were then centrifuged, and 5 ml was transferred to sample cuvettes and read in a modified Turner Model 111 Fluorometer. The samples were subsequently acidified and read in the fluorometer for phaeopigment determinations (Strickland and Parsons 1968). Readings of extracted chlorophyll with the fluorometer were taken both on board ship and in our laboratories in Ann Arbor. Samples were maintained in the cold and dark until readings were taken.

Laboratory Analyses

Frozen samples were transferred from the ship's freezers to large insulated coolers and brought back to the Ann Arbor laboratory. The trip was normally 6 hr. Samples remained frozen during transit and were immediately stored in laboratory freezers. The containers used for transport were large plywood boxes insulated with 5 cm of styrofoam. Sometimes smaller picnic coolers were used for extra samples, and in this case blocks of dry ice were used to maintain freezing temperatures during transport.

Samples were brought back to the laboratory usually at the end of each cruise, which was normally after a week. Analyses were usually completed within a week to a month's time depending upon the availability of personnel to do the analyses.

Chemical analyses for ammonia, total phosphorus, total soluble phosphorus, chloride and sulfate were performed on thawed samples with the Technicon AutoAnalyzer in the laboratory. Most of the methods employed were Technicon AutoAnalyzer methods or modified ones. All analyses except the one for total phosphorus were performed on samples of filtered water.

Ammonia was oxidized to nitrous acid by hypochlorite which reacts with phenol to give a blue color. The reaction was catalyzed by nitroprusside and buffered by EDTA. The color produced was measured at 630 mμ (H. E. Allen, U.S. Bureau Sport Fish. and Wildlife, Ann Arbor, Mich., unpublished manuscript). A special sampling chamber wherein acid-scrubbed air was constantly purged was used to minimize ammonia contamination from the atmosphere.

Samples for total phosphorus and total soluble phosphorus were concentrated by evaporation and digested with potassium persulfate for 1.5 hr in an oven at 110°C. The samples were then treated with an acidic solution of ammonium molybdate to give phosphomolybdate which was then reduced by ascorbic acid to give a blue color and measured at 630 mμ.

Chloride reacts with mercuric thiocyanate to form mercuric chloride. The released thiocyanate reacts with ferric ammonium sulfate to form a red complex, $Fe(SCN)_3$. The resulting color was measured at 480 mμ.

An automated turbidimetric method was used for the determination of sulfate. The turbidity produced by the reaction of $BaCl_2$ in HCl with sulfate was measured at 420 mμ. An NH_4-OH-EDTA rinse was used to prevent the coating of the $BASO_4$ precipitate on the walls of the manifold system and the flow cells (Santiago et al. 1975).

3.2 EPILIMNETIC AVERAGES AND SEASONAL VARIATION

Data from the averages for eight parameters indicate the range of conditions observed in surface waters during the three cruises (Table 3.1). Averages for different groups of stations represent conditions for different parts of the study area: Stations 01-06 for Lake Michigan, Stations 40-45 for Lake Huron and Stations 46-48 for the St. Marys River.

Table 3.1. AVERAGES OF ENVIRONMENTAL PARAMETERS OF EPILIMNETIC WATERS ON THREE CRUISES IN THE STRAITS OF MACKINAC, 1973. Data are mean ± one standard deviation.

Stations	Cruise 1	Cruise 2	Cruise 3	Stations	Cruise 1	Cruise 2	Cruise 3
	Temperature (C)				Chlorophyll *a* ($mg\ m^{-3}$)		
1-6	21.1 ± 0.44	15.4 ± 0.87	14.4 ± 0.49	1-6	1.51 ± 0.14	1.73 ± 0.70	1.60 ± 0.24
7-10	19.5 ± 1.44	11.4 ± 1.10	12.2 ± 0.29	7-10	1.25 ± 0.17	1.21 ± 0.36	1.45 ± 0.16
13-23	21.3 ± 0.77	14.4 ± 0.46	13.4 ± 0.51	13-23	1.22 ± 0.16	1.67 ± 0.10	1.33 ± 0.28
24-27	21.6 ± 0.70	13.1 ± 1.07	12.4 ± 0.28	24-27	1.12 ± 0.11	1.78 ± 0.12	1.56 ± 0.39
28-31	20.9 ± 0.55	10.1 ± 1.48	12.4 ± 0.68	28-31	1.16 ± 0.23	1.26 ± 0.29	1.71 ± 0.36
32-37	20.3 ± 0.83	N.S.	12.2 ± 0.28	32-37	1.22 ± 0.17	N.S.	1.56 ± 0.29
40-45	N.S.	13.3 ± 2.13	11.2 ± 0.80	40-45	N.S.	1.71 ± 0.17	1.43 ± 0.40
46-48	N.S.	12.7 ± 1.35	13.6 ± 0.78	46-48	N.S.	1.38 ± 0.24	1.26 ± 0.24
	Specific conductance (10^{-4}mho cm^{-1})				Silica (mg SiO_2 l^{-1})		
1-6	2.496 ± 0.056	2.354 ± 0.127	2.462 ± 0.062	1-6	0.510 ± 0.090	0.951 ± 0.162	1.292 ± 0.129
7-10	2.397 ± 0.062	2.270 ± 0.059	2.018 ± 0.063	7-10	0.696 ± 0.104	1.235 ± 0.082	1.416 ± 0.081
13-23	2.445 ± 0.040	2.348 ± 0.115	2.300 ± 0.138	13-23	0.586 ± 0.117	1.007 ± 0.053	1.162 ± 0.213
24-27	2.101 ± 0.102	2.280 ± 0.100	1.940 ± 0.085	24-27	0.689 ± 0.082	1.047 ± 0.032	1.144 ± 0.071
28-31	2.208 ± 0.086	2.025 ± 0.182	1.768 ± 0.075	28-31	0.679 ± 0.117	1.299 ± 0.172	1.318 ± 0.133
32-37	2.272 ± 0.064	N.S.	1.934 ± 0.131	32-37	0.635 ± 0.120	N.S.	1.504 ± 0.128
40-45	N.S.	2.064 ± 0.136	2.045 ± 0.098	40-45	N.S.	0.946 ± 0.160	1.150 ± 0.111
46-48	N.S.	1.500 ± 0.194	1.498 ± 0.226	46-48	N.S.	1.754 ± 0.140	1.674 ± 0.269

Table 3.1 continued.

Stations	Cruise 1	Cruise 2	Cruise 3
		pH	
1-6	8.658 ± 0.050	8.514 ± 0.063	8.416 ± 0.065
7-10	8.635 ± 0.050	8.372 ± 0.098	8.226 ± 0.063
13-23	8.657 ± 0.021	8.498 ± 0.048	8.401 ± 0.060
24-27	8.662 ± 0.017	8.512 ± 0.048	8.284 ± 0.058
28-31	8.627 ± 0.025	8.315 ± 0.099	8.236 ± 0.047
32-37	8.653 ± 0.016	N.S.	8.240 ± 0.065
40-45	N.S.	8.441 ± 0.093	8.335 ± 0.055
46-48	N.S.	8.123 ± 0.038	8.140 ± 0.060
	Secchi transparency (m)		
1-6	5.02 ± 0.32	3.86 ± 0.79	6.82 ± 0.76
7-10	6.03 ± 0.15	4.88 ± 0.48	7.20 ± 0.85
13-23	5.62 ± 0.43	4.63 ± 0.25	6.55 ± 0.72
24-27	8.08 ± 0.43	5.67 ± 0.76	7.32 ± 0.54
28-31	8.00 ± 0.66	6.67 ± 1.76	7.10 ± 0.84
32-37	6.70 ± 0.47	N.S.	8.33 ± 0.93
40-45	N.S.	6.73 ± 1.47	9.42 ± 2.08
46-48	N.S.	3.83 ± 1.44	4.77 ± 1.97

Stations	Cruise 1	Cruise 2	Cruise 3
		Nitrate (µgN l^{-1})	
1-6	143 ± 16	212 ± 69	177 ± 19
7-10	159 ± 16	276 ± 19	308 ± 9
13-23	187 ± 37	241 ± 51	246 ± 18
24-27	222 ± 33	241 ± 41	310 ± 16
28-31	198 ± 15	341 ± 33	322 ± 11
32-37	180 ± 12	N.S.	299 ± 31
40-45	N.S.	246 ± 41	285 ± 16
46-48	N.S.	293 ± 19	323 ± 5
		Total phosphorus (µgP l^{-1})	
1-6	4.63 ± 0.93	4.76 ± 0.90	5.10 ± 0.53
7-10	3.35 ± 1.20	3.26 ± 2.12	5.17 ± 1.78
13-23	3.16 ± 0.98	3.96 ± 1.27	4.02 ± 1.80
24-27	1.45 ± 0.47	3.32 ± 0.83	4.49 ± 1.14
28-31	3.02 ± 1.06	4.08 ± 1.20	3.93 ± 1.02
32-37	2.88 ± 0.73	N.S.	4.50 ± 1.67
40-45	N.S.	3.21 ± 1.66	3.66 ± 1.12
46-48	N.S.	4.20 ± 0.72	3.66 ± 1.42

Water Temperature

Surface water temperatures, as would be expected, generally decreased during the three cruises. On the August cruise, surface temperatures were generally greater than 20°C, but the easternmost transect, where lower temperatures from water flowing out of the St. Marys River might have been observed, was not sampled. Most of the surface water cooling occurred between Cruises 1 and 2; a much smaller amount of cooling and in fact an increase in temperatures occurred at some stations between Cruises 2 and 3 (Table 3.1).

Temperature relationships among the groups of stations on the three cruises were strongly influenced by two factors on the September cruise. As pointed out below, the depth of the mixed layer increased between Cruises 1 and 2, and upwelled water in September tended to decrease average surface temperatures. The presence of upwelled water was evident from average temperatures for Stations 28-31 and 07-10. At these two groups of stations epilimnetic temperatures were lowest on Cruise 2.

By Cruise 3, average temperatures for Stations 46-48 were greater than the adjacent waters, reflecting the large amount of thermal inertia in Lake Superior or indicating a relatively constant temperature in the outflow from Lake Superior between the two cruises (App. C-18, C-19).

Specific Conductance

From a conservative parameter such as specific conductance, inferences can be made about relationships and origins of water masses. It was obvious, for example, that on all three cruises water sampled at Stations 01-06 in Lake Michigan was diluted with Lake Huron water, as the specific conductance (Table 3.1) was lower than the expected range of 260-270 μmho cm^{-1} (Table 1.1) in northern Lake Michigan. The influence of water flowing out of Detour Passage from Lake Superior via the St. Marys River was evident also in the average specific conductance for Stations 46-48. Although averages were much lower for Stations 46-48 than for other stations, they were considerably greater than the average of 95 μmho cm^{-1} for Lake Superior or the minimum value of about 120 measured on Cruise 3. Averages larger than Lake Superior values were due to dilution with Lake Huron water, with an average specific conductance of 205 μmho cm^{-1} at Stations 40-45 for Cruises 2 and 3 (Table 3.1).

It was evident from these data that on each cruise water found at Stations 01-06 had a specific conductance most closely related to water found at Stations 13-23. Values at these two groups of stations also were the largest of any sampled, indicating the largest proportion of Lake Michigan water in the study area.

Dilution and mixing of surface water masses originating from Lake Superior, Lake Huron and Lake Michigan are evident from the data on average specific conductance and are considered in greater detail in Section 4.0.

Hydrogen Ion Concentration

Obvious features of the pH data were largest values in Lake Michigan with smallest values in the area near Detour Passage and a general decrease in values seasonally (Table 3.1). Larger values were found in Lake Michigan due to a greater buffering capacity than present in either Lake Huron or Lake Superior; in addition, waters of Lake Michigan are buffered above the equilibrium pH of about 8.4 (Schelske and Callender 1970), leading to the precipitation of marl or "milky water" (Ladewski and Stoermer 1973). Photosynthetic activity and increasing water temperature during the summer cause the pH to be greater than the equilibrium values. The decrease in pH during the sampling period was due to mixing surface waters with colder subsurface waters of lower pH and to the decrease in water temperature which increases the solubility of carbon dioxide and reduces pH (Schelske and Callender 1970).

Secchi Transparency

There was no seasonal trend in Secchi disc transparency; lowest readings were found on the second cruise.

Transparency was least in two areas, one in Lake Michigan waters represented by Stations 01-06 and 13-23 and the other in St. Marys River water represented by Stations 46-48 (Table 3.1). The smaller transparencies in these areas were not entirely a reflection of relatively large standing crops of phytoplankton, as the lowest chlorophyll concentrations were found at Stations 46-48. Inorganic turbidity must have contributed to reduced transparency at Stations 46-48 and also, possibly, at Stations 01-06 and 13-23. Ladewski and Stoermer (1973) found that minimum Secchi disc transparency in September was caused by milky water. Greatest transparencies were found in the areas most remote from Lake Michigan and Detour Passage and were at Stations 24-31 on Cruise 1, Stations 28-31 and 40-45 on Cruise 2, and Stations 40-45 on Cruise 3.

Chlorophyll a

Concentrations of chlorophyll *a* varied little among the data for the survey. Averages for groups of stations ranged only from 1.1-1.8 during the study (Table 3.1). For most stations, the largest average was found on Cruise 2 when the water transparency was lowest. With the small difference between the averages, additional discussion of chlorophyll averages is not warranted other than to point out that many of the standard deviations were less than 10% of the mean values. Variance in chlorophyll data is frequently much larger.

Soluble Reactive Silica

Silica changed seasonally, with concentrations increasing from the first to the last cruise. Water at Stations 01-06 and 13-23, with the greatest proportion of Lake Michigan water, contained the smallest concentrations of silica; largest concentrations were at Stations 46-48 due to the input of St. Marys River water (Table 3.1).

Concentrations of silica in Lake Michigan water (Stations 01-06) on Cruise 1 averaged greater than 0.5 mg/liter, a value greater than expected for Lake Michigan water in August or September. In late August, concentrations of silica in surface waters of Lake Michigan would be less than 0.2 mg/liter and possibly less than 0.1 mg/liter. Concentrations of silica on Cruises 2 and 3 also were greater than expected for Lake Michigan surface waters. Silica concentrations higher than expected resulted from the mixing of water relatively enriched with silica from Lake Huron with water from Lake Michigan in the Straits area. The source of water for the increased concentrations was not Lake Michigan, as surface water concentrations remain below 1.4 mg/liter until December or January (Rousar 1973). The source of silica-rich water was the westerly subsurface flow from Lake Huron.

Nitrate Nitrogen

On each cruise, the smallest average nitrate nitrogen concentration was found at Stations 01-06 in Lake Michigan; the largest concentrations were found at Stations 46-48 near Detour Passage and at Stations 28-31 (Table 3.1). These relationships are due to the input of water with relatively low nitrate concentration from Lake Michigan and water with relatively high nitrate concentration from Lake Superior (Table 1.1). At Stations 28-31 the large average in September was due to upwelled water (App. C-14) with high nitrate concentrations. The data also show that Lake Huron waters contained relatively large concentrations of nitrate in comparison to Lake Michigan waters.

Nitrates generally increased during the three cruises, but the trend was not as definite as found for silica. The large average for nitrate on Cruise 2 at Stations 01-06 was probably due to a smaller proportion of Lake Michigan water than on Cruises 1 and 3; on Cruise 2, the average specific conductance was the lowest of the three cruises, indicating greater intrusion of waters from Lake Huron, Lake Superior, or both sources (Table 3.1).

Total Phosphorus

There were no obvious seasonal trends in total phosphorus and, with the exception of Stations 24-27, there was very little difference in the average concentrations. With the exception of the one value of 1.5 μg P/liter, averages ranged from 2.9 to 5.2 μg P/liter. For the three cruises, the largest averages were for Stations 01-06, ranging from 4.6 to 5.1 μg P/liter (Table 3.1). There is some indication that the lowest values for each group of stations occurred on Cruise 1; however, if there were smaller concentrations during the first cruise, the differences appeared to be too small to be detected statistically due to the relatively large variances.

Because phosphorus limits algal growth in the upper Great Lakes, small concentrations should be associated with small standing crops of phytoplankton. The smallest average for total phosphorus, 1.5 μg P/liter was found for Stations 24-27 on Cruise 1. At these stations, chlorophyll concentrations were also minimal and Secchi disc transparency was relatively large, indicating that phytoplankton standing crops were smaller than at surrounding stations (Table 3.1). Generally, however, there were no obvious relationships between averages for total phosphorus and algal standing crops. One probably should not expect to see definite relationships between means of total phosphorus and chlorophyll since the range of these variables was small during the study. For the complete data set the expected relationship was obtained, i.e. that small standing crops of chlorophyll would be associated with small concentrations of phosphorus.

3.3 PHYSICAL-CHEMICAL CONDITIONS IN AUGUST

The description here and in 3.4 and 3.5 for the September and October cruises is based on data presented in Appendix A and Appendix C. Raw data are tabulated in Appendix A, while isopleths of water temperature, pH, specific conductance and silica are plotted in Appendix C for depth profiles of each transect sampled. Specific references will not be made to these appendices each time data are presented, but will be added when data in appendices may be of particular interest to the reader.

Water Temperature

On the August cruise, surface water temperatures were fairly uniform over the study area (Table 3.1). Temperature on the Lake Michigan transect (Stations 01-06) varied from 21.0° to 21.8°C. South of Bois Blanc Island temperatures ranged from 21.0° to 22.0°C. On the transect to the east of Bois Blanc Island (Stations 24-31), surface temperatures ranged from 20°C at the northern end of the transect to 22°C at the southern end. At Station 07 near Rabbit's Back Peak, water was relatively cold; the temperature was 17°C at the surface and the isotherms indicate that upwelling may have occurred in this vicinity (App. C.4). Water in the harbor at St. Ignace at this time was very cold, as attested by members of the ship's scientific crew who attempted to swim after the day's work was completed on 31 August.

Thermal stratification was pronounced on all transects sampled except the three south of Bois Blanc Island, and even on these transects stratification was present although not as strong as found at other sampling sites. The minimum isotherm south of Bois Blanc Island was 12°C, which was one degree warmer than the minimum isotherm for the Lake Michigan transect (Stations 01-06). At these stations the epilimnion extended to a depth of about 15 m. North and east of Bois Blanc Island the thermocline was much shallower with the epilimnion extending only to about 10 m. At Stations 31 and 32, the distribution of isotherms near the surface indicates intrusion of relatively cold water along the north shore (App. C.13 and C.16). The origin of this cold water may be related to the upwelling noted for Station 07.

Specific Conductance

Epilimnetic waters on the Lake Michigan transect (Stations 01-06) had values for specific conductance >250 µmhos. South of Bois Blanc Island specific conductance in the epilimnion was >240 µmhos. On these same transects, subsurface values for specific conductance were lower, decreasing to 220 µmhos near the bottom (App. C.1, C.7, C.10). These low values indicate intrusion of Lake Huron water below the thermocline (Lake Michigan water would have a specific conductance of at least 260 µmhos).

On the transect north of Bois Blanc Island (Stations 32-37) (App. C.16) and on the transect east of Bois Blanc Island (Stations 24-31), values for specific conductance were comparable to the minimum values found south of the island or about 220 µmhos (App. C.13). On both of these transects, however, there is a minimum for specific conductance at 15-20 m that is most obvious between Stations 26-30 and Stations 34-37. These relatively low values are indicative of a separate water mass.

Hydrogen Ion Concentration

Values of pH in the epilimnetic water at Stations 01-06 and for the three transects (Stations 13-23) on the south side of Bois Blanc Island were greater than 8.6 (Table 3.1). Maximum values were 8.70 at Stations 01, 05 and 06. At the other stations sampled on this cruise, surface values were also above 8.6 except Stations 07 and 31 where the values were 8.58 and 8.57 respectively.

In the relatively deep waters on transects 32-37 and 24-31, values for pH were less than 7.8. On the Lake Michigan transect, Stations 01-06, the minimum isopleth was 8.2 at 25 m--pH values of 8.2 were also found at 20 m on the next transect to the east, Stations 13-16.

Silica

Surface values for silica were generally lowest on the Lake Michigan transect, Stations 01-06, and on the three transects south of Bois Blanc Island, Stations 13-23, with the range of values being about 0.1 mg/liter or from less than 0.5 to less than 0.6 mg/liter. The lowest value observed at all the stations was 0.36 mg/liter at Station 32, representing a pocket of low silica water that probably originated in Search Bay or some other nearshore area (App. C.16).

Highest values for silica in surface waters, values greater than 0.7 mg/liter, were found at Stations 07, 33, and 31 along the north shore of the Straits and at Stations 25 and 26 east of Bois Blanc Island. These high values undoubtedly represent the presence of water masses with a greater percent composition of Lake Huron or Lake Superior water than the other stations.

Vertical stratification of silica was very pronounced at all stations, although to a lesser degree at the stations with the highest silica values. Values for bottom samples ranged from 1.4 mg/liter at 25 m on the Lake Michigan transect (App. C.1) to 1.8 mg/liter on the transects with deeper water, i.e., the transect north of Mackinac Island (App. C.4) and the two transects north and east of Bois Blanc Island (App. C.13, C.16). On the transect north of Mackinac Island, 1.8 mg/liter was found at depths >30 m while on the other transects this much silica was not present at all stations and if present was restricted to water below 30 m.

3.4 PHYSICAL-CHEMICAL CONDITIONS IN SEPTEMBER

On the September cruise the distribution of environmental parameters was more varied than on the preceding cruise due to the effects of weather and the fact that an additional transect, Stations 40-48, was sampled. Strong winds from the south made it impossible to sample Stations 13, 20, and 21 located on the windward shore, and had a profound effect on the water masses--including producing upwelling between Stations 29 and 30.

Water Temperature

Surface water temperatures varied from a maximum of 16°C in Cecil Bay at Station 01 to less than 9°C at Station 30 in an upwelling area. Temperatures west of the Straits (Stations 01-06) and south of Bois Blanc Island (Stations 13-23) were warmer than in other areas, and greater than 14°C at all stations. North of Mackinac Island and on transects east of Bois Blanc Island, surface temperatures were less than 13°C except along the south shore where they exceeded 16°C at some stations.

Thermal stratification was weak or nonexistent at stations west of the Straits and those south of Bois Blanc Island. Epilimnetic depths on these transects were 15-20 m--there was evidence of stratification at Station 19 due to the presence of 10°C at a depth of 20 m.

Two temperature distributions on this cruise were not observed on the previous cruise. One was the presence of upwelled water in the vicinity of Station 29; the other was the presence of relatively warm water flowing out of Detour Passage, that was sampled at Stations 46-48. These two water masses are easily identifiable also by chemical parameters, particularly specific conductance and silica (App. C.13, C.18).

Specific Conductance

Patterns of specific conductance were not related to distribution of temperature on the Lake Michigan transect, Stations 01-06, and on transects south of Bois Blanc Island, Stations 13-23. Water with high specific conductance was found along the south shore at Stations 01 (App. C.2) and 23 (App. C.11) where water temperatures were greatest. Highest specific conductance water was found at Stations 22 and 23, indicating a greater proportion of Lake Michigan water than found at other stations; relatively high specific conductance water was present as far east and south as Stations 40, 41 and 42 (App. C.18), indicating flow of Lake Michigan water to this area. One or two lenses of low specific conductance water were also found near the surface on transect 1-6. These results indicate a considerable amount of mixing in an area extending from Lake Michigan south of Bois Blanc Island to Stations 40-42 in Lake Huron.

Water flowing out of Detour Passage was identifiable by low specific conductance, less than 130 μmhos at Station 48, and by relatively warm temperature (App. C.18).

On transect 24-31, upwelled water had specific conductance values of less than 2.1 in the vicinity of Station 30. There was also a lens of low specific conductance water near Government Island at Station 31--this lens was associated with relatively low water temperature but was not correlated with either silica or pH (App. C.14).

Hydrogen Ion Concentration

Largest values for pH were found on transect 1-6, at transects 13-23 south of Bois Blanc Island and at the south end of the two transects east of Bois Blanc Island. These values ranged from >8.4 to >8.6, values which would be typical of Lake Michigan water. Highest values were found at Station 01 at the surface and between 10 and 15 m at Stations 18 and 19. Since Station 20 was not sampled, it is difficult to ascertain the distribution of water masses on transect 17-20.

Minimum values for pH ranged from 8.0-8.1 and were found in deep waters on the two transects east of Bois Blanc Island, north of Mackinac Island and in the water flowing out of Detour Passage.

Silica

High silica concentrations were found at Station 04 in Lake Michigan. Since these high values were associated with values for specific conductance of 220 μmho they presumably can be attributed to the intrusion of

Lake Huron water (App. C.2). South of Bois Blanc Island, the isopleths for silica appear to run in the vertical plane rather than horizontal; interesting is the fact that on two transects the largest values are on the south shore and on the other transect they are on the north shore (App. C.8, C.11). The presence of isopleths in this area that extend from the surface to the bottom, separating the water into horizontal components, is suggested also by the data for water temperature, specific conductance and pH. The relationships suggest mixing of Lake Huron and Lake Michigan waters. It is very obvious on transect 24-31 (App. C.14) that discrete water masses are present in the horizontal plane--partly due to the surface water mass along the south shore and partly to the upwelled water in the vicinity of Station 30.

Epilimnetic water with a silica concentration of 1.8 mg/liter can be attributed to the influence of water flowing out of Detour Passage. As would be expected, high silica water is present in the deeper waters of the two transects east of Bois Blanc Island (App. C.14, C.18). These values range from 1.8 to 2.2 mg/liter--concentrations characteristic of Lake Superior water; however, due to the conductivities greater than 200 μmho associated with this water, the origin of high silica is not attributable directly to the presence of Lake Superior water. The specific conductance indicates that a considerable portion of this water originated in Lake Huron.

3.5 PHYSICAL-CHEMICAL CONDITIONS IN OCTOBER

Water Temperature

In October there was no thermal stratification on the Lake Michigan transect nor on those south of Bois Blanc Island (App. C.3, C.9, C.12). Temperature on these transects ranged from 12° to 14°C. On transects north and west of Bois Blanc Island, the epilimnion was 25-30 m deep, (App. C.15, C.19) but on the transect northwest from Mackinac Island (App. C.6) there was no thermal stratification to a depth of 35 or 40 m. Warmest temperatures were found on the transect in Lake Michigan and in the water flowing out of Detour Passage (Stations 46-48).

Specific Conductance

On the Lake Michigan transect, the relatively homothermous waters were reflected by small variations in specific conductance with values ranging from <240 μmho to <250 μmhos (App. C.3). On two transects south of Bois Blanc Island (App. C.12) there was an intrusion of lower conductivity water along the south shore of Bois Blanc Island with values ranging from 200-220 μmhos. This low conductivity water, based on conductivities on transect 24-31, apparently represented an intrusion of Lake Huron water (App. C.15). Relatively high conductivity water extended along the south shore of the study area from Station 01 to Station 40.

Water from Detour Passage was easily identified by low specific conductance values, ranging as low as 120 μmho at Station 48 (App. C.19).

Hydrogen Ion Concentration

Values for pH were relatively uniform on the Lake Michigan transect and on those south of Bois Blanc Island. Like specific conductance, larger values were present along the south shore of the study area, but unlike specific conductance, there was less variation from east to west with the range of values being approximately 0.2 pH units or from >8.3 to >8.5. East and north of Bois Blanc Island, surface pH values ranged from 8.10 to <8.3 with water from the Detour Passage having a pH of about 8.1. Subsurface values for pH ranged as low as 7.8 at Station 37 north of Bois Blanc Island, but in general most values were not lower than 8.0.

Silica

On the Lake Michigan transect, Stations 01-06, there was evidence of vertical as well as horizontal distributions of silica (App. C.3). Vertical stratification was present at the three stations on the south end of the transect, but to the north of Station 03 the gradients were horizontal, increasing northward from 1.2 to >1.4 mg/liter. The same range of values was present at Stations 01-03, but with values increasing with depth from the surface to the bottom.

South of Bois Blanc Island the distribution of silica was relatively complex, with different patterns of distribution on each of the three transects sampled. Smallest values were found on transect 13-16, values that were less than or equal to those found on the Lake Michigan transect (App. C.9). On the next transect to the east, 17-20, the values were all equal to or greater than the largest values for transect 13-16. In addition, on transect 17-20 the smallest values were found in the middle of the transect, which was due partly to two large values for silica found at Station 17 (App. C.12). One of the values at Station 17 exceeded 2.0 mg/liter (surface), but this value appeared real since the 5-m value was 1.7 mg/liter. The pattern of low values at mid-transect was repeated on transect 21-23, and on both transects 17-20 and 21-23 isopleths indicated horizontal gradients of silica. Horizontal gradients of silica concentration were also found on the transect north of Mackinac Island (App. C.6), along the north end on transect 32-37 (App. C.17) and possibly on the north end on transect 24-31 (App. C.15). These relationships indicate a homogeneous mass of water along the north shore which may be a mixture of water from Detour Passage (App. C.19) and Lake Huron. If this is the case, as suggested by the distribution of specific conductance, then it may have been produced by westerly currents along the north shore.

Water flowing out of Detour Passage had a silica concentration of 2.2 mg/liter, comparable to what would be expected from a source in Lake Superior

(Table 1.1). Below 30 m on the three transects with deep water north and east of Bois Blanc Island, vertical stratification of silica was also present.

On this cruise, surface values for silica were generally higher along the north shore of the study area and lowest on the south shore. The one obvious exception is Station 17 along the south shore, which had one of the highest values for silica, the origin of which is not known.

3.6 CORRELATION OF PHYSICAL, CHEMICAL AND PHYTOPLANKTON COMMUNITY PARAMETERS

As a preliminary step to data analysis, 14 correlation matrices were run, one for each of the following tables:

Table 3.2	All cruises, all depths, with missing data
3.3	All cruises, 5-m depths, without missing data
3.4	August, all stations, all depths
3.5	September, all stations, all depths
3.6	October, all stations, all depths
	All cruises, all depths:
3.7	Stations 01-06
3.8	07-10
3.9	11-12
3.10	13-23
3.11	24-31
3.12	32-37
3.13	38, 39, 49, 50
3.14	40-45
3.15	46-48

The data were therefore analyzed as a total group, as groups for each cruise, and as groups similar to those listed in Table 3.1.

Although significant correlations do not connote causal or functional relationships between two factors, they do indicate associated variables and how one parameter varies in relation to another parameter. Several associations were found by examining the correlation matrices.

Relationships Among Temperature, pH, Nitrate and Silica

Highly significant correlation coefficients were found for the six possible correlation coefficients for temperature, pH, nitrate and silica (Table 3.2). These results show that high silica and nitrate concentrations and low pH values are associated with cold water with the converse being true for warm water, or that temperature was correlated negatively with silica and nitrate and positively with pH. Highly significant

Table 3.2. CORRELATION OF DATA FOR ALL CRUISES, ALL DEPTHS. N = 768, R @ .99 = .10.

	Secchi	Temp	pH	C14-ls	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.33	1.00						
pH	-0.32	0.86	1.00					
C14-ls	-0.36	0.11	0.16	1.00				
Chl	-0.24	0.41	0.48	0.24	1.00			
SiO_2	0.23	-0.79	-0.84	-0.16	-0.36	1.00		
NO_3	0.33	-0.78	-0.78	-0.38	-0.36	0.75	1.00	
P Tot	-0.09	0.14	0.10	0.16	0.23	-0.04	-0.11	1.00

Table 3.3. CORRELATION OF DATA FOR ALL CRUISES, 5-M DEPTHS WITH NO MISSING VALUES. N = 98, R @ .99 = .26.

	Secchi	Temp	pH	C14-ls	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.22	1.00						
pH	-0.17	0.78	1.00					
C14-ls	-0.37	0.13	0.16	1.00				
Chl	-0.06	-0.25	-0.21	0.26	1.00			
SiO_2	-0.02	-0.68	-0.80	-0.15	0.29	1.00		
NO_3	0.21	-0.68	-0.73	-0.42	0.08	0.62	1.00	
P Tot	-0.16	-0.02	-0.13	0.20	0.11	0.20	-0.10	1.00

Table 3.4. CORRELATION OF DATA FOR AUGUST--ALL STATIONS, ALL DEPTHS. N = 199, R @ .99 = .19.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.42	1.00						
pH	-0.42	0.95	1.00					
C14-1s	-0.34	0.19	0.08	1.00				
Chl	-0.35	0.34	0.44	0.04	1.00			
SiO_2	0.47	-0.95	-0.96	-0.20	-0.40	1.00		
NO_3	0.49	-0.87	-0.86	-0.25	-0.34	0.87	1.00	
P Tot	-0.61	0.28	0.28	-0.03	0.31	-0.29	-0.25	1.00

Table 3.5. CORRELATION OF DATA FOR SEPTEMBER--ALL STATIONS, ALL DEPTHS. N = 259, R @ .99 = .16.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.58	1.00						
pH	-0.39	0.82	1.00					
C14-1s	-0.43	0.31	0.21	1.00				
Chl	-0.32	0.66	0.65	0.19	1.00			
SiO_2	0.23	-0.70	-0.76	-0.40	-0.61	1.00		
NO_3	0.40	-0.73	-0.62	-0.40	-0.50	0.74	1.00	
P Tot	-0.09	0.21	0.07	0.12	0.15	-0.11	-0.16	1.00

Table 3.6. CORRELATION OF DATA FOR OCTOBER--ALL STATIONS, ALL DEPTHS. N = 313, R @ .99 = .15.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.49	1.00						
pH	-0.16	0.72	1.00					
C14-1s	-0.12	0.39	0.14	1.00				
Chl	-0.17	0.68	0.59	0.38	1.00			
SiO_2	0.01	-0.34	-0.60	0.05	-0.33	1.00		
NO_3	0.23	-0.62	-0.75	-0.54	-0.40	0.39	1.00	
P Tot	-0.01	0.26	0.17	0.36	0.27	0.01	-0.16	1.00

Table 3.7. CORRELATION OF DATA FOR STATIONS 01-06, ALL CRUISES, ALL DEPTHS. N = 77, R @ .99 = .30.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.23	1.00						
pH	-0.36	0.87	1.00					
C14-1s	-0.15	-0.12	-0.65	1.00				
Chl	-0.33	-0.05	-0.10	0.76	1.00			
SiO_2	0.50	-0.89	-0.90	0.31	0.55	1.00		
NO_3	-0.15	-0.55	-0.50	-0.23	-0.02	0.44	1.00	
P Tot	0.15	-0.03	-0.08	0.38	0.29	0.14	-0.05	1.00

Table 3.8. CORRELATION OF DATA FOR STATIONS 07-10, ALL CRUISES, ALL DEPTHS. N = 66, R @ .99 = .32.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	0.38	1.00						
pH	-0.04	0.85	1.00					
C14-1s	-0.36	-0.14	0.02	1.00				
Chl	0.49	0.41	0.29	-0.18	1.00			
SiO_2	-0.07	-0.91	-0.95	-0.14	-0.27	1.00		
NO_3	0.02	-0.90	-0.95	-0.08	-0.23	0.97	1.00	
P Tot	0.59	0.12	-0.08	-0.37	0.25	-0.05	0.09	1.00

Table. 3.9. CORRELATION OF DATA FOR STATIONS 11-12, ALL CRUISES, ALL DEPTHS. N = 27, R @ .99 = .49.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	0.03	1.00						
pH	-0.41	0.86	1.00					
C14-1s	-0.55	0.09	0.46	1.00				
Chl	-0.18	-0.29	-0.06	0.17	1.00			
SiO_2	0.38	-0.84	-0.93	-0.41	0.22	1.00		
NO_3	0.15	-0.95	-0.91	-0.29	0.12	0.87	1.00	
P Tot	-0.12	-0.18	-0.12	-0.20	0.09	0.20	0.84	1.00

Table 3.10. CORRELATION OF DATA FOR STATIONS 13-23, ALL CRUISES, ALL DEPTHS. N = 110, R @ .99 = .25.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.17	1.00						
pH	-0.35	0.90	1.00					
C14-1s	-0.73	0.15	0.32	1.00				
Chl	-0.43	-0.37	-0.23	0.32	1.00			
SiO_2	0.23	-0.82	-0.73	-0.21	0.23	1.00		
NO_3	0.10	-0.54	-0.59	-0.31	0.11	0.39	1.00	
P Tot	0.10	0.03	-0.05	-0.02	-0.12	0.01	0.13	1.00

Table 3.11. CORRELATION OF DATA FOR STATIONS 24-31, ALL CRUISES, ALL DEPTHS. N = 207, R @ .99 = .18.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	0.10	1.00						
pH	-0.10	0.85	1.00					
C14-1s	-0.50	0.26	0.60	1.00				
Chl	-0.17	0.36	0.46	0.13	1.00			
SiO_2	-0.02	-0.88	-0.87	-0.47	-0.39	1.00		
NO_3	-0.03	-0.84	-0.74	-0.53	-0.31	0.85	1.00	
P Tot	-0.17	-0.15	-0.05	-0.38	0.20	0.13	0.20	1.00

Table 3.12. CORRELATION OF DATA FOR STATIONS 32-37, ALL CRUISES, ALL DEPTHS. N = 90, R @ .99 = .27.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.19	1.00						
pH	-0.34	0.90	1.00					
C14-1s	0.38	-0.79	-0.77	1.00				
Chl	0.07	0.41	0.50	0.66	1.00			
SiO_2	0.39	-0.86	-0.92	0.82	-0.33	1.00		
NO_3	0.40	-0.88	-0.84	0.68	-0.25	0.82	1.00	
P Tot	0.57	-0.05	-0.12	0.14	0.24	0.22	0.32	1.00

Table 3.13. CORRELATION OF DATA FOR STATIONS 38, 39, 49, 50, ALL CRUISES, ALL DEPTHS. N = 57, R @ .99 = .34.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.39	1.00						
pH	-0.46	0.66	1.00					
C14-1s	-0.67	0.78	0.63	1.00				
Chl	-0.15	0.74	0.53	0.23	1.00			
SiO_2	0.28	-0.68	-0.69	-0.38	-0.58	1.00		
NO_3	0.25	-0.44	-0.57	-0.49	-0.53	0.75	1.00	
P Tot	-0.02	-0.16	-0.003	0.20	0.05	-0.03	-0.29	1.00

Table 3.14. CORRELATION OF DATA FOR STATIONS 40-45, ALL CRUISES, ALL DEPTHS. N = 104, R @ .99 = .25.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.20	1.00						
pH	-0.14	0.83	1.00					
C14-1s	0.08	-0.24	-0.20	1.00				
Chl	-0.09	0.69	0.83	0.12	1.00			
SiO_2	0.13	-0.62	-0.58	-0.70	-0.59	1.00		
NO_3	0.28	-0.67	-0.60	-0.62	-0.51	0.84	1.00	
P Tot	0.09	0.27	0.15	0.14	0.18	-0.21	-0.28	1.00

Table 3.15. CORRELATION OF DATA FOR STATIONS 46-48, ALL CRUISES, ALL DEPTHS. N = 32, R @ .99 = .45.

	Secchi	Temp	pH	C14-1s	Chl	SiO_2	NO_3	P Tot
Secchi	1.00							
Temp	-0.30	1.00						
pH	0.53	0.32	1.00					
C14-1s	-0.37	-0.58	-0.04	1.00				
Chl	-0.25	0.35	0.13	0.71	1.00			
SiO_2	-0.66	0.43	-0.26	0.28	0.48	1.00		
NO_3	0.43	-0.18	0.07	-0.26	-0.32	-0.42	1.00	
P Tot	-0.28	0.14	-0.26	0.29	0.55	0.39	-0.16	1.00

correlation coefficients were found because the water column was stratified thermally and chemically for most of the stations. To a lesser extent, these relationships were found because water from Lake Huron and the outflow from the St. Marys River were usually colder than the surface waters of Lake Michigan (Table 3.3). Surface water from Lake Michigan had higher pH and lower silica and nitrate than the other waters.

That nitrate, silica, and pH were correlated with temperature can be seen from the correlation matrices for the three cruises. On Cruise 1, when water temperature differences were greatest among the stations, the six correlation coefficients for the variables ranged from .86 to .96 (Table 3.4) and on Cruise 2 from .62 to .82 (Table 3.5). By Cruise 3, when thermal stratification was limited to a few stations, correlation coefficients of silica with temperature and nitrate were -.34 and .39 and the other correlation coefficients ranged from .60 to .75 (Table 3.6). Only eight other correlation coefficients for silica, nitrate, temperature and pH were less than 0.5. Two of these were between nitrate and silica for Stations 13-23 (Table 3.10) and between nitrate and temperature for Stations 38, 39, 49, 50 (Table 3.13). The remaining six were all the coefficients for Stations 46-48 (Table 3.15).

Correlations for nitrate, silica, pH and temperature at Stations 46-48 obviously differed from the other stations. Not only were all the correlation coefficients less than .42 (Table 3.15), but some had opposite signs in comparison to the other groups. The correlation coefficient for silica and nitrate was -.42 whereas all other coefficients for this pair of variables were positive (Tables 3.2-3.14). Silica likewise was positively correlated with temperature, but the relationship was negative at other stations. The positive correlation of silica and temperature is related to water originating in the St. Marys River with higher silica and temperature than the adjacent waters in Lake Huron. In other areas of the lake, warm surface waters were silica-depleted in relation to the colder and deeper waters.

Relationship of Nutrients and Chlorophyll

In nutrient-limited systems, the standing crop of phytoplankton might be expected to be correlated with nutrients and other phytoplankton community parameters. These relationships can be tested partly from correlation coefficients between the standing crop of phytoplankton, measured as chlorophyll *a*, and other parameters such as concentration of silica, nitrate and total phosphorus, rate of carbon-14 uptake, and Secchi disc transparency. Although chlorophyll was not consistently correlated with any of these parameters, most of the correlations among these variables were highly significant (Table 3.16).

Correlation coefficients for silica and chlorophyll were highly significant, excepting those for Stations 07-10, 11-12, and 13-23 (Table 3.16). Some of the highly significant correlations, however, were positive while others were negative. Highly significant positive correlation coefficients

Table 3.16. CORRELATIONS OF RATE OF CARBON FIXATION, SECCHI DISC TRANSPARENCY, AND CONCENTRATION OF SILICA, NITRATE AND TOTAL PHOSPHORUS WITH CHLOROPHYLL *A*. Data from Tables 3.2-3.15.

r[a]	Station	N	C-14	Secchi	SiO_2	NO_3	TPO_4
.30	01-06	77	.76	-.33	.55	-.02	.29
.32	07-10	66	-.18	.49	-.27	-.23	.25
.49	11-12	27	.17	-.18	.22	.12	.09
.25	13-23	110	.32	-.43	.23	.11	-.12
.18	24-31	207	.13	-.17	-.39	-.31	.20
.27	32-37	90	.66	.07	-.33	-.25	.24
.34	38, 39, 49, 50	57	.23	-.15	-.58	-.53	.05
.25	40-45	104	.12	-.09	-.59	-.51	.18
.45	46-48	32	.71	-.25	.48	-.32	.55
.26	all[b]	98	.26	-.06	.29	.08	.11
.10	all	768	.24	-.24	-.36	-.36	.23
.19	A	199	.04	-.35	-.40	-.34	.31
.16	S	259	.19	-.32	-.61	-.50	.15
.15	O	313	.38	-.17	-.33	-.40	.27

[a]Approximate critical value for r at the .01 probability level.

[b]Only at 5-meter depths where there were no missing data.

were obtained at Stations 01-06 with the most silica-depleted water (Table 3.7) and with the complete set of data that included only near-surface samples for which all data were available (Table 3.3). Both sets of data indicate silica was limiting, since standing crops increased with larger concentrations of silica. At Stations 46-48, the positive correlation coefficient seems to have resulted from relatively large concentrations of silica in the St. Marys River water (Table 3.15). Correlation coefficients for chlorophyl of .71 with carbon fixation and .55 with total phosphorus indicate that water from the St. Marys River was phosphorus-limited, as the phytoplankton community parameters increased with phosphorus concentration.

Highly significant correlation coefficients for nitrate and chlorophyll were all negative, indicating that in at least these groups of stations nitrate was not limiting or that increased standing crops of chlorophyll reflected nutrient decreases or nutrient utilization by phytoplankton (Table 3.16).

Few highly significant correlations were obtained between chlorophyll and total phosphorus (Table 3.16). It is important to note, however, that for the complete data set and for the data by cruises there were highly significant correlations. The correlation coefficients were small, probably reflecting the large variances in these two groups of data.

Most of the correlations between rates of carbon fixation and chlorophyll were positive, as expected, but only about half of the coefficients were highly significant (Table 3.16). Since rates of carbon fixation were measured at only 5 m, the only meaningful correlation may be the one for the 5-m samples. For this group of samples the correlation coefficient and the critical value for r were equal. Only three sets of coefficients indicated that measurements of chlorophyll *a* and rates of carbon-14 were as highly related as measurements of temperature, nitrate, silica and pH. These were the coefficients for Stations 01-06, 32-37 and 46-48, but the causes for only finding a small number of these highly related measures are not obvious.

Most of the correlations between Secchi disc transparency and chlorophyll were negative, as expected, but only half of the coefficients were highly significant (Table 3.16). One of the highly significant values, .49 for Stations 07-10, was positive, which we cannot explain. Like chlorophyll, the complete data set and the samples by cruises had highly significant correlations. In addition, highly significant correlations were found for Stations 01-06 and 13-23. It was obvious that transparency measurements could not have been used to estimate standing crops of chlorophyll.

Correlations by themselves are not particularly illuminating. In Section V, multivariate techniques are used to analyze the data set.

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SECTION IV

WATER MASSES AND DILUTION OF SURFACE WATERS IN THE STRAITS AREA

by

Theodore B. Ladewski

Epilimnetic water may be considered to be bounded on the top by the air-water interface and on the bottom by the thermocline. The degree to which the epilimnetic water is affected by inputs across the top and bottom boundaries is difficult to quantify, but will be a function of the transit time of water through the Straits area, which was estimated to be 19 days. Inputs across the upper surface will be assumed to be unimportant over this transit time and will be ignored. Except in the case of obvious upwelling, inputs from the hypolimnion will also be ignored, leaving three major inputs to the Straits survey area: Lake Michigan, the St. Marys River, and Lake Huron. The flow from the St. Marys River at Detour Passage was estimated to be 2000 $m^3\ sec^{-1}$ (Powers and Ayers 1960). The average net flow at the Straits between 9 August and 13 November 1973 above 20 m was 3320 $m^3\ sec^{-1}$ (Saylor and Sloss, In press). The next largest source of water is the Cheboygan River with an average flow of 21 $m^3\ sec^{-1}$ between August and October 1973 (USGS 1973, 1974). Since this source is dwarfed by comparison with the flow from Lake Michigan and the St. Marys River, it and other rivers in the area likely have only minor effects on the surface waters.

The purpose of this section is to describe and provide background information on relationships among surface-water masses related to the three major inputs during the period of our study.

To trace the water movements from Lake Michigan and the St. Marys River into the Straits area, conservative parameters were needed. "Conservative concentrations" are defined by Sverdrup et al. (1942) as those "that are altered locally, except at the boundaries, by the processes of diffusion and advection only." An alternate definition for "conservative," used in this paper, is: A quantity is conservative if its measured value X in a mixture of volumes V_i of water from N different sources is equal to:

$$X = \frac{\sum_{i=1}^{N} V_i X_i}{\sum_{i=1}^{N} V_i} \qquad (1)$$

where X_i = measured value of the parameter at source i. This relationship may be rewritten as:

$$X = \sum_{i=1}^{N} F_i X_i \qquad \text{where } F_i = \frac{V_i}{\sum_{j=1}^{N} V_j}$$

A conservative parameter therefore is one which dilutes proportionately with its quantity in the water. Examples of parameters not conserved according to this definition are pH, Secchi depth or any which are subject to biological or chemical reactions or to phase change.

Temperature and conductivity were chosen as conservative parameters to be used to trace water masses because these measurements are simple and subject to little experimental error. Conductivity is a function of concentrations of all ions including bicarbonate. However, its correlation with chloride at 5 m is quite high (r = .96) so it may be considered to be relatively unaffected by the biota. Water temperature could not be considered conservative if local cooling or warming rates are comparable to rates of temperature change due to surface-water mixing. The size of the survey region is sufficiently small on a meteorological scale so it is reasonable to expect air temperatures and other meteorological conditions to be relatively uniform over the area at any one time. Climatic cooling will reduce the resolution of the technique of using water temperature to distinguish water masses but is not likely to be a factor during a 3-day cruise.

4.1 RESULTS

To identify water masses, temperature was plotted vs. conductivity. Clusters of stations with similar temperature and conductivity were circled and labeled on Figure 4.1 and the geographical locations indicated on Figure 4.2. The difference in the locations between 24 and 24R or 30 and 30R, two stations which were sampled on different days, indicated the extent of daily variation and measurement error of temperature and conductivity. It is evident that there are three extreme regions: M_1 located west of the Straits in Lake Michigan at Stations 01-03, H_1 located east of the Straits in Lake Huron at Stations 41 and 42, and S_1 located at Station 48 at the mouth of the St. Marys River.

Sources of water with temperature and conductivity for each of the regions in Figure 4.2 are shown in Table 4.1. It is evident that the regions cannot be distinguished from temperature alone since water from the St. Marys River and Lake Michigan have similar temperatures. Resolution of water masses, however, is possible for specific conductance (Table 4.1).

Stations 01, 42, and 48 may be considered as the primary sources of water due to their location on the triangle in Figure 4.1. The plot of

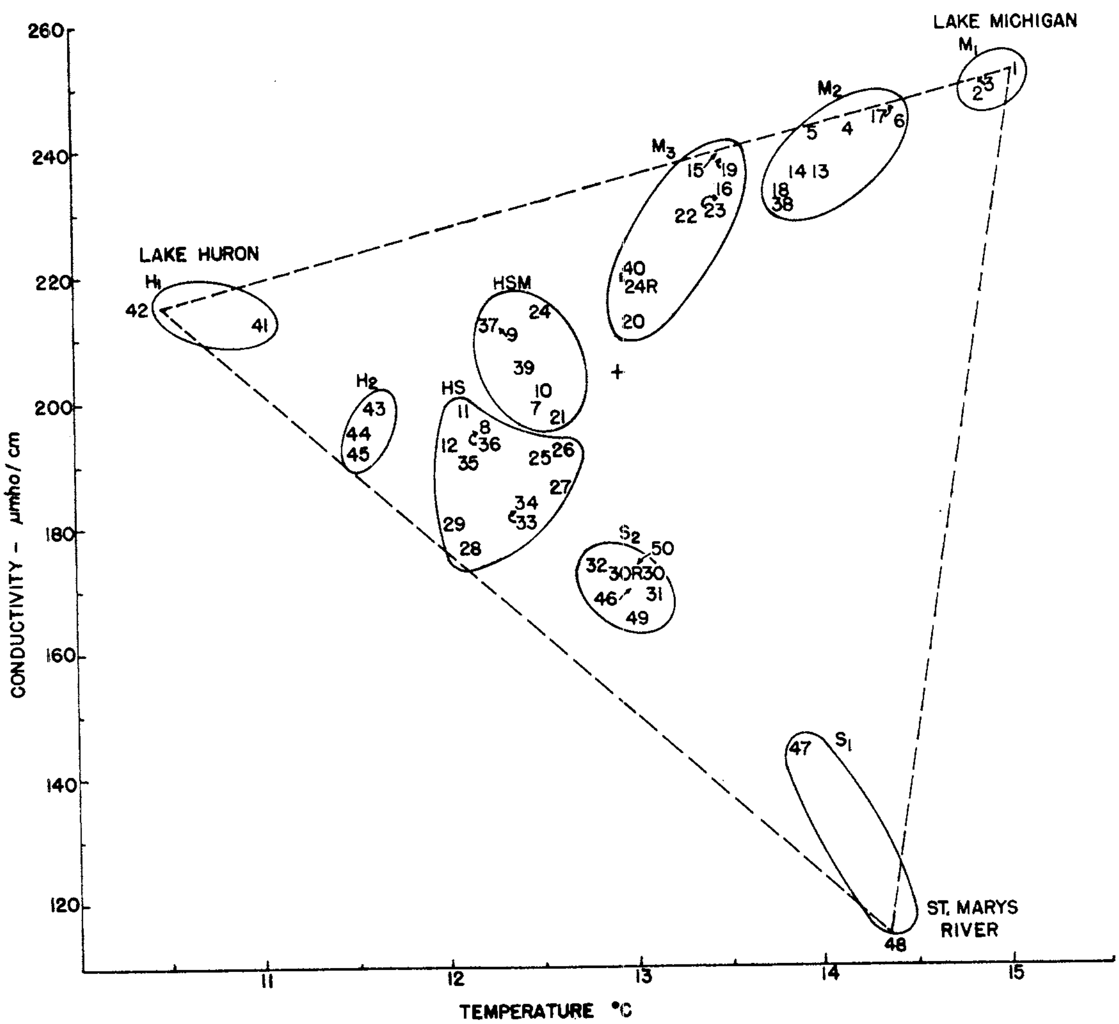

Figure 4.1. TEMPERATURE-CONDUCTIVITY PLOT FOR OCTOBER 5-M SAMPLES. Numbers refer to the stations at which the samples were taken. The temperature and conductivity of a station (at 5 m) is indicated by the position of its number. Note that all stations are included by a triangle connecting Stations 01, 42, and 48. See Figure 4.2 for the geographic locations of the labeled regions.

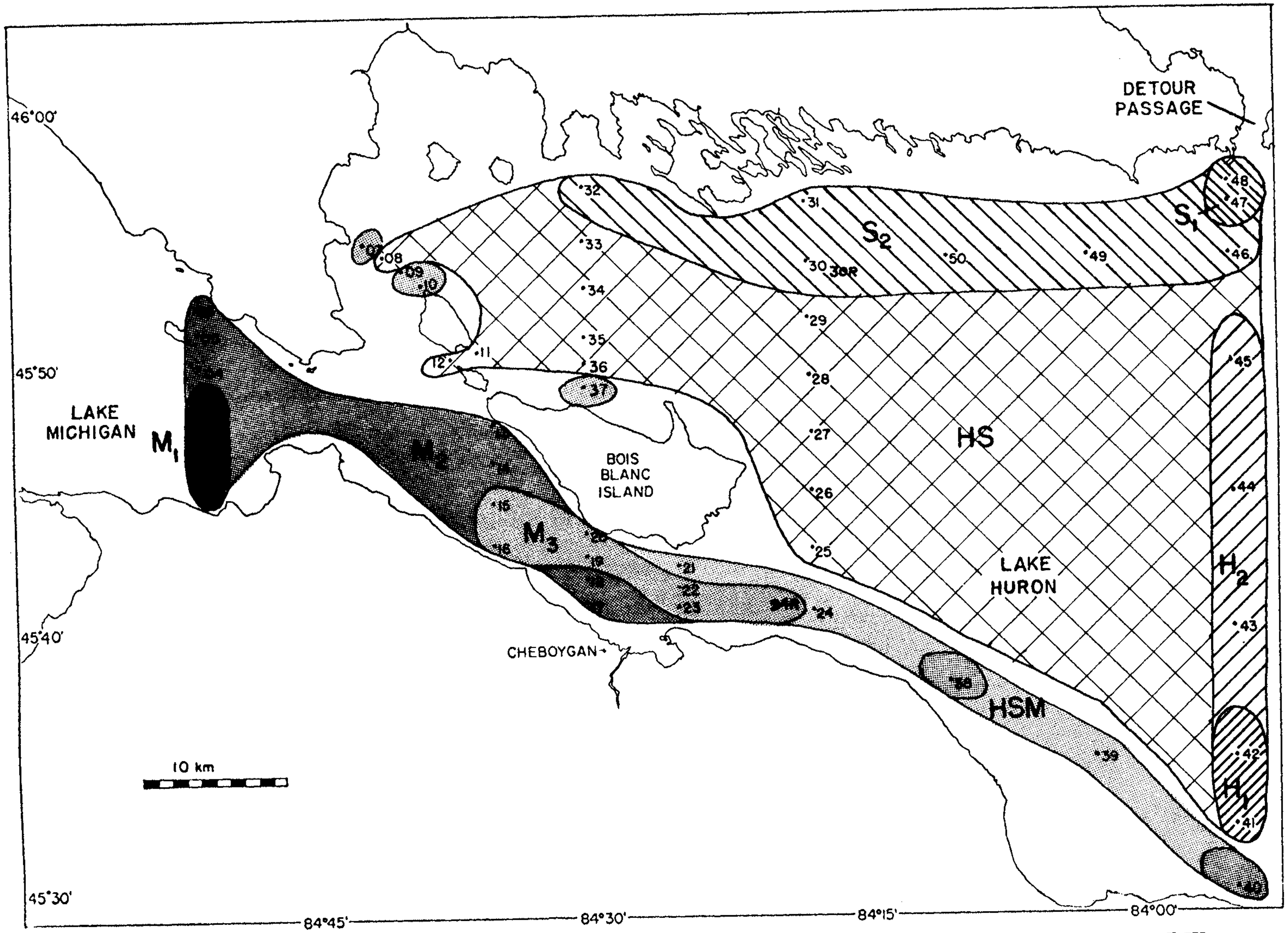

Figure 4.2. GEOGRAPHIC LOCATIONS OF REGIONS IDENTIFIED IN THE TEMPERATURE-CONDUCTIVITY PLOT OF FIGURE 4.1.

Table 4.1. SOURCES OF WATER WITH RANGES OF TEMPERATURE AND CONDUCTIVITY FOR REGIONS M_1, H_1 AND S_1 IN FIGURE 4.2.

Region	Source	Temperature	Conductivity
M_1	Lake Michigan	High (14.8-15.0)	High (248-252)
H_1	Lake Huron	Low (10.5-11.0)	Intermed. (214-218)
S_1	Lake Superior	High (13.8-14.3)	Low (118-146)

the regions (Fig. 4.2) also suggests that water is diluted from the three sources into the central stations of the survey area.

Assuming three sources of water represented by Stations 01, 42 and 48, it is possible to estimate the fraction of each of the three water types at the surface location $\vec{X}$, if $F_i(\vec{X})$ is defined as the fraction of water at $\vec{X}$ originating from source $\underline{i}$, where:

i=1 represents the source at Station 01,
i=2 represents the source at Station 42,
i=3 represents the source at Station 48.

Since there are three sources assumed:

$$\sum_{i=1}^{3} F_i(\vec{X}) = F_1(\vec{X}) + F_2(\vec{X}) + F_3(\vec{X}) = 1 \tag{2}$$

for any surface point $\vec{X}$ inside the survey area. Since temperature and conductivity are assumed to be conserved (see Eq. 1):

$$\sum_{i=1}^{3} F_i(\vec{X})\ T_i = T(\vec{X}) \qquad \text{and} \tag{3}$$

$$\sum_{i=1}^{3} F_i(\vec{X})\ C_i = C(\vec{X}) \tag{4}$$

where: T_i is the temperature at source $\underline{i}$, C_i the conductivity at source $\underline{i}$, $T(\vec{X})$ the temperature at point $\vec{X}$, and $C(\vec{X})$ the conductivity at point $\vec{X}$. Equations 2, 3 and 4 were solved simultaneously for the F_i at each station.

Several general conclusions may be drawn from the distribution of calculated fractions of water from Lake Michigan, Lake Huron and the St. Marys River (Figs. 4.3-4.5) during the October cruise. First, the contours are generally smooth, indicating that the assumptions behind Eqs. 2-4 and the hypothesis that water types can be traced using temperature and con-

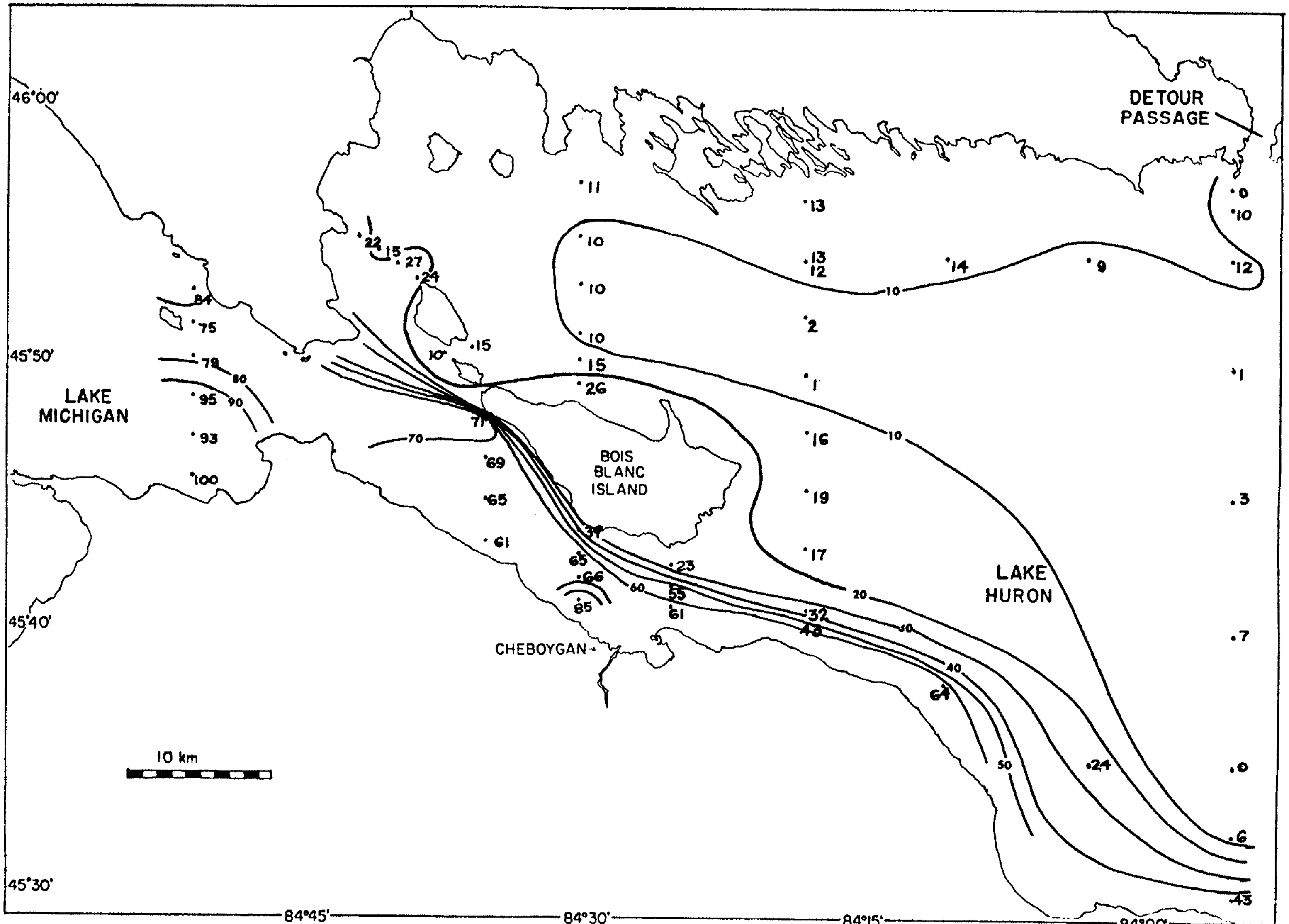

Figure 4.3. PERCENT OF LAKE MICHIGAN WATER AT 5 M FOR OCTOBER. Lake Michigan water is assumed to be represented by Station 01. Numbers written at each station give the percentage of Lake Michigan water as calculated using temperature and conductivity.

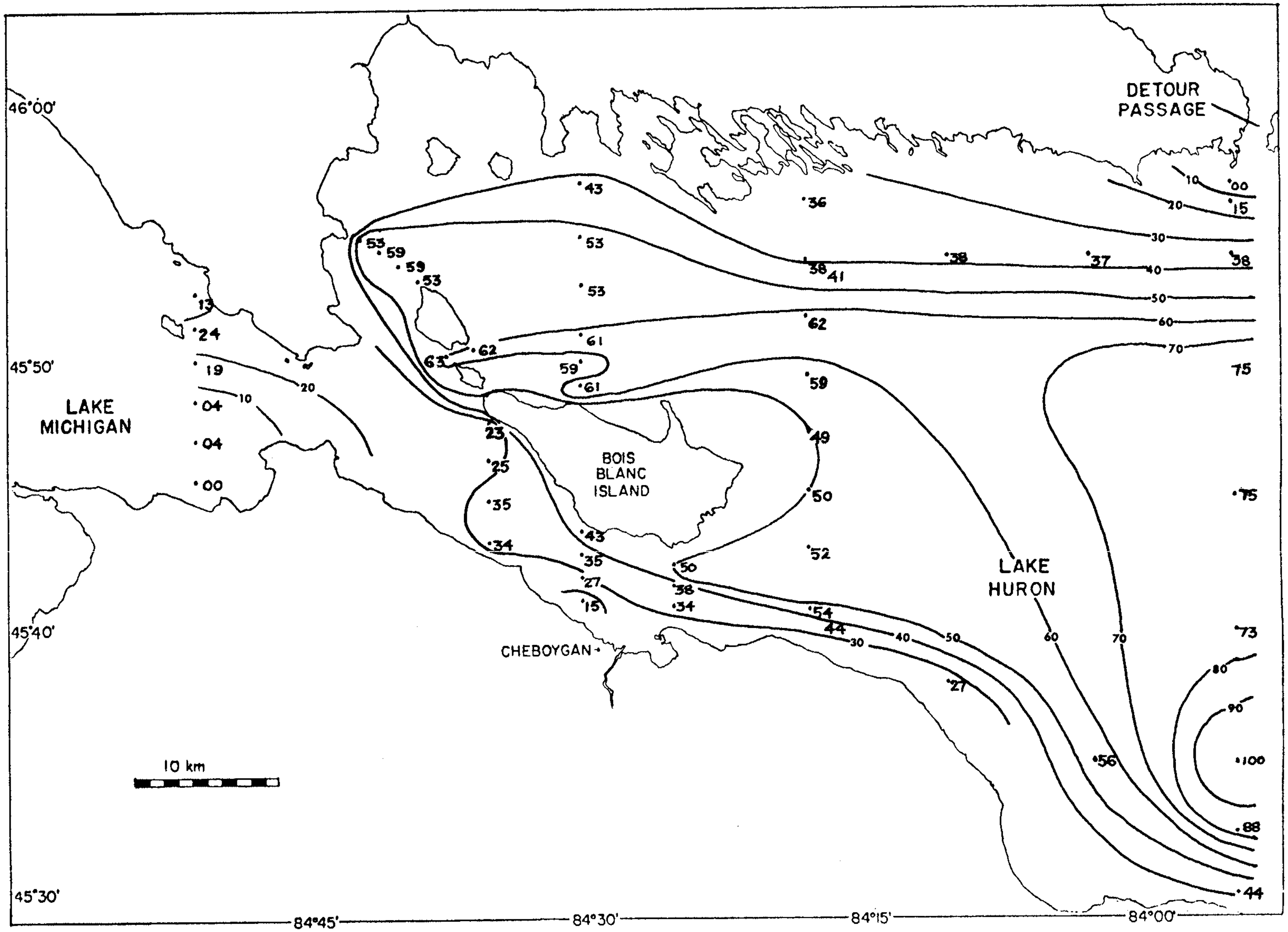

Figure 4.4. PERCENT OF LAKE HURON WATER AT 5 M FOR OCTOBER.

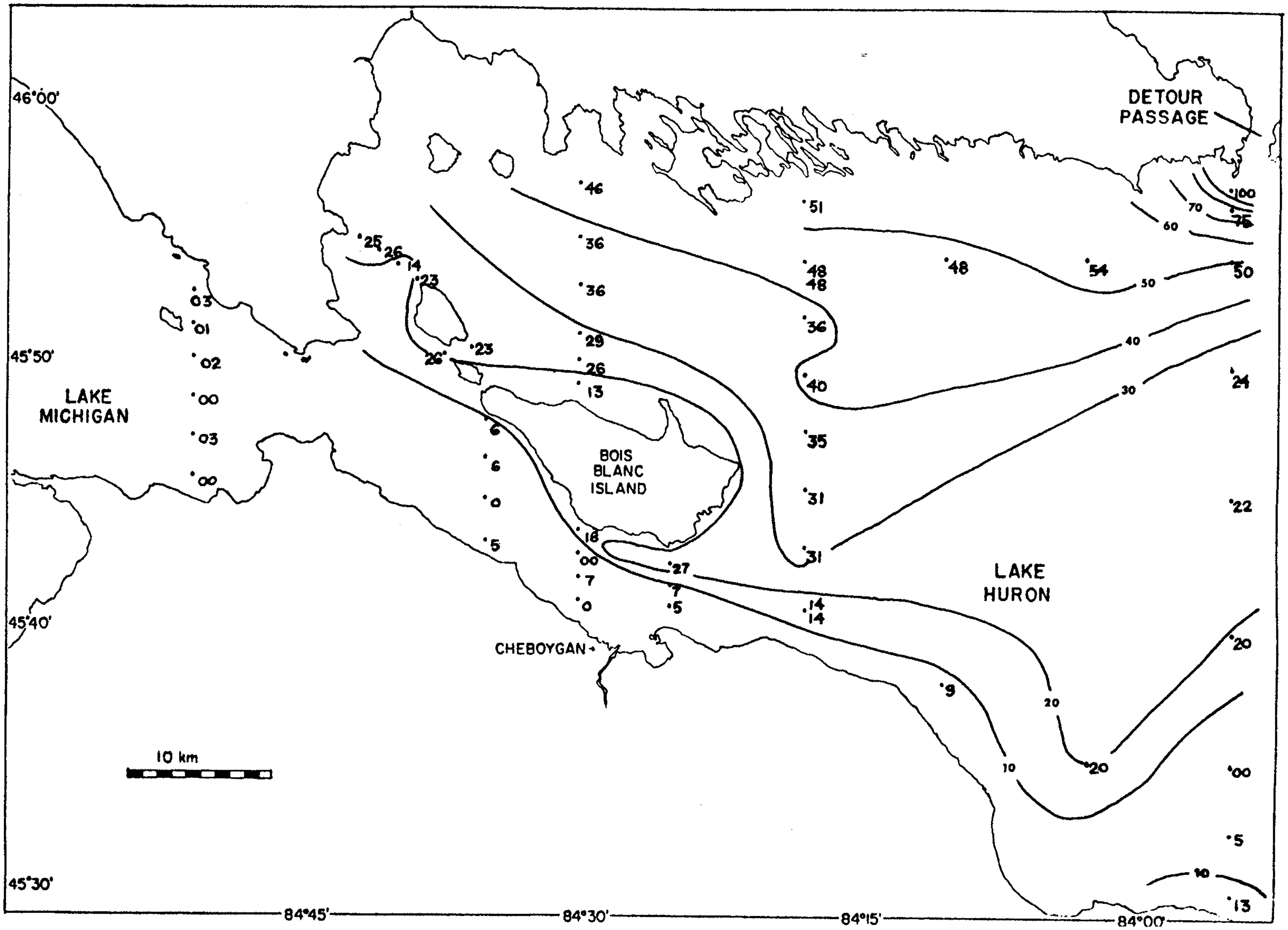

Figure 4.5. PERCENT OF ST. MARYS RIVER WATER AT 5 M FOR OCTOBER.

ductivity are valid. One apparent inconsistency for Station 17 may be due to effects from the Cheboygan River which would be expected to have a high temperature and conductivity, thus making it appear, on the basis of these parameters, as a station characteristic of Lake Michigan.

Second, little water from Lake Michigan was present in the northeastern corner of the sample area. Water from Lake Michigan flowed along the southern shore and was evident at Station 40, on the southeastern corner of the survey area, where approximately 43% of the water was from the source in Lake Michigan. This flow of water into Lake Huron from Lake Michigan closely parallels the results of Ayers et al. (1956), who showed water of high temperature and conductivity and high concentrations of magnesium and calcium flowing eastward through the Straits and along the southern shore in all three of their synoptic cruises.

Third, water comprised of a mixture from the St. Marys River and Lake Huron flowed westward along the northern shore from Detour Passage. Since Detour Passage is situated on the eastern edge of the survey area, it is not clear whether there is an additional flow eastward. Either an eastward or westward current may occur at Detour Passage, although the westward current appears more predominant (Ayers et al. 1956). In addition, the water from the area of Station 42, initially identified as coming from Lake Huron, appears to be moving north and west. This apparent northward current at Station 42 is consistent with observation of similar northward currents measured by drogues in the summer of 1966 (Sloss and Saylor, In press). Apparently, mixing of Lake Huron and St. Marys River water occurred in the northeastern half of the survey area with very little inclusion of Lake Michigan water (Fig. 4.3).

Six regions were identified from the plot of temperature vs. conductivity (Fig. 4.6) for September samples, as indicated on the map of the study area (Fig. 4.7). At this time one distinct water mass, S, was identified as originating from the St. Marys River. The remaining five regions are distributed along a gradient from M_1, with the highest temperature and conductivity, to U with the coldest temperature and an intermediate conductivity. In contrast with the previous cruise, Lake Michigan water with a specific conductance of 265 μmho was not present at Stations 01-06; the highest specific conductance, 250 μmho, was found at Station 23. These conductivity relationships indicate that considerable mixing of Lake Michigan and Lake Huron waters occurred in the M_1 and M_2 regions.

Region U is cold with a high nitrate concentration characteristic of hypolimnetic water (Table 4.2), suggesting that upwelling occurred at region U prior to the time of sampling. The conductivity is lower in region U than in the hypolimnion, indicating that hypolimnetic water mixed with westward flowing water from the St. Marys River.

Regions US and UM appear to be derived from a mixture of waters from U and S and U amd M. The location of these regions (Fig. 4.7) and their intermediate temperature suggests they orginated from an upwelling along

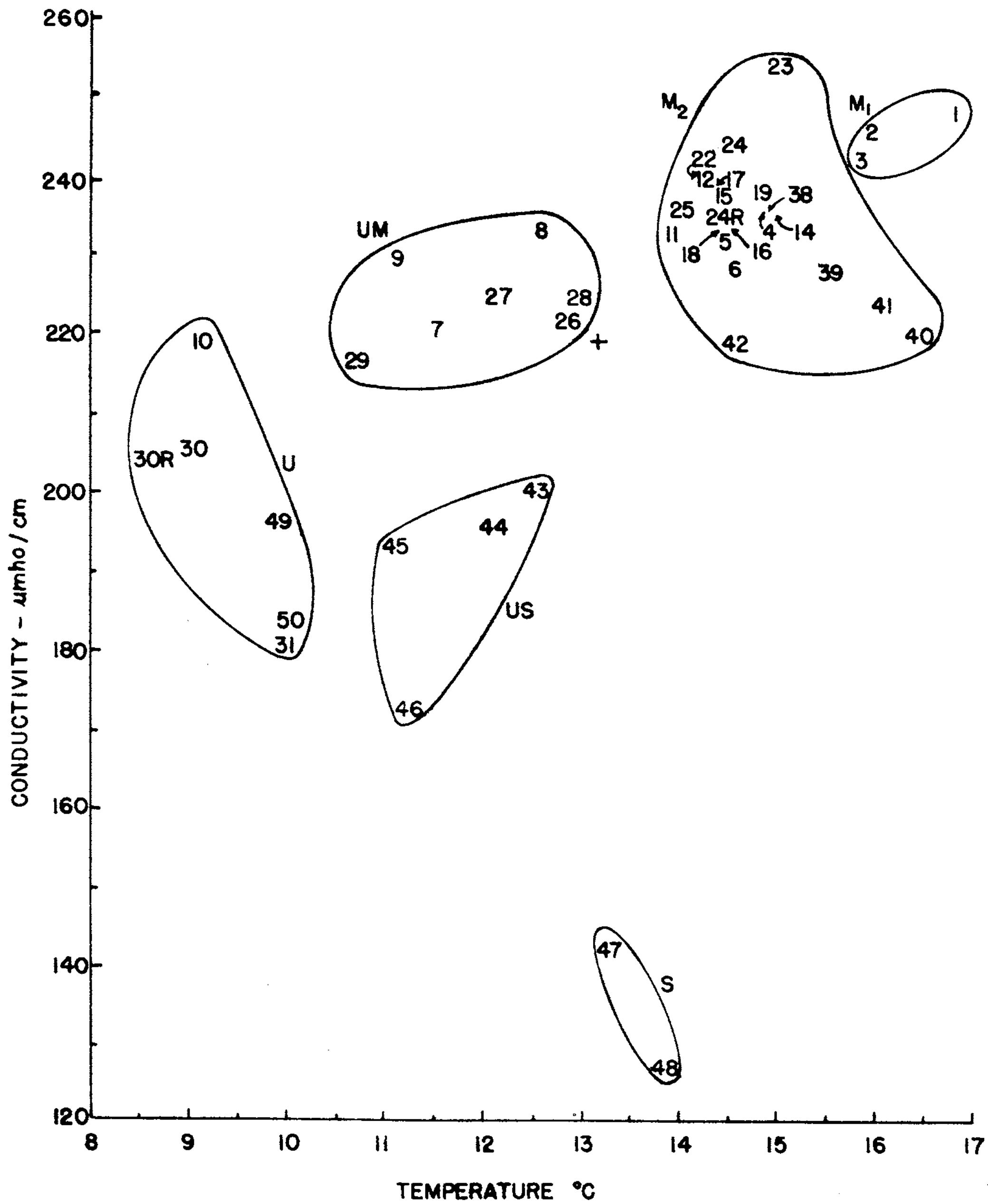

Figure 4.6. TEMPERATURE-CONDUCTIVITY PLOT FOR SEPTEMBER 5-M SAMPLES. Numbers refer to stations at which the samples were taken. See Figure 4.7 for the geographic locations of the labeled regions.

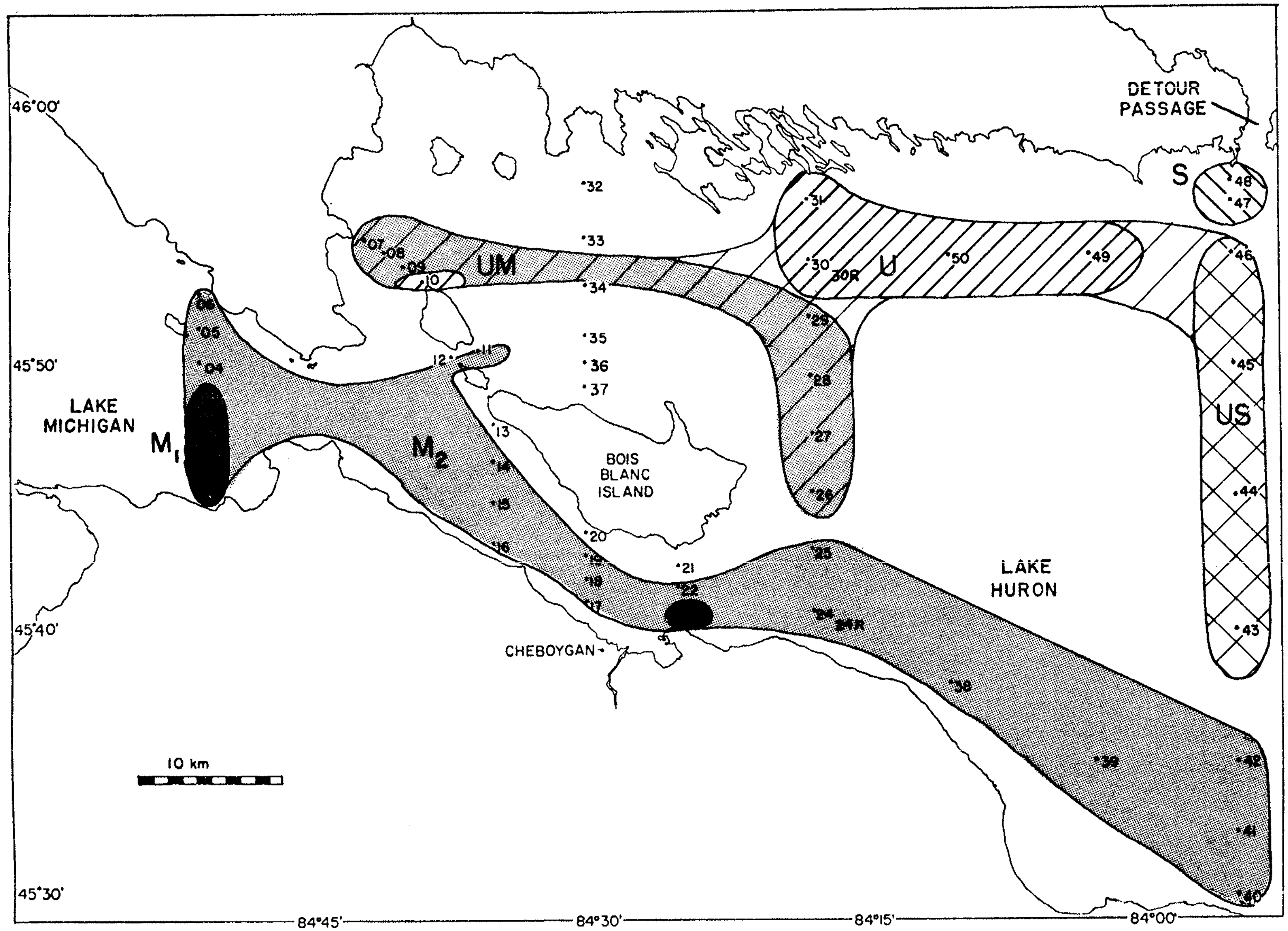

Figure 4.7. GEOGRAPHIC LOCATIONS OF THE REGIONS IDENTIFIED ON THE BASIS OF THE T–C PLOT OF FIGURE 4.6.

Table 4.2. SUMMARY OF NITRATE, SILICA, TEMPERATURE, AND CONDUCTIVITY VALUES FOR SEPTEMBER.

Parameter	Overall range for 5-m samples	Range for samples below 40 m	Range in region U (5 m)	Range in region S (5 m)	Range in region M_1 (5 m)	Units
NO_3	133 - 362	296 - 393	274 - 362	258 - 295	133 - 252	μgN/1
SiO_2	.73 - 1.89	1.32 - 2.23	1.26 - 1.50	1.85 - 1.89	.73 - .87	$mgSiO_2/1$
Temp.	8.5 - 16.8	4.2 - 6.1	8.5 - 10.0	13.2 - 13.8	15.8 - 16.8	°C
Cond.	126 - 253	220 - 222	163 - 219	126 - 142	223 - 247	μmho/cm

Table 4.3. SUMMARY OF NITRATE, SILICA, TEMPERATURE, AND CONDUCTIVITY VALUES FOR AUGUST.

Parameter	Overall range for 5-m samples	Range for samples below 40 m	Range in region U (5 m)	Value at region H (station 25, 5 m)	Units
NO_3	126 - 244	306 - 364	188 - 244	214	μgN/1
SiO_2	.43 - .96	1.45 - 1.96	.43 - .91	.70	$mgSiO_2/1$
Temp.	17.0 - 22.0	4.5 - 7.5	17.0 - 18.1	20.9	°C
Cond.	196 - 225	215 - 222	200 - 227	197	μmho/cm

the northern shore some time prior to the survey or to an intrusion of relatively cool Lake Huron water.

Unfortunately stations representative of the sources were not sampled, as indicated by Figure 4.6, so it is not possible to compute the fraction of water from each source as was done for the October samples (Figs. 4.3-4.5). Instead of three sources, there appear to be at least four sources for surface water in the survey area: surface waters of Lake Michigan, Lake Huron, and the St. Marys River, plus the hypolimnion of Lake Huron. An additional conservative parameter would be needed to compute fractions from each source. Nevertheless, the stations do form a rough triangle, suggesting that the most important sources are Lake Michigan, St. Marys River and the hypolimnion of Lake Huron.

Five regions were identified on the plot of temperatures vs. conductivity for the August samples, one region including only Station 25 (Fig. 4.8), and the relationship among the water masses is much more difficult to interpret than the previous cruise. A water mass characteristic of Lake Michigan extends through the Straits and south of Bois Blanc Island (Fig. 4.9). Upwelled water is present along the north shore, but the limited sampling area makes it difficult to determine its extent and origin. According to chemical data, the upwelled water mass, U, and the water mass at Station 25 appear to be Lake Huron water (Table 4.3) because NO_3-N, SiO_2 and conductivity are more characteristic of Lake Huron than of the other lakes.

4.2 LITERATURE CITED

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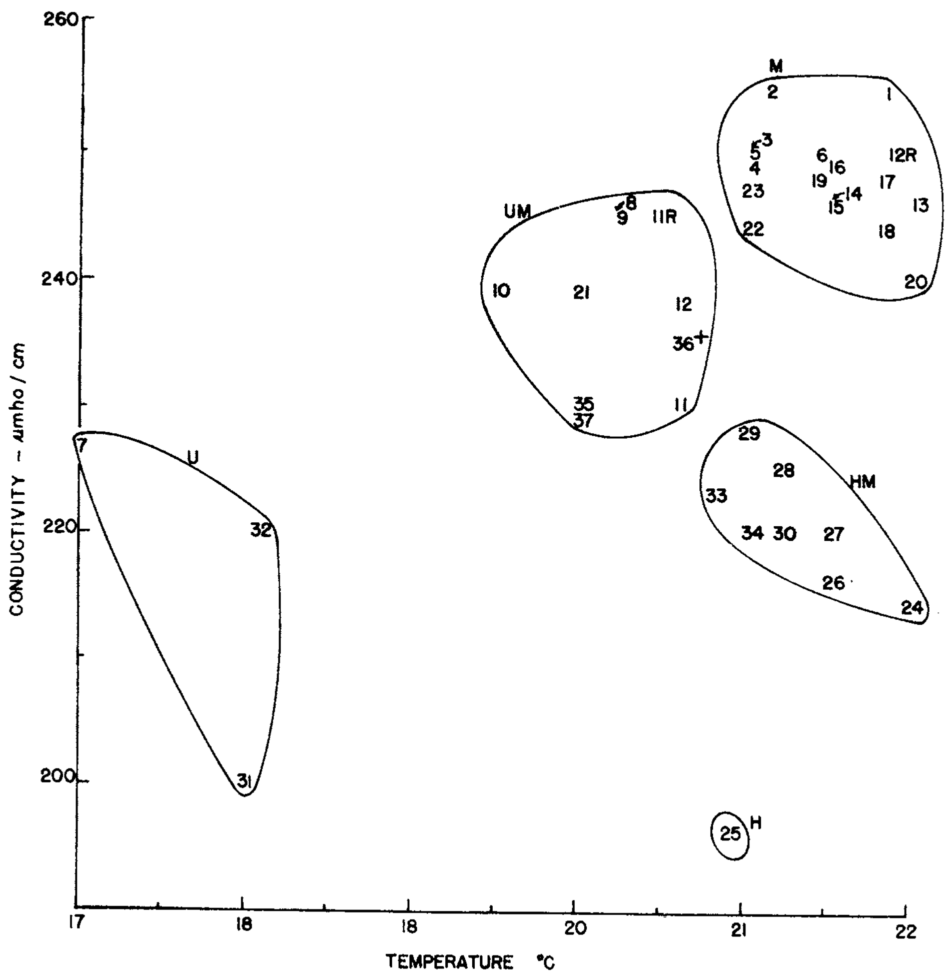

Figure 4.8. TEMPERATURE-CONDUCTIVITY PLOT FOR AUGUST 5-M SAMPLES. Numbers refer to stations at which the samples were taken. See Figure 4.9 for geographic locations.

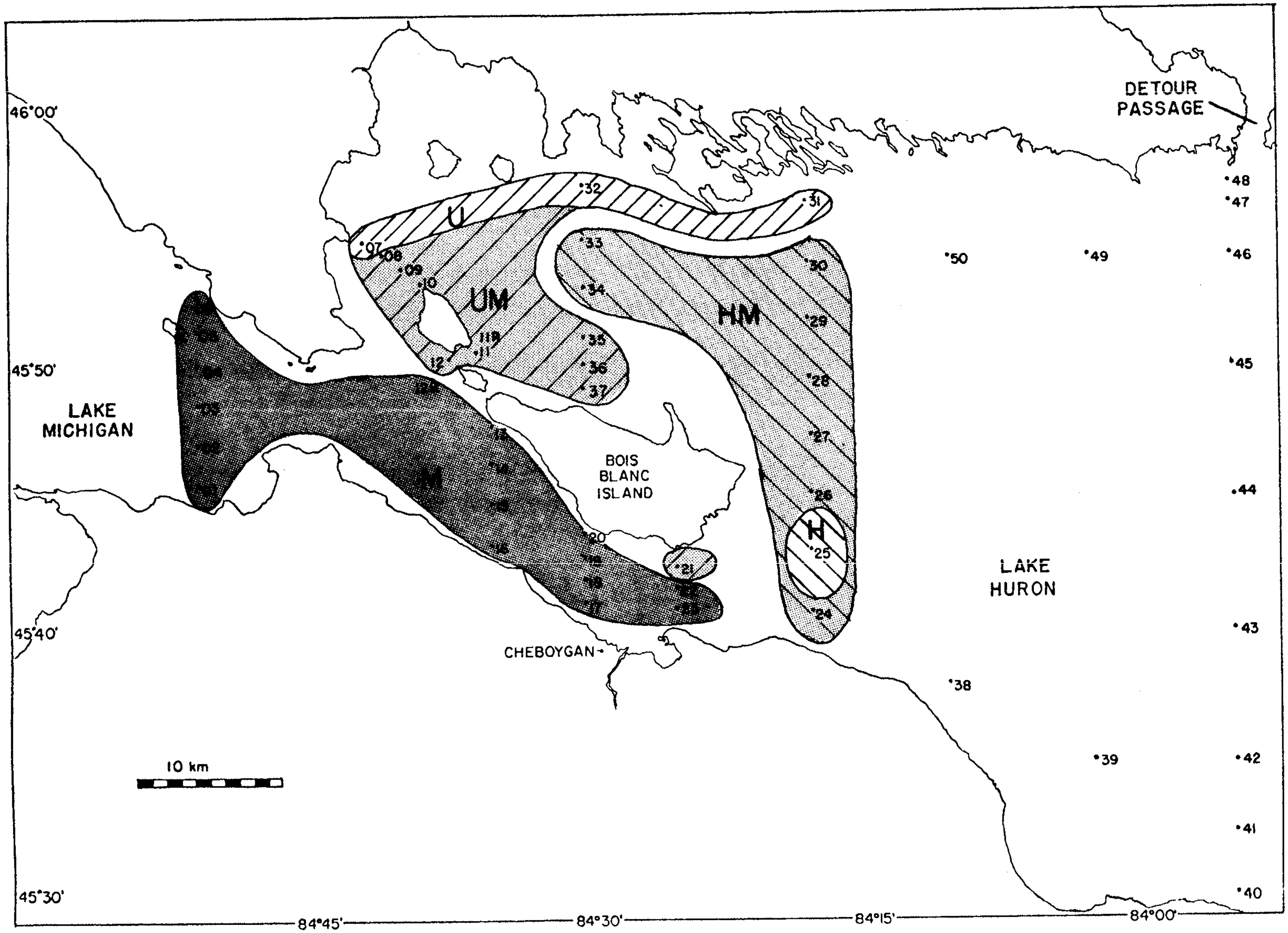

Figure 4.9. GEOGRAPHIC LOCATIONS OF THE REGIONS IDENTIFIED ON THE BASIS OF THE T-C PLOT OF FIGURE 4.8 FOR SEPTEMBER SAMPLES.

SECTION V

MULTIVARIATE STATISTICAL ANALYSIS OF PHYSICAL, CHEMICAL AND PHYTOPLANKTON COMMUNITY PARAMETERS

by

Russell A. Moll

The Straits of Mackinac is one of the most interesting areas of the Laurentian Great Lakes in terms of physics, chemistry, and biology (Henson 1962, 1970; Powers and Ayers 1960). The narrow juncture between Lake Michigan and Lake Huron is known for its unusual current conditions, as water is exchanged between the two lakes (Powers and Ayers 1960; Murty and Rao 1970; FWPCA 1967; Mortimer 1975). Knowledge of the distribution and movement of water masses in relation to biological characteristics and processes is relatively poor. As an initial attempt to describe the dynamics and biology of the area, studies were conducted during the late summer and early fall of 1973 on the biological, chemical and physical characteristics, including measurement of nutrients and phytoplankton productivity and the distribution and abundance of phytoplankton and zooplankton. Only the physical and chemical variables will be discussed here. For a more extensive and comprehensive treatment of the results in this section, see Moll et al. (In press).

The purpose of this section is to show that multivariate statistical techniques can be used to analyze large sets of data from the Great Lakes. Specifically it will be shown that water masses can be identified from cluster analysis of several variables. Data used are the same as those discussed in Section III, except duplicate sampling of stations were not used in the analysis. Several questions were studied: What is the spatial relationship among stations? Was there an effect of depth on the parameters sampled? Did the relationships among stations and depths vary from cruise to cruise?

5.1 METHODS

For factor and cluster analyses, data were normalized to mean 0.0 and variance 1.0 which reduces units for each variable to the same numerical range (Pielou 1969). Computer programs used for cluster and factor analysis are included in MIDAS (Michigan Interactive Data Analysis System), statistical software at the University of Michigan Computing Center. Several clustering algorithms were used, but the best results were obtained with the unweighted pair group method (Sokal and Sneath 1963 or Sneath and Sokal 1973).

The relationship of each variable to other variables and the relative importance of each variable were investigated with correlation analysis; correlations calculated between variables were also used in a factor analysis to show major factors affecting variability in the data (Van de Geer 1971; Mulaik 1972). Only factor loadings with eigenvalues greater than 1.00 were used (Rummel 1970). Values of the communalities for each variable were estimated using the iterative principal axis factor solution (Harman 1967). Iteration was continued until succeeding estimates of communalities differed by less than 1.0×10^{-3} or for 20 iterations. An orthogonal varimax rotation was performed on the factor matrix.

Cluster analyses were run to determine the similarities between different stations based on nine chemical and physical parameters. In the clustering analyses, the similarity coefficient between samples was either Euclidean distances or correlation, with the Euclidean distances consistently yielding higher cophenetic correlations. A cophenetic correlation coefficient was calculated for every clustering analysis performed, and only analyses with cophenetic correlations greater than +0.700 were considered. The cophenetic correlation coefficient indicates the concurrence between the original distance matrix and the end result of the clustering analysis (Sneath and Sokal 1973). The only associations which were considered of interest were those found in the lower half (based on the number of branchings) of the phenogram. The hierarchy of station relationships was displayed in the phenogram by circling clusters of stations on a map of the sampling area.

5.2 RESULTS

Factor Analyses

Factor analysis determined the communality or the amount of variation unique to each variable. A communality of 1.00 indicates the variation was common to all variables sampled, while a value of 0.00 indicates no variation common to the data set. In the Straits of Mackinac data (Table 5.1), Secchi disc readings had the smallest communality (0.1399); this result implied that the measure of Secchi disc values in this area had little intrinsic value other than the knowledge of the Secchi disc reading itself. Chlorophyll values also produced a low communality of 0.2226, which could have been in part explained by the absence of any other phytoplankton biomass measures in the data set. Other communalities in the data set were reasonably high.

Two factors were extracted from the factor analysis with eigenvalues of 3.8676 and 1.2366 (Table 5.1). The first factor showed an underlying source of variation in the data composed of water temperature and pH, to a lesser extent specific conductance and chlorophyll, and in the opposite sign, silica and nitrate. This could have been considered a depth and/or water mass factor. Silica and nitrate generally increased with depth while temperature, pH, and to a lesser degree specific conductance decreased with depth. Likewise, water masses with high silica and nitrate

Table 5.1. FACTOR ANALYSIS OF STRAITS DATA. N = 719, number of factors = 2, Kaiser's statistic = .9328, where N = number of observations.

Variable	Communalities	Scaled factor loadings (1)	Scaled factor loadings (2)
Secchi	.13992	-.37403	.00544
Temp.	.78508	.88553	.03025
pH	.90970	.95352	-.02228
Chlorophyll	.22256	.40315	.24500
SiO_2	-.80841	-.88669	.14898
NO_3	-.78010	-.88073	-.06652
Total P	-.72711	.06099	.85052
Sol P	.41525	-.03489	.64345
Cond.	.31606	.55223	-.10537
	Eigenvalue	3.8676	1.2366
	% variance	43.0	56.7

had low temperature, pH, and specific conductance. The second factor, apparently a phosphorus factor, had high loadings for both total and soluble phosphorus. These results indicate three major factors influenced the data set: depth, water masses, and phosphorus.

Cluster Analyses

Several groupings of data were used for clustering analyses: 1) all the data from Cruise 1, 2) data from 0, 5, 10, 15, 20, 30, and 40 m for each cruise, and 3) a reduced data set of water temperature, pH, silica, nitrate and total phosphorus for 0, 5, and 10-m samples for each cruise. Analysis of the entire data set for one cruise indicated that similarities among stations were related primarily to depth and that the data should be analyzed by depth.

Clusters of data for depths greater than 10 m were not reliable, as cophenetic correlations were less than 0.700 and were therefore difficult to interpret. Relatively few stations were deeper than 15 m, and data from 20, 30 and 40 m were more homogeneous than surface waters so the analysis had little value. Definite geographical patterns of stations were obtained from clusters of data for 0, 5, and 10 m so these results are discussed in the greatest detail. Clusters from the 15-m depth showed a transition between the definite patterns found at 10 m and the lack of obvious patterns at 20 m.

Maps for Cruise 1 suggested a pattern of surface water flow from Lake Michigan through the Straits, then south of Bois Blanc Island into Lake Huron (Figs. 5.1-5.3). This flow pattern is indicated by the distribution of water masses. At the surface, one water mass extended from the western edge of Mackinac Island to the southeastern edge of Bois Blanc Island (Fig. 5.1). There were two additional large water masses of surface water, one directly north of Bois Blanc Island and a second in the northwest part of the study area. At 5 m, stations south of Bois Blanc Island were joined with those west of the Straits, indicating a flow of water south of Bois Blanc Island (Fig. 5.2). There was no indication that the water mass north and northeast of Bois Blanc Island (Stations 27-37) was related to the water located south of the island and west of the Straits. Winds during the cruise period were low in velocity and from the southwest. Current meters set by the Great Lakes Environmental Research Laboratory, NOAA, showed that water above 10 m flowed from Lake Michigan south of Bois Blanc Island into Lake Huron (Saylor and Sloss, In press).

On Cruise 2, Stations 38-50 were added to the sampling grid, but the pattern of water masses was similar to Cruise 1. It was obvious that a distinct water mass was found to the south and southeast of Bois Blanc Island (Figs. 5.4-5.6); this water mass was also related to stations west of the Straits. These data indicate that a related water mass extended from stations west of the Straits in Lake Michigan to stations north of Forty Mile Point in Lake Huron. Data for water temperature, specific conductance, and nitrate-nitrogen (Table 3.1) indicated that this area contained a mixture of Lake Michigan and Lake Huron water, with greater proportions of Lake Michigan water on the west and of Lake Huron water on the east. Current meters set by NOAA also showed that water flowed south of Bois Blanc Island from Lake Michigan into Lake Huron.

Other areas of related stations were identified: First was the cluster of Stations 47 and 48 (Figs. 5.4-5.6), obviously different from the other stations in specific conductance, pH, silica, and nitrate (Table 3.1). The chemical differences are due to the discharge of Lake Superior water through Detour Passage. Second are the clusters of stations in the northern part of the area. These east-west clusters were related to upwelling along the northern shore that is evident at Stations 29-31 (App. C.14); this upwelled water can be traced along the northern shore, as shown in Section IV.

The final cruise occurred during a period of east winds rather than the prevailing westerly winds. More distinct patches or clusters of water were identified during this cruise than from the previous cruises. A distinct water mass was again present south of Bois Blanc Island, but it was not connected to stations west of the Straits and appeared as a large homogeneous area south of the island, extending southeast to Forty Mile Point (Figs. 5.7-5.9). Two other water masses were evident, one composed of stations surrounding Mackinac Island, the other of stations east of Bois Blanc Island. Current meter data from the Straits showed little surface flow of water into Lake Huron from Lake Michigan and a transport from Lake Huron exceeding 30,000 $m^3\ sec^{-1}$ on 6 October (Saylor and Sloss,

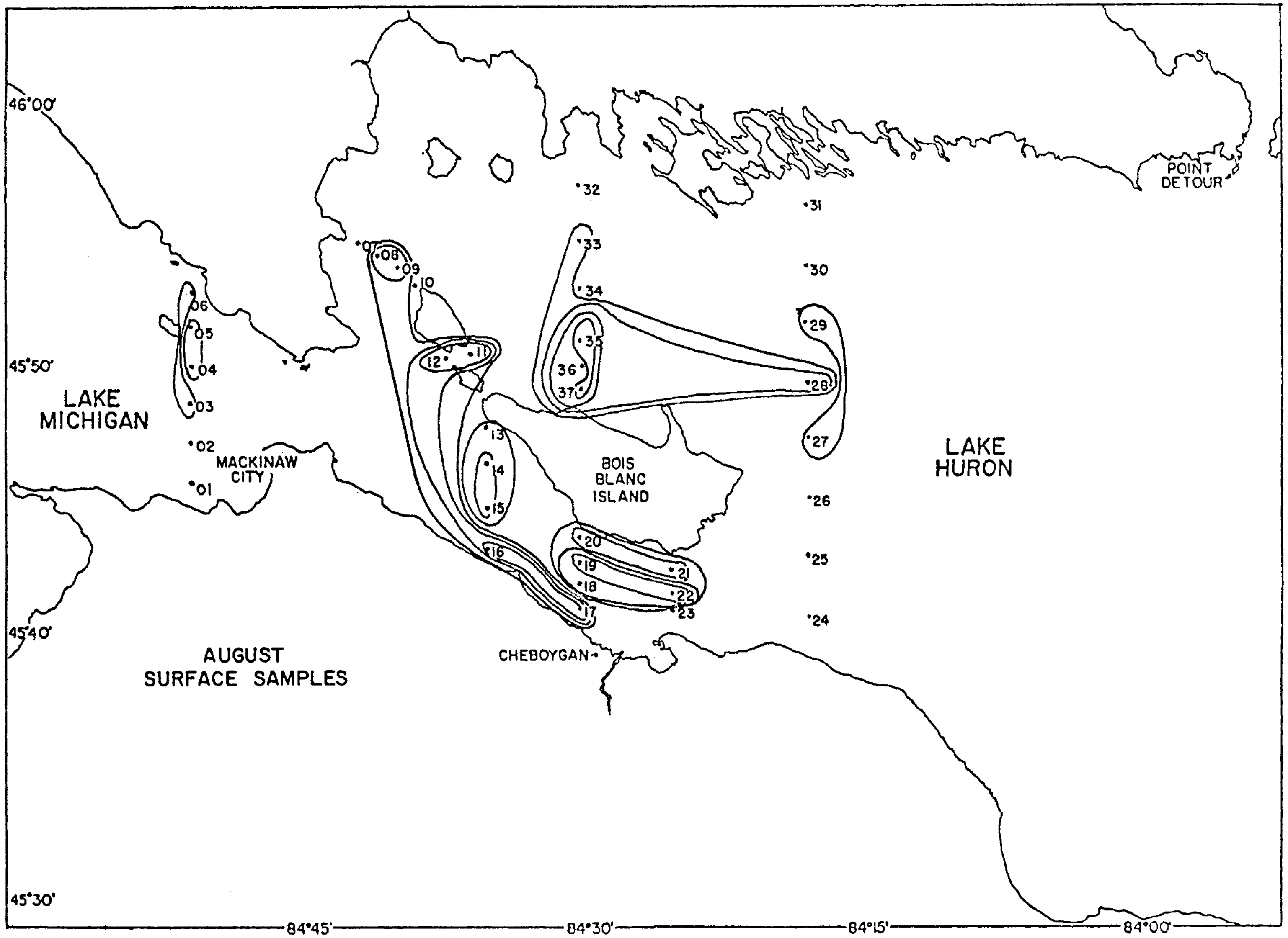

Figure 5.1. SURFACE WATER DISTRIBUTION IN AUGUST. Only the strongest cluster associations are shown.

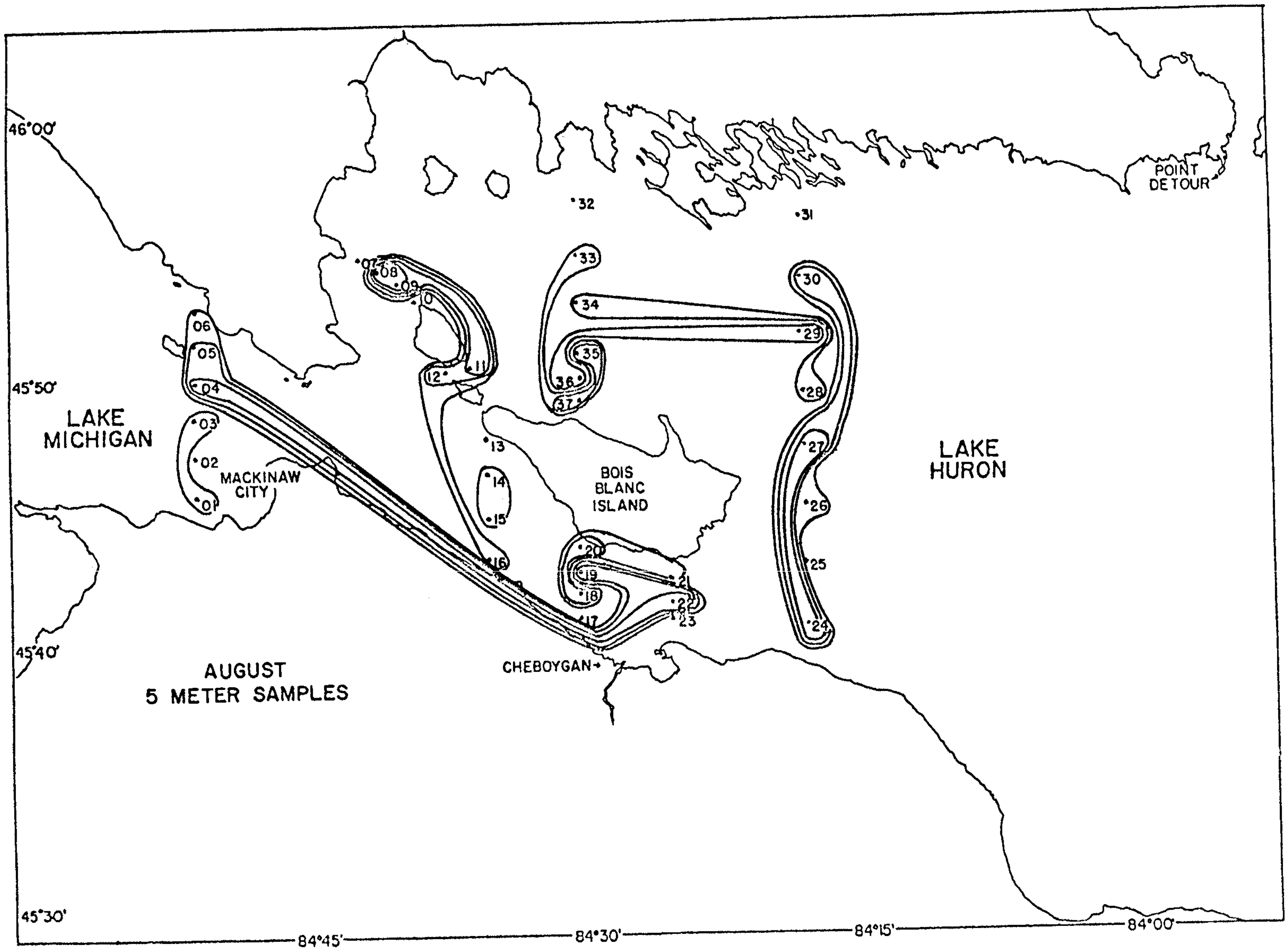

Figure 5.2. FIVE-METER WATER DISTRIBUTION IN AUGUST. Only the strongest cluster associations are shown.

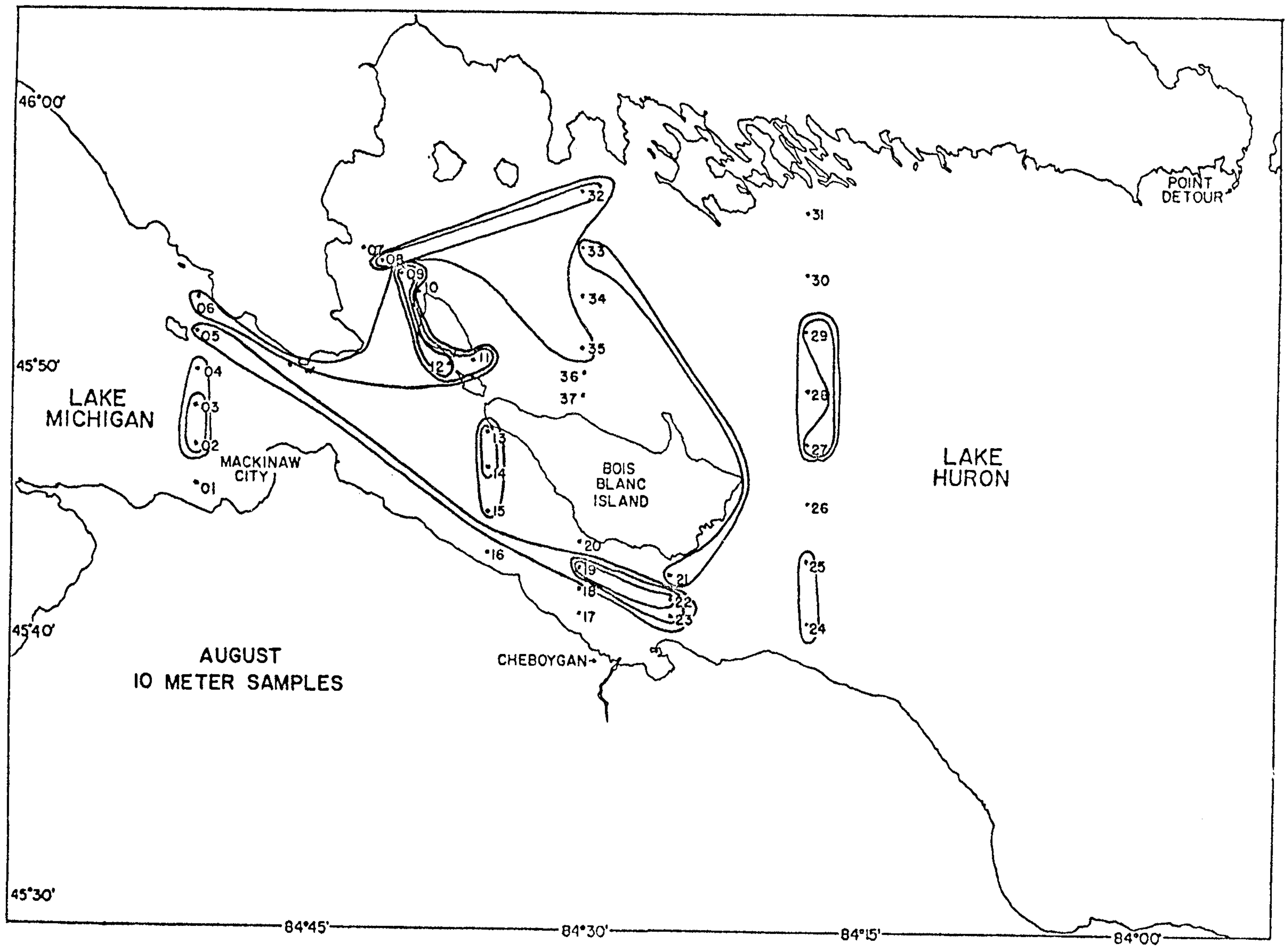

Figure 5.3. TEN-METER WATER DISTRIBUTION IN AUGUST. Only the strongest cluster associations are shown.

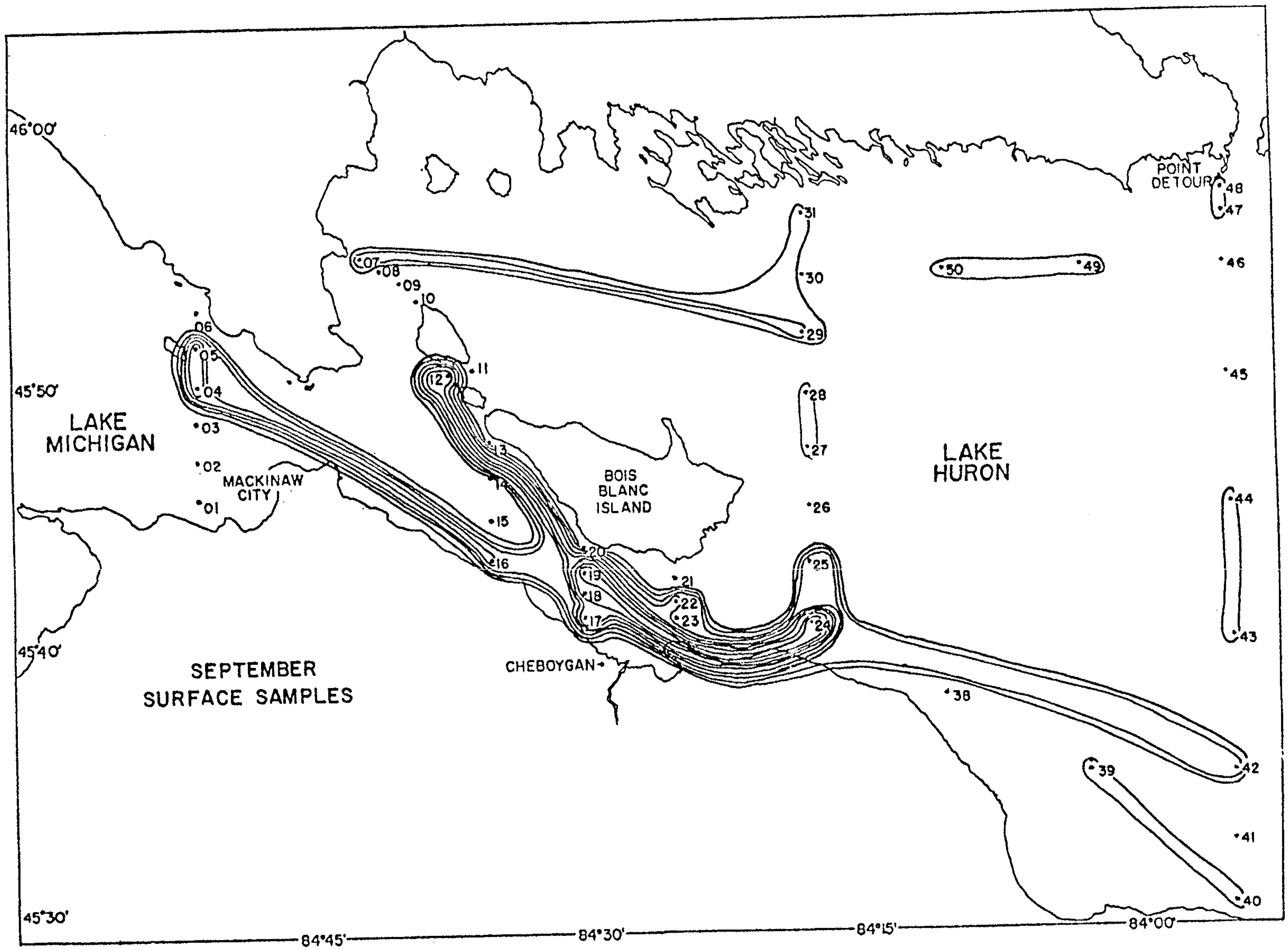

Figure 5.4. SURFACE WATER DISTRIBUTION IN SEPTEMBER. Only the strongest cluster associations are shown.

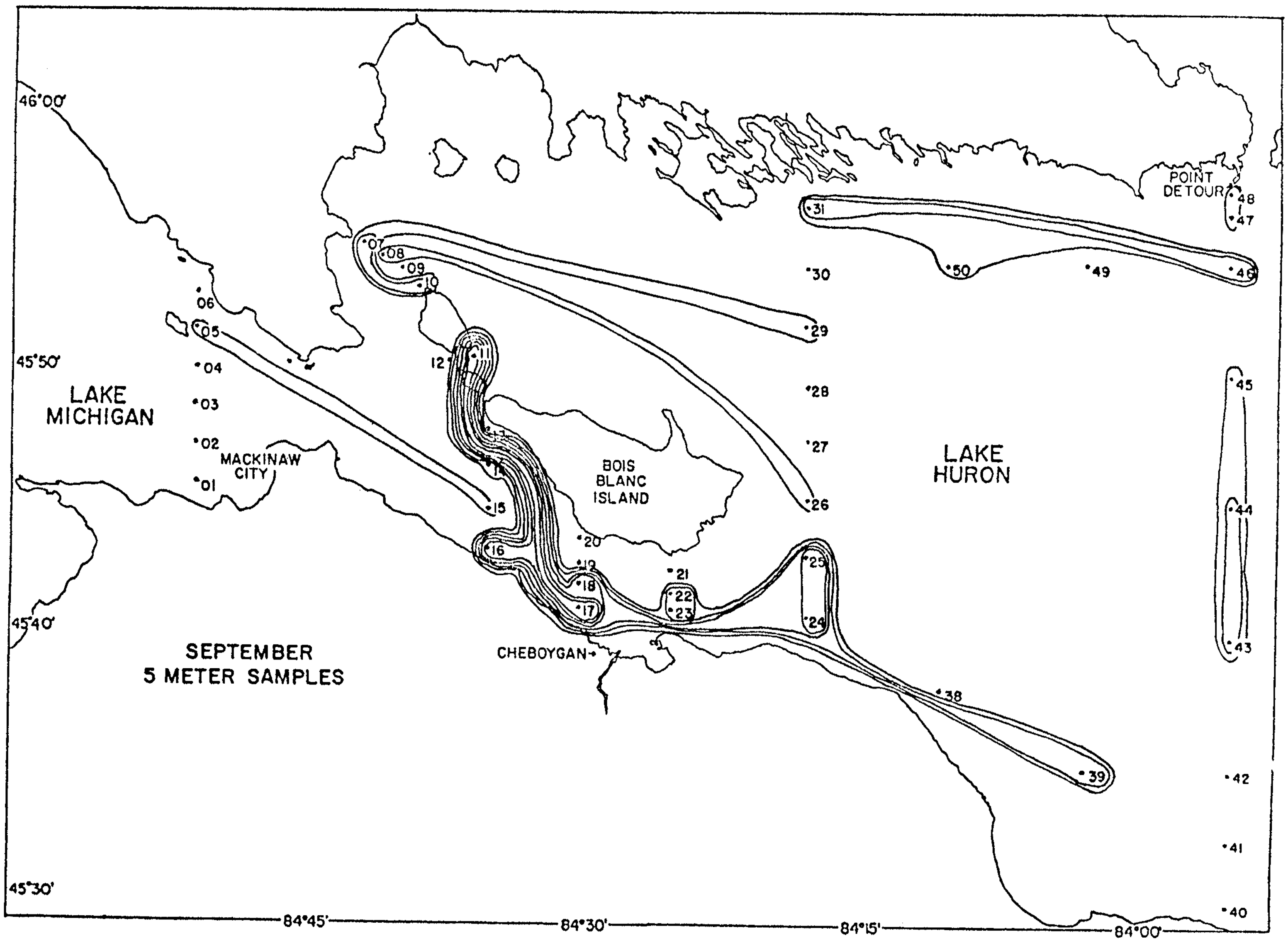

Figure 5.5. FIVE-METER WATER DISTRIBUTION IN SEPTEMBER. Only the strongest cluster associations are shown.

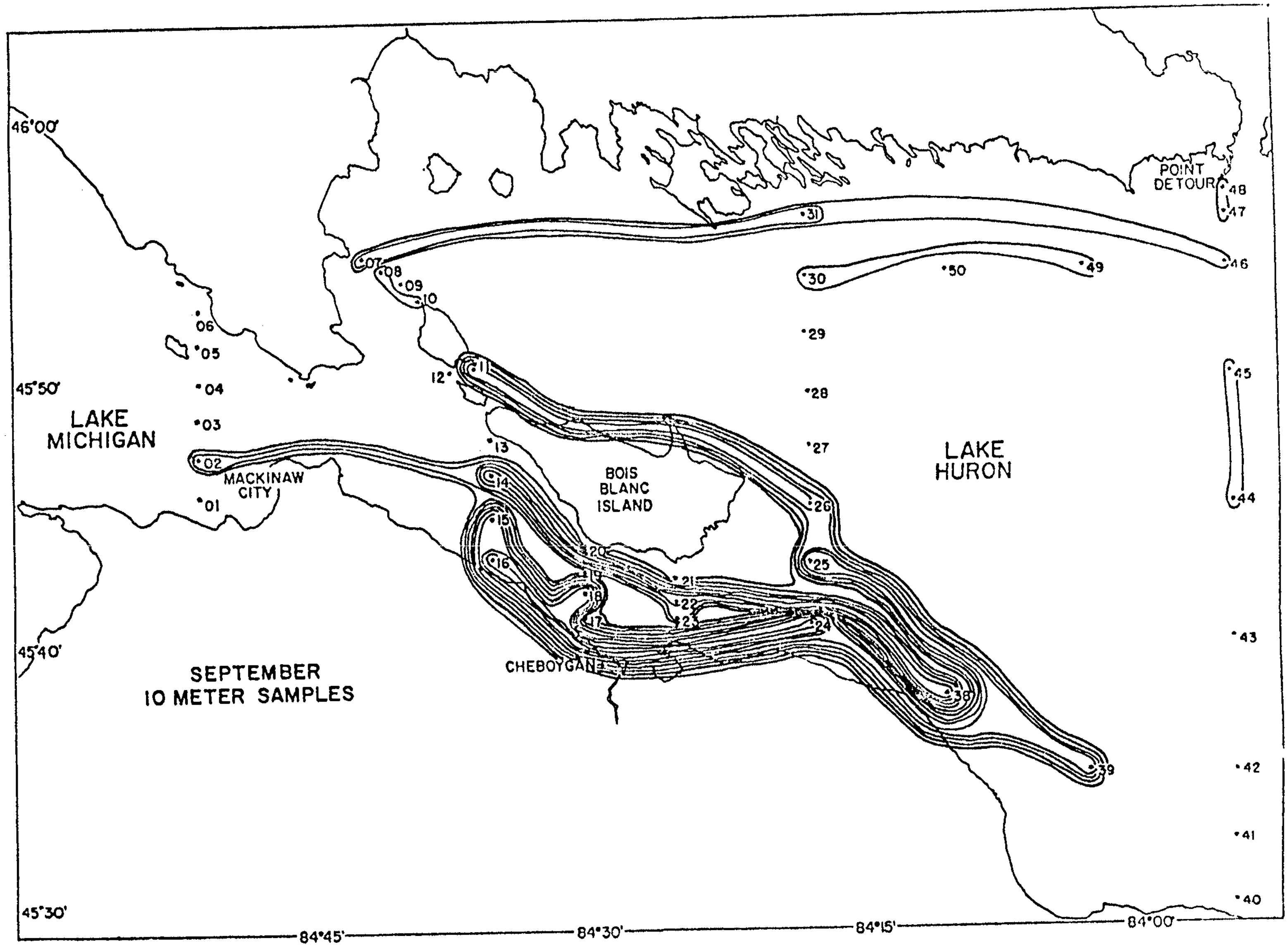

Figure 5.6. TEN-METER WATER DISTRIBUTION IN SEPTEMBER. Only the strongest cluster associations are shown.

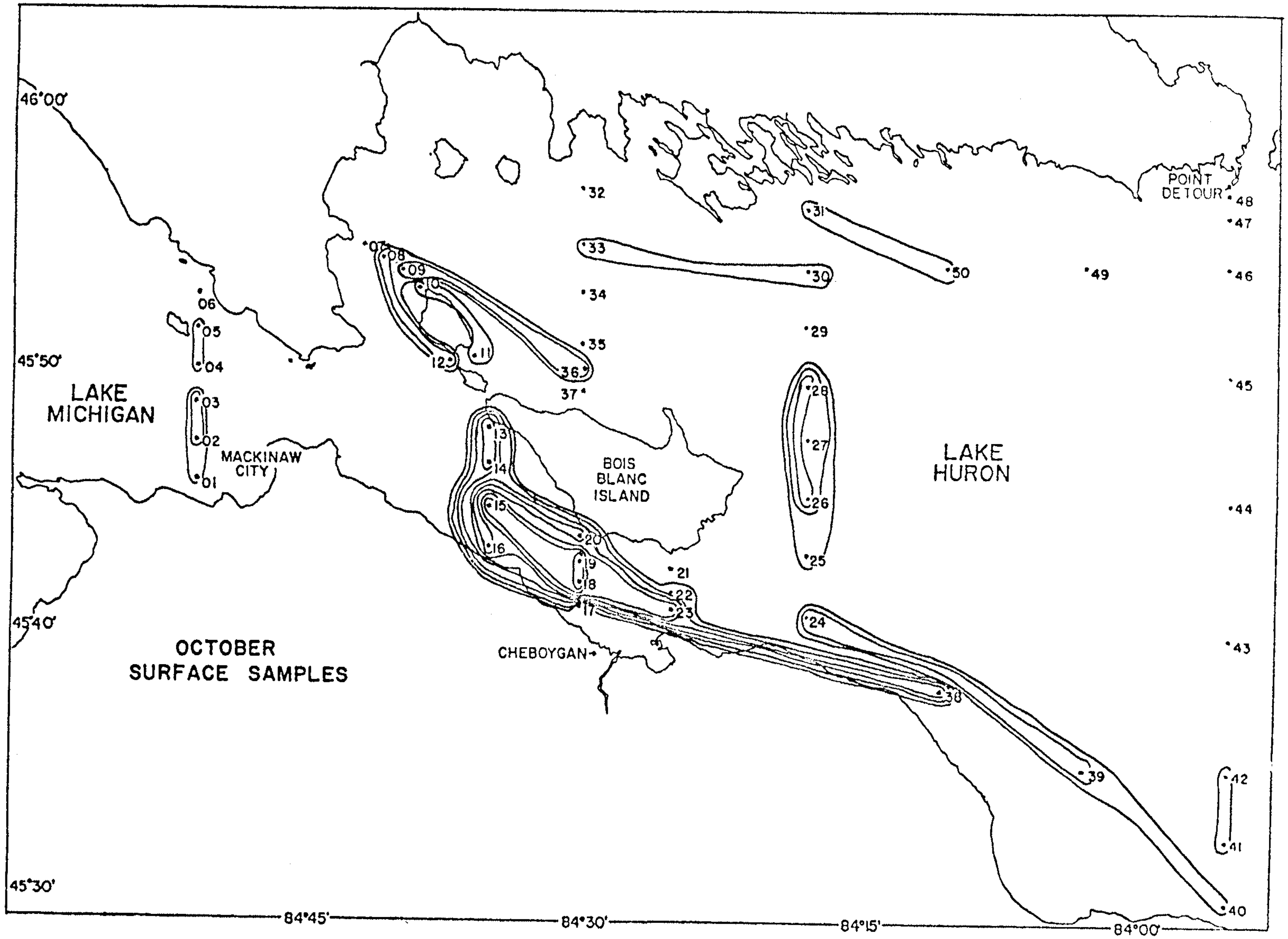

Figure 5.7. SURFACE WATER DISTRIBUTION IN OCTOBER. Only the strongest cluster associations are shown.

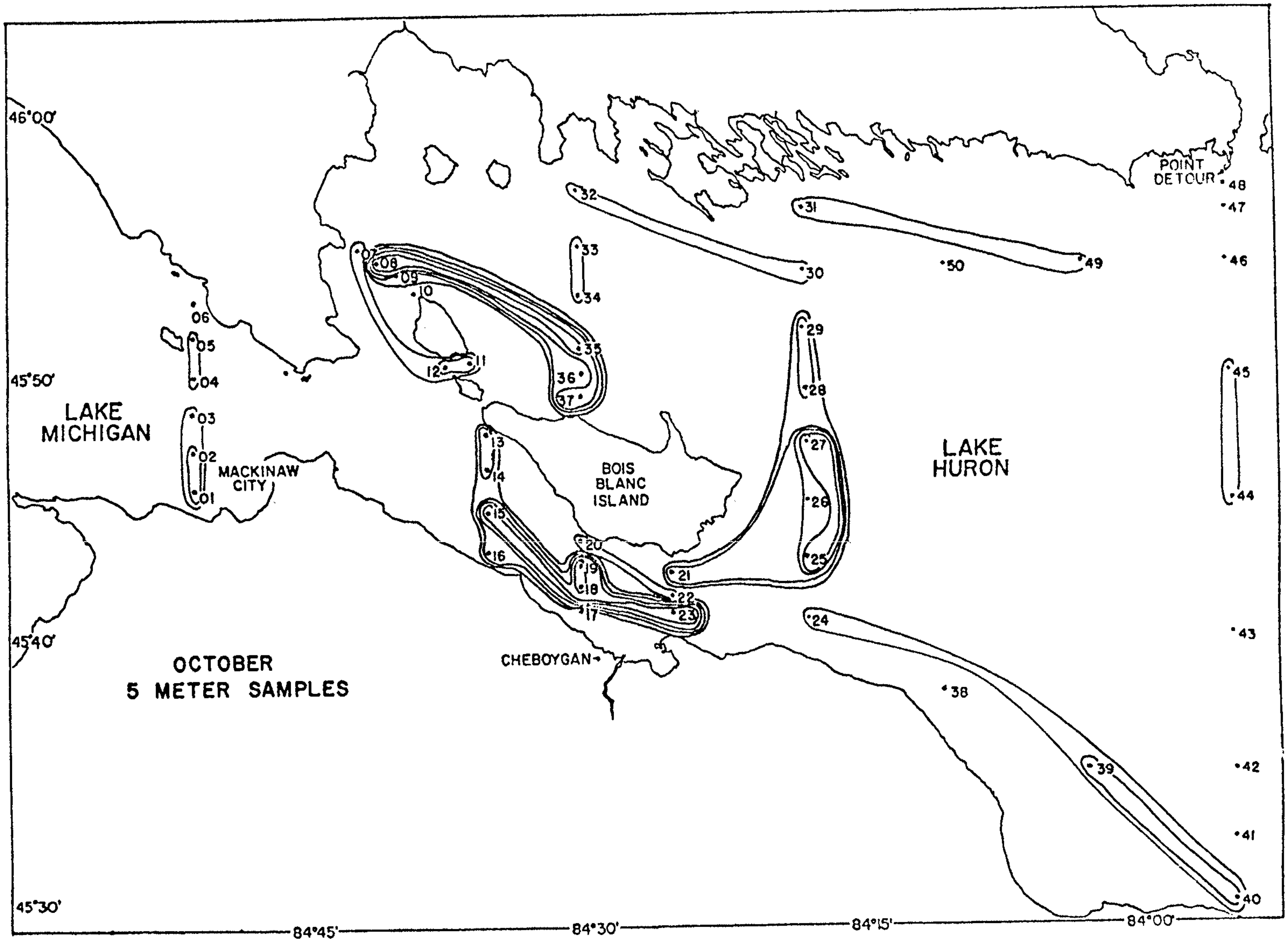

Figure 5.8. FIVE-METER WATER DISTRIBUTIONS IN OCTOBER. Only the strongest cluster associations are shown.

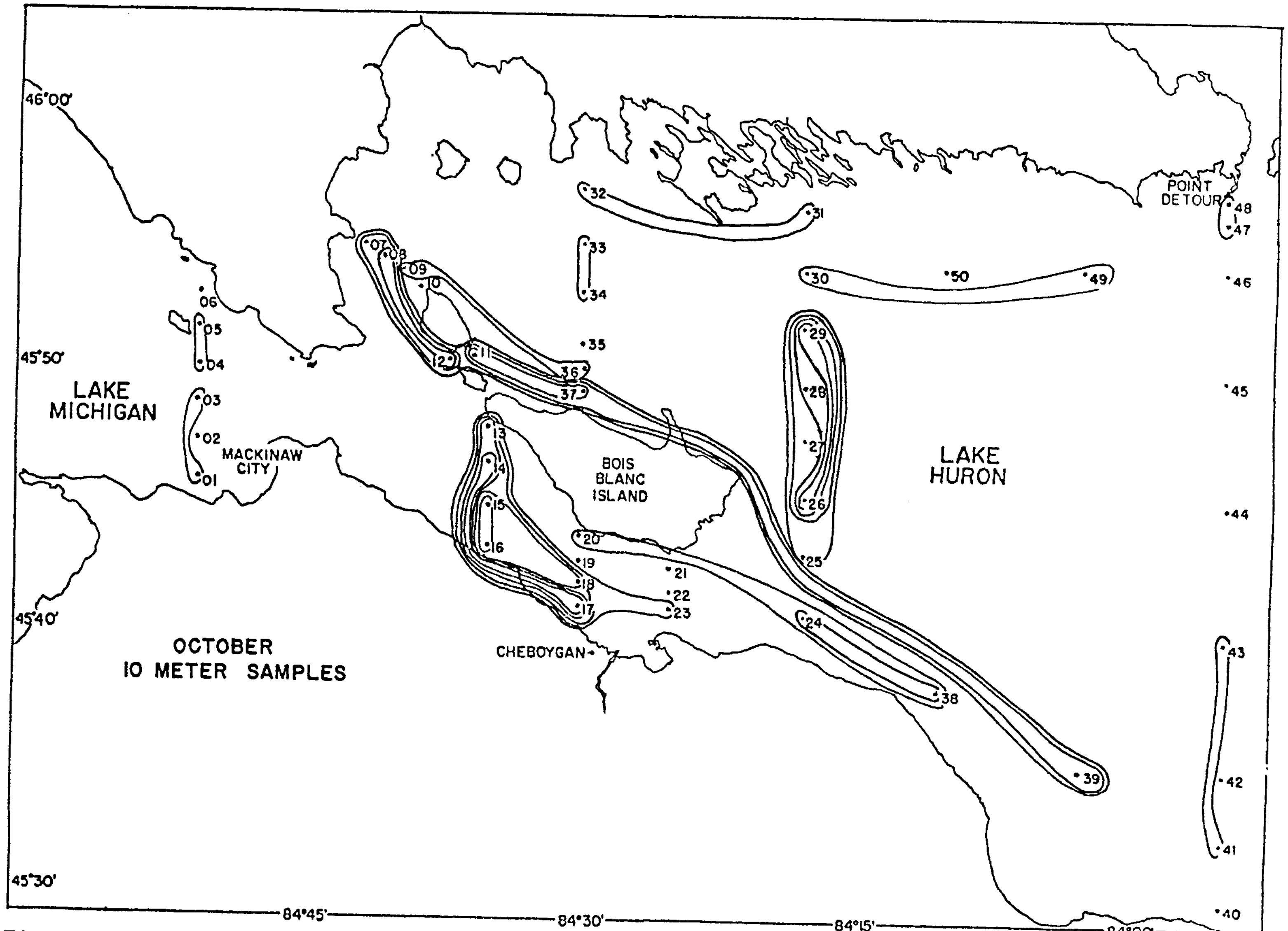

Figure 5.9. TEN-METER WATER DISTRIBUTION IN OCTOBER. Only the strongest cluster associations are shown.

In press). This 3-day period was unusual in that the flow from Lake Michigan was small; however, on the day preceding the cruise (5 Oct.) the transport from Lake Michigan to Lake Huron exceeded 50,000 m^3 sec^{-1}. Thermal stratification was no longer present at Stations 01-06 and 13-23 on this cruise, as surface water temperature had decreased (Table 3.1).

A final series of clustering analyses was performed with a reduced data set to determine the importance of certain key variables in the relationships obtained from the complete data set. Clustering analyses from each cruise for 0, 5, and 10-m samples were rerun using only water temperature, pH, silica, nitrate, and total phosphorus--the variables identified as major factors from the factor analysis (Table 5.1). Clusters produced from the analysis of the reduced data set were generally comparable with clusters from the full data set. For instance, surface samples from Cruise 1 with a reduced data set showed clusters south and north of Bois Blanc Island as well as a water mass west of Mackinac Island, just as did the analysis using the full data set (Fig. 5.2). The results differed in that the cluster north of Bois Blanc Island was a little larger in the reduced data set than for the full data set. Likewise, the full data set showed the water mass west of Mackinac Island was related to the mass south of Bois Blanc Island while the reduced data set did not show this association. These differences between the full and reduced data sets for the surface samples of Cruise 1 were typical of most comparisons between the full and reduced data sets. Results from the two data sets were most similar on Cruise 3 and least similar on Cruise 1.

Comparison of all variables with variables identified as major factors pointed out the pitfalls of sampling only a small number of parameters to describe water masses. Under certain conditions (e.g., as the calm winds during Cruise 3) both the full and reduced data sets gave the same results. Under other conditions, different conclusions would have resulted from analysis of the full data set than from analysis of the reduced set. Certain variables can be considered "key" or major variables all of the time with a good degree of reliability, but the interaction between those major variables and other variables can rarely be predicted. Due to unpredictable interactions, it is necessary to sample many variables to adequately describe water masses in unknown regions.

From results of all the clustering analyses, some general conclusions about the Straits area could be made. A large, homogeneous area of water extended from Lake Michigan into Lake Huron, although this area was disrupted by winds from the east and southeast during the cruise. The water mass extended generally from Lake Michigan through the Straits, past the western shore of Mackinac Island and south of Bois Blanc Island. Water characteristics were not greatly changed as the water mass passed near the shore and over shallow areas south of Bois Blanc Island, although there was evidence of greater proportions of Lake Huron water to the eastward. Water from Lake Huron was frequently identified at the extreme central-eastern part of the sampling area (Stations 43, 44, 45), yet was never associated with any water in the rest of the area. Water from the

St. Marys River, identified by several chemical parameters, was released into Lake Huron through Detour Passage. This water was identifiable only at Stations 47 and 48 in the immediate vicinity of the passage. Most water-mass associations were found only in the upper 10 m of the water column, with the deeper water remaining unmixed with the surface waters, except in areas of upwelling.

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SECTION VI

DISTRIBUTION AND ABUNDANCE OF PHYTOPLANKTON

by

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Theodore B. Ladewski

The major objective of this phase of the investigation was to determine if there were consistent differences in the quantitative and qualitative aspects of phytoplankton assemblages in Lake Michigan and Lake Huron and, if so, to what extent populations developed in Lake Michigan were transported to Lake Huron. Available information (Schelske and Roth 1973; Schelske 1975; Vollenweider et al. 1974) suggests that Lake Michigan is more eutrophied than Lake Huron. It appears that eutrophication of Lake Michigan has proceeded to the point where silica is becoming secondarily limiting during summer stratification (Schelske and Stoermer 1971), resulting in a shift of dominance in the phytoplankton assemblage from organisms requiring silica to those which do not (Schelske and Stoermer 1972; Stoermer 1972). Possibly also secondarily related to eutrophication, Ladewski and Stoermer (1973) show that some areas of Lake Michigan now have a midsummer transparency minimum similar to that observed in Lake Ontario (Dobson et al. 1974). Satellite altitude images of Lake Michigan (Strong et al. 1974) indicate that this phenomonon is probably most highly developed in the southern and eastern portions of the lake. Unfortunately, the area of our study is not included in the imagery reported by the above authors.

Although comprehensive studies are lacking, those available (Stoermer and Yang 1969; Schelske and Roth 1973; Schelske et al. 1974) indicate that the phytoplankton assemblages of both northern Lake Michigan and northern Lake Huron still retain elements of the oligotrophic *Cyclotella* flora characteristic of large boreal and alpine lakes, including relatively undisturbed portions of the Laurentian Great Lakes (Hutchinson 1967).

Due to the limited area covered by this investigation and the high probability of exchange and mixing between the two systems, effects in the Straits of Mackinac region might be expected to be subtle and highly time dependent. The evidence presented in this section, therefore, should be viewed as representative of specific situations. While the data presented may be representative of the general or average case, it would be desirable to investigate other seasons of the year and specific meteorological conditions.

6.1 MATERIALS AND METHODS

The material utilized in this phase of the investigation was obtained from the same stations and depths sampled for other parameters. At stations where a thermocline was present, samples were taken from 0 and 5 m and from depths just above and just below the thermocline. At shallow stations, samples were taken from the first four depths sampled. In addition to the stations sampled, a limited number of additional collections from the same time interval were inspected to confirm identity of questionable taxa or to attempt to further determine occurrence patterns of rare species. Immediately after collection in Niskin bottles, 50 ml of water were fixed with 4% glutaraldehyde, stored at 4.0°C in the dark for 1-4 hr to ensure complete fixation and then filtered onto 0.8 µm AA Millipore®, membrane filters (25 mm diameter). The filtered preparations were subsequently partially dehydrated in an ethanol series, cleared with beechwood creosote, and mounted on glass slides (Stoermer et al. 1974).

All identifications and enumerations reported were made using a Leitz Ortholux microscope fitted with an oil immersion objective and condenser system furnishing 1.32 numerical aperture and approximately 1200 X magnification. Population estimates were based on counting two 150-µm width, transects 10 mm in length. Reference samples have been retained in our laboratory.

Raw counts were coded and prepared so all data could be reduced by computer. Initial data reduction furnished population estimates in the form given in Table 6.1. Raw data in this form have been transmitted to the project officer and are available upon request.

Principal component analysis (PCA) was chosen as a parametric multivariate technique for analysis of phytoplankton cell concentrations. Untransformed cell densities were used in the correlation matrix. Taxa for PCA analysis were selected using three criteria. First, each taxon should be well defined taxonomically--composite categories were avoided. Second, each taxon should be counted with reasonable accuracy. Consequently it was required that each taxon exceed 5 colonies or individuals in at least one sample. Third, each taxon should be observed in at least 30% of all samples, eliminating locally or erratically distributed taxa; it was never applied directly since all taxa satisfying the second criterion also satisfied this one. Fourteen taxa fulfilled these criteria for the August and September cruises and 13 for the October cruise (Table 6.2).

Principal component analysis is a technique which reduces the number of dimensions in multidimensional data and at the same time retains a maximum amount of information in the original multidimensional data set. PCA performs the following operations on the data set. First, each parameter (taxon abundance) is scaled to its standard deviation. This allows taxa found in low abundances to be weighted equivalently to the more abundant taxa. Second, each taxon is, in effect, assigned an axis in a multidimensional Cartesian coordinate system, and each station is assigned a location in the coordinate system relative to the abundances

Table 6.1. EXAMPLE OF TABULATION OF PHYTOPLANKTON COUNTS.

EPA Straits of Mackinac October 1973

project:	EPA	survey number:	3
year:	1973	Julian day:	280 (7 Oct)
station:	49	depth:	5.0 m
latitude:	45° 54.1'	longitude:	84° 02.6'
number of cells counted:	367	volume of water scanned:	0.477 ml
diversity:	1.856	evenness:	0.557

division	number of species	cells/ml	SE	CV	% pop.
Cyanophyta (blue-green algae) . .	0	0.0	0.0	****	0.0
Chlorophyta (green algae)	2	10.5	2.1	0.20	1.362
Bacillariophyta (diatoms)	19	282.7	85.9	0.30	36.785
Chrysophyta (chrysophytes). . . .	3	437.7	123.6	0.28	56.948
Cryptophyta (cryptomonads). . . .	2	23.0	2.1	0.09	2.997
Pyrrophyta (dinoflagellates). . .	1	2.1	2.1	1.00	0.272
other	0	0.0	0.0	****	0.0
undetermined.	1	12.6	4.2	0.33	1.635
total	28	768.6	39.8	0.05	100.000

species name	cells/ml	SE	CV	% pop.
Chrysosphaerella longispina	414.7	104.7	0.25	53.951
Fragilaria crotonensis.	100.5	92.2	0.92	13.079
Asterionella formosa.	62.8	12.6	0.20	8.174
Cyclotella ocellata	25.1	8.4	0.33	3.270
Cyclotella stelligera	20.9	4.2	0.20	2.725
Dinobryon questionable sp. #1	20.9	20.9	1.00	2.725
Rhodomonas minuta var. nannoplanctica . . .	16.8	4.2	0.25	2.180
Undetermined cyst	12.6	4.2	0.33	1.635
Melosira distans var. alpigena.	12.6	12.6	1.00	1.635
Tabellaria fenestrata	12.6	12.6	1.00	1.635
Stephanodiscus minutus.	10.5	2.1	0.20	1.362
Cyclotella michiganiana	8.4	0.0	0.0	1.090
Ankistrodesmus sp. #3	6.3	2.1	0.33	0.817
Cryptomonas ovata	6.3	6.3	1.00	0.817
Rhizosolenia eriensis	6.3	2.1	0.33	0.817
Nitzschia acicularis.	4.2	4.2	1.00	0.545
Oocystis questionable spp..	4.2	4.2	1.00	0.545
Achnanthes clevei var. rostrata	2.1	2.1	1.00	0.272
Anomoeoneis vitrea.	2.1	2.1	1.00	0.272
Ceratium hirundinella	2.1	2.1	1.00	0.272
Cyclotella comta.	2.1	2.1	1.00	0.272
Cyclotella meneghiniana var. plana.	2.1	2.1	1.00	0.272
Cyclotella operculata	2.1	2.1	1.00	0.272
Diploneis elliptica var. pygmaea.	2.1	2.1	1.00	0.272
Diploneis oculata	2.1	2.1	1.00	0.272
Eucocconeis lapponica	2.1	2.1	1.00	0.272
Mallomonas pseudocoronata	2.1	2.1	1.00	0.272
Rhizosolenia gracilis	2.1	2.1	1.00	0.272

Table 6.2. SPECIES AND DATA PROCESSING CODE FOR PHYTOPLANKTON USED IN THE PRINCIPAL COMPONENT ANALYSIS.

Code	Taxon name	Type	Used in the PCA for Aug	Sep	Oct
ANINCE	*Anacystis incerta*	Blue-green	X	X	X
ANTHER	*Anacystis thermalis*	Blue-green	X	X	X
ASFORM	*Asterionella formosa*	Diatom			X
CHDOKI	*Chrysococcus dokidophorus*	Chrysophyte		X	X
CNOVAT	*Cryptomonas ovata*	Cryptomonad	X	X	X
CRQUAD	*Crucigenia quadrata*	Green	X		
CYCOMT	*Cyclotella comta*	Diatom	X	X	X
CYMICH	*Cyclotella michiganiana*	Diatom	X	X	X
CYSTEL	*Cyclotella stelligera*	Diatom	X	X	X
CYOCEL	*Cyclotella ocellata*	Diatom	X	X	X
CYOPER	*Cyclotella operculata*	Diatom	X	X	
ETSPEQ	*Eutetramorus* species #1	Green	X		
GLPLAN	*Gloeocystis planktonica*	Green	X		
GMLACU	*Gomphosphaeria lacustris*	Blue-green	X	X	
OOSPP	*Oocystis* spp.	Green	X	X	X
RDMINU	*Rhodomonas minuta* v. *nannoplanctica*	Cryptomonad	X	X	X
RHERIE	*Rhizosolenia eriensis*	Diatom		X	X
SYFILI	*Synedra filiformis*	Diatom		X	X

of the taxa at that station. Stations with similar phytoplankton compositions, after the previously performed standardization, will in a Euclidean sense be closer to each other in the multidimensional space than stations dissimilar in composition. PCA projects the location of each station in multidimensional space to a new set of mutually orthogonal axes called principal components.

Associated with each taxon and principal component is a loading factor which may be interpreted as the cosine of the angle the taxon's axis makes with the principal component. The loading factor indicates how important that taxon is in determining the principal component (PC). The first axis (the first PC) is chosen to contain the maximum possible variance and thus will provide the best discrimination between stations of any of the PCs. The second axis (second PC) contains the greatest variance possible under the constraint of orthogonality with the first. The data set can be completely described only by determining all principal components. If the data set contains more stations than taxa, that number of PCs will be equal to the number of taxa. However, if the first few PCs contain a large percentage of the variance, they will contain enough information to justify ignoring all the rest for the sake of simplicity of interpretation. Since the PCs are chosen to be orthogonal, scores of stations relative to the principal components may be used as coordinates in a plot to show the location of stations relative to one another. Relative locations of stations on the plot will roughly approximate relative locations of stations in the multidimensional space. Stations very dissimilar in composition may be identified and, to a somewhat lower degree of certainty, very similar stations may be identified also on the basis of proximity on the plot. If only the first two PCs are retained, PCA reduces the multidimensional data set to two dimensions. More complete descriptions of the technique are given by Orloci (1966) and Morrison (1967).

Additional information about the application of PCA to phytoplankton cell densities is found in the discussion of results from October (Sec. 6.4). Information on the cumulative percent variance, eigenvalue, and statistical significance of each principal component derived from the analysis of the August, September and October phytoplankton data is presented in Table 6.3.

6.2 TAXONOMIC COMPOSITION OF THE PHYTOPLANKTON ASSEMBLAGE

A list of taxa encountered in this study is given in Appendix D. Many of the 289 taxa recorded are primarily benthic in habitat preference, and their occurrence in plankton collections is probably accidental. As would be expected, numbers of pseudoplankton were greatest at stations nearest shore although some occurrences were noted in most samples examined. Pseudoplankton was most common in the Detour Passage region (Stations 46, 47, 48) where a large number of species apparently were derived from the St. Marys River. Abundance estimates for most of these taxa were small and subject to large errors, so primary emphasis has been given to euplanktonic taxa in the analysis of data.

Bacillariophyta were the dominant organisms in the taxonomic listing, comprising 222 of the 289 species and 34 of the 67 genera (Table 6.4). Eight common genera accounted for 160 of the species of diatoms; only 62 species occurred in the other 26 genera of diatoms. Most species that were not diatoms were Chlorophyta or green algae. Only five species of blue-green algae were recorded.

Abundance of phytoplankton was greatest during the August cruise and least during the October cruise, with relatively small variations in total counts among stations during each cruise (Fig. 6.1). In September, total counts were smaller at stations in the northeastern sector of the sampling area than those on the most westerly transect and along the southern shore. This difference in abundance was present in October, but the range in total cell counts was smaller than in September.

The taxonomic composition of the phytoplankton also changed during the study; the abundance of blue-green and green algae decreased during successive sampling periods (Figs. 6.2 and 6.3). In both cases highest numbers were found on the August cruise. Blue-greens and greens were less abundant in September when the abundance of greens was very small.

Table 6.3. RESULTS OF THE PCA OF 5-M PHYTOPLANKTON SAMPLES FOR THE FIRST THREE PRINCIPAL COMPONENTS.

August

Number of samples: 39
Number of taxa: 14

	PC1	PC2	PC3
Cumulative % variance	29%	43%	55%
Eigenvalue	4.0	2.1	1.6
Significance[a]	.002	.025	.084

September

Number of samples: 32
Number of taxa: 14

	PC1	PC2	PC3
Cumulative % variance	34%	48%	60%
Eigenvalue	4.8	2.0	1.7
Significance	.000	.002	.011

October

Number of samples: 40
Number of taxa: 13

	PC1	PC2	PC3
Cumulative % variance	35%	50%	61%
Eigenvalue	4.5	2.0	1.4
Significance	.000	.001	.005

[a]The significance values result from Bartlett's test of the hypothesis that the determinant of the residual matrix is zero (eg. Cooley and Lohnes 1971).

Table 6.4. PHYTOPLANKTON IN THE STRAITS OF MACKINAC.

Species		
Bacillariophyta		222
Chlorophyta		44
Chrysophyta		12
Cryptophyta		3
Cyanophyta		5
Pyrrophyta		3
	Total	289
Genera		
Bacillariophyta		34
Chlorophyta		21
Chrysophyta		4
Cryptophyta		2
Cyanophyta		4
Pyrrophyta		2
	Total	67
Species of Common Bacillariophyta		
Navicula		26
Nitzschia		26
Achnanthes		23
Fragilaria		22
Cyclotella		19
Synedra		18
Cymbella		16
Stephanodiscus		10
	Total	160

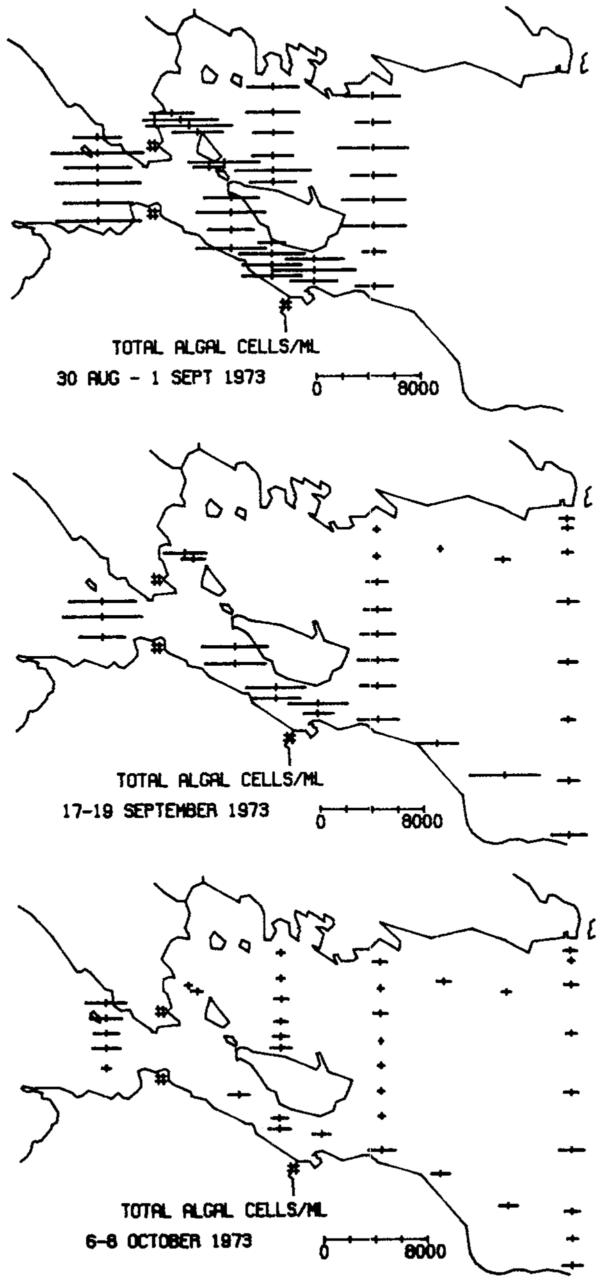


Figure 6.1. DISTRIBUTION OF TOTAL ALGAL CELL COUNTS.

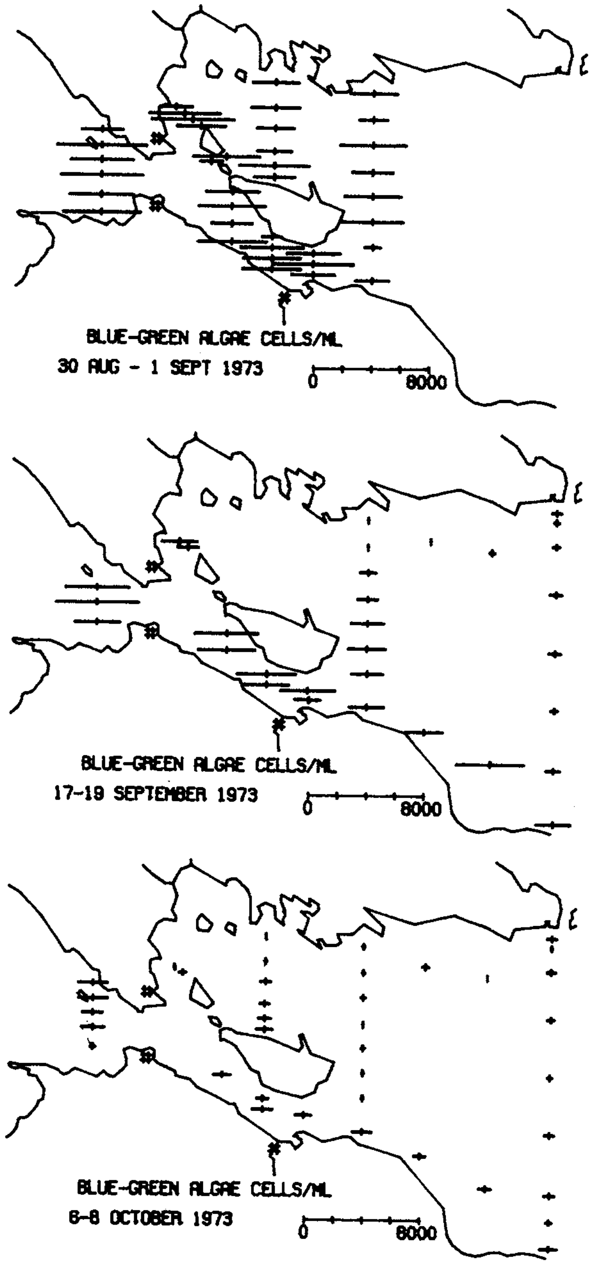


Figure 6.2. DISTRIBUTION OF BLUE-GREEN ALGAE.

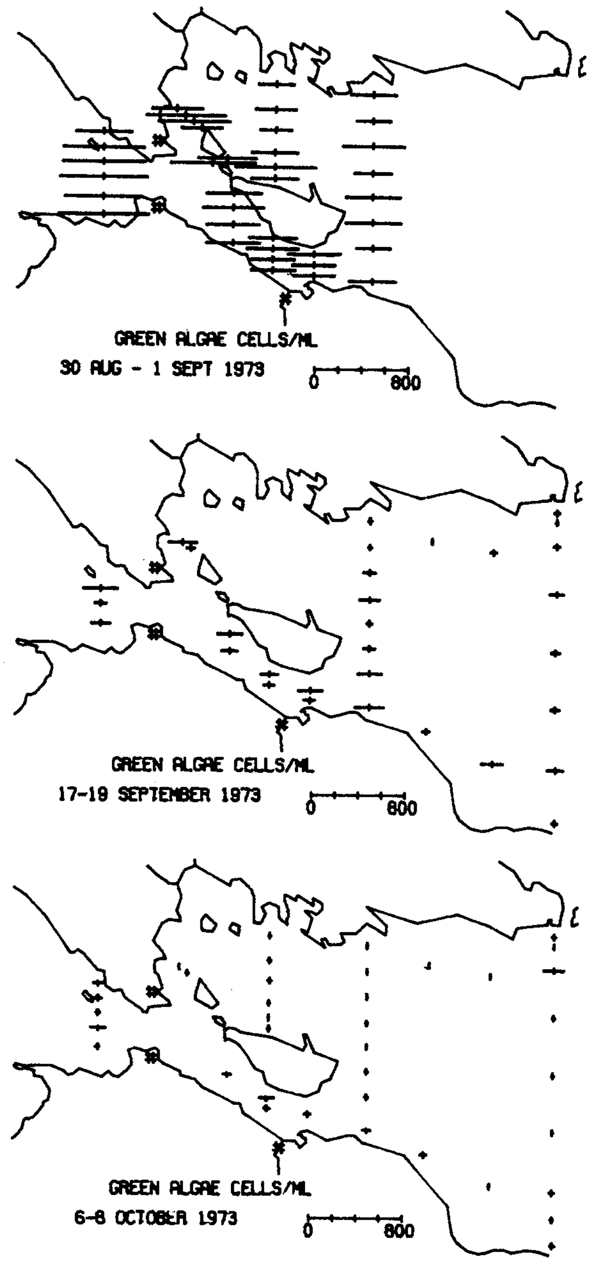


Figure 6.3. DISTRIBUTION OF GREEN ALGAE.

Blue-greens and greens tended to be more abundant at western stations and those along the southern shore than at other locations. The abundance of diatoms (Fig. 6.4) fluctuated much less drastically, and no clear patterns were apparent in their occurrence.

6.3 DISTRIBUTION OF MAJOR SPECIES

Asterionella formosa is apparently an extremely eurytopic diatom, occurring in a wide variety of habitats (Huber-Pestalozzi 1942) and thriving under most conditions found in the Great Lakes. According to Hohn (1969) it is one of the species whose absolute abundance did not change appreciably in Lake Erie between 1938 and 1965. Scattered populations were found in our August samples (Fig. 6.5) and no discernible pattern of occurrence was apparent. Some increase in average abundance was noted in September with an apparent tendency for highest population levels to occur at stations nearest shore. In October, *A. formosa* was abundant at most stations sampled but population levels remained low at offshore stations in Lake Huron.

Cyclotella comta is a species widely reported from mesotrophic to oligotrophic habitats. It is common in the upper lakes but apparently absent from Lake Erie (Hohn 1969) and exceedingly rare in Lake Ontario (Stoermer et al. 1974). Populations were noted at all stations sampled during August (Fig. 6.6), with highest abundance being found at stations on the most easterly transect sampled. In September, relatively high population levels were found at Stations 40-45 on the most easterly transect, not sampled the previous month; but abundance was substantially lower at stations west of this transect. Although still present at most stations sampled during October, *C. comta* had declined to a relatively minor element of the assemblage by this time and no marked trends in distribution were evident.

Cyclotella ocellata appears to be characteristic of relatively undisturbed habitats in the Great Lakes (Stoermer and Yang 1970). Only a few isolated populations were noted in August (Fig. 6.7), but it was quite abundant in September at some stations in the northeastern sector of the area sampled. Abundance of *C. ocellata* was more uniform in October than on the two previous cruises. Our evidence suggests that this species maintains metalimnetic populations during the summer, and population increases in September and October are at least partially the result of upwelling and metalimnetic entrainment.

Cyclotella operculata (Fig. 6.8) appears to have similar ecological affinities to *C. ocellata* (Stoermer and Yang 1970). In our samples, it is consistently less abundant than that species and, partially because of the low population levels, its distribution pattern is not as clear. In all months sampled, highest population levels were found at stations in the eastern section of the sampling area.

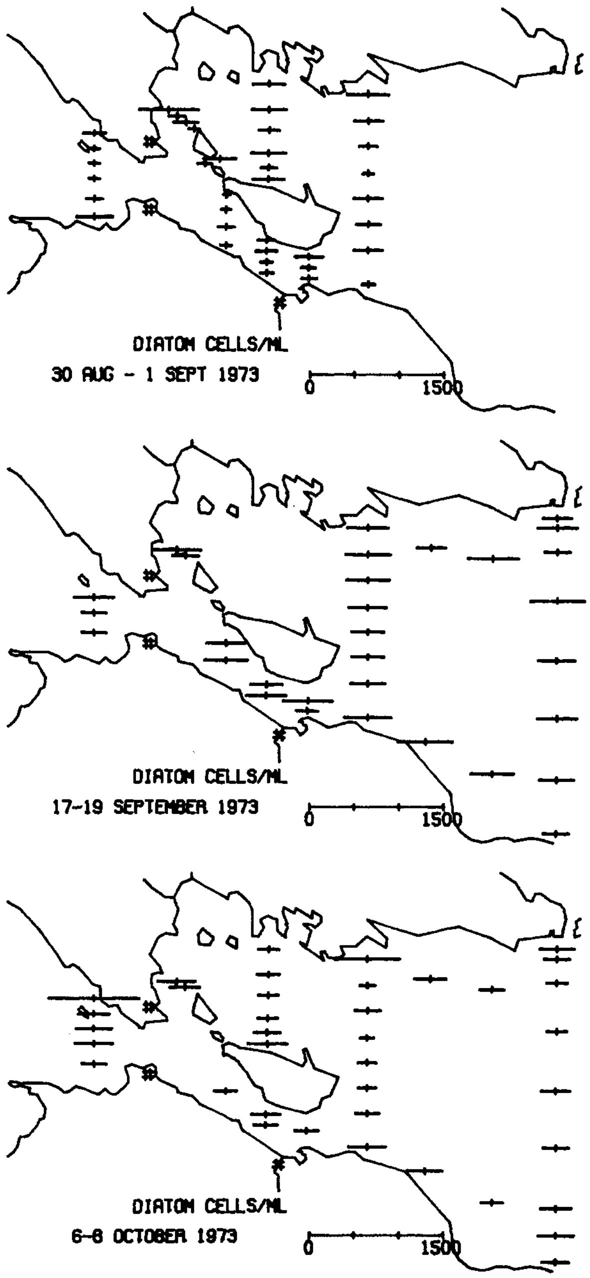


Figure 6.4. DISTRIBUTION OF DIATOMS.

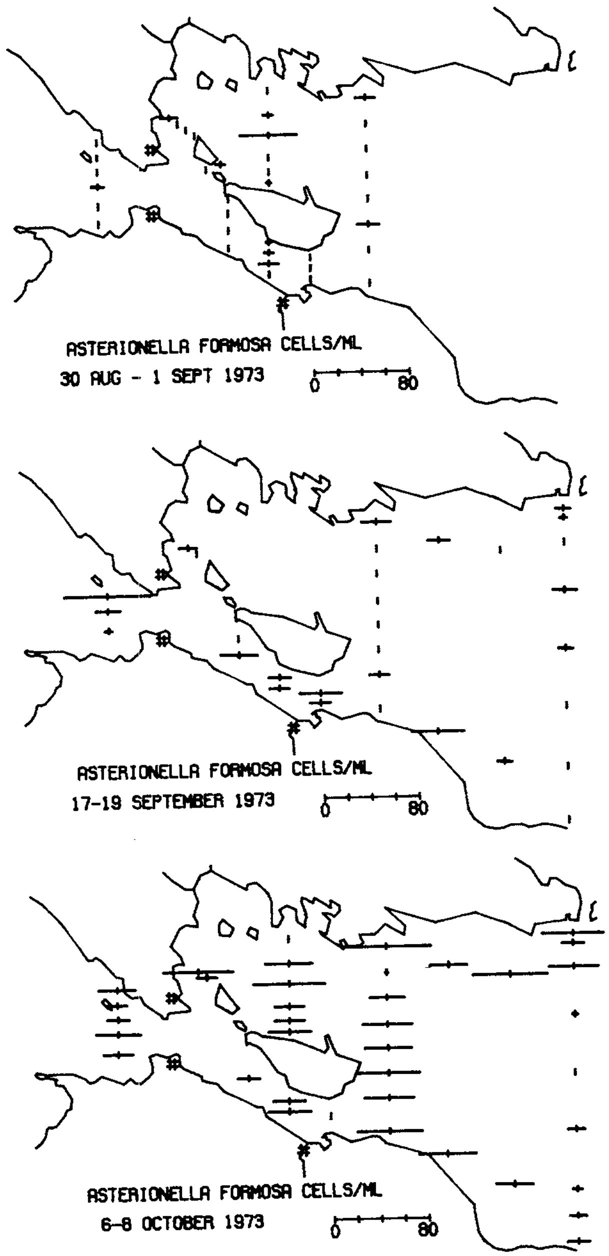


Figure 6.5. DISTRIBUTION OF *ASTERIONELLA FORMOSA*.

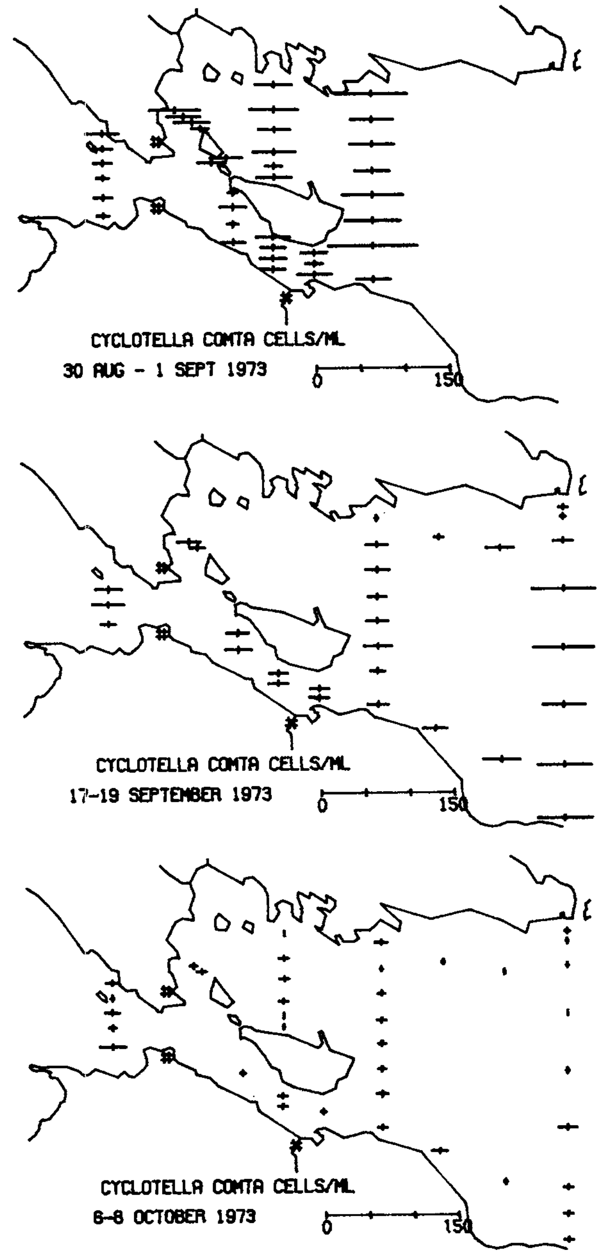


Figure 6.6. DISTRIBUTION OF *CYCLOTELLA COMTA*.

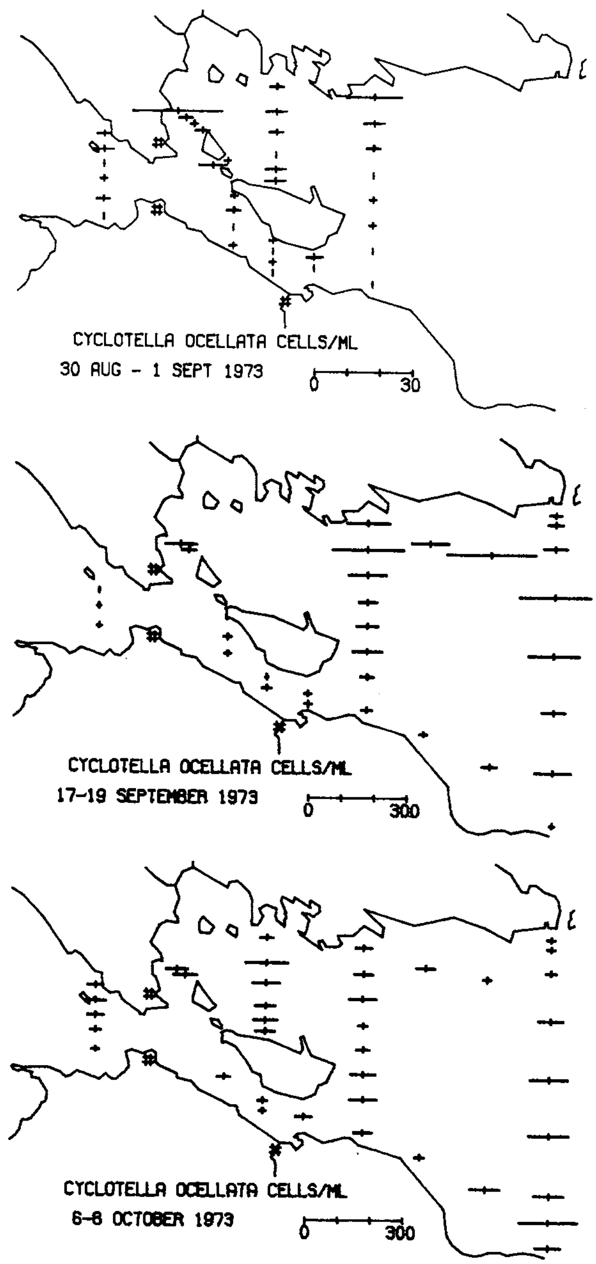


Figure 6.7. DISTRIBUTION OF *CYCLOTELLA OCELLATA*.

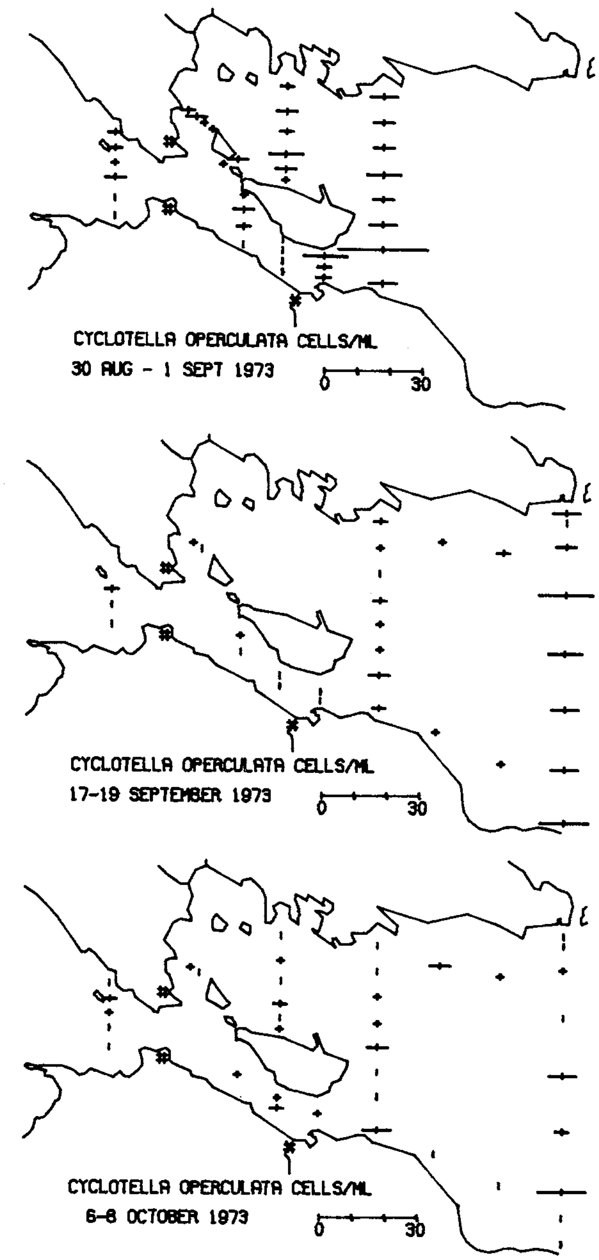


Figure 6.8. DISTRIBUTION OF *CYCLOTELLA OPERCULATA*.

Cyclotella michiganiana (Fig. 6.9) is very widely distributed in the phytoplankton of the upper Great Lakes. Available evidence suggests that it is tolerant of low levels of eutrophication but is eliminated from habitats which have been grossly modified (Schelske et al. 1974). It was fairly abundant and evenly distributed in August with an apparent trend toward higher population levels at offshore stations in Lake Huron. This pattern was reversed in September; population levels increased at stations along the southern shore and on the Lake Michigan side of the Straits but remained static or declined in the northeastern sector. The trend toward higher populations in Lake Michigan was accentuated in the results from the October cruise.

Cyclotella stelligera (Fig. 6.10) is a common component of the offshore phytoplankton flora of the upper Great Lakes. Similar to *C. michiganiana*, it appears to be favored by low levels of eutrophication and responds strongly to experimental nutrient enrichment (Schelske and Stoermer 1972; Schelske et al. 1972). Apparently, however, it is not tolerant of high levels of pollution. Hohn (1969) lists it as one of the species that decreased markedly in abundance in Lake Erie between 1938 and 1965. Its abundance in Saginaw Bay (Schelske et al. 1974) and the nearshore waters of Lake Michigan is reduced relative to less eutrophic open waters. During August this species was present in remarkably uniform numbers at most stations sampled. There was some tendency for higher values to occur nearer the northern Lake Huron shore and the lowest values near the southern shore. Abundance was greatest in September at all stations sampled. By October, abundance decreased at stations in the northeastern sector of the sampling area, but *C. stelligera* remained relatively abundant at stations along the southern shore and on the Lake Michigan side of the Straits.

Fragilaria crotonensis (Fig. 6.11) is one of the eurytopic plankton dominants which apparently can tolerate the extreme range of environmental conditions presently found in the Great Lakes. Similar to *Asterionella formosa*, it did not show strong trends in regional or seasonal abundance during the study. Interpretation of its distribution is complicated by large uncertainties in population estimates resulting from patterns of indeterminate colonial growth.

Synedra filiformis (Fig. 6.12) has not been widely reported from the Great Lakes, and its distribution and ecological affinities are relatively poorly known. It is apparently abundant in the offshore waters of Lake Michigan (Stoermer and Yang 1970) and during the spring phytoplankton maximum in Grand Traverse Bay (Stoermer et al. 1972). Published reports, however, indicate that it is abundant only at stations near the mouth of Saginaw Bay in Lake Huron (Schelske et al. 1974). In the present study, its distribution was remarkable in that populations were largely restricted to stations along the southern coast and on the Lake Michigan side of the Straits. Small populations were noted in the Detour Passage region during September and October. This species was present in low densities, but showed a general trend towards increased abundance during the period studied.

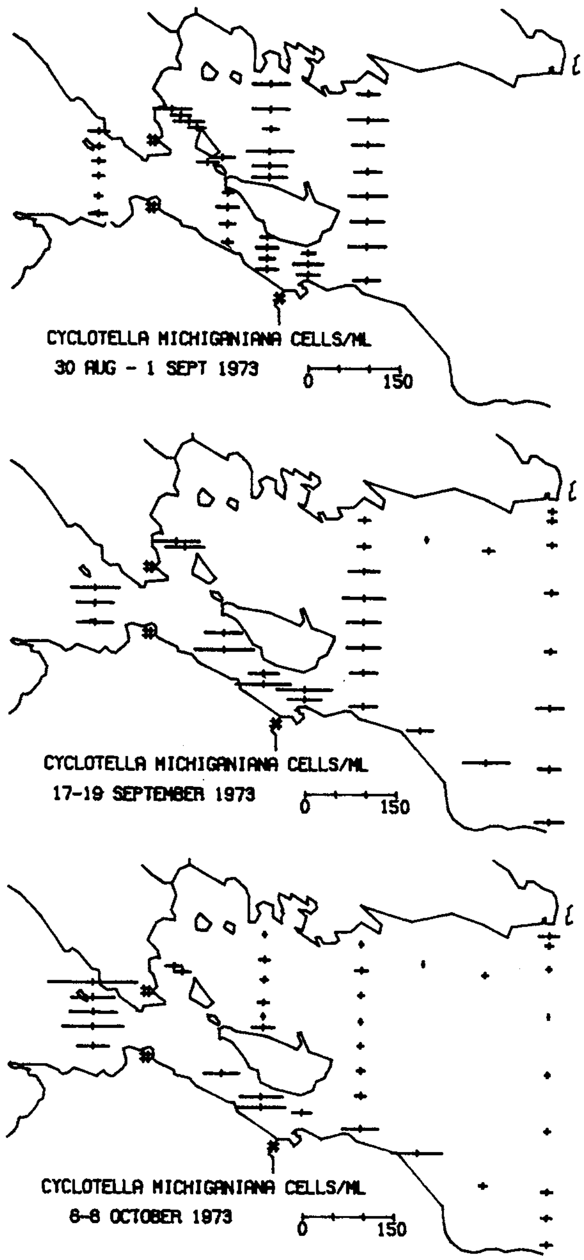


Figure 6.9. DISTRIBUTION OF *CYCLOTELLA MICHIGANIANA*.

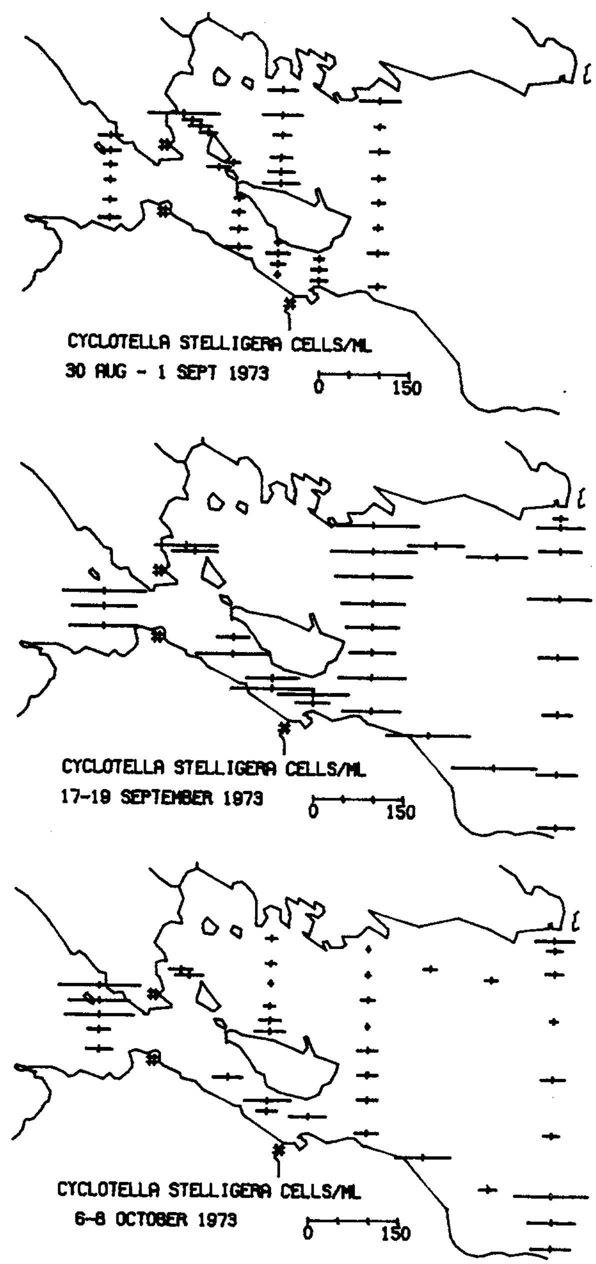


Figure 6.10. DISTRIBUTION OF *CYCLOTELLA STELLIGERA*.

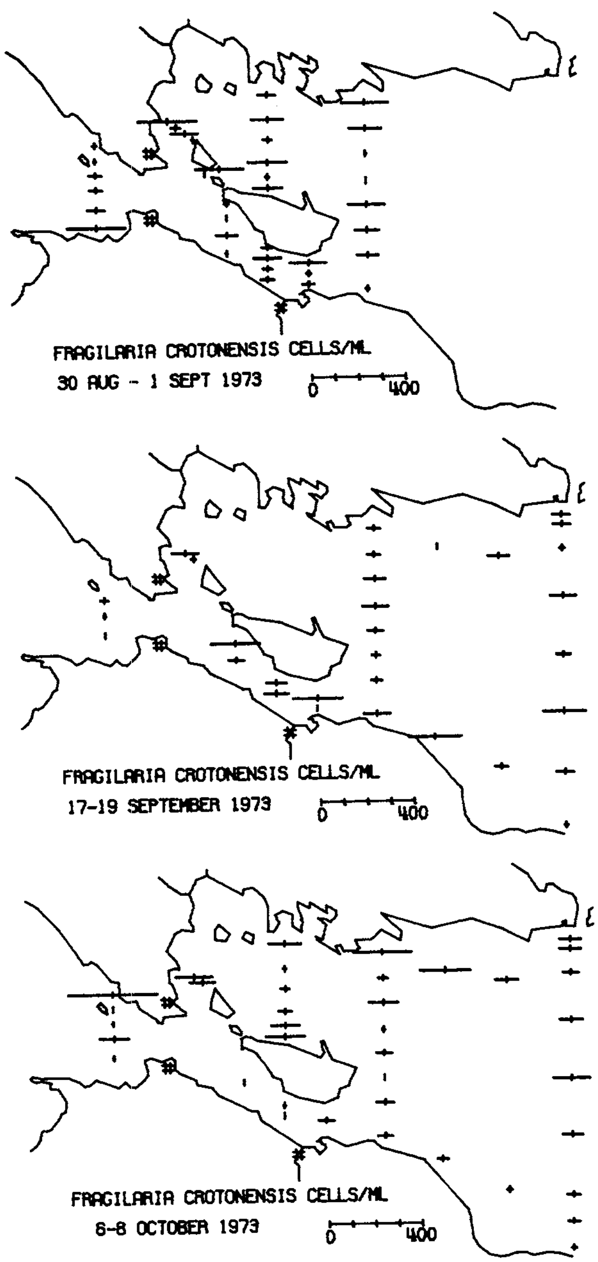


Figure 6.11. DISTRIBUTION OF *FRAGILARIA CROTONENSIS*.

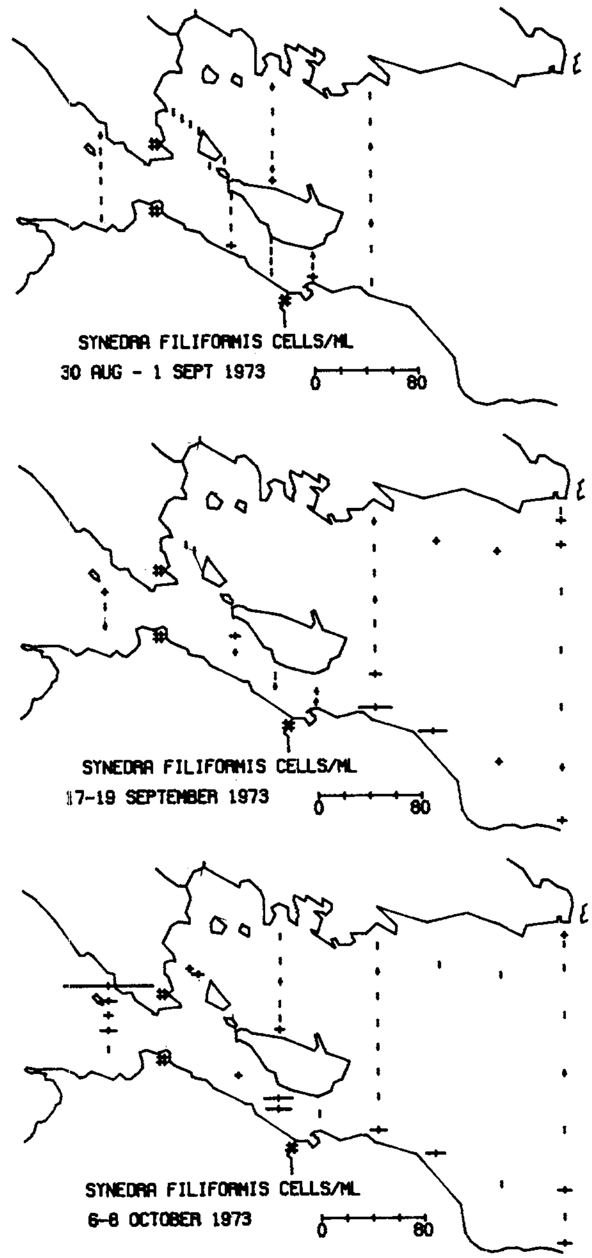


Figure 6.12. DISTRIBUTION OF *SYNEDRA FILIFORMIS*.

Rhizosolenia eriensis (Fig. 6.13) is one of the characteristic species of phytoplankton assemblages in the upper Great Lakes. In recent decades its abundance has been reduced in Lake Erie (Hohn 1969) and Lake Ontario (Stoermer et al. 1974), but it continues to be a fairly important component of assemblages in the upper lakes. The known distribution of *R. eriensis* suggests that it is a summer ephemeral, developing transient population maxima rapidly in regions where favorable conditions exist.

Only a few scattered occurrences of this species were noted in our August samples. Population densities increased generally at stations sampled during the September cruise, with largest increases noted in the northeastern and eastern segment of the region sampled. During the October cruise, population densities remained relatively high with a more uniform distribution than had been observed previously.

The genus *Tabellaria* is common throughout the Great Lakes system. A number of growth forms are present (Koppen 1975), and at the present time the precise taxonomic affinities of the populations which occur in the Straits of Mackinac area are uncertain. In the present study we have adopted the taxonomic criteria and nomenclature of Hustedt (1930). Populations identified as *T. fenestrata* (Fig. 6.14) on this basis were rare in samples from the August cruise, and the three occurrences noted were at stations north of Bois Blanc Island. Scattered populations were noted in September samples and there was no readily discernible pattern of occurrence. In October this entity had high levels of abundance at stations in the northern sector of the study area in Lake Huron, and it was either present in very low densities or absent in the southeastern sector.

Scattered populations of *Tabellaria fenestrata* var. *intermedia* (Fig. 6.15) were found at stations sampled during the August cruise, with no obvious pattern of greatest abundance. During September it was noted only in samples from the Detour Passage vicinity and at a few stations south of Bois Blanc Island. A similar pattern of occurrence was noted in October, but *T. fenestrata* var. *intermedia* was also present at stations west of the Straits where it had not occurred the previous month.

Chrysococcus (*dokidophorus* Pasch.?), a species of questionable taxonomic status, had an unusual temporal and areal distribution. It was not noted during August (Fig. 6.16), but was present in most samples and locally abundant in September. Largest populations in September were found in open-water Lake Huron stations east and northeast of Bois Blanc Island, but in October it was relatively abundant at most stations sampled, with no obvious trend in its distribution. This species has not been reported previously from the Great Lakes and its ecological affinities are very poorly known.

Chrysophaerella longispina (Fig. 6.17) has rarely been reported from the Great Lakes, but large populations were found at certain stations in Lake Huron during October. Isolated populations were noted in August but not in September. Its distribution is unusual in that occurrences were restricted to stations east and north of Bois Blanc and Mackinac Islands.

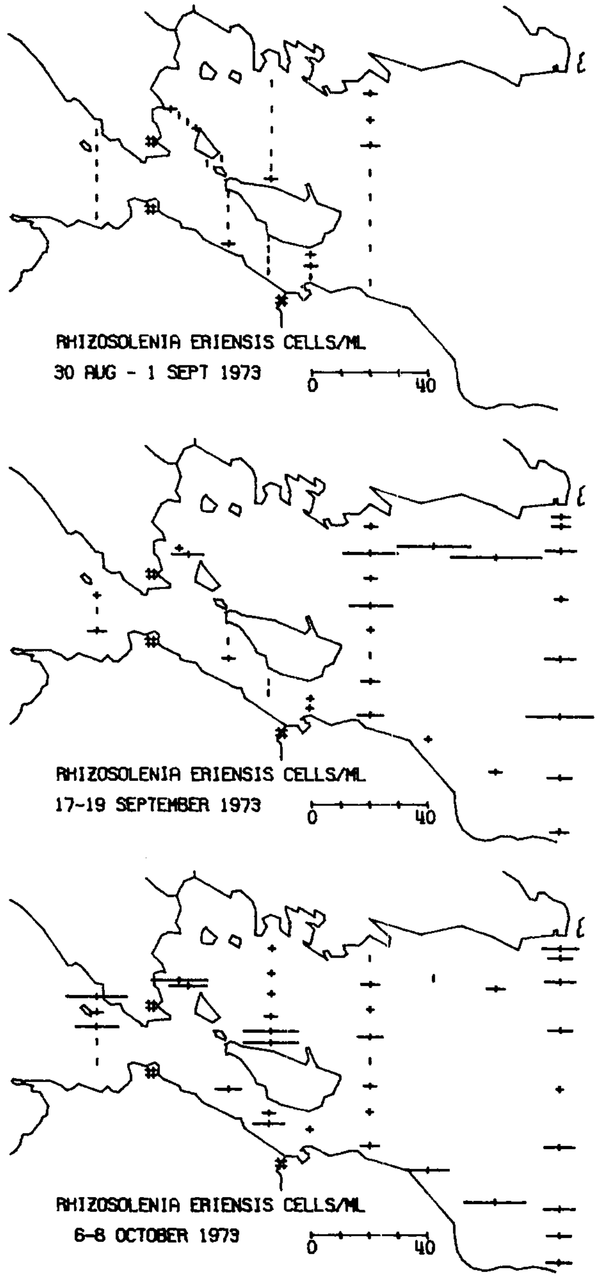


Figure 6.13. DISTRIBUTION OF
RHIZOSOLENIA ERIENSIS.

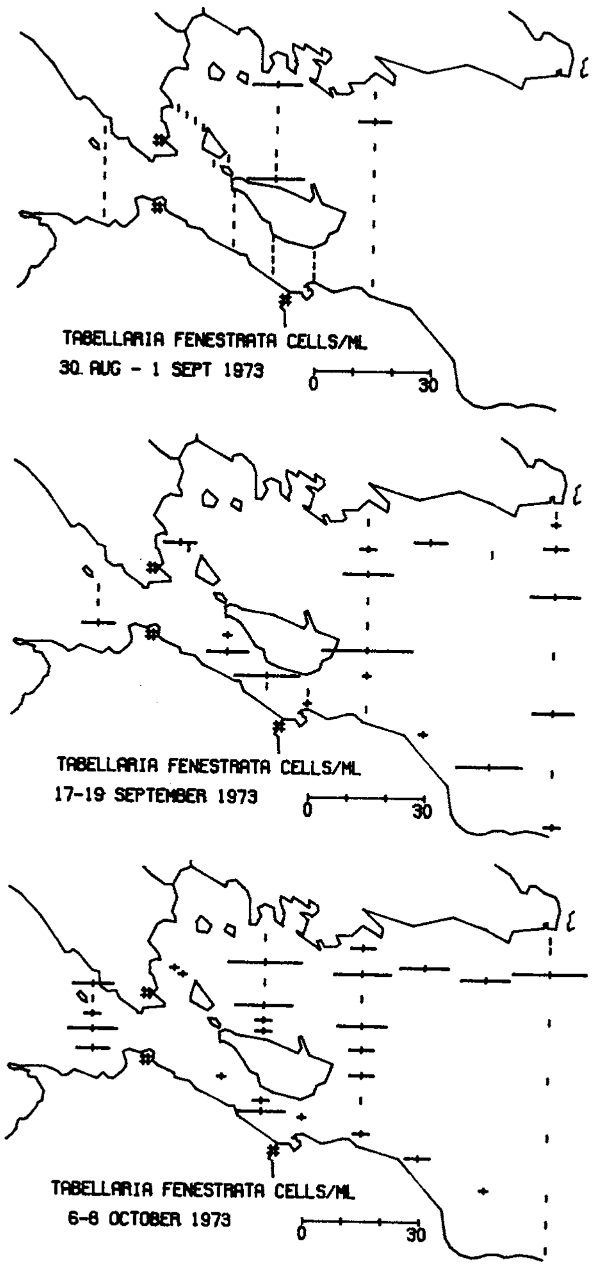


Figure 6.14. DISTRIBUTION OF *TABELLARIA FENESTRATA*.

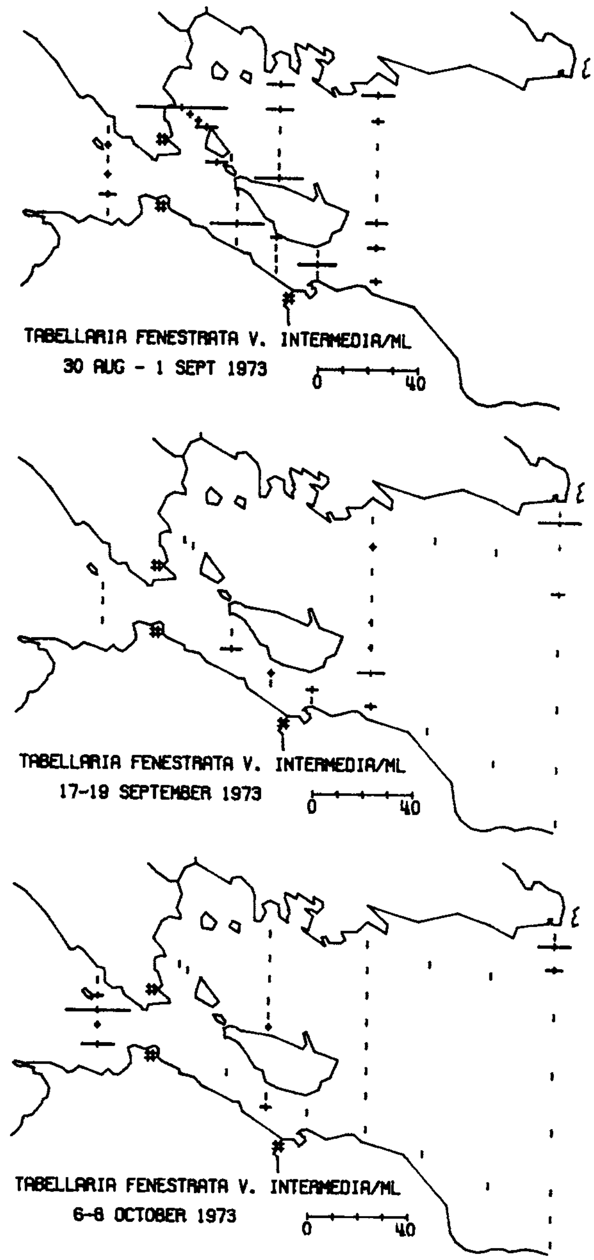


Figure 6.15. DISTRIBUTION OF *TABELLARIA FENESTRATA* var. *INTERMEDIA*.

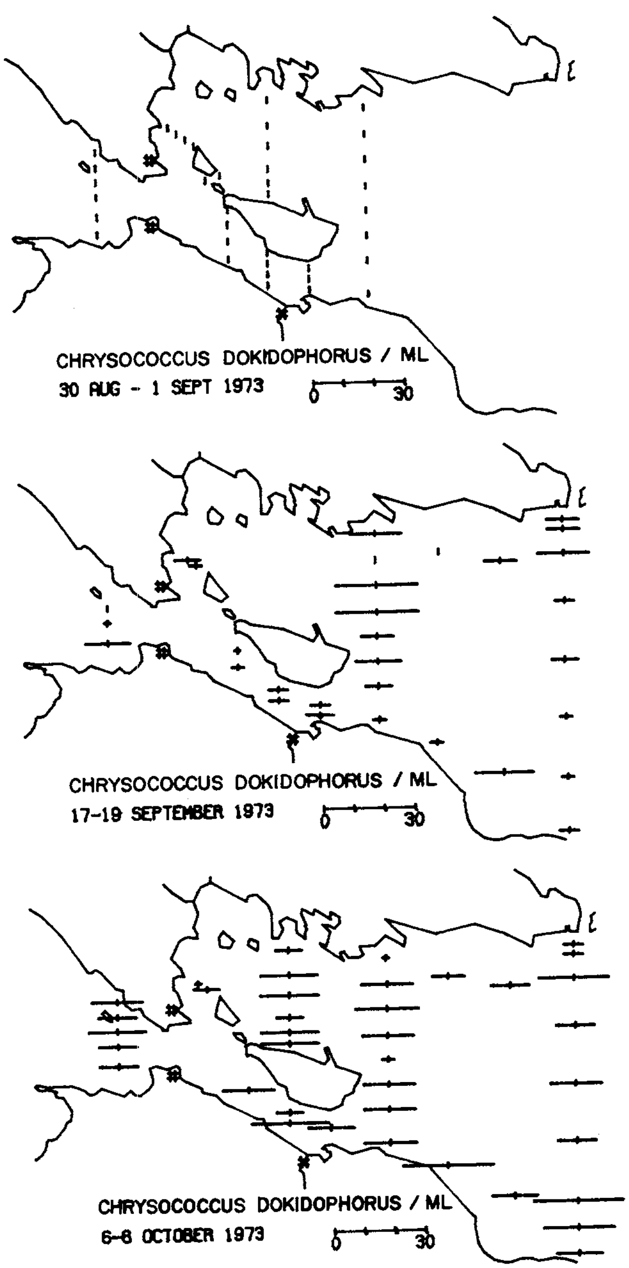


Figure 6.16. DISTRIBUTION OF *CHRYSOCOCCUS DOKIDOPHORUS*.

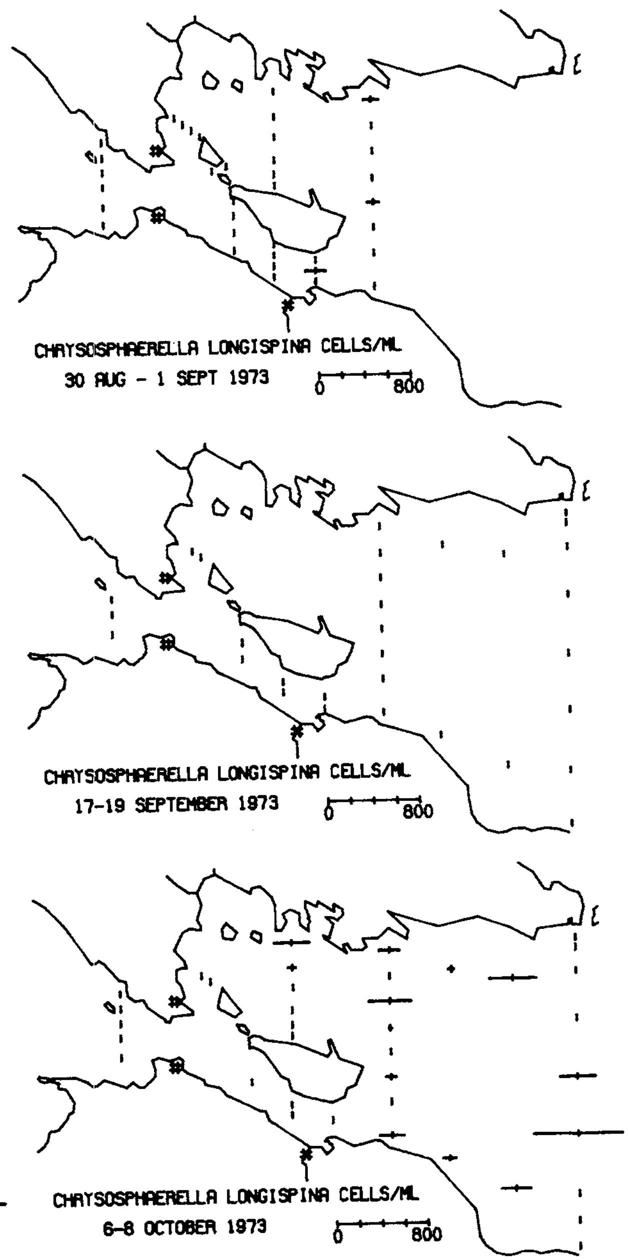


Figure 6.17. DISTRIBUTION OF *CHRYSOSPHAERELLA LONGISPINA*.

Rhodomonas minuta var. *nannoplanktonica* (Fig. 6.18) is a common element of phytoplankton assemblages in the Great Lakes. Its ecological affinities are relatively poorly known, but it appears to be tolerant of conditions in the offshore waters of Lake Ontario (Munawar and Nauwerck 1971) as well as the upper lakes. During August, relatively large populations were found at stations north and east of Bois Blanc Island, with smaller populations noted at many other stations. In September this species was present at most stations sampled; highest populations were found offshore in Lake Huron, and it was notably rare on the Lake Michigan side of the Straits. Measurable populations were also found at most stations sampled during October, however abundance appeared to be least at stations in Lake Michigan and along both the northern and southern shores.

Cryptomonas ovata (Fig. 6.19) seems to be a ubiquitous member of phytoplankton assemblages from all regions of the Great Lakes. It was present in nearly all samples taken during this study and exhibited no pronounced patterns in either seasonal or areal distribution.

Species of *Ankistrodesmus* (Fig. 6.20) are common elements of phytoplankton assemblages in the Great Lakes. Several species are apparently present in all the lakes and some, such as *A. falcatus*, reach relatively high population levels in eutrophied areas (Stoermer et al. 1974). The identity and ecological affinities of the particular species most abundant in the study area are unknown. It was present at most stations sampled throughout the study and was particularly abundant along the southeastern shore in September and October.

Crucigenia quadrata (Fig. 6.21) is a common minor element of the offshore phytoplankton of many areas of the Great Lakes during the summer. In our experience, population levels as high as those found in the present study are unusual. Populations generally declined during the three months sampled, and there was a slight trend toward higher population levels at stations near Bois Blanc and Mackinac Islands.

Eutetramorus sp. (Fig. 6.22) was a numerically important member of assemblages collected in August, when it was quite abundant and very evenly distributed over the sampling area. By September these populations had disappeared, with only isolated minor populations remaining at stations in the southwestern sector. Only a few isolated populations were noted in the October samples. The ecological affinities of this organism are unknown and it has not been reported from the Great Lakes previously.

Gloeocystis planctonica (Fig. 6.23) was present at most stations sampled in August, and there was a trend toward higher population levels on the Lake Michigan side of the Straits and near Mackinac and Bois Blanc Islands. Abundance of this species was reduced considerably in September and October. Our observations indicate that it is a characteristic member of summer phytoplankton associations in southern Lake Michigan that develop when diatoms are silica-limited.

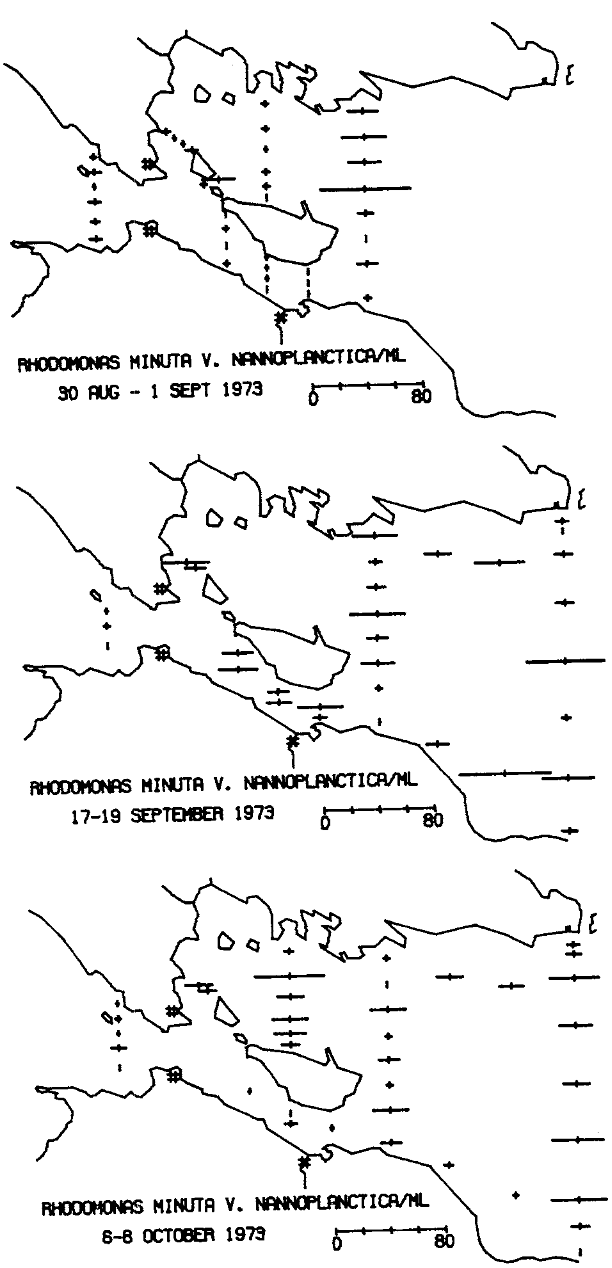


Figure 6.18. DISTRIBUTION OF *RHODOMONAS MINUTA* var. *NANNOPLANCTICA*.

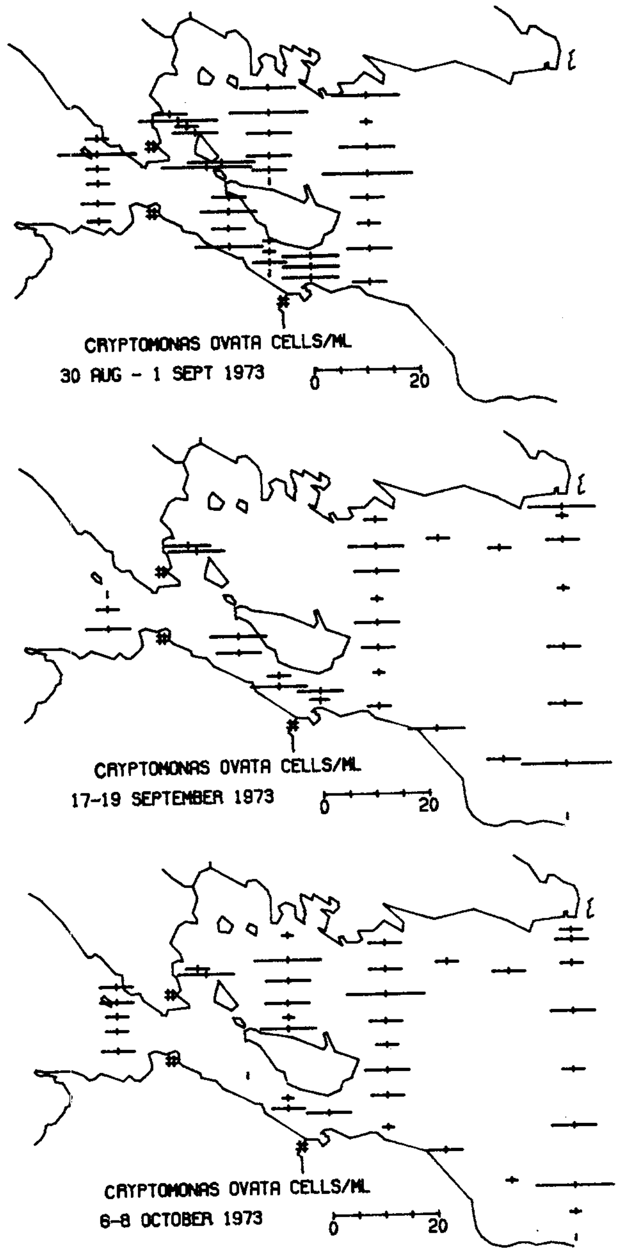


Figure 6.19. DISTRIBUTION OF *CRYPTOMONAS OVATA*.

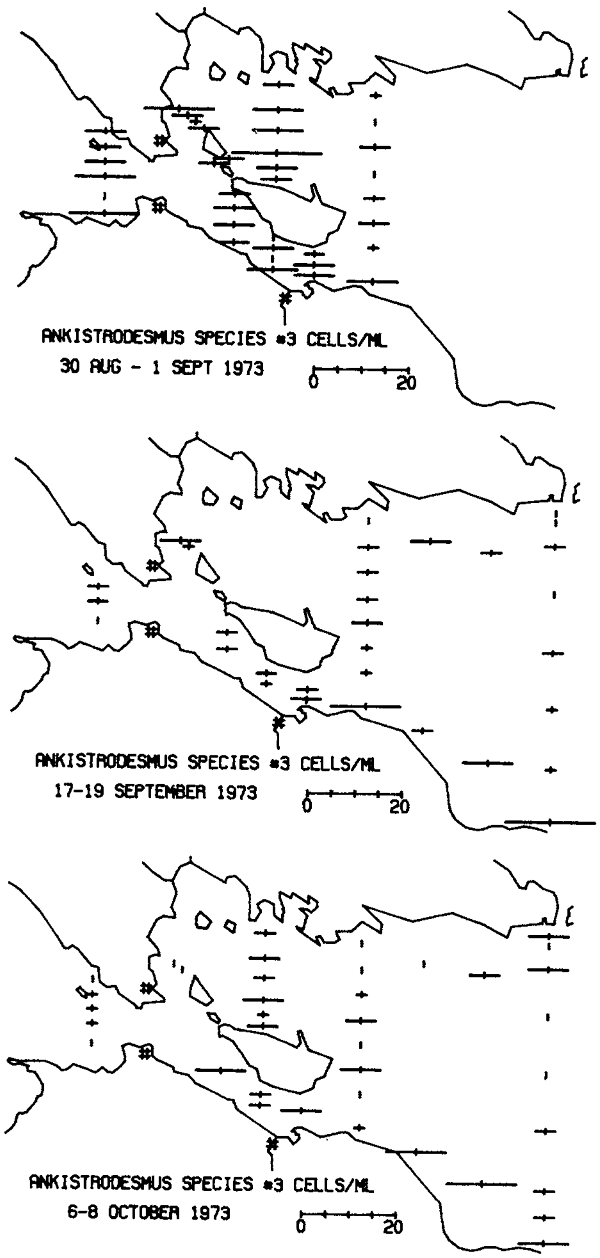


Figure 6.20. DISTRIBUTION OF *ANKISTRODESMUS* species #3.

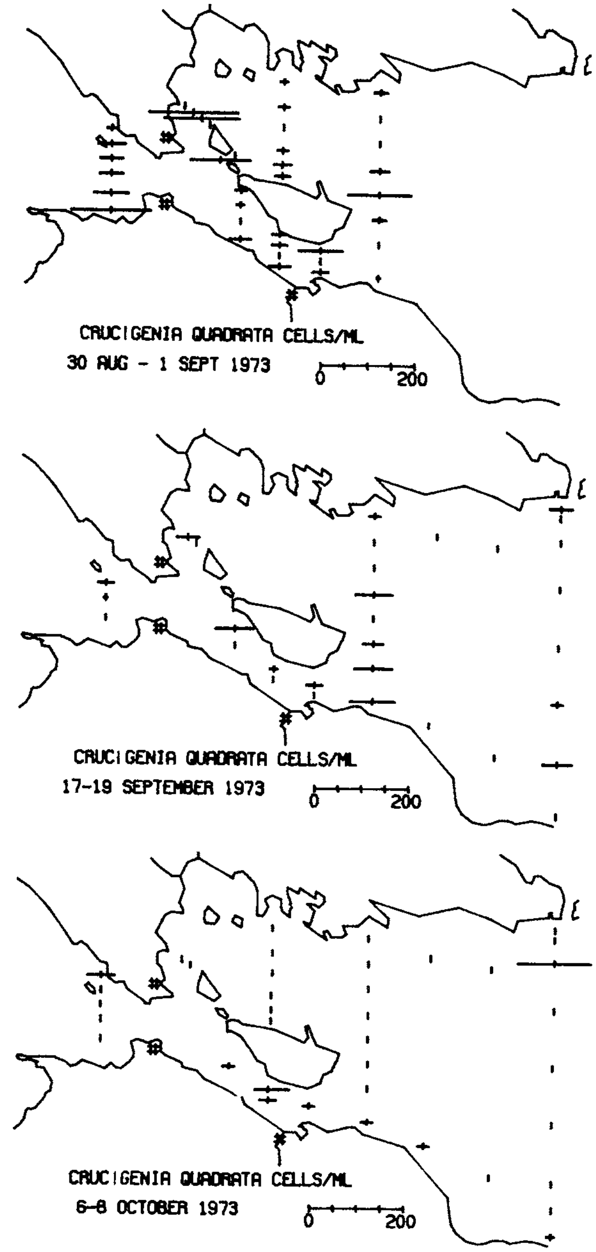


Figure 6.21. DISTRIBUTION OF *CRUCIGENIA QUADRATA*.

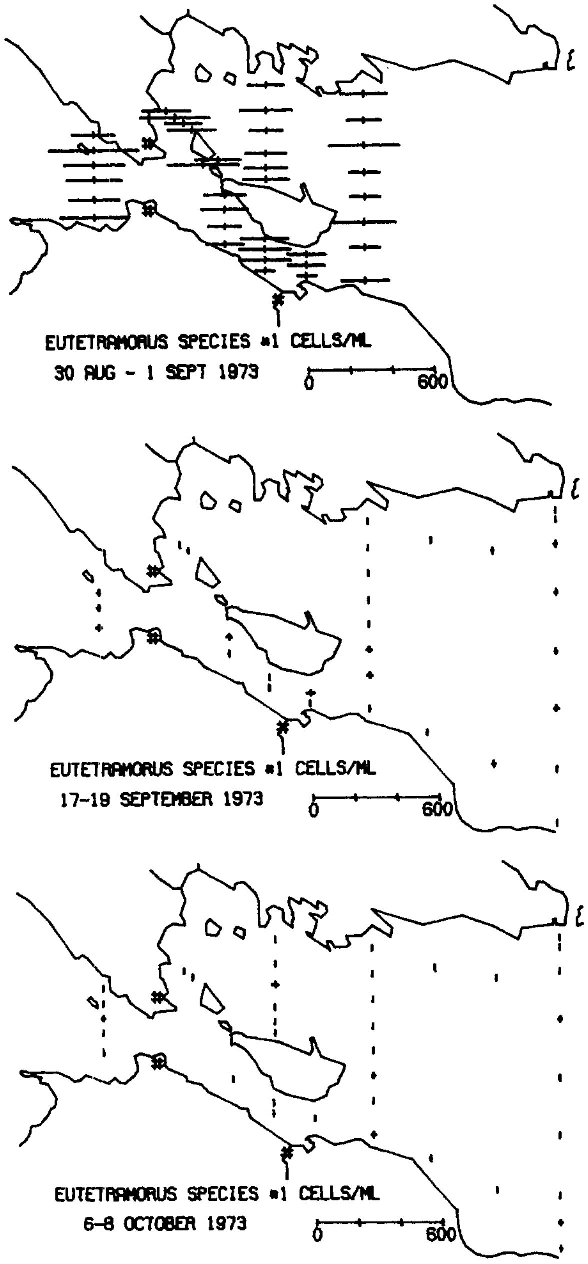


Figure 6.22. DISTRIBUTION OF *EUTETRAMORUS* species #1.

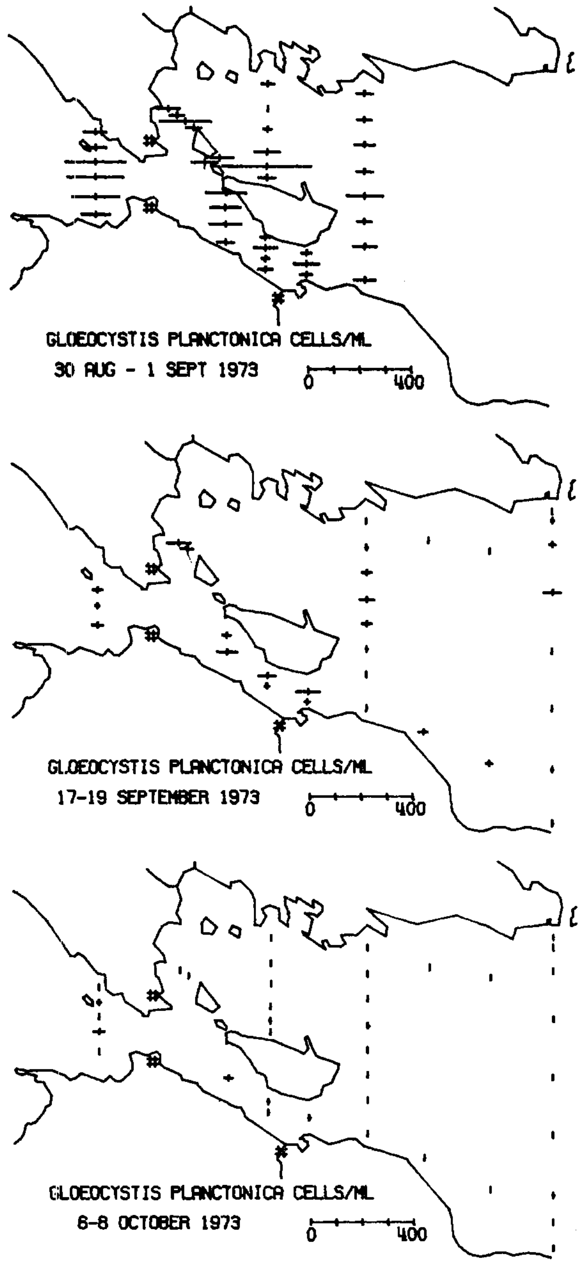


Figure 6.23. DISTRIBUTION OF *GLOEOCYSTIS PLANCTONICA*.

Although somewhat less abundant than *Gloeocystis*, species of *Oocystis* (Fig. 6.24) had a similar pattern of distribution. Measurable populations were found at all stations sampled during August, and there was a definite trend toward higher population levels in the southwestern sector of the sampling area. Average population abundance was reduced in September, and there was a weak trend toward higher population levels at stations in Lake Michigan and along the southern shore. Population levels were further reduced in October but the same trend in distribution was apparent. Members of this genus are widely distributed in summer phytoplankton assemblages from the upper Great Lakes but, like *Gloeocystis*, it appears to be favored when diatoms are silica-limited and it has become more abundant in southern Lake Michigan in recent years.

Anabaena flos-aquae (Fig. 6.25) is a common minor constituent of summer phytoplankton assemblages in the Great Lakes. It is one of the eurytopic species favored by eutrophication and has the potential for forming nuisance blooms under nutrient-rich conditions. Its pattern of indeterminate colonial growth leads to rather large uncertainties in abundance estimates. Isolated populations were noted in August, and it was most consistently present at stations in the southwestern sector of the sampling area. Reduced population levels were noted in September at stations on the Lake Michigan side of the Straits and along the southern shore. A similar situation was found in October, except several sizable populations were also found at offshore stations in Lake Huron.

Anacystis incerta (Fig. 6.26) is a common element of summer and fall phytoplankton assemblages throughout the Great Lakes. It is usually not abundant in the upper lakes but has the potential for forming nuisance blooms because of its large colonies and the presence of gas vacuoles in the cells (Drouet and Daily 1956). It was the most abundant member of assemblages collected in August and tended to be especially abundant at stations in the southwestern sector of the sampling area. In September it remained abundant at stations on the Lake Michigan side of the Straits and along the southern shore, but only relatively minor populations were found in the rest of the area sampled. In October small populations were restricted to stations on the Lake Michigan side of the Straits and along the southern shore.

Anacystis thermalis (Fig. 6.27), like the previous species, is a common element of summer phytoplankton assemblages in the Great Lakes. It does not, however, have the potential to produce nuisance blooms since the colonies are small and the cells lack gas vacuoles. Our observations indicate that it also has a different ecologic range than *A. incerta*. It apparently is favored by low levels of eutrophication and has become much more abundant in southern Lake Michigan in recent years. It apparently cannot tolerate gross perturbation. *Anacystis thermalis* is either present in very low numbers or absent from areas such as Saginaw Bay and western Lake Erie and is much less abundant than *A. incerta* in Lake Ontario (Stoermer et al. 1974). It was present at all stations during August and tended to be most abundant in the southwestern sector of the

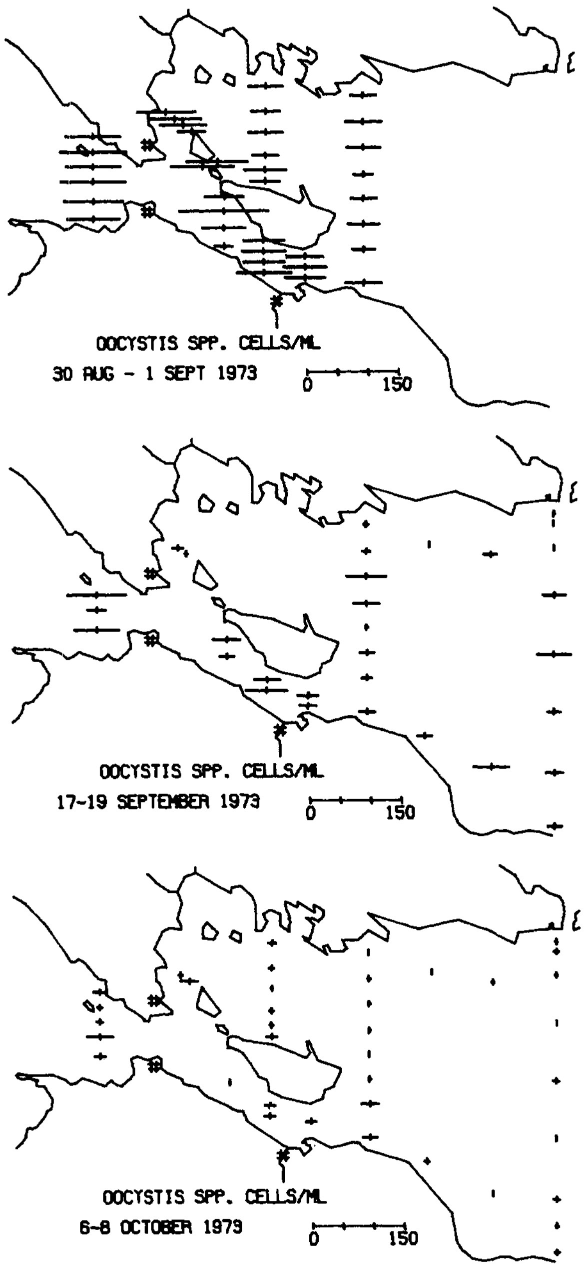


Figure 6.24. DISTRIBUTION OF *OOCYSTIS* SPP.

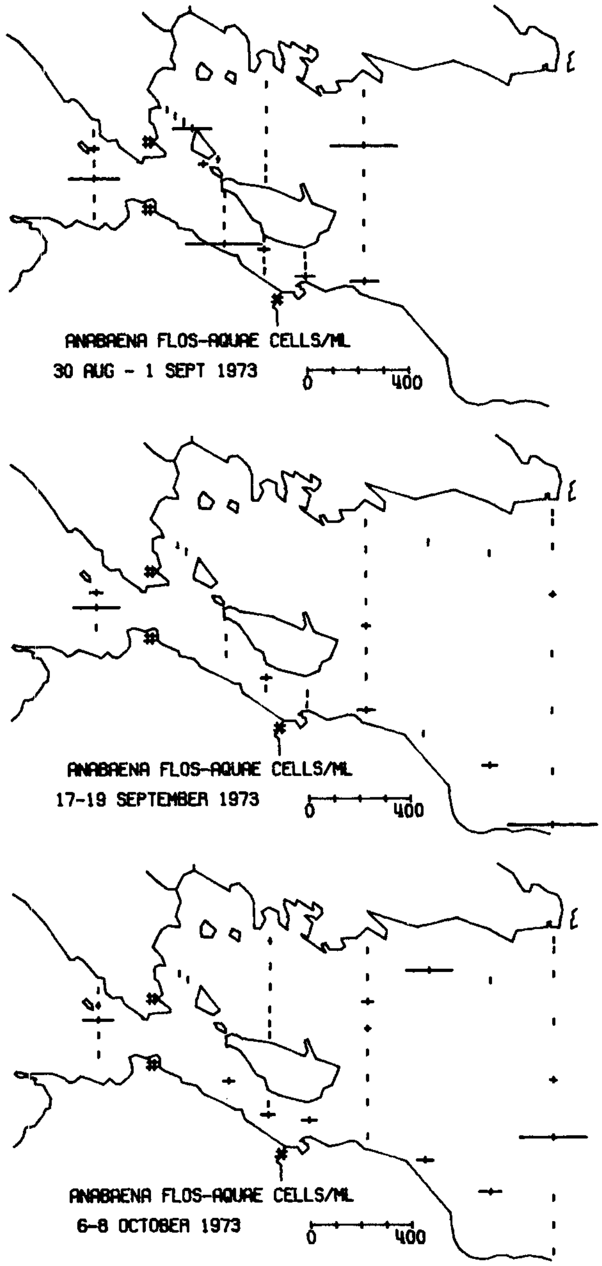


Figure 6.25. DISTRIBUTION OF *ANABAENA FLOS-AQUAE*.

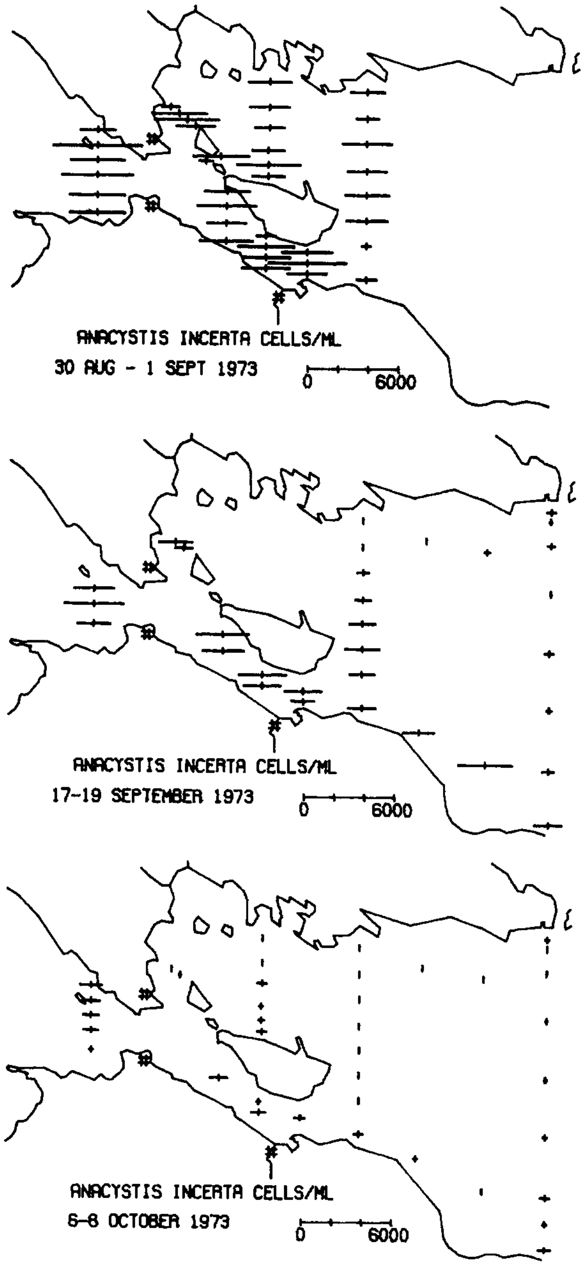


Figure 6.26. DISTRIBUTION OF *ANACYSTIS INCERTA*.

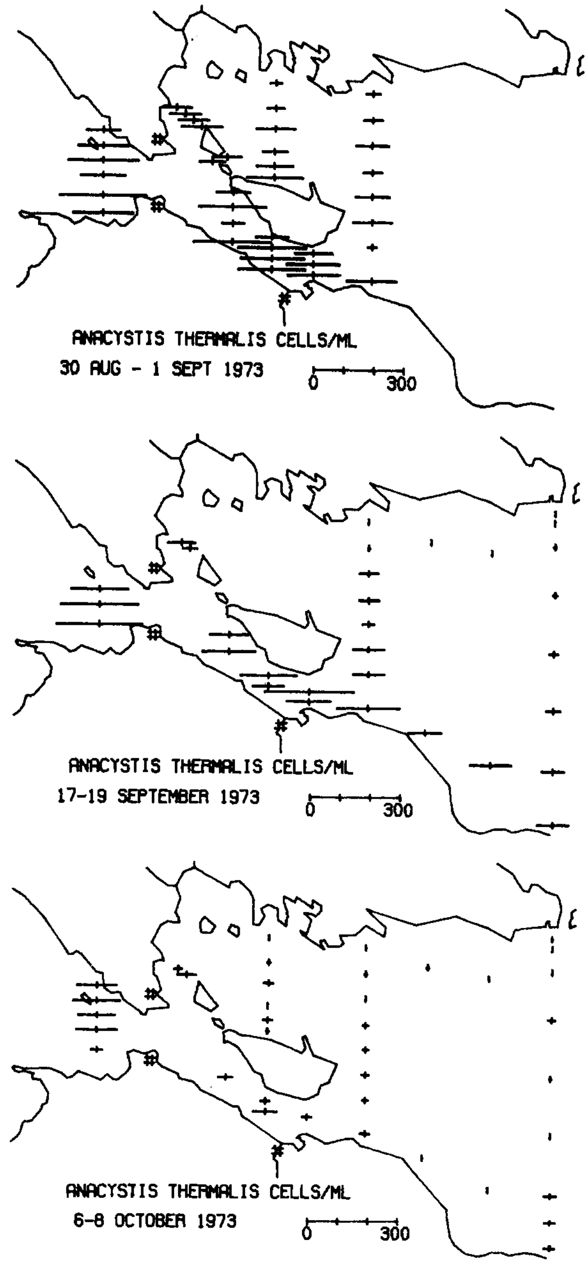


Figure 6.27. DISTRIBUTION OF *ANACYSTIS THERMALIS*.

sampling area. In September, population levels were low at offshore stations in Lake Huron but remained abundant on the Lake Michigan side of the Straits and along the southern shore. In October, population levels comparable to those found previously occurred only at stations on the Lake Michigan side of the Straits, and only relatively small populations were found in Lake Huron with greatest abundance along the southern shore.

Gomphosphaeria lacustris (Fig. 6.28) is a common element of phytoplankton communities in the Great Lakes. It is apparently eurytopic and tolerates the range of conditions between Lake Superior and Lake Ontario. Its abundance is reduced in grossly perturbed areas such as the inner reaches of Saginaw Bay. It was most abundant in August but no obvious trends in distribution were apparent. In September it was most abundant on the Lake Michigan side of the Straits and along the southern shore. Some indication of the same distribution pattern as September was evident in October although occurrences were more scattered with smaller ranges in populations.

Scattered populations of *Oscillatoria bornetii* (Fig. 6.29) were noted in the samples from all three cruises. This species tended to increase in abundance, especially in October, but no strong trends in areal distribution were apparent.

6.4 ORDINATION ANALYSIS OF PHYTOPLANKTON ASSEMBLAGES

Data on ordination analysis of phytoplankton are presented in the reverse order of collection, as the October cruise comprises the most complete data set. In October all 50 stations were sampled, whereas Stations 38-50 were not sampled in August and Stations 32-37 were not sampled in September.

Near-surface Associations in October

The ordination analysis of October samples revealed an east-west or Lake Huron-Lake Michigan axis for the first principal component (PC). Stations in region A_1 found on the extreme right end of the first PC were generally located west of the Straits, and stations in regions B, BC, and C on the opposite end of the first PC were located generally northeast of the Straits (Fig. 6.30a). Region A_2 was composed of stations located between the two extremes. Since the first PC removes the greatest variance from the data, it may be concluded that the greatest difference in surface phytoplankton communities was between the communities found in Lake Michigan and those found east of the Straits.

A plot (Fig. 6.30b) of the 13 taxa used in the principal component analysis (PCA) relative to the loading factors of the first two PCs illustrates the composition of the communities for various regions

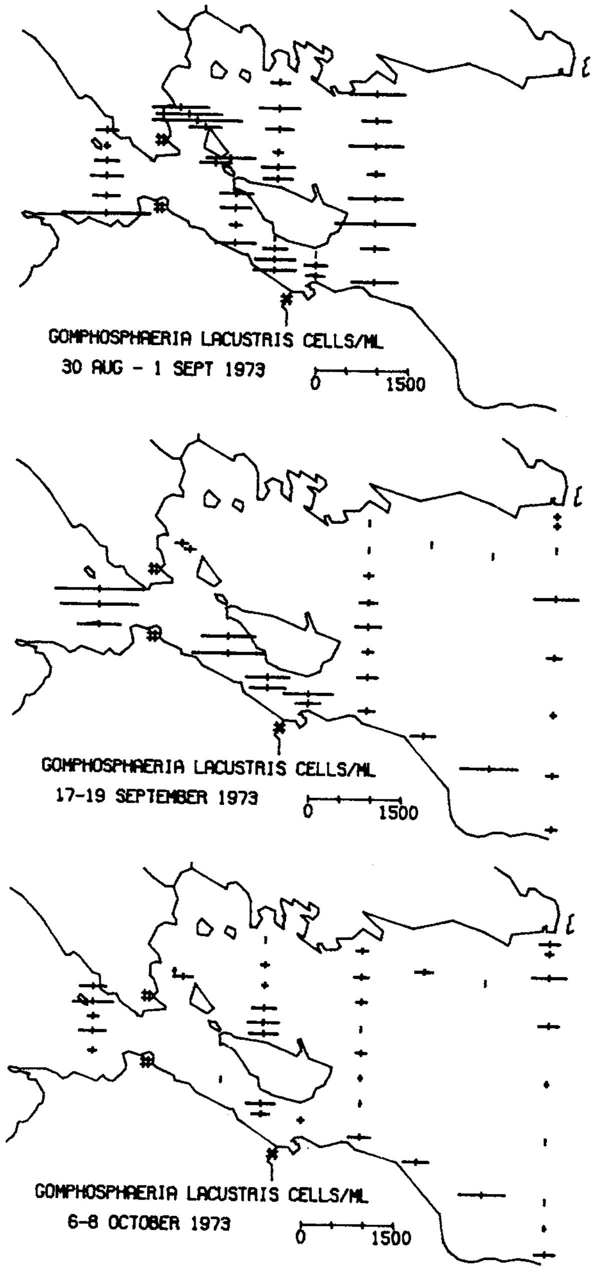


Figure 6.28. DISTRIBUTION OF *GOMPHOSPHAERIA LACUSTRIS*.

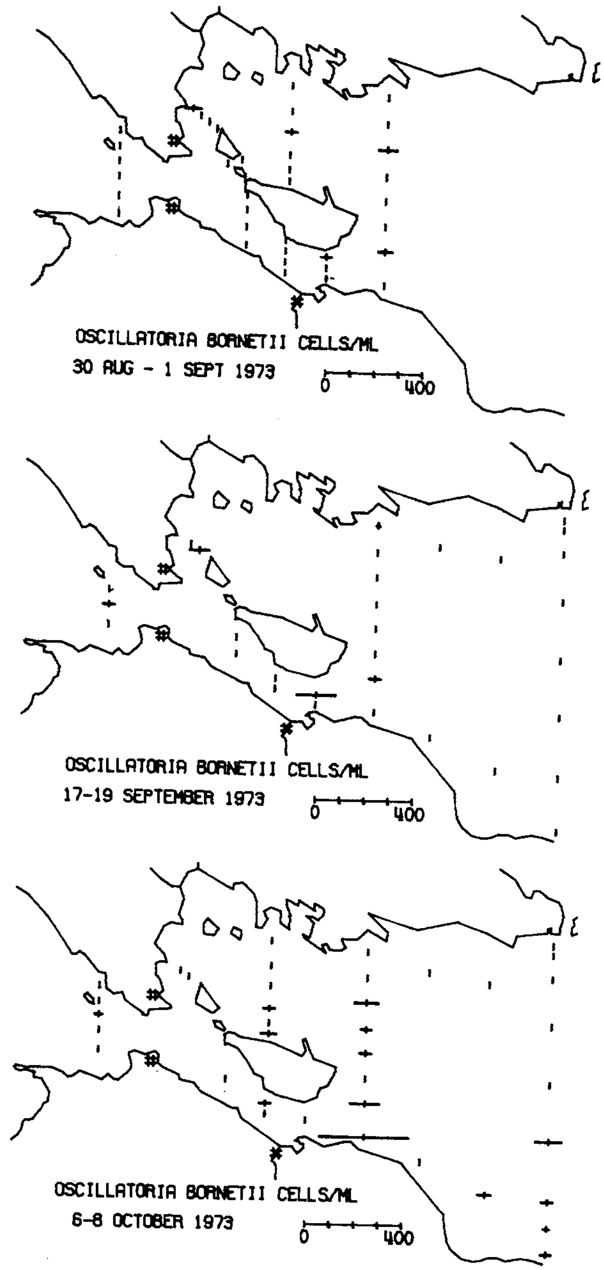
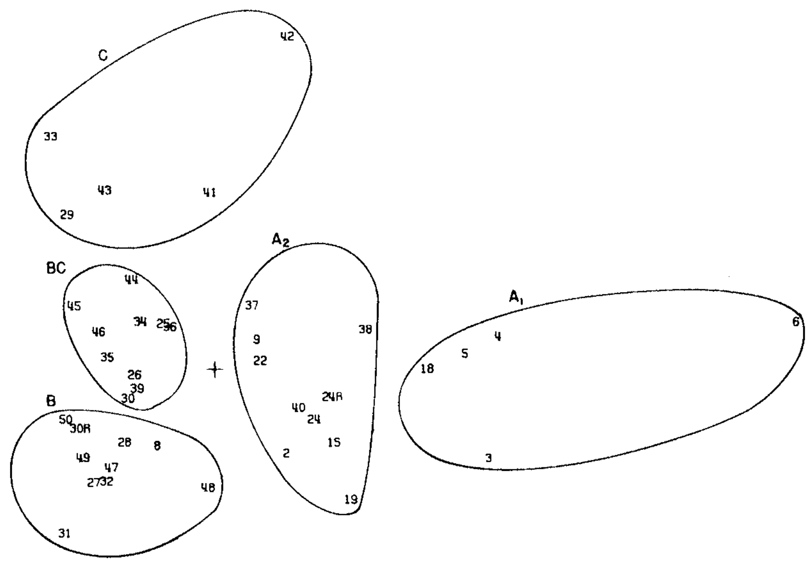
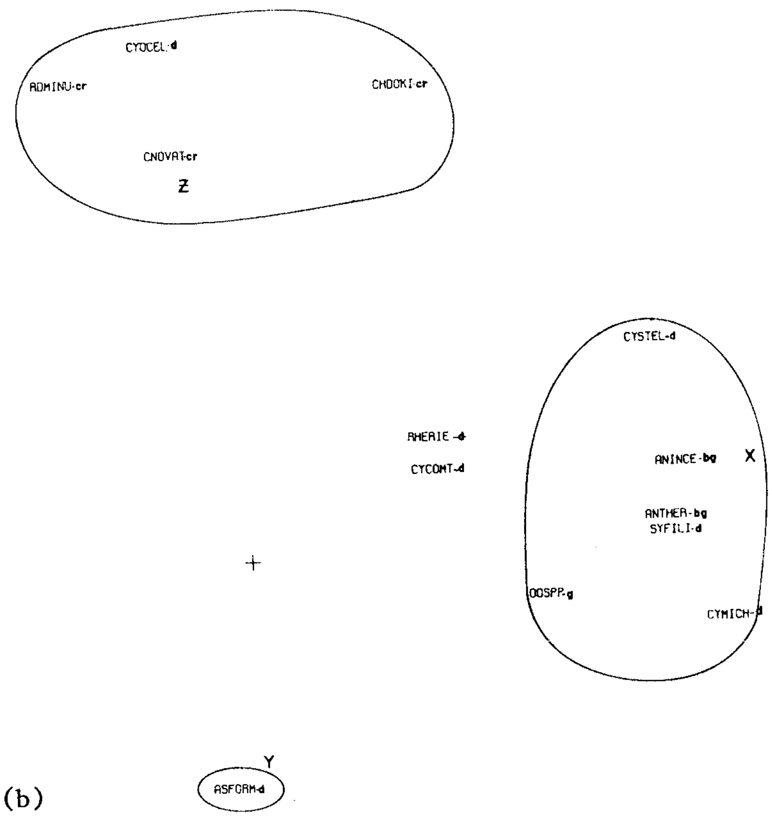


Figure 6.29. DISTRIBUTION OF *OSCILLATORIA BORNETII*.



(a)



(b)

Figure 6.30. OCTOBER 5-M SAMPLE ORDINATION PLOTS. The first principal component is represented on the horizontal axis and the second on the vertical axis. The cross indicates the location of the origin. The exact location of the station or taxon is at the lower left-hand corner of its label.

(a) Station ordination plot. Stations are located relative to the first two principal component scores. See Figure 2.1 or Figure 6.31 for station locations.

(b) Phytoplankton taxa ordination. Taxa are located relative to the loading factors of the first two principal components. See Table 6.2 for the taxa abbreviations. The small letters following the taxon abbreviation indicates the division: diatom, chrysophyte, green, blue-green, cryptomonad.

depicted in Figure 6.31. A station with relatively high densities of taxa located on the right side of Figure 6.30b will be located on the right side of Figure 6.30a, or any station with relatively low densities of these taxa on the right side of Figure 6.30b will be situated on the left side of Figure 6.30a. Similarly, any station with high densities of species at the top of Figure 6.30b will appear toward the top of Figure 6.30a, but if it has low densities of these taxa it will appear toward the bottom of Figure 6.30a. The cluster labeled "Z" (Fig. 6.30b) defines a community of four species with similar patterns of distribution corresponding to region C (Fig. 6.31). These species tend to be abundant in the same places, and where these species are abundant the taxa of community X and community Y (Fig. 6.30b) are relatively rare. Conversely, where the taxa of community X are abundant, those of Z and Y are rare. Likewise stations of region A_1 would tend to have high concentrations of the taxa of community X.

Two species, *Rhizosolenia eriensis* and *Cyclotella comta*, have relatively small loading factors for both the first and second component, i.e., they appear close to the origin (Fig. 6.30b). These species apparently show no clear distribution patterns relative to the others or occur in equally high abundances in more than one of the regions A_1, B and C. It might also be expected that, although *Chrysococcus dokidophorus* appears to belong to community Z, its relatively high loading factor for PC_1 indicates that it may also be found in region A_1 as well as in region C. Community Y is represented by only one species, *Asterionella formosa* and it would be found primarily in region B.

Regions containing characteristic phytoplankton communities as identified on the basis of the ordination plots (Fig. 6.30a) have been plotted in Figure 6.31. This map suggests a close geographical proximity between stations with similar phytoplankton communities. The similarity between Figures 6.31 and 4.2 suggests that the grouping is determined primarily by water currents.

Hypolimnetic Associations in October

A PCA was performed for all samples collected in October, including the 5-m as well as a small number of hypolimnetic samples (Fig. 6.32a). Regions A_1, A_2, B_1 and C are based on the results of the PCA for the 5-m samples as shown in Figure 6.30a; relative positions of these regions have been changed little by including hypolimnetic samples in the analysis. A new group of stations, region D (Fig. 6.32a) corresponds to hypolimnetic samples collected east and north of Bois Blanc Island in Lake Huron. Associated with region D is a phytoplankton assemblage, W, consisting of *Cyclotella ocellata* and *Rhizosolenia eriensis*. This hypolimnetic association can be distinguished from assemblage Z found in the surface water which is characterized by *Rhodomonas minuta* v. *nannoplanctica*, *Cryptomonas ovata* and *Chrysococcus dokidophorus*.

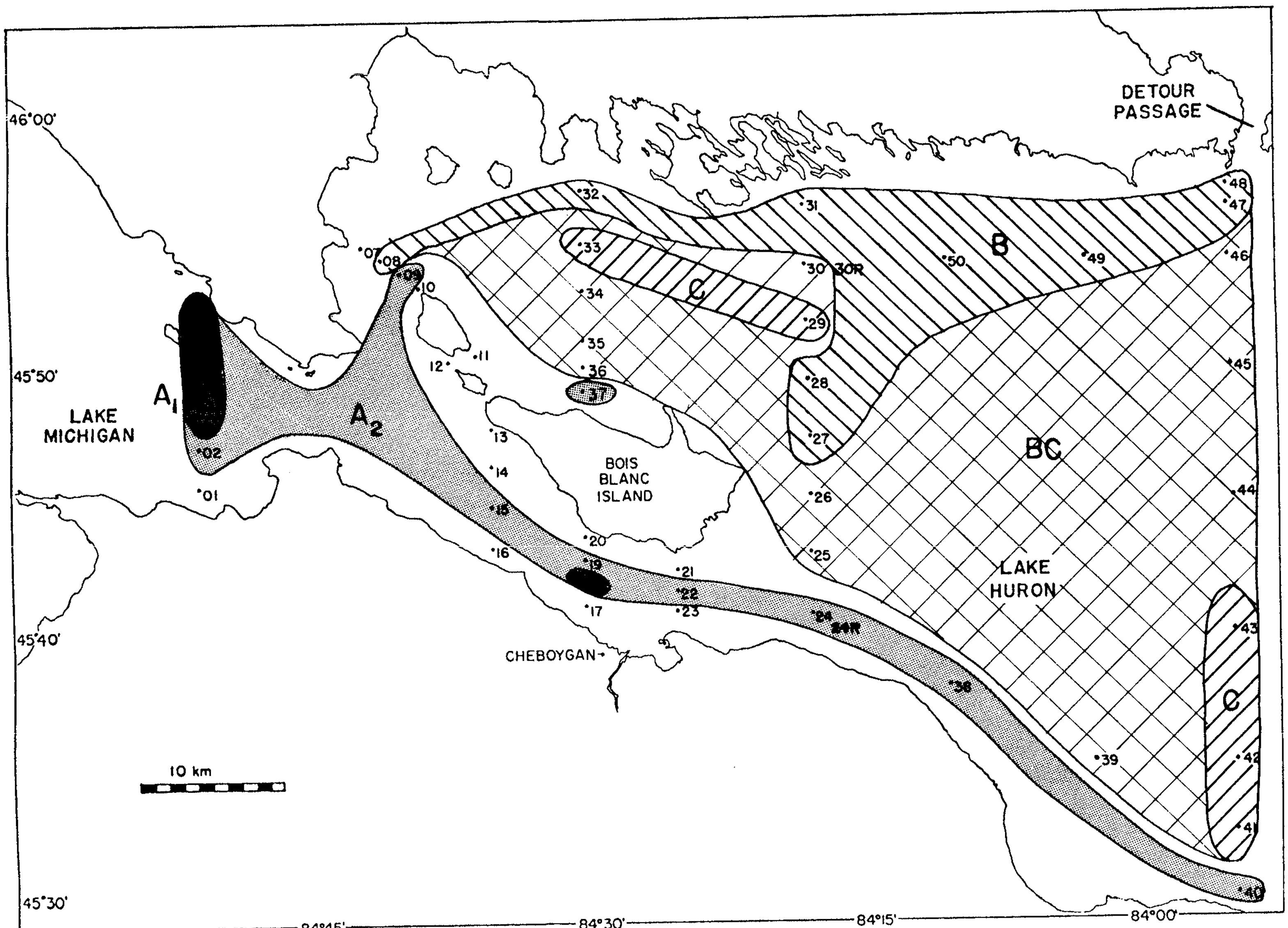
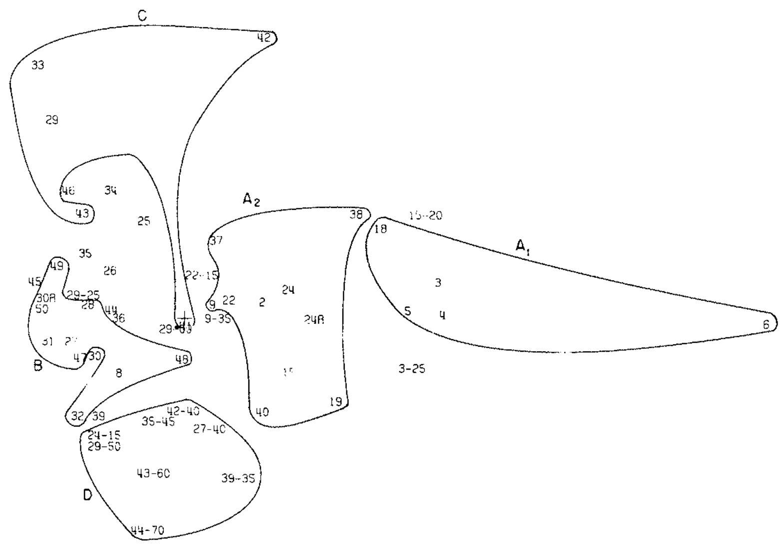
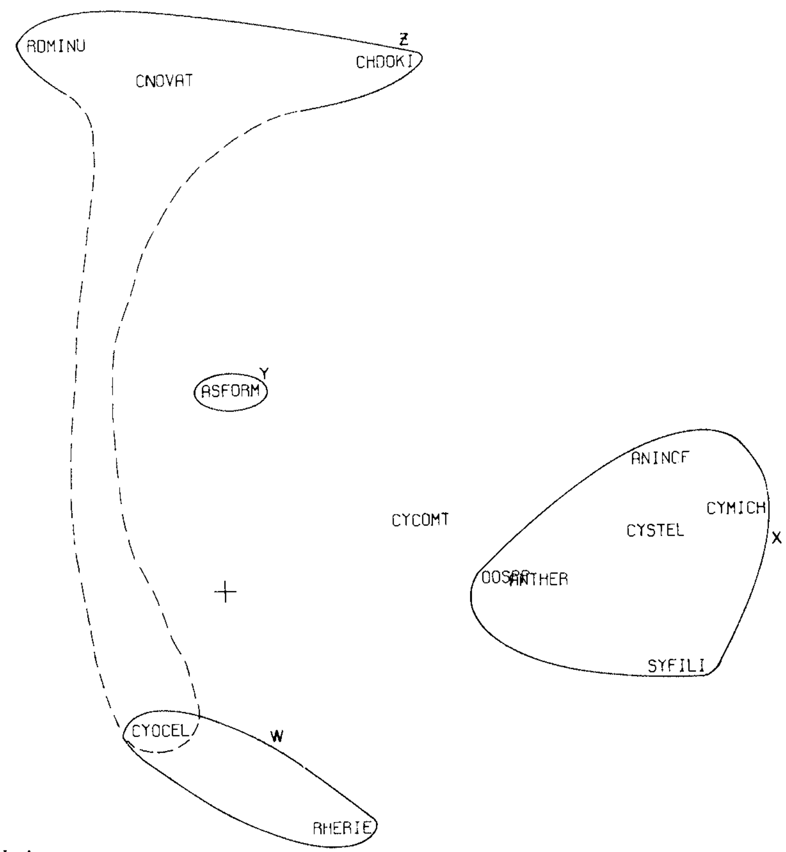


Figure 6.31. GEOGRAPHIC LOCATIONS OF 5-M OCTOBER PHYTOPLANKTON COMMUNITIES. Regions are determined on the basis of the ordination plot of Figure 6.30. Phytoplankton data are not available for stations not included in one of the four regions.



(a)



(b)

Figure 6.32. ORDINATION PLOTS FOR OCTOBER SURFACE AND SUBSURFACE SAMPLES.

(a) Station ordination plot. The number preceding the hyphen refers to the station, and the number following the hyphen refers to the depth in meters at which the sample was taken. Unhyphenated numbers refer to samples collected at 5 m. Samples are located relative to the first two principal components.

(b) Phytoplankton taxa ordination. Taxa are located relative to their loading factors. The first principal component is represented on the horizontal axis and the second on the vertical axis. See caption for Figure 6.30a and b for further explanation.

The assemblages in surface and hypolimnetic samples from stations in Lake Michigan were similar. Subsurface samples taken at Stations 03 and 15 appeared to have the same phytoplankton community as the 5-m samples (Fig. 6.32a).

Total cell densities are highest at the surface and lowest in the hypolimnion, but diatom densities are highest below the thermocline at Station 29 (Table 6.5). Diatoms constitute 15% of the assemblage at 0 m for Station 29 but 93% of the assemblage below the thermocline at 50 m.

Results of the ordination analyses are qualitative and may be considered ambiguous; the differences, however, between standing crops of different species of phytoplankton in each region also can be evaluated from the average standing crops. It can be seen that the six species identified as community X in region A_1 (Fig. 6.32b) by ordination analysis are those that were more abundant in region X than in the other regions (Table 6.6). *Cyclotella ocellata* and *Rhizosolenia eriensis*, the hypolimnetic assemblage W, from Lake Huron had the greatest cell densities in region D (Table 6.6).

Stations with unusual or extreme communities on the basis of the ordination plot are 06, 42 and 31 (Fig. 6.30a). Station 06, located NW of the Straits, had near-surface cell densities for *Cyclotella stelligera, C. michiganiana,* and *Synedra filiformis* that were at least three times more abundant than at any other station (Table 6.6). It also had extremely high densities of *Fragilaria crotonensis*, a species not used in the PCA, and *Rhizosolenia eriensis.* Station 06 had the highest near-surface cell densities for total algae, total blue-greens, and total diatoms of all stations sampled in October. Station 42, SE of the Straits, had the highest 5-m cell density for *Cyclotella operculata* but also had extremely high densities of *Cryptomonas ovata, Chrysococcus dokidophorus, Rhodomonas minuta* var. *nannoplanctica* and *Cyclotella stelligera*. Station 31, located in the northcentral part of the survey area, had the highest 5-m density of all stations for *Asterionella formosa* and high density of *Fragilaria crotonensis* but also, by contrast, had extremely low concentrations for a number of species including *Chrysococcus dokidophorus, Cyclotella stelligera, Rhodomonas minuta* var. *nannoplanctica, Anacystis incerta,* and *Anacystis thermalis*.

Near-surface Associations in September

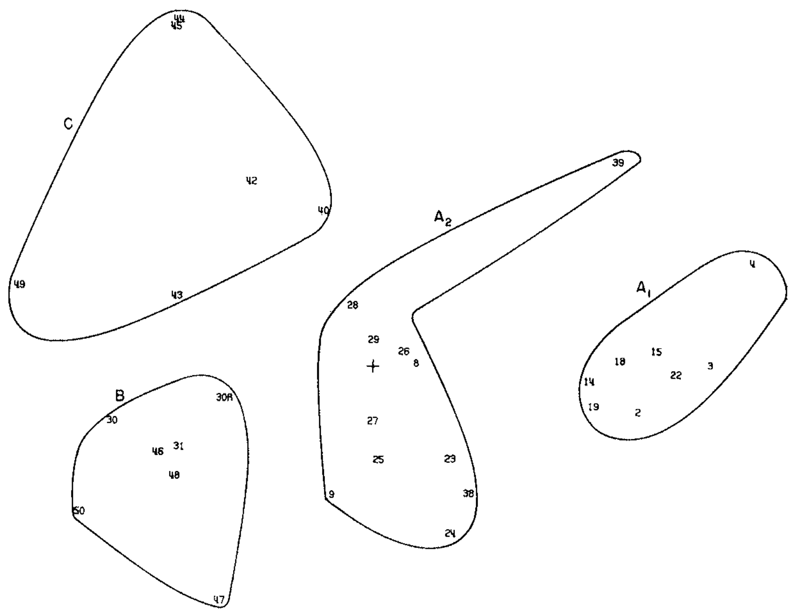
The ordination plots for September (Fig. 6.33) were analyzed from a smaller set of samples and are therefore more difficult to interpret than those for October (Figs. 6.30 and 6.32). Plots for September do not show the well segregated clusters found in October. Station 39 had a particularly unusual phytoplankton assemblage which included very high densities of *Anacystis incerta, A. thermalis, Cyclotella michiganiana*, characteristic of region A_1 (Fig. 6.33a), and *Rhodomonas minuta* var. *nannoplanctica,* and *Chrysococcus dokidophorus* which were more abundant in the northeastern corner of the survey area. Inclusion of Station 39 with region A_2 is therefore somewhat arbitrary.

Table 6.5. CELL DENSITIES AT STATION 29 ABOVE, IN, AND BELOW THE THERMOCLINE FOR THE AUGUST, SEPTEMBER AND OCTOBER CRUISES. Letters "E," "T" and "H" refer to epilimnion, thermocline, and hypolimnion. Under "apparent trend" is indicated the regions in which a taxon attains highest densities. Under "dep" is indicated the depth which, at Station 29, the taxon appears to be concentrated. This determination is made subjectively on the basis of the cell densities at Station 29. Under "epi" is the surface region where the taxon is most abundant as indicated on Tables 6.6, 6.7 and 6.8. For each taxon, cell densities (in cells/ml) are given above the standard error of the mean, which is determined on the basis of a replicate cell count of the sample.

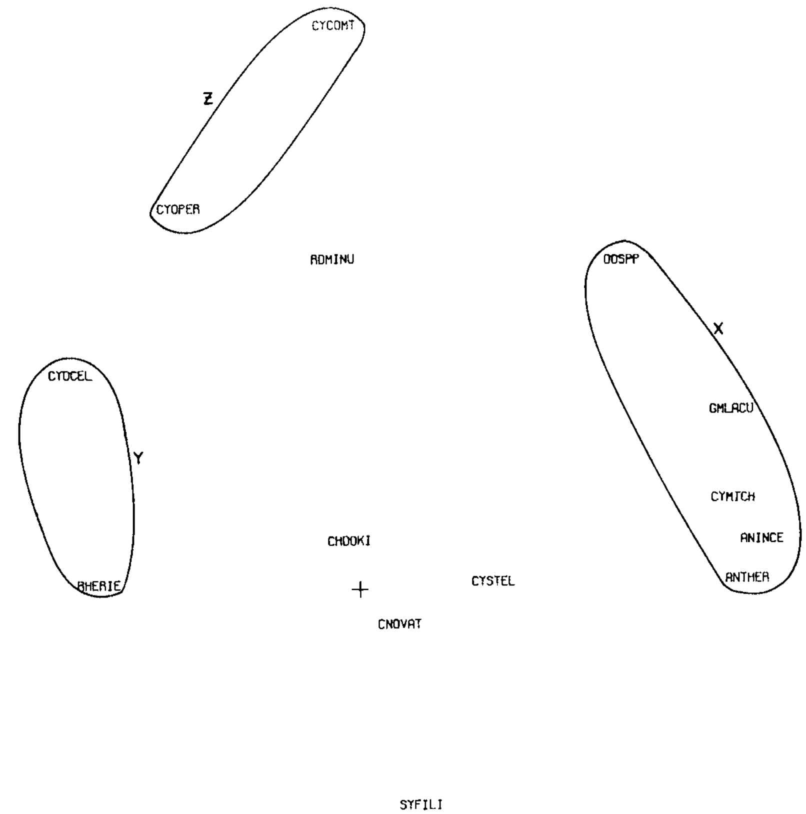
	August						September						October					
	Sample depth				Apparent trend		Sample depth				Apparent trend		Sample depth				Apparent trend	
	E	E	T	H			E	E	T	H			E	E	T	H		
	0m	5m	20m	50m	dep	epi	0m	5m	20m	50m	dep	epi	0m	5m	20m	50m	dep	epi
Anacystis incerta	1697	3288	147	105	E	A	712	838	168	314	E	A	0	21	105	21	T	A
	691	649	147	105				545	168	63				21	63	21		
Anacystis thermalis	0	111	0	0	E	A	67	63	34	0	E	A	272	0	8	0	?	A
		52						4	34				272					
Synedra filiformis	0	2	0	19	H	?	4	0	0	6	?	?	0	0	0	4	?	A
		2		2			4			2								
Cyclotella michiganiana	65	52	69	17	E	BC	21	50	61	2	ET	A	4	8	15	11	TH	A
	6	11	2	8			13	21	19	2				4	2	6		
Gomphosphaeria lacustris	607	880	607	0	E	C?	335	147	0	0	E	A	0	168	0	0	?	A
	398	335	189	0			335	147						168				
Cyclotella stelligera	23	31	73	44	T	C	130	128	128	140	ETH	AB?	23	23	17	36	ETH	A
	19	2	6	15			4	27	2	2			6	2	4	15		
Oocystis spp.	80	55	21	0	E	A	15	65	13	13	E	A	13	4	6	0	?	A
	34		8				2	6	4	13			13		6			
Gloeocystis planctonica	40	78	38	0	E	A	0	36	8	17	?	A	25	0	25	0	?	A
	23	2	21					36	8				25		25			
Crucigenia quadrata	92	0	0	0	?	A	0	0	0	0	?	?	0	0	0	0	?	A?
	92																	
Cyclotella comta	23	50	82	13	T	B	13	27	61	21	T	C	2	8	2	13	H	AC
	11	13	19	4				2	6				2	4	2	4		
Chrysococcus dokidophorus	0	0	0	0	?	?	17	27	6	0	E	?	8	21	15	4	E	AC
							4	11	2				4	4	2			
Rhizosolenia eriensis	0	6	19	0	T	?	0	4	19	52	H	C	0	2	4	13	H	?
		6	6						15	6				2	4	13		
Eutetramorus species #1	260	335	34	0	E	A	0	0	19	0	T	A	0	0	0	0	?	?
	38	21	34						2									
Anabaena flos-aquae	354	262	0	0	E	A?	0	0	0	0	?	?	0	46	0	0	?	?
	138	262												46				
Fragilaria crotonensis	136	6	293	0	?	C	159	90	82	191	?	?	48	124	147	191	?	?
	2	6	75				113	69	82	48			19	40	96	191		
Tabellaria fenestrata	6	0	4	4	?	?	0	13	2	2	?	?	2	0	6	4	?	?
	6		4					8	2	2			2		6			
Cyclotella operculata	0	6	8	4	?	B	0	0	0	0	?	C	2	2	2	2	?	?
		2	4										2	2	2	2		
Asterionella formosa	0	0	0	0	?	C	0	0	0	0	?	A	0	29	57	0	T	B
														29	31			
Cryptomonas ovata	0	11	0	0	E	?	4	8	6	2	?	?	6	15	8	6	E	C
		2						4	2	2			2	2	8	6		
Chrysosphaerella longispina	0	0	0	0	?	?	0	0	0	0	?	?	484	375	0	0	E	C?
													182	358				
Rhodomonas minuta v. *nannoplanctica*	2	23	8	0	E	BC	19	13	8	2	E	?	17	25	4	2	E	C
	2	2	4				6	4	8	2				17	4	2		
Cyclotella ocellata	0	4	82	27	T	C	124	115	245	352	H	C	61	88	124	157	H	C
		4	6	11			36	10	44	38			15	21	44	27		
Total cells/ml	3424	5408	1539	300			1711	1690	1273	1357			984	1066	771	522		
Total blue-green cells/ml	2656	4616	754	105			1114	1047	545	404			272	331	251	21		
% blue-green	78	85	49	35			65	62	43	30			28	31	33	4		
Total green cells/ml	499	519	96	0			23	111	48	107			48	6	52	0		
% green	15	10	6	0			1	7	4	8			5	.6	7	0		
Total diatoms/ml	264	205	679	195			532	482	658	840			149	293	400	486		
% diatoms	8	4	44	65			31	29	52	62			15	28	52	93		
Temperature (°C)	21.5	21.0	9.0	4.5			10.6	10.6	8.0	5.8			10.6	10.6	6.0	4.6		
Conductivity (μmho/cm)	226	228	202	218			216	216	207	214			216	216	212	219		

Table 6.6. OCTOBER PHYTOPLANKTON CELL DENSITIES. Average densities (in cells/ml) for each region (Figs. 6.30a and 6.31) are given over the standard error of the mean. Standard errors are omitted when values used in the average are identical. Columns titled "apparent trend" indicate regions of maximum and minimum abundance. Taxa are grouped according to apparent trend. Taxa most abundant in region A_1 are listed first, those showing no pattern relative to the regions are listed second, and those taxa most abundant in regions B or C are listed last. Taxa identified with an (*) were used in the PCA.

	Region label and Number of stations						Apparent trend	
	A_1 5	A_2 10	B 10	BC 10	C 5	D 8	High	Low
*Anacystis incerta**	1114 88	494 107	31 31	170 63	256 110	20 15	A	B,D
*Anacystis thermalis**	126 13	30 6	8 3	16 4	18 9	27 20	A	B
*Synedra filiformis**	24 11	10 2	.8 .6	.6 .3	2 2	9 2	A	B,C
*Cyclotella michiganiana**	95 14	48 7	12 3	12 2	14 2	14 1	A	
Gomphosphaeria lacustris	394 82	276 51	134 38	300 78	67 34	168 89	A	C
*Cyclotella stelligera**	85 21	58 5	24 6	25 4	54 21	42 7	A	B
Oocystis spp.*	21 6	16 2	5 1	7 2	5 2	10 3	A	
Gloeocystis planctonica	12 8	5 3	.8 .8	.6 .6	2 2	16 15	A	B
Crucigenia quadrata	19 12	23 8	0	16 16	0	4 4	A?	
*Cyclotella comta**	11 2	11 2	6 1	5 1	12 2	10 1	A,C,D	
*Chrysococcus dokidophorus**	17 2	16 2	8 1	16 1	21 3	5.5 .8	A,C	B,D
*Rhizosolenia eriensis**	10 4	8 2	6 2	8 2	7 2	17 4	D	
Eutetramorus species #1	3 3	6 3	0	7 3	3 3	5 3		
Anabaena flos-aquae	37 23	16 8	21 18	11 9	62 52	0		D
Fragilaria crotonensis	103 74	49 18	168 49	67 15	65 19	86 22		
Tabellaria fenestrata	8 3	3.8 .8	6 2	6 2	4 4	9 3		
Cyclotella operculata	2.1 .9	1.7 .8	3 1	1.5 .9	5 3	1.6 .5		
*Asterionella formosa**	28 4	27 5	41 7	28 7	21 6	18 7	B	
*Cryptomonas ovata**	5.4 .5	5 1	5.4 .7	5.9 .8	10 2	4 1	C	
Chrysosphaerella longispina	0	34 24	100 48	67 38	245 150	0	C?	A,D
Rhodomonas minuta v. *nannoplanctica**	5 2	5 2	11 2	18 4	33 7	3 1	D	A,D
*Cyclotella ocellata**	43 7	47 6	38 5	75 7	121 16	142 19	C,D	



(a)



(b)

Figure 6.33. SEPTEMBER 5-M WATER SAMPLE ORDINATION PLOTS. See Figures 6.30a and 6.31 for further discussion. Station locations are given on Figure 6.34. Communities shown are chosen with the help of Table 6.5.

(a) Station ordination plot.

(b) Phytoplankton ordination plot.

Comparison of the phytoplankton distribution in September (Fig. 6.34) with that of October shows that the general orientation and locations of regions A, B, and C were similar in the two months. The species composition of community X for September (Fig. 6.33b) is similar to community X in October; both are characteristic of region A_1 and A_2 (Lake Michigan water) and have several species in common: *Anacystis incerta*, *A. thermalis*, *Cyclotella michiganiana*, *Oocystis* spp., and *Gomphosphaeria lacustris* (Tables 6.6 and 6.7).

Community Z for September, consisting of two diatoms, *Cyclotella comta* and *C. operculata*, is quite different from community Z for October which includes a diatom, chrysophyte, and two cryptomonads. These Z communities are found in region C which is located in approximately the same area for the two cruises. Community Y in September consists of *Cyclotella ocellata* and *Rhizosolenia eriensis*, which corresponds with the hypolimnetic community W of October.

Hypolimnetic Associations in September

Ordination plots for stations and taxa of all 5-m samples plus some selected hypolimnetic samples show an overlap of samples in regions B and D (Fig. 6.35). Community Y, consisting of *Cyclotella ocellata* and *Rhizosolenia eriensis*, is found in both regions, indicating that upwelled water is present at the surface in region B. In this deep water region (Table 6.7), *C. ocellata* and *R. eriensis* attain extremely high densities and are the only taxa more abundant below the thermocline than above it.

Near-surface Associations in August

In August, region A_1 in Lake Michigan combined with region A_2 has a phytoplankton assemblage, X, that is similar to that found in September and October except that it contains no diatoms (Fig. 6.36). Two blue-green algal taxa (*Anacystis incerta* and *A. thermalis*) and four green algal taxa (*Gloeocystis planctonica*, *Crucigenia quadrata*, *Oocystis* spp. and a *Eutetramorus* species) dominate the assemblage.

A second region, C, consists of a single station (25) which has a unique community for this cruise. The densities of *Anacystis incerta* and *A. thermalis* were the lowest at this station at 5 m, while densities of two diatoms, *Cyclotella operculata* and *C. comta*, were highest (Table 6.8). The community includes *Rhodomonas minuta* var. *nannoplanctica*, a species found in the Lake Huron community of October, and *Cyclotella michiganiana*, found in the Lake Michigan community for September and October.

Region B is located along the northern coast of the survey area (Fig. 6.37) and is characterized by a community, Y, of two diatoms: *Cyclotella ocellata* and *C. stelligera* (Fig. 6.36).

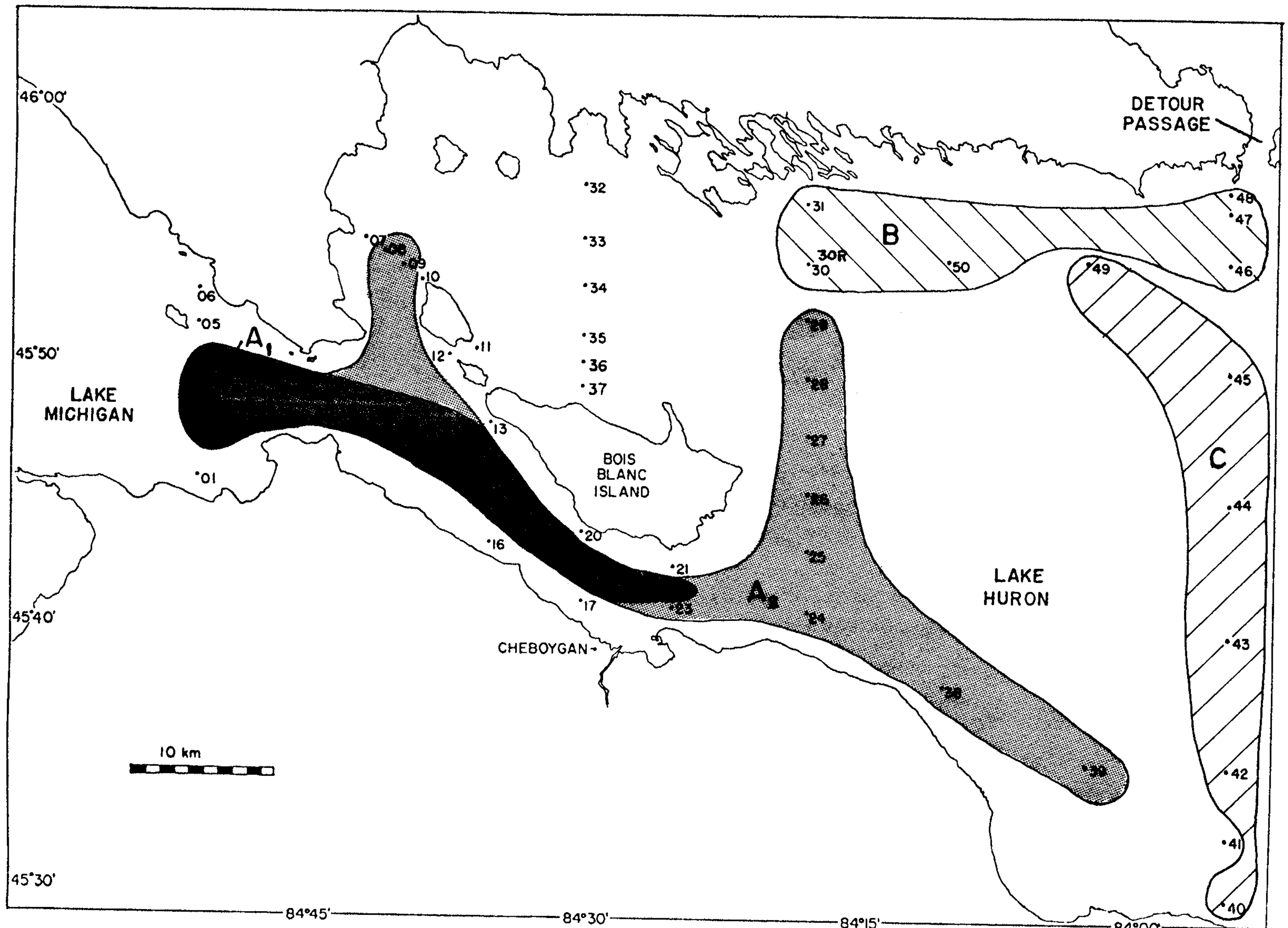
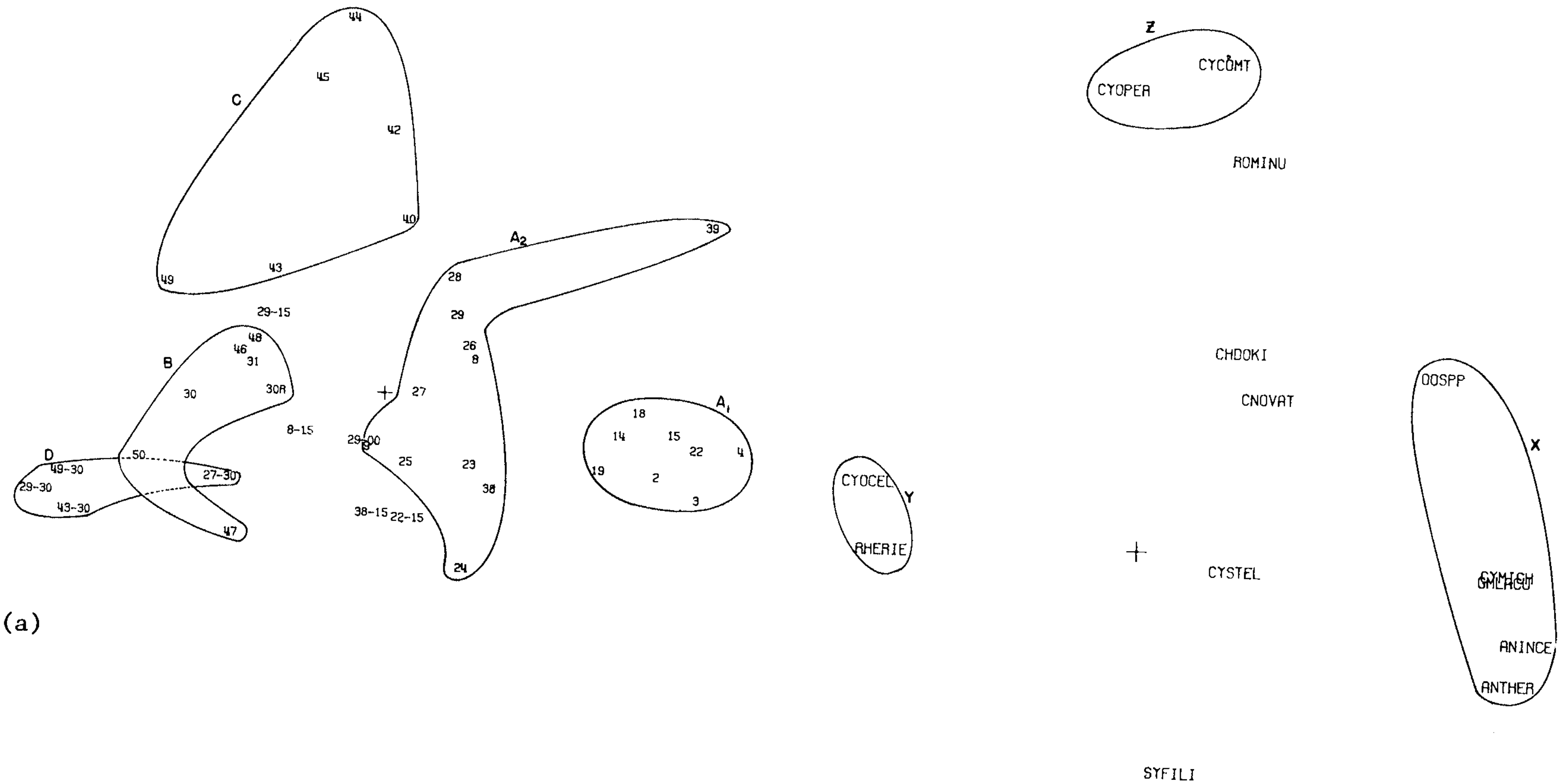


Figure 6.34. GEOGRAPHIC LOCATIONS OF 5-M SEPTEMBER PHYTOPLANKTON COMMUNITIES. Regions are determined on the basis of the ordination plot of Figure 6.33a. Phytoplankton data are not available for stations not included in one of the four regions.

Table 6.7. SEPTEMBER PHYTOPLANKTON CELL DENSITIES. Averages (cells/ml) are given over standard error of the mean. Format same as Table 6.6. Region D is discussed under "Hypolimnetic associations in September." Last 3 columns show average densities for epilimnion of northern Lake Michigan (NLM) Stations 52-54 (11 samples), epilimnion of Stations 20-23 (16 samples), and hypolimnion of Stations 20-23 (14 samples). Stations were sampled on 20-23 Sept. 1973, immediately after sampling of the Straits survey area. See Figure 8.1 for NLM station locations. The epilimnion is taken to be represented by samples above 20 m and the hypolimnion by those below 30 m.

	Region label and number of stations					Apparent trend		NLM	NLM	NLM
	A_1 9	A_2 10	B 7	C 6	D 4	High	Low	52-54 epi	20-23 epi	20-23 hypo
*Gomphosphaeria lacustris**	933	279	30	231	0	A	B,D			
	99	34	19	102						
*Anacystis incerta**	2951	1629	200	681	84	A	B,D	2712	2093	49
	196	155	86	238	77			222	213	22
*Anacystis thermalis**	197	98	8	46	5	A	B,D	218	227	12
	23	16	6	16	4			28	18	5
Oocystis spp.*	52	24	5	31	7	A	B,D			
	8	6	2	5	3					
*Cyclotella michiganiana**	73	55	15	31	10	A	B,D	54	8.5	2.4
	6	3	2	5	4			4	1.5	.7
Gloeocystis planctonica	44	32	10	13	4	A	D			
	9	9	4	11	4					
Eutetramorus species #1	16	7	4	9	0	A	B,D			
	4	3	3	4						
Asterionella formosa	24	9	14	6	7	A	C,D	27	2.2	3.9
	7	5	5	4	4			7	1.5	1.1
Crucigenia quadrata	19	34	12	14	0		D			
	9	12	7	10						
*Cyclotella stelligera**	113	97	102	75	92	A,B?	C?	87	29	26
	9	8	19	10	16			8	5	4
Fragilaria crotonensis	84	81	61	89	73			55	10	3.7
	26	20	19	22	43			14	6	1.2
Tabellaria fenestrata	6	5	3	5	4					
	2	2	1	2	2					
*Synedra filiformis**	2.8	6	4	2	3					
	.9	3	1	1	1					
Anabaena flos-aquae	37	10	0	62	0					
	20	7		58						
*Chrysococcus dokidophorus**	7	12	8	7	.5					
	2	3	3	1	.5					
*Cryptomonas ovata**	7	6	6	6	.5					
	1	1	2	2	.5					
Chrysosphaerella longispina	0	0	0	0	0					
Rhodomonas minuta v. *nannoplanctica**	20	17	17	27	2.6		D			
	7	4	6	8	.5					
*Cyclotella comta**	27	24	14	57	19	C	B,D	19	3.4	1.5
	3	1	3	6	3			3	.9	.5
*Cyclotella operculata**	.9	2.3	4	10	0	C	A,D	1.1	0	0
	.5	.7	1	2				.4		
*Rhizosolenia eriensis**	2.1	5	11	14	26	D,C,B				
	.8	1	3	4	9					
*Cyclotella ocellata**	20	58	108	141	317	D,C,B		15	1.2	15
	4	10	24	38	84			2	.6	1



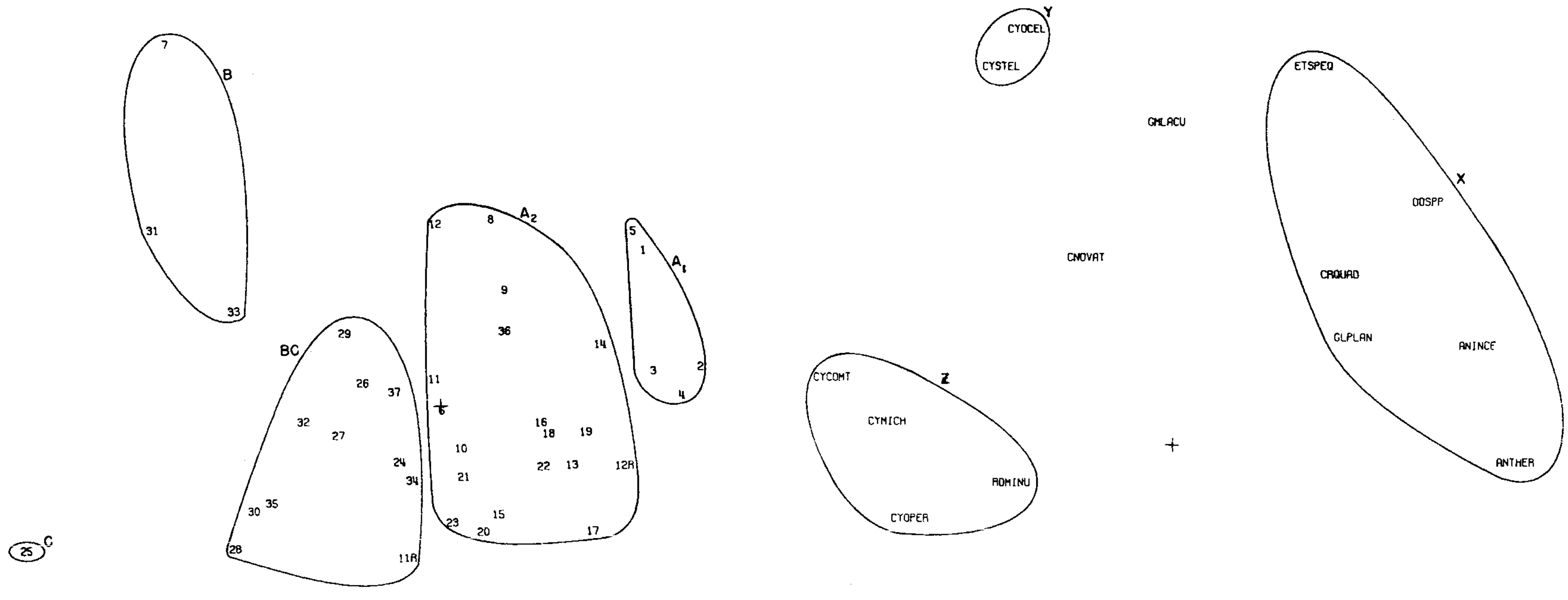
(a)

(b)

Figure 6.35. ORDINATION PLOTS FOR SEPTEMBER SURFACE AND SUBSURFACE SAMPLES. See caption for Figure 6.32 for further information.

(a) Station ordination plot.

(b) Phytoplankton ordination plot.



(a)

(b)

Figure 6.36. AUGUST 5-M WATER SAMPLE ORDINATION PLOTS. See Figures 6.30 and 6.37 for further discussion. Station locations are given on Figure 6.37.

(a) Station ordination plot.

(b) Phytoplankton ordination plot.

Table 6.8. AUGUST PHYTOPLANKTON CELL DENSITIES. Average densities (in cells/ml) for each region (Figs. 6.36 and 6.37) are given over the standard error of the mean. Format is the same as for Table 6.6. Region H consists of only one station, and its standard errors are calculated from replicate phytoplankton counts from the 5-m sample at that station. Region D is discussed under "Hypolimnetic associations in August." Standard errors for region C are based on two replicate counts on one slide. Taxa identified with an (*) were used in the PCA.

	Region label and Number of stations							Apparent trend	
	A_1 5	A_2 19	BC 11	C 1	B 3	D_1 3	D_2 4	High	Low
*Anacystis incerta**	4348	3171	2363	2032	607	35	1079	A	C,D
	448	231	184	453	398	35	360		
*Anacystis thermalis**	208	150	109	68	29	0	54	A	C,D
	25	13	13	15	29		41		
*Crucigenia quadrata**	80	55	29	17	0	0	8	A	C,D
	22	15	11	9			8		
*Gloeocystis planctonica**	165	99	70	50	90	0	53	A	D
	29	17	9	25	6		9		
Oocystis spp.*	98	75	50	61	38	3	25	A	D
	5	6	3	17	13	3	2		
Eutetramorus species #1*	308	204	192	230	145	0	92	A	D
	32	14	22	9	6		30		
Anabaena flos-aquae	46	32	38	0	0	0	23	A?	
	38	17	24				23		
Synedra filiformis	0	1.0	1.0	0	0	10	4	D?	
		.5	.4			5	2		
Chrysococcus dokidophorus	0	0	0	0	0	.7	.5		
						.7	.5		
Tabellaria fenestrata	0	0	3	0	0	13	9	D?	
			2			6	4		
*Cryptomonas ovata**	7	8	7	11	8	2	7		
	2	1	2	3	4	1	3		
Rhizosolenia eriensis	0	.8	1.1	3	0	17	6	D?	
		.4	.7	1		8	4		
Chrysosphaerella longispina	0	9	10	45	0	0	0		
		9	10	45					
*Cyclotella operculata**	3	3.3	6.3	6	27	1	6	C	
	1	.8	.9	1	6	1	2		
*Cyclotella comta**	19	28	46	64	101	17	50	C	A,D
	2	2	4	9	4	3	12		
*Cyclotella michiganiana**	20	32	54	52	61	17	47	B,C	
	3	2	4	8	6	2	16		
Rhodomonas minuta v. *nannoplanctica**	7	3	14	10	14	3	8	B,C	
	1	1	6	5	2	2	2		
*Gomphosphaeria lacustris**	574	501	535	817	440	28	508	B	D
	225	79	114	84	440	28	123		
Fragilaria crotonensis	87	54	82	194	90	22	163	B	
	42	13	18	32	6	22	52		
*Cyclotella stelligera**	25	28	31	83	34	78	53	B,D	A
	4	2	4	17	8	17	9		
*Cyclotella ocellata**	3	2.5	3.0	17	0	48	39	B,D	
	1	.5	.7	6		14	15		
Asterionella formosa	3	2	7	13	0	2	8	B	
	3	1	4	3		2	6		

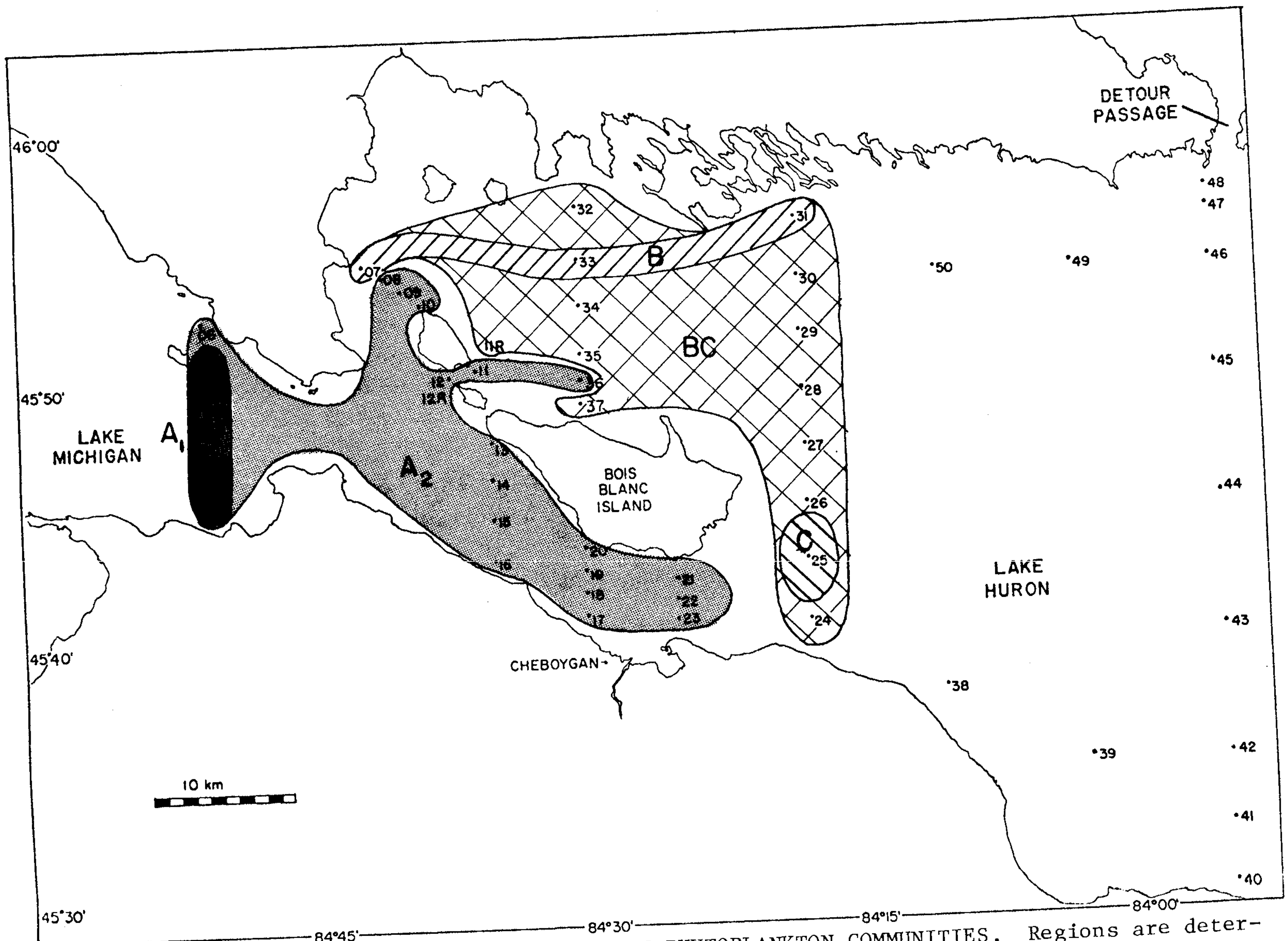


Figure 6.37. GEOGRAPHIC LOCATIONS OF 5-M AUGUST PHYTOPLANKTON COMMUNITIES. Regions are determined on the basis of the ordination plot of Figure 6.36. Stations east of a line from Station 24 to Station 31 were not sampled.

Hypolimnetic Associations in August

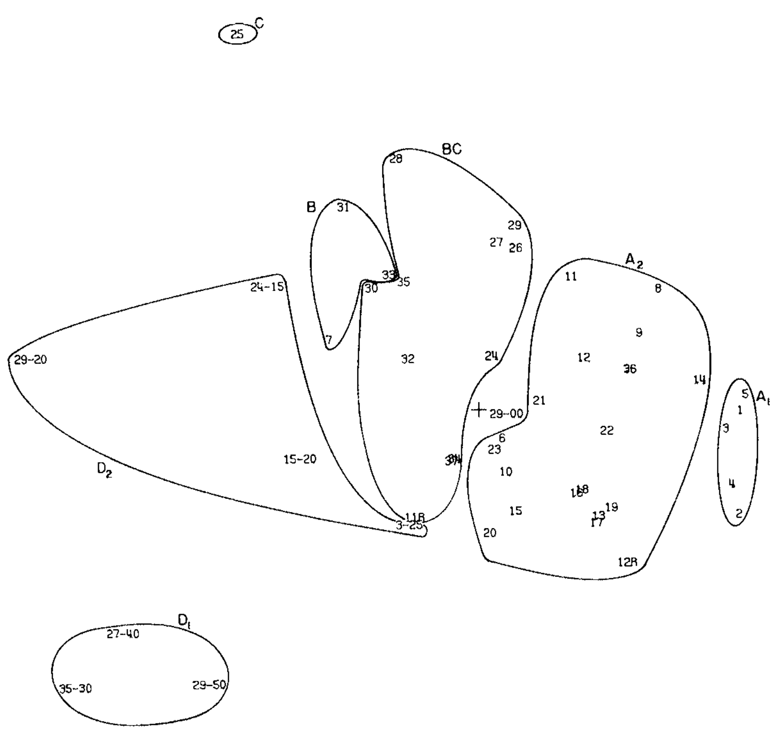
Including seven deep samples with the 5-m samples in the PCA analysis gave an orientation similar to that for the 5-m samples (Fig. 6.38). The deep samples added to the analysis are in regions D_1 and D_2, which show closest proximity to region B and some samples in region BC. This is evidence that the community in region B is related to the hypolimnetic community and that region B is upwelled, but also suggests that some additional stations (11R, 37, 34, 30 and 35) might be upwelled. These additional stations are located north and east of Bois Blanc Island near region B (Fig. 6.37).

The hypolimnetic community found at Stations 27, 29 and 35 is characterized by two species of *Cyclotella, C. ocellata* and *C. stelligera* (Fig. 6.38). These two taxa also constitute community Z, identified as the community at region B from the 5-m samples (Fig. 6.36). These conclusions that *C. ocellata* and *C. stelligera* are favored in region B and in the hypolimnion is supported by the absolute abundance of these species (Table 6.8).

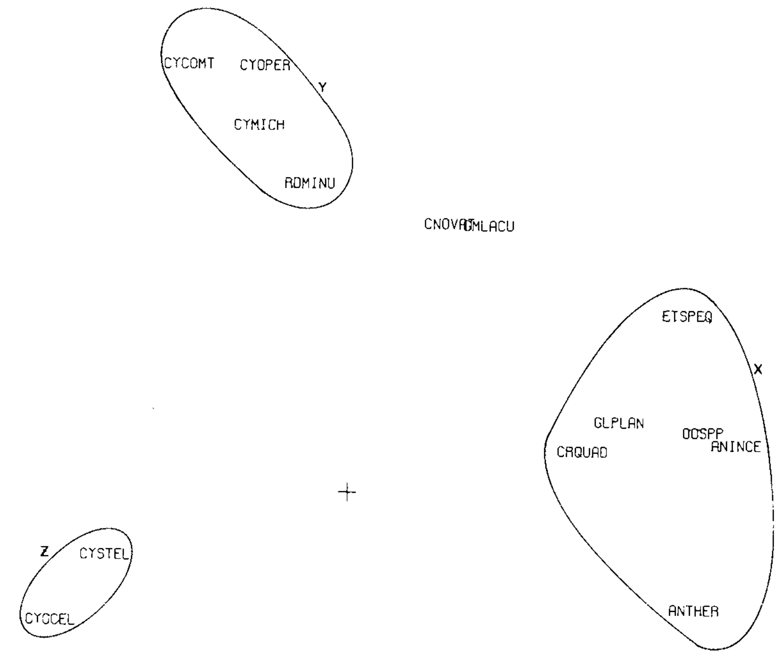
Region D_2, intermediate between region D_1 and the surface sample regions (Fig. 6.38), consists of subsurface samples at stations located for the most part in the southwestern side of the survey area. For example, the 5-m sample at Station 03 (in the western side of Lake Michigan) belongs with region A_1, which contains community X (green and blue-green algae). The 25-m sample at the same station, on the basis of Figure 6.38a appears to have a community intermediate between community X at 5 m and community Z of the hypolimnion of the northwestern section. This implies that deep-water samples do not all have the same phytoplankton community. The hypolimnion in the northeastern part of the survey area has a phytoplankton community consisting mainly of *Cyclotella ocellata* and *C. stelligera* (Table 6.8, Figs. 6.38a and b). The hypolimnion of the southwestern side (identified as having Lake Michigan water at its surface) has a community somewhat intermediate between those of surface Lake Michigan and the hypolimnion of the more northern stations. One possible explanation is that deep westward currents are carrying the *C. ocellata* and *C. stelligera* (and any other deep-water taxa east of the Straits) into the hypolimnion of Lake Michigan.

6.5 COMPARISON OF TEMPERATURE-CONDUCTIVITY AND PHYTOPLANKTON COMMUNITY PATTERNS

If certain phytoplankton communities are associated with specific water masses, then individual taxa in these water masses should be diluted with the mixing of water masses. It should, therefore, be possible to determine how much of the distribution pattern of a given taxa is due to dilution of water masses and how much is due to other factors.



(a)



(b)

Figure 6.38. ORDINATION PLOTS FOR AUGUST SURFACE AND SUBSURFACE SAMPLES. See caption for Figure 6.32 for further information.

(a) Station ordination plot.

(b) Phytoplankton ordination plot.

If a parameter follows water movement and is conservative, then its value at any surface point $\vec{x}$ should follow the same rules set forth above for temperature and conductivity (Sec. IV). If $V(\vec{x})$ is the value of this conservative parameter at $\vec{x}$ then

$$V(\vec{x}) = \sum_{i=1}^{3} V_i F_i(\vec{x})$$

where $F_i(\vec{x})$ is, as before, the fraction of water at $\vec{x}$ originating from $\underline{i}$ and V_i is the value of the parameter at source $\underline{i}$. It is shown in Appendix E that in a system consisting of three water sources it is possible to express any conservative parameter as a linear combination of any other two conservative parameters (but only if neither of these two has equal values at all sources and only if they are linearly independent). It then follows that:

> The value of the conserved parameter $V(\vec{x})$ at surface point $\vec{x}$ in the Straits survey area is expressible as a linear combination of temperature, $T(\vec{x})$, and conductivity, $C(\vec{x})$, at that point.

If the density of a phytoplankton taxon is conservative (that is, if it can be viewed as a passive tracer of water masses and does not grow, die, sink or get eaten), then it should be possible to obtain a large value of R^2 from a linear regression of the plankton's density against temperature and conductivity. (It should be understood that this regression is not meant to predict phytoplankton density from temperature and conductivity in the usual sense, but rather to examine the relationship of phytoplankton density with water dilution.) The value of R^2 is interpretable as the fraction of variance removed by the regression. Consequently, the larger R^2 is, the better the dilution model explains the distribution of the plankton. Conversely, a low value of R^2 suggests that water-mass dilution is not the major factor determining the density estimates of the plankton in the surface samples.

Measurement errors also contribute to the unexplained fraction of the variance. Since the number of colonies of any one species observed on a slide did not exceed 50 and was usually very much less than this (Tables 6.9, 6.10), it is apparent that statistical variability in species counts will be an important contributor to the unexplained variance. Water-mass dilution accounts for 21 to 74% of the observed densities for the most abundant taxa, whereas it can account for less than 10% for the least abundant ones. These results indicate that the values of R^2 are at least partly dependent on counting error, i.e., that the largest values for R^2 are associated with the most abundant species.

It is possible to estimate the contribution to the statistical variability due to the counting procedure. The regression model for R^2 may be written

Table 6.9. VALUES OF R^2 AND RELATED STATISTICS FROM REGRESSIONS OF CELL DENSITIES AGAINST TEMPERATURE AND CONDUCTIVITY FOR THE MOST ABUNDANT TAXA.

Taxon name	Estimated maximum number of colonies observed on a slide	R^2	R^2_{est}	$\frac{R^2}{R^2_{est}}$	Standard error of the angle (SD)
Anacystis incerta	8	.521	.628	.83	10.3°
Anacystis thermalis	11	.543	.718	.76	10.1
Synedra filiformis	22	.307	.867	.35	16.7
Cyclotella michiganiana	42	.743	.895	.83	6.6
Cyclotella stelligera	29	.344	.803	.43	13.8
Cyclotella comta	14	.206	.484	.43	20.7
Chrysococcus dokidophorus	14	.210	.265	.79	15.0
Rhodomonas minuta v. *nannoplanctica*	16	.354	.703	.50	14.2
Cyclotella ocellata	35	.515	.729	.71	8.3

Table 6.10. VALUES OF R^2 FROM REGRESSIONS OF CELL DENSITIES AGAINST TEMPERATURE AND CONDUCTIVITY FOR LESS ABUNDANT TAXA.

Taxon name	Estimated maximum number of colonies observed on a slide	R^2	Standard error of the angle (SD)
Asterionella formosa	6	.126	20.2°
Oocystis spp.	7	.326	15.9
Gloeocystis planctonica	2	.241	19.5
Anabaena flos-aquae	3	.013	68.8
Rhizosolenia eriensis	7	.020	55.2
Eutetramorus species #1	2	.059	30.9
Cyclotella operculata	5	.148	20.5
Cryptomonas ovata	6	.099	31.3
Chrysosphaerella longispina	5	.092	34.3
Fragilaria crotonensis	5	.056	34.8
Tabellaria fenestrata	3	.085	26.4
Crucigenia quadrata	4	.062	43.3
Gomphosphaeria lacustris	4	.111	31.4

as:

$$R^2 = \frac{SST-SSE}{SST}$$

where SST = total sum of squares = $\sum_{i=1}^{N} (y_i-\bar{y})^2$

SSE = total sum of squares = $\sum_{i=1}^{N} (\hat{y}_i-y_i)^2$

N = number of samples (or stations or slides)

y_i = measured value of dependent variable (number of colonies) for sample $\underline{i}$

$\hat{y}_i$ = predicted value of the dependent variable based on the regression

$\bar{y}$ = average number of colonies per slide = $\frac{\sum_{i=1}^{N} y_i}{N}$

Since we have verified that the colonies are distributed randomly on the slides, it may be assumed that colony counts follow a Poisson distribution. Let λ_i be the Poisson parameter for the colony counts made of the species in question over a fixed area A of slide $\underline{i}$. (λ_i may be thought of as the average number of colonies counted in a very large number of non-overlapping scans each covering an area A of this slide.) From the properties of the Poisson distribution, λ_i equals the variance and the mean. Each slide count is a sample of size one from a Poisson distribution with parameter λ_i, and thus λ_i may be estimated as either:

$$\lambda_i \cong y_i$$

or

$$\lambda_i \cong MSE = (\hat{y}_i-y_i)^2 .$$

Consequently:

$$SSE = \sum_{i=1}^{N} (\hat{y}_i-y_i)^2$$

$$\cong \sum_{i=1}^{N} \lambda_i$$

$$\cong \sum_{i=1}^{N} y_i .$$

This permits an estimate for R^2 which is based on the number of colonies counted on a slide:

$$R^2_{est} = \frac{SST-SSE_{est}}{SST}$$

where $$SSE_{est} = \sum_{i=1}^{N} y_i$$

The R^2_{est} can be calculated before the regression is performed and provides a means of evaluating the R^2 resulting from the regression analysis. If R^2 nearly equals R^2_{est}, it may be concluded that the fraction of the variance not explained by the regression can be accounted for mainly by counting error.

The ratio of R^2/R^2_{est} may be interpreted as the fraction of the variance of cell density accounted for by dilution. The unexplained fraction includes contributions due to sample preparation (believed to be much smaller than the contribution due to counting, which was considered above and is included in R^2_{est}) and other factors including patchiness, growth, death, sinking, and predation. Very large fractions (over 70%) of the variance of the densities for *Anacystis incerta, Anacystis thermalis, Cyclotella michiganiana, Chrysococcus dokidophorus,* and *Cyclotella ocellata* are apparently explained by water mixing, whereas other taxa have between 35% and 50% of the variance explained by dilution (Table 6.9). The species with the lowest fraction explainable by dilution is *Synedra filiformis*. The unaccounted fraction is almost entirely the result of the extremely high density at Station 06. For the other taxa, the difference between R^2 and R^2_{est} is not explained as simply.

An examination of the residuals of the regression might help identify additional factors determining cell density. If, for example, the residuals (residual is defined as the value predicted on the basis of the regression minus the measured value: $[\hat{y}_i - y_i]$) for a species most abundant in Lake Michigan increase toward the southeast, then this species is probably sinking or being preyed upon faster than it is reproducing as water moves from Lake Michigan to Lake Huron. Another explanation might be that cell densities at the source are increasing but that net production is not equal to the rate of dilution with Lake Huron or St. Marys River water. Examination of residuals of these species (Table 6.9), however, do not show any simple patterns. Instead, the factors affecting the residuals appear for the most part to be local and erratic. For example, the extremely high cell density of *Synedra filiformis* at Station 06 is inconsistent with the dilution patterns as defined by temperature and conductivity. *Cyclotella stelligera* attains high densities at Stations 04 and 05 as well as at 06. The densities of *C. stelligera* between Stations 02 and 06 are not consistent with dilution patterns. The very high density at Station 42 is also highly inconsistent with dilution patterns.

The general conclusion to be drawn from the analysis of phytoplankton densities relative to the water-mass dilution is that, for most species, simple dilution seems to be a very important factor determining distribution patterns and that for some it may be the only significant factor. Most phytoplankton species therefore appear to be semi-conservative in the sense that at least half of the density variance is explainable by water dilution.

The regressions of plankton densities vs. temperature and conductivity can also be used to indicate diagrammatically where the plankton are found (Fig. 6.39). Multiple linear regression with two independent variables is usually viewed as a technique of finding the least squares plane passing through points in three-dimensional space. It can also be viewed, however, as a two-dimensional problem. The regression of cell density D on temperature and conductivity determines statistical parameters α, β and γ for the regression model

$$D_i = \beta T_i + \gamma C_i + \alpha + e_i$$

where
D_i = density at station i
T_i = temperature at station i
C_i = conductivity at station i
e_i = error

such that the canonical variable $(\beta T + \gamma C + \alpha)$ maximally correlates with D. In this sense it is very similar to canonical correlation. If the regression coefficients β and γ are normalized:

$$\beta' = \frac{\beta}{\sqrt{\beta^2 + \gamma^2}} \quad \text{and} \quad \gamma' = \frac{\gamma}{\sqrt{\beta^2 + \gamma^2}}$$

then β' and γ' may be interpreted as direction cosine for the axis of the canonical variable $(\beta T + \gamma C + \alpha)$ in the T-C plane.

It is also possible to estimate the angular error associated with the direction of each arrow. Using a Taylor expansion, it is possible to show that (derivation is omitted):

$$SD^2 = \mathrm{Var}[\arctan(y/x)] \cong$$

$$\frac{(n-3)^2\ [xy(\mathrm{Var}_x - \mathrm{Var}_y) + (y^2 - x^2)\mathrm{Cov}_{xy}]^2}{n(n-1)(x^2+y^2)^4} + \frac{(n-3)(y^2\mathrm{Var}_x - xy\mathrm{Cov}_{xy} + x^2\mathrm{Var}_y)}{(n-1)(x^2+y^2)^2} .$$

Here, y is the regression coefficient associated with conductivity and x is the regression coefficient associated with temperature. Simulations to test the accuracy of this approximation show that, for $n > 30$, it is accurate to about 2% for SD in the range 2° to 10° and accurate to about 15% for SD in the range 50° to 70°. The approximation shows a tendency to underestimate that is especially noticeable when SD is greater than

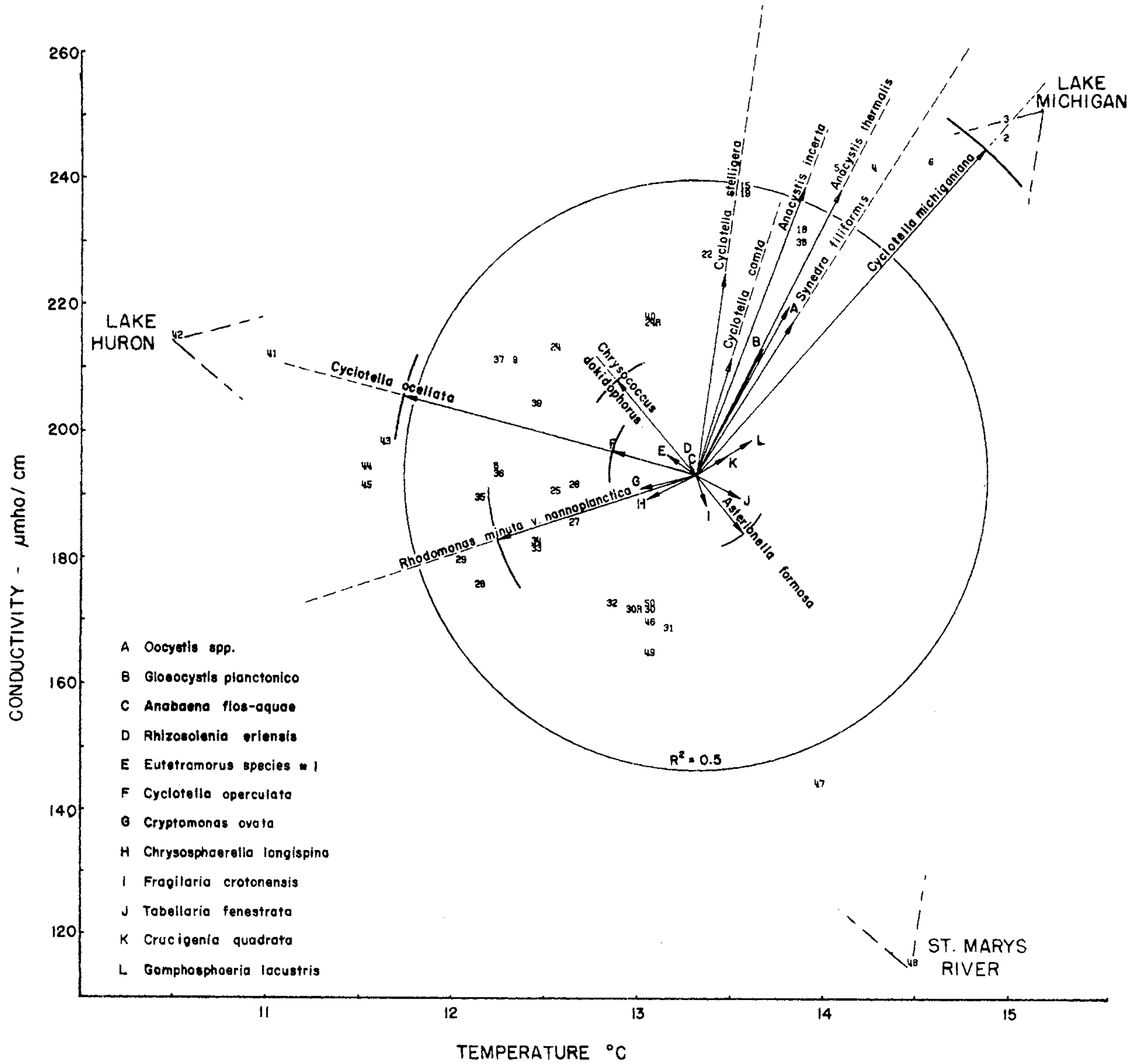


Figure 6.39. PHYTOPLANKTON TRENDS ON THE T-C PLANE. Numbers refer to stations and are plotted in the T-C plane. Only 5-m samples are considered, and only stations for which phytoplankton data exist are shown. Each arrow shows the direction in the T-C plane in which the corresponding phytoplankton taxon tends to be most abundant; length of arrow indicates strength of tendency. Directions for arrows are taken from multiple linear regressions of cell density against temperature and conductivity; length of arrow represents value of R^2 for that regression. Arcs at arrow tips represent standard error of the angle as estimated from the variance-covariance matrix of the regression coefficients. Dashed line indicates value of R^2_{est}.

30°. As might be expected, SD increases as R^2 and the number of colonies counted decreases (Tables 6.9, 6.10). The values of SD shown are, for the most part, relatively small and indicate that the directions on the arrows shown in Figure 6.39 are reasonably accurate.

The plot in Figure 6.39 may be seen as an ordination of stations and phytoplankton, but of a different nature than the ones shown in Figure 6.30 where each station and phytoplankton taxon is ordinated relative to the phytoplankton community. In Figure 6.39 the relationships of both stations and phytoplankton are shown relative to water-mass dilution as revealed by temperature and conductivity. Figure 6.30 displays results of a single multivariate ordination; the use of the term "multivariate" means that the ordination examines community relationships. In Figure 6.39, the results of univariate analyses for temperature and specific conductance and 22 phytoplankton taxa are shown. If Figure 6.39 is rotated 45° clockwise relative to Figure 6.30, rather striking similarities are revealed between station locations as well as taxa locations. This again supports the conclusion that the distribution of communities illustrated in Figure 6.31 is due mainly to the dilution of the individual taxa found in the communities of Lake Michigan, Lake Huron and the St. Marys River.

The direction of an arrow in Figure 6.39 indicates direction of highest occurrences, and the length of the arrow the strength of the trend. The arrow for *Cyclotella michiganiana*, for example, points in the direction of the Lake Michigan stations. It therefore appears to show a tendency toward high densities in Lake Michigan and low densities in Lake Huron and the St. Marys River. The length of the arrow or the R^2 indicates that this tendency is very strong. Arrows for *Anacystis incerta* and *A. thermalis* are shifted more toward the Lake Huron stations than the arrow for *C. michiganiana*. It would be concluded that these species, though most abundant in Lake Michigan, are more abundant at Lake Huron stations than at stations of the St. Marys River. The arrow of *Cyclotella stelligera* points almost straight up. It is abundant both at Lake Huron and Lake Michigan stations but relatively rare at the St. Marys River. *Cyclotella ocellata* is most abundant toward Lake Huron stations, whereas *Rhodomonas minuta* var. *nannoplanctica*, though very abundant at Lake Huron stations, is more abundant at St. Marys River than in Lake Michigan since its arrow points generally toward Lake Huron stations but also somewhat toward St. Marys River stations and away from Lake Michigan stations. Only three species, *Asterionella formosa, Tabellaria fenestrata,* and *Fragilaria crotonensis,* appear to be most abundant at the St. Marys River--all have relatively small values of R^2.

It is apparent that most arrows in Figure 6.39 tend to be oriented toward Lake Michigan, Lake Huron or the St. Marys River, implying that most of the 22 taxa are abundant in only one of the three water types. Few taxa appear to be equally abundant in two water types simultaneously. A taxon occurring equally at all three water types would have a nondirected arrow--that is one of very short length.

The actual cell densities of *Cyclotella michiganiana, C. ocellata,* and *C. stelligera* at stations in the survey area are shown in Figures 6.40, 6.41 and 6.42, and can be compared with the results shown in Figure 6.39. *Cyclotella michiganiana* is most abundant at Lake Michigan stations and becomes less abundant as Lake Michigan water dilutes with Lake Huron or St. Marys River water (Fig. 6.40). Highest densities of *C. ocellata* are toward Lake Huron and lower densities toward Lake Michigan and the St. Marys River (Fig. 6.41). These conclusions are consistent with the results shown in Figure 6.39 and Table 6.2.

As suggested by Figure 6.39, *C. stelligera* appears to be most abundant in Lakes Michigan and Huron, although it is also found at the St. Marys River. Its densities, however, are low at stations in the center of Figure 6.42, being higher at the sources than at stations where the waters from these sources mix. This pattern is quite inconsistent with the dilution model which results in the large difference between R^2 and $R^2{}_{est}$ given in Table 6.9, and was not evident in the distribution of any other taxa, although it is possible that counting the algae samples more fully would uncover such patterns for other phytoplankton. One possible cause for the odd distribution of *C. stelligera* would be the occurrence of very rapidly developing blooms simultaneously at each of the sources (but not in the mixed water) immediately before or during the time the samples were collected.

Distribution of Chemical-Physical Parameters at 5 m During October

Regressions of several physical-chemical parameters and rates of phytoplankton carbon fixation vs. temperature and specific conductance were calculated for the data from 5 m in October. Results are listed in Table 6.11 and plotted in Figure 6.43.

The R^2 for chloride is nearly 1.0, indicating chloride behaves as a conservative parameter (Table 6.11). Since the arrow for chloride is parallel to the conductivity axis, it appears that conductivity and chloride analyses measure the same thing in these samples or are, at least, redundant. That the R^2 value is not 1.0 may be explained by measurement errors. Since the arrow for chloride points away from the vertex for the St. Marys River, chloride values are very low there relative to the other sources. Chloride is higher in Lake Michigan than in Lake Huron, since the arrow points more nearly in the direction of the Lake Michigan source.

Alkalinity, surprisingly, based on the R^2 from the regression, acts as a nearly conserved property (Table 6.11). The changes induced by the biota through photosynthesis and respiration may be too slow relative to the transit time of the water through the survey area to affect the results attributed to dilution. Alkalinity is very large in Lake Michigan compared to values in the St. Marys River, which also may account for the apparent conservative behavior.

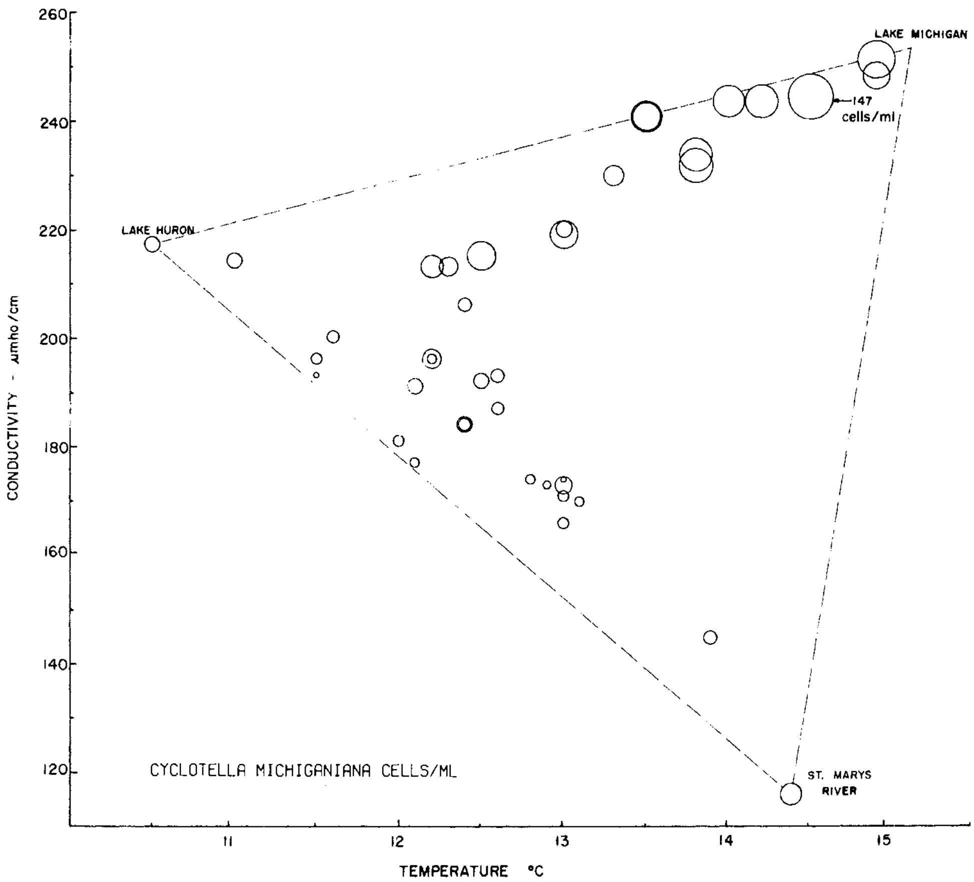


Figure 6.40. CELL DENSITIES FOR *CYCLOTELLA MICHIGANIANA* ON THE T-C PLANE FOR OCTOBER. Each 5-m sample is located on the T-C plane. At the location of the sample in this plane, a circle is drawn which has an area proportional to the cell density. These plots may be used to help interpret Figure 6.39. Use Figure 6.39 as a key to determine with which station a circle corresponds.

The pH data are not, strictly speaking, conserved mainly due to strong buffering capacity of the Great Lakes and to the fact that pH relationships are not linear, i.e., pH is not conserved because it does not follow the definition of equation 1 of Section IV. Nonetheless, pH shows a surprisingly high value of R^2. Its distribution is virtually identical with that of alkalinity but is less nearly conservative.

Sulfate is generally considered to be a conservative parameter. Its relatively low value of R^2 may be explained by the analytical technique which, at the time of this project, was still being developed at this laboratory (Santiago et al. 1975). Sulfate concentrations are largest in Lake Michigan.

Nitrate nitrogen has a surprisingly high R^2 for a nutrient required by phytoplankton. Since it is not limiting in the upper Great Lakes

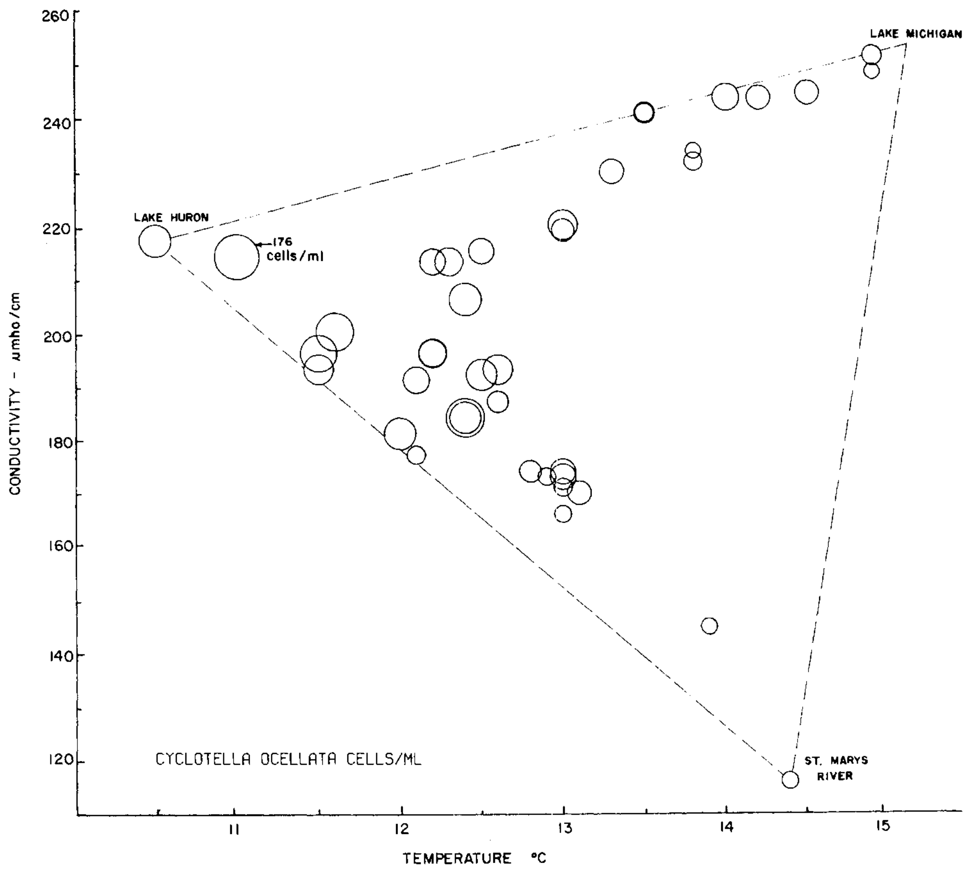


Figure 6.41. CELL DENSITIES FOR *CYCLOTELLA OCELLATA*. See caption for Figure 6.40.

(Schelske 1975) and is found in relatively high concentrations, apparently it is changed slowly by the biota and acts like a nearly conservative parameter. Nitrate was highest at the St. Marys River and very low in Lake Michigan.

Rates of carbon fixation, soluble reactive silica and total phosphorus were not conservative, as expected and shown by the relatively low R^2 (Table 6.11). Carbon fixation was about equal in Lake Huron and the St. Marys River but was larger in Lake Michigan. Silica is limiting for diatoms in the Great Lakes (Schelske 1975), and its small value for R^2 indicates silica concentration was not conservative. Silica concentrations were much larger in the St. Marys River than in Lake Michigan or Lake Huron. R^2 for total phosphorus and soluble phosphorus was very low, indicating that dilution was not a large factor relative to explaining concentrations in the study area.

The relatively large variance in total phosphorus results (Table 3.1) suggests that analytical or sampling methods are not precise. The variance is large not only relative to the mean but also to the range of

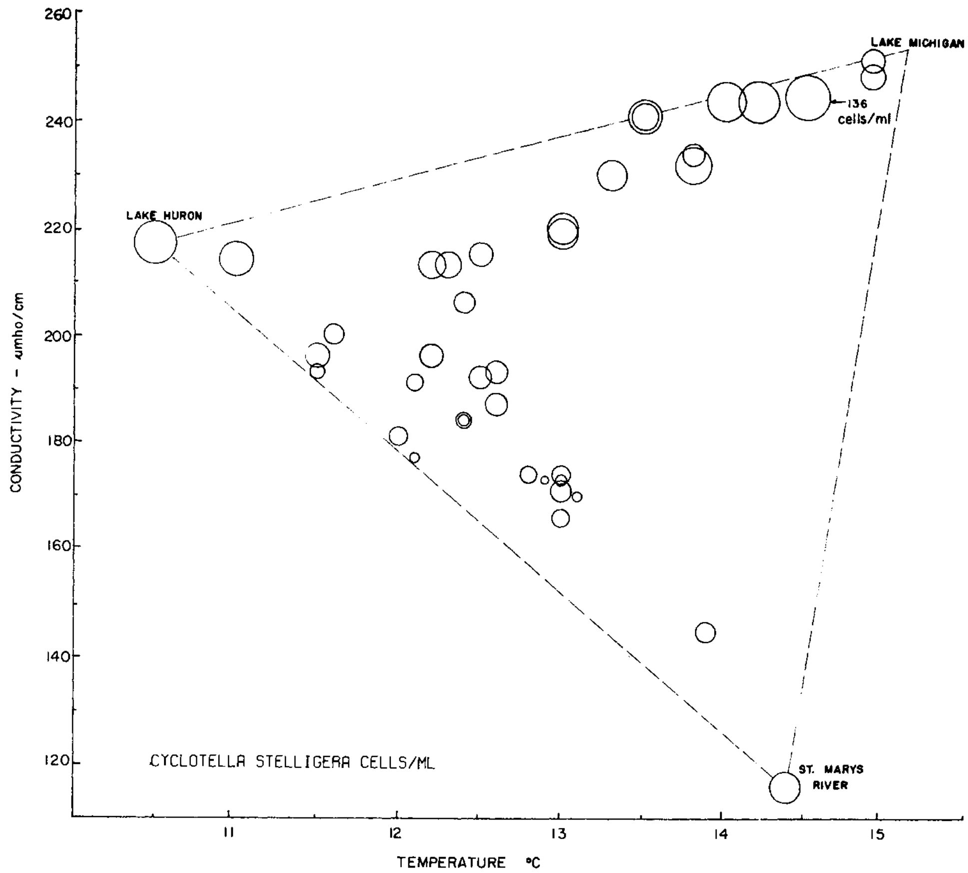


Figure 6.42. CELL DENSITIES FOR *CYCLOTELLA STELLIGERA*. See caption for Figure 6.40.

averages for different groups of stations. If it were not for the problem of variable results with phosphorus, one would have to conclude that biological and other environmental processes, not dilution, control the concentrations of silica and phosphorus. Nitrate is probably an exception due to the fact that it is not limiting, that the soluble component is measured (instead of the particulate and soluble in the case of total phosphorus) and that the concentration difference is large between Lake Michigan and the St. Marys River.

Although the Secchi depth transparency is not conserved (i.e. does not obey eq. 1 of Sec. IV), its reciprocal, which may be associated with extinction coefficient (e.g. Ladewski and Stoermer 1973), can be taken as an estimate of suspended particulate material, which may in turn be conserved if biological activity and sinking can be neglected. The reciprocal Secchi depth is highest at the St. Marys River where the water is quite turbid, due probably to inorganic materials, and lowest in Lake Huron where the water is relatively clear. The moderate value of R^2 suggests that particulate loading might be semi-conservative if measured with a more accurate instrument.

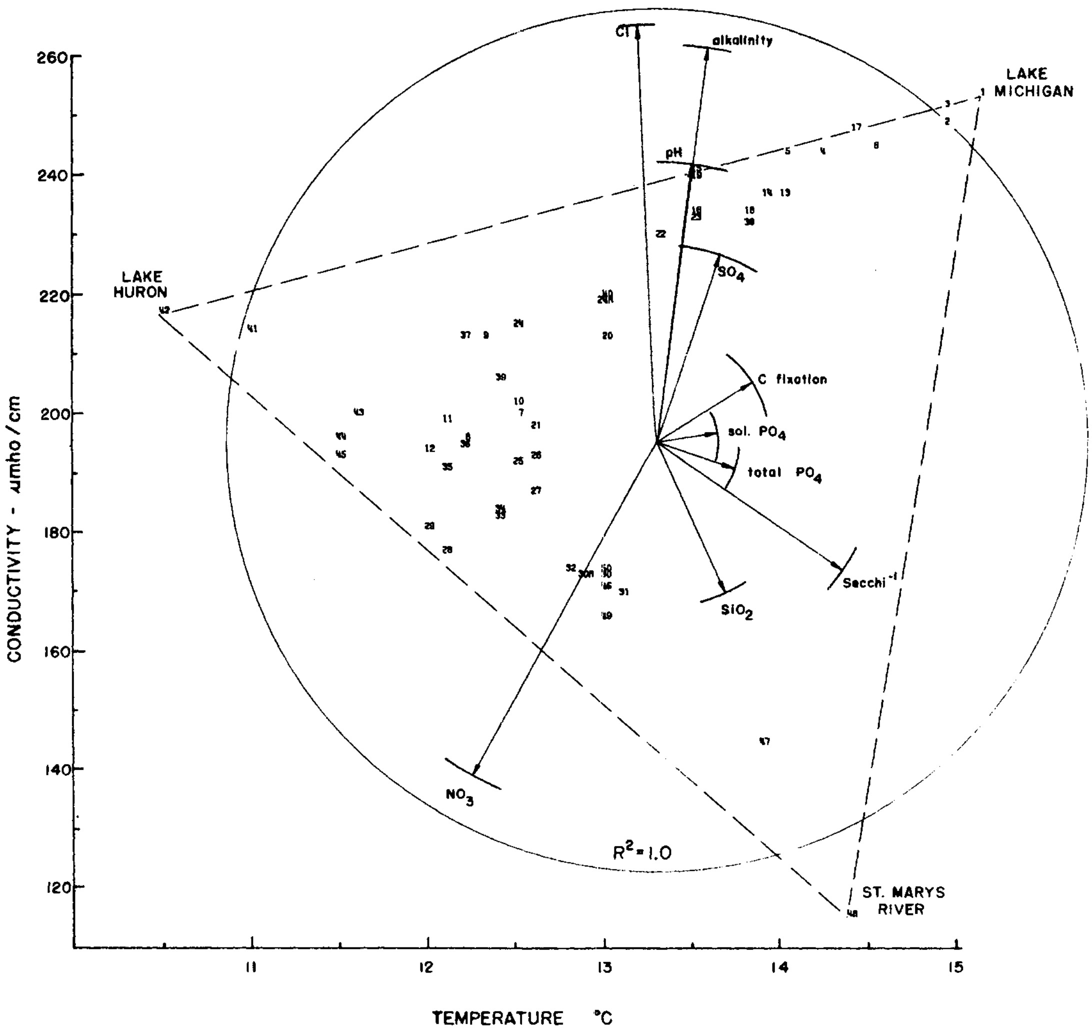


Figure 6.43. TRENDS OF PHYSICAL AND CHEMICAL PARAMETERS IN THE T-C PLANE. Concept and format same as Figure 6.39.

Table 6.11. VALUES OF R^2 AND SD FROM REGRESSIONS OF PHYSICAL-CHEMICAL PARAMETERS AGAINST TEMPERATURE AND CONDUCTIVITY.

Parameter	R^2	Standard deviation (SD) of the angle in degrees
Cl	.933	2.3
Alkalinity	.868	3.7
pH	.609	7.5
SO_4	.433	11.8
Carbon fixation	.247	19.3
Total soluble PO_4	.135	24.4
Total PO_4	.179	15.4
$Secchi^{-1}$	.494	6.3
SiO_2	.363	8.9
NO_3	.836	4.8

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SECTION VII

CRUSTACEAN ZOOPLANKTON OF THE STRAITS OF MACKINAC AND NORTHERN LAKE MICHIGAN

by

John E. Gannon, Kathryn S. Bricker and Theodore B. Ladewski

7.1 INTRODUCTION

Zooplankton samples were first procured from the Laurentian Great Lakes nearly 100 years ago. However, due to the difficulty and high cost of sampling such large water bodies, our knowledge of zooplankton ecology in the Great Lakes has accrued slowly. Relatively few studies have been conducted, and knowledge of zooplankton has barely advanced beyond descriptive ecology (Gannon 1969). Our current understanding of zooplankton species composition, abundance, and distribution in the open waters of the Great Lakes is fairly complete and has recently been reviewed by Davis (1966), Patalas (1972), and Watson and Carpenter (1974). However, many ecologically and economically strategic regions such as embayments, inshore areas, and interconnecting waterways remain to be investigated. One of these important areas is the Straits of Mackinac, the zone of water exchange between Lakes Michigan and Huron.

As part of a physicochemical and biological investigation of this limnologically dynamic region, we studied crustacean zooplankton in the Straits of Mackinac during 1973. Since this was the first investigation of zooplankton in this region, our primary objective was to provide benchmark data on species composition, distribution, and abundance. Our second objective was to analyze zooplankton community structure in relation to the interactions of Lake Michigan and Lake Huron waters. A third objective was to provide information on crustacean zooplankton in northern Lake Michigan, as most prior zooplankton investigations in Lake Michigan have focused only on the southern third of the lake (Gannon 1974a). These data are included primarily to contrast and compare zooplankton community structure between northern Lake Michigan and the Straits of Mackinac.

7.2 METHODS AND MATERIALS

Field

Samples were obtained with a 0.5-m diameter cylinder-cone net towed vertically from near bottom to the surface at approximately 0.5 m/sec. The net material consisted of nylon monofilament screen cloth of 250 μ mesh apertures with a porosity of 44%. This mesh size closely corresponds to the No. 6 mesh (239 μ) of the old silk bolting cloth rating system (Welch 1948). Since the net was 2 m long, vertical tows were from 2 m off bottom to the surface. Extra care was taken to insure that the cod end of the net hit bottom before beginning the vertical ascent. Single samples were procured at most stations. However, several stations were sampled twice during a cruise in order to investigate variations in species composition and abundance over a short time span.

The tow net was fitted with a Nansen throttling mechanism and split tows were obtained at deep stations where a distinct thermocline was present. Two vertical tows, one from the bottom to the top of the hypolimnion and the other from the bottom of the thermocline to the surface, were made at approximately one-third of the stations during each cruise. The Nansen closing net was employed primarily to reduce effects of net clogging during long vertical tows.

Another plankton tow from near bottom to the surface was made at each station using a 0.5-m diameter No. 20 (76 μ mesh size) conical net. This net was employed to qualitatively collect smaller plankters such as rotifers. These samples have not been analyzed to date.

In order to aid in the interpretation of zooplankton data in the Straits region, samples were also taken in northern Lake Michigan at 18 stations during 20-23 September 1973 (Fig. 7.1). Vertical tows from near bottom to the surface were obtained with both the No. 6 and No. 20 mesh nets.

Upon completion of each vertical haul, the net was washed thoroughly and the contents of the cod end bucket were carefully transferred to an 8-oz screw cap jar. Carbonated water (club soda) was immediately added as a narcotizing agent (Gannon and Gannon 1975). After approximately 5 min, most locomotor activity had ceased, and the sample was preserved in 5% buffered formalin.

The mesh size used in any study should be sufficiently small to capture the desired organisms but large enough to avoid clogging by phytoplankton. The mesh size of 250 μ was chosen for its good filtration characteristics and to catch all adult crustacean zooplankters. Net filtration efficiency tests were not conducted in the Straits region. However, such tests were made using flowmeters in the offshore waters of Lake Michigan where filtration efficiency ranged from 86.7-99.7% (Gannon 1972a). In order to test the efficiency of the net to capture crustacean zooplankton, comparisons of the catch of the net and a 7-liter capacity transparent Van Dorn bottle were made at a station in Lake Huron near the mouth of Saginaw Bay on 15 August 1974. Quantitative analyses of these samples revealed that numbers of the smallest zooplankters (*Chydorus sphaericus, Bosmina longirostris, Eubosmina coregoni, Ceriodaphnia lacustris, C. quadrangula, Tropocyclops prasinus mexicanus,* and cyclopoid copepodids) were relatively lower in the net tow than in the water bottle. Consequently, these species appear to be somewhat under-sampled by the No. 6 mesh net.

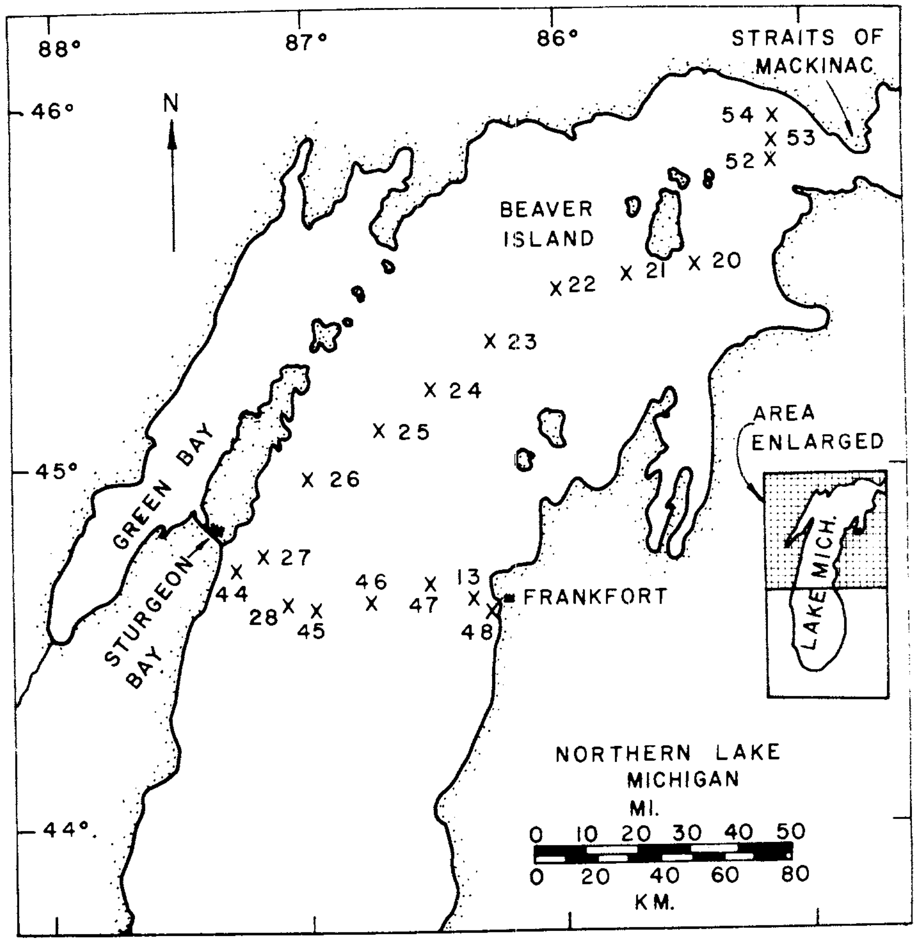


Figure 7.1. LOCATION OF ZOOPLANKTON SAMPLING STATIONS IN NORTHERN LAKE MICHIGAN, SEPTEMBER 1973.

A test was conducted on 25 July 1974 at a 27-m deep station in the Straits of Mackinac to compare the efficiency of the Nansen closing net in capturing crustacean zooplankton. A vertical tow was made from near bottom to surface and then two tows, one in the hypolimnion and the other in the thermocline and epilimnion, were conducted using the Nansen closing mechanism. Numbers of Crustacea were somewhat higher in the split tows than in the tow of the entire water column. Consequently some clogging in long tows through the entire water column is suspected.

Species composition and abundance of zooplankton were similar at those stations sampled twice within a few hours. In those instances where a station sampling was repeated after many hours, zooplankton abundance varied considerably. However, even though abundance was decidely different, percent composition of species remained closely similar. For example, Station 24 was sampled on 7 and 8 October 1973. The abundance of calanoid copepods was 3,086 individuals/m^3 on the first day and 7,533/m^3 on the second, but percent composition increased only from 64.1 to 69.4%. Consequently, interpretation of data based upon percent composition rather than abundances may be more valid.

Laboratory

All adult crustacean zooplankton were identified to species. Copepodids were identified to species except those of *Diaptomus* and *Cyclops*, which were identified to genus only. Identifications were made according to Yeatman (1959) for cyclopoid copepods, Wilson (1959) for calanoid copepods, Brooks (1957) for *Daphnia*, Deevey and Deevey (1971) for *Eubosmina*, and Brooks (1959) for remaining Cladocera.

Each sample was adjusted to a standard volume in a graduated cylinder. The sample was mixed thoroughly by random movements of a Hensen-Stempel pipette; then a subsample was quickly drawn from the middle of the cylinder with the pipette. Aliquots of 0.5, 1.0, or 5.0 ml were obtained with properly calibrated pipettes depending upon concentration of organisms. The subsample was transferred to a chambered counting cell (Gannon 1971). The entire contents of the cell, usually 150-300 individuals, were enumerated at 30-60 X under a Bausch and Lomb stereozoom microscope. Those organisms requiring higher magnification for identification were transferred to an American Optical compound microscope and observed at 100 or 430 X. Two subsamples were counted from each sample and the results averaged. If the counts varied more than 30%, a third subsample was enumerated and only the two counts in closest agreement were retained. Data were calculated in numbers of individuals per m^3 assuming 100% filtration efficiency. These data appear in Appendix F.1-.3 for the Straits of Mackinac and Appendix F.4 for northern Lake Michigan. Percent relative abundance was also calculated for each species.

The subsampling and counting procedure was tested for accuracy and reproducibility. Errors in the procedure were random, indicating that the methods employed were reliable (Gannon 1972a). Further statistical tests using least squares regression analysis were performed on the subsampling and counting procedure. It was found that when an error estimate of 25% at the 95% confidence level is desired, a minimum of 12 individuals per species must be counted. Numerical estimates of those rarer species in which there were less than 12 individuals per subsample, i.e., roughly less than 150 individuals/m^3, were considered as statistically unreliable.

Analytical

Principal component analysis (PCA) as described in Section 6.1 was used as the analytical technique. Three criteria were used to select the taxa for the principal component analysis (PCA) of a particular month. First, it was required that each taxon be well enough defined taxonomically that its contribution to the results of the analysis is interpretable. With the exception of *Diaptomus* spp. copepodids, composite categories were avoided. *Diaptomus* spp. copepodite stages are believed to have similar ecological requirements and thus were expected to show interpretable distributional patterns relative to the other taxa. The second criterion was that each taxon must be observed at more than 30% of the stations of the particular cruise in question. Taxa which are not widely distributed tend to dominate PCA by making the few stations at which they do occur look particularly unusual. This is a problem common among parametric multivariate techniques, which in general perform poorly on data which are badly skewed or include a large number of tied cases. The non-inclusion of locally distributed taxa is further justified on the basis that the distributions of such taxa are generally easy to describe without the use of multivariate analysis. The choice of 30% as a cutoff point is based largely on past experience with PCA and represents the compromise of including as many taxa as possible without including ones which are locally or erratically distributed. The third criterion for inclusion of a taxa was that it be counted with reasonable accuracy. It was consequently required that each taxon exceed 10 individuals in at least one sample. This criterion was never directly imposed, however, because all taxa which satisfied the second criterion also easily satisfied this third one.

Using these criteria, 19 taxa were chosen for analysis of the August data and 17 for the September and October data. Initial principal component analyses were performed on each month's data. One rare species, *Diaphanosoma leuchtenbergianum*, which was included in the original analyses of each cruise, showed no distributional patterns consistent with the regions determined by the PCAs. Consequently it was decided not to include this species in the final analyses but instead to discuss its distribution independently.

Separate PCAs were performed for each cruise, using the correlation matrix of the percent composition of the selected taxa. The percent composition, P_{ij}, for taxon $\underline{i}$ at station $\underline{j}$ was computed as: $P_{ij} = (N_{ij}/N_{Tj}) \times 100\%$, where N_{ij} is the number of individuals of taxon $\underline{i}$ found at station $\underline{j}$ and N_{Tj} is the total zooplankton count at station $\underline{j}$. Station 40 was not used in determining the principal components for the October data since the zooplankton community at that station was particularly unusual and did not correspond with the community of any other station in the survey area. The cumulative percentages of the total variance contributed by each of the first four principal components for the analyses are:

Cruise number	Number of stations	PC1	PC2	PC3	PC4
1 (August)	37	35%	46%	55%	63%
2 (September)	40	42	52	62	71
3 (October)	49	26	43	55	63

Plots were drawn showing the location of each of the stations relative to the first two PCs. The stations belonging to different regions on these PCA plots are identified on maps of the survey area, and simple averages for each taxon in each region are tabulated to determine the distribution pattern of each taxon relative to those regions. We consider the maps and tables of averages and not the original PC plots to be of most importance. The choice of Euclidean distance as a measure of similarity (rather than, for example, coefficient of community or percent similarity) and the decision not to use a non-linear data transformation (for example, arcsine $\sqrt{P_{ij}}$) were made for this reason.

For each cruise, the first PC was interpretable as a Lake Michigan-Lake Huron axis. Consequently, the largest share of the variance in the data may be interpreted as being due to an east-west or Lake Michigan-Lake Huron effect. The first PC of Cruise 2 by itself accounted for a large percentage of the total variance. Third and higher PCs were not used in interpreting any of the analyses.

7.3 RESULTS AND DISCUSSION

Straits of Mackinac

Twenty-nine taxa of crustacean zooplankton were recorded in the Straits region (Table 7.1). Twenty-three species of Cladocera and Copepoda were characteristic of limnetic waters, while six cladocerans were considered as benthic and littoral forms that sporadically appeared in the plankton. Seven calanoid and three cyclopoid copepods were represented. *Diaptomus oregonensis, D. minutus,* and *Epischura lacustris* were the numerically predominant calanoid copepods. *Cyclops bicuspidatus thomasi* was by far the most abundant cyclopoid copepod. Cladocera were represented by 13 limnetic and six littoral and benthic species. *Daphnia galeata mendotae, D. retrocurva, Holopedium gibberum* and *Eubosmina coregoni* were the predominant limnetic cladocerans. *Ceriodaphnia reticulata* was represented only by a single individual at Station 20 during Cruise 1. Single specimens of *Drepanothrix dentata* were observed at Station 23 during Cruise 2 and Station 03 during Cruise 3. These two species are apparently new records for Lakes Michigan and Huron.

The opposum shrimp, *Mysis relicta* Lovén, and the deepwater amphipod, *Pontoporeia affinis* Lindstrom, were occasionally collected in plankton samples. *Mysis* was observed at Stations 08, 44, and 50 on Cruise 2 and at Station 47 on Cruise 3. *Pontoporeia* was observed at Station 35 during Cruise 3. Since these organisms are predominantly benthic during the daytime, they were undoubtedly inadequately sampled by the plankton net and these data by no means reflect their abundance or distribution in the Straits region.

Table 7.1. LIST OF CRUSTACEAN ZOOPLANKTON SPECIES COLLECTED IN THE STRAITS OF MACKINAC REGION DURING 1973. The symbol (*) denotes those species that are predominantly benthic and appear adventitiously in the plankton.

Calanoid Copepoda

Diaptomus ashlandi Marsh
Diaptomus minutus Lilljeborg
Diaptomus oregonensis Lilljeborg
Diaptomus sicilis Lilljeborg
Epischura lacustris Forbes
Limnocalanus macrurus Sars
Senecella calanoides Juday

Cyclopoid Copepoda

Cyclops bicuspidatus thomasi Forbes
Mesocyclops edax Forbes
Tropocyclops prasinus mexicanus Kiefer

Cladocera

Family Leptodoridae
Leptodora kindtii (Focke)

Family Polyphemidae
Polyphemus pediculus (L.)

Family Sididae
Diaphanosoma leuchtenbergianum Fischer
**Sida crystallina* (Müller)

Family Holopedidae
Holopedium gibberum Zaddach

Family Daphnidae
Ceriodaphnia lacustris Birge
Ceriodaphnia quadrangula Müller
Ceriodaphnia reticulata (Jurine)
Daphnia galeata mendotae Birge
Daphnia longiremis Sars
Daphnia retrocurva Forbes

Family Bosminidae
Bosmina longirostris (Müller)
Eubosmina coregoni (Baird)

Family Chydoridae
**Acroperus harpae* Baird
**Alona affinis* (Leydig)
**Alona quadrangularis* (Müller)
Chydorus sphaericus Müller
**Drepanothrix dentata* (Eurén)
**Eurycercus lamellatus* (Müller)

Abundance of total Crustacea at various stations ranged from nearly 1,000 individuals/m^3 to almost 28,000/m^3 during the study period (Fig. 7.2). Average standing crops for Cruises 1, 2, and 3 were 8,642, 5,014, and 11,975/m^3, respectively. Higher numbers in October mainly reflect recruitment of young instars, especially of *Diaptomus* spp., into the population. Concentrations of organisms were often higher at inshore stations and near Bois Blanc and Mackinac Islands.

Calanoid copepods were an important fraction of the plankton in the Straits region. They increased from an average of 3,862/m^3 (42% of total Crustacea) in August to 6,417/m^3 (57% of total Crustacea) in October (Fig. 7.3). A pronounced east-west difference in abundance of calanoid copepods was observed during August and September. Numbers of calanoid copepods were approximately 2-10 times lower west of the Mackinac Bridge and in the South Channel (south of Bois Blanc Island) than towards the Lake Huron portion of the Straits. This pattern was less pronounced in October as distribution of calanoids was more uniform throughout the study area.

Four species of *Diaptomus* were observed in the Straits region. *Diaptomus oregonensis* was most abundant (4% of total Crustacea) and was decidedly more prevalent west of the Mackinac Bridge and in the South Channel during August and September (Fig. 7.4). This species was considerably less abundant in October and its distribution was more uniform. Adults of *D. minutus* were also most prevalent west of the Mackinac Bridge and in the South Channel in August (Fig. 7.5). In September and October, it was low in abundance and more evenly distributed throughout the Straits area. Adults of *D. ashlandi* and *D. sicilis* were relatively low in abundance throughout the study period and comprised near 1% and 0.5%, respectively, of total Crustacea during each cruise. Numbers of *D. ashlandi* decreased while numbers of *D. sicilis* increased throughout the study period. No distinct pattern of distribution was observed for *D. ashlandi*, but *D. sicilis* was somewhat more abundant towards Lake Huron (Figs. 7.6 and 7.7).

Whereas adults of most diaptomids, especially *D. oregonensis* and *D. minutus*, were most prevalent towards Lake Michigan and in the South Channel, copepodids of *Diaptomus* spp. were distinctly most abundant, especially during August and September, towards Lake Huron and north of Bois Blanc Island (Fig. 7.8). Recruitment of young copepods into the population is indicated throughout the study period as numbers of *Diaptomus* copepodids increased from an average of 2,893/m^3 in August to 5,968/m^3 in October. They comprised an average of about 30% of total Crustacea in August and September and 53% in October. Since *Diaptomus* spp. copepodids were so abundant, the distribution pattern noted for total calanoids (Fig. 7.3) largely reflects the distribution of *Diaptomus* spp. copepodids (Fig. 7.8).

The other calanoid copepods, *Limnocalanus, Senecella,* and *Epischura*, were low in relative abundance throughout the study period but exhibited distinct patterns of distribution. *Limnocalanus* was decidedly more abundant

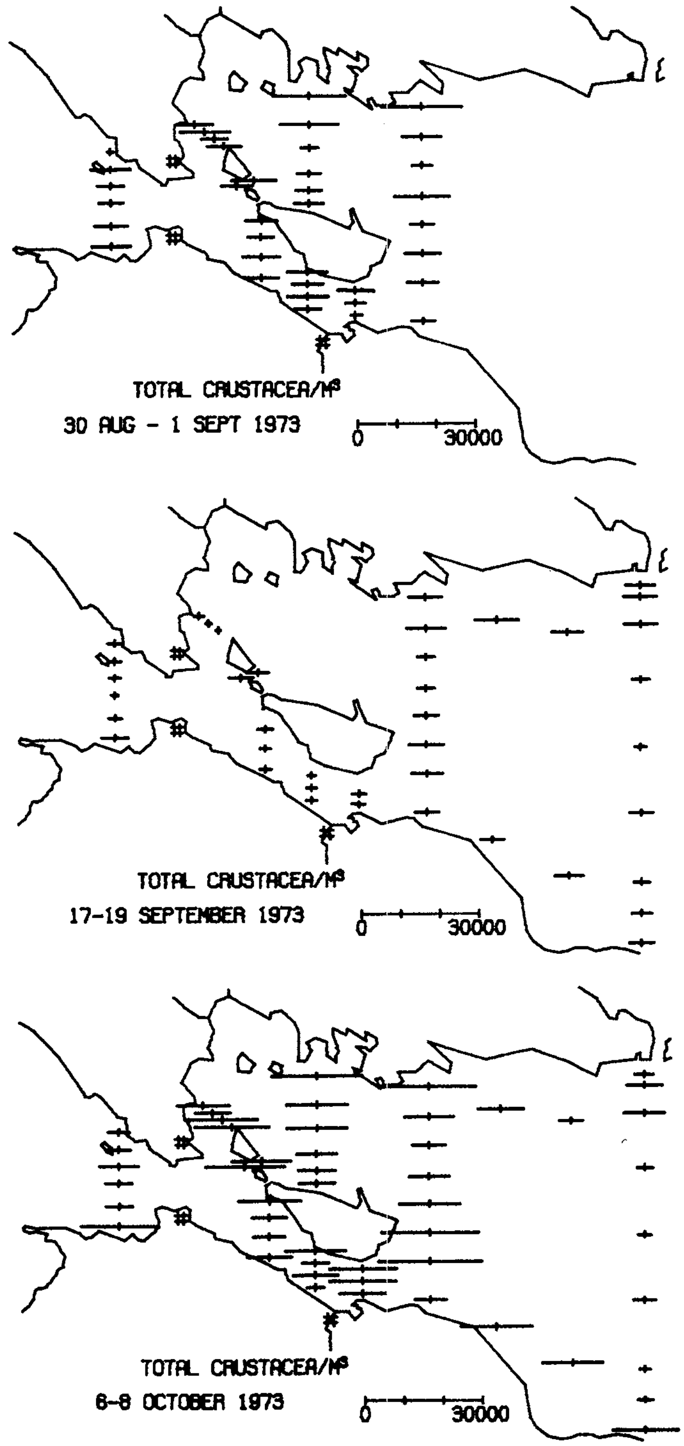


Figure 7.2. DISTRIBUTION AND ABUNDANCE (NUMBERS OF INDIVIDUALS PER M^3) OF TOTAL CRUSTACEAN ZOOPLANKTON IN THE STRAITS OF MACKINAC ON THREE CRUISES, 1973.

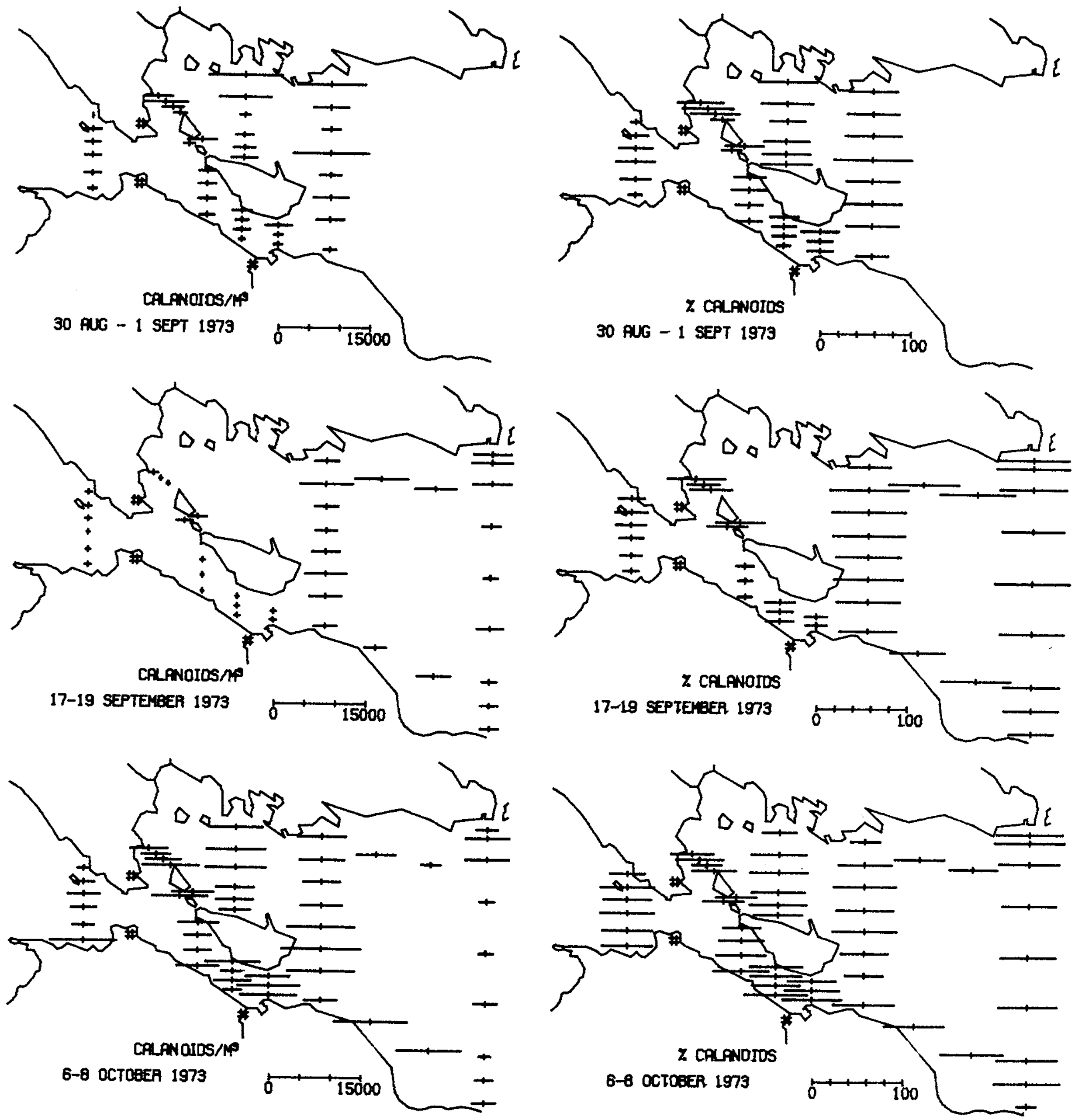


Figure 7.3. DISTRIBUTION AND ABUNDANCE (NUMBERS PER M^3 AND PERCENT COMPOSITION) OF CALANOID COPEPODS IN THE STRAITS REGION.

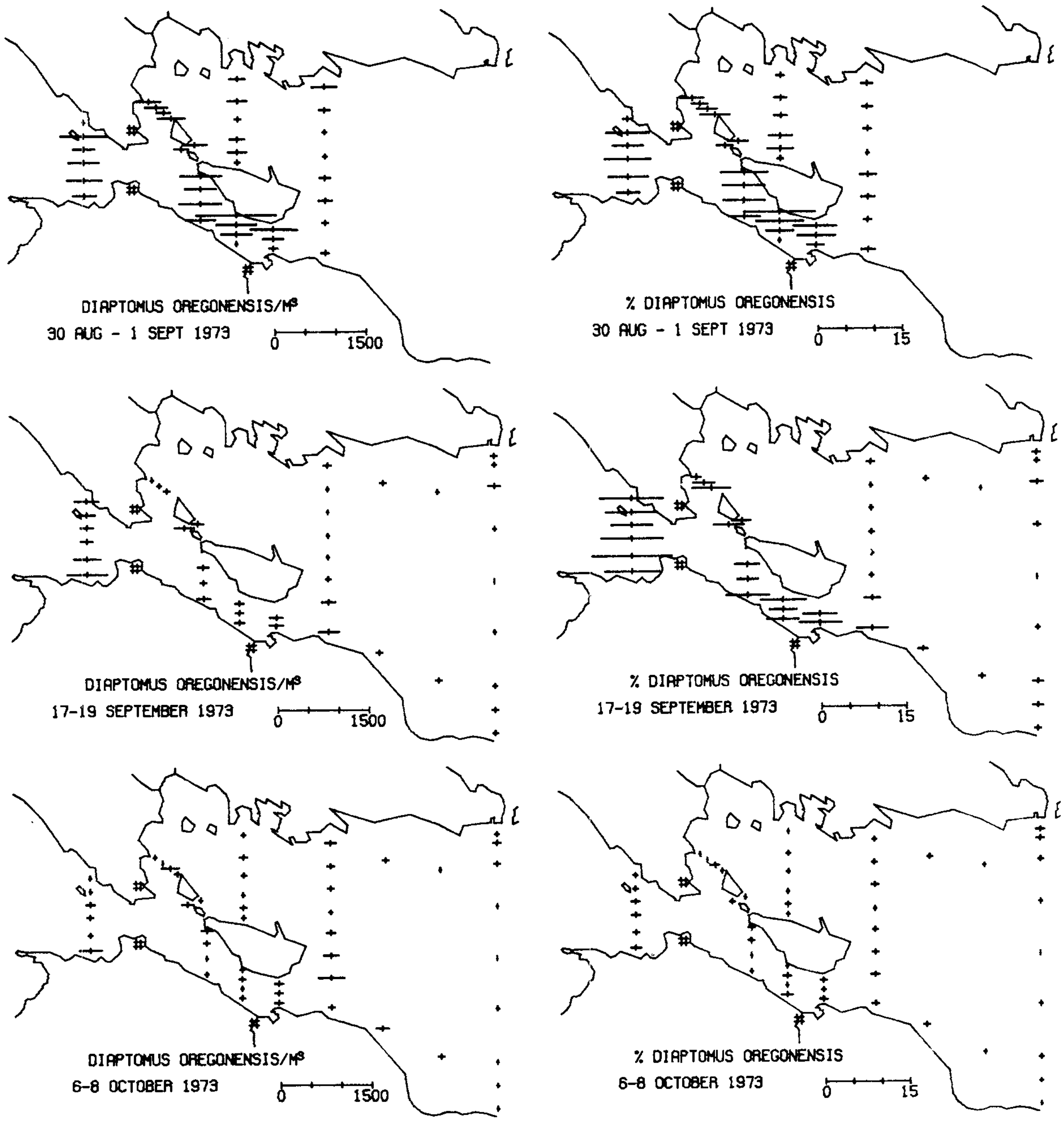


Figure 7.4. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS OREGONENSIS* IN THE STRAITS REGION.

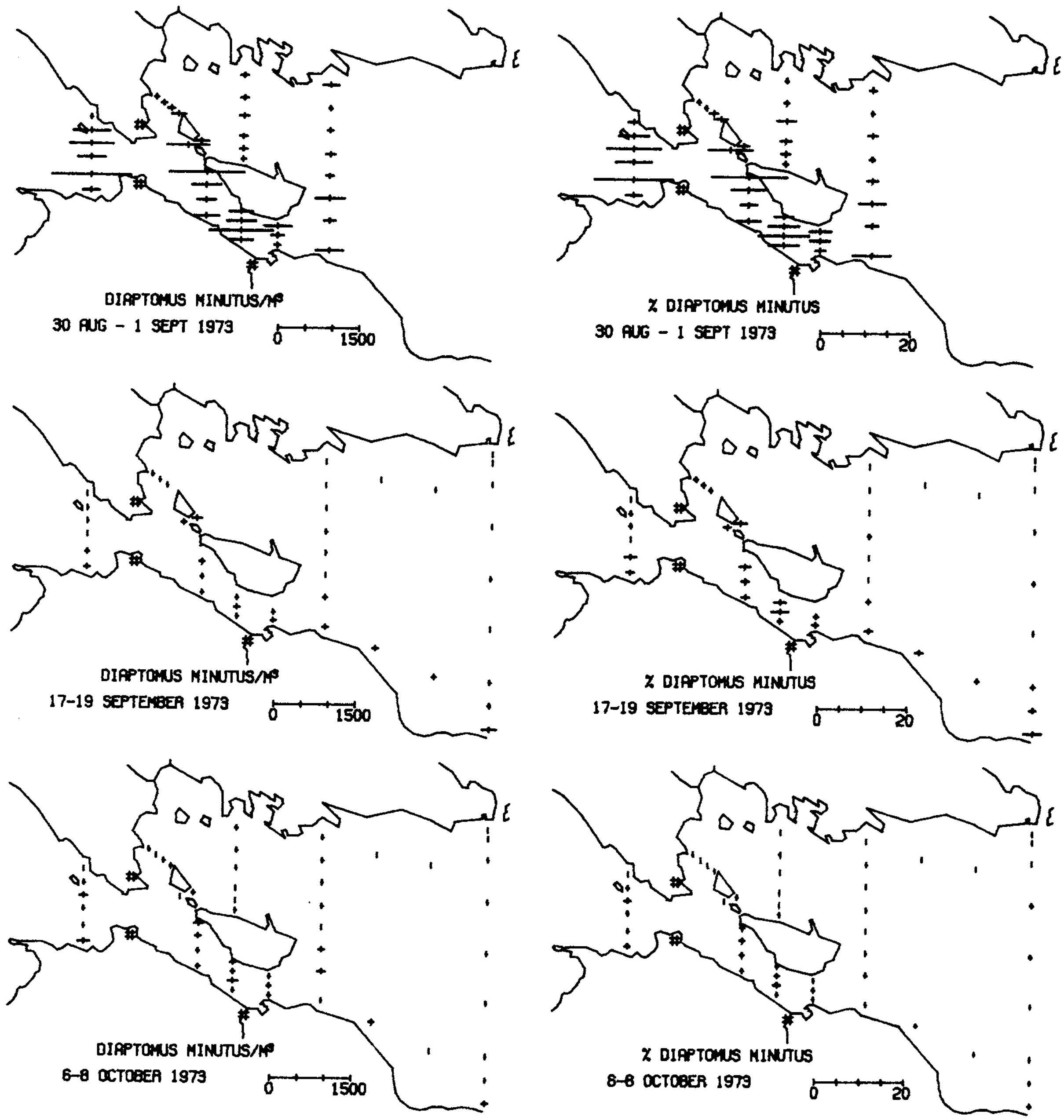


Figure 7.5. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS MINUTUS* IN THE STRAITS REGION.

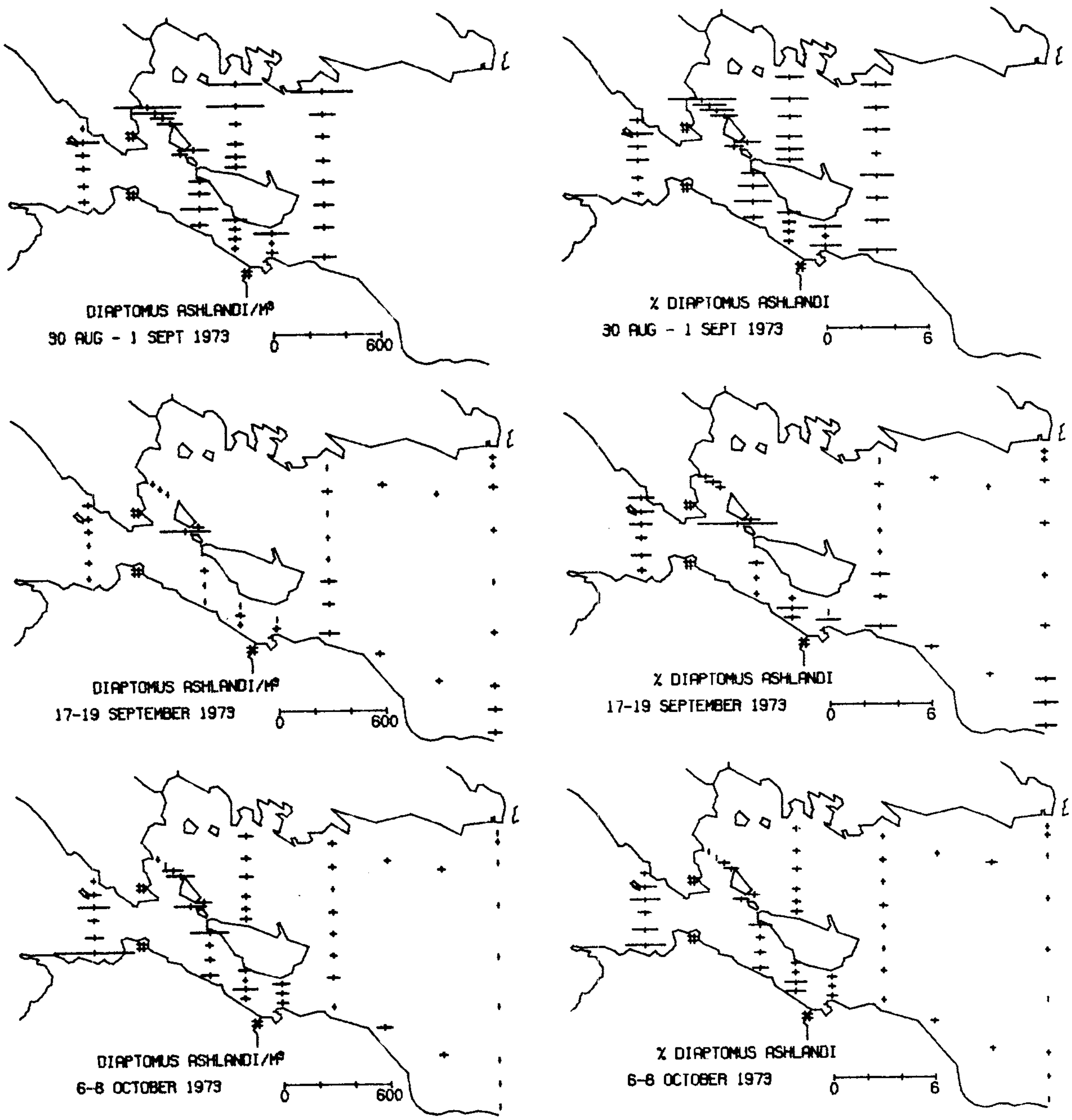


Figure 7.6. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS ASHLANDI* IN THE STRAITS REGION.

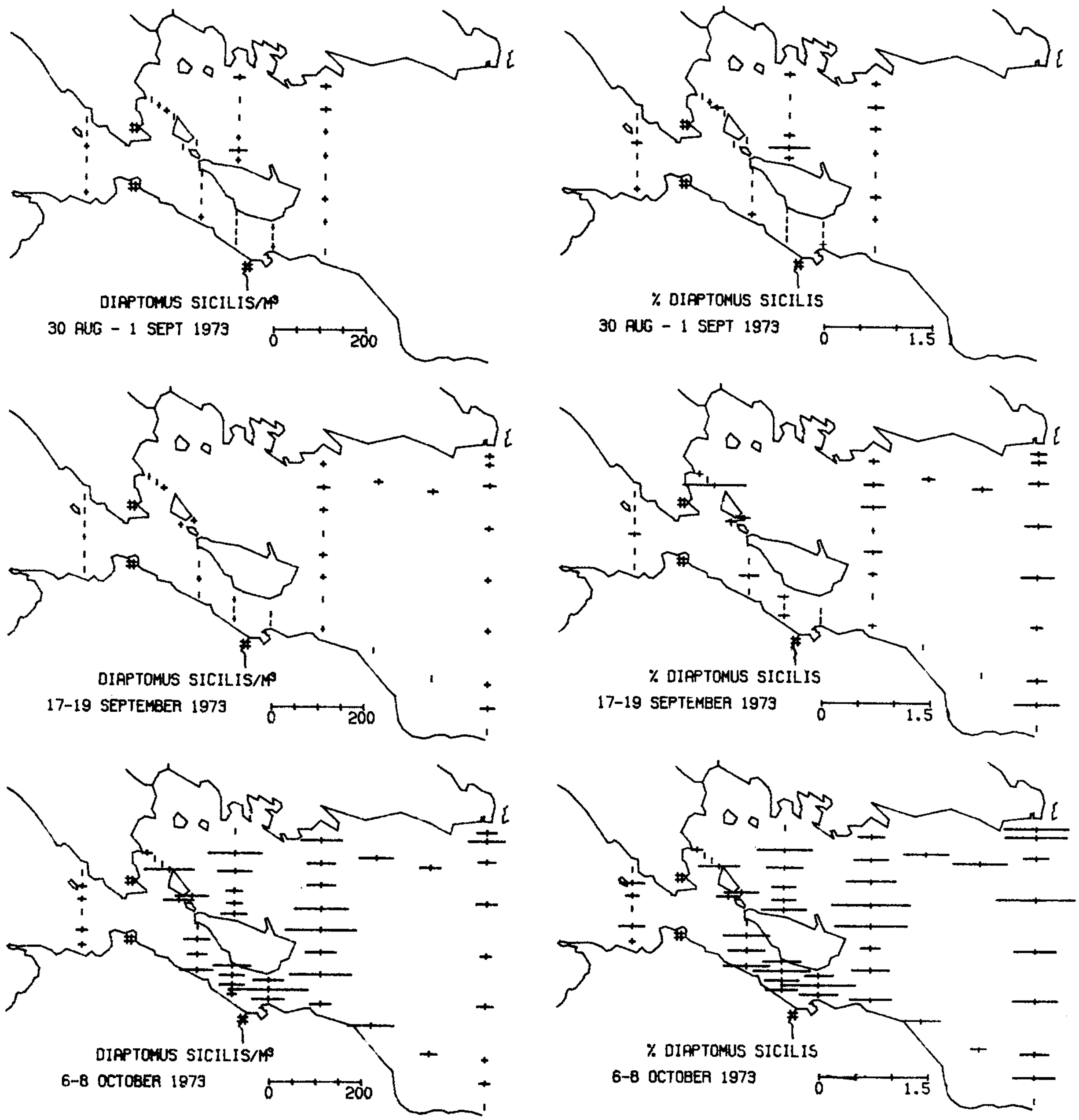


Figure 7.7. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS SICILIS* IN THE STRAITS REGION.

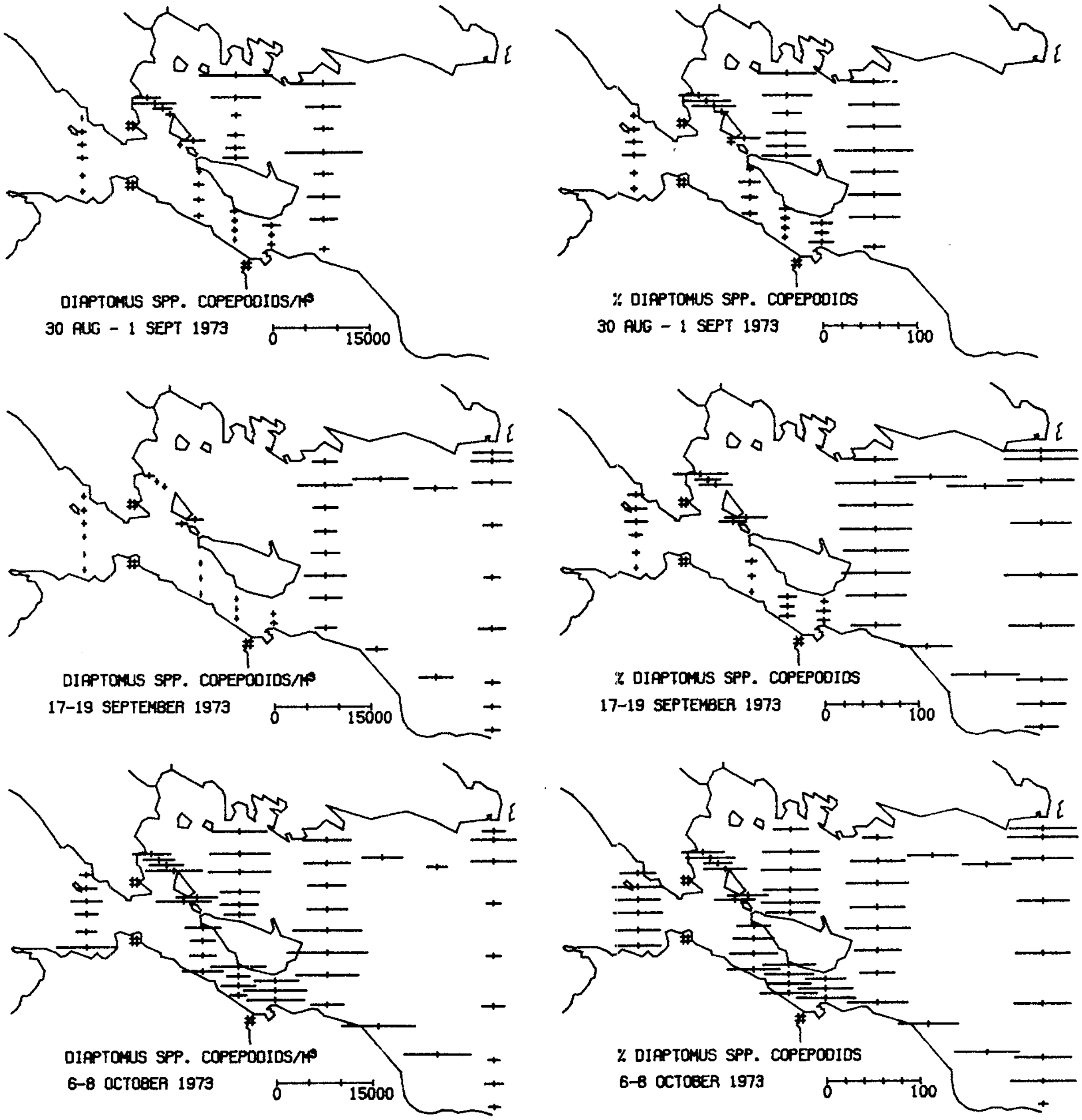


Figure 7.8. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS* SPP. COPEPODIDS IN THE STRAITS REGION.

in open waters towards Lake Huron (Fig. 7.9). For example, the average abundance of *Limnocalanus* during all cruises at stations west of the Mackinac Bridge was 2.3 individuals/m^3 (0.04% of total Crustacea), whereas abundance of this species (86.3/m^3 or 0.6% of total Crustacea) was distinctly greater along the transect of stations from Cordwood Point to Government Island toward Lake Huron. As to be expected from this cold-water stenothermic species, *Limnocalanus* was most prevalent at offshore stations (Fig. 7.9). The other cold-water stenotherm, *Senecella*, exhibited a pattern of distribution similar to *Limnocalanus*. *Senecella* was absent from stations toward Lake Michigan and in the South Channel and was most abundant at offshore stations toward Lake Huron (Fig. 7.10). In contrast, *Epischura* was more abundant toward Lake Michigan and in the South Channel than in the Lake Huron portion of the Straits region. It was somewhat more abundant at nearshore stations, especially in South Channel (Fig. 7.11).

Cyclopoid copepods were considerably less prevalent in the Straits region than either calanoid copepods or cladocerans. Average abundance of cyclopoid copepods ranged from 232-1,018/m^3 during the study period. During Cruises 1, 2, and 3, they comprised 5, 4, and 9%, respectively, of total crustacean plankton. The cyclopoid copepods did not exhibit any striking distribution patterns within the Straits region (Fig. 7.12).

The cyclopoid copepods were composed almost entirely of one species, *Cyclops bicuspidatus thomasi*, which comprised over 97% of total cyclopoids during the study period. Obviously, the relatively uniform distribution of total cyclopoids (Fig. 7.12) is due to the distribution of *Cyclops bicuspidatus thomasi* (Fig. 7.13). *Mesocyclops edax*, although low in numbers, was slightly more prevalent towards Lake Huron in August and September but was more evenly distributed throughout the study area in October (App. F.1-3). *Tropocyclops prasinus mexicanus* was likely undersampled by the mesh size of the net utilized in this investigation. It was collected sporadically at stations throughout the study area during August and September (App. F.1-2).

The Cladocera constituted a significant portion of crustacean plankton, particularly in August when they averaged 53% of total Crustacea. Actual numbers were highest in October (average 4,541/m^3), but Cladocera comprised only 35% of total Crustacea due to increased abundance of copepods at this time. The Cladocera were distinctly more abundant towards Lake Michigan and in the South Channel than towards Lake Huron (Fig. 7.14). This trend was most prominent in August and September. There was also a trend for Cladocera to be more prevalent at stations near shore (Fig. 7.14).

Daphnia galeata mendotae was the most abundant cladoceran throughout the study period. It averaged 1,401 individuals/m^3 in August and comprised 17% of total Crustacea. This species exhibited a distinct pattern of greatest abundance towards Lake Michigan and in the South Channel (Fig. 7.15). A similar pattern was observed in September, but patchier distribution was noted in October. It was most abundant in nearshore

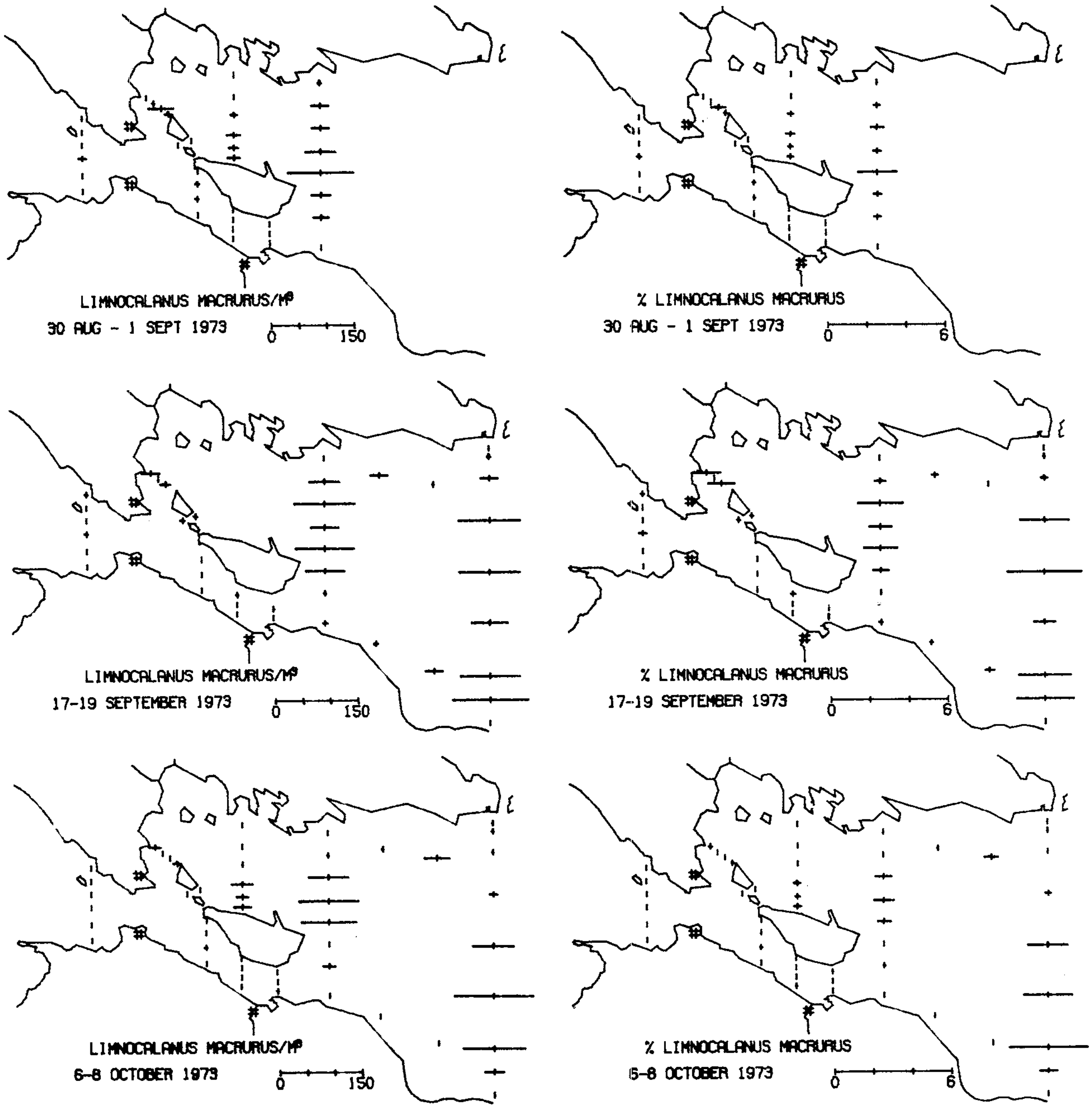


Figure 7.9. DISTRIBUTION AND ABUNDANCE OF *LIMNOCALANUS MACRURUS* IN THE STRAITS REGION.

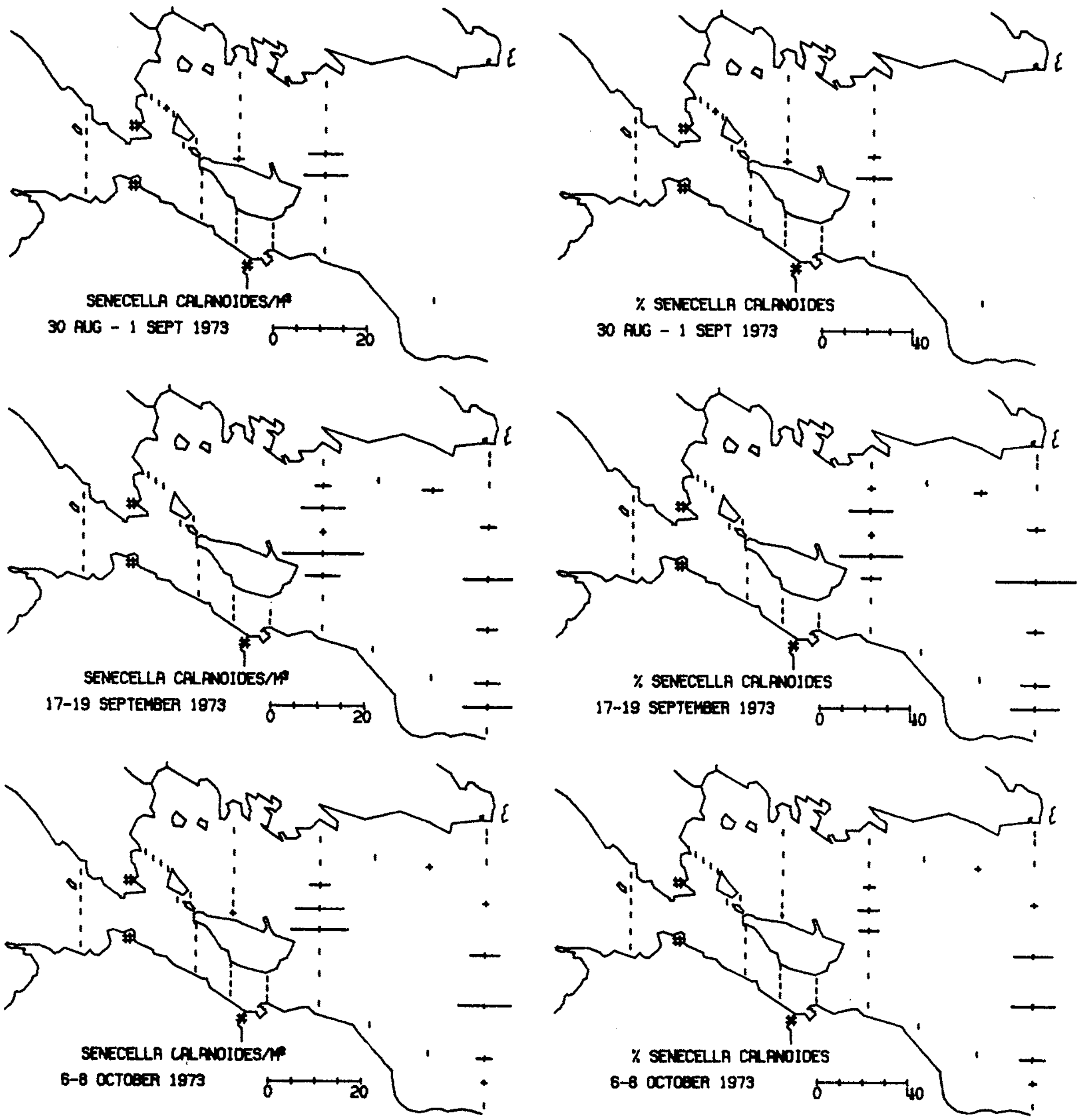


Figure 7.10. DISTRIBUTION AND ABUNDANCE OF *SENECELLA CALANOIDES* IN THE STRAITS REGION.

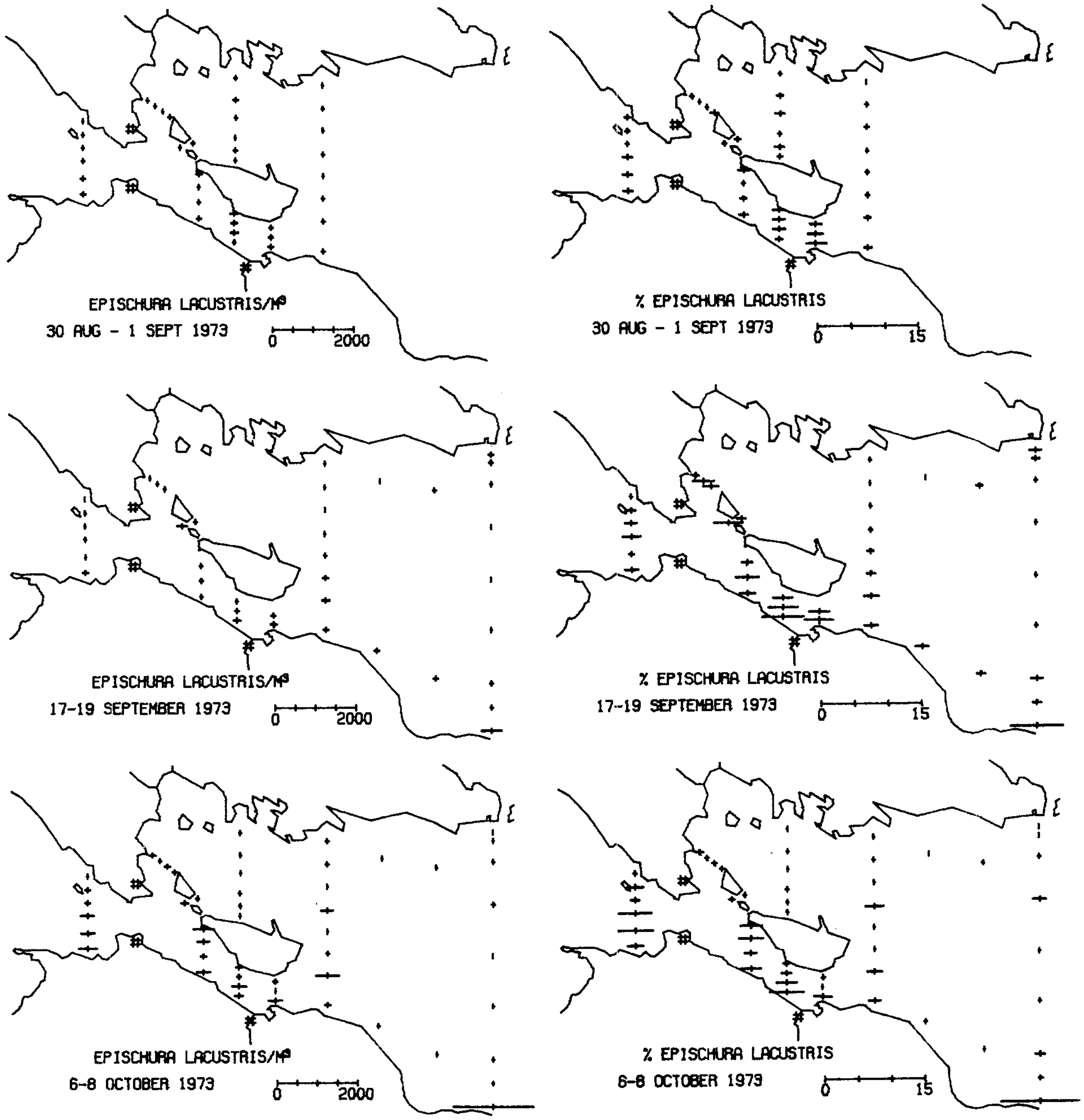


Figure 7.11. DISTRIBUTION AND ABUNDANCE OF *EPISCHURA LACUSTRIS* IN THE STRAITS REGION.

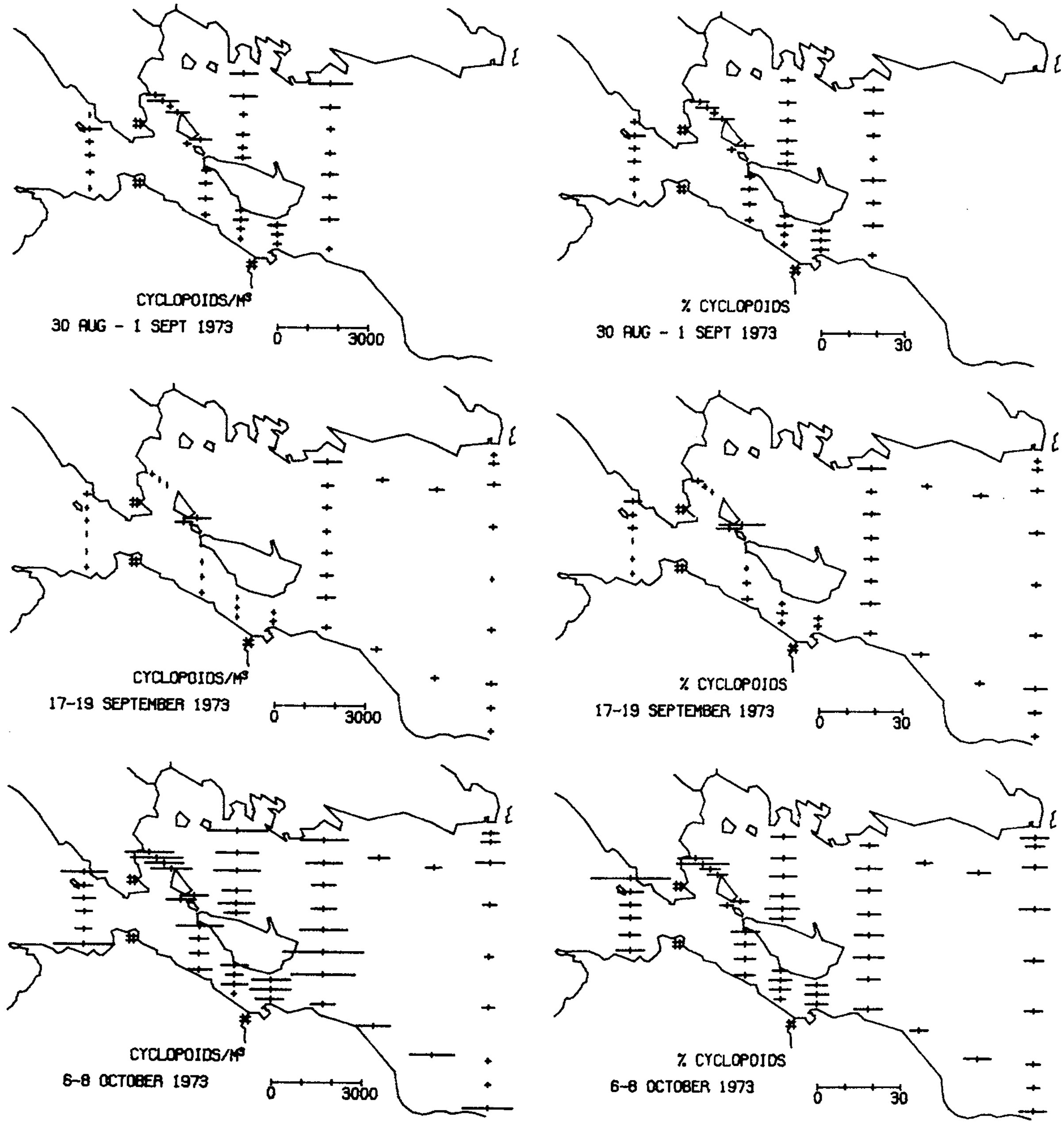


Figure 7.12. DISTRIBUTION AND ABUNDANCE OF CYCLOPOID COPEPODS IN THE STRAITS REGION.

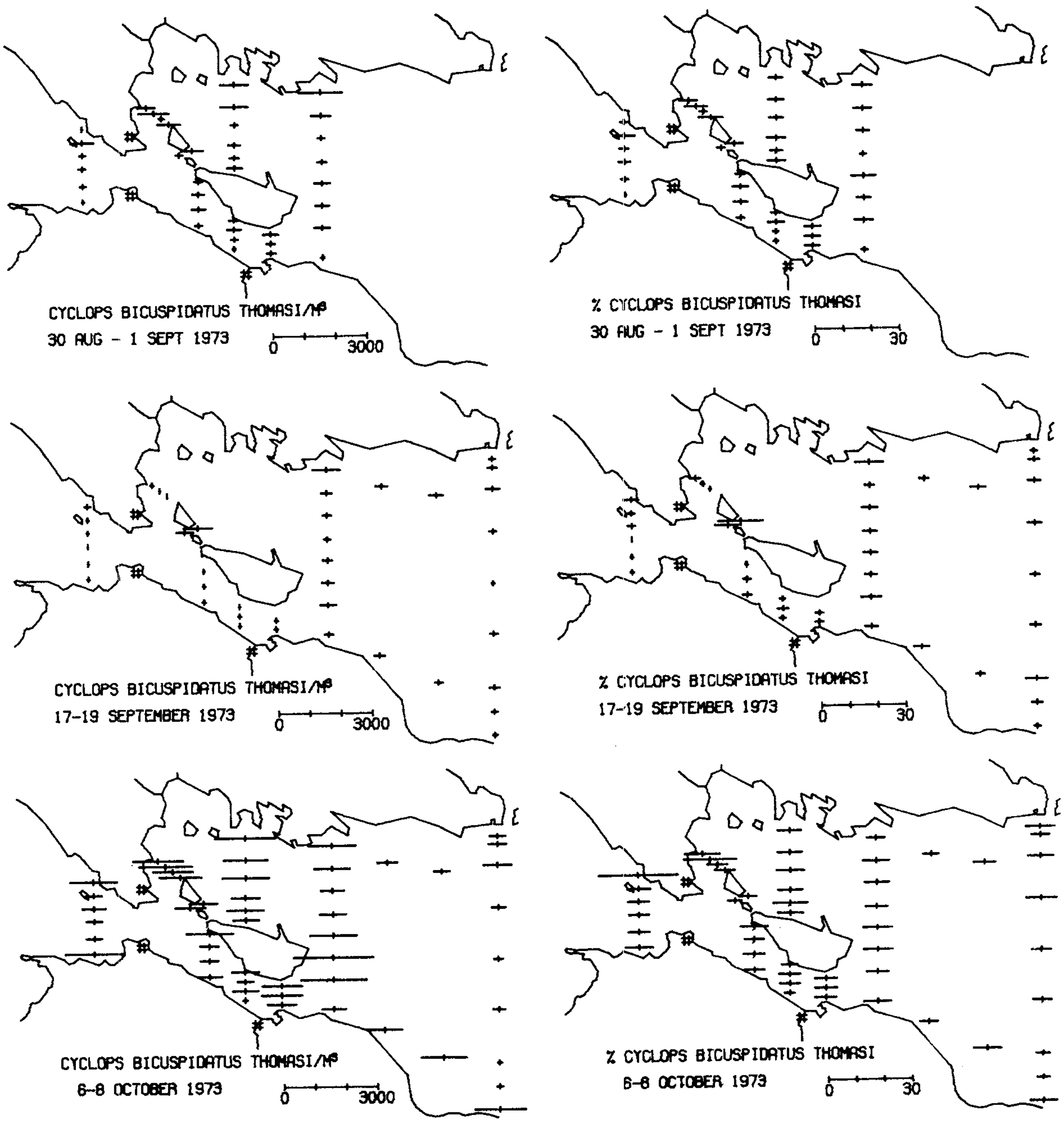


Figure 7.13. DISTRIBUTION AND ABUNDANCE OF *CYCLOPS BICUSPIDATUS THOMASI* IN THE STRAITS REGION.

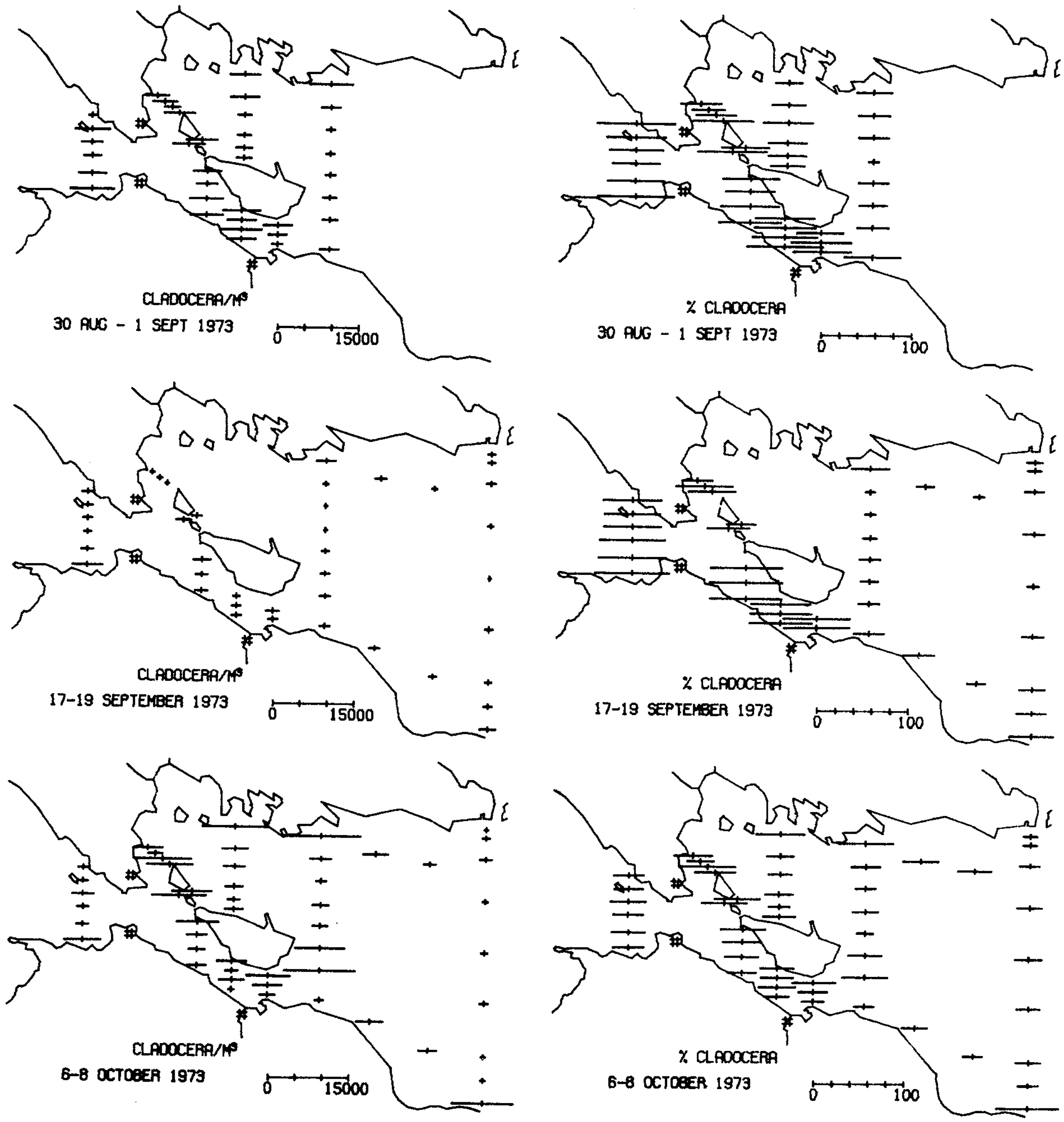


Figure 7.14. DISTRIBUTION AND ABUNDANCE OF CLADOCERA IN THE STRAITS REGION.

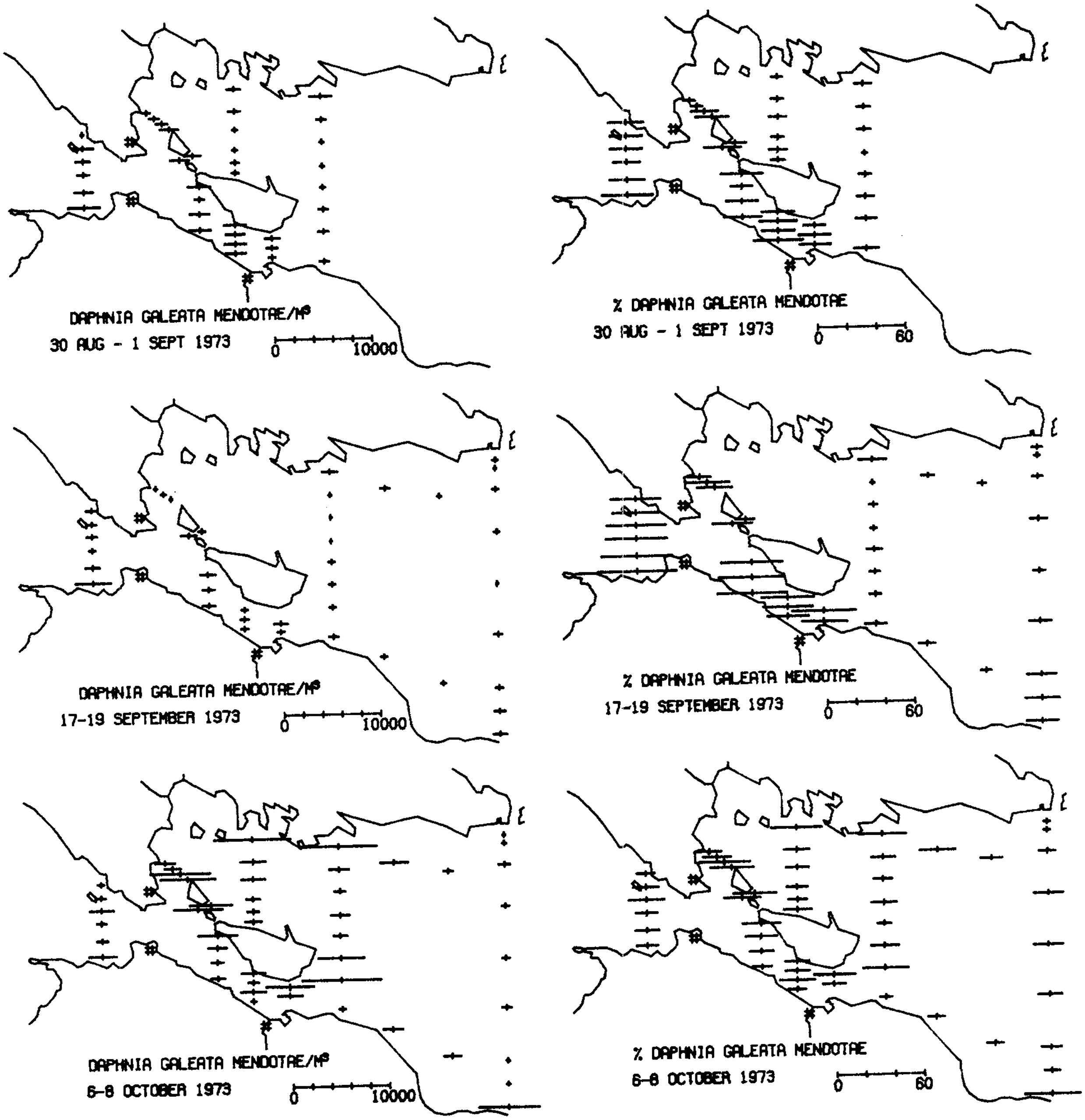


Figure 7.15. DISTRIBUTION AND ABUNDANCE OF *DAPHNIA GALEATA MENDOTAE* IN THE STRAITS REGION.

areas, especially off the islands and the north shore of the study area during October (Fig. 7.15).

Daphnia retrocurva was also an abundant cladoceran in the Straits region where it comprised an average of near 10% of total Crustacea during August and September. Its contribution (4%) to total Crustacea was considerably less during October. This species was predominantly distributed in waters toward Lake Michigan and in the South Channel during all three cruises (Fig. 7.16). It was also more abundant at nearshore stations.

In contrast to *D. galeata mendotae* and *D. retrocurva, D. longiremis* was less abundant and its patterns of distribution were not as distinctive. *Daphnia longiremis* comprised an average of 4, 3, and 1% of total Crustacea during August, September, and October, respectively. It was most abundant north of the islands in August; no decisive pattern was evident in September and October (Fig. 7.17).

Holopedium gibberum was an important constituent of the plankton community in the Straits region. It was most abundant during August when an average of 905/m^3 or 5% of total Crustacea was observed. *Holopedium* exhibited greatest abundance in waters toward Lake Michigan and in the South Channel, especially during August and September (Fig. 7.18). Its distribution in October was less distinct, with some tendencies to be more prevalent near shore.

The carnivorous species *Leptodora kindtii* was never sufficiently abundant to comprise 1% of total Crustacea. However, it was distributed throughout the study area and was considerably more abundant toward Lake Michigan and in the South Channel (Fig. 7.19). The other carnivorous cladoceran, *Polyphemus pediculus*, was less abundant than *L. kindtii*, but its distribution pattern was strikingly similar, especially in August and September (App. F.1-3).

Eubosmina coregoni was approximately two to three times more abundant in the Straits region than *Bosmina longirostris*. The relative abundance of *E. coregoni* decreased from 7% of total Crustacea in August to 3% in October while *B. longirostris* increased slightly from 1% in August to 2% in October. The distribution patterns of the two species were notably different; *E. coregoni* was most characteristic of waters towards Lake Michigan and in the South Channel (Fig. 7.20), *B. longirostris* was most prevalent near the north shore especially at the mouth of the St. Marys River as well as shallow stations elsewhere (Fig. 7.21).

The remaining Cladocera were present in low levels of abundance, considerably less than 1% of total Crustacea. *Diaphanosoma leuchtenbergianum* was distributed throughout the Straits region during the study period. Its distribution was exceedingly irregular in August and September. In October, it was most prevalent along the north shore and another patch of relative abundance was noted at Station 16 in the South Channel

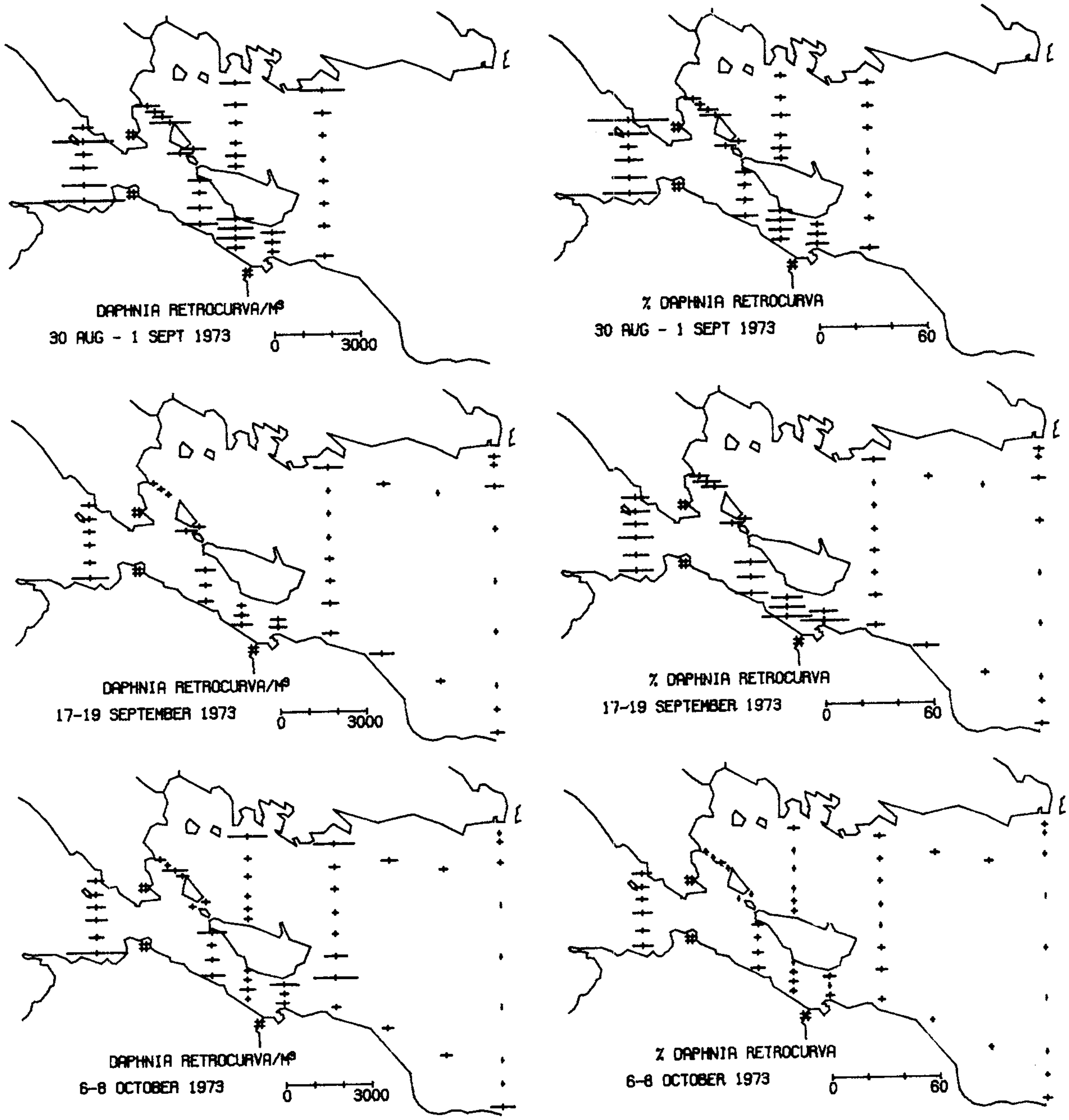


Figure 7.16. DISTRIBUTION AND ABUNDANCE OF *DAPHNIA RETROCURVA* IN THE STRAITS REGION.

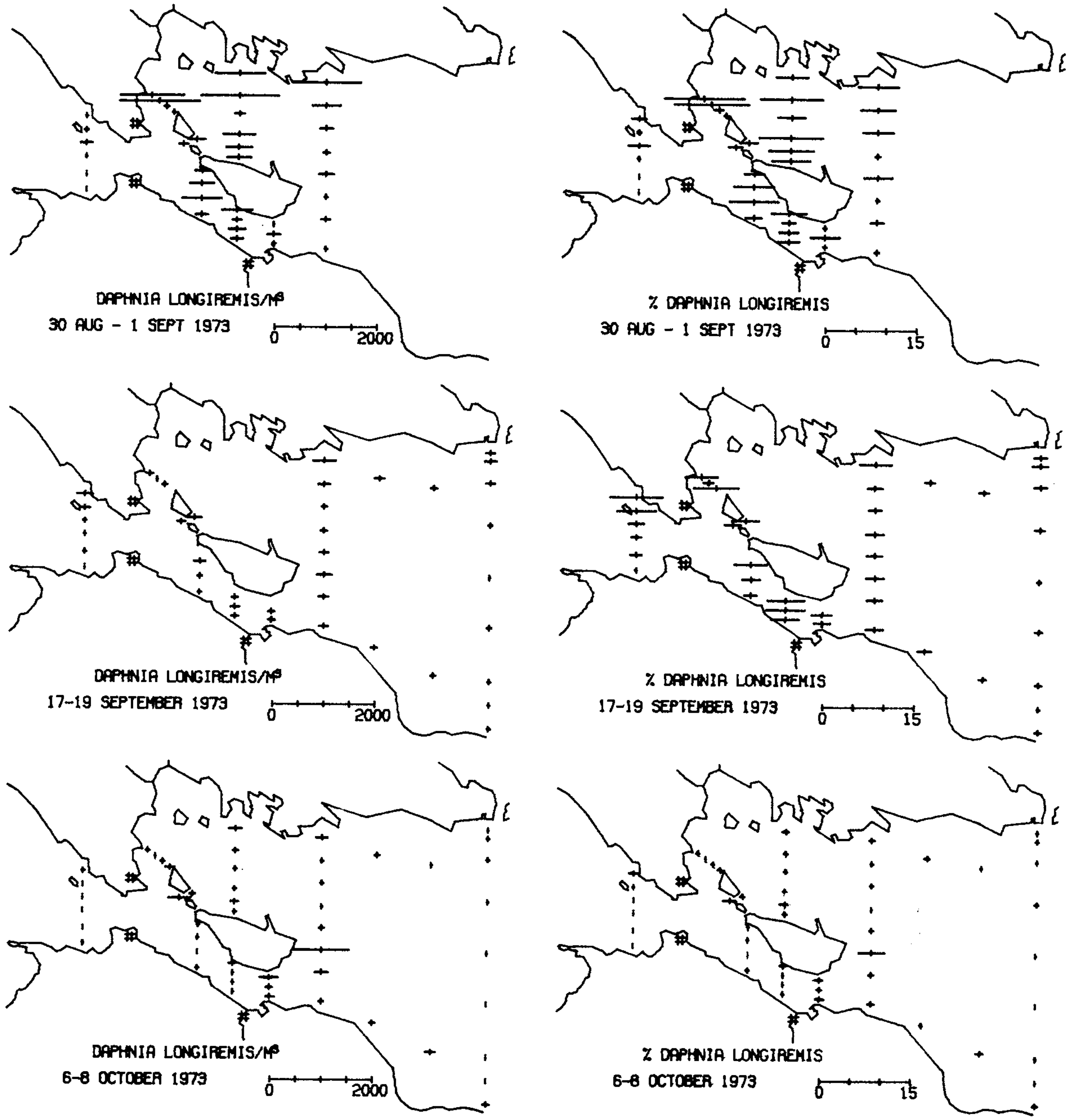


Figure 7.17. DISTRIBUTION AND ABUNDANCE OF *DAPHNIA LONGIREMIS* IN THE STRAITS REGION.

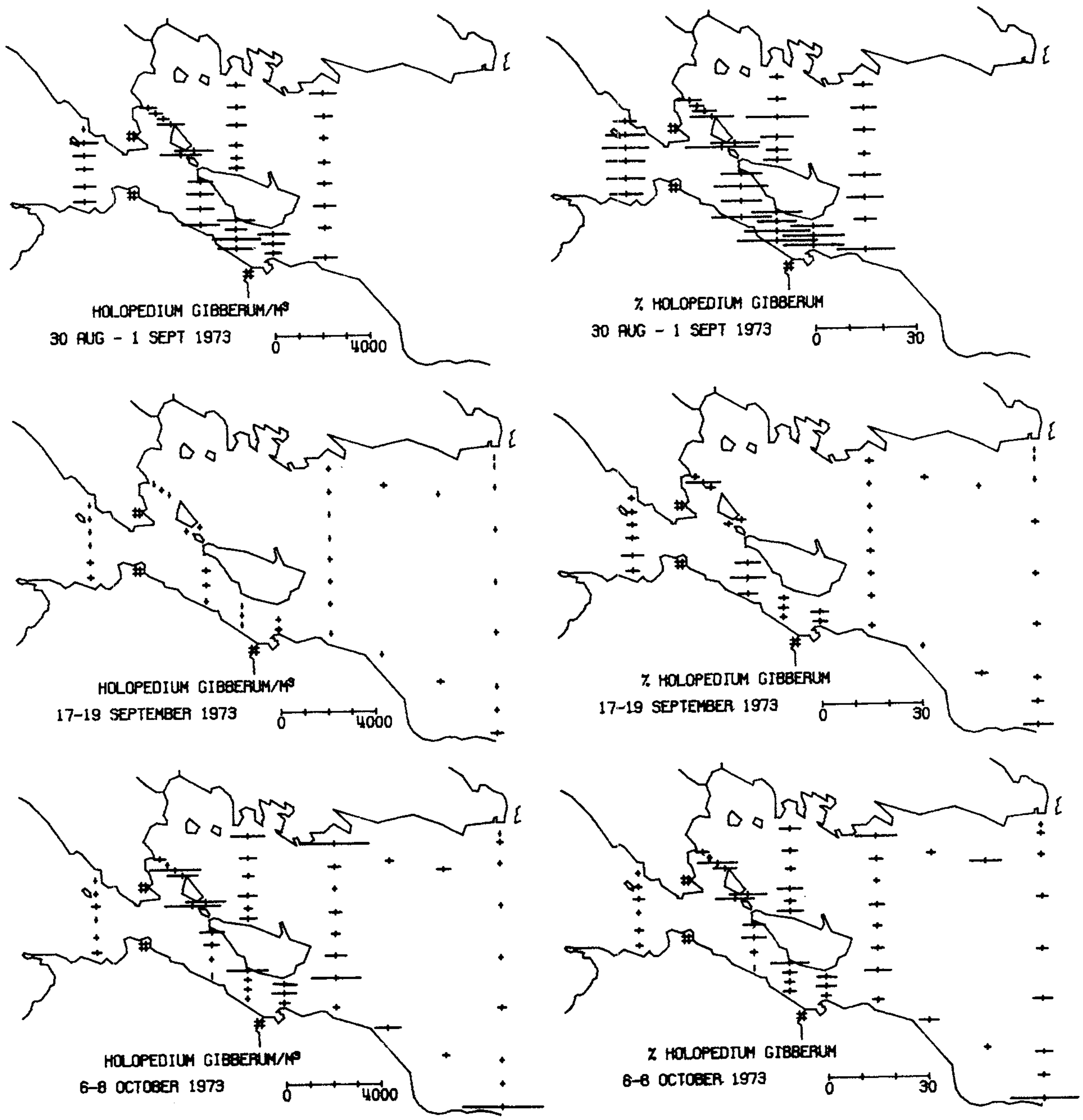


Figure 7.18. DISTRIBUTION AND ABUNDANCE OF *HOLOPEDIUM GIBBERUM* IN THE STRAITS REGION.

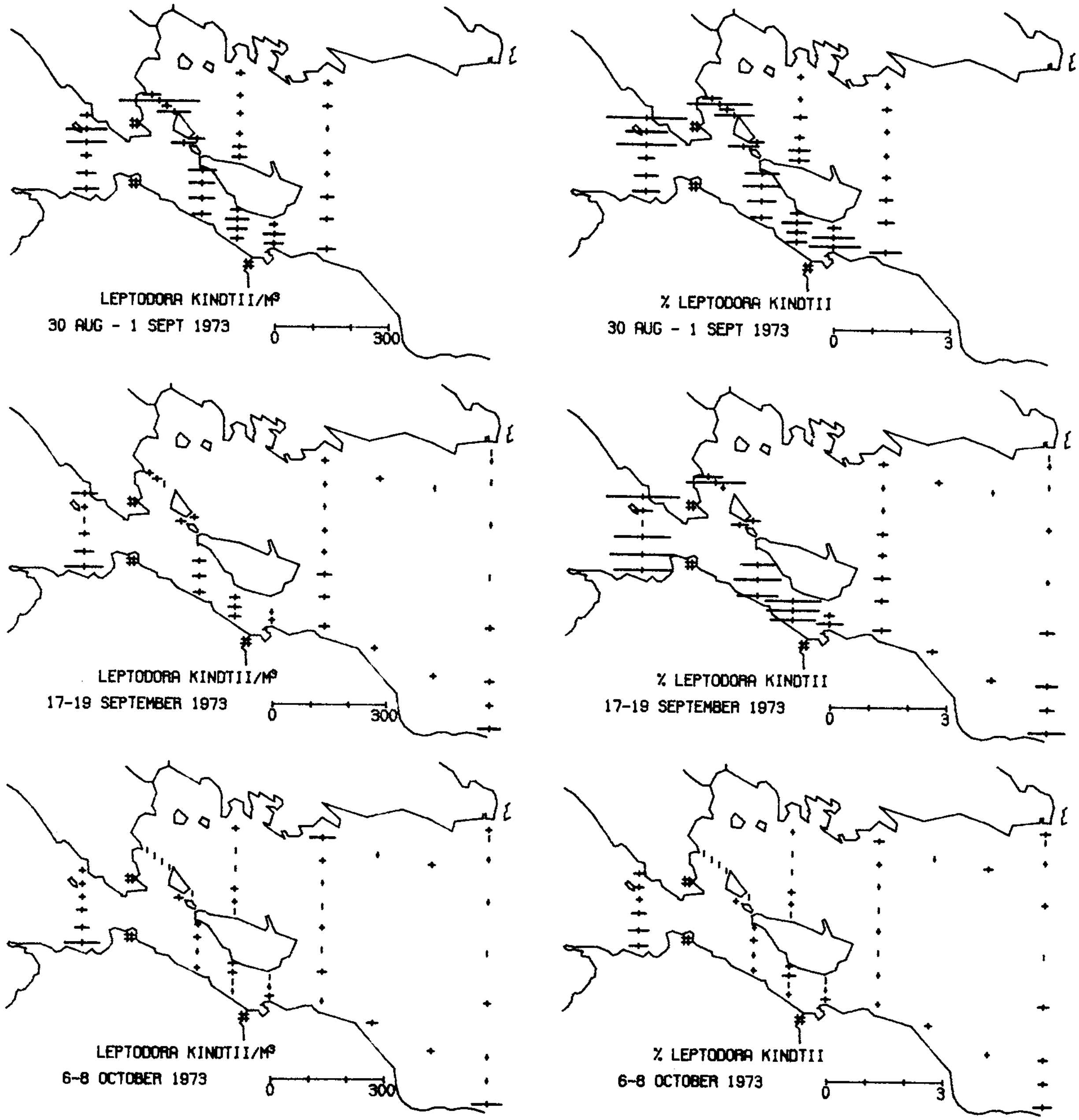


Figure 7.19. DISTRIBUTION AND ABUNDANCE OF *LEPTODORA KINDTII* IN THE STRAITS REGION.

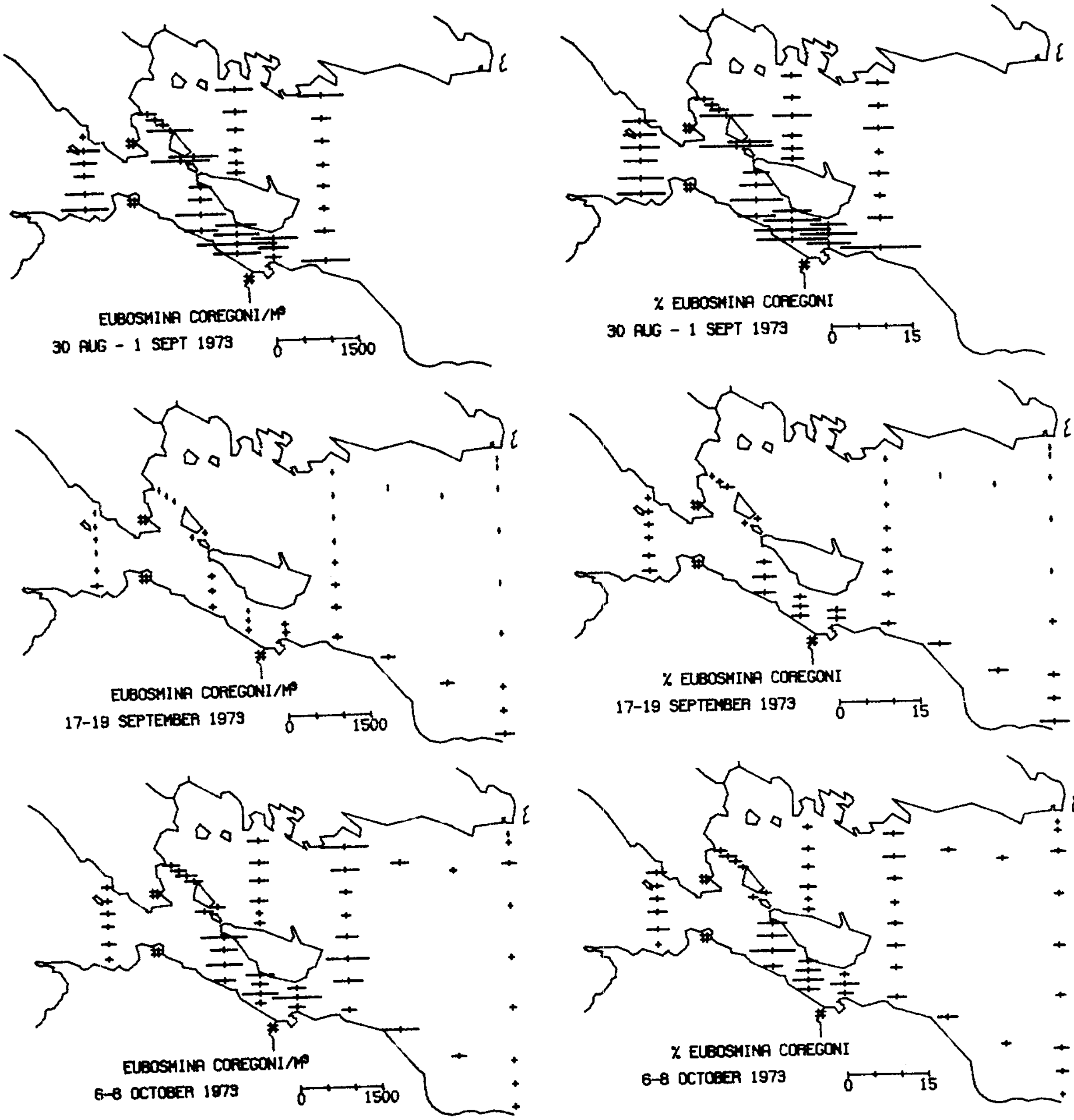


Figure 7.20. DISTRIBUTION AND ABUNDANCE OF *EUBOSMINA COREGONI* IN THE STRAITS REGION.

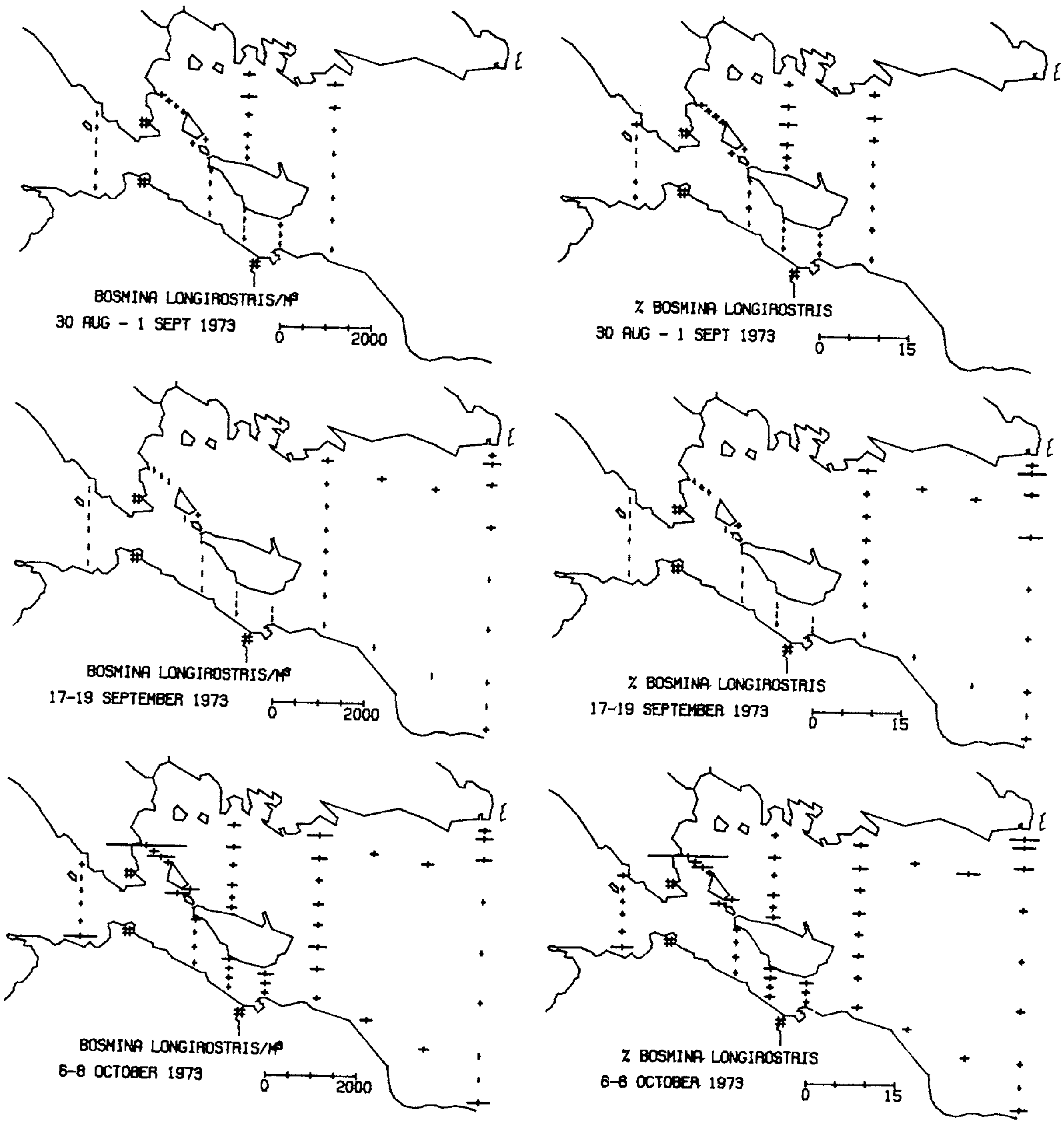


Figure 7.21. DISTRIBUTION AND ABUNDANCE OF *BOSMINA LONGIROSTRIS* IN THE STRAITS REGION.

(Fig. 7.22). *Ceriodaphnia lacustris, C. quadrangula*, and *Chydorus sphaericus* were observed throughout the Straits region but exhibited no noteworthy patterns of distribution. *Sida crystallina*, a littoral species, was observed only in September near the mouth of the St. Marys River. Other species were predominantly littoral forms that occasionally appeared as one or two individuals at nearshore stations (App. F.1-3).

In summary, the preceding simple inspection of data reveals that there were differences in the community structure of crustacean zooplankton within the Straits of Mackinac. Although the species composition was practically identical at every station, prominent and consistent patterns were evident in the relative proportions of species to one another in specific subregions within the Straits. The relative abundance of zooplankters towards Lake Michigan (west of the Mackinac Bridge) and in the South Channel (south of Bois Blanc Island) shared many resemblances. This region was characterized by a distinct preponderance of cladocerans, especially *Daphnia retrocurva* and *D. galeata mendotae*. Other cladocerans, such as *Holopedium gibberum, Eubosmina coregoni, Leptodora kindtii*, and *Polyphemus pediculus*, were also most prevalent in this region. In addition, the calanoid copepods *Epischura lacustris, Diaptomus oregonensis*, and *D. minutus* were generally characteristic of this region. In contrast, calanoid copepods as a group were relatively most abundant in waters towards Lake Huron, i.e., north and east of Bois Blanc Island. The preponderance of calanoid copepods in this region was mainly due to copepodids of *Diaptomus* spp., *D. sicilis* adults, *Limnocalanus macrurus* and *Senecella calanoides*. Cyclopoid copepods, predominantly *Cyclops bicuspidatus thomasi*, did not show any distinctive trends but appeared somewhat more prevalent toward Lake Huron. Cladocerans, such as *Bosmina longirostris*, were mainly characteristic of inshore stations in this region.

Principal component analysis (PCA) allowed us to more clearly observe some of these trends and defined other trends not discernible simply by inspection. Two major regions, here arbitrarily termed L and M, were deliniated by PCA based upon similarities in relative abundance of zooplankters at various stations. The L region lies toward Lake Michigan and in the South Channel while the M region consists of waters towards Lake Huron and north of Bois Blanc Island. On August and October cruises, the M region was divided into two subregions, M east of Bois Blanc Island and N north of the island. The N subregion was not sampled due to inclement weather during the September cruise. These major regions were remarkably consistent both in areal coverage and in species associations throughout the study (Figs. 7.23-7.25).

During the August cruise, the waters toward Lake Michigan and in the South Channel (L_2) were characterized by a greater relative abundance of *Daphnia retrocurva, D. galeata mendotae, Holopedium gibberum, Eubosmina coregoni, Epischura lacustris, Diaptomus oregonensis*, and *D. minutus* (Fig. 7.23). Stations within the L_1 subregion showed the greatest affinities due to a preponderance of *Daphnia galeata mendotae, D. retrocurva*, and *Diaptomus minutus* (Table 7.2). L_3 was characterized by greater

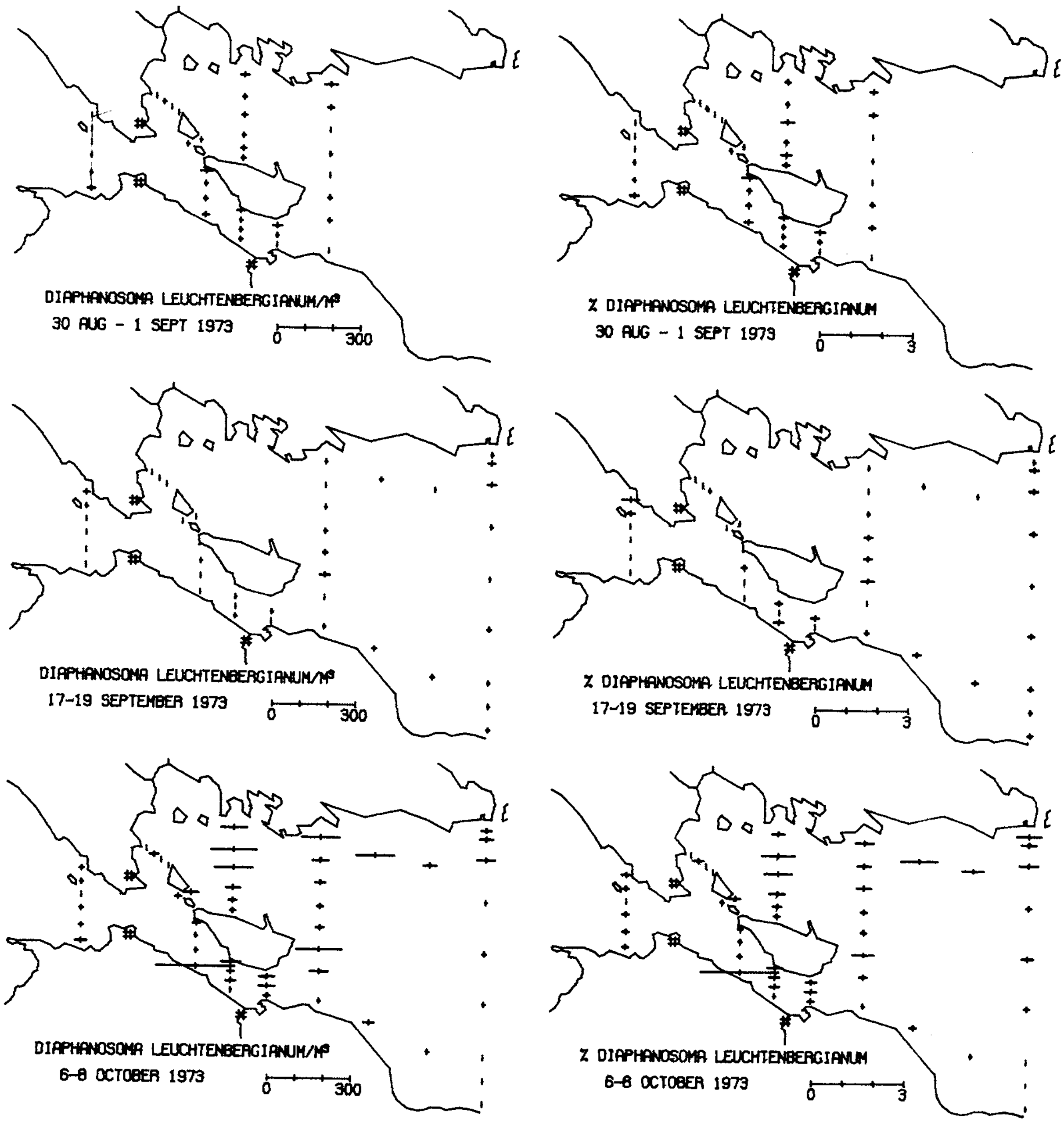


Figure 7.22. DISTRIBUTION AND ABUNDANCE OF *DIAPHANOSOMA LEUCHTENBERGIANUM* IN THE STRAITS REGION.

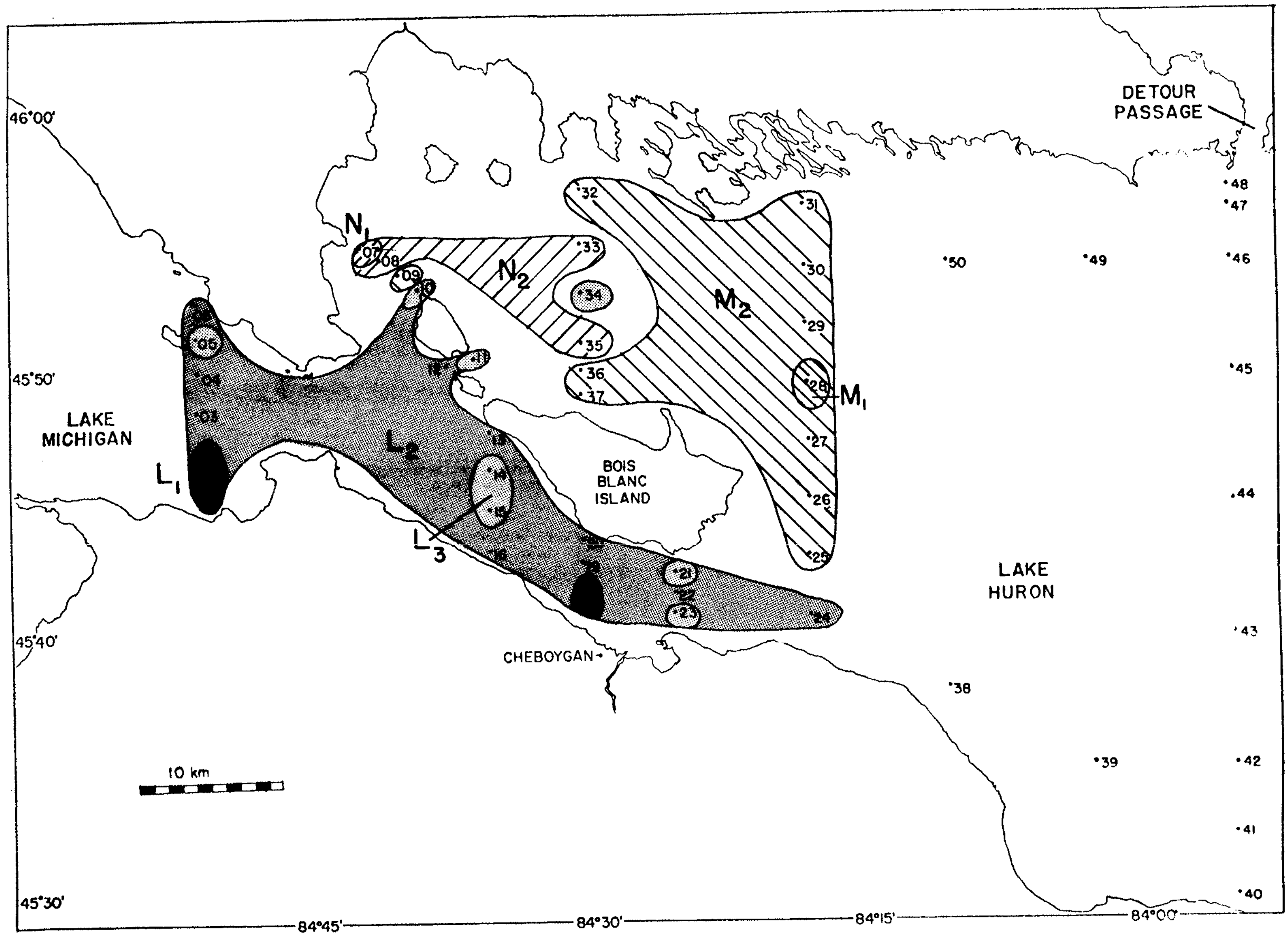


Figure 7.23. ZONES OF SIMILARITY IN COMMUNITY STRUCTURE OF CRUSTACEAN ZOOPLANKTON IN THE STRAITS REGION DURING AUGUST 1973. These zones, arbitrarily labeled L, M, and N, were determined by principal component analysis using percent composition of 16 species.

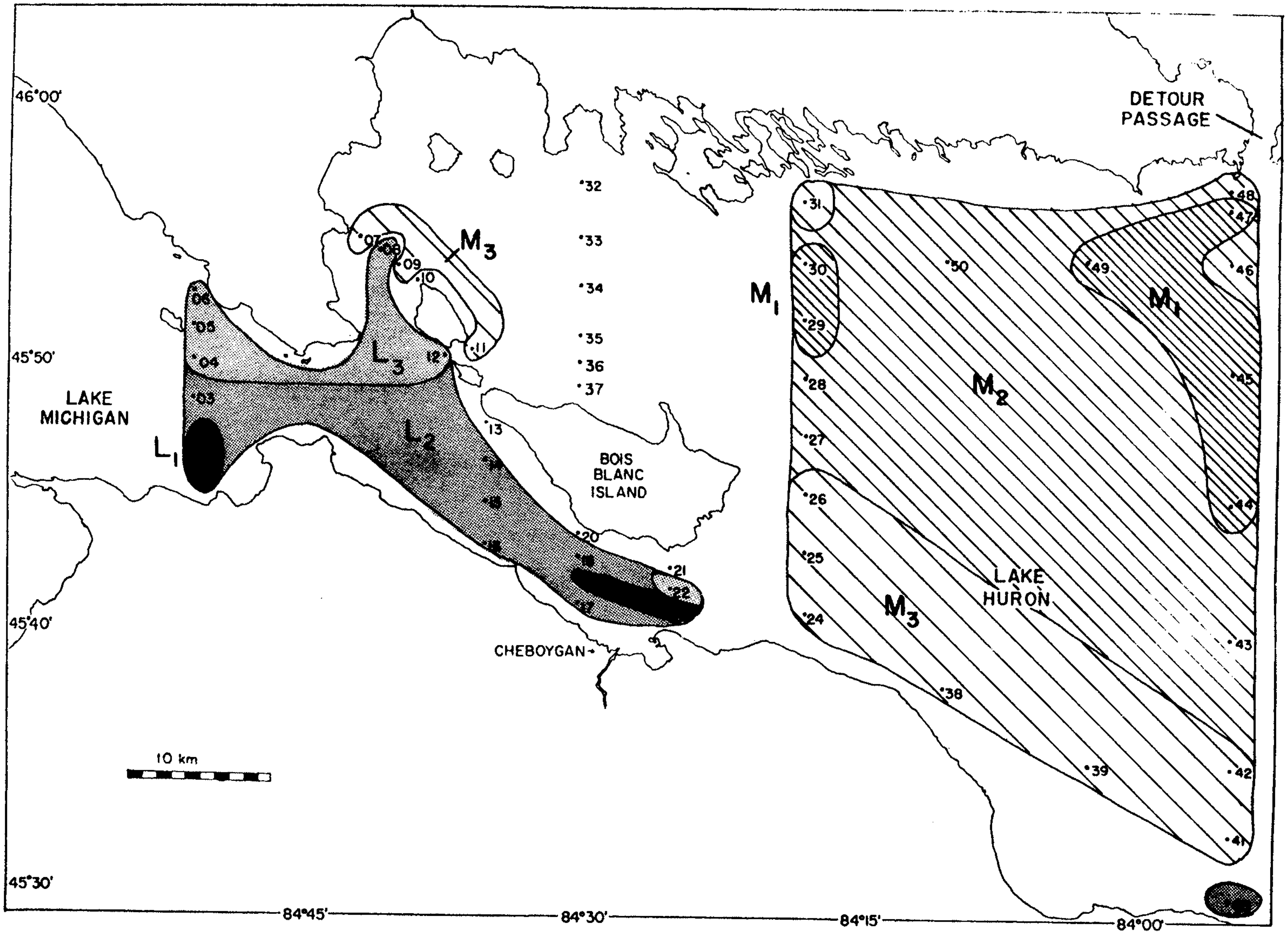


Figure 7.24. ZONES OF SIMILARITY IN COMMUNITY STRUCTURE OF CRUSTACEAN ZOOPLANKTON IN THE STRAITS REGION DURING SEPTEMBER 1973 AS DETERMINED BY PRINCIPAL COMPONENT ANALYSIS.

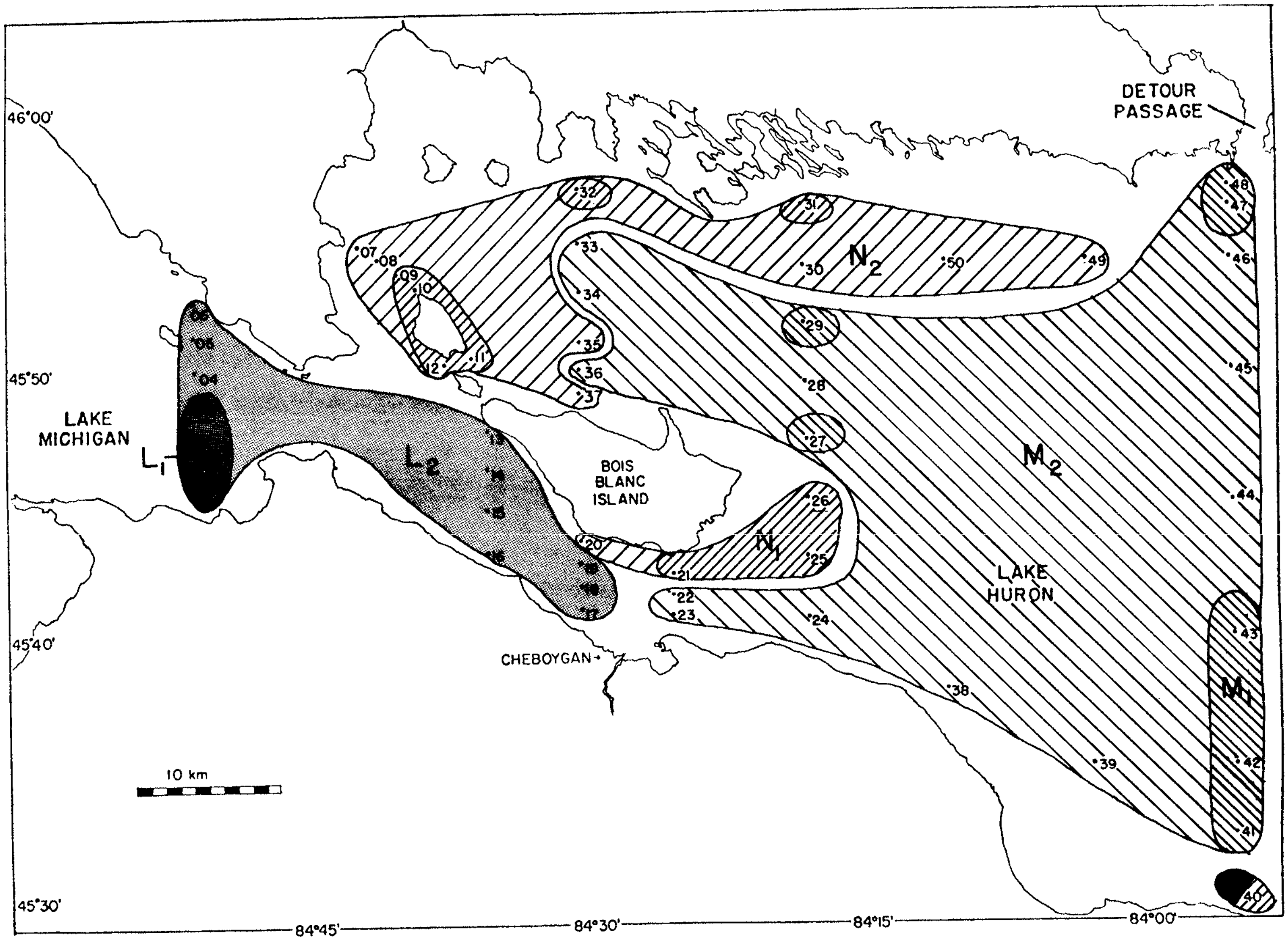


Figure 7.25. ZONES OF SIMILARITY IN COMMUNITY STRUCTURE OF CRUSTACEAN ZOOPLANKTON IN THE STRAITS REGION DURING OCTOBER 1973 AS DETERMINED BY PRINCIPAL COMPONENT ANALYSIS.

Table 7.2. DISTRIBUTION OF ZOOPLANKTON DURING AUGUST 1973. Relative abundances (in percent composition) for each region (Fig. 7.23) are given over the standard error of the mean. Standard errors are omitted when values used in the average are identical. Taxa are grouped according to apparent trend. Taxa most abundant in L_1 are listed first, and those most prevalent in M_1 appear last.

	Region and number of stations						
	L_1	L_2	L_3	N_1	N_2	M_2	M_1
	4	10	8	1	3	9	1
Daphnia retrocurva	17.2	15	11	8.5	5.4	5.7	1.0
	4.4	3	2		.4	.7	
Epischura lacustris	1.4	1.3	1.2	.59	.55	.63	.31
	.1	.2	.2		.17	.12	
Diaptomus minutus	10	7.9	4.4	.77	1.4	2.1	1.2
	3	1.3	.7		.5	.5	
Holopedium gibberum	16	14	15	6.8	6.2	7.0	3.4
	3	1	1		1.7	.7	
Eubosmina coregoni	11	8.5	7.8	3.2	2.8	3.7	1.3
	1	1.1	.5		.3	.3	
Daphnia galeata mendotae	28	23	18	8.1	8.7	10.5	3.2
	3	1	1		.5	.7	
Diaptomus oregonensis	4.1	6.2	5.6	4.2	3.1	2.1	.57
	1.3	1.1	.8		.6	.4	
Leptodora kindtii	.56	.91	.73	.47	.66	.28	.11
	.04	.16	.14		.50	.06	
Polyphemus pediculus	.14	.41	.19	.09	.02	.15	.05
	.09	.13	.08		.02	.06	
Mesocyclops edax	.11	.21	.15	.09	.09	.13	.02
	.07	.14	.06		.03	.06	
Daphnia longiremis	1.6	2.7	3.4	13	11.1	4.8	.87
	.9	.5	1.0		.6	.7	
Ceriodaphnia lacustris	.09	.08	.13	.26	.10	.05	0
	.05	.03	.03		.05	.01	
Bosmina longirostris	.38	.46	.84	1.7	1.8	1.1	.30
	.13	.14	.31		.4	.2	
Diaptomus ashlandi	.54	1.1	1.69	3.9	1.8	1.51	.48
	.02	.1	.08		.2	.07	
Cyclops bicuspidatus thomasi	1.7	3.5	6.0	6.1	6.8	5.9	2.1
	.4	.4	.5		.6	.5	
Diaptomus sicilis	.02	.02	.01	0	.05	.16	.05
	.02	.02	.01		.04	.05	
Diaptomus spp. *copepodids*	6.1	13	22	41	48	52	84
	.5	2	3		3	2	
Limnocalanus macrurus	0	.02	.07	0	.15	.46	.38
		.02	.03		.14	.20	

relative abundance of *Diaptomus oregonensis*. Stations in the M region northeast of Bois Blanc Island showed affinities based upon greater relative abundance of *Diaptomus sicilis*, *Diaptomus* spp. copepodids and *Limnocalanus macrurus*. These species also comprised a major constituent in the N region northwest of Bois Blanc Island, but this region was more characterized by the relative abundance of *Diaptomus ashlandi*, *Daphnia longiremis*, *Bosmina longirostris*, and *Cyclops bicuspidatus thomasi* (Fig. 7.23). Only one (*Mesocyclops edax*) of the 16 species analyzed did not show any strong trends in distribution during August (Table 7.2).

Trends in species associations were strongest during the September cruise, a period characterized by strong westerly winds (Fig. 7.24). The L region was characterized by the same species predominance as observed in August. *Daphnia retrocurva*, *D. galeata mendotae*, and *Diaptomus oregonensis* were most prevalent in the L_1 subregion, while *Holopedium gibberum* and *Epischura lacustris* most characterized the L_3 subregion. The M region was also characterized by the same predominant species as in August. Stations in the M_1 subregion had a relatively greater abundance of *Diaptomus* spp. copepodids, *D. sicilis*, *Limnocalanus macrurus*, and *Bosmina longirostris*, while the M_3 subregion had more *Cyclops bicuspidatus thomasi* (Fig. 7.24). Only *Mesocyclops edax*, *Daphnia longiremis*, and *Diaptomus ashlandi* did not show any strong trends in distribution during this cruise (Table 7.3).

Trends in relative abundance of zooplankters were least distinct during the October cruise, when weak easterly winds were blowing (Fig. 7.25). The L region included the same species predominance as the previous cruise with the addition of *Mesocyclops edax* and *Eubosmina coregoni* and the exclusion of *Holopedium gibberum* and *Daphnia galeata mendotae*. The L_1 subregion was predominated by *Daphnia retrocurva*, *Diaptomus ashlandi*, *D. oregonensis*, *Epischura lacustris*, and *Leptodora kindtii* while L_2 was characterized by a greater preponderance of *Eubosmina coregoni* and *Diaptomus minutus*. The M and N subregions were more distinct from one another than on previous cruises. *Daphnia longiremis*, *D. galeata mendotae*, and *Holopedium gibberum* were most prevalent in the N subregion while, as in previous cruises, *Diaptomus* spp. copepodids, *D. sicilis* and *Limnocalanus macrurus* characterized the M subregion (Fig. 7.25). Station 40, inshore in the extreme southeastern corner of the study area, was an entity in itself during this cruise. It contained strong characteristics of both L and N regions with a preponderance of *Epischura lacustris*, *Leptodora kindtii*, *Daphnia longiremis*, *D. galeata mendotae*, and *Holopedium gibberum* (Fig. 7.25). Only *Cyclops bicuspidatus thomasi* and *Bosmina longirostris* were not characteristic of any particular portion of the Straits region during this cruise (Table 7.4).

The distribution and abundance of crustacean zooplankton is related to temperature, food requirements, and competitive interactions among species. Our understanding of the interrelationships between physico-chemical and biological factors expressed in different growth and reproduction rates of various species is indeed meager. Nevertheless, the

Table 7.3. DISTRIBUTION OF ZOOPLANKTON DURING SEPTEMBER 1973. Relative abundances (in percent composition) for each region (Fig. 7.24) are given over the standard error of the mean. Taxa are grouped according to apparent trend. Taxa most abundant in L_1 are listed first, and those most prevalent in M_1 appear last.

	Region and number of stations					
	L_1 4	L_2 7	L_3 6	M_3 11	M_2 6	M_1 6
Leptodora kindtii	1.3	1.14	.74	.35	.16	.07
	.2	.08	.31	.05	.06	.01
Diaptomus oregonensis	9.0	5.9	7.1	2.6	1.1	.62
	1.9	3.2	1.1	.6	.2	.16
Daphnia retrocurva	19	17	14.1	7.6	4.1	1.9
	3	2	.5	1.3	.8	.4
Diaptomus minutus	2.4	1.9	.81	1.1	.18	.15
	.5	.5	.18	.2	.10	.08
Eubosmina coregoni	2.6	3.1	1.4	2.0	.65	.33
	.3	.5	.3	.3	.23	.08
Daphnia galeata mendotae	42	38	35	15	9.2	6.5
	5	4	3	2	1.5	1.4
Epischura lacustris	2.9	3.8	2.3	1.5	.65	.50
	.9	.9	.6	.2	.23	.16
Holopedium gibberum	4.2	5.6	4.0	2.2	1.3	1.2
	.9	1.2	1.3	.3	.3	.2
Diaptomus ashlandi	1.1	.60	1.6	.85	.35	.33
	.3	.13	.6	.15	.05	.07
Daphnia longiremis	2.8	3.4	4.2	3.2	2.1	1.8
	1.3	.7	1.1	.6	.3	.3
Mesocyclops edax	.04	.20	.13	.22	.10	.09
	.04	.09	.09	.07	.03	.02
Bosmina longirostris	0	.27	.13	.63	1.4	2.1
		.21	.10	.22	.2	.7
Cyclops bicuspidatus thomasi	2.1	1.8	3.9	6.0	3.9	4.3
	.6	.4	1.1	1.3	.4	.5
Diaptomus sicilis	0	.11	.02	.21	.18	.31
		.04	.02	.08	.04	.04
Diaptomus spp. *copepodids*	8.7	15	22	55	73	78
	2.5	4	2	3	2	3
Limnocalanus macrurus	0	.09	.05	.90	.77	1.5
		.06	.03	.31	.26	.6

Table 7.4. DISTRIBUTION OF ZOOPLANKTON DURING OCTOBER 1973. Relative abundances (in percent composition) for each region (Fig. 7.25) are given over the standard error of the mean. Standard errors are omitted when values used in the average are identical. Taxa are grouped according to apparent trend. Taxa most abundant in L_1 are listed first, and those most prevalent in M_1 appear last.

	Region and Number of stations						
	L_1	L_2	LN	N_1	N_2	M_2	M_1
	3	10	1	9	8	12	7
Epischura lacustris	4.2	2.5	12	.64	.57	.90	.43
	.9	.4		.21	.12	.29	.17
Daphnia retrocurva	9.5	5.8	4.9	4.0	2.7	2.0	1.7
	1.1	.7		.7	.5	.3	.3
Diaptomus minutus	.75	.90	.61	.24	.17	.32	.12
	.24	.14		.05	.08	.06	.04
Diaptomus ashlandi	1.5	.92	0	.47	.34	.32	.15
	.4	.15		.09	.08	.04	.02
Leptodora kindtii	.45	.15	.46	.06	.09	.08	.16
	.04	.03		.03	.03	.02	.04
Mesocyclops edax	.34	.30	.15	.09	.14	.11	.09
	.10	.06		.05	.04	.03	.03
Diaptomus oregonensis	1.5	1.0	.15	.88	.52	.78	1.0
	.2	.2		.16	.10	.10	.1
Eubosmina coregoni	2.6	4.4	.61	2.1	2.7	2.4	1.9
	1.0	.5		.2	.2	.3	.3
Cyclops bicuspidatus thomasi	8.0	9.3	10	7.3	9.6	8.9	7.3
	.8	2.1		.5	1.5	.5	.9
Bosmina longirostris	1.7	1.0	2.8	1.9	3.6	1.4	1.9
	.9	.2		.3	1.4	.2	.6
Daphnia longiremis	.10	.33	.76	1.4	.53	.71	.35
	.02	.13		.4	.09	.12	.08
Holopedium gibberum	1.8	3.2	20	8.5	5.8	3.6	3.0
	.4	.7		1.1	1.3	.4	.7
Daphnia galeata mendotae	15.4	18	38	30	17	14	11
	.6	2		2	1	1	2
Diaptomus spp. *copepodids*	49	48	10	40	53	62	68
	2	3		2	1	1	2
Diaptomus sicilis	.15	.27	0	.32	.43	.63	.71
	.11	.08		.07	.09	.09	.08
Limnocalanus macrurus	0	.01	0	.02	.21	.31	1.3
		.01		.01	.09	.18	.6

distribution and abundance of crustacean zooplankton observed in the Straits of Mackinac region are interpretable in light of our knowledge of responses of zooplankton communities to different trophic conditions.

Calanoid copepods generally appear best adapted for oligotrophic conditions in the Great Lakes. In more eutrophic waters, cladocerans, cyclopoid copepods, and rotifers are relatively more abundant than calanoid copepods. This trend has been observed in Lakes Superior, Huron, Erie, and Ontario by Patalas (1972) and in Lake Michigan by Gannon (1972a; 1972b; 1974b; 1975). In the Straits of Mackinac, the simple ratio of calanoid copepods to cyclopoid copepods and cladocerans appeared to be an indicator of trophic conditions (Figs. 7.26-7.28). Higher values were generally obtained towards Lake Huron and lower values towards Lake Michigan during each cruise. The actual numbers obtained in this simple ratio do not seem important but relative differences from station to station are revealing. Monitoring changes in the ratio of calanoid copepods to cladocerans and cyclopoid copepods during summer stratification may be a useful indicator of eutrophication trends in the Great Lakes.

In summer, even though physicochemical characteristics of water at various stations in the Straits region differed only subtly, distinct water masses were identified. Similarities between water masses discerned by cluster analyses (see Sec. V) and regions of homogeneity in zooplankton community structure (Figs. 7.23-7.25) were remarkable. Cladocerans were relatively most abundant in the slightly more eutrophic waters towards Lake Michigan and in the South Channel, while calanoid copepods prevailed in the slightly more oligotrophic waters towards Lake Huron. Although the species of crustacean zooplankton were nearly identical throughout the study area, the community structure appeared to be a sensitive indicator of water quality even in the waters of the Straits region where nutrient conditions differ so subtly.

Northern Lake Michigan

All of the eulimnetic crustacean zooplankton noted in the Straits region were observed in northern Lake Michigan during September except *Tropocyclops prasinus mexicanus* and *Polyphemus pediculus* (App. F.4). Littoral and benthic species were absent in the plankton except for a few individuals of *Acroperus harpae* at the shallowest station (10 m) off the Sturgeon Bay Ship Canal. *Mysis relicta* was observed in the plankton at most stations greater than 120 m deep. *Pontoporeia affinis* was observed in the plankton only at Station 24, 164 m deep (App. F.4).

Average numbers of crustacean zooplankton were considerably lower at stations in northern Lake Michigan ($1,537/m^3$) than in the Straits region ($5,014/m^3$) in September (Fig. 7.29). Highest numbers ($>3,000/m^3$) were noted at an inshore station near Sturgeon Bay and stations nearest the Straits region. The lowest numbers ($<1,000/m^3$) were located at the

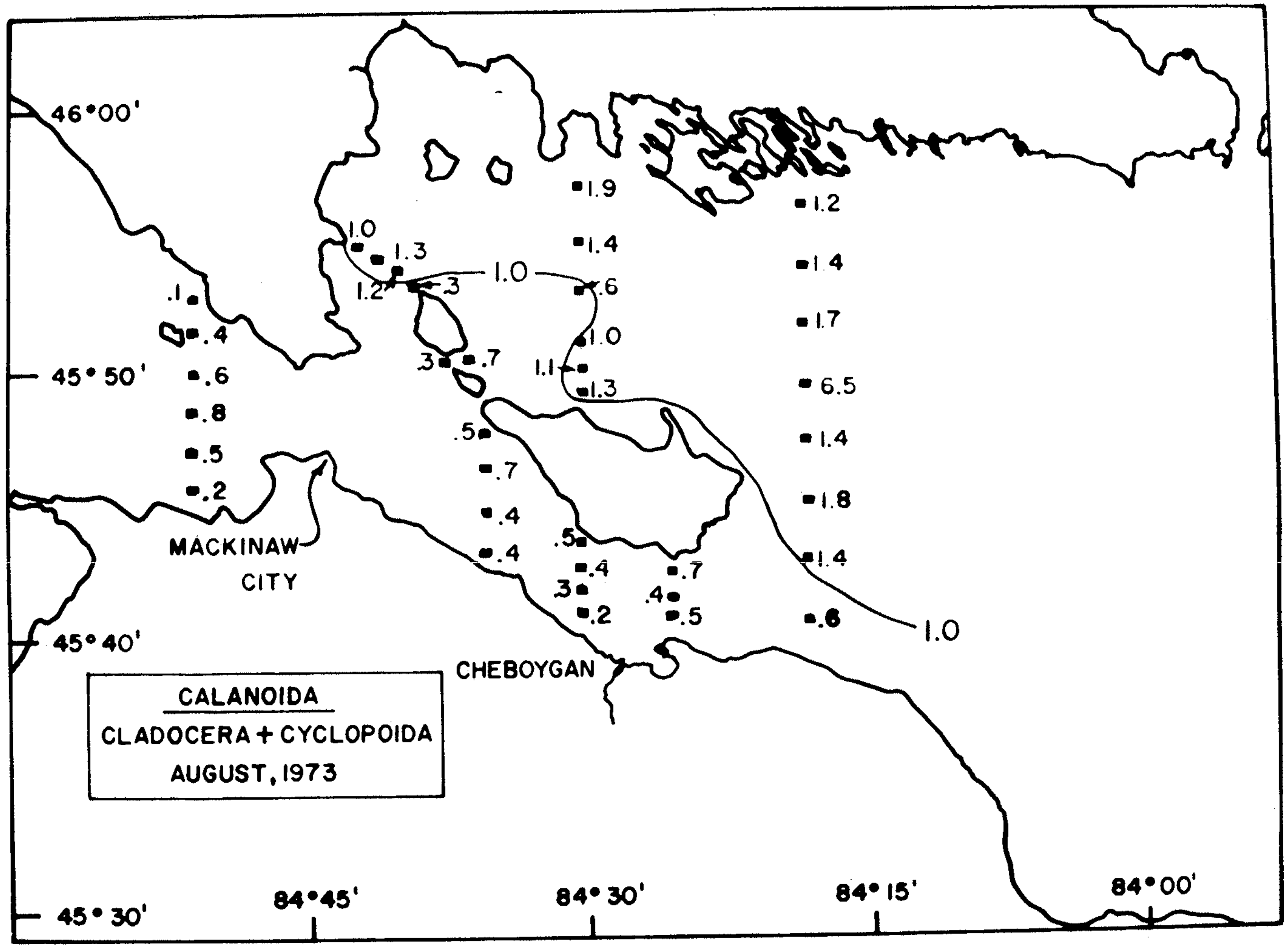


Figure 7.26. THE RATIO OF CALANOID COPEPODS TO CLADOCERANS AND CYCLOPOID COPEPODS IN THE STRAITS REGION DURING AUGUST 1973.

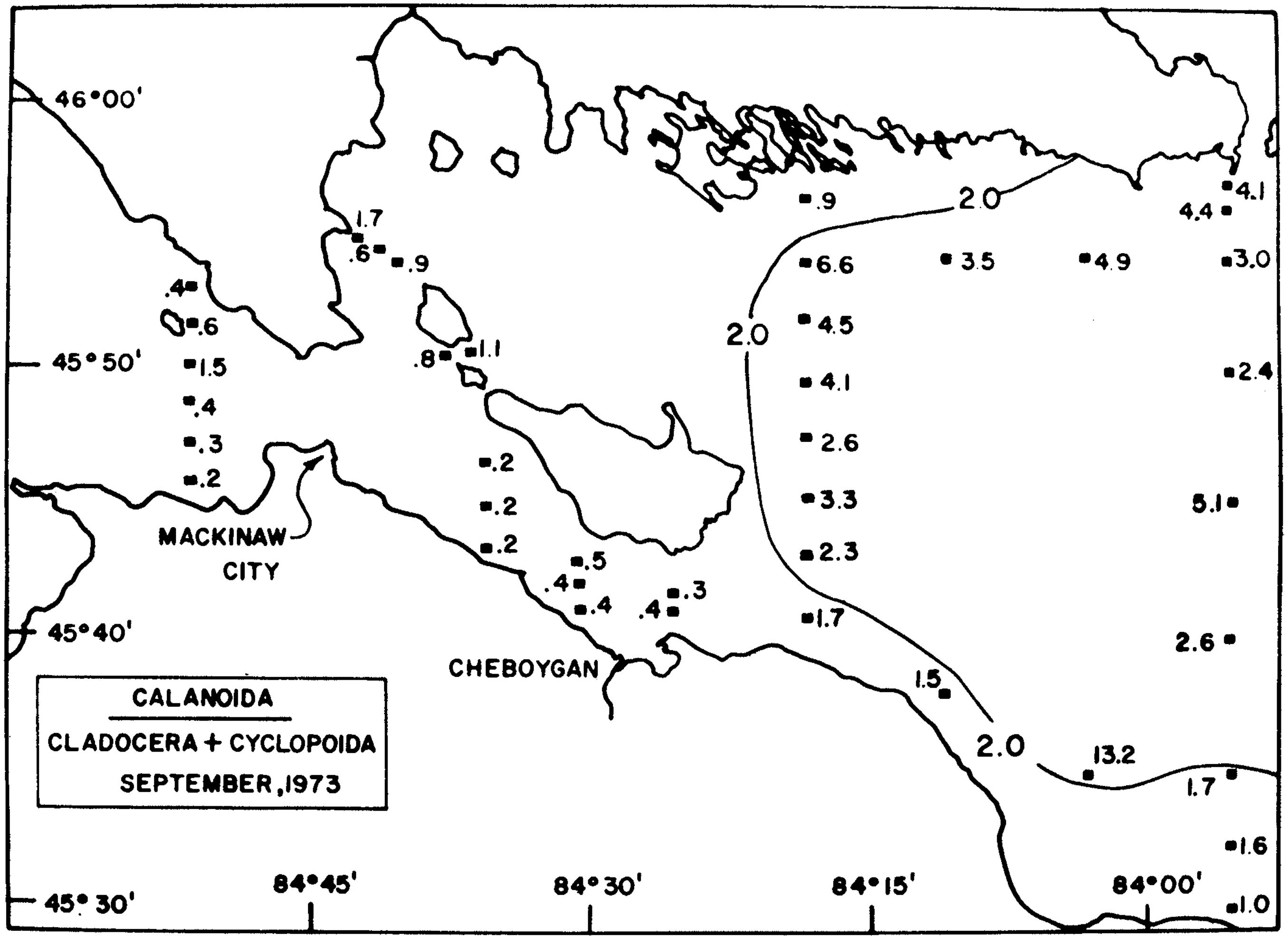


Figure 7.27. THE RATIO OF CALANOID COPEPODS TO CLADOCERANS AND CYCLOPOID COPEPODS IN THE STRAITS REGION DURING SEPTEMBER 1973.

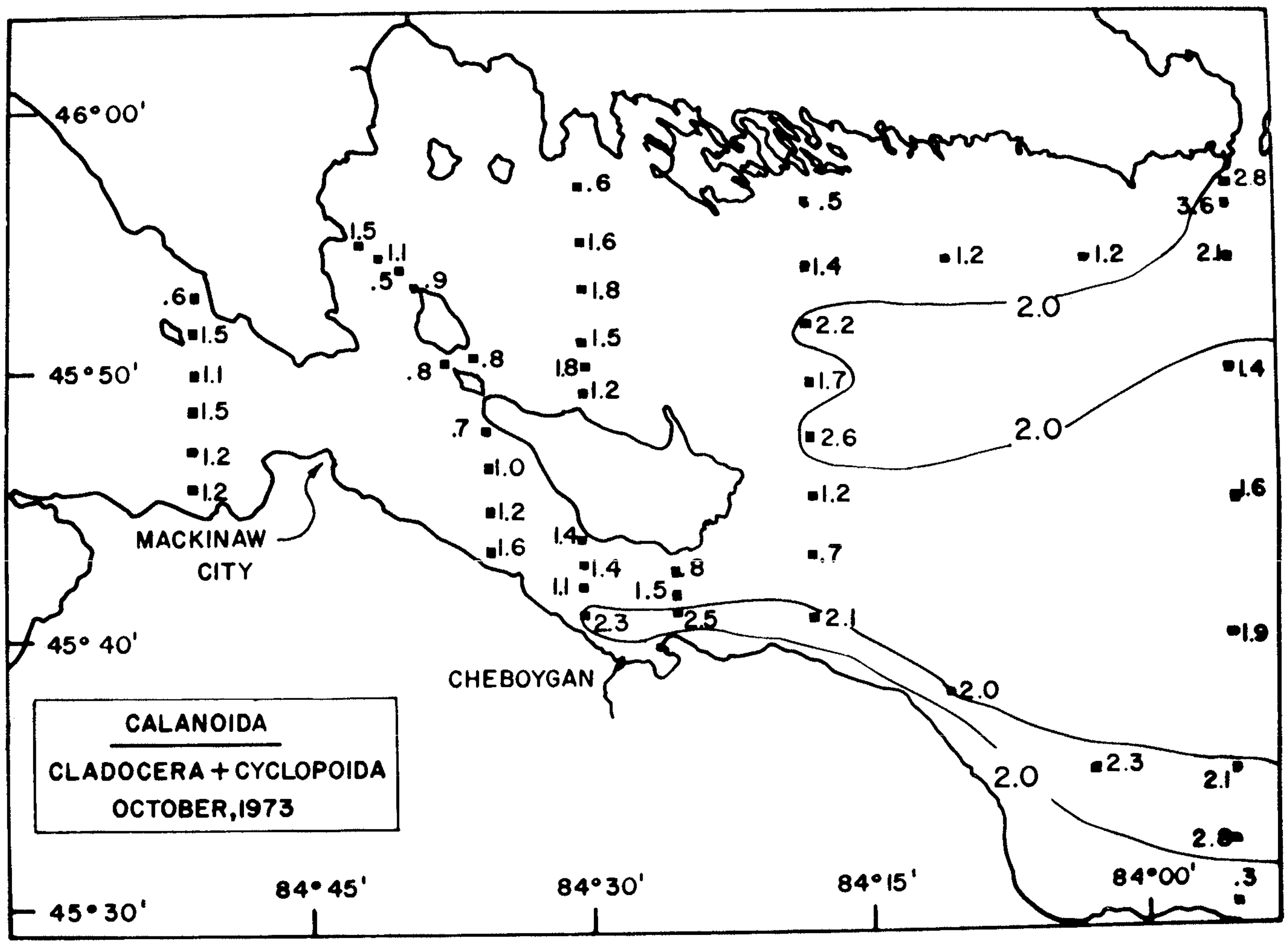


Figure 7.28. THE RATIO OF CALANOID COPEPODS TO CLADOCERANS AND CYCLOPOID COPEPODS IN THE STRAITS REGION DURING OCTOBER 1973.

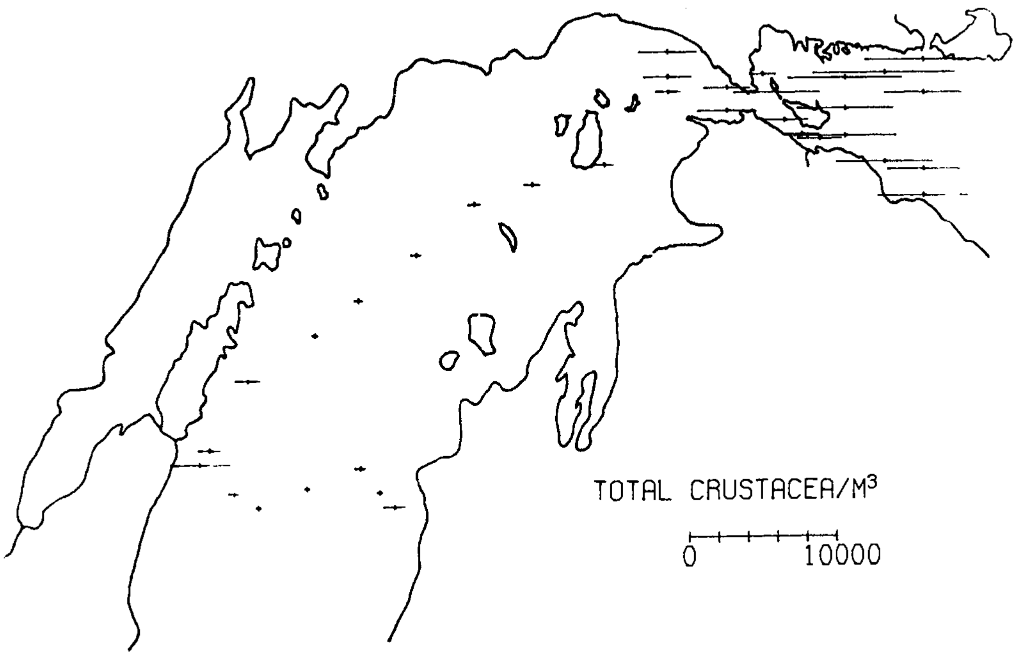
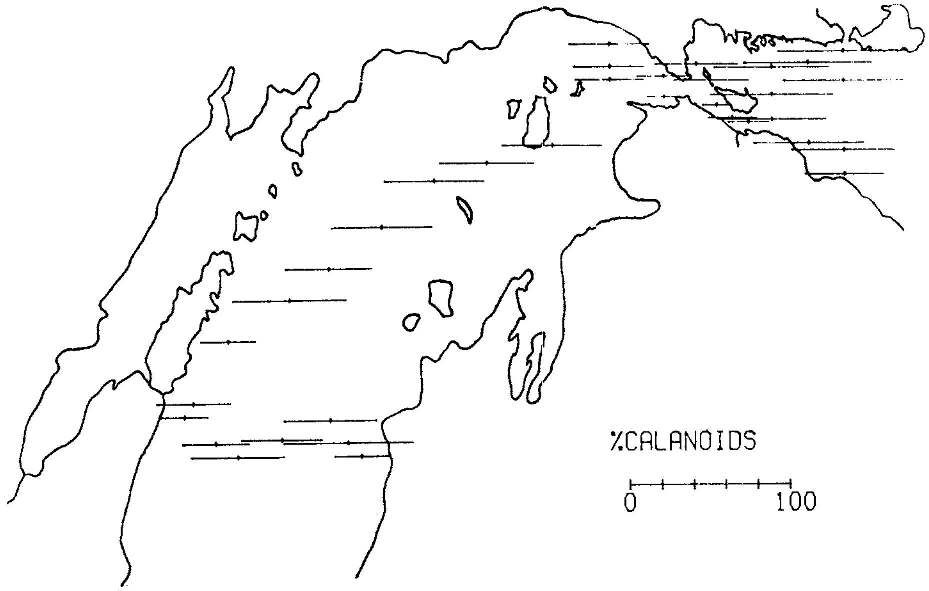


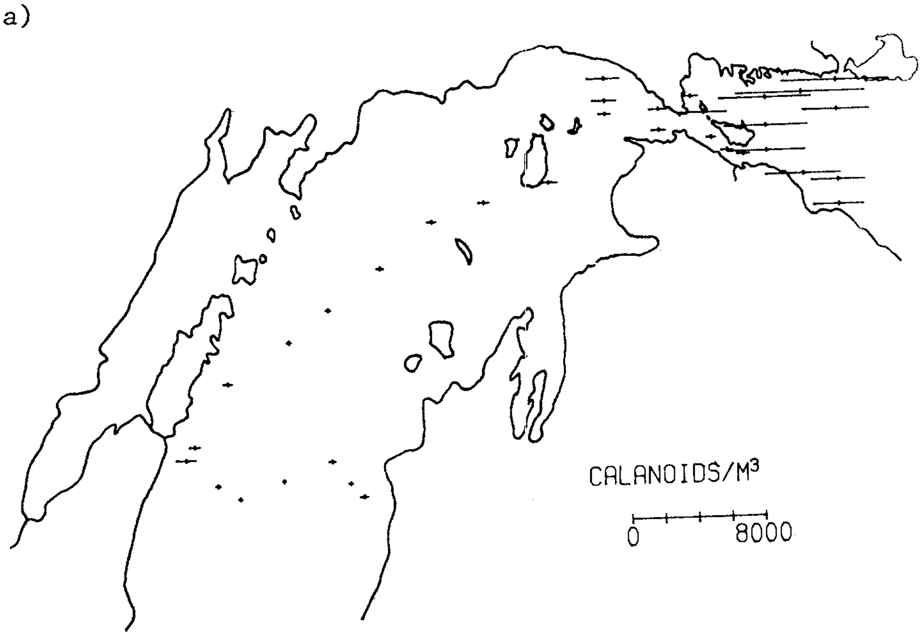
Figure 7.29. DISTRIBUTION AND ABUNDANCE (NUMBERS OF INDIVIDUALS PER M^3) OF TOTAL CRUSTACEAN ZOOPLANKTON IN NORTHERN LAKE MICHIGAN DURING SEPTEMBER 1973.

deepest offshore stations. Calanoid copepods and cladocerans each composed about half of the crustacean zooplankton. Cyclopoid copepods represented a minor component in the fauna. Predominant species were *Daphnia galeata mendotae* and *D. retrocurva* followed by *Limnocalanus macrurus, Diaptomus oregonensis, Eubosmina coregoni,* and *Diaptomus sicilis*.

Calanoid copepods comprised an average of 51% of total Crustacea (Fig. 7.30). Approximately half of the calanoids were *Diaptomus* spp. copepodids. These immature copepods did not exhibit any appreciable pattern of distribution in northern Lake Michigan (Fig. 7.31)). Adult *Diaptomus oregonensis* (Fig. 7.32) and *D. ashlandi* (App. F.4) were slightly more abundant at stations nearest the Straits of Mackinac than elsewhere in northern Lake Michigan. In contrast, *D. sicilis* was generally more prevalent at deep stations southwest of Beaver Island (Fig. 7.33). *Limnocalanus macrurus* was found at all stations but was generally most abundant at deeper offshore stations (App. F.4). An exception was a relatively large number (191/m^3) at shallow Station 44. *Senecella calanoides* was not observed at stations less than 120 m deep. *Diaptomus minutus* and *Epischura lacustris* were both low in abundance and did not exhibit any noteworthy patterns of distribution (App. F.4).



(a)

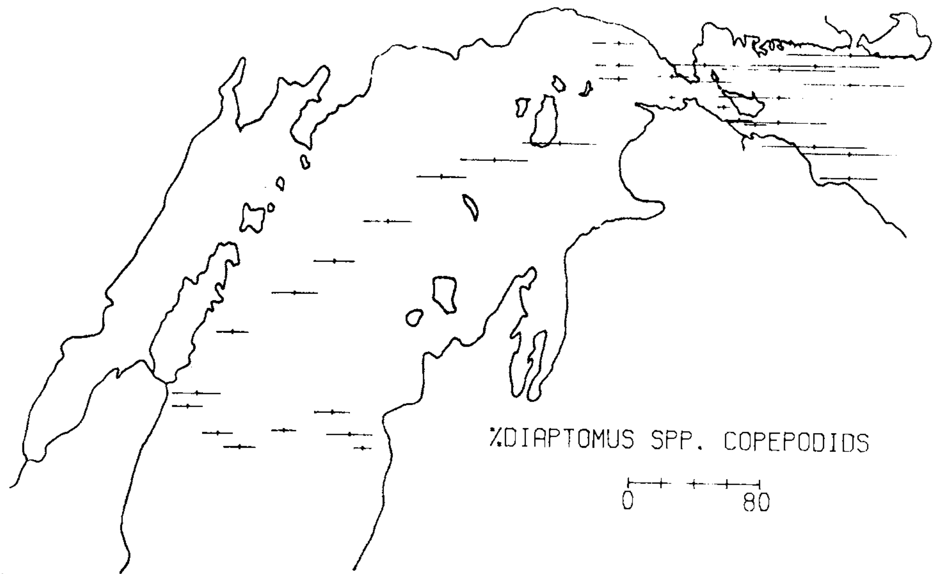


(b)

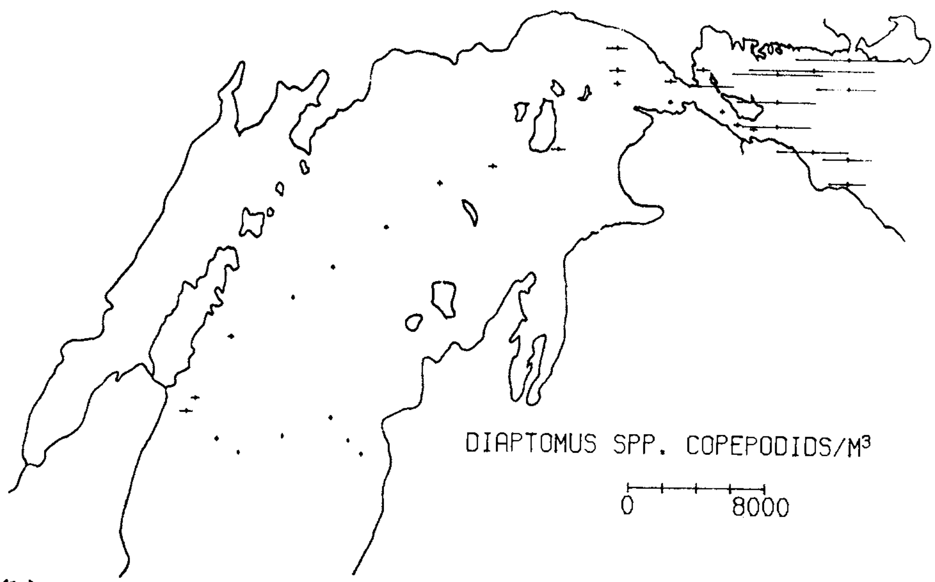
Figure 7.30. DISTRIBUTION AND ABUNDANCE OF CALANOID COPEPODS IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.



(a)

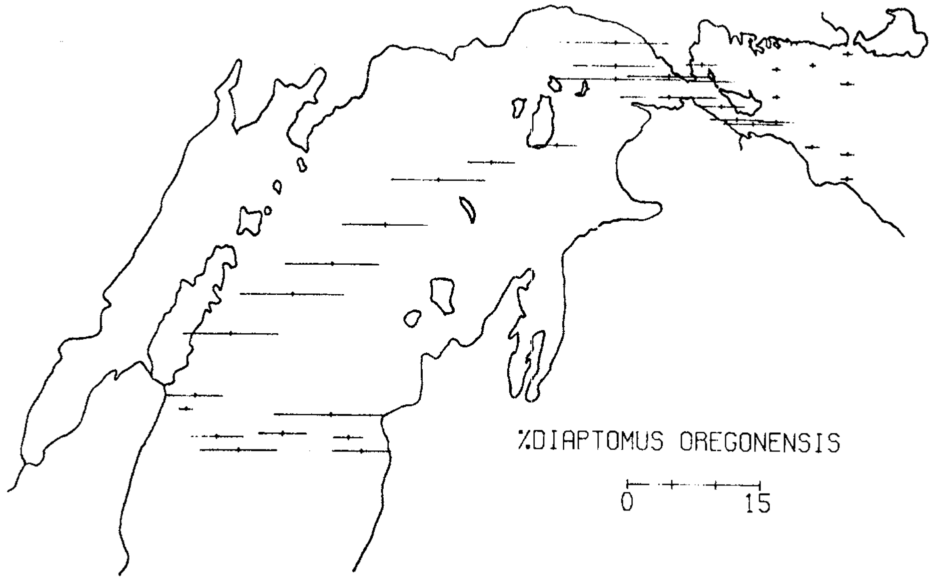


(b)

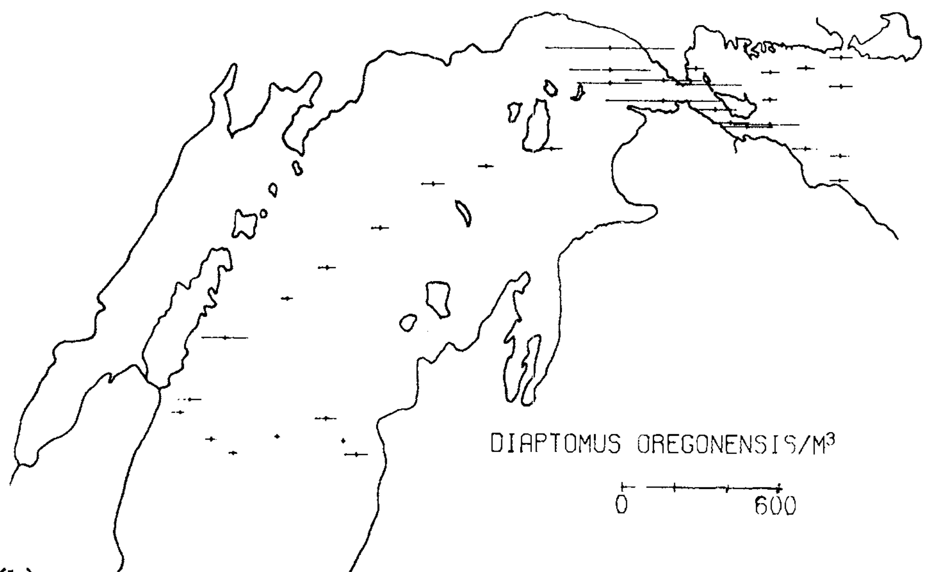
Figure 7.31. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS* spp. COPEPODIDS IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.



(a)



(b)

Figure 7.32. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS OREGONENSIS* IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.

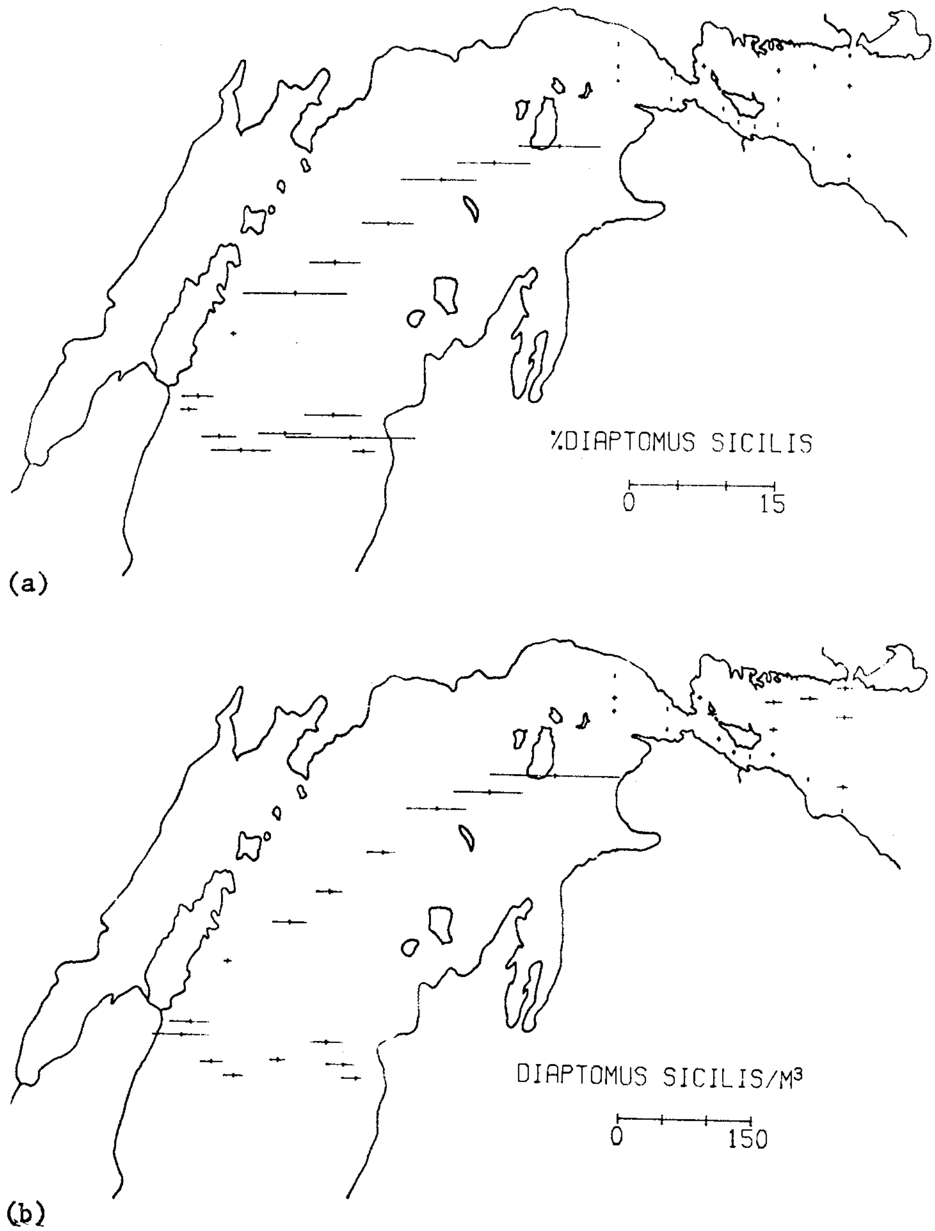


Figure 7.33. DISTRIBUTION AND ABUNDANCE OF *DIAPTOMUS SICILIS* IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.

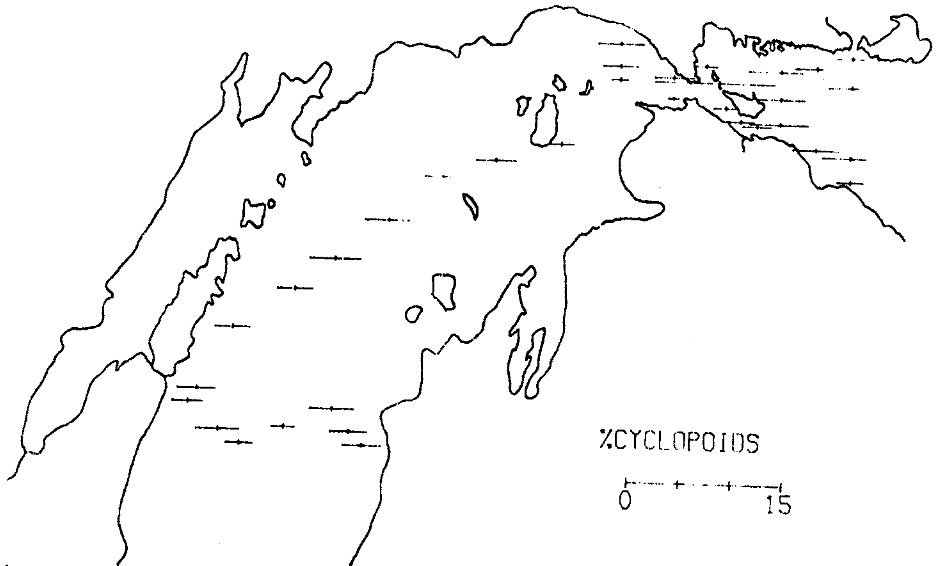
Cyclopoid copepods represented only a small fraction (average 3.4%) of total Crustacea (Fig. 7.34). *Cyclops bicuspidatus thomasi* was more abundant than *Mesocyclops edax* at shallow stations (<30 m deep), but the reverse was true at deep stations (App. F.4).

Cladocera comprised an average of 46.4% of total Crustacea (Fig. 7.35). Predominant species were *Daphnia galeata mendotae* and *D. retrocurva,* which both represented an average of about 17% of Crustacea at all stations. These species were most prevalent at the shallowest stations near the Straits of Mackinac and off Frankfort, Mich., and the Sturgeon Bay Shipping Canal (Figs. 7.36 and 7.37). *Eubosmina coregoni* comprised an average of 6.5% of the crustacean zooplankton and was most abundant off the Sturgeon Bay Shipping Canal (Fig. 7.38). Likewise, *Holopedium gibberum,* comprising an average of 2.9% of total Crustacea, was most prevalent at Station 44 off of Sturgeon Bay. Otherwise, this species did not exhibit any discernible pattern of distribution in northern Lake Michigan (Fig. 7.39). The remaining cladocerans represented considerably less than 1% of total Crustacea at all stations. Most species, such as *Leptodora kindtii,* exhibited greatest abundance at Station 44 (App. F.4). *Chydorus sphaericus* was represented by only a few individuals at Station 28 (App. F.4).

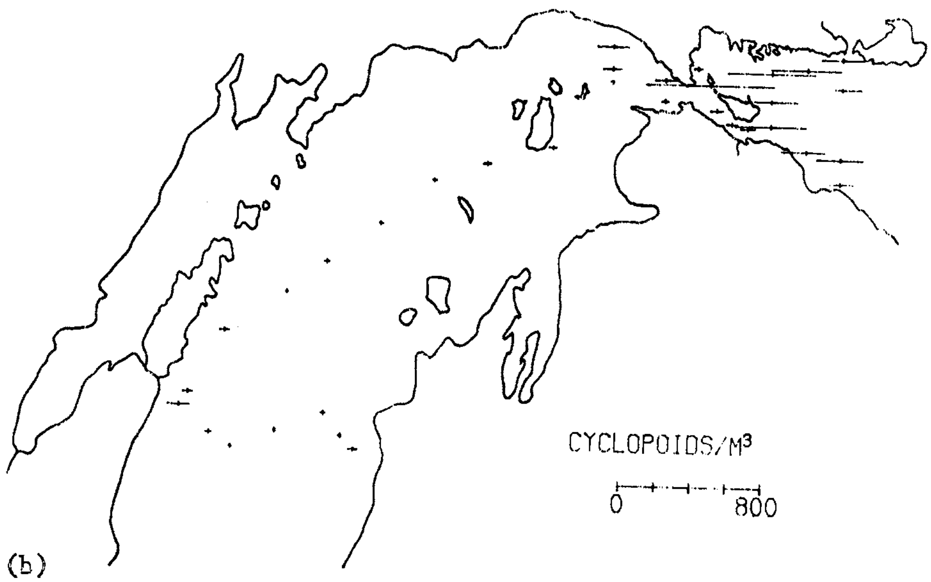
As would be expected, species composition of crustacean zooplankton in northern Lake Michigan was nearly identical to that observed in the Straits region. The larger number of *Mysis relicta* collected in northern Lake Michigan is undoubtedly due to the greater depths of these waters. It is well known that a large portion of the *Mysis* population spends the day off bottom in deep waters (Beeton 1960; Robertson et al. 1968) and therefore are more readily obtainable by plankton nets.

By first inspection of these zooplankton data, it appears that the biomass of zooplankton is higher in the Straits region than in northern Lake Michigan. However, there may be an apparent but false reduction of numbers of individuals per unit volume at deeper stations simply because a longer water column was sampled. Consequently, data calculated in terms of percent composition of various species may be more useful for comparative purposes than abundance per unit volume. An indication that this supposition is true can be obtained by comparing two stations of similar depth. Stations 03 in the Straits region and 26 in northern Lake Michigan are 53 and 55 m deep, respectively. Abundance of total crustacean zooplankton in the Straits (1,883/m^3) was slightly higher than in northern Lake Michigan (1,591/m^3). In contrast, biomass of zooplankton was considerably higher (6,491/m^3) at a station 60 m deep in southern Lake Michigan during September 1969 using identical methods (Gannon 1972a). Although these data are limited, they do suggest that there may be substantial differences in numbers of zooplankters per unit volume in southern and northern Lake Michigan.

Although depth-adjusted volumes of zooplankton may be comparable in northern Lake Michigan and the Straits of Mackinac, some interesting dif-



(a)

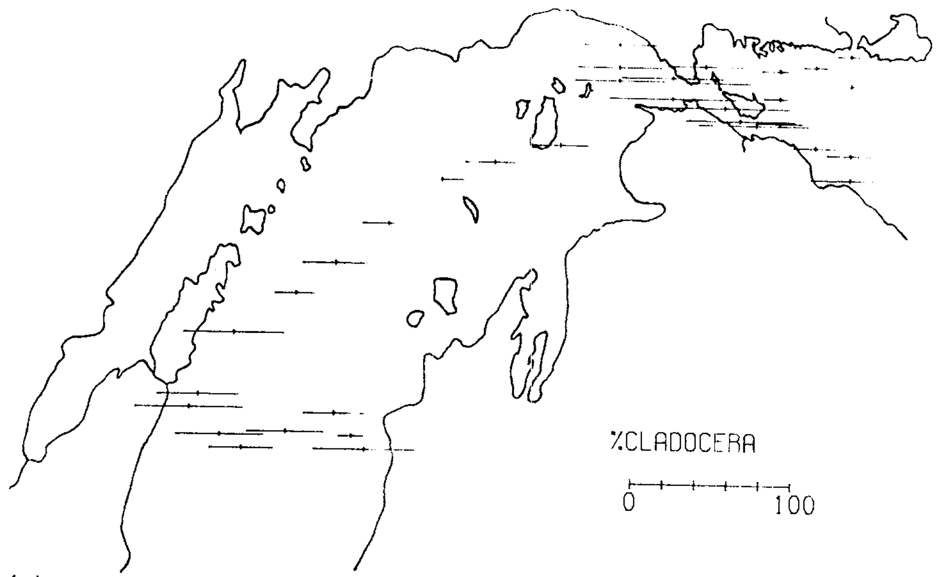


(b)

Figure 7.34. DISTRIBUTION AND ABUNDANCE OF CYCLOPOID COPEPODS IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.



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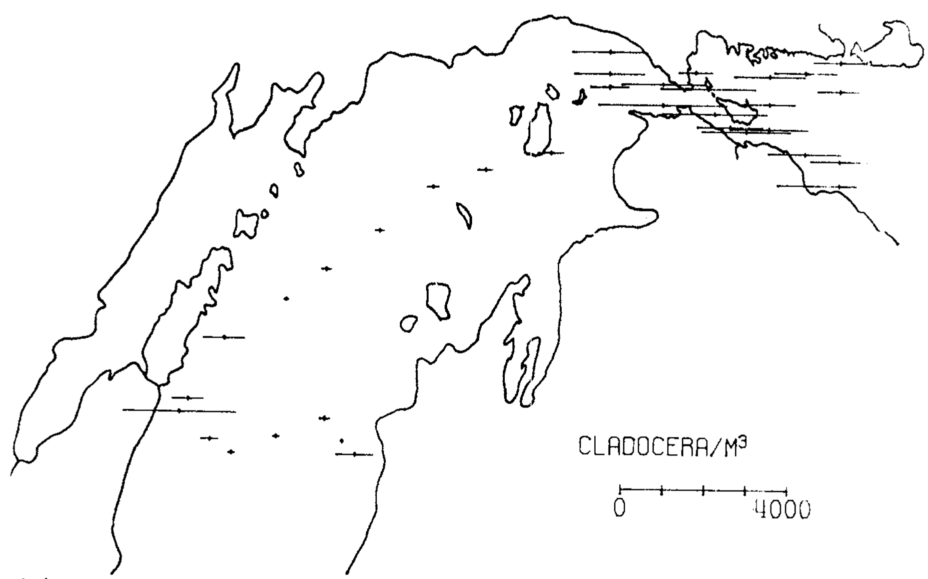


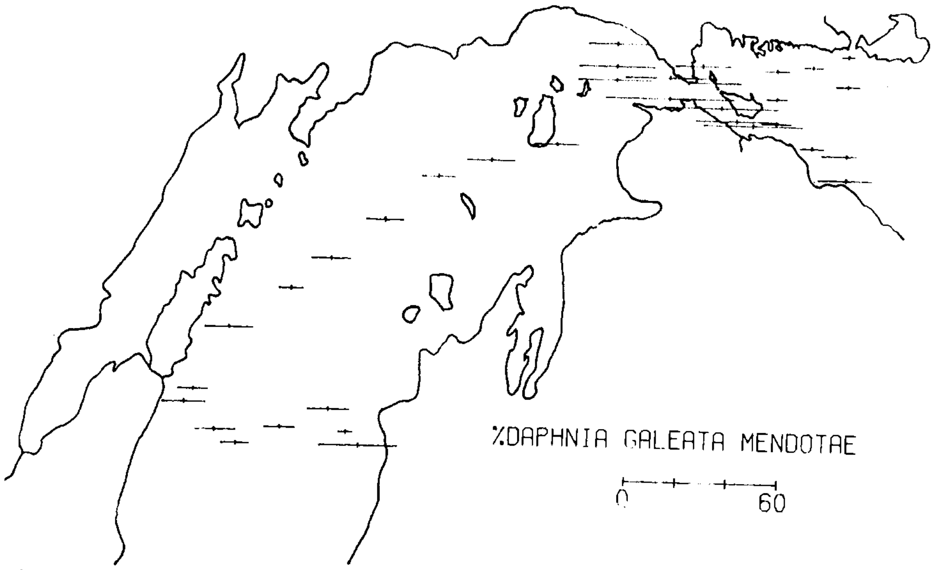
(b)

Figure 7.35. DISTRIBUTION AND ABUNDANCE OF CLADOCERA IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.

(a)



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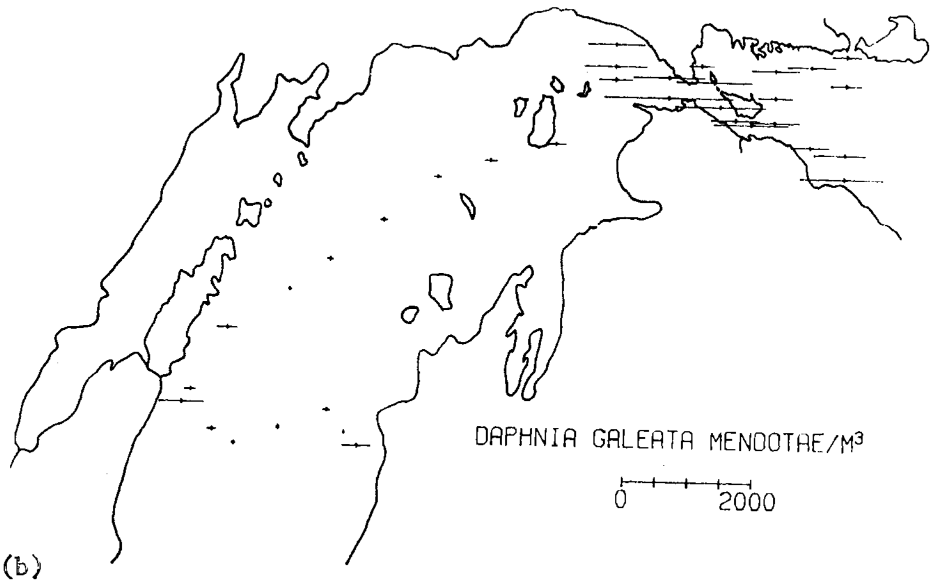
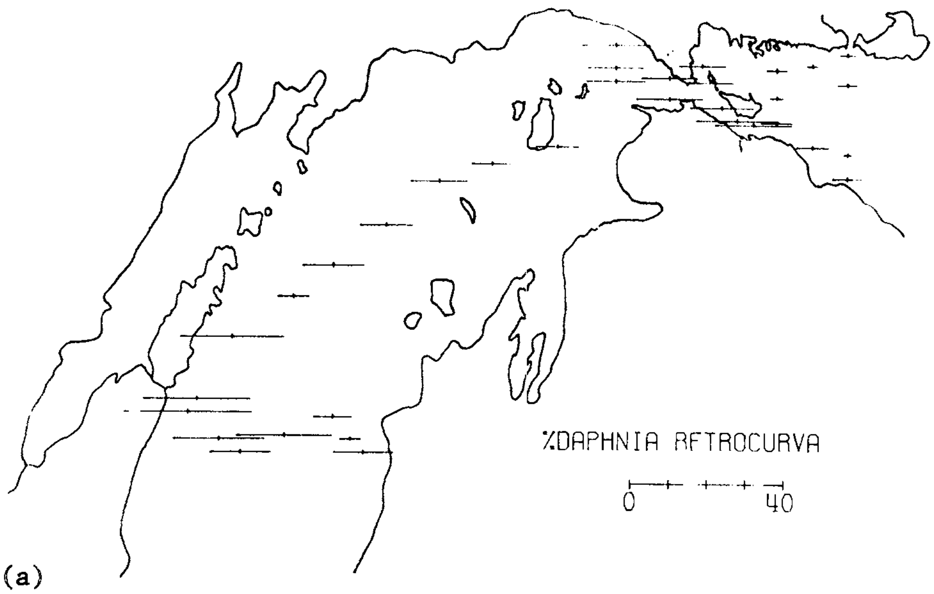


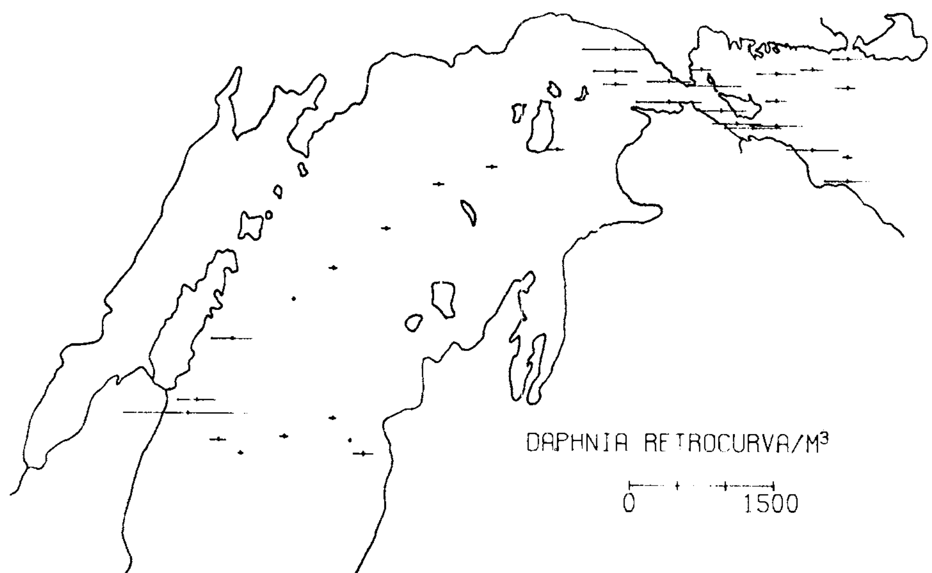
Figure 7.36. DISTRIBUTION AND ABUNDANCE OF *DAPHNIA GALEATA MENDOTAE* IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.



(a)

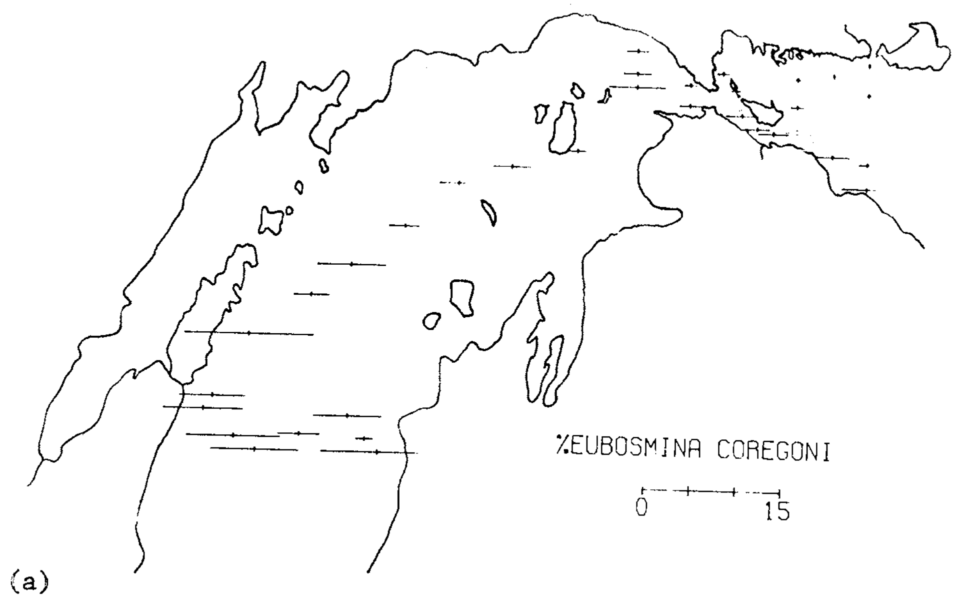


(b)

Figure 7.37. DISTRIBUTION AND ABUNDANCE OF *DAPHNIA RETROCURVA* IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.



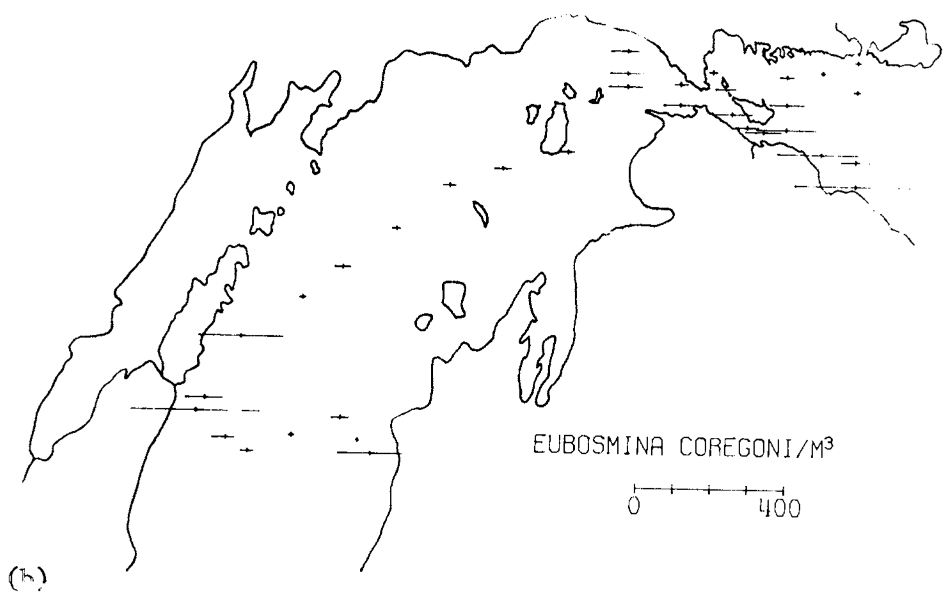
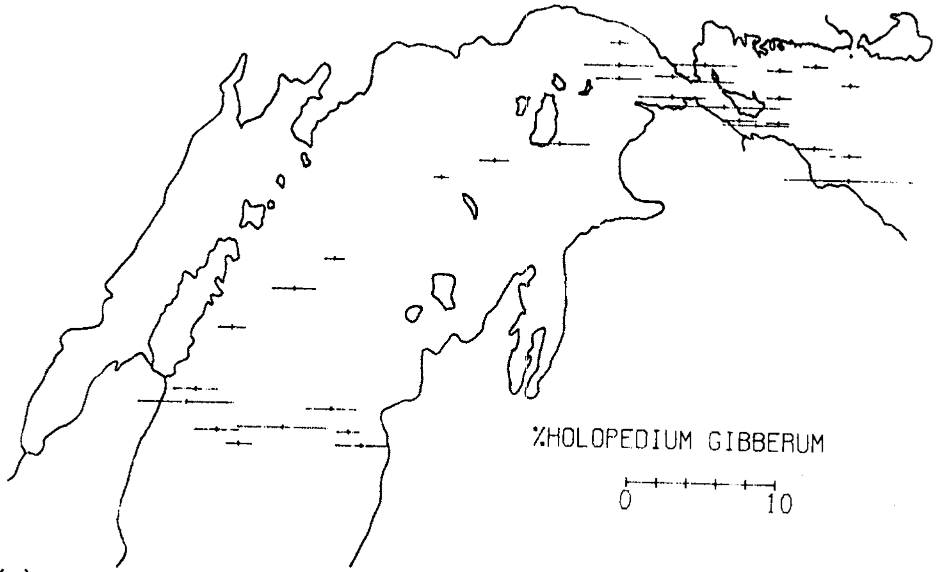


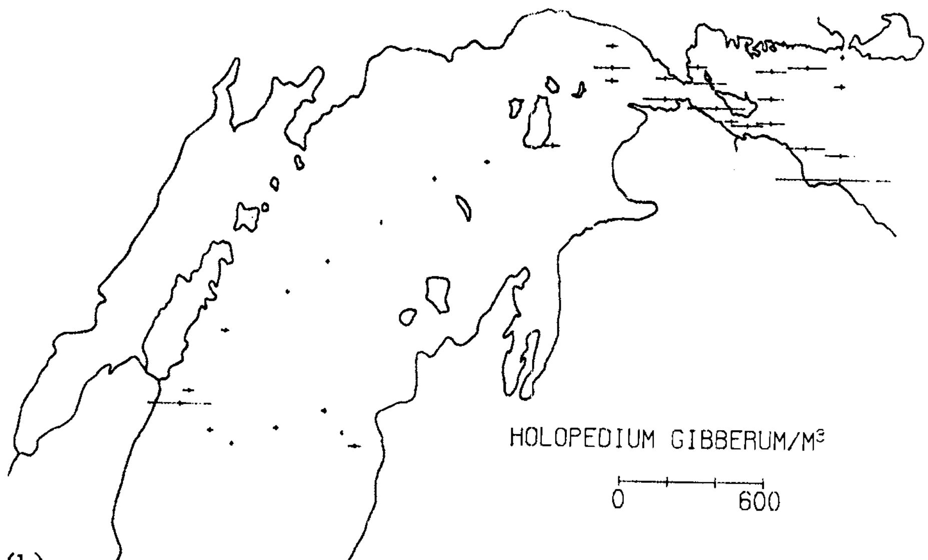
Figure 7.38. DISTRIBUTION AND ABUNDANCE OF *EUBOSMINA COREGONI* IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.



(a)



(b)

Figure 7.39. DISTRIBUTION AND ABUNDANCE OF *HOLOPEDIUM GIBBERUM* IN NORTHERN LAKE MICHIGAN.

(a) Numbers per m^3.

(b) Percent composition.

ferences in relative abundance did exist in September 1973. The percent composition of calanoid copepods was slightly higher in northern Lake Michigan, predominantly due to greater abundance of *Diaptomus sicilis*. The relative abundance of cladocerans was substantially higher in the Straits region and in the most southerly tier of stations in Lake Michigan than at stations in between. This pattern of distribution was due mostly to *Daphnia retrocurva*, *Eubosmina coregoni*, and *Holopedium gibberum*.

It is apparent that water in the Straits of Mackinac is sufficiently modified by the proximity of shallow, nearshore waters and by mixing with Lake Huron water to have different physicochemical and biological characteristics than water in northern Lake Michigan. Further data are needed to better understand the community structure of zooplankton in northern Lake Michigan as related to differences in water quality between this region and the Straits of Mackinac as well as the southern portion of Lake Michigan.

7.4 SUMMARY

Crustacean zooplankton were investigated in the Straits of Mackinac region to: 1) provide benchmark data on species composition, distribution, and abundance; 2) analyze zooplankton community structure in relation to the interactions of Lake Michigan and Lake Huron waters; and 3) contrast and compare zooplankton community structure between northern Lake Michigan and the Straits of Mackinac. Fifty stations were set up along eight transects. Samples were collected on three cruises in August, September, and October 1973 using vertical tows of a 0.5-m diameter cylinder-cone net (250 μ mesh size) fitted with a Nansen throttling mechanism.

The community of crustacean zooplankton in the Straits of Mackinac was comprised of 29 species. Twenty-three species of Cladocera and Copepoda were characteristic of limnetic waters, while six cladocerans were benthic and littoral forms that sporadically appear in the plankton. Abundance of total Crustacea at various stations during the study period ranged from near 1,000 individuals per m^3 to almost 28,000 per m^3.

Distinct differences in community structure of zooplankton were readily apparent within the Straits of Mackinac. Although species composition was nearly identical at every station, prominent and consistent patterns were evident in the relative proportions of species to one another in specific sub-regions within the Straits. The relative abundance of zooplankters towards Lake Michigan (west of the Straits of Mackinac) and in the South Channel (south of Bois Blanc Island) shared many resemblances. This region was characterized by a distinct preponderance of cladocerans, especially *Daphnia retrocurva* and *D. galeata mendotae*. Other cladocerans, such as *Holopedium gibberum*, *Eubosmina coregoni*, *Leptodora kindtii*, and *Polyphemus pediculus* were also most prevalent in this region. The calanoid copepods *Epischura lacustris*, *Diaptomus oregonensis*, and *D. minutus* generally were characteristic of the region. In contrast, calanoid copepods as a group were relatively most abundant in waters toward Lake Huron, i.e., north and east of Bois Blanc Island, mainly due to copepodids of *Diaptomus* spp., *Diaptomus sicilis* adults, *Limnocalanus macrurus*, and *Senecella calanoides*. Cyclopoid copepods, predominately *Cyclops bicuspidatus thomasi*, did not show any distinctive trends but appeared somewhat more prevalent toward Lake Huron. Cladocerans, such as *Bosmina longirostris*, were mainly characteristic of inshore stations in this region.

Regions of homogeneity of zooplankton community structure, as determined by principal component analysis, were remarkably similar to water masses identified by cluster analysis (Sec. V). Cladocerans were relatively most abundant in the slightly more eutrophic waters toward Lake Michigan and in the South Channel, while calanoid copepods prevailed in the slightly more oligotrophic waters toward Lake Huron. The community structure of crustacean zooplankton appears to be a sensitive indicator of water quality in the Straits of Mackinac where nutrient conditions are only subtly different.

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SECTION VIII

COMPARISON OF PHYTOPLANKTON AND NUTRIENTS IN NORTHERN LAKE MICHIGAN AND THE STRAITS OF MACKINAC

In September, after the regular sampling survey of the study area, 18 stations were sampled in northern Lake Michigan (Fig. 8.1). At these stations, sampling procedures and methodology were the same as those that were used on the three cruises of the Straits survey area. Comparing data obtained in September enabled us to conclude that certain biological conditions were unique to the Straits area. In addition, data for September provide the basis for verification of environmental conditions in Lake Michigan at stations removed from the influence of mixing between Lake Michigan and Lake Huron waters. It is obvious from the data presented below that the Straits survey area did not include stations with characteristic Lake Michigan conditions, i.e. water samples collected at Stations 01-06, the westernmost transect, contained a mixture of Lake Michigan and Lake Huron or Lake Superior water.

8.1 PHYSICAL-CHEMICAL CONDITIONS

Mixing apparently occurred over a broad geographic area west of the Straits and was not uniform in one area for the three cruises. For example, the average specific conductance at Stations 01-06 ranged from 235 to 250 μmho cm^{-1} on the three cruises (Table 3.1). These data also therefore indicate that some fraction of Lake Huron water was present at this westernmost transect on all of the cruises.

In September the water flowing out of Lake Michigan was cooled in the Straits of Mackinac due to the mixing with colder waters from Lake Huron. Epilimnetic water temperatures in the main part of Lake Michigan averaged about 17°C (Table 8.1), but in the Straits area decreased to 15°C at Stations LM 52-54 (Table 8.1) and to temperatures as low as 14°C as the water flowed eastward to the south of Bois Blanc Island (Table 3.1, App. C.10 and C.11). Evidence for mixing of colder Lake Huron water with Lake Michigan water can also be found for data on specific conductance, pH, silica and nitrate; there is no question therefore that mixing occurred at least in the area extending east from Stations LM 52-54 in Lake Michigan (Fig. 8.1) to at least Stations 24-26 in Lake Huron (Fig. 1.1).

In Lake Michigan, specific conductance at Stations LM 20-22, LM 23-25 and LM 45-47 that are outside the area influenced by mixing in the Straits of

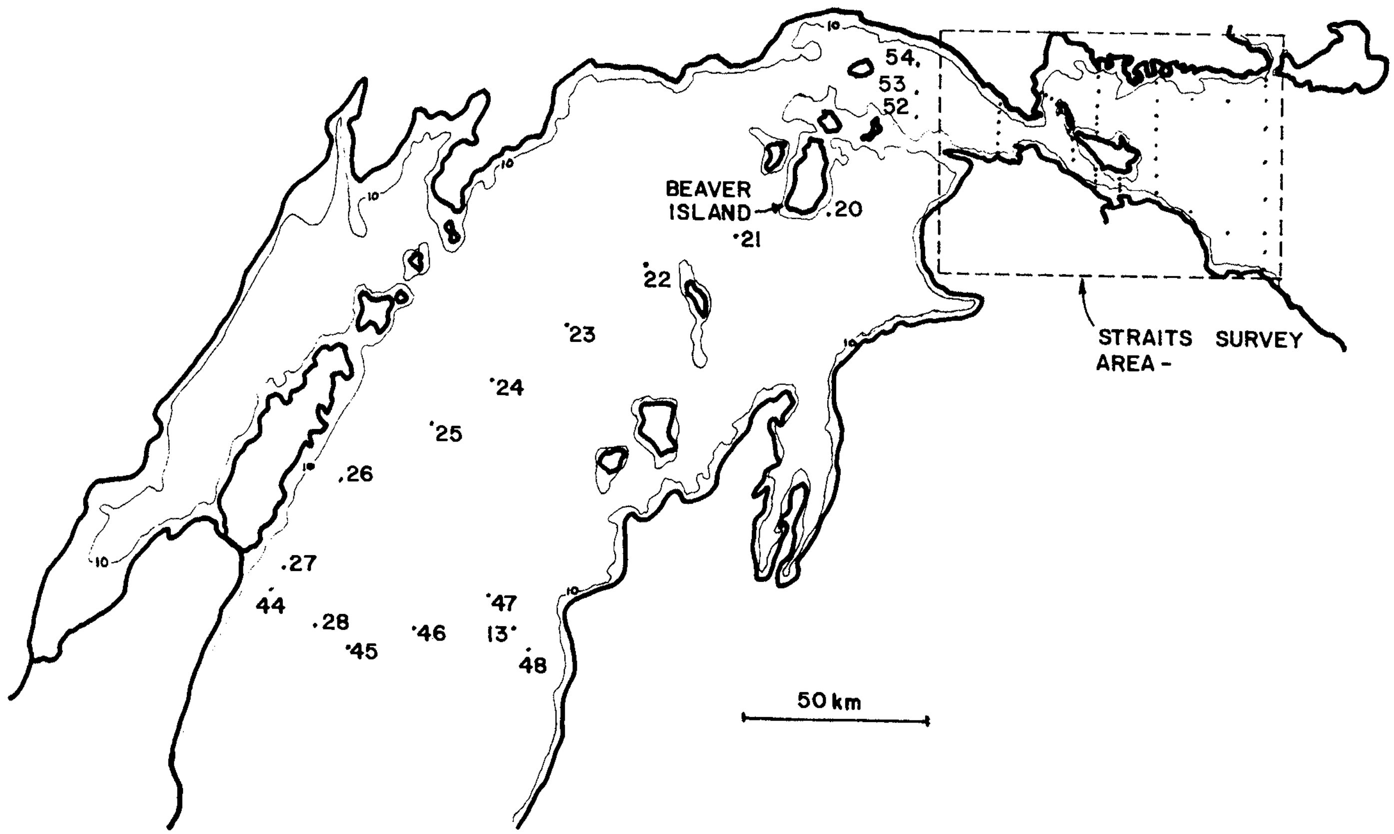


Figure 8.1. LOCATION OF NORTHERN LAKE MICHIGAN STATIONS SAMPLED 20-23 SEPTEMBER 1973 IMMEDIATELY AFTER THE SAMPLING OF THE STRAITS SURVEY AREA. In the text stations shown in Figure 8.1 are designated LM to distinguish them from the stations in the Straits survey area shown in Figure 1.1.

Table 8.1. AVERAGES OF ENVIRONMENTAL PARAMETERS OF EPILIMNETIC WATERS IN LAKE MICHIGAN, SEPTEMBER 1973. Data are mean ± one standard deviation.

Stations[1]	Temperature (C)	Specific conductance (10^{-4}mho cm^{-1})	pH	Secchi disc (m)
LM20-22[2]	16.8 ± 0.93	2.676 ± 0.038	8.578 ± 0.029	5.00 ± 0.50
LM23-25[3]	17.4 ± 0.22	2.673 ± 0.064	8.587 ± 0.081	5.00 ± 0.50
LM45-47[4]	16.6 ± 0.54	2.668 ± 0.056	8.625 ± 0.051	4.83 ± 0.35
LM52-54[5]	15.0 ± 0.45	2.489 ± 0.020	8.539 ± 0.055	5.17 ± 0.58
1-6[6]	15.4 ± 0.87	2.354 ± 0.127	8.514 ± 0.063	3.86 ± 0.79

	Chlorophyll *a* (mg m^{-3})	Silica (mg $SiO_2 l^{-1}$)	Nitrate (µgN l^{-1})	Total phosphorus (µgP l^{-1})
LM20-22[2]	1.50 ± 0.22	0.343 ± 0.082	74.0 ± 42.0	5.62 ± 0.66
LM23-25[3]	1.29 ± 0.37	0.222 ± 0.046	77.0 ± 19.0	5.10 ± 1.21
LM45-47[4]	1.44 ± 0.35	0.217 ± 0.075	50.0 ± 33.0	5.07 ± 0.67
LM52-54[5]	1.45 ± 0.15	0.895 ± 0.109	161 ± 101	5.79 ± 0.58
1-6[6]	1.73 ± 0.70	0.951 ± 0.162	212 ± 69	4.76 ± 0.90

[1]Stations excepting 1-6 were sampled only in September. See Fig. 8.1.
[2]Average of 12 samples, depths ranging from 0-20 m.
[3]Average of 15 samples, depths ranging from 0-30 m.
[4]Average of 15 samples, depths ranging from 0-30 m.
[5]Average of 11 samples, depths ranging from 0-20 m.
[6]Data from Table 3.1.

Mackinac averaged about 267 μmho cm^{-1} (Table 8.1). Lake Michigan waters were diluted to the extent that at stations LM 52-54 in Lake Michigan specific conductance averaged 249 and at Stations 01-06 in the Straits area averaged 235 μmho cm^{-1} (Table 3.1). It can be seen from data in Table 3.1 that dilution of Lake Michigan water was greater in September than during the other two months since specific conductance was least during this month.

In the Straits area, the pH of Lake Michigan water was reduced, but only slightly, as the result of mixing with waters from Lake Huron or Lake Superior. In Lake Michigan at Stations LM 45-47, pH averaged greater than 8.6 which was reduced to 8.54 at Stations LM 52-54 (Table 8.1) and to 8.51 and 8.50 at Stations 01-06 and 13-23 in the Straits area (Table 3.1). These differences in pH were probably real, as the measurements for pH were very precise.

South of Beaver Island, the epilimnetic waters of Lake Michigan were nearly silica-depleted, with average concentrations being as low as 0.2 mg SiO_2 $liter^{-1}$ (Table 8.1). In the Straits area, average concentrations ranged from 0.9-1.0 mg SiO_2 $liter^{-1}$ for Stations LM 52-54 in Lake Michigan and Stations 13-23 south of Bois Blanc Island (Table 3.1). It is obvious in comparing epilimnetic averages for the survey area (Table 3.1) that the water needed to enrich the silica concentrations in the Straits area was not epilimnetic water from Lake Huron, so the source of silica must be attributable to sources in the thermocline or hypolimnion.

The waters of Lake Michigan also were depleted in nitrate nitrogen relative to waters in the Straits survey area. In Lake Michigan south of Beaver Island, nitrate concentrations averaged less than 80 μg NO_3 $liter^{-1}$ and as low as 50 μg NO_3 $liter^{-1}$ at Stations LM 45-47 (Table 8.1), whereas in the Straits survey area concentrations averaged 210 at Stations 01-06 and 240 at Stations 13-23 (Table 3.1). At Stations LM 52-54, located west of Stations 01-06, nitrate concentrations averaged 160 μg NO_3 $liter^{-1}$.

The large standard deviations of the mean for Stations LM 52-54 and Stations 01-06 compared to other means for silica and nitrate provide additional evidence that mixing occurred west of the Straits of Mackinac. The enrichment of waters with nitrate in the Straits, as was the case with silica, has to be attributed to mixing with metalimnetic or hypolimnetic waters. Concentrations of nitrate and silica were greater at Stations 28-31 and Stations 07-10 (Table 3.1), where there was evidence of upwelling, than were found at stations characterized by epilimnetic waters.

Total phosphorus concentrations in the Straits survey area seemed to be affected least by the mixing of Lake Huron and Lake Michigan waters. Since Lake Michigan concentrations (Table 8.1) were larger than those for Lake Huron (Stations 24-31 and 40-45, Table 3.1), the result expected from mixing would be lower concentrations in the Straits survey area than in Lake Michigan. A slightly lower concentration was found at Stations 01-06, but the concentration at Stations LM 52-54 averaged greater than the Lake Michigan stations. Since the variance in the averages was large, these differences in the averages may not be significant. The data do suggest that there may be an enrichment of phosphorus in the Straits area; if such an enrichment process existed, it might be attributable to biological factors or possibly to morphometric effects.

In September, Secchi disc transparency seemed to be greater in Lake Michigan (Table 8.1) than in the Straits area at Stations 01-06 and Stations 13-23 (Table 3.1); however, the differences were small. In Lake Huron, Secchi disc transparency was obviously greater than in Lake Michigan. These data and the data for chlorophyll suggest that standing crops in the Straits area were greater than either in Lake Michigan or Lake Huron. These differences, if real, were small since average chlorophyll concentrations ranged from 1.21 to 1.78 mg chlorophyll *a* $liter^{-1}$ (Tables 3.1 and 8.1).

8.2 PHYTOPLANKTON

Data on the distribution of phytoplankton for the three cruises have been summarized in relation to temperature-specific conductance regions and in relation to results of ordination analysis. Other data are presented in Section VI, summarizing abundance and distribution of the 289 phytoplankton species collected as part of the study.

It is obvious that the phytoplankton community associated with Lake Michigan water in August and September (Tables 8.2 and 8.3) was primarily green and blue-green algae. In these two months, the communities unique to Lake Michigan waters did not contain diatoms due to the effects of silica limitation. Stations 40-48 were not sampled in August, so the community associated with regions typical of Lake Huron were not sampled; however, one station, 25, with a community of three diatoms and one cryptomonad, was identified from ordination analysis. *Cyclotella comta* and *C. operculata* were the two diatoms in the community identified in Lake Huron samples from September.

Hypolimnetic samples from August and September were characterized with ordination analysis as diatom communities. The August community consisted of *Cyclotella ocellata* and *C. stelligera*, and *C. ocellata* was also present in the September community with *Rhizosolenia eriensis* replacing *C. stelligera*. These hypolimnetic communities were also identified for both months from cold regions along the northern shore, which is evidence of upwelling (Tables 8.2 and 8.3).

In October, diatoms as well as blue-green and green algae were identified in the phytoplankton community found in the waters of Lake Michigan (Table 8.4). Water flowing from the St. Marys River was characterized by a community in which *Asterionella formosa* was dominant while the community in Lake Huron was primarily diatoms and cryptomonads. As is September, the hypolimnetic community consisted of *C. ocellata* and *R. eriensis*.

The influence of water transport from Lake Michigan and mixing of Lake Michigan and Lake Huron water in the Straits area on the distribution and abundance of phytoplankton can be inferred from data collected in

Table 8.2. SUMMARY OF RELATIONSHIPS BETWEEN T-C PATTERNS AND PHYTOPLANKTON COMMUNITY PATTERNS OF AUGUST SAMPLES.

Region based on T-C	Location and description	Region based on phytoplankton communities	Associated community (Figs. 6.36b and 6.38b)	Community description
M	Lake Michigan and south of Bois Blanc Island; 5-m depth; warm; high conductivity	A	X	Green and blue-green algae
U	Surface along northern shore; cold; apparently upwelled	B	Y	Two diatoms: *Cyclotella ocellata* and *Cyclotella stelligera*
H	Single station (#25) in southeastern corner; low conductivity; water probably from Lake Huron but possibly from the St. Marys River	C	Z	Three diatoms, one cryptomonad
-	Hypolimnion of northeastern stations	D	Y	Two diatoms: *Cyclotella ocellata* and *Cyclotella stelligera*

Table 8.3. SUMMARY OF RELATIONSHIPS BETWEEN T-C PATTERNS AND PHYTOPLANKTON COMMUNITY PATTERNS OF SEPTEMBER SAMPLES.

Region based on T-C	Location and description	Region based on phytoplankton communities	Associated community (Figs. 6.36b and 6.38b)	Community description
M	Lake Michigan and south of Bois Blanc Island; 5-m depth; warm, high conductivity	A	X	mainly green and blue-green algae
U	Surface along northern shore; cold	B	Y	Two diatoms: *Cyclotella ocellata* and *Rhizosolenia eriensis*
US	Southeastern section of survey area	C	Z	Two diatoms: *Cyclotella comta* and *Cyclotella operculata*
S	Mouth of St. Marys River; 5-m depth; warm, low conductivity	none		
-	Hypolimnion of northeastern section	D	Y	Two diatoms: *Cyclotella ocellata* and *Rhizosolenia eriensis*

Table 8.4. SUMMARY OF RELATIONSHIPS BETWEEN TEMPERATURE-CONDUCTIVITY PATTERNS AND PHYTOPLANKTON COMMUNITY PATTERNS OF OCTOBER SAMPLES.

Region based on T-C	Location and description	Region based on phytoplankton communities	Associated community (Figs. 6.36b and 6.38b)	Community description
M	Lake Michigan and south of Bois Blanc Island; 5-m depth; warm; high conductivity	A	X	mixture of blue-greens, greens, and diatoms
S	Mouth of St. Marys River; 5-m depth; warm; very low conductivity	B	Y	*Asterionella formosa* relatively abundant; very low total cell density
H	Eastern section of survey area; 5-m; cold, moderate conductivity	C	Z	Primarily diatoms and cryptomonads; very low densities of greens and blue-greens
-	Hypolimnion of northeastern section	D	W	Two diatoms: *Cyclotella ocellata* and *Rhizosolenia eriensis*

September. The distribution and abundance of nine species were investigated from samples collected in the Straits survey area plus the stations sampled in Lake Michigan (Fig. 8.1). Data for the comparisons among these phytoplankton were plotted as averages. For the Straits survey area, 5-m samples were averaged for the regions plotted; for Lake Michigan (Fig. 8.1), samples from 0, 5, 10 and 20 m were averaged for each station since there was no evidence of thermal stratification.

Two species of blue-green algae were found in fairly uniform abundances at all stations sampled in Lake Michigan. Both species, *Anacystis incerta* and *A. thermalis*, seemed to be transported through the Straits south of Bois Blanc Island into Lake Huron (Figs. 8.2 and 8.3), a pattern identified previously in the Straits survey area (Table 8.3, Fig. 6.34). These species were not abundant outside of region A (Fig. 6.34), indicating that transport was the main mechanism that could be used to explain the distribution. None of the remaining seven species had distributions of this type.

Five species of diatoms were found in the Straits survey area and at stations LM 52-54 in Lake Michigan. In general, these species were found in only limited abundance at other stations in Lake Michigan, and therefore seemed to be favored by conditions in the Straits area or in the area where waters from the two lakes mixed. Three of the species, *Fragilaria crotonensis*, *Cyclotella stelligera* and *C. comta*, seemed to be equally abundant at all stations including those in Lake Michigan, Lake Huron and at the mouth of the St. Marys River (Figs. 8.4-8.6), although *C. comta* and *F. crotonensis* seemed to be more abundant in Lake Huron. Reasons for the ubiquitous distribution are not apparent. The other two species of diatoms, *Cyclotella michiganiana* and *Asterionella formosa*, were most

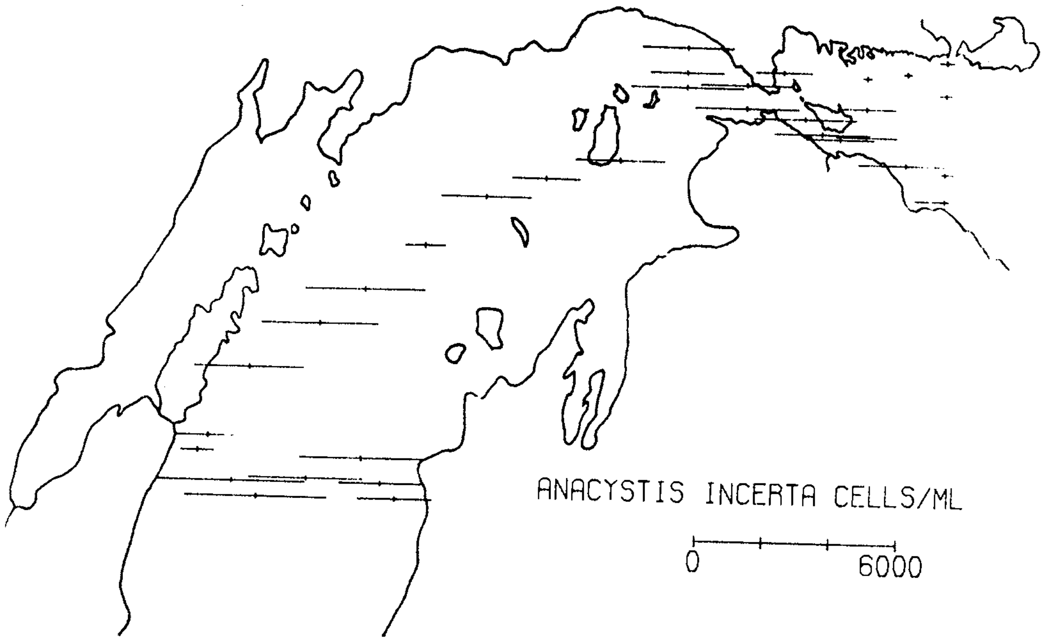


Figure 8.2. DISTRIBUTION OF *ANACYSTIS INCERTA*.

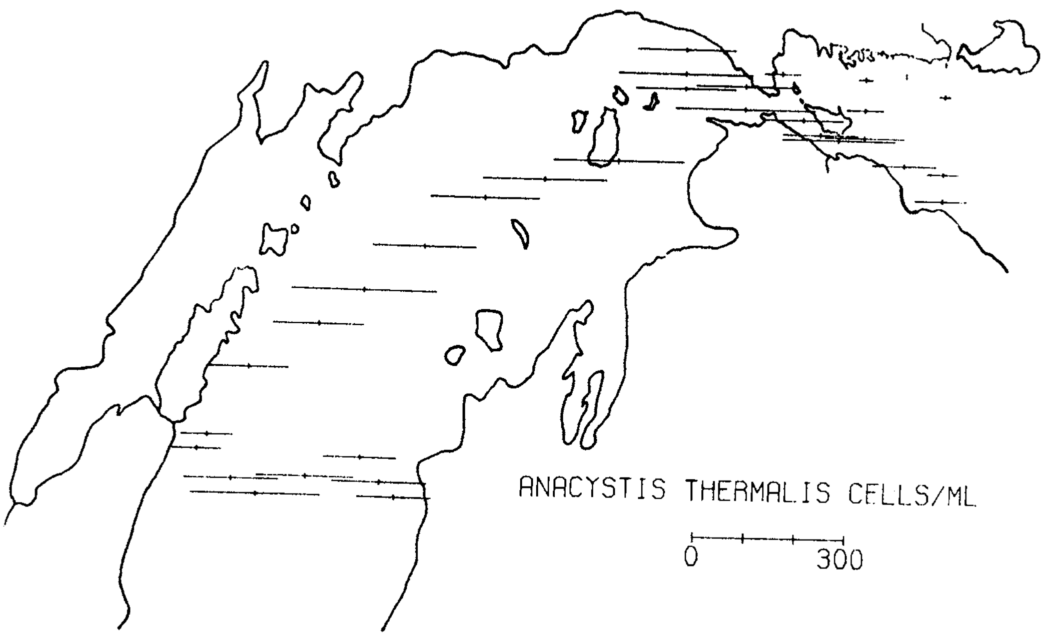


Figure 8.3. DISTRIBUTION OF *ANACYSTIS THERMALIS*.

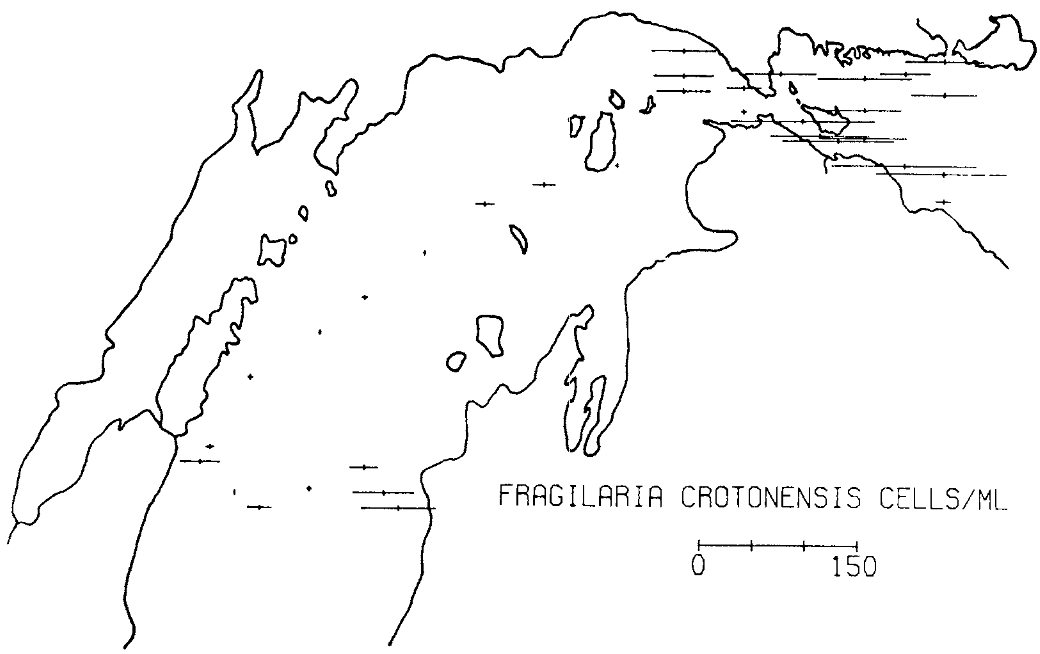


Figure 8.4. DISTRIBUTION OF *FRAGILARIA CROTONENSIS*.

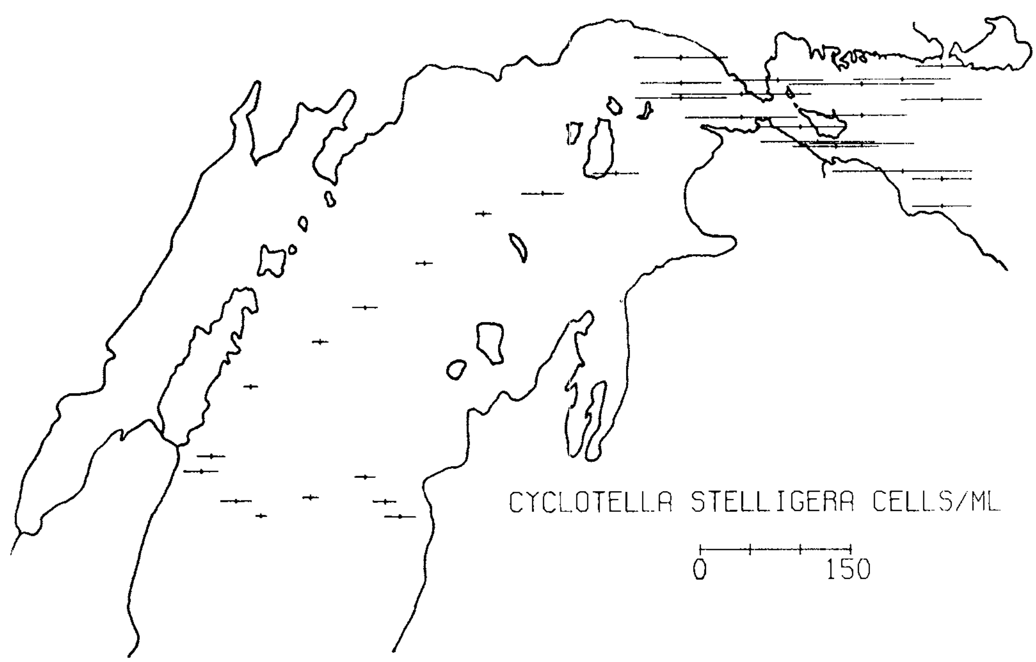


Figure 8.5. DISTRIBUTION OF *CYCLOTELLA STELLIGERA*.

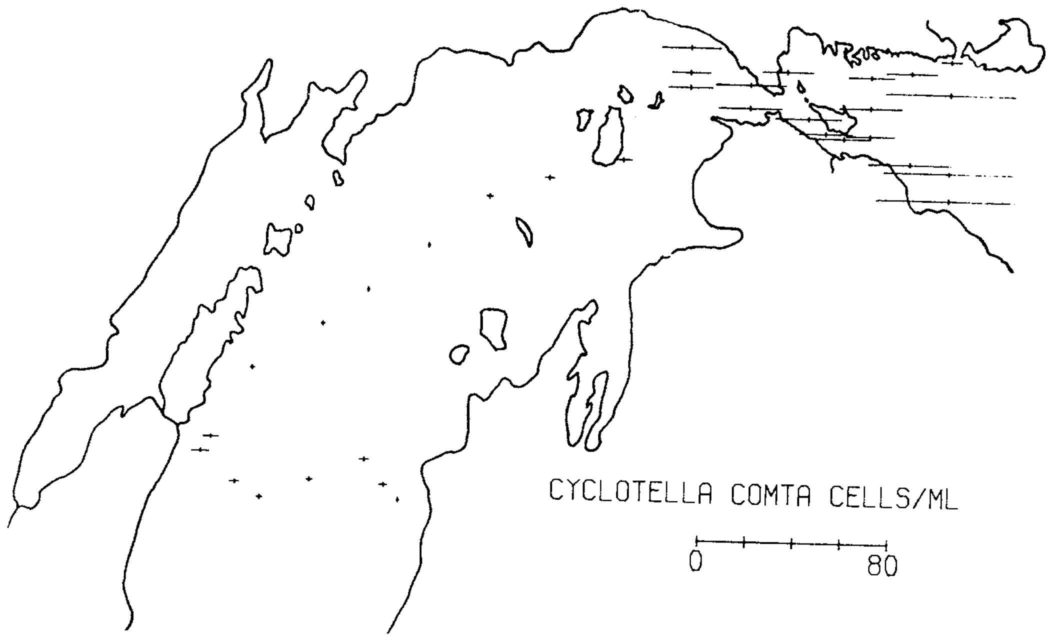


Figure 8.6. DISTRIBUTION OF *CYCLOTELLA COMTA*.

abundant in Lake Michigan and south and east of Bois Blanc Island (Figs. 8.7 and 8.8) or in region M (Table 8.3).

Finally, the distribution of two species of *Cyclotella, C. ocellata* and *C. operculata* (Figs. 8.9 and 8.10), seemed to be restricted mainly to the stations east of Bois Blanc Island. *C. ocellata* was characteristic of the hypolimnetic community (Table 8.3)--the fact that this species was not found west of the Straits in relatively large abundances indicates either that hypolimnetic water was not transported to the west or that this species did not thrive in the mixed water.

8.3 SUMMARY

Many of the results obtained as part of the study of the Straits area and northern Lake Michigan can be explained as being due either to mixing of water transported from Lake Michigan into Lake Huron or as the result of transport of Lake Huron water westward into Lake Michigan.

The general pattern of surface water transport from Lake Michigan, as delineated by our results, was from Lake Michigan through the Straits of Mackinac and then south of Bois Blanc Island to Lake Huron. This transport appeared to be similar when the water was stratified thermally in August as well as in October when there was no thermal stratification

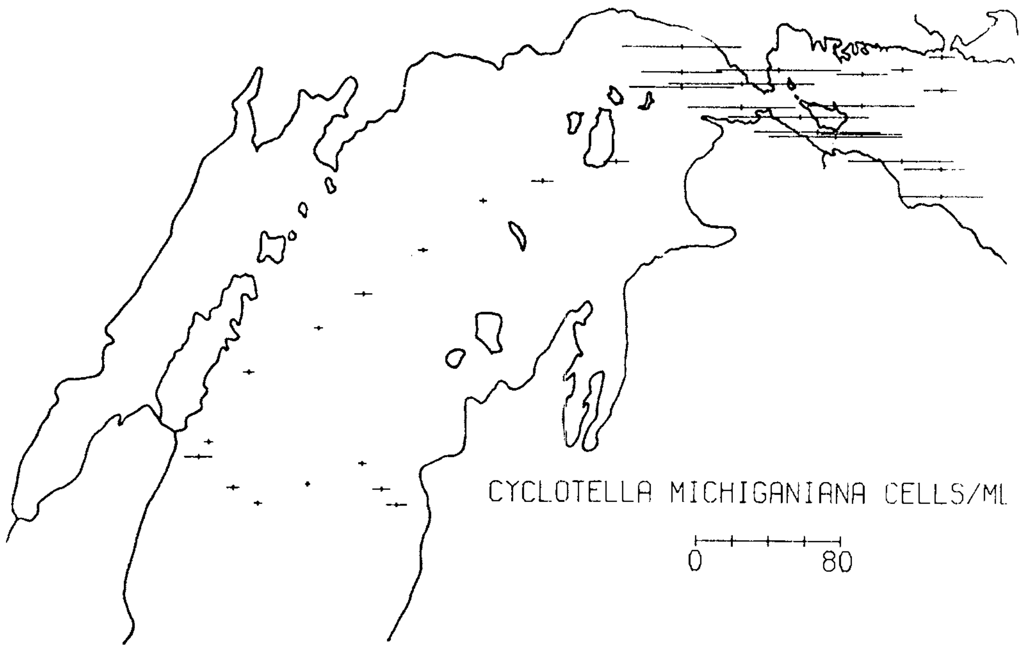


Figure 8.7. DISTRIBUTION OF *CYCLOTELLA MICHIGANIANA*.

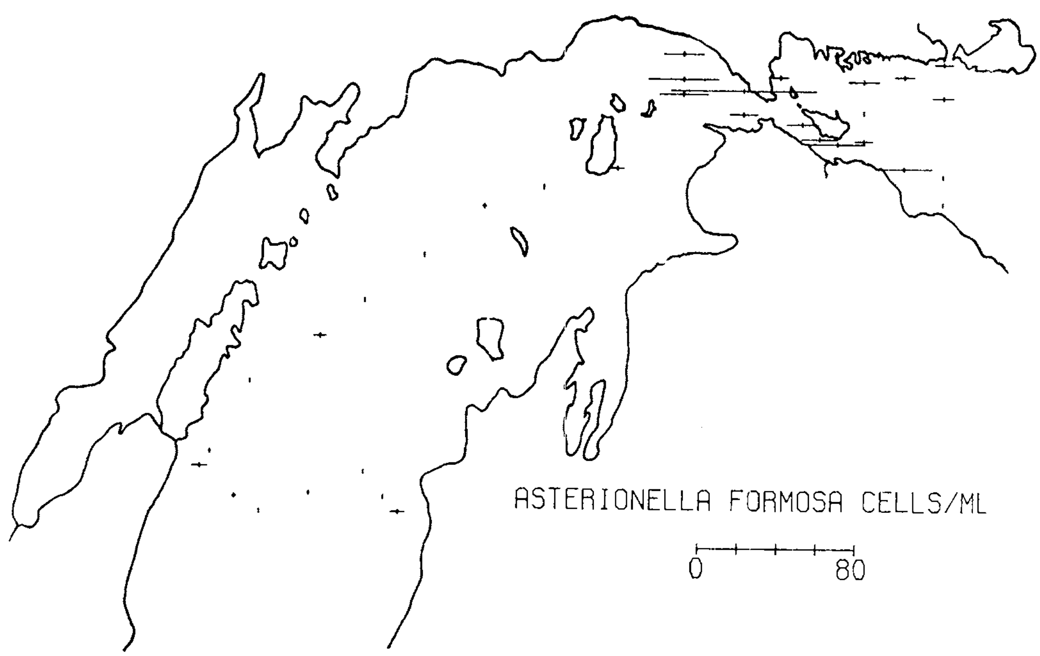


Figure 8.8. DISTRIBUTION OF *ASTERIONELLA FORMOSA*.

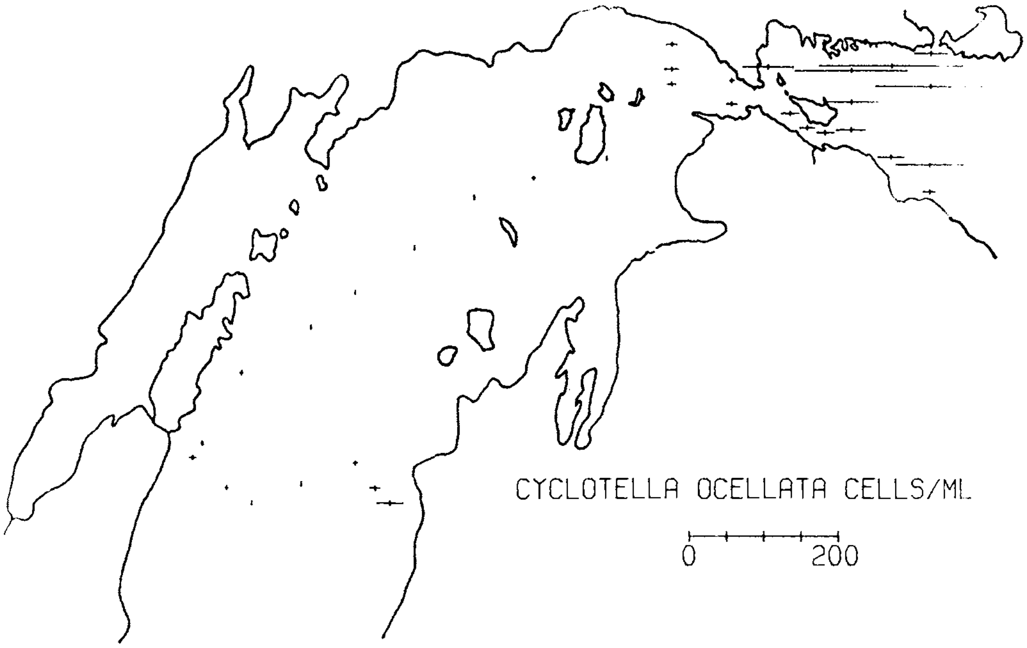


Figure 8.9. DISTRIBUTION OF *CYCLOTELLA OCELLATA*.

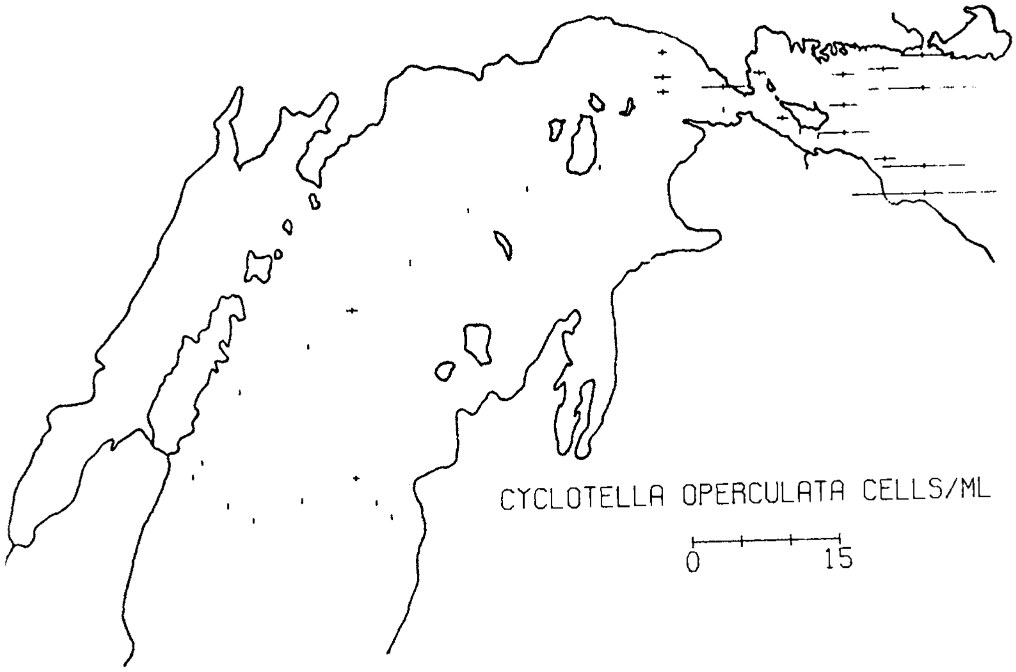


Figure 8.10. DISTRIBUTION OF *CYCLOTELLA OPERCULATA*.

south of Bois Blanc Island.

Transport of Lake Huron water to Lake Michigan when the lakes were not stratified thermally appeared to be complex, being controlled by the oscillatory flow between the two lakes. Under thermally stratified conditions, Lake Huron water flowed west under the epilimnion, eventually being entrained and mixed with Lake Michigan water west of the Straits. Based on morphometry, the subsurface flow was north of Bois Blanc Island along the northeast side of Mackinac Island, then south between Mackinac Island and Rabbit's Back Peak and finally west through the Straits into Lake Michigan; water can be transported in this pattern in a well-defined channel at depths of 40 m.

APPENDIX A. Physical and chemical data collected in the vicinity of the Straits of Mackinac, 1973

Appendix A.1 Cruise 1, August 1973

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
1	0	1	4.5	21.8	8.70	2.29	1.63	.09	.44	117.4	6.17	2.49	15.94	7.79
1	5	2	4.5	21.8	8.68	2.55	1.60	.11	.45	125.9	5.10	3.52	16.71	7.71
1	10	3	4.5	21.5	8.68	2.53	1.64	.09	.45	125.9	5.86	5.24	17.75	7.78
2	0	4	5.0	21.1	8.62	2.50	1.55	.08	.44	145.9	6.57	2.69	17.81	7.59
2	5	5	5.0	21.1	8.60	2.55	1.52	.11	.65	151.6	5.07	2.67	18.29	7.66
2	10	6	5.0	21.1	8.60	2.55	1.49	.11	.44	157.3	4.55	2.69	15.80	6.78
2	15	7	5.0	21.1	8.52	2.55	1.56	.13	.45	157.3	4.46	2.65	17.97	7.68
2	20	8	5.0	18.0	8.52	2.55	1.52	.14	.50	147.3	5.05	3.65	17.18	7.68
3	0	9	5.0	21.0	8.67	2.50	1.58	.03	.43	144.5	4.26	2.14	16.11	7.48
3	5	10	5.0	21.0	8.68	2.50	1.74	.10	.43	145.9	4.61	2.36	16.02	7.36
3	10	11	5.0	21.0	8.66	2.50	1.56	.07	.43	138.8	3.83	2.97	16.22	7.51
3	15	12	5.0	21.0	8.66	2.50	1.74	.07	.44	158.7	5.40	2.61	15.43	6.78
3	20	13	5.0	15.8	8.53	2.40	1.54	.19	.80	200.1	5.30	2.20	15.20	6.97
3	25	14	5.0	12.0	8.42	2.35	1.31	.18	1.14	224.3	4.57	2.98	14.69	6.58
3	30	15	5.0	10.8	8.14	2.16	1.46	.24	1.42	265.7	3.39	1.86	12.91	5.64
4	0	16	5.1	21.0	8.69	2.52	1.57	.06	.49	146.2	4.47	4.49	16.21	7.40
4	5	17	5.1	21.0	8.69	2.49	1.42	.13	.48	132.7	5.60	2.42	16.69	7.51
4	10	18	5.1	21.0	8.67	2.51	1.30	.15	.50	135.4	4.45	2.16	16.89	7.51
4	15	19	5.1	20.0	8.62	2.46	1.39	.18	.60	150.3	6.14	3.33	15.96	7.23
4	20	20	5.1	13.0	8.32	2.24	1.60	.15	1.22	246.4	3.69	5.23	13.19	5.83
5	0	21	5.0	21.0	8.70	2.50	1.29	.10	.52	134.1	3.77	3.38	16.35	7.45
5	5	22	5.0	21.0	8.69	2.50	1.34	.11	.53	131.3	4.16	3.53	16.55	7.41
5	10	23	5.0	21.0	8.58	2.43	1.56	.18	.76	171.9	4.28	3.16	15.19	6.80
6	0	24	5.5	21.4	8.70	2.50	1.41	.13	.58	130.0	3.14	1.95	16.52	7.32
6	5	25	5.5	21.4	8.71	2.50	1.32	.15	.59	127.3	3.46	1.98	16.72	7.43
6	10	26	5.5	20.0	8.70	2.49	1.39	.15	.60	130.0	3.48	1.74	16.35	7.38
7	0	27	6.2	17.0	8.58	2.32	1.31	.11	.84	165.9	3.68	2.03	14.85	6.39
7	5	28	6.2	17.0	8.52	2.27	1.35	.11	.91	197.6	6.35	2.44	13.91	6.12
7	10	29	6.2	15.0	8.43	2.19	1.40	.10	.99	221.6	4.61	1.70	13.41	5.78
8	0	30	6.0	20.2	8.66	2.44	1.18	.15	.63	144.3	2.93	1.67	15.86	7.17
8	5	31	6.0	20.2	8.66	2.45	1.22	.20	.63	146.8	2.89	1.60	14.79	7.13
8	10	32	6.0	16.0	8.40	2.07	1.87	.11	1.14	246.9	3.88	1.27	12.30	5.43
8	15	33	6.0	12.2	8.21	2.05	1.60	.21	1.31	278.5	5.55	1.63	12.07	5.23
8	20	34	6.0	11.0	8.10	2.05	1.73	.13	1.39	289.9	4.52	1.68	11.99	5.19
9	0	39	5.9	21.0	8.67	2.47	1.10	.10	.69	161.9	2.92	1.90	15.44	7.30
9	5	40	5.9	20.2	8.67	2.45	1.29	.10	.59	145.4	2.92	1.40	15.49	7.25
9	10	41	5.9	19.5	8.68	2.40	1.41	.11	.64	149.2	3.49	1.77	15.83	7.09
9	15	42	5.9	13.5	8.52		1.79	.13	.97	218.8		2.22	12.92	5.62
9	20	43	5.9	9.0	8.22	2.14	1.40	.18	1.38	279.6	3.61	2.04	12.13	5.35
9	25	44	5.9	7.5	8.02	2.20	.97	.27	1.71	298.5	4.02	2.11	11.90	5.23
9	30	45	5.9	7.2	7.96	2.16	.89	.35	1.79	321.3	4.07	2.45	11.95	5.22

App. A.1 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
10	0	48		21.1	8.62	2.39	.94	.19	.74	169.3	2.99	1.78	13.56	6.54
10	5	49		19.5	8.65	2.39	1.19	.23	.65	156.6	2.57	2.43	15.17	6.98
10	10	50		19.4	8.64	2.39	1.54	.06	.64	157.8	4.09	1.85	15.37	7.02
10	15	51		18.0	8.59	2.31	1.54	.21	.75	176.8	3.67	1.97	13.73	6.10
10	20	52		8.0	8.26	2.15	1.10	.25	1.54	279.4	3.89	1.70	12.37	5.35
11	0	53	6.5	21.5	8.70	2.30	1.00	.21	.61	162.8	2.69	1.64	14.13	6.64
11	5	54	6.5	20.6	8.70	2.20	1.13	.17	.59	155.1	3.03	1.44	14.18	6.64
11	10	55	6.5	18.0	8.60	2.31	1.45	.18	.67	170.3	3.77	2.29	13.81	6.60
11	15	56	6.5	13.2	8.43	2.07	1.83	.14	1.02	237.4	3.59	1.80	12.46	5.74
11	20	57	6.5	10.8	8.24	2.10	1.75	.06	1.34	276.6	3.59	2.27	11.66	5.40
11	25	58	6.5	10.0	8.10	2.06	1.53	.18	1.48	288.0	3.08	1.63	12.28	5.29
12	0	59	6.0	21.0	3.67	2.36	1.12	.12	.59	146.9	2.48	1.74	14.60	7.04
12	5	60	6.0	20.6	8.68	2.38	1.35	.12	.58	144.0	2.71	1.65	15.36	7.11
12	10	61	6.0	19.2	8.67	2.37	1.37	.15	.62	149.2	5.01	3.36	14.85	7.07
13	0	62	5.4	22.0	8.65	2.46	1.39	.10	.56	192.7	4.42	4.17	15.48	7.29
13	5	63	5.4	22.0	8.65	2.46	1.20	.19	.57	148.0	4.38		15.95	7.44
13	10	64	5.4	22.0	8.64	2.46	1.43	.15	.49	177.3	5.28	3.45	16.15	7.44
14	0	65	6.0	21.5	8.64	2.45	1.01	.15	.57	218.8	4.52	3.59	15.50	7.17
14	5	66	6.0	21.5	8.66	2.46	1.13	.14	.57	191.6	4.70	3.46	15.70	7.36
14	10	67	6.0	21.5	8.65	2.47	1.32	-.06	.53	153.6	4.68	3.57	15.47	7.31
14	15	68	6.0	20.0	8.59	2.43	1.52	.21	.62	158.7	4.39	3.38	15.24	6.37
14	20	69	6.0	12.0	8.17	2.24	1.08	.25	1.21	378.8	5.32	3.49	13.18	6.07
15	0	70	5.8	21.5	8.64	2.46	1.03	.16	.53	159.4	5.46	5.32	15.61	7.42
15	5	71	5.8	21.5	8.65	2.46	1.07	.18	.54	169.8	4.76	4.01	15.55	7.34
15	10	72	5.8	20.0	8.63	2.45	1.34	.23	.58	190.9	4.63	3.14	13.32	6.06
15	15	73	5.8	17.5	8.51	2.40	.99	.25	.76	203.5	4.47	3.64	15.01	6.85
15	20	74	5.8	12.0	8.26	2.25	1.41	.24	1.15	304.6	4.63	2.83	12.65	5.35
16	0	75	4.7	21.5	8.65	2.49	1.28	.18	.51	170.2	6.93	3.24	15.96	7.48
16	5	76	4.7	21.5	8.66	2.49	1.25	.18	.51	171.6	4.21	3.46	16.16	7.33
16	15	77	4.7	19.0	8.60	2.44	1.38	.12	.64	178.4	5.18	3.74	15.29	7.10
17	0	78	5.2	21.8	8.67	2.47	.98	.12	.55	164.3	4.10	2.77	15.76	7.32
17	4	79	5.2	21.8	8.67	2.48	1.26	.15	.54	157.6	3.37	2.56	15.97	7.35
17	8	80	5.2	20.9	3.67	2.49	1.39	.23	.57	194.1	3.64	2.59	14.82	6.67
18	0	81	6.0	22.0	8.67	2.45	.88	.14	.53	159.0	3.50	2.99	15.97	7.23
18	5	82	6.0	21.8	8.67	2.44	1.04	.21	.53	149.6	4.38	2.89	15.77	7.12

App. A.1 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND -4mho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
19	0	84	5.6	22.0	8.67	2.45	1.11	.18	.53	156.4	4.23	2.70	15.71	7.23
19	5	85	5.6	21.4	8.68	2.48	1.46	.22	.55	164.5	3.73	2.87	16.18	7.30
19	10	86	5.6	20.8	8.65	2.34	1.60	.19	.60	180.8	4.54	2.64	14.90	6.81
19	15	87	5.6	17.5	8.56	2.34	1.54	.19	.40	184.9	3.68	2.82	14.56	6.58
19	20	88	5.6	13.8	8.31	2.28	1.51	.23	1.12	186.3	4.19	3.19	13.96	6.24
20	0	89	6.0	22.0	8.66	2.40	1.15	.18	.58	176.8	3.95	3.20	15.38	7.10
20	5	90	6.0	22.0	8.65	2.40	.97	.20	.57	175.5	3.43	2.70	15.04	6.99
20	10	91	6.0	21.5	8.66	2.44	1.19	.20	.55	162.0	3.62	3.10	15.52	7.17
21	0	92	6.1	21.5	8.67	2.41	1.00	.17	.57	191.3	3.76	3.11	15.18	6.98
21	5	93	6.1	20.0	8.68	2.39	1.13	.17	.55	161.5	3.67	2.90	14.85	6.68
21	10	94	6.1	18.0	8.57	2.23	1.58	.19	.75	196.8	4.12	2.85	13.84	6.07
22	0	95	5.3	21.5	8.68	2.44	1.10	.19	.54	146.9	4.00	2.77	15.39	7.01
22	5	96	5.3	21.0	8.69	2.44	1.19	.19	.53	163.4	5.38	2.70	15.73	7.08
22	10	97	5.3	20.0	8.55	2.32	1.45	.21	.62	169.6	3.90	3.20	15.12	6.66
22	15	98	5.3	16.0	8.45	2.20	1.92	.19	.94	230.5	3.94	2.75	13.57	5.84
23	0	99	5.7	22.0	8.67	2.50	1.11	.21	1.09	108.6	3.83	3.00	14.05	6.17
23	5	100	5.7	21.0	8.68	2.47	1.21	.17	.96	152.6	3.49	2.76	15.20	6.96
23	10	101	5.7	20.5	8.66	2.46	1.52	.20	.61	181.5	3.46	2.61	16.08	7.10
24	0	102	7.6	22.1	8.67	2.22	1.04	.14	.69	212.4	1.48		13.85	6.19
24	5	103	7.6	22.0	8.68	2.14	1.11	.17	.65	212.4	1.15	.68	13.52	5.90
24	10	105	7.6	21.2	8.69	2.01	1.12	.10	.65	227.4	.87	.43	12.71	5.54
24	15	104	7.6	15.0	8.50	2.17	1.68	.19	.93	249.4	2.31	.60	12.91	5.76
25	0	106	8.2	22.0	8.65	2.00	1.06	.15	.89	305.9	.96	.65	12.51	5.47
25	5	107	8.2	20.9	8.65	1.96	1.22	.10	.70	214.0	1.03	.65	11.91	5.37
25	10	108	8.2	21.0	8.64	1.96	1.33	.15	.67	253.7	1.60	.50	12.11	5.23
25	15	109	8.2	13.0	8.42	2.10	1.79	.16	.93	255.0	1.56	.16	12.18	5.46
25	25	110	8.2	8.5	7.35	2.11	1.39	.24	1.69	341.4	1.56	.48	11.98	5.20
26	0	111	8.6	22.5	8.64	2.12	.98	.07	.73		1.61	.72	12.05	5.25
26	5	112	8.6	21.5	8.63	2.16	.96	.16	.79	204.7	1.15	.42	10.50	3.19
26	10	113	8.6	20.8	8.66	2.03	1.22	.21	.64	212.9	1.44		10.30	3.24
26	15	114	8.6	13.0	8.41	2.02	1.47	.13	.96	249.9	1.37	.06	11.72	5.35
26	20	115	8.6	10.0	8.11	2.03	1.60	.15	1.44	303.3	1.38	.30	10.98	4.39
26	25	116	8.6	8.5	7.92	2.13	1.61	.19	1.72	334.8	1.68	.45	11.99	5.43
26	30	117	8.6	7.5	7.83	2.18	1.25	.28	1.87	354.0	2.58	3.50	11.93	5.37
27	0	118	7.9	23.0	8.64	2.19	1.12	-.03	.55	200.4	1.84	1.06	13.21	6.27
27	5	119	7.9	21.5	8.67	2.20	1.07	.09	.61	187.1	1.70	1.16	11.12	6.54
27	10	120	7.9	21.0	8.67	2.22	1.17	.21	.60	207.0	2.57	1.08	13.48	6.47
27	15	121	7.9	17.0	8.43	2.08	1.69	.18	.88	234.8	2.81	1.25	12.20	5.62
27	20	122	7.9	11.5	8.21	2.07	1.57	.21	1.21	285.1	9.44	1.74	11.73	5.33
27	25	123	7.9	9.5	8.05	2.06	1.24	.26	1.44	309.0	4.85		11.13	4.78
27	30	124	7.9	8.5	7.93	2.11	.96	.35	1.54	319.6	3.16	2.07	11.87	5.31
27	35	125	7.9	7.5	7.89	2.13	.77	.30	1.59	326.1	3.04	1.90	11.67	5.43
27	40	126	7.9	6.5	7.81	2.16	.75	.41	1.64	324.8	2.30	1.31	11.74	5.51
27	49	127	7.9	5.9	7.82	2.20	.64	.48	1.78	306.2	3.91		11.81	5.70

App. A.1 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m^3	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m^3	TPO4 mgP/m^3	SPO4 mgP/m^3	SO4 mgSO4/l	CL mgCl/l
28	0	128	7.1	21.3	8.62	2.22	1.04	.11	.66	183.5	2.70	2.44	13.36	6.64
28	5	129	7.1	21.2	8.64	2.25	1.17	.04	.60	194.1	3.98	2.32	14.11	6.76
28	10	130	7.1	20.0	8.64	2.20	1.34	.13	.62	228.6	2.60	2.01	13.10	6.47
28	15	131	7.1	16.8	8.49	2.06	1.74	.14	.81	229.9	2.93	1.52	11.47	5.73
28	20	132	7.1	11.5	8.25	2.05	1.28	.21	1.14	280.2	3.64	1.16	10.68	4.54
28	25	133	7.1	9.5	8.11	2.06	1.27	.20	1.28	292.1	2.95	1.49	11.50	5.13
28	30	134	7.1	8.5	8.01	2.10	1.05	.28	1.37	321.3	2.22	1.16	11.44	5.13
28	40	135	7.1	7.5	7.93	2.15	.66	.41	1.58	323.9	1.28	1.84	11.53	5.21
28	50	136	7.1	6.4	7.78	2.22	.53	.41	1.45	326.5	2.59	.48	11.62	5.32
28	60	137	7.1	5.9	7.80	2.22	.45	.53	1.56	333.1	2.65	.54	11.85	5.32
29	0	138	7.9	21.5	8.61	2.26	1.45	.06	.66	190.3	2.29	1.08	13.55	6.55
29	5	139	7.9	21.0	8.66	2.28	1.31	.13	.59	177.1	2.79	1.00	14.07	6.48
29	10	140	7.9	20.5	8.64	2.24	1.37	.15	.61	194.2	1.70	.57	13.58	6.37
29	15	141	7.9	15.5	8.51	2.11	1.87	.19	.83	225.8	2.71	1.90	12.50	5.51
29	20	142	7.9	9.0	8.23	2.02	1.26	.20	1.15	285.2	2.62	.80	11.27	4.88
29	25	143	7.9	7.0	8.15	2.09	1.02	.22	1.25	323.4	1.53	.67	11.79	5.00
29	30	144	7.9	6.0	8.03	2.13	.82	.33	1.35	315.5	1.39	.38	12.17	5.01
29	40	145	7.9	5.0	7.95	2.17	.57	.44	1.51	329.9	1.43	.69	11.53	5.09
29	50	146	7.9	4.5	7.84	2.18	.39	.54	1.70	331.2	2.86	1.23	11.91	5.25
29	60	147	7.9	4.5	7.77	2.20	.33	.69	1.96	364.2	2.18	.49	10.83	4.29
30	0	148	8.5	21.2	8.63	2.23	.84	.16	.69	205.1	4.99	.69	13.11	6.04
30	5	149	8.5	21.2	8.63	2.20	1.06	.14	.71	199.8	2.18	1.14	12.76	5.94
30	10	150	8.5	17.0	8.54	2.04	1.61	.09	.86	240.7	2.06	.25	11.83	5.34
30	15	151	8.5	13.0	8.37	1.94	1.42	.13	1.09	282.9	1.78	1.01	11.18	
30	20	152	8.5	10.4	8.22	1.97	1.23	.19	1.35	304.0	2.80	.63	11.42	5.00
30	25	153	8.5	8.0	8.06	2.10	1.00	.31	1.55	338.2	2.64	.86	11.80	5.15
30	30	154	8.5	7.8	8.02	2.14	.79	.40	1.61	346.1	2.35	1.36	10.72	4.45
30	35	155	8.5	7.0	8.00	2.16	.83	.38	1.67	332.9	2.24	1.52	11.83	5.38
30	40	156	8.5	6.5	7.97	2.19	.76	.42	1.70	344.7	2.69	.89	11.77	5.27
31	0	157	8.5	20.1	8.57	1.99	.82	.11	.97	211.9	3.94	2.70	12.15	5.27
31	5	158	8.5	13.9	8.55	2.00	1.12	.11	.86	244.9	2.51	1.40	11.51	5.12
31	10	159	8.5	13.6	8.43	1.94	1.19	.13	1.06	275.2	3.44	1.19	11.01	4.60
31	15	160	8.5	11.5	8.25	1.96	1.40	.16	1.27	301.5	4.82	1.50	11.39	4.79
31	20	161	8.5	11.0	8.19	2.00	1.39	.20	1.31	313.4	3.11	2.34	11.19	4.83
32	0	162	6.0	19.9	8.66	2.23	.78	.13	.36	161.3	2.60	2.45	12.89	5.98
32	5	163	6.0	18.1	8.66	2.20	1.25	.13	.43	188.4	4.85	1.62	12.24	5.68
32	10	164	6.0	15.0	8.50	2.00	1.78	.06	1.05	259.7	3.84	1.49	10.43	3.98
32	20	165	6.0	10.4	8.30	1.96	1.61	.18	1.59	316.8	5.34	1.74	11.39	4.83
33	0	166	6.2	20.3	8.67	2.25	1.29	.17	.74	186.8	2.87	2.27	12.21	5.72
33	5	167	6.2	20.3	8.66	2.23	1.47	.16	.76	185.3	3.08	1.44	12.74	6.13
33	10	168	6.2	15.0	8.56	2.15	1.53	.10	.85	228.0	4.68	2.28	11.66	5.57
33	20	169	6.2	10.2	8.36	2.06	1.52	.21	1.40	313.7	5.42	1.59	11.31	4.98

App. A.1 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND µmho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
34	0	170	7.0	21.2	8.66	2.28	1.25	.08	.69	187.9	2.61	1.69	12.86	6.10
34	5	171	7.0	21.0	8.67	2.15	1.08	.07	.68	180.7	3.49	1.99	13.83	6.44
34	10	172	7.0	13.6	8.54	2.15	1.81	.14	.90	250.6	3.32	1.86	12.01	5.43
34	15	173	7.0	11.2	8.36	2.05	1.58	.15	1.26	313.4	4.78	1.65	9.90	3.62
34	20	174	7.0	10.0	8.28	2.10	1.30	.21	1.37	343.3	3.00	2.57	11.16	4.91
34	25	175	7.0	9.0	8.22	2.12	1.38	.17	1.43	346.1	2.52	1.57	11.11	4.95
34	30	176	7.0	8.0	8.21	2.14	.86	.33	1.57	354.6	2.66	1.83	11.78	5.17
34	35	177	7.0	7.5	8.15	2.09	.81	.34	1.60	364.4	2.88	1.52	11.14	4.91
35	0	178	7.0	20.9	8.64	2.36	1.14	.14	.66	194.4	2.61	1.92	14.15	6.44
35	5	179	7.0	20.0	8.62	2.30	1.39	.11	.69	187.2	2.68	1.80	13.95	6.44
35	10	180	7.0	14.0	8.41	2.04	1.81	.11	1.00	271.4	2.94	1.51	12.28	5.47
35	15	181	7.0	11.0	8.34	2.03	1.61	.11	1.19	309.8	3.18	1.39	11.05	5.03
35	20	182	7.0	9.5	8.25	2.10	1.54	.13	1.34	335.5	2.79	1.32	11.14	5.03
35	25	183	7.0	8.6	8.16	2.10	1.05	.25	1.47	349.6	2.07	2.07	11.08	4.99
35	30	184	7.0	8.2	8.08	2.16	.77	.35	1.59	353.8	4.70	1.19	11.17	5.14
35	35	185	7.0	7.5	8.07	2.20	.75	.37	1.60	355.1	1.95	1.50	11.26	5.18
36	0	188	7.0	20.6	8.63	2.33	1.22	.13	.70	162.5	2.33	1.05	12.81	6.22
36	5	189	7.0	20.6	8.67	2.35	1.20	.12	.63	163.8	2.13	1.05	14.07	6.75
36	10	190	7.0	16.0	8.60	2.25	1.72	.09	.76	198.9	2.01	1.02	12.98	6.19
36	15	191	7.0	10.9	8.39	2.06	1.65	.16	1.09	281.4	2.39	1.11	11.17	5.11
36	20	193	7.0	9.8	8.25	2.10	1.35	.16	1.32	344.9	2.01	1.20	11.11	5.18
36	25	194	7.0	9.0	8.15	2.12	1.17	.25	1.49	327.3	1.98	.61	11.77	5.11
36	30	195	7.0	8.4	8.08	2.16	.86	.35	1.51	334.0	2.15	.77	11.57	4.92
36	35	196	7.0	7.8	8.01	2.16	.74	.36	1.47	335.3	3.00	1.01	11.79	5.07
36	40	197	7.0	7.0	7.99	2.16	.62	.37	1.55	335.3	2.62	.89	11.88	5.15
36	45	198	7.0	6.5	7.93	2.21	.64	.42	1.82	342.0	2.45	1.74	11.96	5.22
37	0	199	7.0	20.0	8.65	2.26	1.24	.14	.65	187.8	2.28	1.74	14.15	6.53
37	5	200	7.0	20.0	8.65	2.32	1.33	.14	.63	174.2	3.09	1.45	13.82	6.42
37	10	201	7.0	13.0	8.61	2.25	1.31	.13	.75	201.2	2.17	1.14	13.90	6.23
37	15	202	7.0	10.8	8.34	2.06	1.51	.20	1.20	289.1	2.59	1.82	12.29	5.12
37	20	203	7.0	9.8	8.13	2.12	1.13	.19	1.44	321.5	2.62	.81	11.96	5.12
37	25	204	7.0	9.0	8.05	2.16	1.00	.30	1.53	328.2	2.26	1.47	11.90	5.04
37	30	205	7.0	8.1	7.94	2.17	.70	.43	1.65	337.7	2.09	1.04	11.84	5.08
37	35	206	7.0	7.5	7.89	2.16	.87	.25	1.83	353.8	2.64	1.25	11.93	5.16
37	40	207	7.0	7.0	7.84	2.17	.76	.41	1.88	355.2	2.71	1.18	11.87	5.19
37	45	208	7.0	6.5	7.82	2.16	.62	.45	1.93	351.1	2.57	1.16	11.95	5.23
111	0	212	5.7	21.0	8.65	2.46	1.12	.21	.53	132.0	2.40	1.30	15.24	6.95
111	5	213	5.7	20.5	8.64	2.45	1.36	.14	.54	141.4	2.80	1.01	15.46	7.14
111	10	214	5.7	20.0	8.64	2.39	1.37	.15	.62	136.4	3.18	1.34	14.42	6.77
111	15	215	5.7	13.0	8.45	2.24	1.71	.18	.89	207.6		.99	13.38	5.95
111	20	216	5.7	9.9	8.11	2.08	1.52	.18	1.40	274.9	2.05	1.19	11.78	5.09
111	25	217	5.7	8.4	7.97	2.13	1.34	.24	1.53	294.8	2.22	.79	11.86	4.94
112	0	209	5.8	22.0	8.64	2.50	1.20	.07	.50	122.1	2.23	1.27	14.15	6.80
112	5	210	5.8	21.9	8.66	2.50	1.35	.19	.50	144.7	2.49	1.06	15.07	7.10
112	10	211	5.8	21.0	8.56	2.47	.41	.19	.52	135.7	2.59	1.60	12.76	5.79

Appendix A.2 Cruise 2, September 1973

STA	DEP M	SAMP	SEC m	TEMP °C	PH	CCND -µmho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	Cl mgCl/l
1	0	447	4.0	16.8	8.65	2.46	1.57	.10	.74	194.5	4.61	2.95	15.37	7.02
1	5	448	4.0	16.8	8.63	2.47	1.69	.03	.73	133.0	4.27	2.54	15.16	7.00
1	10	449	4.0	16.8	8.57	2.48	1.60	.01	.75	133.6	4.16	3.23	15.22	6.95
2	0	442	4.3	15.9	8.58	2.18	1.58	.08	.87	191.9	4.90	2.58	15.16	6.72
2	5	443	4.3	15.9	8.53	2.45	1.54	.04	.87	207.8	5.09	4.01	14.71	6.59
2	10	444	4.3	15.9	8.55	2.19	1.57	.09	.87	243.1	5.20	3.29	15.15	6.68
2	15	445	4.3	15.9	8.54	2.45	1.53	.09	.87	235.8	3.95	3.35	15.33	6.78
2	20	446	4.3	15.9	8.55	2.46	1.46	.11	.87	233.2	3.92	3.27	14.17	6.68
3	0	435		15.8	8.49	2.46			.87	267.1	5.13	2.89	14.95	6.77
3	5	436		15.8	8.52	2.23	1.47	.11	.84	252.6	5.14	4.74	15.46	6.84
3	10	437		15.8	8.54	2.46	1.42	.17	.84	161.0	4.60	2.97	15.39	6.76
3	15	438		15.8	8.53	2.46	1.49	.22	.84	148.1	4.26	4.16	15.70	6.76
3	20	439		15.6	8.55	2.39	1.47	.13	.88	126.9	5.90	2.89	15.25	6.69
3	25	440		14.0	8.49	2.36	1.38	.13	.84	120.1	4.54	3.96	15.94	6.72
3	30	441		11.5	8.29	2.22	1.19	.19	1.35	199.4	4.68	3.60	14.09	6.00
4	0	430	4.5	14.8	8.46	2.40	1.74	.00	1.09	192.7	4.74	2.70	14.23	6.50
4	5	431	4.5	14.8	8.49	2.15	1.64	.19	1.08	178.3	4.07	2.40	12.32	5.74
4	10	432	4.5	14.5	8.48	2.15	.45	.20	1.08	162.3	3.76	3.55	13.59	6.46
4	15	433	4.5	13.0	8.47	2.31	.40	.17	1.15	207.7	3.67	4.18	13.76	6.48
4	20	434	4.5	11.5	8.28	2.17			1.34	251.6	4.04	2.58	12.83	5.85
5	0	427	4.0	14.4	8.43	2.40	1.74	.17	1.16	206.1	5.69	2.44	13.84	6.41
5	5	428	4.0	14.4	8.44	2.14	1.51	.21	1.17	357.1	3.49	1.80	14.26	6.33
5	10	429	4.0	14.2	8.45	2.37			1.20	334.8	7.58	2.98	14.06	6.43
6	0	424	2.5	14.4	8.42	2.21	4.16	.17						
6	5	425	2.5	14.4	8.45	2.42	2.32	.27	1.17	203.5	4.91	2.42	14.00	6.32
6	10	426	2.5	14.4	8.46	2.41	2.69	.25	1.18	207.9	4.60	3.21	14.04	6.39
7	0	328	5.5	11.2	8.34	2.23	1.07	.12	1.26	292.6	4.49	3.14	13.75	
7	5	330	5.5	11.4	8.19	2.20	1.21	.06	1.24	299.8	2.90	1.56	9.36	
7	10	329	5.5	7.2	8.18	2.06	.92	.31	1.53	351.4	3.26	1.45	12.87	
8	0	331	5.0	13.2	8.48	2.35	1.21	.10	1.12	254.0	1.78	.79	13.59	
8	5	332	5.0	12.5	8.48	2.33	1.67	.06	1.16	255.4	2.54	.60	14.96	
8	10	333	5.0	10.4	8.39	2.32	1.76	.04	1.29	278.0	3.80	1.33	14.67	
8	15	334	5.0	7.0	8.27	2.19	1.14	.15	1.38	288.4	2.94	.92	9.38	
8	20	335	5.0	6.5	8.13	2.15	.86	.23	1.58	348.7	1.98	1.95	8.97	
8	25	336	5.0	6.4	8.04	2.19	.72	.34	1.66	366.8	1.16		8.91	
9	0	340	4.5	11.0	8.39	2.27	1.30	.11	1.28	277.5	2.44		8.86	
9	5	341	4.5	11.0	8.42	2.30	1.65	.04	1.20	260.8	.93	2.16	8.92	
9	10	342	4.5	9.6	8.26	2.19	1.12	.23	1.42	313.6	1.79		8.87	
9	15	343	4.5	8.0	8.18	2.17	.93	.26	1.54	336.1	2.13		8.69	
9	20	344	4.5	7.6	8.16	2.21	.83	.32	1.58	336.0	2.00		9.23	
9	25	345	4.5	6.9	8.13	2.22	.77	.34	1.64	351.0	1.90		8.70	
9	30	346	4.5	6.6	8.11	2.21	.71	.37	1.71	360.0	2.62	1.45	8.89	
9	35	347	4.5	6:6	8.08	2.23	.62	.42	1.73	356.9	1.40		8.71	
9	40	348	4.5	6.1	8.06	2.21	.66	.44	1.75	359.8	4.95	.12	11.39	

App. A.2 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND -^{4}mho/cm	CHL mg/m^3	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m^3	TPO4 mgP/m^3	SPO4 mgP/m^3	SO4 mgSO4/l	CL mgCl/l
10	0	349	4.5	11.5	8.39	2.29	.54	.31	1.23	268.9	7.84	6.06	9.43	
10	5	350	4.5	9.0	8.29	2.19	1.01	.18	1.39	299.0	3.15	.82	8.78	
10	10	351	4.5	9.5	8.29	2.20	1.36	.18	1.35	291.4	2.23	.66	8.85	
10	15	352	4.5	8.9	8.30	2.22	1.36	.13	1.34	324.5	2.62	.35	13.43	
10	20	353	4.5	8.9	8.25	2.18	1.25	.17	1.42	307.8	2.82	.40	9.10	
11	0	354	4.5	14.0	8.46	2.32	1.74	.15	1.14	241.1	5.78	.56	8.80	
11	5	355	4.5	13.9	8.53	2.32	1.76	.07	1.02	233.4	3.52	1.48	9.10	
11	10	356	4.5	12.2	8.46	2.17	2.12	.05	1.12	283.2	3.27	1.90	13.69	
11	15	357	4.5	11.4	8.40	2.14	1.44	.04	1.19	305.7	3.05	.95	8.76	
11	20	358	4.5	11.0	8.34	2.08	1.15	.14	1.27	316.2	2.01	1.26	8.58	
11	25	359	4.5	9.0	8.18	2.05	.94	.27		356.9	5.77	3.01	8.88	
12	0	360	4.0	15.1	8.52	2.39	1.38	.14	.98	222.4	3.19	1.82	15.25	
12	5	361	4.0	14.2	8.56	2.39	1.49	.16	.98	210.2	4.71	.84	8.89	
12	10	362	4.0	12.9	8.48	2.29	1.45	.15	1.12	250.9	3.34	1.24	12.29	
14	0	450	4.5	15.0	8.49	2.42	1.71	.06		212.8	4.78	3.80	14.51	6.58
14	5	454	4.5	15.0	8.54	2.35	1.72	.10	.95	233.6	4.31	2.46	14.31	6.56
14	10	455	4.5	15.0	8.54	2.35	1.66	.08	.96	228.4	3.75	2.20	14.23	6.49
14	15	456	4.5	14.0	8.52	2.35	1.47	.15	1.05	348.2	3.89	1.81	14.03	6.41
14	20	457	4.5	13.2	8.46	2.35	1.45	.10	1.04	339.7	3.20	1.80	13.83	6.31
15	0	458	5.2	14.4	8.46	2.35	1.62	.09	1.03	431.9	3.56	1.99	14.01	6.43
15	5	459	5.2	14.4	8.48	2.35	1.60	.07	1.02	306.7	3.02	2.33	13.81	6.39
15	10	460	5.2	14.4	8.52	2.24	1.66	.12	1.03	218.8	3.67	1.32	10.43	3.55
15	15	461	5.2	14.4	8.53	2.40	1.69	.09	1.02	200.7	4.39	1.98	13.53	6.37
15	20	462	5.2	14.2	8.47	2.10	1.60	.13	1.04	315.5	3.44	2.25	13.21	6.14
16	0	463	4.8	14.5	8.43	2.35	1.78	.12	1.01	277.9	4.84	2.16	12.50	5.93
16	5	464	4.8	14.5	8.48	2.27	1.74	.06	1.02	219.2	3.35	2.00	13.69	6.40
16	10	465	4.8	14.5	8.47	2.37	1.78	.10	1.03	201.1	2.68	1.47	13.87	6.50
17	0	477	4.5	14.5	8.45	2.18	1.66	.17	1.02	210.4	4.26	2.27	14.10	6.43
17	5	478	4.5	14.4	8.48	2.33	1.74	.17	1.02	249.6	3.73	1.93	14.41	6.39
17	10	479	4.5	14.4	8.58	2.50	1.64	.13	1.02	307.4	3.19	1.80	14.71	6.39
18	0	475	4.5	14.4	8.50	2.20	1.73	.11	1.02	211.5	3.94	1.52	14.37	6.42
18	5	474	4.5	14.4	8.50	2.11	1.71	.06	1.04	229.8	2.94	1.68	11.02	4.68
18	10	476	4.5	14.0	8.52	2.35	1.73	.17	1.07	213.5	3.52	1.75	12.90	5.94
19	0	469	4.5	14.8	8.46	2.37	1.78	.10	.95	211.3	3.78	2.03	13.42	6.44
19	5	470	4.5	14.8	8.56	2.37	1.67	.15	.97	284.3	2.74	2.67	14.11	6.50
19	10	471	4.5	14.6	8.58	2.17	1.66	.05	.97	267.7	9.88	2.18	14.03	6.57
19	15	472	4.5	14.5	8.62	2.38	1.81	.07	.98	251.1	3.52	2.65	13.96	6.51
19	20	473	4.5	10.5	8.27	2.18	1.78	-.01	.97	237.9	2.63	2.78	14.27	6.45

App. A.2 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND μmho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
22	0	483	4.5	14.2	8.45	2.55	1.72	-.08	1.02	246.9	3.28	2.11	15.02	6.53
22	5	484	4.5	14.2	8.46	2.40	1.47	.20	1.04	181.3	3.99	2.47	14.44	6.37
22	10	485	4.5	14.0	8.46	2.35	1.76	.08	1.06	230.6	3.98	2.74	14.62	6.33
22	15	486	4.5	13.2	8.41	2.32	1.46	.17	1.13	251.2	4.15	2.30	14.29	6.20
23	0	487	4.5	15.1	8.47	2.52	1.77	.07	.89	224.5	5.14	2.44	14.60	6.64
23	5	488	4.5	15.0	8.53	2.53	1.58	.09	.89	191.0	3.87	2.68	14.78	6.60
23	10	489	4.5	14.9	8.51	2.51	1.72	.10	.92	169.3	3.94	2.44	14.45	6.54
24	0	363	5.0	14.5	8.56	2.42	1.79	.11	1.05	220.6	5.30	2.54	14.85	6.43
24	5	364	5.0	14.5	8.61	2.43	1.88	.12	1.05	207.2	3.22	1.65	15.27	6.59
24	10	365	5.0	13.2	8.51	2.34	1.85	.10	1.05	189.0	2.95	1.63	14.26	6.33
24	15	366	5.0	12.5	8.43	2.26	1.85	.13	1.15	222.0	6.39	2.06	11.35	4.72
25	0	367	5.5	14.0	8.55	2.38	1.56	.10	1.00	195.0	4.24	2.10	14.63	6.47
25	5	368	5.5	14.0	8.54	2.35	1.73	.11	1.00	188.0	2.91	1.51	14.33	6.47
25	10	369	5.5	13.1	8.50	2.24	1.54	.08	1.03	221.0	2.57	1.00	13.21	5.94
25	15	370	5.5	11.9	8.38	2.10			1.10	266.3	3.20	2.83	13.87	5.48
25	20	371	5.5	10.0	8.33	2.07	1.47	.11	1.24	299.3	2.37	2.23	12.03	5.38
25	25	372	5.5	8.0	8.25	2.09	1.47	.12	1.31	315.4	2.59	1.36	8.15	5.15
26	0	373	6.5	12.9	8.48	2.20	1.84	-.01	1.05	266.9	4.02	1.41	10.05	6.03
26	5	374	6.5	12.8	8.48	2.21	1.89	.04	1.04	260.0	3.23	1.38	9.00	5.96
26	10	375	6.5	12.4	8.52	2.20	1.87	-.08	1.03	274.5	2.91	1.57	8.94	5.88
26	15	376	6.5	10.0	8.40	2.09	1.45	.08	1.13	299.8	3.54	.89	7.40	5.40
26	20	377	6.5	7.0	8.18	2.10	1.39	.14	1.50	348.2	2.38	1.23	6.72	5.20
26	25	378	6.5	6.5	8.09	2.16	.91	.30	1.73	444.2	2.95	1.06	6.16	5.01
26	30	379	6.5	6.0	8.05	2.18	.71	.39	1.96	388.1	2.88	1.58	6.84	5.29
27	0	380		12.1	8.48	2.23	1.85	.08	1.11	278.1	3.19	1.92	7.63	5.91
27	5	381		12.1	8.48	2.24	1.77	.01	1.06	294.1	2.27	1.33	3.64	3.85
27	10	382		11.0	8.43	2.12			1.09	294.9	3.08	1.48	5.54	5.00
27	15	383		10.4	8.35	2.05	1.51	.02	1.11	314.0	3.10	1.55	3.02	3.73
27	20	384		9.9	8.32	2.04	1.30	.07	1.18	322.4	2.83	1.02	1.97	.69
27	25	385		7.4	8.21	2.13	1.08	.18	1.61	357.0	3.15	1.55	10.24	4.09
27	30	386		6.8	8.11	2.15	1.15	.20	1.60	363.8	4.57	.99	9.56	3.28
27	35	387		5.5	8.05	2.20	.56	.44	1.95	384.5	1.88	1.71	12.16	5.26
27	40	388		5.3	8.07	2.22	.52	.50	2.01	389.8	4.07	3.66	9.90	3.28
27	50	389		5.2	8.06	2.22	.58	.46	2.03	389.0	3.20	1.51	11.04	4.63
28	0	390		12.9	8.49	2.26	1.74	.06	1.02	268.9	3.88	1.97	9.50	2.83
28	5	391		12.9	8.49	2.24	1.71	.02	1.05	336.7	2.94	1.56	13.81	6.05
28	10	392		10.8	8.40	2.09	1.80	.03	1.07	334.9	4.12	1.87	9.96	3.70
28	15	393		10.0	8.30	2.09	1.44	.04	1.26	358.4	2.76	2.49	12.32	5.39
28	20	394		8.0	8.37	2.06	1.41	.08	1.06	348.6	3.35	1.89	12.49	5.27
28	25	395		6.8	8.11	2.13	1.22	.20	1.33	369.0	3.47	1.87	9.73	3.37
28	30	396		6.4	8.11	2.16	.95	.23	1.45	397.2	3.09	1.71	11.85	5.23
28	40	397		5.8	8.16	2.19	.89	.22	1.32	369.0	4.24	2.69	11.04	4.69
28	50	398		5.5	8.15	2.19	.70	.41	1.36	380.9	6.66	1.92	12.19	5.37
28	60	399		5.2	8.14	2.22	.51	.50	1.56	368.0	2.75	2.90	9.31	2.26

App. A.2 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND µmho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
29	0	400	6.5	10.6	8.35	2.16	1.32	.13	1.16	304.5	3.59	2.27	12.64	
29	5	401	6.5	10.6	8.41	2.16			1.18	313.8	3.13	1.53	12.69	
29	10	402	6.5	10.5	8.37	2.13	1.61	-.01	1.18	311.9	7.59	2.62	12.98	
29	15	403	6.5	8.0	8.34	2.07	2.75	-.02	1.12	327.5	4.54	3.21	12.78	
29	20	404	6.5	6.9	8.26	2.12	1.37	.06	1.27	343.1	3.82	3.13	9.29	
29	25	405	6.5	6.0	8.26	2.12	1.46	.26	1.15	350.8	3.35	2.06	12.02	
29	30	406	6.5	5.8	8.20	2.14	1.26	.22	1.31	358.5	3.47	2.12	9.14	
29	40	407	6.5	5.0	8.09	2.18	.67	.36	1.54	415.2	3.56	2.30	11.75	
29	50	408	6.5	4.6	8.05	2.19	.59	.34	1.61	386.5	3.79	4.00	9.24	
29	60	409	6.5	4.5	8.05	2.20	.57	.44	1.65	392.6	5.03	3.06	11.96	
30	0	410	8.5	8.8	8.22	2.05	.96	.07	1.28	352.8	3.53	3.32	11.28	
30	5	411	8.5	8.9	8.29	2.05	.97	.08	1.26	363.6	4.18	2.30	9.13	
30	10	412	8.5	8.5	8.22	2.04	1.09	.17	1.40	357.1	4.22	2.97	9.18	
30	15	413	8.5	8.2	8.21	2.04	1.05	.18	1.40	386.9	5.12	2.65	11.17	
30	20	414	8.5	7.2	8.13	2.10	.92	.24	1.52	396.2	5.18	2.82	11.58	
30	25	415	8.5	6.8	8.10	2.15	.99	.21	1.51	367.4	4.52	2.42	9.07	
30	30	416	8.5	6.5	8.11	2.14	.87	.28	1.51	383.0	3.83	2.12	9.00	
30	35	417	8.5	6.5	8.10	2.24	.87	.31	1.53	379.6	4.59	2.65	11.48	
30	40	418	8.5	6.4	8.12	2.01	.88	.30	1.51	376.2	5.44	4.75	8.97	
31	0	419	5.0	10.0	8.26	1.83	1.15	.12	1.49	353.8	3.83	2.67	9.50	
31	5	420	5.0	9.9	8.26	1.63	1.37	.10	1.50	345.7	4.08	2.04	9.18	
31	10	421	5.0	9.8	8.24	1.87	1.33	.05	1.49	370.8	3.18	1.80	9.71	
31	15	422	5.0	9.5	8.28	1.86	1.27	.10	1.48	362.6	3.82	2.03	10.13	
31	20	423	5.0	8.0	8.18	2.03	1.07	.18	1.53	375.1	3.46	2.78	9.08	
38	0	320	4.5	14.9	8.52	2.35	2.02	.06	.94	226.6	3.37	2.62	16.45	6.54
38	5	321	4.5	14.9	8.53	2.35	1.76	.07	.93	211.3	7.04	1.45	16.52	6.49
38	10	322	4.5	14.9	8.50	2.37	1.80	.03	.93	214.0	4.07	2.31	15.63	6.56
38	15	323	4.5	14.0	8.48	2.28	1.68	.09	.98	236.2	3.58	2.83	14.39	6.17
39	0	312	5.5	15.7	8.54	2.06	1.60	.08	.76	193.6	3.17	.90	14.75	6.30
39	5	313	5.5	15.5	8.53	2.27	1.63	.08	.84	221.3	3.47	1.23	14.70	6.28
39	10	314	5.5	14.1	8.53	2.20	1.94	.03	.86	247.7	3.98	1.11	14.64	5.93
39	15	315	5.5	13.5	8.46	2.10	1.47	.03	.89	261.5	5.19	2.03	14.23	5.67
39	20	316	5.5	12.2	8.47	2.03	1.37	.07	.97	287.9	2.83	3.39	15.25	6.29
39	25	317	5.5	8.0	8.17	2.05	1.08	.28	1.40	350.4	2.88	1.38	12.22	5.14
39	30	318	5.5	8.0	8.04	2.00	.85	.31	1.78	386.4	4.49	3.85	13.11	5.47
39	35	319	5.5	6.2	8.02	2.15	.97	.25	1.81	390.6	3.29	1.48	12.23	5.14
40	0	310	4.5	16.5	8.58	2.17	1.60	.03	.72	158.4	2.39	1.15	14.39	6.17
40	5	311	4.5	16.5	8.56	2.19	1.53	.05	.75	187.3	2.41	1.18	13.26	5.70

App. A.2 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	CCND -•mho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
41	0	300	5.5	16.1	8.51	2.27	1.81	.05	.78	211.1	8.72	1.37	13.04	6.15
41	5	309	5.5	16.1	8.58	2.23	1.85	.03	.75	179.4	3.29	1.29	12.64	6.15
41	10	308	5.5	15.5	8.53	2.24	1.60	.07	.83	201.7	3.32	1.40	14.30	6.13
41	15	307	5.5	11.0	8.39	2.05	1.34	.17	.96	267.5	2.80	1.11	11.65	5.40
41	20	306	5.5	8.5	8.20	2.09	1.12	.25	1.18	306.4	3.65	.84	11.27	4.91
41	25	305	5.5	7.6	8.10	2.11	.87	.29	1.29	319.7	2.18	.76	10.43	4.41
41	30	304	5.5	7.0	8.04	2.03	.67	.31	1.43	329.2	3.11	.46	10.95	5.11
41	35	303	5.5	6.6	8.00	1.89	.45	.44	1.79	348.9	1.59	.95	10.91	5.17
41	40	302	5.5	6.1	8.00	2.15	.31	.60	2.00	368.7	2.14	1.01	11.77	5.40
41	45	301	5.5	6.0	8.02	2.17	.36	.52	1.97	347.4	3.20	2.34	11.38	5.23
42	0	290	6.9	15.0	8.48	2.20	1.47	.15	.79	222.8	4.04	2.77	12.60	5.89
42	5	291	6.9	14.5	8.48	2.18	1.54	.11	.80	244.0	5.36	2.99	13.55	6.03
42	10	292	6.9	14.0	8.48	2.21			.92	272.9	4.48	1.92	12.69	5.52
42	15	293	6.9	12.0	8.40	2.04	1.25	.21	.96	292.8	3.57	2.63	10.69	4.84
42	20	294	6.9	11.0	8.34	1.99	1.41	.12	1.04	315.3	2.91	1.70	10.39	5.01
42	30	295	6.9	5.5	8.06	2.11	.83	.20	1.40	353.2	3.37	1.45	11.01	5.14
42	40	296	6.9	4.9	8.04	2.15	.54	.38	1.71	314.3	2.76	2.15	10.82	5.28
42	50	297	6.9	4.5	8.00	2.17	.46	.47	1.84	379.0	3.27	1.01	10.53	5.20
42	60	298	6.9	4.5	7.96	2.11	.39	.50	1.90	387.4	2.12	1.08	11.25	5.24
42	70	299	6.9	4.4	7.96	2.16	.37	.53	1.97	381.8	2.88	1.29	10.62	4.88
43	0	280	8.5	12.5	8.37	2.03	1.92	.01	1.02	261.7	2.41	.88	11.25	5.09
43	5	281	8.5	12.5	8.43	2.00	1.81	.05	.99	259.0		.87	10.95	5.13
43	10	282	8.5	12.5	8.46	2.00	1.78	.04	1.00	252.6	2.45		11.00	5.13
43	15	283	8.5	12.4	8.42	2.00	1.73	.09	.99	254.7	3.08	2.06	10.59	4.93
43	20	284	8.5	6.0	8.32	2.20	2.19	.09	1.20	293.0	4.45	1.24	11.65	5.36
43	30	285	8.5	4.6	8.18	2.16	1.23	.23	1.38	326.4	3.32	1.48	10.79	5.08
43	40	286	8.5	4.4	8.12	2.17	.73	.27	1.44	335.7	3.18	1.53	11.29	5.35
43	50	287	8.5	4.4	8.11	2.19	.55	.30	1.46	323.4	3.45	3.00	11.56	5.16
43	60	288	8.5	4.4	8.12	2.21	.33	.47	1.55	325.4	2.41	1.66	12.96	5.72
43	70	289	8.5	4.4	8.11	2.22	.22	.67	2.05	345.6	3.55	2.10	11.31	5.19
44	0	270	7.5	12.0	8.46	1.96	1.94	.03	.98	274.7	2.69	1.39	10.92	5.01
44	5	271	7.5	12.0	8.42	1.95	1.87	-.06	.95	264.7	2.33	1.70	10.85	4.88
44	10	272	7.5	11.5	8.41	1.95	1.94	-.06	.98	266.8	2.53	1.14	11.92	5.03
44	20	273	7.5	5.9	8.65	1.74	1.98	-.03	1.01	306.3	2.03	.95	11.05	5.18
44	30	274	7.5	4.5	8.40	2.10	2.83	.08	1.23	325.2	1.94	1.24	11.55	5.30
44	50	275	7.5	4.4	8.12	2.12	.83	.20	1.43	330.9	1.78	1.05	12.05	5.37
44	70	276	7.5	4.4	8.17	2.12	.59	.22	1.50	329.4	1.59	.32	11.19	4.92
44	90	277	7.5	4.2	8.08	2.11	.23	.57	1.61	335.1		.39	12.14	5.39
44	100	278	7.5	4.2	8.07	2.07	.24	.63	2.09	354.1	2.46	1.35	11.27	5.21
44	110	279	7.5	4.2	8.03	2.16	.20	.70	2.23	361.0	3.70	1.70	11.89	5.43

App. A.2 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND →mho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
45	0	260	7.5	11.0	8.28	1.88	1.69	.06	1.14	290.0	1.62	.89	11.27	4.91
45	5	261	7.5	11.0	8.33	1.93	1.56	.07	1.14	280.0	2.07	.78	11.77	4.85
45	10	262	7.5	10.5	8.32	1.92	1.69	.00	1.27	302.6	2.55	1.32	11.25	4.97
45	15	263	7.5	10.5	8.28	1.90	1.43	.08	1.17	291.5	3.97	1.04	10.72	4.91
45	20	264	7.5	8.2	8.26	1.82	1.58	.09	1.23	311.6	2.69	1.44	11.79	5.24
45	30	265	7.5	4.5	8.14	1.76	1.67	.23	1.37	320.9	2.13	1.26	11.04	4.96
45	40	266	7.5	4.5	8.13	2.00	.78	.24	1.45	327.9	2.08	1.24	11.42	5.33
45	50	267	7.5	4.4	8.13	2.14	.54	.33	1.49	332.3	2.18	1.24	11.58	5.33
45	60	268	7.5	4.4	8.13	2.15	.39	.39	1.60	330.8	1.55	1.27	12.76	5.41
45	70	269	7.5	4.4	8.07	2.15	.36	.50	1.77	337.7	3.65	2.63	12.69	5.42
46	0	253	5.5	11.8	8.18	1.68	1.80	.04	1.61	324.9	5.36	2.00	9.15	3.52
46	5	254	5.5	11.1	8.18	1.72	1.66	.08	1.58	308.9	4.31	1.89	9.19	3.97
46	10	255	5.5	10.5	8.11	1.80	1.34	.11	1.54	306.1	3.74	.81	9.69	4.18
46	15	256	5.5	9.5	8.14	1.84	1.19	.22	1.56	315.5	2.68	3.71	9.62	4.08
46	20	257	5.5	7.2	8.12	2.04	1.21	.18	1.51	322.4	1.78	.39	12.16	4.98
46	25	258	5.5	6.8	8.10	2.12	1.12	.21	1.51	329.3	1.64	.67	11.52	5.23
46	30	259	5.5	6.5	8.10	2.17	.95	.26	1.60	327.7	2.77	2.18	13.15	5.66
47	0	248	3.0	14.0	8.12	1.30	1.34	.17	1.88	283.1	3.75	2.03	8.36	2.05
47	5	249	3.0	13.2	8.08	1.42	1.43	-.01	1.85	294.9	3.86	3.38	8.29	2.58
47	10	250	3.0	12.6	8.07	1.42	1.35	.08	1.83	294.5	4.48	2.60	8.22	2.11
47	15	251	3.0	8.5	8.03	1.96	1.12	.17	1.66	335.2	4.72	2.57	10.76	4.64
47	20	252	3.0	8.0	8.05	1.95	1.11	.11	1.61	334.9	6.32	1.51	10.92	4.87
48	0	244	3.0	14.5	8.13	1.36	1.24	.17	1.84	280.8	4.94	3.17	8.64	2.33
48	5	245	3.0	13.8	8.12	1.26	1.28	.19	1.90	257.6	4.46	2.13	8.23	1.73
48	10	246	3.0	12.8	8.12	1.54	.98	.10	1.76	286.2	2.94	1.91	8.50	3.03
48	15	247	3.0	9.0	8.06	1.94	.53	.61	1.61	316.0	2.85	1.51	10.58	4.70
49	0	235	9.0	9.8	8.24	1.94	1.20	.10	1.36	289.8	5.67	3.48	10.51	4.57
49	5	236	9.0	9.8	8.24	1.96	1.60	-.01	1.25	273.8	3.78	2.82	11.00	4.94
49	10	237	9.0	9.8	8.26	1.95	1.62	.05	1.24	269.9	4.66	2.42	11.73	4.82
49	15	238	9.0	9.0	8.30	1.96	1.39	.01	1.27	276.8	4.45	4.15	10.87	4.86
49	20	239	9.0	8.5	8.21	2.03	1.33	.12	1.24	284.9	5.90	3.89	11.48	5.09
49	25	240	9.0	7.4	8.19	2.14	1.32	.24	1.27	293.0	5.26	3.03	12.09	5.26
49	30	241	9.0	6.5	8.19	2.16	1.09	.28	1.38	298.7	2.99	3.17	12.70	5.32
49	40	242	9.0	5.8	8.02	2.00	.77	.32	1.69	322.5	3.82	1.94	12.40	5.39
49	50	243	9.0	5.8	7.98	1.99	.69	.33	1.80	324.6	3.04	2.70	11.31	4.75
50	0	227	6.0	10.2	8.19	1.83	1.21	.25	1.45	274.3	5.60	3.73	10.38	4.37
50	5	228	6.0	10.0	8.16	1.82	1.41	.06	1.45	274.0	4.36	2.80	10.76	4.48
50	10	229	6.0	9.2	8.15	1.84	1.26	.13	1.46	279.7	8.09	2.94	10.81	4.64
50	15	230	6.0	8.0	8.12	1.94	1.22	.17	1.46	296.3	4.52	3.87	11.99	5.01
50	20	231	6.0	7.5	8.11	2.02	1.04	.27	1.48	295.9	6.22	3.56	10.22	4.40
50	25	232	6.0	7.0	8.10	2.12	1.02	.27	1.49	306.5	5.12	3.37	11.73	5.16
50	30	233	6.0	6.3	8.05	2.15	1.17	.27	1.56	301.3	7.02	4.49	11.78	5.23
50	35	234	6.0	6.6	8.06	2.12	1.00	.32	1.63	307.0	4.14	3.68	12.28	5.35

App. A.2 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	CCND µmho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
124	0	324	5.0	14.4	8.47	2.33	1.72	.06	.98	211.1	4.01	1.60	16.23	6.60
124	5	325	5.0	14.4	8.46	2.34	1.66	.07	.96	219.4	4.69	4.46	16.18	6.63
124	10	326	5.0	12.0	8.45	2.30	1.68	.08	1.07	260.9	3.08	1.19	14.10	6.17
124	15	327	5.0	10.8	8.28	1.87	1.59	.14	1.20	277.6	7.94	1.22	13.10	5.44
130	0	218	7.5	8.5	8.11	1.99	.90	.14	1.30	332.8	4.08		12.25	5.30
130	5	219	7.5	8.5	8.18	2.04	.94	.14	1.34	327.6	3.94	3.66	12.18	5.28
130	10	220	7.5	7.5	8.15	2.05	1.12	.14	1.41	324.9	5.95	2.62	12.11	5.24
130	15	221	7.5	6.9	8.15	2.13	1.32	.06	1.42	316.1	4.37	5.07	13.63	6.19
130	20	222	7.5	6.5	8.09	2.08	1.29	.11	1.47	321.8	6.67	3.71	12.43	5.54
130	25	223	7.5	6.5	8.06	2.19	.88	.33	1.48	307.0	4.39	3.14	12.24	5.37
130	30	224	7.5	6.4	8.03	2.08	1.09	.24	1.52	306.7	4.43	3.68	9.57	3.79
130	35	225	7.5	6.0	8.04	2.19	.81	.41	1.55	301.5	5.08	4.11	13.13	5.46
130	40	226	7.5	6.0	8.05	2.13	1.12	.14	1.55	296.4	5.75	3.56	12.49	5.62

Appendix A.3 Cruise 3, October 1973

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND -^{4}mho/cm	CHL mg/m^3	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m^3	TPO4 mgP/m^3	SPO4 mgP/m^3	SO4 mgSO4/l	CL mgCl/l
1	0	513	6.5	15.1	8.51	2.59	1.51	.13	1.03	158.6	4.64	3.66	13.99	6.67
1	5	514	6.5	15.1	8.51	2.54	1.67	.19	1.33	158.4	5.46	3.87	14.04	6.50
1	10	515	6.5	15.1	8.49	2.51	1.65	.21	1.03	162.6	4.50	3.79	14.30	6.63
2	0	508	6.0	15.0	8.45	2.51	1.81	-.07	1.13	182.4	4.47	3.28	14.09	6.52
2	5	509	6.0	14.9	8.46	2.49	1.63	.15	1.15	175.0	5.43	4.49	13.93	6.55
2	10	510	6.0	14.6	8.46	2.46	1.65	.13		176.3	4.56	4.58	14.09	6.28
2	15	511	6.0	14.6	8.46	2.48	1.65	.13	1.19	180.5	5.12	3.53	13.50	6.25
2	20	512	6.0	14.5	8.44	2.42	1.55	.11	1.27	193.2	5.51	4.23	13.30	6.21
3	0	501	7.3	14.9	8.43	2.48	1.67	.17	1.17	170.6	4.66	3.99	14.34	6.64
3	5	502	7.3	14.9	8.46	2.52	1.73	.14	1.20	167.5	4.44	4.46	14.40	6.81
3	10	503	7.3	14.9	8.43	2.52	1.74	.13	1.14	163.1	5.09	3.55	14.24	6.54
3	15	504	7.3	14.8	8.41	2.47	1.61	.14	1.25	175.8	4.92	4.20	13.71	6.34
3	20	505	7.3	14.0	8.37	2.44	1.59	.15	1.36	194.3	4.91	3.29	13.55	6.14
3	25	506	7.3	13.5	8.33	2.38	1.27	.24	1.41	215.7	4.39	3.41	12.97	6.00
3	30	507	7.3	13.5	8.31	2.33	1.28	.26	1.47	221.3	4.43	3.33	12.92	5.83
4	0	496	7.3	14.2	8.42	2.45	1.41	.19	1.35	171.4	5.41	4.39	14.39	6.73
4	5	497	7.3	14.2	8.44	2.44	1.35	.23	1.32	176.9	5.93	4.78	14.45	6.49
4	10	498	7.3	14.2	8.44	2.47	1.47	.19	1.32	215.6	5.10	4.30	14.08	6.49
4	15	499	7.3	14.0	8.41	2.46	1.39	.23	1.32	185.2	5.36	4.56	14.56	6.32
4	20	500	7.3	14.0	8.41	2.45	1.27	.27	1.39	190.8	4.58	3.86	13.81	6.35
5	0	493	7.8	14.0	8.35	2.29	1.59	.14	1.43	171.8	5.33	4.70	14.55	6.44
5	5	494	7.8	14.0	8.37	2.44	1.49	.16	1.38	177.4	5.85	5.22	15.19	6.34
5	10	495	7.8	13.8	8.40	2.49	1.40	.17	1.40	178.7	4.89	4.87	14.34	6.40
6	0	490	6.0	14.5	8.44	2.47	1.84	.16	1.43	140.7	5.47	5.84	15.29	6.58
6	5	491	6.0	14.5	8.21	2.45	2.24	.12	1.40	153.5	6.07	5.27	15.66	6.58
6	10	492	6.0	14.4	8.40	2.94	2.14	.14	1.44	154.8	6.03	4.88	15.03	6.41
7	0	571	6.0	12.5	8.11	2.00	1.58	.05	1.55	324.9	4.69	3.75	10.83	4.89
7	5	572	6.0	12.5	8.24	2.00	1.49	.06	1.51	311.0	4.69	3.06	11.12	5.15
7	10	573	6.0	12.2	8.28	2.01	1.56	.07	1.49	303.2	5.15	3.06	11.22	5.38
8	0	574	7.3	12.4	8.23	2.10	1.32	.10	1.46	302.8	4.27	3.37	11.72	5.32
8	5	575	7.3	12.2	8.24	1.96	1.56	.12	1.45	307.0	3.70	2.53	11.42	5.11
8	10	576	7.3	12.1	8.29	1.96	1.62	.16	1.53	314.2	4.16	2.03	10.80	4.81
8	15	577	7.3	12.1	8.25	1.89	1.65	.17	1.50	315.4	3.36	2.34	10.77	4.78
8	20	578	7.3	12.1	8.20	1.92	1.60	.19	1.52	325.6	4.53	1.56	10.73	4.76
9	0	583	7.5	12.4	8.11	2.13	1.44	.16	1.34	305.7	3.51	1.76	11.76	5.55
9	5	584	7.5	12.3	8.11	2.13	1.51	.15	1.44	297.8	3.50	2.08	11.66	5.67
9	10	585	7.5	12.2	8.22	2.09	1.56	.15	1.44	286.9	7.84	2.16	10.84	4.97
9	15	586	7.5	12.2	8.25	2.02	1.57	.08	1.43	307.7	10.40	2.65	11.33	5.58
9	20	587	7.5	12.2	8.29	2.02	1.51	.12	1.37	304.4	4.19	2.81	10.90	5.13
9	25	588	7.5	12.2	8.34	2.00	1.58	.11	1.34	302.5	4.64	2.08	11.27	5.29
9	30	589	7.5	12.2	8.24	2.04	1.43	.11	1.31	303.7	4.06	2.52	11.50	5.51
9	35	590	7.5	12.0	8.17	2.05	1.13	.23	1.39	301.9	4.06	2.03	11.53	5.34
9	40	591	7.5	12.0	8.18	2.07	1.22	.19	1.30	301.6	5.40	3.00	11.50	5.53

App. A.3 cont.

STA	DEP M	SAMP	SFC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m^3	PHAE fraction	SIO2 $mgSiO_2/l$	NO3 mgN/m^3	TPO4 mgP/m^3	SPO4 mgP/m^3	SO4 $mgSO_4/l$	CL $mgCl/l$
10	0	592	8.0	12.5	8.28	2.02	1.09	.13	1.33	308.8	5.77	3.82	11.01	5.05
10	5	593	8.0	12.5	8.26	2.02	1.46	.10	1.33	314.5	5.44	4.38	10.98	5.20
10	10	594	8.0	12.4	8.29	2.04	1.24	.25	1.35	308.1	8.79	4.75	11.08	5.11
10	15	595	8.0	11.8	8.22	1.96	1.52	.13	1.32	310.8	6.25	5.15	11.31	5.15
10	20	596	8.0	11.2	8.17	1.96	1.27	.22	1.46	325.5	5.43	3.81	11.15	5.09
11	0	519	7.5	12.1	8.22	2.00	1.06	.17	1.65	298.4	5.37	2.78	9.75	5.13
11	5	520	7.5	12.1	8.23	1.99	1.35	.10	1.58	295.4	3.32	3.25	10.01	5.36
11	10	521	7.5	12.1	8.29	2.00	1.35	.08	1.58	309.6	2.16	.95	9.75	5.36
11	15	522	7.5	12.1	8.21	2.00	1.53	.09	1.58	293.6	2.08	1.43	9.80	5.19
11	20	523	7.5	12.0	8.20	1.99	1.60	.09	1.59	299.2	5.28	1.50	9.86	5.22
11	25	524	7.5	12.0	8.11	1.97	1.24	.15	1.58	303.4	2.17	1.61	9.70	5.08
12	0	516	7.0	12.0	8.22	1.96	1.37	.10	1.64	263.0	3.89	2.87	10.22	4.20
12	5	517	7.0	12.0	8.21	1.94	1.51	.07	1.64	288.7	4.24	2.96	9.74	5.11
12	10	518	7.0	12.0	8.21	1.94	1.38	.17	1.59	300.0	3.67	2.69	9.80	5.10
13	0	707	7.0	14.0	8.42	2.37	1.40	.12	1.01	248.0	2.84	2.33	12.66	6.60
13	5	708	7.0	14.0	8.48	2.37	1.44	.16	.96	234.1	3.23	2.75	12.68	6.68
13	10	709	7.0	14.0	8.49	2.37	1.46	.17	.95	229.2	2.96	2.14	12.76	6.62
14	0	710	6.5	13.9	8.41	2.40	1.41	.15	.96	243.6	2.54	1.91	12.62	6.63
14	5	711	6.5	13.9	8.39	2.37	1.54	.13	.96	254.6	2.69	2.33	12.59	6.55
14	10	712	6.5	13.8	8.42	2.35	1.70	.15	1.03	246.7	3.15	2.29	12.51	5.95
14	15	713	6.5	13.0	8.40	2.32	1.44	.21	1.04	250.7	2.88	2.14	11.48	6.30
14	20	714	6.5	13.0	8.38	2.30	1.27	.31	1.17	259.2	3.58	1.83	11.67	6.31
15	0	715	6.5	13.5	8.34	2.43	1.03	.14	1.08	246.8	3.42	2.06	12.47	6.46
15	5	716	6.5	13.5	8.37	2.41	1.26	.17	1.07	247.8	3.62	2.37	12.27	6.47
15	10	717	6.5	13.5	8.44	2.32	1.05	.22	1.06	245.8	3.04	2.45	11.91	6.65
15	15	718	6.5	13.4	8.42	2.32	1.48	.14	1.09	249.8	3.50	2.26	12.05	6.56
15	20	719	6.5	13.0	8.36	2.34	1.33	.11	1.12	259.8	3.50	2.26	11.52	6.40
16	0	720	5.5	13.5	8.44	2.37	1.25	.24	1.08	247.4	3.31	1.50	12.10	6.44
16	5	721	5.5	13.5	8.42	2.34	1.17	.27	1.05	236.5	2.96	1.89	11.46	6.35
16	10	722	5.5	13.5	8.41	2.34	1.16	.07	1.11	244.9	3.43	2.60	11.76	6.70
17	0	723	6.0	14.5	8.52	2.54	1.22	.18	2.12	193.7	4.10	2.33	9.47	6.14
17	5	724	6.0	14.4	8.50	2.48	1.47	.17	1.73	200.7	3.95	2.61	10.82	6.39
17	10	725	6.0	13.5	8.44	2.33	1.51	.13	1.17	228.6	3.45	2.22	11.51	6.50
18	0	726	6.5	13.8	8.37	2.39	1.24	.13	1.02	235.6	3.65	2.69	19.88	6.88
18	5	727	6.5	13.8	8.47	2.34	1.19	.22	1.13	238.1	4.35	2.97	20.19	6.69
18	10	729	6.5	13.3	8.37	2.34	1.20	.18	1.08	236.1	3.93	2.47	17.21	6.23

App. A.3 cont.

STA	DEP m	SAMP	SEC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m^3	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m^3	TPO4 mgP/m^3	SPO4 mgP/m^3	SO4 mgSO4/l	CL mgCl/l
19	0	729	7.0	13.5	8.41	2.38	1.18	.24	1.02	238.6	3.04	2.75	20.45	6.58
19	5	730	7.0	13.5	8.45	2.41	1.10	.21	1.03	245.6	3.43	3.14	20.65	6.82
19	10	731	7.0	13.4	8.47	2.34	.59	.20	1.07	236.2	3.48	2.99	20.72	6.60
19	15	732	7.0	12.9	8.37	2.26	1.64	.22	1.28	255.1	4.38	3.58	18.80	6.34
19	20	733	7.0	12.8	8.24	2.25	2.03	.19	1.25	242.7	4.42	2.34	14.31	5.50
20	0	734	5.5	13.5	8.43	2.27	1.23	.14	1.15	245.2	3.45	2.66	16.02	5.82
20	5	735	5.5	13.0	8.44	2.13	1.16	.25	1.31	256.3	6.38	2.70	15.39	5.66
20	10	736	5.5	13.0	8.41	2.07	1.79	.08	1.29	253.3	3.73	3.05	9.49	4.40
21	0	737	8.0	12.6	8.35	2.03	.54	.24	1.37	270.7	4.36	4.03	9.22	4.31
21	5	738	8.0	12.6	8.34	1.98	1.72	.03	1.32	268.7	3.94	2.52	8.36	3.99
21	10	739	8.0	12.5	8.29	1.93	1.06	.20	1.22	298.1		2.80	10.18	4.53
22	0	740	6.5	13.5	8.41	2.36	1.59	.09	1.11	258.8	4.49	3.81	17.63	6.12
22	5	741	6.5	13.3	8.41	2.30	1.17	.15	1.11	259.8	5.51	2.61	16.89	5.93
22	10	742	6.5	12.8	8.28	2.09	1.60	.05	1.05	256.4	3.96	3.01	9.23	4.33
22	15	743	6.5	12.5	8.29	2.00	1.43	.16	1.12	223.1	4.55	2.43	6.26	2.85
23	0	744	7.0	13.6	8.37	2.39	1.36	.16	1.25	245.0	3.85	2.47	16.41	6.06
23	5	745	7.0	13.5	8.40	2.34	1.36	.15	1.27	240.0	3.93	2.29	17.42	6.11
23	10	746	7.0	12.5	8.41	2.34	1.45	.16	1.27	247.0	3.98	2.64	16.68	5.98
24	0	747	6.8	12.6	8.32	2.17	1.35	.12	1.30	283.9	3.17	2.92	14.40	5.69
24	5	748	6.8	12.5	8.34	2.15	.91	.38	1.21	284.9	3.60	2.26	14.01	5.57
24	10	749	6.8	12.0	8.37	2.05	1.63	.15	1.13	278.5	5.39	2.31	13.03	5.27
24	15	750	6.8	11.8	8.27	1.89	1.40	.23	1.16	312.3	4.70	2.31	9.94	4.58
25	0	751	8.0	12.5	8.28	1.94	2.19	.04	1.11	310.4	4.59	2.47	9.90	4.59
25	5	752	8.0	12.5	8.30	1.92	1.89	.01	1.10	296.4	3.85	2.32	8.10	4.04
25	10	753	8.0	12.4	8.34	1.90	2.08	.06	1.10	301.9	4.63	2.02	8.41	4.31
25	15	754	8.0	12.4	8.37	1.90	1.51	.13	1.13	319.4	3.86	3.03	10.24	4.69
25	20	755	8.0	12.3	8.28	1.93	1.03	.21	1.10	310.0	3.13	2.18	9.84	4.60
26	0	756	7.5	12.8	8.25	1.95	1.83	.01	1.12	314.0	3.37	2.27	9.79	4.68
26	5	757	7.5	12.6	8.32	1.93	1.78	.11	1.20	323.9	3.61	2.62	9.99	4.66
26	10	758	7.5	12.5	8.25	1.90	1.81	.06	1.00	314.5	3.88	2.20	8.54	4.74
26	15	759	7.5	12.5	8.29	1.91	1.77	.07	1.12	309.6	5.01	2.32	9.66	4.68
26	20	760	7.5	12.4	8.25	1.91	1.38	.13	1.08	307.6	3.85	2.60	10.22	4.76
26	25	761	7.5	11.5	8.12	1.91	.89	.25	1.18	316.1	3.09	2.02	10.29	4.80
26	30	762	7.5	11.0	7.98	1.92	.72	.30	1.37	321.6	2.98	1.76	10.48	4.81
27	0	763	7.0	12.8	8.29	1.90	1.81	.00	1.28	321.1	4.76	2.23	8.32	4.39
27	5	764	7.0	12.6	8.32	1.87	1.81	.01	1.08	310.2	3.76	2.00	6.53	4.10
27	10	765	7.0	12.5	8.28	1.85	1.81	.02	1.19	347.0	6.09	2.47	7.54	5.25
27	15	766	7.0	12.4	8.24	1.90	1.52	.13	1.11	321.2	7.11	3.02	8.89	4.69
27	20	767	7.0	12.0	8.16	1.90	.91	.29	1.17	305.8	6.84		9.56	4.73
27	25	768	7.0	11.9	8.15	1.92	.85	.27	1.20	320.2	4.69	4.12	9.99	4.78
27	30	769	7.0	11.6	8.19	1.93	.86	.28	1.16	316.8	4.49	2.55	12.07	4.82
27	35	770	7.0	10.5	8.21	1.95	.70	.33	1.22	317.8	3.61	2.93	12.15	4.83
27	40	771	7.0	7.5	8.09	2.00	.71	.24	1.30	330.8	3.65	2.09	13.05	4.94
27	50	772	7.0	7.2	7.94	2.12	.61	.43	1.65	360.1	3.87	2.32	14.89	5.29

App. A.3 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND -⁴mho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
28	0	773	7.0	12.2	8.24	1.83	1.92	.00	1.22	323.8	3.60	2.54	10.20	4.17
28	5	774	7.0	12.1	8.24	1.77	1.92	.01	1.32	333.8	3.60	2.31	9.83	4.08
28	10	775	7.0	12.0	8.29	1.79	1.88	-.00	1.16	321.4	2.87	2.49	10.14	4.25
28	15	776	7.0	11.6	8.31	1.86	1.54	.08	1.30	319.4	3.17	1.77	11.28	4.53
28	20	777	7.0	11.4	8.29	1.91	.95	.25	1.18	310.0	3.02	1.96	11.95	4.77
28	25	778	7.0	11.0	8.24	1.92	.81	.36	1.20	315.5	2.98	2.10	12.28	4.92
28	30	779	7.0	10.5	8.17	1.97	.76	.34	1.12	316.5	4.72	2.37	12.13	4.76
28	40	780	7.0	8.8	8.14	2.00	.74	.34	1.32	331.0	3.50	2.86	13.61	5.07
28	50	781	7.0	6.9	7.94	2.11	.71	.40	1.61	351.4	3.00	2.02	14.75	5.32
28	60	782	7.0	6.9	7.96	2.13	.49	.53	1.53	364.4	3.23	2.28	15.43	5.33
29	0	783	7.4	12.1	8.22	1.78	1.94	-.02	1.19	317.6	5.70	2.20	10.03	4.11
29	5	784	7.4	12.0	8.20	1.81	2.01	.05	1.19	321.6	3.71	2.80	10.35	4.29
29	10	785	7.4	11.9	8.21	1.81	1.77	.05	1.15	318.2	3.37	2.42	10.32	4.43
29	15	786	7.4	11.8	8.20	1.81	2.12	.03	1.16	311.7	3.74	2.19	10.53	4.27
29	20	787	7.4	11.5	8.29	1.83	1.67	.13	1.13	312.7	3.70	2.26	11.20	4.45
29	25	788	7.4	10.8	8.24	1.90	1.21	.25	1.18	303.3	3.17	2.45	11.53	4.53
29	30	789	7.4	10.0	8.20	1.88	.88	.24	1.20	313.3	3.01	2.02	11.96	4.67
29	40	790	7.4	5.8	8.11	2.00	.57	.40	1.37	344.2	2.66	1.94	13.68	5.22
29	50	791	7.4	5.0	8.08	1.98	.63	.44	1.42	354.7	2.81	1.90	15.40	5.23
29	60	792	7.4	4.8	8.02	2.11	.45	.47	1.50	397.6	3.04	2.20	15.02	5.31
30	0	793	6.0	13.0	8.22	1.71	1.87	.08	1.41	349.3	6.05	1.93	8.93	3.58
30	5	794	6.0	13.0	8.25	1.73	1.96	.02	1.48	330.6	3.94	3.75	8.56	3.66
30	10	795	6.0	13.0	8.19	1.65	1.81	.06	1.40	341.6	3.48	1.77	8.17	3.90
30	15	796	6.0	13.0	8.18	1.67	1.94	.04	1.45	313.7	2.95	1.73	8.50	3.65
30	20	797	6.0	12.8	8.14	1.71	1.30	.31	1.31	322.4	3.66	1.58	9.17	3.86
30	25	798	6.0	12.0	8.16	1.77	1.08	.16	1.45	312.9	2.90	2.18	9.60	4.20
30	30	799	6.0	10.5	8.05	1.87	.76	.30	1.49	333.0	3.16	2.33	11.68	4.58
30	35	800	6.0	10.0	8.04	1.92	.65	.40	1.49	325.7	3.31	1.98	12.35	4.73
30	40	801	6.0	9.9	7.99	1.95	.96	.34	1.55	350.4	3.31	2.40	13.37	4.81
31	0	802	8.0	13.1	8.24	1.72	1.77	.07	1.46	318.0	3.34	2.09	9.37	3.85
31	5	803	8.0	13.1	8.30	1.70	1.70	.02	1.53	310.7	4.14	2.35	8.89	3.79
31	10	804	8.0	13.1	8.29	1.70	1.89	.04	1.42	312.6	5.82	2.84	8.97	3.84
31	15	805	8.0	13.1	8.24	1.70	2.00	.04	1.46	341.8	5.01	2.61	8.94	3.82
31	20	806	8.0	13.1	8.25	1.71	1.86	.00	1.43	330.0	5.62	2.76	8.92	3.96
32	0	567	7.5	12.8	8.22	1.80	1.79	.05	1.60	330.8	5.52	4.24	10.42	4.04
32	5	568	7.5	12.8	8.21	1.74	2.01	-.10	1.53	322.9	5.22	4.09	10.06	4.01
32	10	569	7.5	12.6	8.21	1.77	1.88	-.00	1.57	348.2	5.49	3.97	10.03	4.03
32	15	570	7.5	12.5	8.17	1.73	1.33	.15	1.59	329.8	4.65	3.44	10.00	4.07
33	0	563	9.5	12.5	8.24	1.87	1.79	.08	1.28	332.1	5.71	5.00	10.55	4.77
33	5	564	9.5	12.4	8.21	1.84	1.81	-.01	1.36	328.7	5.63	4.62	10.52	4.50
33	10	565	9.5	12.2	8.27	1.87	2.01	-.02	1.30	319.4	5.21	4.58	10.49	4.47
33	15	566	9.5	12.1	8.28	1.81	1.89	-.02	1.36	328.1	4.91	4.32	10.86	4.45

App. A.3 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m^3	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m^3	TPO4 mgP/m^3	SPO4 mgP/m^3	SO4 mgSO4/l	CL mgCl/l
34	0	555	9.5	12.4	8.10	1.84	1.68	.08	1.51	322.6	6.35	6.68	10.94	4.92
34	5	556	9.5	12.4	8.29	1.84	1.84	.09	1.41	311.8	6.55	5.46	10.78	4.37
34	10	557	9.5	12.2	8.25	1.79	1.87	-.03	1.46	317.5	7.23	5.69	10.74	4.84
34	15	558	9.5	12.0	8.22	1.87	1.34	.12	1.59	318.6	7.85	9.79	11.70	5.99
34	20	559	9.5	11.9	8.14	1.89	1.20	.15	1.56	316.8	5.78	5.99	11.54	5.25
34	25	560	9.5	11.3	8.10	1.87	.84	.31	1.50	322.5	5.44	5.46	10.78	4.66
34	30	561	9.5	10.7	8.15	1.96	.80	.31	1.67	328.2	6.09	5.80	11.01	5.03
34	35	562	9.5	9.0	7.98	2.00	.89	.22	1.57	336.9	5.25	5.15	11.12	4.76
35	0	545	8.0	12.2	8.24	1.95	1.80	.00	1.69	297.3	3.88	8.89	12.78	6.84
35	5	546	8.0	12.1	8.27	1.91	1.71	.05	1.40	294.0	3.38	2.05	11.36	4.79
35	10	547	8.0	12.0	8.28	1.91	1.69	.03	1.82	289.1	5.09	9.41	12.58	7.19
35	15	548	8.0	12.0	8.45	1.88	1.42	.14	1.41	306.9	3.69	1.87	11.03	5.13
35	20	549	8.0	11.8	8.28	1.84	.93	.29	1.42	305.0	2.75	1.98	10.87	4.72
35	25	550	8.0	11.3	8.25	1.92	.79	.35	1.57	292.6	2.54	3.56	11.23	5.19
35	30	551	8.0	10.8	8.17	1.91	.63	.39	1.42	313.4	1.96	1.32	11.20	5.34
35	35	552	8.0	10.0	8.21	2.00	.52	.57	1.51	322.1	5.14	4.59	11.17	5.17
35	40	553	8.0	8.0	7.94	2.01	.57	.41	1.75	339.9	6.16	4.97	11.73	5.29
35	45	554	8.0	7.2	7.98	2.01	.54	.47	1.93	357.7	7.35	5.88	12.49	5.94
36	0	535	8.0	12.2	8.15	2.07	1.32	.11	1.45	294.4	2.74	1.81	9.81	4.98
36	5	536	8.0	12.2	8.18	1.96	1.72	.04	1.47	278.5	2.12	1.68	9.23	4.51
36	10	537	8.0	12.2	8.24	1.96	1.82	.06	1.53	285.5	7.22	2.12	9.39	5.20
36	15	538	8.0	12.0	8.17	2.06	1.34	.19	1.85		3.53	10.81	11.94	8.17
36	20	539	8.0	11.9	8.22	2.04	1.14	.23	1.48	254.0	4.05	2.63	9.71	5.10
36	25	540	8.0	11.5	8.15	1.85	.94	.26	1.55	276.3	2.70	2.10	9.66	5.57
36	30	541	8.0	11.0	8.09	1.93	.65	.36	1.52	294.1	2.41	2.45	9.50	5.51
36	35	542	8.0	10.5	8.10	1.94	.66	.37	1.75	302.8	4.03	6.44	10.51	7.06
36	40	543	8.0	9.8	8.11	2.01	.53	.45	1.60	322.1	2.35	2.44	11.46	5.53
36	45	544	8.0	7.0	7.92	2.08	.78	.30	1.90	344.4	3.48	1.78	11.82	5.51
37	0	525	7.5	12.8	8.28	2.22	1.31	.13	1.41	242.9	2.08	1.75	9.65	4.65
37	5	526	7.5	12.2	8.30	2.13	1.52	.12	1.48	277.2	2.69	1.93	10.18	5.54
37	10	527	7.5	12.2	8.28	2.09	1.56	.10	1.52	284.2	2.48	1.23	10.13	5.47
37	15	528	7.5	12.0	8.27	2.06	1.54	.10	1.52	285.5	2.80	1.75	9.96	5.36
37	20	529	7.5	12.0	8.29	2.07	1.33	.15	1.52	283.9	3.03	1.78	10.23	5.33
37	25	530	7.5	12.0	8.29	2.07	1.17	.13	1.52	280.9	2.98	1.73	9.86	5.23
37	30	531	7.5	12.0	8.19	2.13	1.17	.21	1.52	285.0	1.92	1.76	9.12	5.39
37	35	532	7.5	11.5	8.18	2.13	.84	.29	1.58	286.3	2.56	1.88	9.87	5.25
37	40	533	7.5	8.0	8.00	2.09	.83	.37	1.85	322.0	2.96	1.75	10.02	5.25
37	45	534	7.5	7.5	7.77	2.19	.68	.47	1.99	334.8	3.73	1.86	10.02	5.28
38	0	699	6.5	13.9	8.38	2.31	1.68	.03	1.17	261.8	3.38	2.09	11.51	6.18
38	5	700	6.5	13.8	8.44	2.32	1.86	.06	1.13	247.9	4.15	2.05	11.65	6.16
38	10	701	6.5	12.2	8.47	2.17	1.88	.11	1.22	266.8	5.03	2.67	9.96	5.63
38	15	702	6.5	12.1	8.37	1.85	1.73	.11	1.16	314.1	4.42	2.36	7.56	4.60

App. A.3 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mg N/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	Cl mgCl/l
39	0	691	7.0	12.5	8.30	2.07	1.27	.07	1.15	285.0	2.26	1.86	8.55	5.05
39	5	692	7.0	12.4	8.30	2.06	1.29	.10	1.08	295.0	2.41	1.59	8.47	4.96
39	10	693	7.0	11.8	8.31	2.01	1.41	.06	1.11	312.4	3.22	1.67	8.16	4.97
39	15	694	7.0	11.5	8.28	1.94	1.65	.06	1.13	320.9	3.72	1.59	8.30	4.95
39	20	695	7.0	11.2	8.24	1.98	1.45	.11	1.17	317.4	2.88	1.78	8.54	5.13
39	25	696	7.0	11.2	8.18	2.11	1.06	.27	1.19	318.4	3.72	1.90	9.07	5.34
39	30	697	7.0	11.0	8.17	2.05	1.16	.21	1.25	292.4	3.53	2.59	9.42	5.62
39	35	698	7.0	10.0	8.13	2.05	1.01	.28	1.34	319.5	2.76	2.13	9.39	5.52
40	0	689	6.5	13.0	8.34	2.26	1.02	.24	1.17	290.4	3.10	1.70	10.49	5.94
40	5	690	6.5	13.0	8.34	2.20	1.21	.14	1.14	260.1	2.80	2.05	10.73	5.92
41	0	679	9.0	12.0	8.32	2.16	.81	.29	1.05	290.3	2.94	2.27	10.57	5.82
41	5	680	9.0	11.0	8.31	2.14	.89	.31	1.05	278.6	2.75	2.27	11.03	5.87
41	10	681	9.0	10.6	8.38	2.09	1.85	.01	1.06	281.2	3.79	2.23	10.23	5.85
41	15	682	9.0	10.5	8.37	2.07	1.72	.07	1.00	285.3	3.56	2.16	10.20	5.86
41	20	683	9.0	10.4	8.32	2.14	1.36	.20	1.05	283.7	2.91	2.04	10.17	5.84
41	25	684	9.0	10.4	8.18	2.07	1.27	.16	1.07	289.2	2.75	2.08	10.26	5.92
41	30	685	9.0	8.0	8.17	2.15	1.04	.17	1.13	300.4	2.87	2.85	9.34	5.79
41	35	686	9.0	7.6	8.06	2.10	.91	.34	1.36		5.15	1.81	9.69	5.43
41	40	687	9.0	6.9	7.96	2.17	.71	.41	1.49	321.2	2.79	2.28	9.50	5.38
41	45	688	9.0	6.6	7.87	2.10	.49	.47	1.63	338.6	2.49	1.62	9.31	5.35
42	0	669	8.0	11.0	8.28	2.15	.95	.05	1.29	302.6	3.79	2.20	11.81	5.77
42	5	670	8.0	10.5	8.37	2.17	1.39	.19	1.32	282.3	3.15	2.18	12.22	5.75
42	10	671	8.0	10.4	8.33	2.08	1.49	.17	1.34	286.4	7.09	2.58	11.75	5.76
42	15	672	8.0	10.0	8.30	2.09	1.31	.13	1.38	284.7	4.46	3.17	10.50	5.74
42	20	673	8.0	9.0	8.28	2.09	1.32	.13	1.28	288.8	3.55	2.77	11.41	5.75
42	30	674	8.0	6.6	8.10	2.16	.81	.33	1.28	321.6	3.14	2.23	10.56	5.69
42	40	675	8.0	5.0	8.01	2.09	.96	.23	1.20	311.3	3.17	2.38	10.19	5.71
42	50	676	8.0	5.0	7.84	2.03	.54	.42	1.49	332.7	3.17	3.00	10.71	5.99
42	60	677	8.0	4.9	7.92	2.09	.45	.55	1.45	336.7	3.14	2.46	10.52	5.63
42	70	678	8.0	4.9	7.88	2.13	.53	.46	1.46	337.9	3.10	2.08	9.83	5.61
43	0	659	9.5	12.0	8.34	2.00	1.73	-.02	1.10	299.1	3.02	2.16	11.43	5.14
43	5	660	9.5	11.6	8.37	2.00	2.21	-.01	1.09	287.4	3.19	2.02	11.72	5.05
43	10	661	9.5	11.4	8.43	1.96	1.83	.03	1.09	298.7	3.78	2.23	11.38	5.74
43	15	662	9.5	11.0	8.29	2.00	1.90	.11	1.11	279.8	5.16	2.09	11.80	5.41
43	20	663	9.5	10.0	8.28	2.03	1.32	.17	1.23	295.4	3.50	2.38	11.65	5.36
43	30	664	9.5	6.5	8.18	2.16	1.33	.23	1.32	312.4	3.56	2.31	12.08	5.47
43	40	665	9.5	4.9	8.22	2.06	1.12	.26	1.36	315.0	3.30	3.37	11.73	5.48
43	50	666	9.5	4.5	8.04	2.22	.51	.44	1.66	336.3	2.55	2.27	11.46	5.94
43	60	667	9.5	4.5	8.05	2.12	.41	.43	1.76	340.4	2.64	2.05	11.43	5.57
43	70	668	9.5	4.4	7.98	2.21	.40	.51	1.74	337.3	3.12	2.84	11.39	5.66

App. A.3 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND µmho/cm	CHL mg/m³	PHAE fraction	SIO2 mgSiO2/l	NO3 mgN/m³	TPO4 mgP/m³	SPO4 mgP/m³	SO4 mgSO4/l	CL mgCl/l
44	0	649	11.5	11.5	8.37	1.95	1.22	.05	1.34	285.6	3.28	6.35	12.50	6.45
44	5	650	11.5	11.5	8.39	1.96	1.93	-.01	1.15	278.2	4.07	3.33	11.19	5.06
44	10	651	11.5	11.5	8.42	1.92	2.17	.01	1.12	288.0	3.28	3.07	11.36	5.45
44	20	652	11.5	11.4	8.40	2.02	.93	.35	1.00	230.3	3.18	2.24	10.18	3.34
44	30	653	11.5	8.0	8.25	2.00	1.22	.26	1.13	296.2	3.46	3.07	11.31	5.07
44	50	654	11.5	4.5	8.16	2.17	.54	.48	1.42	331.9	3.01	2.12	11.55	5.32
44	70	655	11.5	4.4	8.11	2.11	.32	.53	1.45	321.6	2.37	2.02	11.27	4.89
44	90	656	11.5	4.2	8.11	2.21	.23	.65	1.82	337.2	2.93	1.73	11.63	5.41
44	100	657	11.5	4.2	8.03	2.14	.19	.70	1.81	351.3	3.22	2.47	11.67	5.62
44	110	658	11.5	4.2	8.03	2.23	.15	.71	1.82	345.3	3.15	2.95	11.90	5.74
45	0	639	12.0	11.5	8.25	1.91	1.03	.11	1.25	257.7	6.90	2.61	10.24	2.94
45	5	640	12.0	11.5	8.30	1.93	1.68	.03	1.21	283.3	3.37	2.82	11.11	4.40
45	10	641	12.0	11.4	8.33	1.93	1.43	.18	1.10	308.9	3.20	2.10	11.54	4.99
45	15	642	12.0	11.0	8.37	1.93	1.41	.07	1.14	295.8	2.98	1.81	11.26	5.24
45	20	643	12.0	10.0	8.34	2.00	1.11	.12	1.05	302.7	3.27	1.71	11.81	5.05
45	30	644	12.0	6.0	8.16	2.08	1.14	.18	1.31	295.3	2.74	1.96	11.14	4.31
45	40	645	12.0	5.0	8.06	2.15	.69	.33	1.61	339.6	2.99	2.55	11.89	5.34
45	50	646	12.0	4.9	8.01	2.12	.56	.38	1.74	342.3	2.69	1.72	11.74	5.39
45	60	647	12.0	4.6	7.99	2.20	.53	.45	1.73	339.2	2.67	2.05	11.84	5.71
45	70	648	12.0	4.5	7.98	2.11	.44	.53	1.78	359.1	3.07	3.34	11.88	5.62
46	0	632	7.0	13.5	8.27	1.67	.82	.14	1.44	326.8	2.33	1.22	10.41	3.76
46	5	633	7.0	13.0	8.17	1.71	1.31	.07	1.45	319.4	3.65	1.05	10.38	3.74
46	10	634	7.0	12.5	8.16	1.71	1.30	.13	1.48	314.8	2.77	1.88	10.49	4.16
46	15	635	7.0	12.2	8.19	1.76	.97	.29	1.40	317.5	3.25	1.39	10.59	4.31
46	20	636	7.0	11.2	8.14	1.87	.94	.22	1.35	323.0	3.31	2.06	11.21	4.69
46	25	637	7.0	9.8	8.09	1.95	.64	.42	1.41	328.5	2.59	1.58	11.31	4.97
46	30	638	7.0	8.8	8.08	2.00	.74	.45	1.55	338.4	3.65	2.29	11.67	5.67
47	0	627	4.0	14.2	8.09	1.32	1.05	.18	1.76	327.4	3.23	1.85	9.89	2.55
47	5	628	4.0	13.9	8.09	1.45	1.50	.08	1.71	322.5	7.16	2.07	9.86	2.70
47	10	629	4.0	12.5	8.08	1.74	1.29	.09	1.46	331.2	3.14	2.06	10.35	3.99
47	15	630	4.0	12.0	8.15	1.82	.97	.23	1.46	338.5	2.38	.93	10.90	4.88
47	20	631	4.0	11.1	8.11	1.83	.91	.30	1.45	256.6	2.45	1.15	10.88	4.50
48	0	623	3.3	14.6	8.10	1.21	1.38	.14	2.25	318.2	4.05		10.62	5.65
48	5	624	3.3	14.4	8.16	1.16	1.60	.13	1.89	319.3	3.85	3.87	9.82	2.51
48	10	625	3.3	13.5	8.14	1.51	1.12	.26	1.63	325.0	2.78	2.57	9.93	2.94
48	15	626	3.3	12.5	8.09	1.73	.97	.15	1.45	333.7	2.81	1.23	10.68	4.31
49	0	614	6.0	13.0	8.21	1.58	1.60	.04	1.53	322.6	3.31	2.79	10.32	3.61
49	5	615	6.0	13.0	8.22	1.66	1.71	.01	1.63	304.2	3.18	1.92	10.17	3.42
49	10	616	6.0	13.0	8.24	1.60	1.76	.02	1.54	328.0	3.17	1.60	10.01	3.78
49	15	617	6.0	12.5	8.22	1.66	1.28	.15	1.47	327.7	2.77	1.36	10.25	3.79
49	20	618	6.0	11.8	8.19	1.84	1.02	.22	1.39	336.4	3.55	1.19	11.38	4.74
49	25	619	6.0	10.5	8.20	1.96	.83	.32	1.36	334.5	2.76	1.80	11.61	5.25
49	30	620	6.0	9.5	8.10	1.96	.91	.33	1.57	319.1	4.04	6.78	13.44	7.82
49	40	621	6.0	8.0	8.04	2.07	.77	.37	1.39	336.9	3.09	1.09	11.88	5.84
49	50	622	6.0	6.8	8.01	2.12	.61	.43	1.63	356.2	2.61	1.04	11.99	5.71

App. A.3 cont.

STA	DEP M	SAMP	SEC m	TEMP °C	PH	COND $^{-4}$mho/cm	CHL mg/m^3	PHAE fraction	SIO2 $mgSiO_2/l$	NO3 mgN/m^3	TPO4 mgP/m^3	SPO4 mgP/m^3	SO4 $mgSO_4/l$	CL $mgCl/l$
50	0	606	8.0	13.0	8.15	1.73	1.98	.05	1.36	329.8	3.15	.42	9.84	3.80
50	5	607	8.0	13.0	8.12	1.74	2.04	.06	1.39	331.0	2.99	1.34	10.49	3.71
50	10	608	8.0	13.0	8.16	1.67	2.09	.03	1.39	329.1	3.67	1.94	10.20	3.69
50	15	609	8.0	13.0	8.28	1.70	1.94	.05	1.44	321.3	4.57	2.52	10.18	3.56
50	20	610	8.0	12.5	8.21	1.69	1.24	.15	1.45	319.4	3.85	1.89	10.16	3.88
50	25	611	8.0	10.1	8.05	1.95	.74	.30	1.45	340.2	4.47	2.23	10.91	5.23
50	30	612	8.0	9.0	8.07	1.88	.75	.28	1.51	333.8	6.19	3.19	11.33	5.45
50	35	613	8.0	9.0	8.02	1.98	.81	.28	1.71	332.0	4.00	4.30	12.27	6.88
124	0	703	8.0	13.0	8.35	2.25	1.44	.07	1.16	288.3	2.99	2.40	10.40	5.89
124	5	704	8.0	13.0	8.34	2.19	1.42	.08	1.14	280.3	3.46	2.52	10.37	5.97
124	10	705	8.0	12.5	8.34	2.21	1.74	.06	1.19	281.3	2.84	2.06	10.51	5.77
124	15	706	8.0	12.0	8.28	2.14	1.98	.08	1.23	310.0	3.15	1.79	9.43	5.43
130	0	597	9.0	12.9	8.22	1.76	1.45	.11	1.27	322.2	4.66	4.54	10.13	4.09
130	5	598	9.0	12.9	8.22	1.73	1.79	.07	1.31	296.2	4.94	3.40	9.96	3.40
130	10	599	9.0	12.9	8.21	1.77	1.78	.04	1.30	315.5	4.53	3.16	9.80	4.00
130	15	600	9.0	12.6	8.27	1.72	1.78	.06	1.32	324.2	4.82	5.71	10.36	4.12
130	20	601	9.0	12.5	8.21	1.78	1.37	.15	1.31	305.8	3.32	1.86	10.00	3.54
130	25	602	9.0	11.5	8.23	1.83	.64	.37	1.30	323.6	2.15	1.46	10.29	4.49
130	30	603	9.0	10.0	8.02	1.95	.74	.30	1.38	335.3	3.19	2.83	10.52	4.61
130	35	604	9.0	8.9	7.96	2.01	.71	.32	1.54	345.5	2.27	1.06	10.76	5.08
130	40	605	9.0	8.0	7.98	2.00	.73	.32	1.45	342.2	1.42	.26	10.99	4.91

APPENDIX B. Primary Productivity at 5 m. Data in $mgCm^{-3}hr^{-1}$

App. B.1 Cruise 1, August 1973

STA	DEP M	SAMP	C14S SCREENS	C14A PPB-C/HR	C14T SCREENS	C14B PPB-C/HR	C14D PPB-C/HR	ALK PPM-C
7	5	28	1	1.8	1	1.7	.15	25.2
8	5	31	1	1.9	1	2.7	.22	25.2
10	5	49	1	2.0	1	2.0	.22	25.8
11	5	54	1	1.7	1	1.7	.18	25.4
12	5	60	1	1.7	1	1.5	.31	25.7
13	5	63	1	1.9	1	1.8	.18	25.5
15	5	71	1	2.0	1	2.1	.31	25.4
16	5	76	1	2.2	1	2.1	.19	25.9
17	4	79	1	2.9	1	3.3	.32	25.8
19	5	85	1	2.9	1	2.6	.26	25.8
20	5	90	1	2.5	1	1.8	.19	25.9
21	5	93	1	2.0	1	2.6	.18	25.2
22	5	96	1	2.4	1	2.2	.17	25.6
23	5	100	1	2.1	1	2.3	.17	25.9
25	5	107	1	1.4	1	1.3	.25	22.6
27	5	119	1	1.9	1	1.8	.20	24.2
29	5	139	1	2.2	1	2.5	.24	24.6
31	5	158	1	2.6	1	2.4	.19	22.9
32	5	163	1	1.8	1	1.7	.12	24.2
33	5	167	1	2.1	1	2.0	.16	24.2
34	5	171	1	1.7	1	1.6	.09	24.6
35	5	179	1	1.8	1	1.8	.14	24.6
36	5	189	1	1.7	1	1.5	.21	25.2

App. B.2 Cruise 2, September 1973

STA	DEP M	SAMP	C14S SCREENS	C14A PPB-C/HR	C14T SCREENS	C14B PPB-C/HR	C14D PPB-C/HR	ALK PPM-C
1	5	448	1	3.1	1	3.2	.24	24.6
2	5	443	1	3.0	1	3.2	.43	24.0
3	5	436	1	3.1	1	2.9	.25	24.1
4	5	431	1	2.9	1	1.8	.22	23.7
5	5	428	1	3.0	1	2.8	.36	21.3
6	5	425	1	4.2	1	3.9	.34	26.6
7	5	330	1	4.5	1	5.4	.34	22.9
8	5	332	1	3.9	1	4.3	.95	22.4
9	5	341	1	1.7	1	1.8	.18	20.5
10	5	350	1	2.6	1	2.5	.15	23.7
11	5	355	1	2.1	1	2.4	.17	25.3
12	5	361	1	1.8	1	2.1	.25	22.1
14	5	454	1	3.0	1	3.5	.29	26.5
15	5	459	1	2.6	1	3.0	.33	23.3
16	5	464	1	3.2	1	3.0	.23	21.5
17	5	478	1	2.5	1	2.2	.18	22.9
18	5	474	1	2.3	1	2.1	.38	22.9
19	5	470	1	2.8	1	2.6	.36	23.1
22	5	484	1	3.8	1	3.2	.40	22.9
23	5	488	1	3.6	1	2.4	.21	23.8
24	5	364	1	3.0	1	2.9	.17	26.3
25	5	368	1	2.4	1	2.4	.16	22.6
26	5	374	1	2.5	1	2.8	.17	24.1
27	5	381	1	2.2			.13	20.9
28	5	391	1	1.7	1	2.0	.14	18.8
29	5	401	1	1.6	1	1.9	.27	20.3
30	5	411	1	1.6	1	1.7	.41	22.1
31	5	420	1	1.5	1	2.0	.14	17.5
38	5	321	1	2.2	1	2.3	.17	20.7
39	5	313	1	2.7	1	3.0	.21	25.0
40	5	311	1	2.2	1	2.6	.18	24.0

App. B.2 cont.

STA	DEP M	SAMP	C14S SCREENS	C14A PPB-C/HR	C14T SCREENS	C14B PPB-C/HR	C14D PPB-C/HR	ALK PPM-C
41	5	309	1	2.2				22.1
41	45	301	1	.6	1	.0	.40	22.1
42	5	291	1	2.3	1	1.9	.34	19.1
43	5	281	1	1.7	1	1.7	.10	17.2
44	5	271	1	1.8	1	1.7	.10	21.5
45	5	261	1	1.6	1	1.8	.13	20.9
46	5	254	1	2.5	1	2.4	.16	21.9
47	5	249	1	2.0	1	2.0	.29	17.5
48	5	245	1	2.0	1	2.0	.11	16.6
49	5	236	1	1.4	1	1.3	.08	17.5
50	5	228	1	1.5	1	1.5	.09	20.3
124	5	325	1	2.4	1	2.7	.14	21.1
130	5	219	1	1.2	1	1.2	.16	21.1

App. B.3 Cruise 3, October 1973

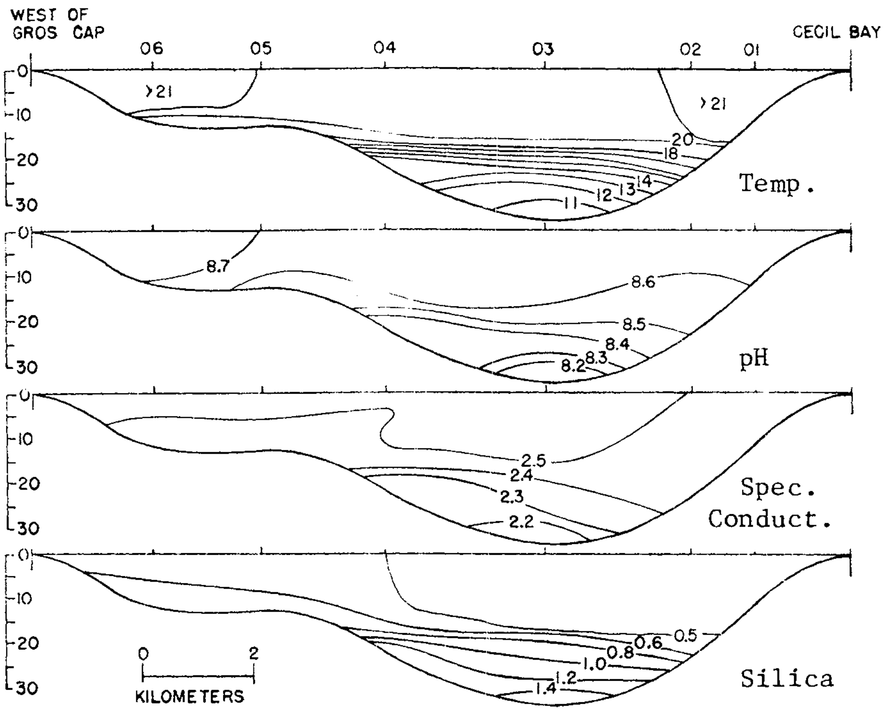
STA	DEP M	SAMP	C14S SCREENS	C14A PPB-C/HR	C14T SCREENS	C14B PPB-C/HR	C14D PPB-C/HR	ALK PPM-C
1	5	514	0	4.5	1	3.6	.46	25.9
2	5	509	0	4.9	1	3.4	.49	25.1
3	5	502	0	4.2	1	2.9	.51	25.2
4	5	497	0	4.2	1	2.9	.36	24.6
5	5	494	0	4.3	1	2.5	.45	24.4
6	5	491	0	4.5	1	6.5	.54	24.6
7	5	572	0	2.4	1	.4		20.7
8	5	575	0	2.9	1	2.1		20.7
9	5	584	0	2.9	1	1.8		21.3
10	5	593	0	2.6	1	1.7		19.8
11	5	520	0	2.7	1	2.0		20.0
12	5	517	0	3.4	1	.4		19.8
13	5	708	0	2.9	1	1.8	.37	22.6
14	5	711	0	2.1	1	1.9	.30	23.7
15	5	716	0	1.7	1	1.5	.18	22.8
16	5	721	0	2.2	1	1.9	.20	22.6
17	5	724	0	2.7	1	2.1	.23	25.3
18	5	727	0	2.0	1	2.5	.34	22.4
19	5	730	0	2.4	1	1.5	1.32	22.3
20	5	735	0	2.6	1	2.7	.37	20.3
21	5	738	0	2.3	1	1.6	.17	20.3
22	5	741	0	1.9	1	1.9	.17	22.8
23	5	745	0	2.3	1	1.7	.16	24.0
24	5	748	0	1.9	1	2.0	.27	20.5
25	5	752	0	2.3	1	1.7	.15	19.1
26	5	757	0	2.6	1	1.6	.15	19.1
27	5	764	0	1.8	1	2.4	.10	18.6
28	5	774	0	1.8	1	1.7	.12	17.2
29	5	784	0	1.9	1	1.7	.18	17.8
30	5	794	0	1.9	1	1.3	.14	17.2
31	5	803	0	1.7	1	1.4	.14	17.5

App. B.3 cont.

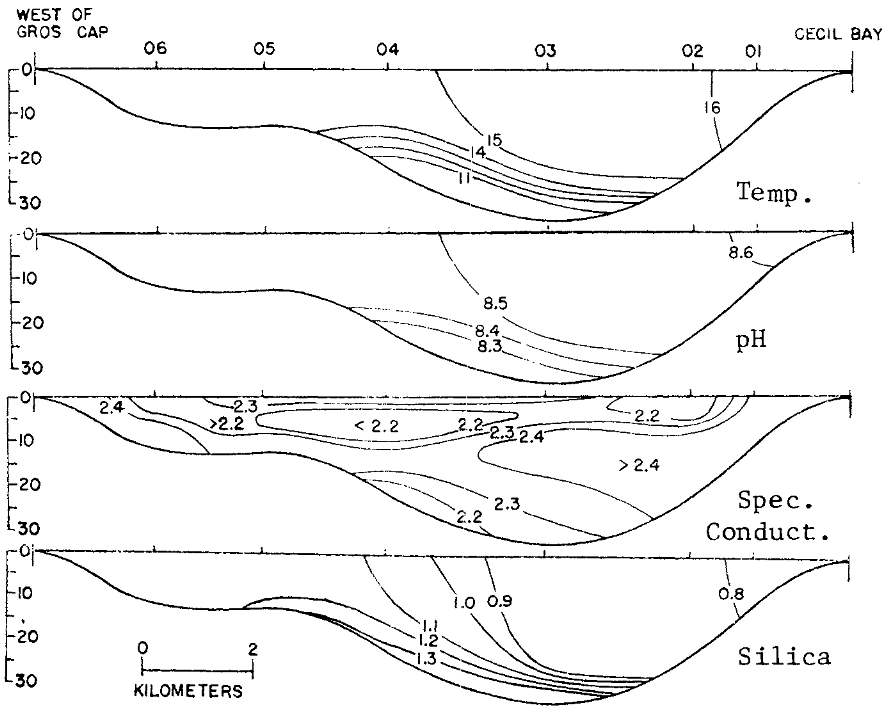
STA	DEP M	SAMP	C14S SCREENS	C14A PPB-C/HR	C14T SCREENS	C14B PPB-C/HR	C14D PPB-C/HR	ALK PPM-C
32	5	568	0	3.4	1	2.4		18.8
33	5	564	0	3.7	1	2.5		19.1
34	5	556	0	3.2	1	2.2		18.8
35	5	546	0	3.7	1	2.1		19.8
36	5	536	0	3.3	1	2.6		20.0
37	5	526	0	3.4	1	3.0		21.3
38	5	700	0	3.8	1	1.7	.44	21.9
39	5	692	0	2.3	1	1.5	.33	19.1
40	5	690	0	2.1	1	1.6	.35	22.1
41	5	680	0	1.5	1	.5	.26	19.6
42	5	670	0	1.8	1	1.9	.27	20.3
43	5	660	0	2.2	1	2.7	.36	18.8
44	5	650	0	2.6	1	1.7	.21	19.3
45	5	640	0	3.0	1	2.2	.29	24.5
46	5	633	0	1.9	1	1.4	1.00	17.5
47	5	628	0	2.6	1	2.1	.30	16.0
48	5	624	0	2.6	1	2.0	.50	14.2
49	5	615	0	2.1	1	2.4	.27	16.9
50	5	607	0	2.1	1	1.6	.29	18.0
124	5	704	0	3.1	1	1.6	.19	21.1
130	5	598	0	2.0	1	1.3	.14	18.0

APPENDIX C. Depth profiles of north-south transects

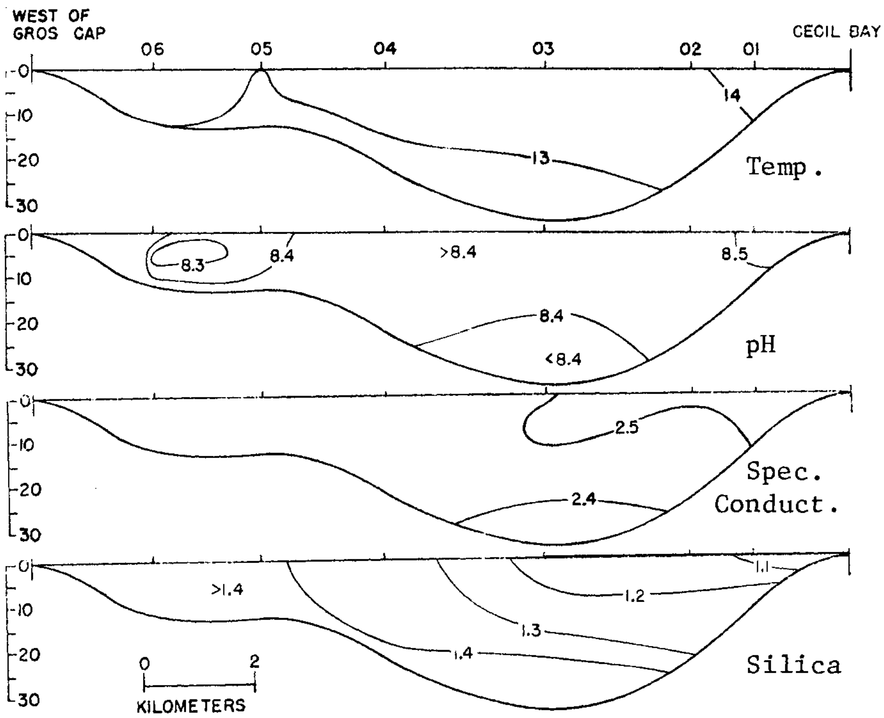
Appendix C.1 Transect 01-06, Cruise 1, August 1973



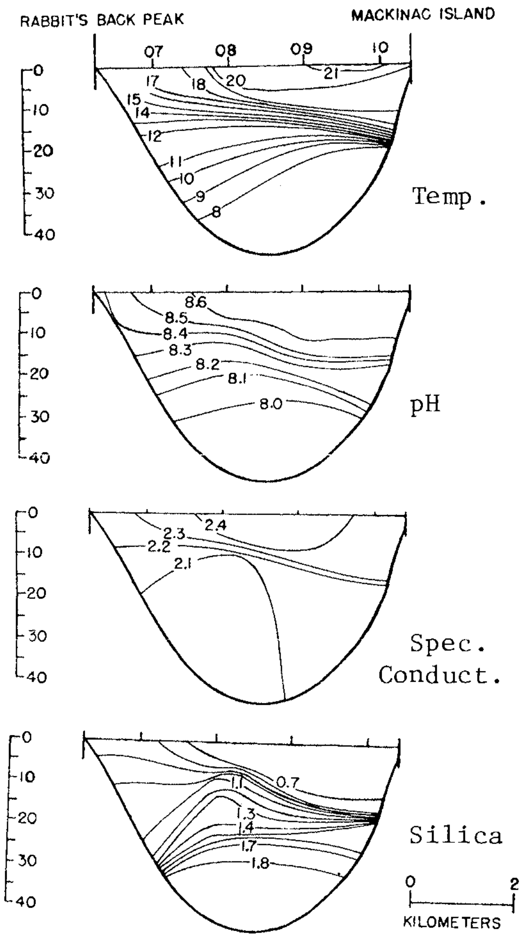
Appendix C.2 Transect 01-06, Cruise 2, September 1973



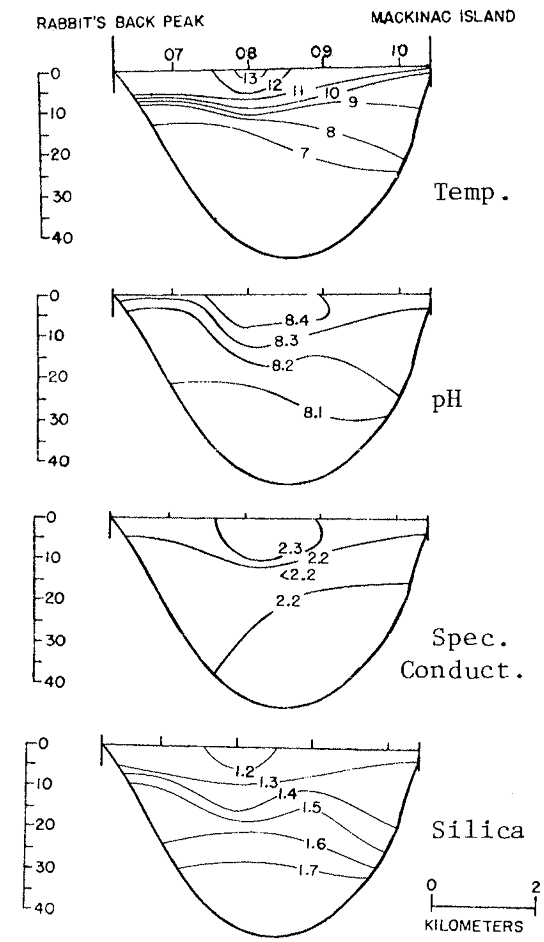
Appendix C.3 Transect 01-06, Cruise 3, October 1973



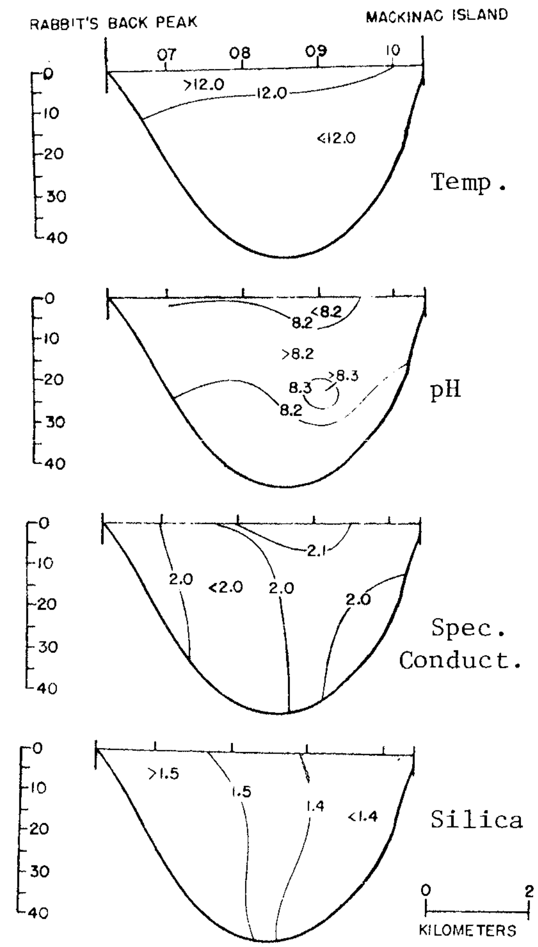
App. C.4
Transect 07-10, Cruise 1
August 1973



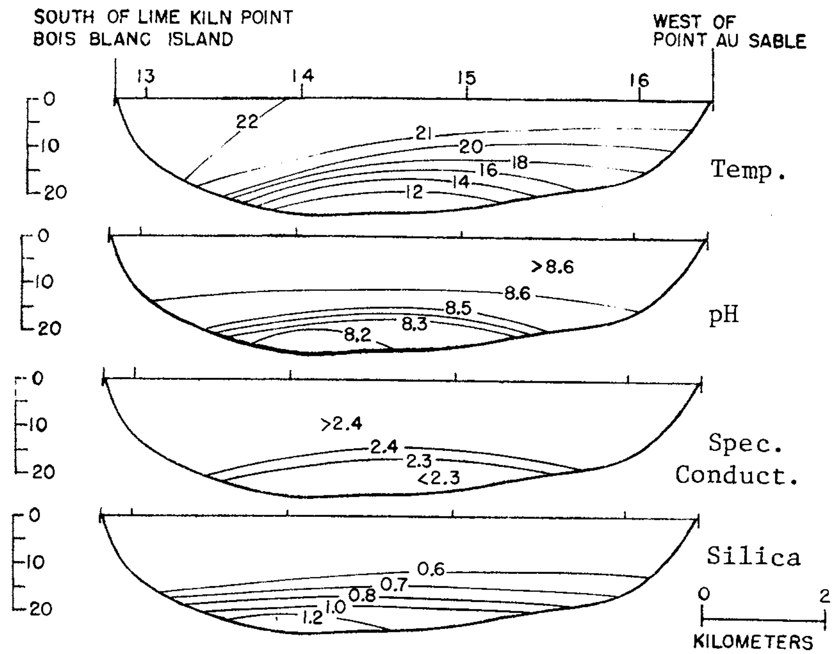
App. C.5
Transect 07-10, Cruise 2
September 1973



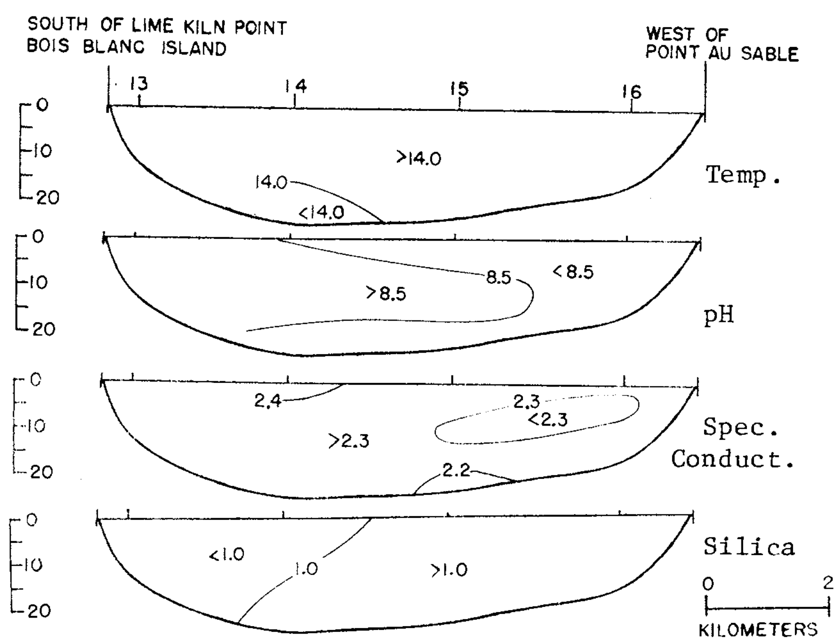
App. C.6
Transect 07-10, Cruise 3
October 1973



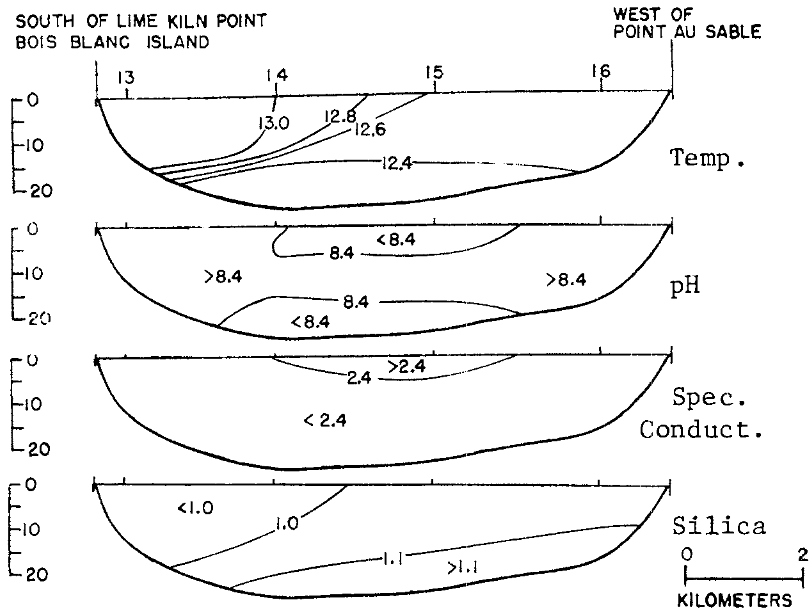
App. C.7 Transect 13-16, Cruise 1, Aug. 1973



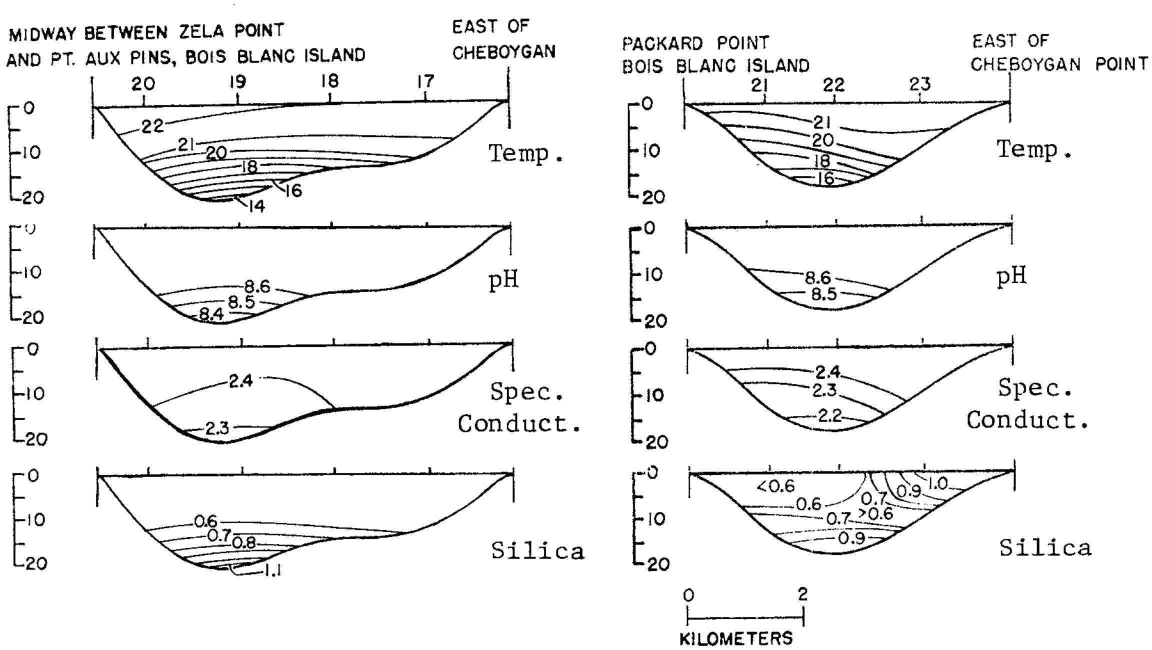
App. C.8 Transect 13-16, Cruise 2, Sept. 1973



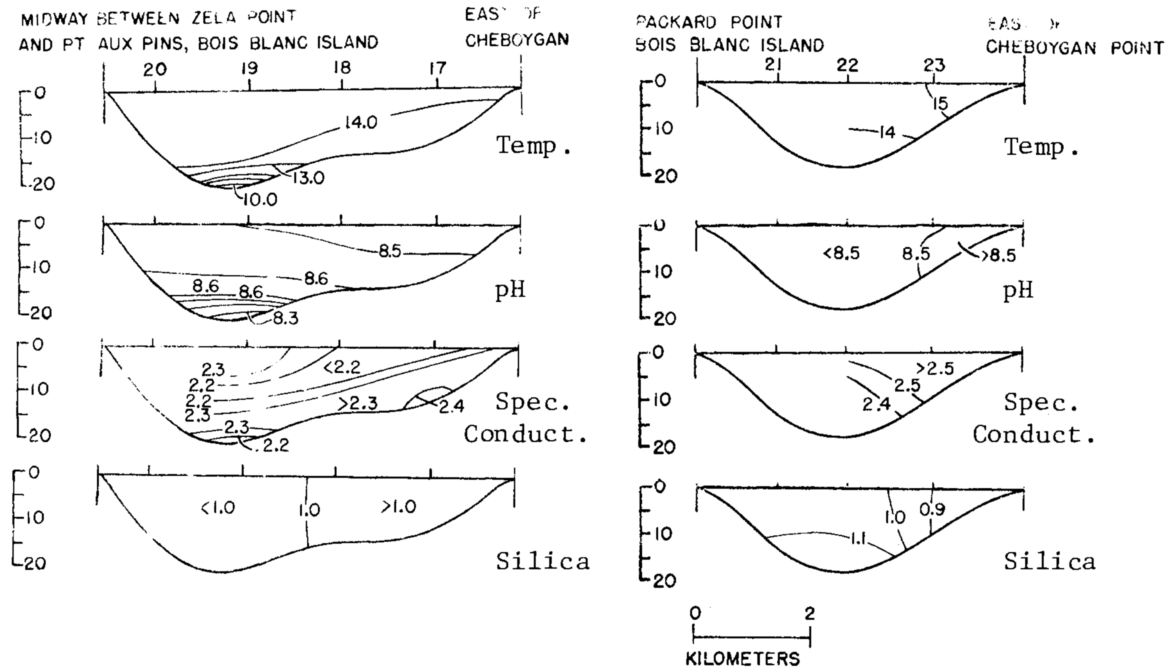
App. C.9 Transect 13-16, Cruise 3, Oct. 1973



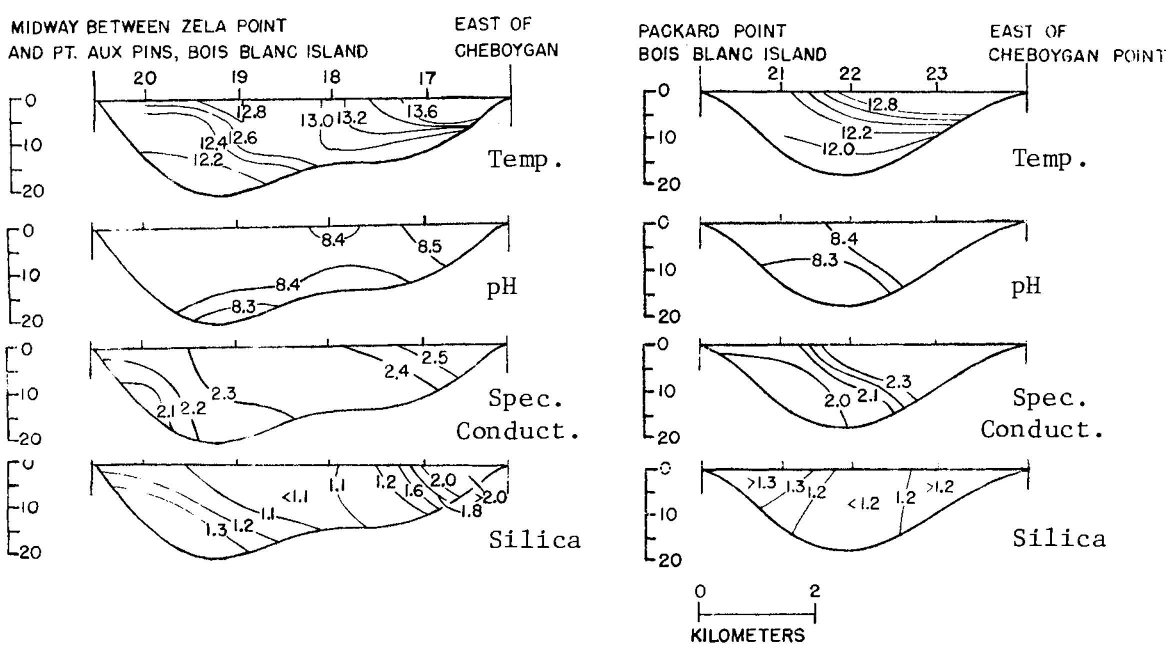
App. C.10 Transect 17-23, Cruise 1, August 1973



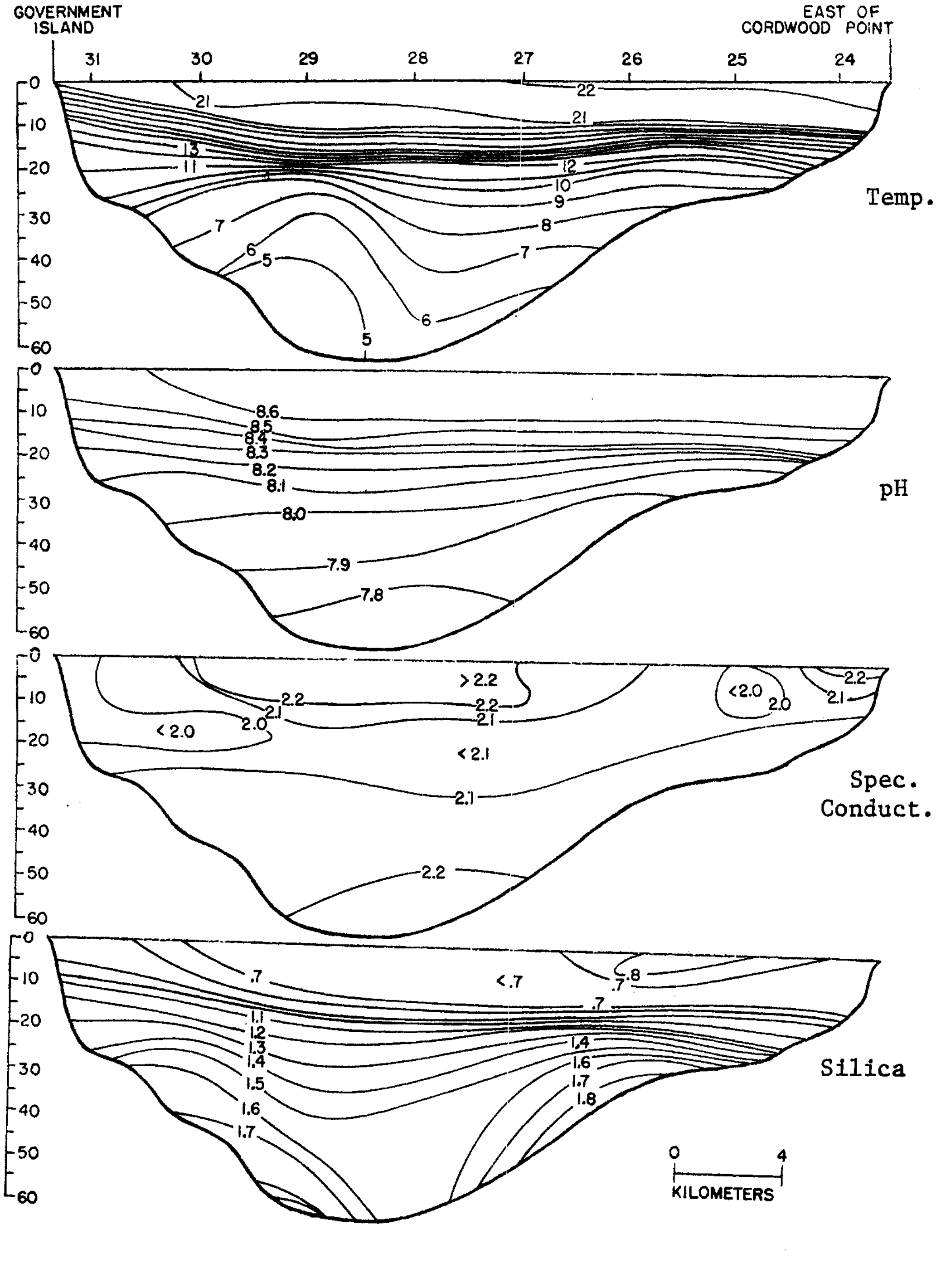
App. C.11 Transect 17-23, Cruise 2, September 1973



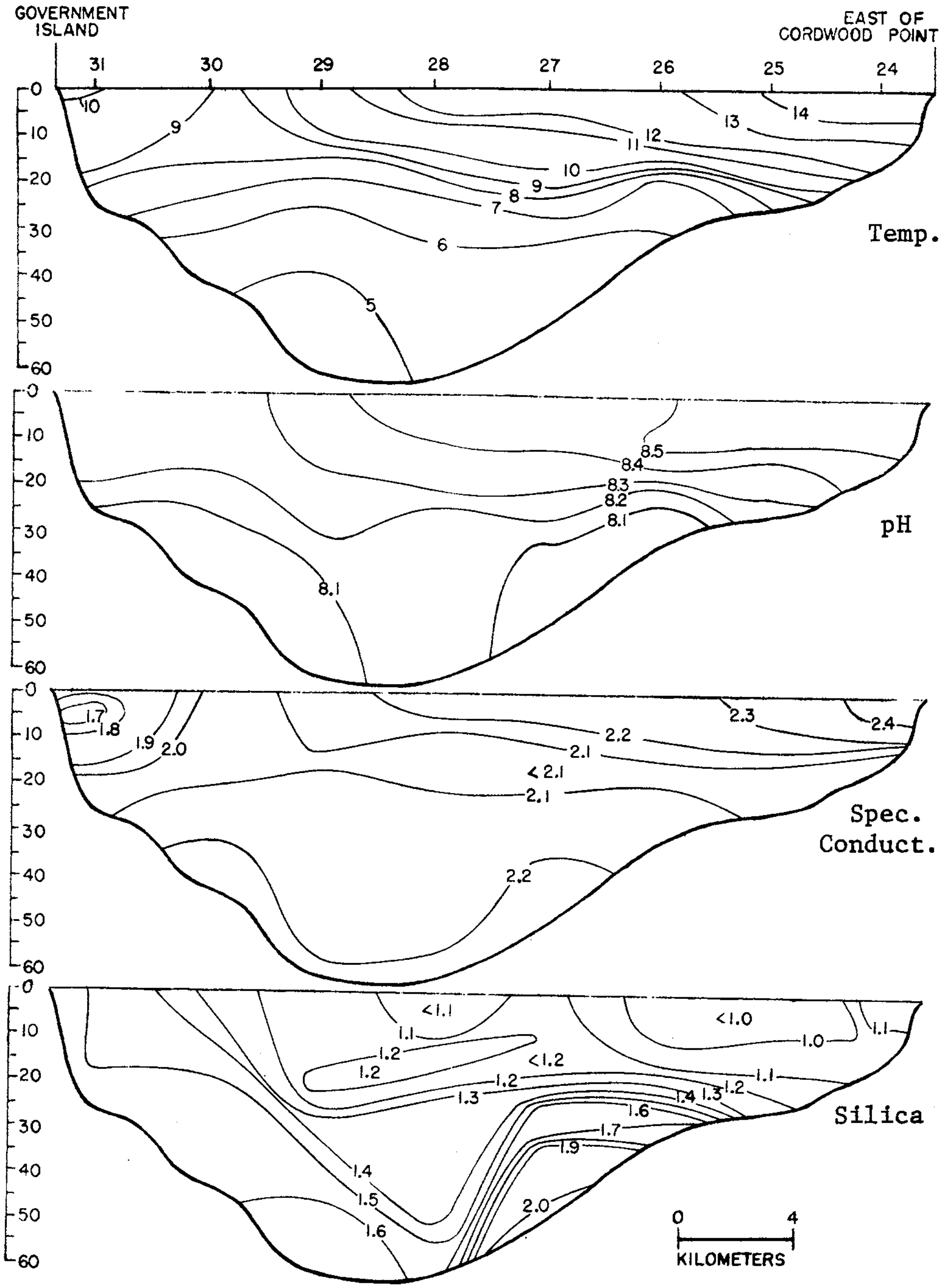
App. C.12 Transect 17-23, Cruise 3, October 1973



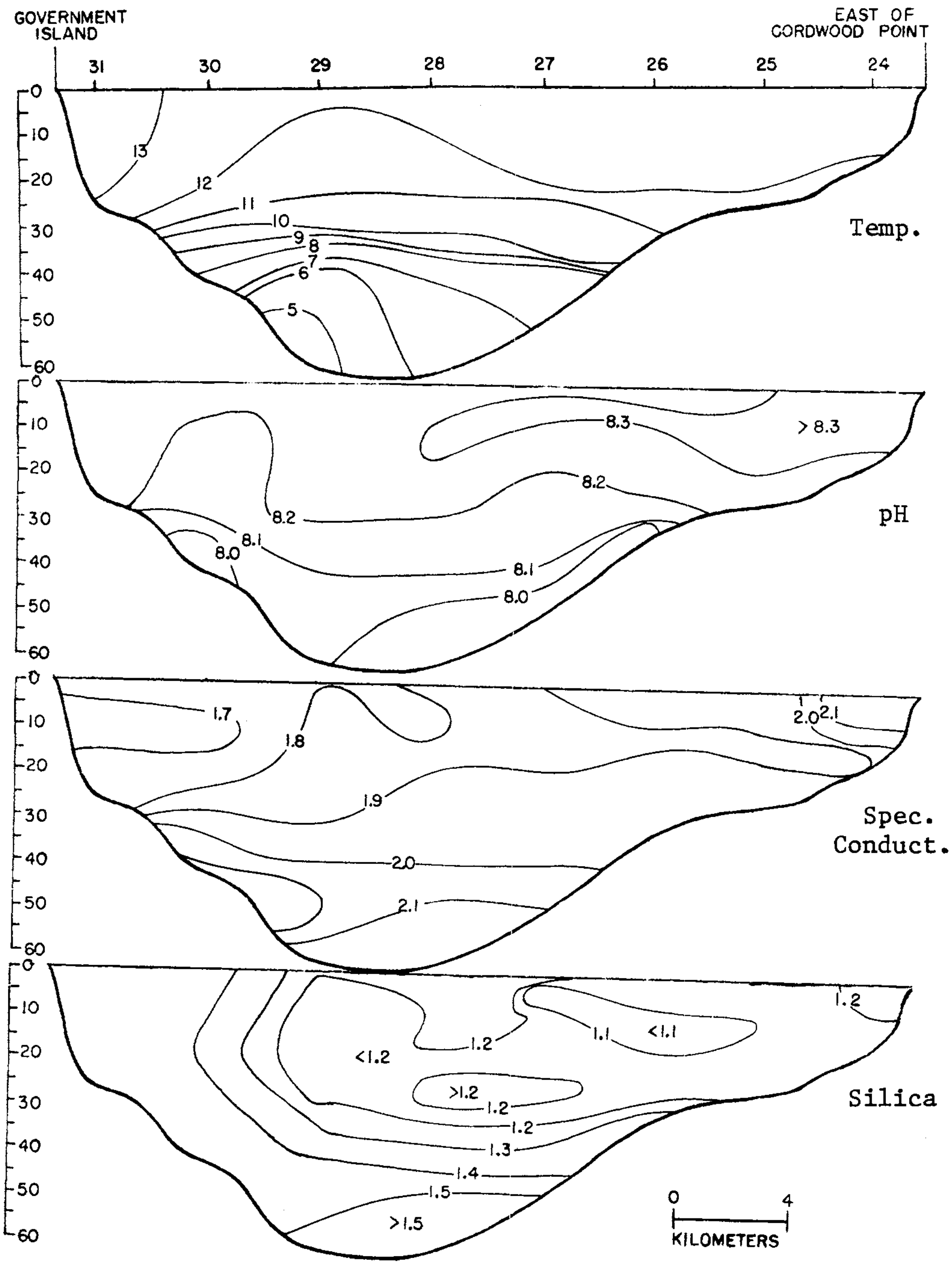
App. C.13 Transect 24-31, Cruise 1, August 1973



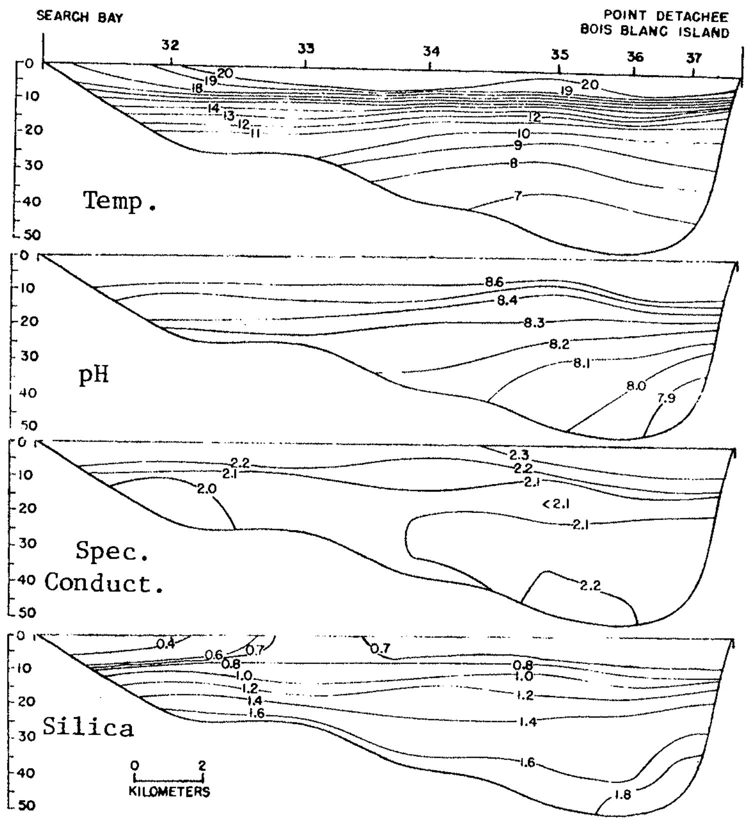
App. C.14 Transect 24-31, Cruise 2, September 1973



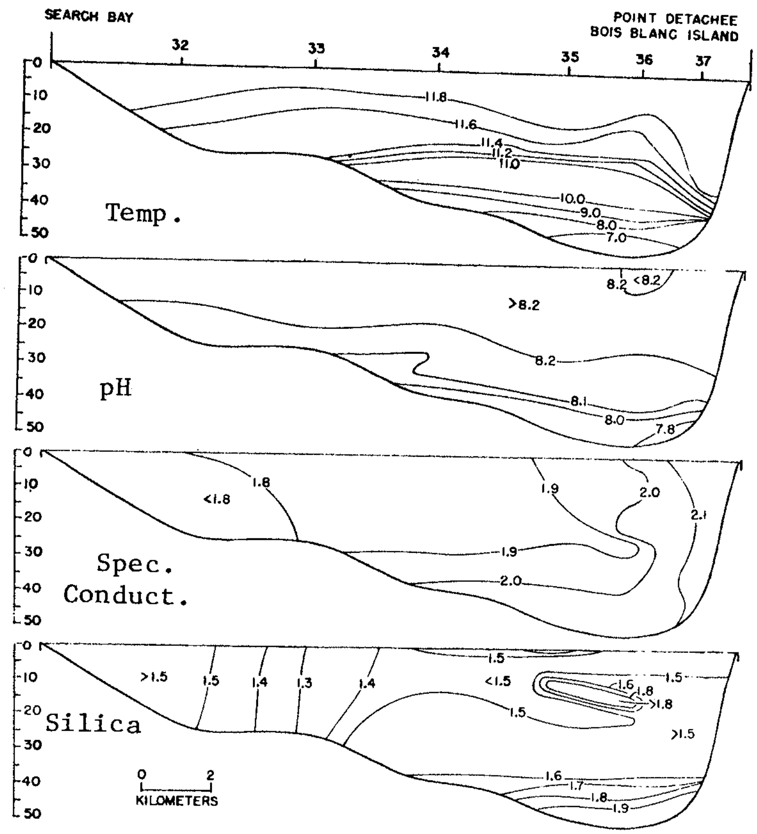
App. C.15 Transect 24-31, Cruise 3, October 1973



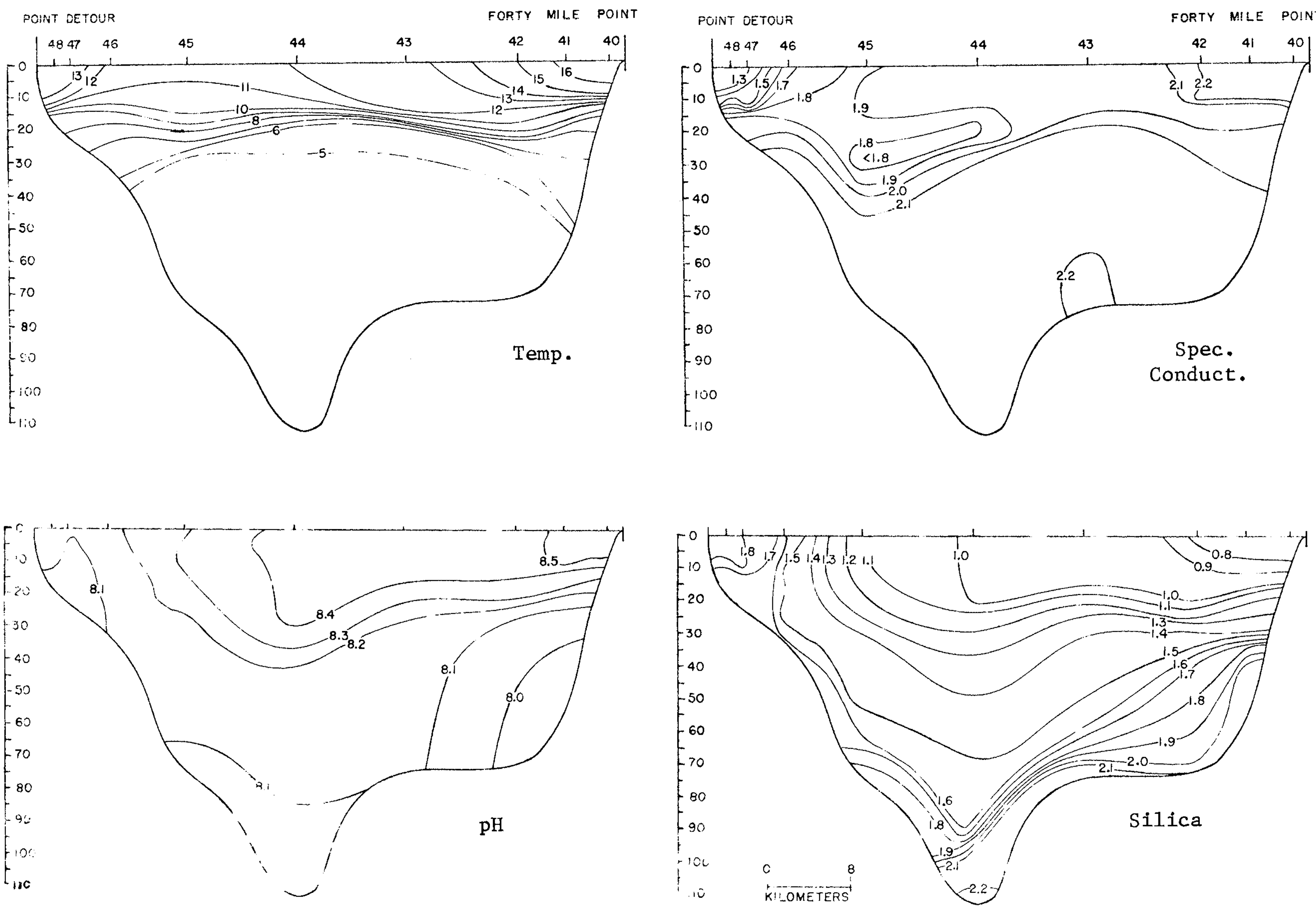
App. C.16
Transect 32-37, Cruise 1, August 1973



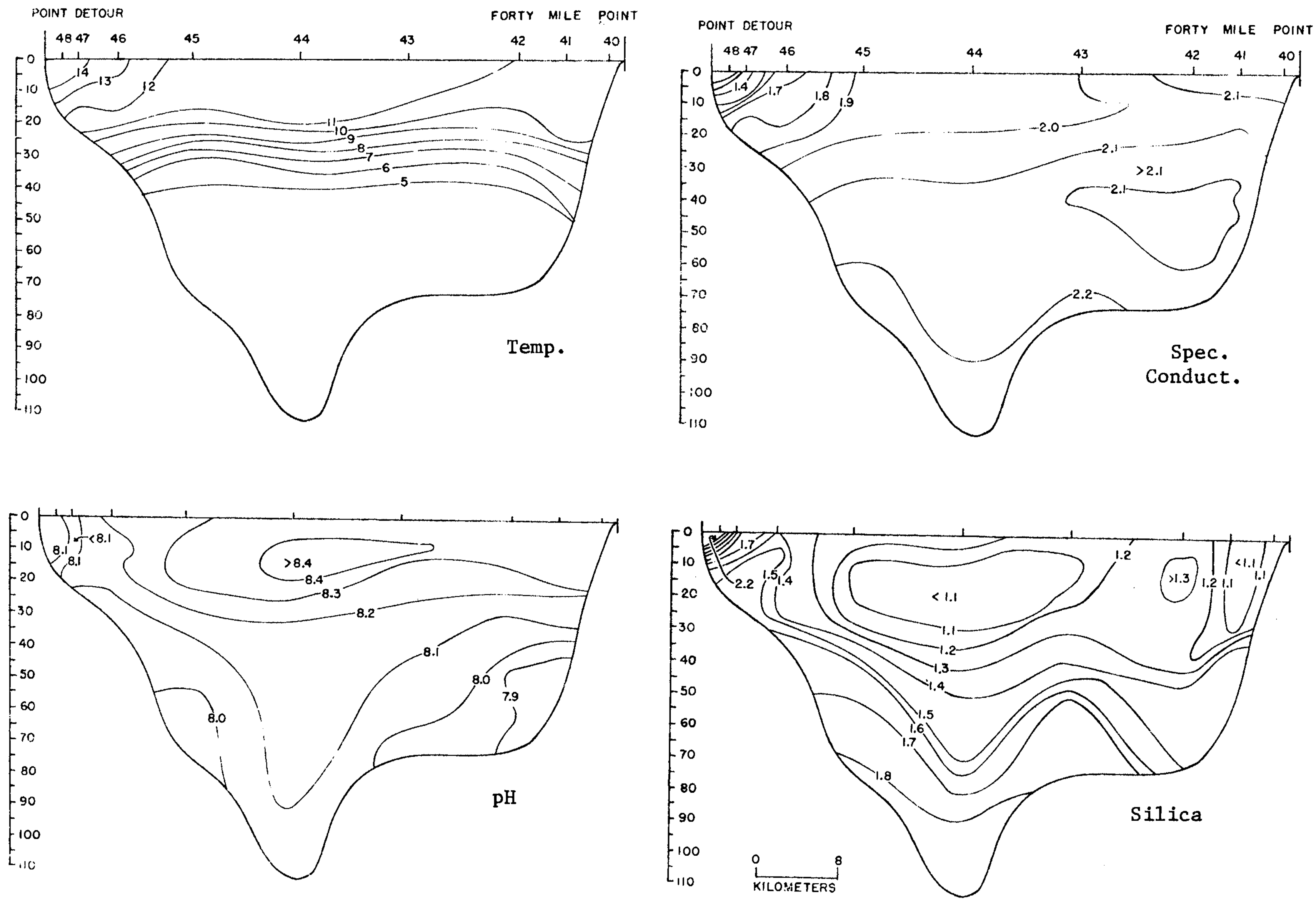
App. C.17
Transect 32-37, Cruise 3, October 1973



App. C.18 Transect 40-48, Cruise 2, September 1973



App. C.19 Transect 40-48, Cruise 3, October 1973



APPENDIX D

List of species found in phytoplankton collections

BACILLARIOPHYTA

Achnanthes affinis Grun.
A. biasolettiana (Kütz.) Grun.
A. clevei Grun.
A. clevei var. *rostrata* Hust.
A. exigua Grun.
A. exigua var. *constricta* (Grun.) Hust.
A. exigua var. *heterovalva* Krasske
A. lanceolata (Bréb.) Grun.
A. lanceolata var. *dubia* Grun.
A. lanceolata var. *omissa* Reim.
A. laterostrata Hust.
A. linearis (Wm. Smith) Grun.
A. linearis fo. *curta* H. L. Smith
A. microcephala (Kütz.) Grun.
A. minutissima Kütz.
A. minutissima var. *cryptocephala* Grun.
A. peragalli Brun
A. pinnata Hust.
A. subsaloides Hust.

Species *incertae sedis*
Achnanthes questionable sp. #1
Achnanthes sp. #1
Achnanthes sp. #15
Achnanthes sp. #28

Amphipleura pellucida Kütz.

Amphiprora ornata Baily

Amphora hemicycla Stoerm. and Yang
A. ovalis var. *libyca* (Ehr.) Cleve
A. ovalis var. *pediculus* (Kütz.) V. H.
A. ovalis Kütz.
A. veneta var. *capitata* Haworth

Species *incertae sedis*
Amphora questionable sp. #1

Anomoeoneis vitrea (Grun.) Ross

Species *incertae sedis*
Anomoeoneis vitrea var. #1 (abnormal)
Anomoeoneis sp. #3

Asterionella formosa Hass.

Caloneis alpestris (Grun.) Cleve

Species *incertae sedis*
Caloneis ventricosa var. #2

Cocconeis diminuta Pant.
C. pediculus Ehr.
C. placentula Ehr.
C. placentula var. *euglypta* (Ehr.) Cleve
C. placentula var. *lineata* (Ehr.) V. H.

Species *incertae sedis*
Cocconeis questionable sp. #1
Cocconeis sp. #4

Cyclotella antiqua Wm. Smith
C. atomus Hust.
C. comensis Grun.
C. comta (Ehr.) Kütz.
C. cryptica Reimann, Lewin, and Guillard
C. kuetzingiana Thwaites
C. kuetzingiana var. *planetophora* Fricke
C. kuetzingiana var. *radiosa* Fricke
C. meneghiniana Kütz.
C. meneghiniana var. *plana* Fricke
C. michiganiana Skv.
C. ocellata Pant.
C. operculata (Agardh) Kütz.
C. stelligera (Cleve and Grun.) V. H.

Species *incertae sedis*
Cyclotella comta auxospore
Cyclotella stelligera auxospore
Cyclotella sp. auxospore
Cyclotella sp. #5
Cyclotella sp. #7

Cymatopleura solea (Bréb. and Godey) Wm. Smith

Cymbella cesatii Grun.
C. cistula (Ehr.) Kirchn.
C. cistula var. *gibbosa* J. Brun
C. delicatula Kütz.
C. hustedtii Krasske
C. leptoceros var. *rostrata* Hust.
C. microcephala Grun.
C. minuta Kütz.
C. obtusiuscula Kütz.
C. parvula Krasske
C. prostrata (Berk.) Cleve
C. subventricosa Cholnoky
C. triangulata (Ehr.) Cleve

Species *incertae sedis*
Cymbella questionable sp. #1
Cymbella sp. #15
Cymbella sp. #21

Denticula tenuis var. *crassula* (Naeg.) Hust.

Diatoma tenue var. *elongatum* Lyngb.

Diploneis boldtiana Cleve
D. elliptica var. *pygmaea* A. Cl.
D. oculata (Bréb.) Cleve
D. parma Cleve

Species *incertae sedis*
Diploneis sp. #2

Epithemia smithii Carruthers

Eucocconeis flexella (Kütz.) Hust.
E. flexella var. *alpestris* (Brun) Hust.
E. lapponica Hust.

Eunotia exigua (Bréb.) Rabh.
E. incisa Wm. Smith
E. praerupta var. *inflata* Grun.

Fragilaria brevistriata Grun.
F. brevistriata var. *inflata* (Pant.) Hust.
F. capucina Desm.
F. construens (Ehr.) Grun.
F. construens var. *minuta* Temp. and Per.
F. construens var. *pumila* Grun.
F. construens var. *venter* (Ehr.) Grun.

Fragilaria crotonensis Kitton
F. crotonensis var. *oregona* Sov.
F. intermedia Grun.
F. intermedia var. *fallax* Grun.
F. lapponica Grun.
F. leptostauron (Ehr.) Hust.
F. leptostauron var. *dubia* (Grun.) Hust.
F. pinnata Ehr.
F. pinnata var. *intercedens* (Grun.) Hust.
F. pinnata var. *lancettula* (Schum.) Hust.
F. vaucheriae (Kütz.) Peters
F. vaucheriae var. *capitellata* (Grun.) Patr.
F. vaucheriae var. *lanceolata* A. Mayer

Species *incertae sedis*
Fragilaria questionable sp. #1
Fragilaria crotonensis Kitton (abnormal)

Frustulia rhomboides var. *amphipleuroides* (Grun.) Cleve

Gomphonema intricatum Kütz.
G. intricatum var. *pumila* Grun.
G. lanceolatum Ehr.

Species *incertae sedis*
Gomphonema questionable sp. #1

Gyrosigma attenuatum (Kütz.) Rabh.
G. spencerii (Quek.) Griff. and Henfr.

Hannaea arcus (Ehr.) Patr.

Mastogloia grevillei Wm. Smith

Melosira distans var. *alpigena* Grun.
M. granulata (Ehr.) Ralfs.
M. granulata var. *angustissima* O. Müll.
M. islandica O. Müll.
M. italica subsp. *subartica* O. Müll.

Navicula anglica var. *subsalsa* (Grun.) Cleve
N. aurora Sov.
N. capitata Ehr.
N. capsa Hohn
N. cryptocephala Kütz.
N. cryptocephala var. *veneta* (Kütz.) Rabh.
N. decussis Østr.
N. exigua Greg. ex. Grun.

Navicula lacustris Greg.
N. lanceolata (Agardh) Kütz.
N. minima Grun.
N. nyassensis O. Müll.
N. placentula var. *rostrata* A. Mayer
N. pseudoscutiformis Hust.
N. pupula Kütz.
N. radiosa Kütz.
N. radiosa var. *parva* Wallace
N. radiosa var. *tenella* (Bréb.) Grun.
N. rhynchocephala Kütz.
N. stroesei A. Cl.
N. tuscula fo. *obtusa* Hust.
N. vulpina Kütz.

Species *incertae sedis*
Navicula questionable sp. #1
Navicula sp. #1
Navicula sp. #12
Navicula sp. #35

Neidium dubium fo. *constrictum* Hust.

Nitzschia acicularis (Kütz.) Wm. Smith
N. acuta Hantz.
N. amphibia Grun.
N. angustata var. *acuta* Grun.
N. bacata Hust.
N. capitellata Hust.
N. confinis Hust.
N. denticula Grun.
N. dissipata (Kütz.) Grun.
N. dissipata var. *media* (Hantz.) Grun.
N. fonticola Grun.
N. insecta Hust.
N. luzonensis Hust.
N. palea (Kütz.) Wm. Smith
N. recta Hantz.
N. sigma (Kütz.) Wm. Smith
N. sigmoidea (Nitz.) Wm. Smith
N. spiculoides Hust.
N. sublinearis Hust.

Species *incertae sedis*
Nitzschia questionable sp. #1
Nitzschia sp. #2
Nitzschia sp. #6

Nitzschia sp. #8
Nitzschia sp. #9
Nitzschia sp. #10
Nitzschia sp. #12

Opephora martyi Hérib.

Rhizosolenia eriensis H. L. Smith
R. gracilis H. L. Smith

Rhoicosphenia curvata (Kütz.) Grun.

Stephanodiscus alpinus Hust. *ex* Huber-Pestalozzi
S. astraea (Ehr.) Grun.
S. hantzschii Grun.
S. minutus Grun. *ex* Cleve and Möll.
S. niagarae Ehr.
S. niagarae var. *magnifica* Fricke
S. subtilis (Van Goor) A. Cl.
S. tenuis Hust.

Species *incertae sedis*
Stephanodiscus sp. #5
Stephanodiscus sp. auxospore

Surirella biseriata Bréb. and Godey
S. ovata Kütz.

Species *incertae sedis*
Surirella sp. #4

Synedra acus Kütz.
S. cyclopum Brutschy
S. delicatissima var. *angustissima* Grun.
S. demerarae Grun.
S. filiformis Grun.
S. minuscula Grun.
S. montana Krasske
S. ostenfeldii (Krieger) A. Cl.
S. parasitica (Wm. Smith) Hust.
S. parasitica var. *subconstricta* (Grun.) Hust.
S. tenera Wm. Smith
S. ulna (Nitz.) Ehr.
S. ulna var. *chaseana* Thomas
S. ulna var. *danica* (Kütz.) V. H.
S. ulna var. *longissima* (Wm. Smith) Brun

Species *incertae sedis*
Synedra questionable sp. #1
Synedra sp. #7
Synedra sp. #17

Tabellaria fenestrata (Lyngb.) Kütz.
T. fenestrata var. *geniculata* A. Cl.
T. fenestrata var. *intermedia* Grun.
T. flocculosa (Roth) Kütz.

CHLOROPHYTA

Ankistrodesmus gelifactum (Chod.) Bourr.
Botryococcus braunii Kütz.
Coelastrum microporum Naeg.
Cosmarium botrytis Menegh.
Crucigenia irregularis Wille
C. quadrata Morren
Eudorina elegans Ehr.
Franceia droescheri (Lemm.) G. M. Smith
Gloeocystis planctonica (W. and W.) Lemm.
Golenkinia radiata (Chod.) Wille
Lagerheimia ciliata (Lag.) Chod.
Nephrocytium agardhianum Naeg.
Pediastrum boryanum (Turp.) Menegh.
Quadrigula chodatii (Tan.-Ful.) G. M. Smith
Q. lacustris (Chod.) G. M. Smith
Scenedesmus arcuatus Lemm.
S. armatus (Chod.) G. M. Smith
S. bijuga (Turp.) Lag.
S. bijuga var. *alternans* (Reinsch) Hansg.
S. helveticus Chod.
S. quadricauda (Turp.) Bréb.
S. serratus (Chod.) Bohl.
Sphaerocystis schroeteri Chod.
Spondylosium planum (Wolle) W. and W.
Staurastrum paradoxum Meyen
S. paradoxum var. *biradiatum* (W. and W.) Griffiths
S. longipes (Nordst.) Teiling
Tetraëdron regulare Kütz.
Ulothrix subconstricta G. S. West

Species *incertae sedis*
Ankistrodesmus sp. #1
Ankistrodesmus sp. #2
Ankistrodesmus sp. #3

Ankistrodesmus sp. #4
Cosmarium sp. #1
Cosmarium sp. #2
Eutetramorus questionable sp. #1
Gloeocystis questionable sp. #1
Oocystis spp.
Staurastrum sp. #2
Undetermined green colony
Undetermined green colony questionable sp. #1
Undetermined green filament #2
Undetermined green filament #3
Undetermined green individual

CHRYSOPHYTA

Chrysococcus (*dokidophorus* Pasch.?)
Chrysosphaerella longispina Lautb.
Dinobryon bavaricum Imhof
D. cylindricum Imhof
D. divergens Imhof
D. sociale Imhof
Mallomonas pseudocoronata Presc.
M. tonsurata var. *alpina* (Pasch. and Ruttn.) Krieger

Species *incertae sedis*
Chrysophyte cyst
Dinobryon cysts
Dinobryon questionable sp. #1
Mallomonas questionable sp. #1

CRYPTOPHYTA

Cryptomonas ovata Ehr.
Rhodomonas minuta var. *nannoplanctica* Skuja

Species *incertae sedis*
Cryptomonas cyst

CYANOPHYTA

Anabaena flos-aquae (Lyngb.) Bréb.
Anacystis incerta (Lemm.) Dr. and Daily
A. thermalis (Menegh.) Dr. and Daily
Gomphosphaeria lacustris Chod.
Oscillatoria bornetii Zukal

PYRROPHYTA

Ceratium hirundinella (O. F. Müll.) Shrank
Peridinium cinctum (O. F. Müll.) Ehr.

Species *incertae sedis*
Peridinium questionable sp. #1

APPENDIX E

Proof that a conservative parameter can be expressed as a linear combination of other conservative parameters

Definition: A conservative parameter is defined as one which has a measured value y in a mixture of volumes V_i from N different sources, such that:

$$\text{i)} \qquad y = \frac{\sum_{i=1}^{N} V_i \, Y_i}{\sum_{j=1}^{N} V_j} = \sum_{i=1}^{N} F_i \, Y_i$$

and where Y_i = measured value of the conservative parameter at source i

and $$F_i = \frac{V_i}{\sum_{j=1}^{N} V_j}$$ = the fraction of water in the final mixture from source i

To show: If Y is a conservative parameter, then it is expressable as a linear combination of any two other conservative parameters T and C in a mixture of water from three water sources.

Proof: For convenience, rewrite eq. i using vector notation:*

$$\text{ii)} \qquad y = \vec{F} \cdot \vec{Y}$$

where $\vec{F} = (F_1, F_2, \ldots, F_N)$ = the vector of fractions

$\vec{Y} = (Y_1, Y_2, \ldots, Y_N)$ = the vector of values of Y at the sources

N = the number of sources = 3, for this case.

Write eq. ii for each of the three conservative parameters:

$$\text{iii)} \qquad t = \vec{F} \cdot \vec{T}$$

$$\text{iv)} \qquad c = \vec{F} \cdot \vec{C}$$

$$\text{v)} \qquad y = \vec{F} \cdot \vec{Y}$$

* This proof uses terminology from linear algebra. Refer to any standard text on that subject.

Note that: $\sum_{i=1}^{N} F_i = \frac{\sum_{i=1}^{N} V_i}{\sum_{j=1}^{N} V_j} = 1$, or:

vi) $\vec{F} \cdot \vec{G} = 1$ where $\vec{G} = (1,1,1)$

We must now make two requirements on $\vec{T}$ and $\vec{C}$. First, it is necessary that $\vec{T}$ and $\vec{C}$ are independent of each other. This is a logical requirement, since if they are not independent, then they are proportional and consequently redundant. Examples of non-independent variables are the concentrations of dissolved nitrate in ppm and μg at/l or, in most cases, the concentrations of Na^+ and Cl^-. Second, it is necessary that $\vec{T}$ and $\vec{C}$ both be independent of $\vec{G}$. This is also a logical requirement. Any parameter not fulfilling this requirement will have the same value at all the sources, thus will be useless as a tracer. If these two requirements are met, then $\vec{T}$, $\vec{C}$, and $\vec{G}$ are mutually independent and are thus a basis for all three-dimensional vectors. Consequently, $\vec{Y}$ is expressable as a linear combination of $\vec{T}$, $\vec{C}$, and $\vec{G}$:

vii) $\vec{Y} = \beta\vec{T} + \gamma\vec{C} + \alpha\vec{G}$

Combining eq. v with eq. vii:

$$
\begin{aligned}
\text{v)}\quad y &= \vec{Y} \cdot \vec{F} \\
&= (\beta\vec{T} + \gamma\vec{C} + \alpha\vec{G}) \cdot \vec{F} \\
&= \beta\vec{T}\cdot\vec{F} + \gamma\vec{C}\cdot\vec{F} + \alpha\vec{G}\cdot\vec{F}
\end{aligned}
$$

viii) $y = \beta t + \gamma c + \alpha$

Equation viii shows that any conservative parameter y can be expressed as a linear combination of any two other independent, non-uniform conservative parameters if there are exactly three sources. By a simple extension of this argument, it can be shown that:

> If there are N sources, then any conservative parameter (as defined in eq. i or ii) can be expressed as a linear combination of N-1 other conservative parameters which are neither uniform at all the sources nor proportional to each other (dependent).

Implicit in this discussion is the assumption that the values of the parameters at the sources do not change with time.

APPENDIX F. Counts of zooplankton from vertical net tows

Appendix F.1

Cruise: 1

Station:	1A*	1B	2A	2B	3	3	4A
Date:	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30
Tow length in meters:	14→S	14→S	21→S	21→S	40→20	20→S	25→S
Species:							
Calanoid Copepoda							
D ash	60	42	27	67	74	76	49
D min	318	311	1626	1282	48	908	752
D oreg	286	481	661	482	292	700	352
D siclis		14					18
D cops	481	523	509	661	2612	437	879
E lac	127	141	116	107	17	149	30
L mac					30		
S cal							
Cyclopoid Copepoda							
C bi th	74	43	259	183	287	233	206
M edax					2		6
T pr mex							
Cladocera							
L kind	71	57	71	27	7	42	115
P ped			9	18		8	42
D leuch	25	28		13			
S cryst							
H gib	923	905	956	916	215	1146	740
D gal me	3325	3282	2127	1805	483	1732	1316
D long	11				50		424
D retro	2638	2900	1653	1372	316	1439	576
C lac			9	18	7		6
C quad	14						6
Cer ret							
B long	67	28	27	58	4		6
E coreg	608	1047	688	634	81	620	418
D dent							
A harp							
A affin							
A quad							
C sphaer							
E lamell							
Clad imm.	156	141			65	140	127
Calan Tot (#/m^3)	1272	1512	2939	2599	3073	2270	2080
Calan Tot (%)	13.9	15.2	33.6	34.0	69.1	29.8	34.3
Cyclo Tot (#/m^3)	74	43	259	183	289	233	212
Cyclo Tot (%)	0.8	0.4	3.0	2.4	6.3	3.1	3.5
Clad Tot (#/m^3)	7838	8388	5540	4861	1228	5127	3776
Clad Tot (%)	85.3	84.4	63.4	63.6	26.8	67.2	62.2
Grand Total	9184	9943	8738	7643	4590	7630	6068

Station:	4B	5A	5B	6	7	8	8
Date:	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30
Tow length in meters:	23→S	16→S	16→S	12→S	14→S	23→S	23→11
Species:							
Calanoid Copepoda							
D ash	89	194	155	12	369	184	326
D min	857	800	543	38	72		41
D oreg	364	715	791	22	396	57	357
D siclis						4	10
D cops	1496	1225	858	79	3824	6164	12844
E lac	40	97	39	13	55	10	31
L mac						8	
S cal							
Cyclopoid Copepoda							
C bi th	243	800	673	40	572	950	1783
M edax					8	4	10
T pr mex							
Cladocera							
L kind	89	109	100	32	44	6	20
P ped	89		12		8		
D leuch							
S cryst							
H gib	1059	1395	897	103	641	30	41
D gal me	1655	2583	1804	374	760	313	509
D long	32	133	21	37	1221	1251	2210
D retro	558	2365	1831	684	796	170	275
C lac	24	24	9		24		
C quad	8					12	
Cer ret							
B long	8	24	9	23	158	99	102
E coreg	493	667	491	93	303	89	132
D dent							
A harp							
A affin							
A quad							
C sphaer							
E lamell							
Clad imm.	121	182	340	9	127		295
Calan Tot (#/m^3)	2846	3031	2386	164	4716	6427	13609
Calan Tot (%)	39.4	26.8	27.8	10.5	50.3	68.7	71.7
Cyclo Tot (#/m^3)	243	800	673	40	580	954	1793
Cyclo Tot (%)	3.4	7.1	7.9	2.6	6.2	10.2	9.4
Clad Tot (#/m^3)	4136	7482	5514	1355	4082	1970	3584
Clad Tot (%)	57.2	66.1	64.3	86.9	43.5	21.1	18.9
Grand Total	7225	11313	8573	1559	9378	9351	18986

*Stations 1, 2, 4, and 5 were sampled twice during the same day. These samples are designated as "A" and "B".

App. F.1 cont.

Cruise: 1

Station:	8	9	9	10	11	11	11	11	12	13	14	14	15	16	17	18
Date:	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30	Aug 30	Sep 1	Sep 1	Aug 30	Sep 1	Sep 1	Sep 1	Sep 1	Sep 1	Sep 1	Sep 1
Tow length in meters:	11→S	33→16	16→S	23→S	29→13	13→S	29→16	16→S	13→S	19→S	25→19	19→S	25→S	22→S	10→S	15→S
Species:																
Calanoid Copepoda																
D ash	241	23	217	133	315	85	90	152	79	110	534	27	199	93	32	59
D min	311	23	212	259	12	116	74	800	771	1388	80	627	347	471	435	1166
D oreg	990	23	424	441	376	224	174	703	220	679	1670	268	694	484	32	500
D siclis		20												8		
D cops	1103	4510	1380	1164	8106	416	5929	1091	557	479	7639	236	1535	1286	350	686
E lac	85	3	42	101		54		267	50	130	46	32	81	115	64	176
L mac		91		12			3				45		7			
S cal		3														
Cyclopoid Copepoda																
C bi th	340	659	255	719	1667	54	722	345	205	260	1577	134	421	225	106	196
M edax				8	12		9			10	12			8	11	29
T pr mex												5				
Cladocera																
L kind	52		42	85	12	77	9	55	61	70	43	70	66	47	32	49
P ped			11	61		39	9	24	37	60	11	21		13		39
D leuch	42				18				8	40		11	15	21	11	[illegible]
S cryst																
H gib	1825	17	817	1091	297	4244	79	1589	1685	979	410	1238	1107	1536	1517	1978
D gal me	2660	113	2165	1904	2553	903	422	2534	1953	2317	2081	777	2030	2220	2133	2253
D long	1500	119	64	53	509	15	457	321	174	260	2254	80	760	225	223	313
D retro	1740	45	1241	1382	1140	370	321	1316	835	769	1227	306	827	1197	573	1283
C lac	28		11	8				30	16	10	11	11	7	8	11	
C quad							9		5							
Cer ret																
B long	170	37	74	97	49	77	15	103	71	40	67	16	66	21	32	
E coreg	806	40	361	812	103	1235	78	1801	1050	379	694	343	893	581	828	1440
D dent																
A harp																
A affin																
A quad																
C sphaer									6							
E lamell																
Clad imm.	523	14	265	174	491	231	106	327	19	200	666	118	362	140	32	127
Calan Tot (#/m³)	2730	4696	[illegible]	2110	8809	895	6279	3013	1677	2786	10014	1190	2863	2457	913	2587
Calan Tot (%)	22.0	81.[illegible]	30.0	24.8	56.3	11.0	73.[illegible]	26.3	21.[illegible]	34.1	52.5	27.5	30.4	28.2	14.2	25.1
Cyclo Tot (#/m³)	340	659	255	727	1679	54	731	345	205	270	1589	139	421	233	117	225
Cyclo Tot (%)	2.7	11.[illegible]	3.4	8.5	10.7	0.7	8.6	3.0	2.6	3.3	8.3	3.2	4.5	2.7	1.8	2.2
Clad Tot (#/m³)	9351	385	5051	5667	5172	7191	1505	8100	5920	5124	7464	2991	6133	6009	5392	7492
Clad Tot (%)	75.3	6.7	66.7	66.6	33.0	88.3	17.7	70.7	75.9	62.6	39.1	69.2	65.1	69.1	84.0	72.7
Grand Total	12421	5740	7576	8504	15660	8140	8515	11458	7802	8180	19067	4320	9417	8699	6422	10304

App. F.1 cont.

Cruise: 1

Station:	19	20	21	22	23	24	25	25	26	26	27	27	28	28	29	29
Date:	Sep 1	Sep 1	Sep 1	Sep 1	Sep 1	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31
Tow length in meters:	24→5	20→5	16→5	19→5	16→5	17→5	29→15	15→5	32→15	15→5	51→1	17→5	58→15	15→5	68→15	15→5
Species:																
Calanoid Copepoda																
D ash	54	127	182	18	56	124	193	40	161	51	91	157	34	158	44	167
D min	532	434	543	227	73	498	45	345	37	1019	4	397	9	622	9	419
D oreg	652	1306	800	336	119	141	157	79	123	306	102	315	16	260	24	209
D siclis					3		8		22				10		9	
D cops	660	1151	2665	701	671	1228	8172	781	9155	611	4035	906	15706	1063	3017	1647
E lac	139	184	115	108	83	62	12	116	6	102		82	1	158	1	139
L mac							61		67		182		74		28	42
S cal											14		9			
Cyclopoid Copepoda																
C bi th	448	307	543	264	169	130	1022	116	726	136	511	502	171	622	185	300
M edax		9	33	72	13	17	17	65	10	17	8	7		11		
T pr mex																
Cladocera																
L kind	58	33	18	54	40	45	4	54	37	25	5	22		57	1	[illegible]
P ped	39	9	18	6	3	62	8	65	4	59			1	3	2	[illegible]
D leuch	8	28	30	6				25		25	1			23	1	
S cryst																
H gib	868	1523	1379	917	562	973	247	702	141	1757	123	1378	28	1709	34	183
D gal me	1952	2268	1807	1102	625	979	1105	1171	605	1528	335	936	130	1347	254	1132
D long	166	585	382	240	13	45	376		83	17	306	225	118	136	183	424
D retro	1192	1250	882	491	311	549	266	399	176	331	140	472	48	396	93	583
C lac	8		9		10			6	4	17						
C quad			12													
Cer ret		14														
B long	23	9	52	24	13	28	27	82	23	34	19	52	20	102	51	110
E coreg	799	707	825	515	268	843	171	487	116	197	52	502	65	521	63	928
D dent																
A harp																
A affin																
A quad																
C sphaer																
E lamell																
Clad imm.	185	373	179	6	40	79	139	68	96	161	22	217	42	373	36	218
Calan Tot (#/m³)	2037	3202	4305	1385	1005	2053	8648	1361	9571	2089	4428	1857	15859	2261	3132	2623
Calan Tot (%)	26.2	31.0	41.1	27.3	32.7	35.4	71.9	29.6	82.5	32.7	74.4	30.1	96.2	29.8	77.6	34.7
Cyclo Tot (#/m³)	448	316	576	336	182	147	1039	181	736	153	519	509	171	633	185	300
Cyclo Tot (%)	5.8	3.1	5.5	6.6	5.9	2.5	8.6	3.9	6.3	2.4	8.7	8.2	1.0	8.3	4.6	4.0
Clad Tot (#/m³)	5298	6799	5593	3361	1885	3603	2343	3059	1295	4151	1003	3804	452	4687	718	4641
Clad Tot (%)	68.1	65.9	53.4	66.1	61.4	62.1	19.5	66.5	11.2	64.9	16.9	61.7	2.7	61.8	17.8	61.4
Grand Total	7783	10317	10474	5082	3072	5803	12030	4601	11602	6393	5950	6170	16482	7581	4035	7564

App. F.1 cont.

Cruise: 1

Station.	30	30	31	31	32	32	33	33	34	34	35	35	36	36	37	37
Date:	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31	Aug 31
Tow length in meters:	44→11	11→S	26→11	11→S	23→11	11→S	23→11	11→S	38→27	11→S	40→29	11→S	49→11	11→S	47→13	13→S
Species:																
Calanoid Copepoda																
D ash	115	194	509	142	511	93	560	93	2	102	5	147	120	51	134	47
D min	25	167	39	574		247	51	240	8	325	12	249	59	370	14	235
D oreg	99	417	470	336	196	302	373	266	4	174	28	411	212	597	65	118
D siclis	21	65	39		38	9						12	35	42	11	
D cops	6863	852	17068	1535	21413	1803	14854	942	1934	718	2573	2211	3299	1273	5211	466
E lac	21	130		37	17	117		245	2	108	5	46	73	162	8	161
L mac	41			15					19	5	39	12	21		29	
S cal															3	
Cyclopoid Copepoda																
C bi th	748	370	1946	732	995	787	1511	256	100	301	219	515	321	185	562	262
M edax	8	9	39	9		15	17	18		20		12		9	3	
T pr mex																
Cladocera																
L kind	21	28	13	28	7	34		23	2	24		23	35	3[illegible]	8	[illegible]
P ped				77		15						6				
D leuch	12	56	39	52		56		30	3	28	4	12	2	79	3	43
S cryst																
H gib	288	1982	457	1858	15	1324	340	1397	23	1420	48	955	252	991	100	1826
D gal me	661	1769	2377	2337	836	1843	1630	974	67	896	40	961	495	1792	326	1626
D long	567	556	2338	151	1238	710	2801	359	43	314	52	1065	457	607	485	423
D retro	329	1157	1450	1602	283	1688	662	873	22	725	18	642	354	1699	261	1105
C lac		28				15		55		5		6	5	9	8	
C quad														9	3	
Cer ret																
B long	181	278	248	404	20	417	323	336	12	216	26	197	35	181	40	98
E coreg	90	1028	261	1445	20	1219	153	642	33	517	31	336	125	634	67	846
D dent																
A harp																
A affin																
A quad																
[illegible] sphaer																
E lamell																
Clad imm.	107	176	[illegible]	262	281	336	306	159	10	76	5	104	87	185	89	208
Calan Tot (#/m^3)	7185	1825	18125	2639	22175	2571	15838	1786	1969	1432	2662	3088	3819	2495	4475	1027
Calan Tot (%)	70.5	19.7	65.2	22.8	85.7	23.3	67.2	25.9	86.2	24.0	85.7	39.0	63.8	28.0	69.6	13.6
Cyclo Tot (#/m^3)	756	379	1985	741	995	802	1528	274	100	321	219	527	321	194	565	262
Cyclo Tot (%)	7.4	4.1	7.1	6.4	3.8	7.3	6.5	4.0	4.4	5.4	7.1	6.7	5.4	2.2	8.8	3.5
Clad Tot (#/m^3)	2256	7058	7705	8216	2700	7657	6215	4848	215	4221	224	4307	1847	6223	1390	6285
Clad Tot (%)	22.1	76.2	27.[illegible]	70.9	10.4	69.4	26.4	70.2	9.4	70.7	7.2	54.4	30.9	69.8	21.6	83.0
Grand Total	10197	9262	[illegible]815	11596	25870	11030	23581	6908	2284	5974	3105	7922	5987	8912	6430	7574

Appendix F.2

Cruise: 2

Station.	1	2	3	4	5	6	7	8	9	11	12	14	15	16
Date:	Sep 19	Sep 19	Sep 19	Sep 19	Sep 19	Sep 19	Sep 18	Sep 18	Sep 18	Sep 18	Sep 18	Sep 19	Sep 19	Sep 19
Tow length in meters:	16→S	22→S	53→S	19→S	13→S	12→S	14→S	28→S	41→S	31→S	15→S	25→S	26→S	21→S
Species:														
Calanoid Copepoda														
D ash	25	34	10	35	43	51	19	13	6	56	274	31	7	7
D min	113	76		20	19	5	19	14	10	164	86	85	42	47
D oreg	651	433	206	205	272	389	40	56	87	187	313	168	99	214
D siclis			3				2		11	9	8		7	
D cops	221	187	250	649	693	556	1384	390	439	2477	1661	402	184	107
E lac	138	25	50	50	39	9	21	46	29	70	251	57	92	65
L mac			7			5	32		17	6	8			
S cal														
Cyclopoid Copepoda														
C bi th	80	34		75	69	185	89	23	10	899	533	30	67	87
M edax			3			19	4					13		18
T pr mex						5								
Cladocera														
L kind	98	51	27		14	65	17	22	1	20	24	33	32	29
P ped							2	9	1					9
D leuch					8	19			1			6		
S cryst														
H gib	258	204	63	75	79	56	45	145	34	138	133	271	276	152
D gal me	3660	1485	786	1141	949	1181	359	447	310	702	1598	1628	1206	1342
D long	15	59	30	72	191	301	125	23	94	252	157	207	78	56
D retro	1262	416	353	379	461	509	229	212	174	395	721	664	393	480
C lac			3			5	2			6				
C quad			3											
Cer ret														
B long			3			5	4	9	4	59				
E coreg	182	59	23	40	43	28	13	15	30	59	47	98	110	107
D dent														
A harp														
A affin						14								
A quad														
C sphaer														
E lameil						14								
Clad imm.	95	17	63	80	114	51	2	44	25	135	78	164	78	83
Calan Tot (#/m^3)	1148	755	526	2842	1066	1015	1517	519	599	2969	2601	743	431	440
Calan Tot (%)	16.9	24.8	27.9	60.4	35.6	29.2	63.0	35.4	46.7	52.7	40.5	19.3	16.1	15.7
Cyclo Tot (#/m^3)	80	34	3	75	69	209	93	23	10	899	533	43	67	105
Cyclo Tot (%)	1.2	1.1	0.2	1.6	2.3	6.0	3.9	1.6	0.8	16.0	8.3	1.1	2.5	3.7
Clad Tot (#/m^3)	5570	2291	1354	1787	1859	2248	798	926	674	1766	2758	3071	2173	2258
Clad Tot (%)	81.9	75.2	71.9	38.0	62.1	64.7	33.1	63.1	52.5	31.3	42.9	79.6	81.4	80.6
Grand Total	6798	3046	1883	4704	2994	3472	2408	1468	1283	5634	6425	3857	2671	2803

App. F.2 cont.

Cruise: 2

Station:	17	18	19	22	23	24	24	24	25	26	26	27	27	28
Date:	Sep 19	Sep 19	Sep 19	Sep 19	Sep 19	Sep 18	Sep 17	Sep 17	Sep 18	Sep 18	Sep 18	Sep 18	Sep 18	Sep 18
Tow length in meters:	9→S	15→S	24→S	18→S	17→S	18→S	18→8	8→S	25→S	33→17	17→S	50→15	15→S	61→S
Species:														
Calanoid Copepoda														
D ash	23	44	6		34	62	108	191	54	13	147	4	31	9
D min	26	94	46	32	47	131	49	60	73		12	3	20	29
D oreg	153	120	140	199	195	304	517	180	218	35	96	27	87	36
D siclis	4		3			6	3	7		25		12	17	1
D cops	428	344	334	477	297	2712	5253	1956	4853	4038	8613	3279	6286	3322
E lac	167	109	50	103	115	92	167	131	174	15	189	28	117	25
L mac			4				34		3	164		149	7	49
S cal										16		24		1
Cyclopoid Copepoda														
C bi th	57	87	31	88	64	296	221	166	522	115	581	144	615	211
M edax				8	4	14	27		13	22	21	4	37	2
T pr mex														
Cladocera														
L kind	31	33	25	8	17	33	38		25	4	63	7	27	1
ped					4		11	11	3					
D leuch	8		4	8		14				2	60		49	10
S cryst														
H gib	46	65	46	167	93	119	27	110	130	31	231	62	219	55
D gal me	757	838	631	1464	806	855	699	1171	623	138	1099	322	1455	204
D long	125	159	106	111	64	215	186	53	196	107	389	83	312	126
D retro	728	470	286	493	675	562	569	488	547	82	407	150	497	120
C lac		1				8			3					
C quad														1
Cer ret														
B long	7					13	10	21	41	16	63	33	107	49
E coreg	80	65	34	103	85	169	70	233	158	51	201	29	229	46
D dent					4									
A harp														
A affin														
A quad														
C sphaer														1
E lamell														
Clad imm.	80	48	19	103	30	45	128	32	54	11	174	10	95	14
Calan Tot (#/m³)	801	711	583	811	688	3307	6131	2525	5375	4306	9057	3526	6565	3472
Calan Tot (%)	29.4	28.7	33.0	24.1	27.2	58.[illegible]	75.5	52.5	69.9	88.1	73.4	80.7	64.4	80.3
Cyclo Tot (#/m³)	57	87	31	96	68	310	248	166	535	137	602	148	652	213
Cyclo Tot (%)	2.1	3.[illegible]	1.8	[illegible].9	[illegible]	5.5	3.1	3.5	7.0	2.8	4.9	3.4	6.4	4.9
Clad Tot (#/m³)	1862	1679	1151	2457	1778	2033	1738	2119	1780	442	2687	696	2985	637
Clad Tot (%)	68.5	67.8	65.2	73.0	70.2	36.0	21.4	44.1	23.1	9.0	21.8	15.9	29.3	14.7
Grand Total	2720	2477	1765	3364	2534	5650	8117	4810	7690	4885	12346	4370	10202	4322

App. F.2 cont.

Cruise: 2

Station:	29	29	30	30	31	38	39	40	41	41	42	42	43	43
Date:	Sep 18	Sep 18	Sep 17	Sep 17	Sep 18	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17
Tow length in meters:	70→20	20→S	44→13	13→S	25→S	21→S	43→S	11→S	53→15	15→S	75→25	25→S	83→20	20→S
Species:														
Calanoid Copepoda														
D ash	3	9	27	106	4	41	28	73	5	221	1	132	1	115
D min	2	4	2	4	4	98	60	252	5	204	1	112	2	25
D oreg	3	99	15	137	116	98	92	75	15	289	2	214	13	140
D siclis	17	9	29	20	11				20	51	12	10	9	13
D cops	3307	4646	8728	7534	3779	3191	5103	2129	1917	3599	622	5132	2151	9983
E lac	2	39	14	27	22	112	101	488	25	119	1	204	7	51
L mac	131	57	61	35		7	32		193		157	10	70	51
S cal	10	8	4						14		8		5	
Cyclopod Copepoda														
C bi th	57	764	222	584	851	324	224	132	52	509	41	856	101	645
M edax	3	8	2		17	11	11	17	15	102	3	20	1	13
T pr mex														
Cladocera														
L kind		9	5	12	17	15	14	57	1	51	2	61	17	38
P ped				8				9				10		
D leuch		13		4	4	15	14	9		17		20	5	38
S cryst														
H gib	9	197	42	353	177	50	267	531	7	526	2	224	41	407
D gal me	17	803	83	893	1557	648	515	1353	105	3480	46	2282	217	3069
D long	19	279	61	615	435	123	89	64	7	68	9	122	25	216
D retro	8	302	36	278	989	818	261	469	17	458	5	153	32	280
C lac														
C quad			1											
Cer ret														
B long	20	113	29	204	225	14	8	92	3	17	11	92	13	153
E coreg	12	69	7	74	50	236	234	323	20	306	11	214	21	140
D dent														
A harp														
A affin														
A quad														
C sphaer														
E lamell														
Clad imm.	1	22	5	51	74	63	73	78	3	68	2	51	17	204
Calan Tot (#/m^3)	3475	4871	8880	7863	3936	3547	5416	3017	2194	4483	804	5814	2258	10378
Calan Tot (%)	96.0	65.4	94.7	71.9	47.2	60.5	76.0	49.0	90.5	44.5	85.9	58.6	82.2	66.6
Cyclo Tot (#/m^3)	60	772	224	584	868	335	235	149	67	611	44	876	102	658
Cyclo Tot (%)	1.7	10.4	2.4	5.3	10.4	5.7	3.3	2.4	2.8	6.1	4.7	8.8	3.7	4.2
Clad Tot (#/m^3)	86	1807	269	2492	3528	1982	1475	2985	163	4991	88	3229	388	4545
Clad Tot (%)	2.4	24.3	2.9	22.8	42.3	33.8	20.7	48.5	6.7	49.5	9.4	32.6	14.1	29.2
Grand Total	3621	7450	9373	10939	8332	5864	7126	6151	2424	10085	936	9919	2748	15581

App. F.2 cont.

Cruise 2

Station:	44	44	45	45	46	46	47	47	48	48	49	49	50	50
Date:	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17	Sep 17
Tow length in meters:	122→20	20→S	84→25	25→S	34→13	13→S	26→12	12→S	20→10	10→S	59→25	25→S	32→10	10→S
Species:														
Calanoid Copepoda														
D ash	1	42	2	73	49	28	22	21	45	13	1	49	24	71
D min		95		17	5	7	9	7	6			4		
D oreg		15	6	166	283	65	124	11	166	53	7	61	55	173
D siclis	8	38	16	17	38		32		34	3	16	30	17	20
D cops	1053	8242	1315	6478	8423	2511	10924	1914	7920	4258	2664	11617	10544	4329
E lac	1	45	1	36	29	30	24	149	130	125	132		3	20
L mac	119	62	159	5	45	11	5	11	3			4	41	10
S cal	12		4								8			
Cyclopoid Copepoda														
C bi th	12	469	50	620	343	460	223	357	170	171	40	949	446	1039
M edax	1	13	6	12	19	4	12	4		3	4	10	3	10
T pr mex														
Cladocera														
L kind		13	1	12	3			11				7	16	20
P ped														
D leuch		15	1	27	11	51	13	35	8			7	4	20
S cryst							3			5				
H gib	3	250	12	261	22	86		25	7	18	3	195	197	295
D gal me	3	1441	22	1723	547	758	347	294	699	456	178	816	481	2017
D long	2	93	17	200	136	217	313	110	246	97	4	286	119	275
D retro	2	214	13	462	509	759	181	272	337	423	11	166	171	91[illegible]
C lac									3					
C quad									4					
Cer ret														
B long	3	85	13	536	82	364	65	683	31	229	17	268	86	376
E coreg	2	23	5	63	11	45	3	25	3	23	4	24	23	10
D dent														
A harp														
A affin														
A quad														
C sphaer			1							5			4	
E lamell														
Clad imm.		89	2	68	35	14	35	18	39	23	19	50	103	
Calan Tot (#/m^3)	1194	8539	1503	6792	8872	2652	11140	2113	8304	4452	2828	11765	10684	4623
Calan Tot (%)	97.7	75.9	91.3	63.0	83.8	49.0	90.3	53.5	84.3	75.4	91.0	80.9	86.6	48.4
Cyclo Tot (#/m^3)	13	482	56	632	362	464	235	361	170	174	44	959	449	1049
Cyclo Tot (%)	1.1	4.3	3.4	5.9	3.4	8.6	1.9	9.1	1.7	2.9	1.4	6.6	3.6	11.0
Clad Tot (#/m^3)	15	2223	87	2352	1356	229[illegible]	960	147[illegible]	1377	1279	[illegible]36	1819	1204	3880
Clad Tot (%)	1.2	19.8	5.3	31.1	12.[illegible]	42.4	[illegible].8	37.[illegible]	14.0	21.[illegible]	[illegible]	12.5	9.3	40.6
Grand Total	1222	11244	1646	10776	1059[illegible]	[illegible]	12335	3947	9851	5905	3108	14543	12337	955[illegible]

Appendix F.3

Cruise: 3

Station:	1	2	3	3	4	5	6	7	8	9	10	10	11	12
Date:	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6
Tow length in meters:	15→S	23→S	38→15	15→S	25→S	16→S	12→S	12→S	23→S	41→S	23→14	14→S	31→S	14→S
Species:														
Calanoid Copepoda														
D ash	444	97	26	88	168	79	22	10		104	25	211	88	170
D min	235	29	17	78	146	36	7	20		26	11	47	53	
D oreg	366	73	28	204	142	46	41	41	6	287	40	131	53	191
D siclis	13	24	1		18	20		20			15	152	70	64
D cops	9272	3124	2008	5826	4698	3142	1962	5724	4693	5171	4667	10702	6375	8467
E lac	457	354	100	689	120	142	26	153	55	131	40	156	73	170
L mac											29	7		
S cal								20						
Cyclopoid Copepoda														
C bi th	1854	500	181	940	744	496	1493	1569	1686	1254	357	1833	896	955
M edax	104	19	12	17		30	21		6			18		
T pr mex														
Cladocera														
L kind	91	34	8	48	13	13	14							21
P ped								20				15	18	
D leuch	39	15	6	27		10	15		30				53	21
S cryst														
H gib	392	160	36	136	337	116	63	448	109	2089	113	1855	1633	2313
D gal me	2847	1106	216	2200	2458	1042	651	2047	1728	6216	327	8345	4373	4987
D long	26	5	6	7	4		72	61	18	78	113	189	105	424
D retro	2089	490	163	1508	607	443	547	346	164	862	62	557	246	233
C lac														21
C quad														
Cer ret														
B long	692	68	19	71	44	36	95	1721	176	575	44	211	351	509
E coreg	131	267	79	407	248	136	186	285	273	366	55	422	263	297
D dent			1											
A harp														
A affin														
A quad				14										
C sphaer	26	5		17										
E lamell														
Clad imm.	379	330	47	336	208	53	107	479	73	496	15	819	316	1231
Calan Tot (#/m^3)	10787	3701	2180	6885	5292	3465	2058	5988	4754	5719	4827	11406	6712	9062
Calan Tot (%)	55.4	55.2	73.8	54.6	53.2	59.3	38.6	49.1	52.7	32.4	81.6	44.4	44.8	45.1
Cyclo Tot (#/m^3)	1958	519	193	957	744	526	1514	1569	1692	1254	357	1851	896	955
Cyclo Tot (%)	10.1	7.7	6.5	7.6	7.5	9.0	28.4	15.5	18.8	7.1	6.0	7.2	6.0	4.8
Clad Tot (#/m^3)	6712	2480	581	4771	3919	1849	1750	2571	2571	10682	729	12413	7358	10057
Clad Tot (%)	34.5	37.0	19.7	37.8	39.4	18.6	33.0	25.4	28.5	60.5	12.3	48.4	49.2	50.1
Grand Total	19457	6700	2954	12613	9955	5840	5322	10128	9017	17655	5913	25670	14966	20074

App. F.3 cont.

Cruise: 3

Station:	13	14	15	16	17	18	19	20	21	22	23	24	24	25
Date:	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 7	Oct 8	Oct 8
Tow length in meters:	22→S	24→S	25→S	17→S	14→S	15→S	24→S	17→S	13→S	20→S	17→S	17→S	17→S	25→S
Species:														
Calanoid Copepoda														
D ash	204	35	50	92	46	131	21	68	93	57	59	25	10	66
D min	166	100	66	75	24	176	63	91	46	66	34	25	13	133
D oreg	178	93	28	59	81	52	99	68	139	125	140	45	159	421
D siclis		54	39	70	18	52	52	79	69	172	64	14	73	133
D cops	5157	3715	3997	6227	2527	5158	3423	8451	7209	9682	8153	2795	7169	9632
E lac	509	305	149	324	209	340	94	136	46	7	306	182	109	576
L mac			6		2						4			22
S cal														
Cyclopoid Copepoda														
C bi th	1502	583	576	779	142	803	496	849	1313	1294	938	595	932	2081
M edax	38	46	11	32	7	20	37	11		42	25	20	30	
T pr mex														
Cladocera														
L kind	13	15	6	14	4		21	23		7	25	3	8	22
P ped												3		
D leuch	25	8	11	20	2	33	21	68	46	59	21	6	8	66
S cryst														
H gib	993	606	161	284	156	307	271	1720	995	974	361	73	394	2059
D gal me	4100	1848	1268	1429	532	2638	1085	2422	5024	2568	896	446	925	8171
D long	38	27		63	14	26	16	136	278	113	136	45	111	244
D retro	980	278	454	837	137	516	230	181	995	262	488	219	361	1528
C lac														
C quad														
Cer ret														
B long	153	46	72	68	68	104	125	306	324	184	119	126	136	266
E coreg	815	463	637	362	163	620	287	487	278	865	301	140	371	509
D dent														
A harp														
A affin														
A quad														
C sphaer												3		
E lamell														
Clad imm.	586	390	316	390	58	248	292	160	162	309	144	51	45	288
Calan Tot (#/m^3)	6214	4302	4335	6847	2907	5909	3752	8893	7602	10109	8760	3086	7533	10983
Calan Tot (%)	40.2	50.0	55.2	61.5	69.4	52.6	58.4	58.3	44.7	60.2	71.7	64.1	69.4	41.9
Cyclo Tot (#/m^3)	1540	629	587	811	149	823	533	860	1313	1336	963	615	962	2081
Cyclo Tot (%)	10.0	7.3	7.5	7.3	3.6	7.3	8.3	5.6	7.7	8.0	7.9	12.8	8.9	7.9
Clad Tot (#/m^3)	7703	3681	2925	3467	1134	4492	2141	5503	8102	5341	2491	1115	2359	13153
Clad Tot (%)	49.8	42.7	37.3	31.2	27.1	40.0	33.3	36.1	47.6	31.8	20.4	23.2	21.7	50.2
Grand Total	15457	8612	7847	11125	4190	11224	6426	15256	17017	16786	12214	4816	10854	26217

App. F.3 cont.

Cruise: 3

Station:	26	27	27	28	28	29	29	30	30	30	30	31	32	33
Date:	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 8	Oct 7	Oct 7	Oct 8	Oct 8	Oct 8	Oct 6	Oct 6
Tow length in meters:	33→S	49→33	33→S	63→44	44→S	71→40	40→S	41→30	30→S	40→26	26→S	25→S	19→S	24→S
Species:														
Calanoid Copepoda														
D ash	33	5	39	11	58	4	19		8	17	98	44	75	46
D min	82				46		19		59		59	44	45	46
D oreg	246	78	177	41	58	18	153	10	68	29	235	177	60	116
D siclis	66	112	170	112	116	65	57	10	34	25	118	89		116
D cops	12387	5968	12608	3666	7060	2456	8206	1384	6221	4477	11008	7396	8434	9213
E lac	49	5	31	3	382	2	25		59	15	118	66	30	35
L mac		332		384		160	6	23		2				
S cal		39		37		10								
Cyclopod Copepoda														
C bi th	2530	509	1968	233	1030	196	1127	57	1282	341	1743	1506	1932	1377
M edax	99	15		10		4	19		17		59	44	45	
T pr mex														
Cladocera														
L kind		5	15	4		1	6		8	4	20	66	15	
P ped									68					
D leuch	164		39	7	23	4	64	5	42	31	98	133	90	162
S cryst														
H gib	854	107	486	72	625	29	236	3	696	44	627	2901	1393	683
D gal me	3779	87	1999	172	2558	27	1986	26	1961	114	3761	7883	7879	2616
D long	1068	5	147	3	35	2	64	5	42	10	78	199	240	93
D retro	789	15	224	16	231	1	376		297	42	627	1395	1348	208
C lac														
C quad														
Cer ret														
B long	378	61	231	27	278	6	191	21	416	75	392	531	240	289
E coreg	756	24	556	23	208	10	363	3	272	42	1097	841	360	313
D dent														
A harp														
A affin														
A quad														
C sphaer														
E lamell														
Clad imm.	411	7	170	20	162	1	32		263	25	39	664	584	185
Calan Tot (#/m^3)	12863	6539	13025	4254	7720	2715	8485	1427	6449	4565	11636	7816	8644	9572
Calan Tot (%)	54.3	88.7	69.1	87.9	60.0	90.6	65.5	92.2	54.6	86.2	57.7	32.6	38.0	61.8
Cyclo Tot (#/m^3)	2629	524	1968	243	1030	200	1146	57	1299	341	1802	1550	1977	1377
Cyclo Tot (%)	11.1	7.1	10.4	5.0	8.0	6.7	8.9	3.7	11.0	6.4	8.9	6.5	8.7	8.9
Clad Tot (#/m^3)	8199	311	3867	344	4120	81	3318	63	4065	387	6739	14613	12149	4549
Clad Tot (%)	34.6	4.2	20.5	7.1	32.0	2.7	25.6	4.1	34.4	7.3	33.4	60.9	53.4	29.4
Grand Total	23691	7374	18860	4841	12870	2996	12949	1547	11813	5293	20177	23979	22770	15498

App. F.3 cont.

Cruise: 3

Station:	34	34	35	35	36	36	37	37	38	39	40	41	41	42
Date:	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 6	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7
Tow length in meters:	38→25	25→S	48→38	38→S	51→40	40→S	50→37	37→S	20→S	38→S	12→S	53→28	28→S	74→40
Species:														
Calanoid Copepoda														
D ash		92		47		51	2	69	85	42		1	9	3
D min	2	20		7		13		28	94	7	102	2	14	
D oreg	36	102	3	47	29	108	42	55	207	99	25	3	46	
S siclis	13	102	32	34	51	38	57	55	99	35		9	32	
D cops	2077	12865	897	6976	1697	7143	2896	5196	11365	10285	1579	680	4315	279
E lac	6	31	6	74		32	17	28	66	28	1961		46	
L mac	2		214		111		137					73		253
S cal							6					2		6
Cyclopoid Copepoda														
C bi th	189	2078	90	1072	110	1407	202	984	1113	1443	1604	20	287	12
M edax	2		9	13		13	8	7	9		25	10		
T pr mex														
Cladocera														
L kind	4			20		13	2		28	14	76	1	14	
P ped														
D leuch	2	194		60		32	2	21	38	7		1		
S cryst														
H gib	46	591	17	931	26	376	103	860	1056	283	3336	7	232	3
D gal me	40	3392	35	1689	41	1483	109	2182	2075	1761	6239	10	746	4
D long	8	92	6	67		178	11	69	85	191	127	2	9	
D retro		285	3	194	6	280	8	310	344	389	815	2	164	1
C lac														
C quad										7				
Cer ret														
B long	2	173		228	8	115	21	241	236	191	458	1	32	1
E coreg	11	479	9	355		121	6	220	655	255	102	3	150	
D dent														
A harp														
A affin														
A quad														
C sphaer														
E lamell														
Clad imm.		418		328		166	13	303	481	127	153	4	159	
Calan Tot (#/m^3)	2136	13212	1152	7185	1888	7385	3157	5431	11916	10496	3667	770	4462	541
Calan Tot (%)	87.5	63.2	87.2	59.2	90.8	63.8	86.7	51.1	66.1	69.2	22.1	92.7	71.3	96.3
Cyclo Tot (#/m^3)	191	2078	99	1085	110	1420	210	991	1122	1443	1629	30	287	12
Cyclo Tot (%)	7.8	9.9	7.5	8.9	5.3	12.3	5.8	9.3	6.2	9.5	9.8	3.6	4.6	2.1
Clad Tot (#/m^3)	113	5624	70	3872	81	2764	275	4206	4998	3225	11306	31	1506	9
Clad Tot (%)	4.6	26.9	5.3	31.9	3.9	23.9	7.6	39.6	27.7	21.3	68.1	3.7	24.1	1.6
Grand Total	2440	20914	1321	12142	2079	11569	3642	10628	18036	15164	16602	831	6255	562

App. F.3 cont.

Cruise: 3

Station:	42	43	43	44	44	45	45	46	46	47	48	49	49	50	50
Date:	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7	Oct 7
Tow length in meters:	40→S	81→35	35→S	120→50	50→S	85→15	15→S	34→18	18→S	25→S	20→S	59→30	30→S	35→19	19→S
Species:															
Calanoid Copepods															
D ash	6		7		20	1	42	10	7	19	6		76	8	40
D min	13		22		61	1	127		28		1				
D oreg	41		87			6	102	63	134	123	72	8	59	61	134
D siclis	19	11	65	6	41	22	136	78	5	78	42	39	51	60	80
D cops	2820	141	7770	89	4828	1487	5467	5738	7894	6873	3379	836	5034	3726	7948
E lac	67		58		20	2	34	2	71	13	5	4	34	2	27
L mac		257		129		16		5		4	1	95		8	
S cal		20		11		1						3			
Cyclopoid Copepoda															
C bi th	245	12	822	6	611	154	1664	413	1344	590	490	46	874	157	978
M edax		1		1		8		12	7	15	5	1	34	10	40
T pr mex															
Cladocera															
L kind	10		36			2	17		14		12	1	25	12	
P ped									7		3	1			
D leuch		1	22		31	1	34	2	113	46	37	3	76	33	214
S cryst															
H gib	236	13	742	5	306	10	679	12	325	194	44	21	1044	22	469
D gal me	694	2	2168	3	1813	54	4015	218	1938	454	224	21	1689	69	4879
D long	16		7		10	7	119	21	57	45	14		34		174
D retro	67	1	29		163	8	382	17	297	172	120		492	5	978
C lac															
C quad															
Cer ret															
B long	38		160		71	11	212	61	531	340	228	5	424	39	214
E coreg	131	3	226	1	173	10	323	17	467	95	28	9	212	17	509
D dent															
A harp															
A affin															
A quad															
C sphaer															
E lamell															
Clad imm.	159	1	175		51	1	289	26	226	51	28	5	297	7	335
Calan Tot (#/m^3)	2966	429	8009	235	4970	1536	5908	5896	8139	7110	3506	985	5254	3865	8229
Calan Tot (%)	65.0	92.7	64.6	93.6	60.6	85.2	43.3	88.1	60.4	78.0	74.0	89.	50.3	91.2	48.4
Cyclo Tot (#/m^3)	245	13	822	7	611	162	1664	425	1351	605	495	47	908	167	1018
Cyclo Tot (%)	5.4	2.8	0.7	2.8	7.5	9.0	12.2	6.3	10.0	6.6	10.4	4.3	8.7	3.9	6.0
Clad Tot (#/m^3)	1351	21	3565	9	2618	104	6070	374	3975	1397	738	66	4293	204	7772
Clad Tot (%)	29.6	4.5	28.8	3.6	31.9	5.8	44.5	5.6	29.5	15.3	15.6	6.0	41.1	4.8	45.7
Grand Total	4562	463	12396	251	8199	1802	13642	6695	13465	9112	4739	1098	10455	4236	17019

Appendix F.4

Cruise: 2 Lake Michigan

Station:	13	20	21	22	23	24	25	26	27
Date:	Sep 23	Sep 21	Sep 21	Sep 21	Sep 21	Sep 21	Sep 21	Sep 21	Sep 23
Tow length in meters:	185	110	90	117	162	164	151	55	84
Species:									
Calanoida Copepoda									
D ash	2	5	8	18	11	7	3	40	23
D min	2	6	3	3	1	2		10	11
D oreg	9	80	55	87	64	58	41	172	90
D siclis	37	144	79	67	34	28	37	8	45
D cops	76	780	424	244	191	136	96	301	415
E lac	1	24	17	24	52	4	2	3	3
L mac	97	38	29	64	60	60	66	14	70
S cal	2	2			1	1	1		
Cyclopoid Copepoda									
C bi th	3	17	14	7	13	7	2	25	28
M edax	7	24	28	21	17	20	10	29	25
Cladocera									
L kind		6	8	6	6	3	5	2	5
D leuch			2	1	1	2	1		2
H gib	4	68	20	8		7	10	29	42
D gal me	15	295	199	104	95	82	32	298	171
D long				1					
D retro	15	189	109	120	89	86	28	427	399
C lac	1		2					2	5
C quad		2							
B long	1	2							
E coreg	5	35	43	34	22	40	13	223	101
A harpae									
C sphaer									
Clad imm.	2	2	2	9		3		8	
Calan Tot (#/m³)	226	1079	615	507	414	296	246	548	657
Calan Tot (%)	81	63	59	62	63	54	71	34	46
Cyclo Tot (#/m³)	10	41	42	28	30	27	12	54	53
Cyclo Tot (%)	4	2	4	3	5	5	3	3	4
Clad Tot (#/m³)	43	599	385	283	213	223	89	989	725
Clad Tot (%)	15	35	37	35	32	41	26	62	51
Grand Total	279	1719	1042	818	657	546	347	1591	1435
Amphipoda									
P. aff. (# in sample)						1			
Mysidacea									
M. rel. (# in sample)	156				96	32	105		

App. F.4 cont.

Cruise: 2 Lake Michigan

Station:	28	44	45	46	47	48	52	53	54
Date:	Sep 23	Sep 23	Sep 23	Sep 23	Sep 23	Sep 23	Sep 20	Sep 20	Sep 20
Tow length in meters:	166	10	274	272	123	12	33	24	17
Species:									
Calanoida Copepoda									
D ash	12	60	8	3	11	31	30	93	145
D min	3	11		1	3	22	5	8	17
D oreg	43	64	30	17	81	91	241	305	490
D siclis	25	64	21	17	37	31	3	4	
D cops	130	718	68	46	137	149	386	880	1254
E lac	9	67	1	3	9	98	27	127	25
L mac	72	191	73	70	89	40	14	12	6
S cal	2			2					
Cyclopoid Copepoda									
C bi th	13	110	2	2	6	40	14	96	149
M edax	17	7	7	5	21	11	14	12	25
Cladocera									
L kind	2	28	2	2	4	14	19	46	19
D leuch	1	7			1	7			6
H gib	21	258	6	19	21	48	49	147	45
D gal me	120	672	39	37	103	424	496	945	870
D long								15	64
D retro	169	1337	55	78	62	213	249	455	687
C lac	2	18	1		3	3		8	4
C quad									
B long									4
E coreg	73	343	33	14	46	170	99	93	89
A harpae		7							
C sphaer	1								
Clad imm.									
Calan Tot (#/m^3)	296	1175	201	159	367	462	706	1429	1937
Calan Tot (%)	41	30	58	50	58	33	43	44	50
Cyclo Tot (#/m^3)	30	117	9	7	27	51	28	108	174
Cyclo Tot (%)	4	3	3	2	4	4	2	3	4
Clad Tot (#/m^3)	389	2670	136	150	240	879	912	1709	1788
Clad Tot (%)	54	67	39	47	38	63	55	53	46
Grand Total	715	3962	346	316	634	1392	1646	3246	3899
Amphipoda									
P. aff. (# in sample)									
Mysidacea									
M. rel. (# in sample)	26		167	201	1				

TECHNICAL REPORT DATA
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15. SUPPLEMENTARY NOTES

16. ABSTRACT

Three cruises were conducted from August to October 1973 in the vicinity of the Straits of Mackinac. Environmental conditions were influenced by the net transport of water from Lake Michigan to Lake Huron, the oscillatory flow of water produced by seiches between the two lakes and the hypolimnetic transport of water from Lake Huron to Lake Michigan during periods of thermal stratification. Different water masses resulted from the mixing of waters from Lake Huron, Lake Michigan and Lake Superior and were identified from single parameters, particularly silica, nitrate, pH, temperature and specific conductance, from cluster analysis of chemical and physical parameters and from ordination analyses of phytoplankton and zooplankton assemblages.

Lake Michigan waters transported through the Straits represent a diffuse and relatively small phosphorus enrichment for Lake Huron, but were depleted in silica and nitrate compared to Lake Huron. In August and September phytoplankton in the silica depleted waters from Lake Michigan were dominated by blue-green algae. The phytoplankton assemblages in the Straits were distinct from those in the open waters of Lake Michigan and Lake Huron. Zooplankton species composition was similar at the 50 stations sampled, but cladocerans were proportionately more prevalent in the more eutrophic waters of Lake Michigan than were calanoid copepods in Lake Huron. It was concluded that water from Lake Michigan had a subtle deleterious effect on water quality in Lake Huron.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Nutrients, phosphorus, silica, chlorophyll, phytoplankton, zooplankton	Straits of Mackinac Lake Michigan Lake Huron Ordination Analyses Cluster Analyses Eutrophication Communities	06C 08H

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